Cinder Lake Landfill Leachate Monitoring Project Final Report

Prepared for:
Ken Fergason
Cinder Lake Landfill Project Manager
6770 E. Landfill Road
Flagstaff, AZ 86004

Submitted By:
TB Associates Inc.
Tristan Wheeler & Brandon Bennehoff
1899 S. San Francisco Street
Flagstaff, AZ 86001

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TB ASSOCIATES INC.

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List of Abbreviations

HELP-Hydraulic Evaluation for Landfill Performance
RCRA-Resource Conservation and Recovery Act
EPA-Environmental Protection Agency
MULTIMED-Multimedia Exposure Assessment Model
MSW-Municipal Solid Waste
SUTRA-Saturated Unsaturated Transport Model
TOUGH2-Transport of Unsaturated Groundwater and Heat
MODFLOW-NWT- Modular Three-Dimensional Finite-Difference Groundwater Flow Model – Newton-Raphson Formulation Technique
USGS- United States Geological Survey

Acknowledgements

The engineering team would like to thank the technical advisors, client, and grading instructor for their contribution to the project.

The TA and client Ken Fergason, Project Manager at Cinder Lake Landfill, helped greatly in the initial site investigation and the procurement of various valuable data used in the research of this project.

The other TA and client Matt Morales, Senior Project Manager at Cinder Lake Landfill, also helped greatly in the initial site investigation by providing the team with his advanced knowledge of the landfill operations.

Dr. Jeffery Heiderscheidt, the team's grading instructor, is due acknowledgement for his continuous support and guidance in ensuring the team stayed in the scope of the project and delivered quality results.

1.0 Introduction

The Cinder Lake Landfill has requested a three-dimensional model of the leachate passing through the unsaturated zone underlying the landfill. The team conducted a preliminary site investigation to obtain necessary landfill data. The data was analyzed to determine the necessary parameters to input into the landfill Hydraulic Evaluation of Landfill Performance model (HELP) the leachate flow through the bottom of thelandfill. Research was conducted to determine the optimal three-dimensional unsaturated zone model, which was used to create a plume of the leachate flow through the unsaturated zone to estimate the time it would take leachate to reach the underlying aquifer after landfill closure.

1.1 Location

The City of Flagstaff Cinder Lake Landfill property sits on 344 acres of land northeast of downtown Flagstaff, Arizona. Figure 1-1 shows the location of the Cinder Lake Landfill in relation to the state of Arizona [1]. The landfill is located in central Northern Arizona, just north of I-40 approximately 11 miles northeast of Flagstaff as shown in Figure 1-2 [1].

Figure 1-1: Landfill Location in Relation to Arizona

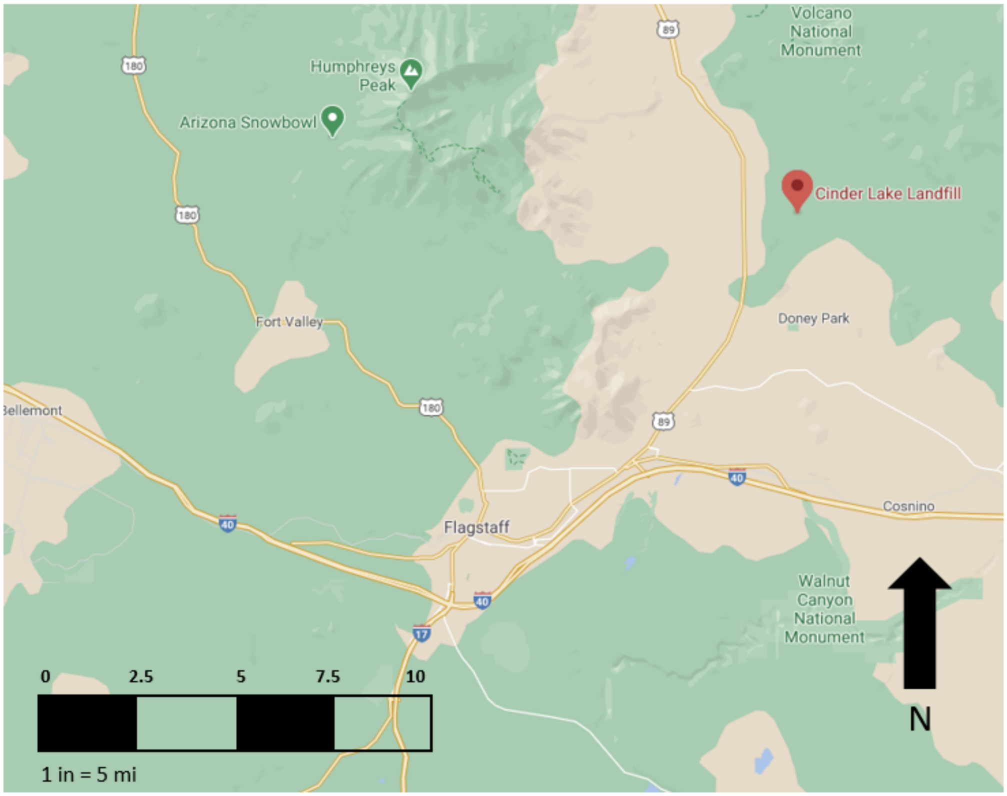


Figure 1-2: Landfill Location in Relation to Flagstaff

1.2 Background

The current operating landfill footprint covers 108 acres consisting of 3 waste cells - A, B, and C. Another two cells, D and E will be used for future expansion purposes and will not be assessed in this report. The Cinder Lake Landfill was designed and constructed before the creation of the Environmental Protection Agency, which now mandates landfills within the U.S. to meet composite liner requirements. The U.S. EPA also mandates laws and regulations under the Resource Conservation and Recovery Act (RCRA) for current landfill monitoring and post closure landfill monitoring with corrective action plans in place. Since the Cinder Lake Landfill lacks an underlying liner, it is suggested that possible migration of leachate created is a threat to the C-Aquifer in the Little Colorado River Basin at the depth of 1,600 feet below the landfill [2].

Figure 1-3 shows the Cinder Lakes Landfill site layout. The image was obtained from the landfill 2018 Solid Waste Plan [2]. Cells A-C show the current cells used for disposal of municipal solid waste. Cells D and E are for future landfill expansion. The entire area of cells A-E is 344 acres. The area of the currently used cells (A-C) is 108 acres. As previously stated, only cells A-C will be considered for project analysis and modeling.

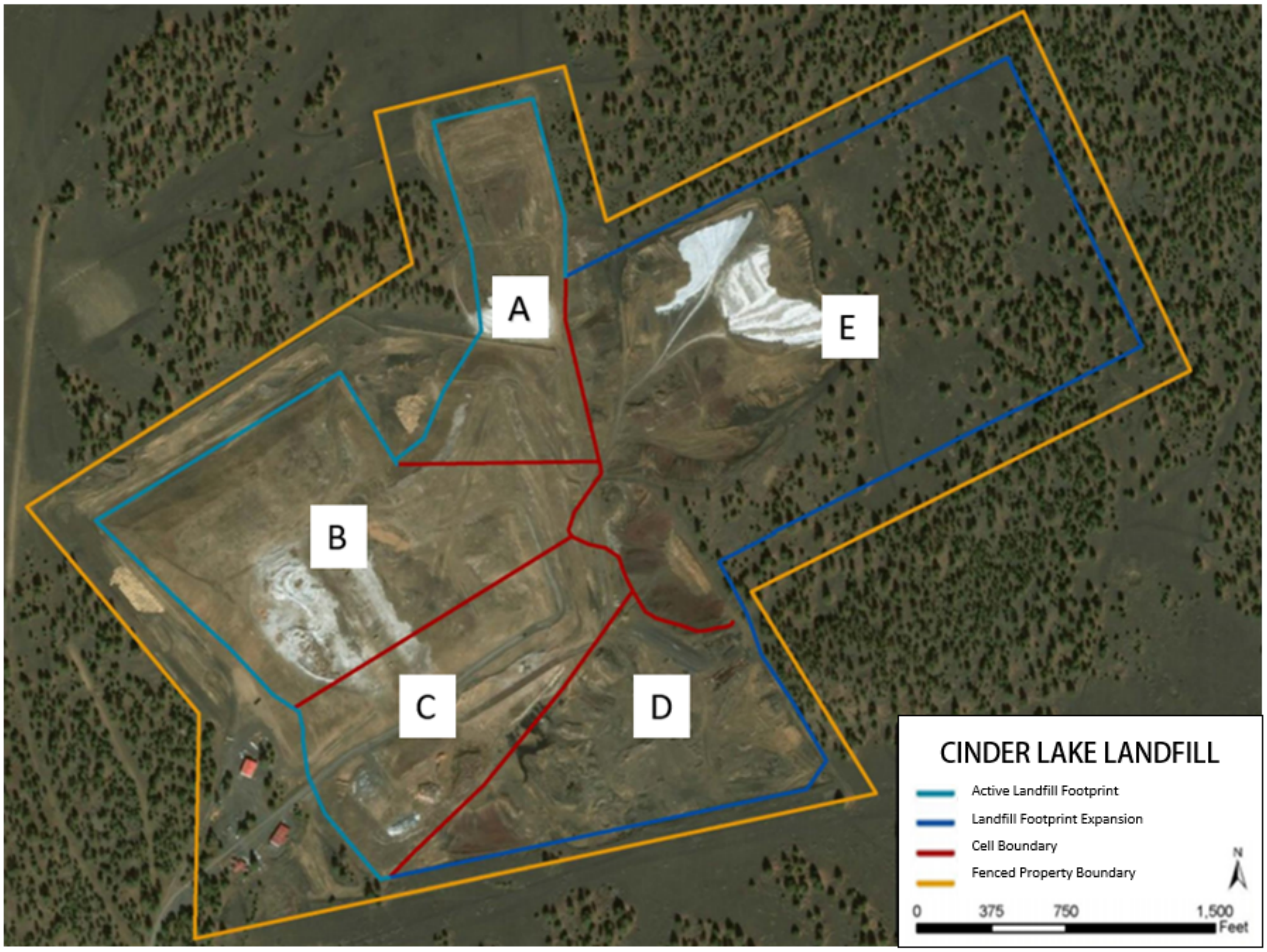
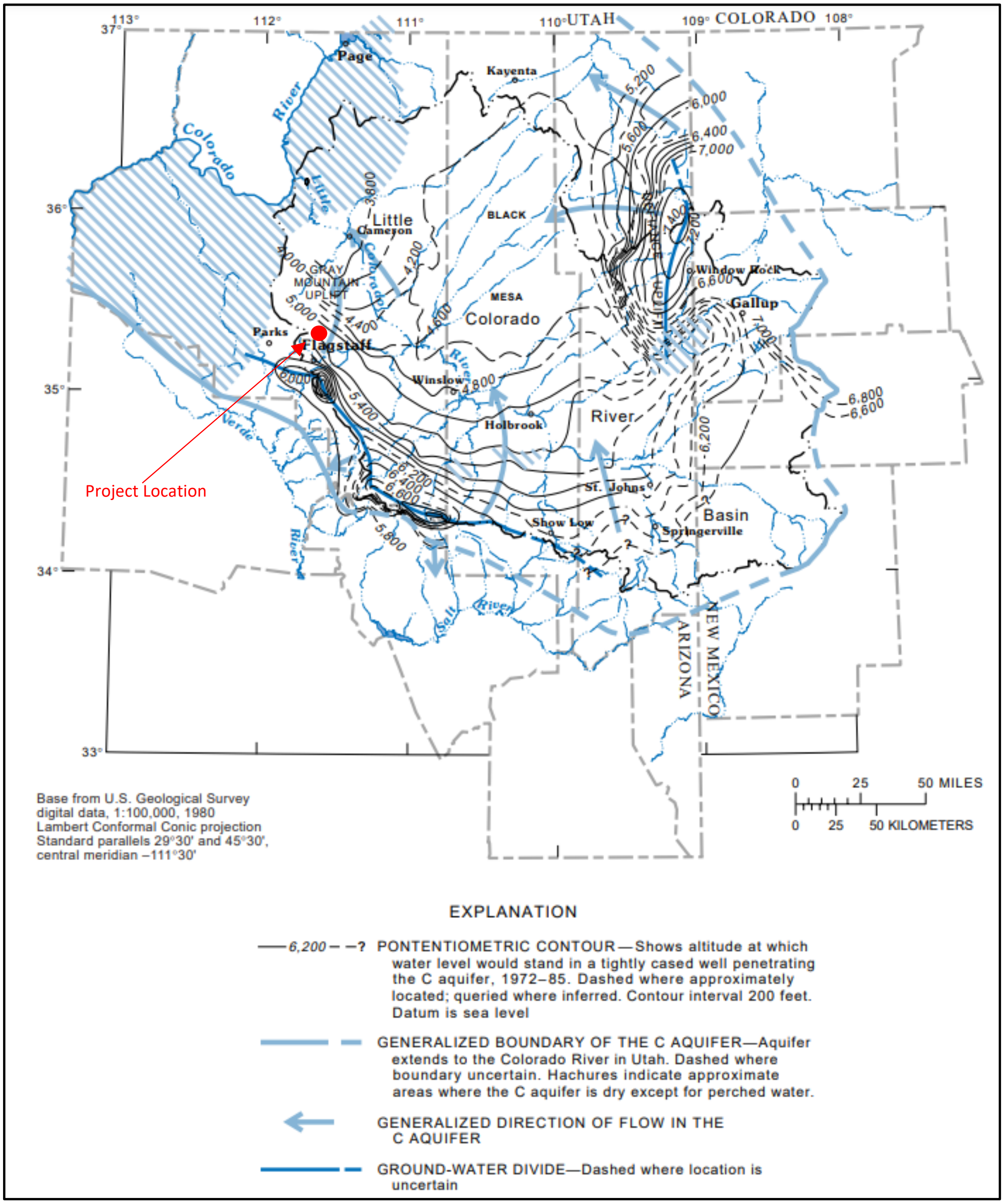


Figure 1-3: Cinder Lake Landfill Site Map

Figure 1-4 below shows the groundwater flows of the Coconino Aquifer in relation to northern Arizona. It is important to note that most of the ground water in the Coconino Aquifer moves north from a ground-water divide that roughly underlies the Mogollon Rim along the southwestern boundary of the Little Colorado River Basin toward the Little Colorado River.



Base from U.S. Geological Survey digital data, 1:100,000, 1980
Lambert Conformal Conic projection
Standard parallels 29°30' and 45°30', central meridian –111°30'

Figure 1-4: Coconino Aquifer Boundary and Direction of Flow [13]

1.3 Constraints and Limitations

There are various constraints and limitations to this project. The main constraint was that the underlying soil beneath the landfill is very complex. The surface of the ground is observed as volcanic cinders, but underlying stratums may consist of basalt flows with variable hardness, thickness, and extent.

Limitations of this project also include the drawbacks of the HELP model. Numerous assumptions are made by the HELP model, which adds uncertainty to the results. The HELP model assumes the landfill's footprint is square, with a uniform waste layer and bottom elevation. Additionally, model assumptions were made due to the various unknown inputs and parameters. However, this is the only model that evaluates landfills hydrologically and is used by many companies and government organizations.

Another limitation in this project was the applicability of the SUTRA3.0 3-D model, in that many in the model about the lithography in the vadose zone due to a lack of available geotechnical data.

1.4 Objectives

The design team had three major objectives, which include:

- Improving the modeling of potential for leachate to migrate to the Coconino Aquifer underlying the landfill
- Provide the client a justification report for the best 3-D modeling software to create a visual leachate migration map
- Determine the time for leachate to travel to the underlying aquifer after landfill closure

1.5 Exclusions

Prior to implementing the scope, the design team lost a member. This affected the initial project scope in that the remaining team had to omit a task to ensure the project still was achievable given the one semester time constraint. The team had to omit Task 4: Research and Compare Geophysical Monitoring Methods. This task was not on the critical path for project completion and was only omitted to ensure the scope of the project was not too large for two team members. Additionally, the project analyzed the leachate leaving the landfill and no other byproducts created by the landfill such as gas emissions. Finally, no soil, leachate or other samples were obtained or analyzed.

2.0 Site Investigation

The site investigation took place on January 13th, 2021. The engineering team was able to tour the Cinder Lake Landfill facility to get an understanding of its size, visual characteristics, operations, and to build a relationship with the client. The team saw firsthand the hydroprobes used for monitoring and the monitoring well locations.

2.1 Site Visit

The team saw firsthand the hydroprobes used for monitoring and the monitoring well locations. The client was able to show the team the 3 observation wells on the property, 2 of which are within the landfill footprint and 1 just outside the landfill used for background conditions. Figure 2-1 shows a photo of one of the active monitoring wells located in the landfill and the location of all three wells is shown on Figure 2-3. Additionally, the team witnessed the process of collecting, separating and moving waste. Furthermore, a drone was used to capture an aerial photograph of the site facing east, which can be seen in Figure 2-2 and the figure on the cover page. The tarps in the middle of the photograph were used to prevent waste from blowing away in the wind. The screens to the left of the photograph were also used to prevent waste from blowing away from the site.

Figure 2-1: Hydroprobe Monitoring Well

Figure 2-2: Aerial Site Photograph

2.2 Obtain Site Data

The initial site investigation also showed the team that the landfill is located in a relatively small, dry sedimentary basin called Cinder Lake that is approximately 5 square miles. Topographically, the regional slope of the basin runs north to south and the terrain is rugged and irregular. The areas surrounding the landfill includes groups of extinct volcanoes that consist of numerous cinder cones with lava flows and cinder deposits. Deposition of alluvial material called cinders in the Cinder Lake basin has formed a relatively flat and treeless area suitable for a landfill. Figure 2-3 shows a topographic map of the landfill and the surrounding area [3]. The 3 vadose zone monitoring wells observed during the site investigation are circled in red. The team also received hydroprobe moisture content data, landfill layer data, and geotechnical data, which was used for further analysis.

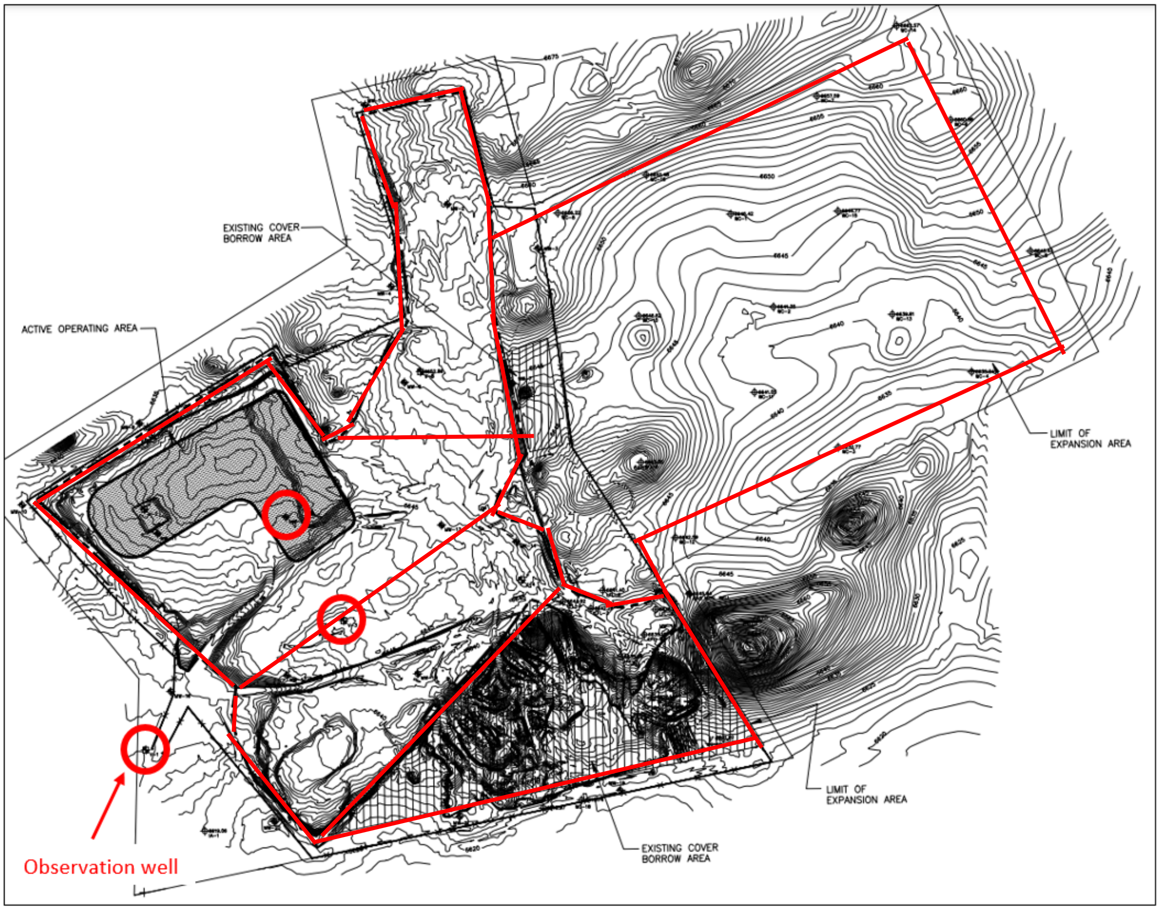


Figure 2-3: Topography of Cinder Lake Landfill

The procurement of hydroprobe moisture data, previous model simulation results, AutoCAD files and additional site documents were completed at this time. Any other data that seemed relevant to this project was easily located on the City of Flagstaff Landfill webpage on the public reports tab.

3.0 Analyze Site Documents

The team sorted through and analyzed previous modeling results, hydroprobe data and landfill layer data. This was done to allow for the creation of an accurate hydrologic model and the ability of the team to analyze the impacts of the hydroprobes in later tasks.

3.1 Previous Modeling Data Collection and Analysis

The team was able to get the modeling results of the HELP model, which was run in 1994 for different layering scenarios by a third party contracted by the landfill. The procurement of previous modeling results was conducted to get a grasp of what should be expected in the model that the team ran. The analysis of the outputs and inputs of the previously ran models showed the team what exact soil parameters were used, the depth of the layers within the landfill, and the percolation rates of leachate leaving the landfill for all scenarios.

3.2 Hydroprobe Data Collection and Analysis

The team was given a log of hydroprobe data from the client that spanned from 1995-2020. The log consisted of quarterly moisture content readings within the monitoring wells taken at 1-foot intervals between the depths of 60-80 feet below surface level within the landfill. Because the data was relatively consistent from 1990-2020, only the previous 5 years of data was used for analysis. The data was then averaged and used as an input into a sensitivity analysis in the HELP model. The average moisture content across all wells in the past 5 years was 18.2%. The highest quarterly measurement was 20.46%, and the lowest was 13.97%. The standard deviation of the data was 0.88, and the median moisture content was 18.03%. The quarterly moisture content data for the 4 different hydroprobes can be seen in Appendix A, specifically tables A-1 to A-4.

3.3 Landfill Layer Data Collection and Analysis

After examining the provided reports and data, cross sectional graphs of boring logs were used to gather the depth of the municipal solid waste (MSW) and the datum elevation of the landfill. Since the landfill currently does not have any complex layers for leachate or gas collection, it is safe to assume only two layers exist in the current landfill: MSW and intermediate cover. The depth values of waste and cover were found for use in future modeling and sensitivity analyses.

4.0 Landfill Leachate Modeling

The team utilized the HELP model to determine a 1-dimensional percolation rate of leachate leaving the bottom of the Cinder Lake Landfill. The team started by calibrating the HELP model using the previous model performed by the landfill in 1994. Then, the HELP model was performed again for the landfill at closure conditions to get an estimate flow rate of the leachate. Finally, a sensitivity analysis was conducted to account for variability of HELP model parameters on the closure conditions.

4.1 Calibrate HELP Model

The HELP Model Version 2.2.0.3, which was developed by Waterloo Hydrogeologic Inc., was the model ran to determine leachate flow out of the landfill. The HELP modeling software is a quasi-2-dimensional flow balance model that calculates the movement of water through and out of landfills [4]. The HELP model was used to determine the percolation rate of leachate exiting the bottom layer of waste from the landfill. The model was run for differing scenarios and input parameters to develop a range of possible leachate percolation rates. The model results are a function of input precipitation, evaporation, soil properties, layer depth, cover material, surface slope, and surface condition. The model is capable of displaying daily, monthly, and annual results for percolation through each landfill layer, runoff, and evapotranspiration. For the purpose of the project, the team was only concerned about the percolation underlying the waste. The software is limited in that it does not allow for modeling of the vadose zone, which is why further modeling was needed to conduct vadose zone modeling. Additionally, the model only provides one-dimensional results, so the percolation rate was assumed to be constant over the entire area of the landfill. Furthermore, the precipitation values provided by the model are based on historical data from 1974-1978 rather than present day. The team was unable to get the model to accept updated precipitation values for the most recent years, so the model default values were used.

The first HELP Model ran by the team duplicated the model ran by Cinder Lake Landfill in 1994. This ensured the HELP model ran correctly and matched all input parameters used by Cinder Lake's Model. The model was ran over a 5-year period to develop the total and average percolation rate of leachate from the landfill. Figure 4-1 shows the cross section of the duplicated model, which has only two input layers. Layer 1 is the top cover layer, which is a 2-foot layer of soil. Layer 2 is the bottom layer, which is composed of 28 feet of waste. The 28 feet of MSW was the current depth measured back in 1994. The layers are separated by a horizontal black line towards the top of Figure 4-1. The green color of both layers indicates they are vertical percolation layers. All inputs for the model can be seen in Appendix B. The average percolation from the duplicate model was 1.85 in/yr. This percolation rate was used to validate the results of the calibration model against the model ran in 1994.

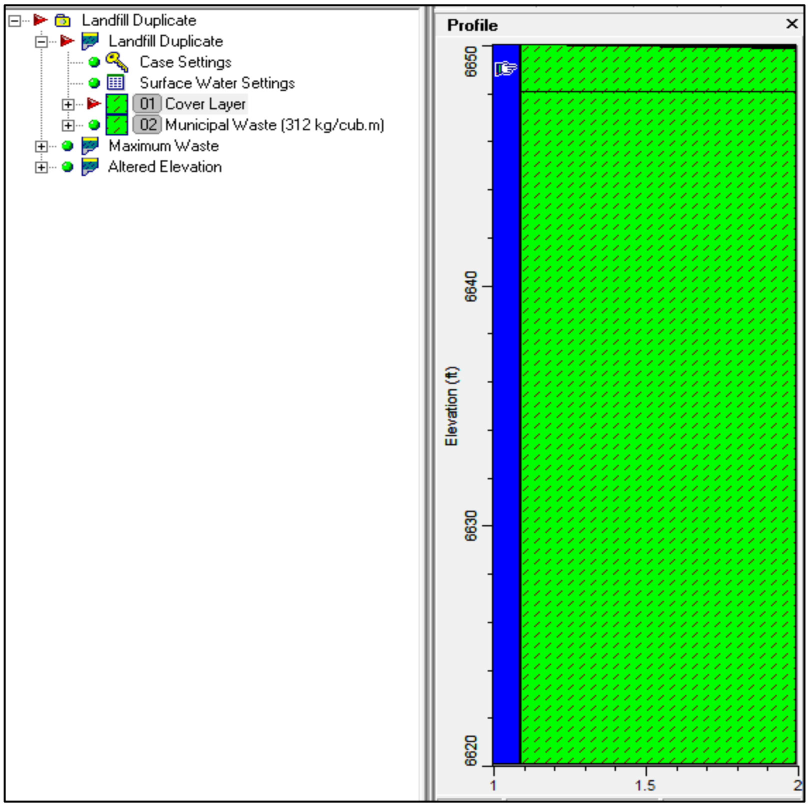


Figure 4-1: Duplicated HELP Model

The HELP Model ran by Cinder Lake Landfill in 1994 resulted in an average leachate percolation rate of 1.84 in/yr. The duplicate HELP Model ran by the team resulted in an average leachate percolation rate of 1.85 in/yr, which is within 0.01 in/yr of the Landfill's previously ran model. This suggests that the model ran by the team was correctly executed. The slight variation of 0.01 in/yr from the resulting percolation rate on the model calibration was most likely due to the inability to change the default precipitation values.

4.2: HELP Model Prediction at Closure

Next, the HELP model was updated to reflect the conditions at the predicted closure of the landfill. This updated HELP model was ran for a predicted scenario at the closure of the landfill, which is estimated to be in 2054 [3]. The only parameter that was changed compared to the duplicate model was the depth of waste, which is predicted to be 100 feet at the time of the landfill closure. The model at the time of closure was ran for 5 years. The average percolation rate of leachate was 2.22 in/yr. Figure 4-2 shows the updated model at the time of landfill closure.

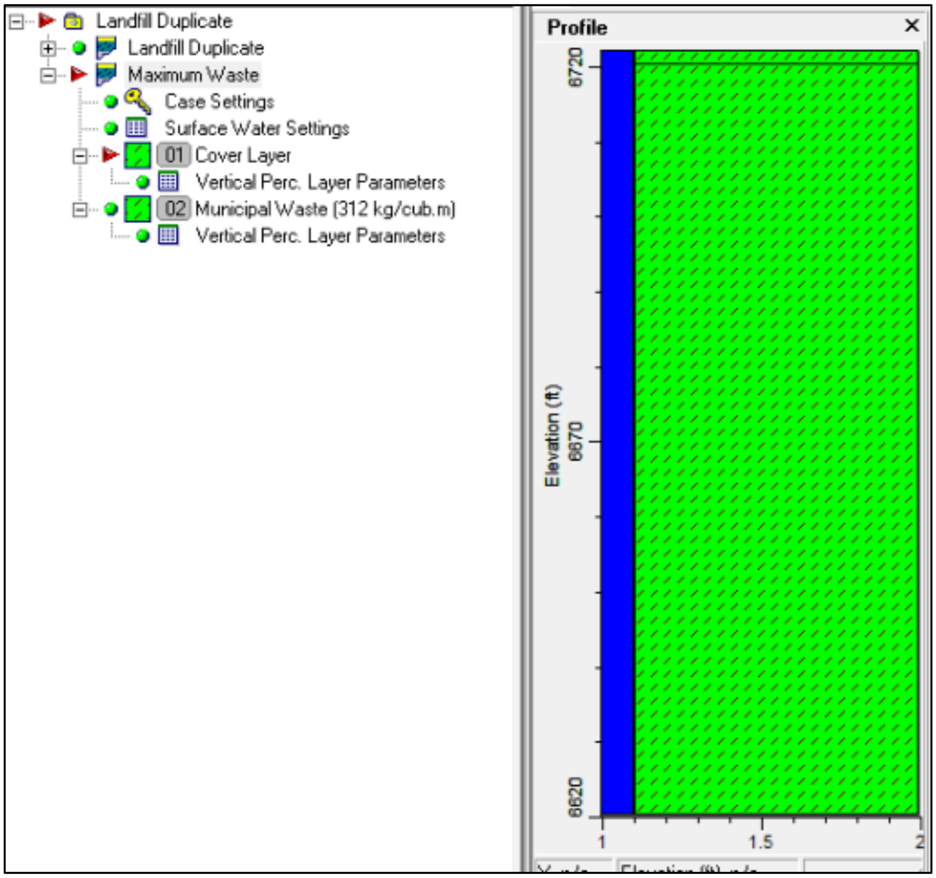


Figure 4-2: HELP Model at Landfill Closure

Table 4-1 shows the average percolation rates and leachate flow rate when the updated HELP model was ran over 5, 10, 50, and 100-year time spans. The model was ran over different time spans to determine if there would be any change in percolation rate. The team wanted to use the highest percolation rate in order to analyze the leachate migration at its worst-case scenario.

Table 4-1: Leachate Percolation and Flow Rates

	Percolation Rate (in/yr)	**Flow Rate (ft^3/yr)**
5-yr	2.22	870,271
10-yr	2.01	787,007
50-yr	2.32	910,491
100-yr	2.48	971,410

Table 4-1 shows that running the updated model over a 100-year time span estimates the largest average leachate percolation rate. Because the client desires the worst-case scenario at closure to be analyzed, the 100-year percolation rate was selected for future analysis.

4.3 HELP Model Sensitivity Analysis

A sensitivity analysis was performed on the model to establish a range of potential leachate percolation rates. This analysis was done for the model closure scenario only. Each sensitivity parameter was analyzed independently because of its potential variability within the landfill. The models with the altered parameters were ran over a 5-year period and compared to the 5-year percolation rates seen in Table 4-1. Table 4-2 shows the differed input parameters and their resulting percolation rate, along with a percent change correlating to the base scenario.

Table 4-2: Sensitivity Analysis

Hydraulic Conductivity	**Top Slope**	**Moisture Content**	**Percolation Rate**	**% Change**
cm/sec	**%**	**%**	**In/yr**	**%**
0.001	0	29.4	2.22	0
0.0001	0	29.4	0.12	-94.6
0.01	0	29.4	2.26	+1.8
0.001	3	29.4	1.37	-38.3
0.001	5	29.4	1.37	-38.3
0.001	0	18.2	5.36E-06	-99.9

The hydraulic conductivity was increased and decreased by a factor of 10 for the sensitivity analysis. Table 4-2 shows that decreasing the hydraulic conductivity by a factor of 10 caused a major decrease of 94.6% in the percolation rates while increasing it only increased the percolation rate by 1.8%. The hydraulic conductivity and moisture parameters were only changed for the waste layer. The table also shows that changing the slope of the cover layer from 0% to 3-5% decreased percolation rates by 38.3%. Additionally, the moisture content of the waste was decreased from 29.4% to 18.2% because the hydroprobe data seen in Appendix A shows that the average moisture content over the last 5 years was 18.2%. Decreasing the moisture content reduced the percolation rate to 5.38E-06 in/yr, a 99.99% decrease in rate change, which is considered a negligible percolation rate. The percolation rates over a five-year span can be seen in Appendix I for each parameter.

5.0 3-D Vadose Zone Plume Model Research

The capstone team was tasked with researching various software programs capable of modeling the migration of leachate from the landfill and through the unsaturated zone over time to determine areas that could potentially contaminant the aquifer. The team researched numerous modeling software programs capable of modeling three-dimensional groundwater flow in the unsaturated zone. Accounting for feasibility and applicability, the team determined three models that were capable of modeling leachate.

5.1 Model Comparison

TOUGH2 (Transport of Unsaturated Groundwater and Heat) is a simulation program for water, gas and heat flow in multi-dimensional porous media. The model can be executed in the unsaturated or saturated zone. The Lawrence Berkley National Laboratory developed the simulation program in 1991 but was not made available to the public until 1999. The model is capable of analyzing several constituents in the unsaturated and saturated zones including water, carbon dioxide, hydrogen, air, brine, oils, and non-condensable gases. Several thermodynamic and linear flow balance equations and mass transfer equations are employed to generate outputs [5]. Additionally, the model can simulate the flow over user-specified time steps [5]. The model assumes local equilibrium between all phases [5]. Furthermore, the model does not take into account potential solutes present in the groundwater, which limits the ability of the model to consider contaminants present in leachate.

SUTRA3.0 is flow simulation model produced by USGS in 2010 that can be employed for 2-D, cross sectional, and 3-D modeling of unsaturated and saturated ground water flow systems over time [6]. SUTRA3.0 solute-transport simulation can be used to model natural or man-induced chemical-species transport including the processes of solute sorption, production and decay [6]. The simulation can also be used to analyze ground-water contaminant transport problems and aquifer restoration designs [6]. The software simulation provides solute concentrations throughout a specified three-dimension mesh grid and utilizes mass balance equations to predict how these concentrations change and migrate over time. The main assumptions of the model are the flow has constant temperature, fluid density, and viscosity. SUTRA3.0 requires many input parameters that the team does not have sufficient data to provide, so several assumptions would have to be made to estimate likely inputs. This will limit the accuracy of the graphical plume created.

MODFLOW-NWT is a Newton-Raphson formulation model for the updated MODFLOW-2005 model created by the USGS in 2011. MODFLOW-2005 simulates steady and non-steady flows in any irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined [7]. Flows from external stress, flows to wells, flows through riverbeds, evapotranspiration flows, and areal recharge flows can all be simulated in this model [7]. For the Cinder Lake Landfill scenario, the areal recharge flow would be used to simulate the 1-D leachate percolation rates determined in the HELP model. If chosen, the team would use the MODFLOW-NWT package coupled with the 2005 version since NWT has 2 improved solutions of unconfined groundwater-flow problems [7]. NWT would utilize an internal unsaturated zone flow package to simulate the unsaturated flow of leachate from the landfill to the underlying aquifer.

5.1.1 Model Ease of Use

TOUGH2 is capable of modeling variable groundwater flow and contaminant transport in the unsaturated zone, which is applicable to accurately modeling leachate flow in the unsaturated zone beneath the landfill. The 1999 TOUGH2 model is the re-engineered version of the TOUGH model, which provides the user with enhanced solving capabilities. The model assumes that fluid flow occurs due to advection in accordance with Darcy's Law, which is acceptable for the project because the flow of leachate is assumed to undergo no chemical reactions with unsaturated media. The model utilizes text files for inputs and outputs, which would be time consuming for the given time constraints the design team has. Therefore, a more user-friendly postprocessor, PetraSim, would be used to allow for simpler inputs and 3-D graphical outputs. PetraSim supports running multiple unsaturated and saturated zone flow models including TOUGH 2 [8]. However, the graphical outputs can be edited by the user to create a comprehensive plume visualization that would be simpler for non-technical viewers to understand. The team would have to invest a significant amount of time learning how to correctly use the PetraSim graphical interface, but tutorials are available that would assist the team in properly applying the software to the project.

SUTRA3.0 can model a variety of contaminants in the unsaturated and saturated zones. SUTRA3.0 is capable of specifically modeling the movement of contaminants in leachate through the unsaturated zone. It can be executed in one, two, or three dimensions under steady state or transient conditions. Transient conditions take into account variations of leachate movement and density over time and space. For modeling in the unsaturated zone, only a transient flow and transient transport mode can be used. The input and output files require complex text-based inputs using numerous file types in order for the program to read the input parameters. Therefore, the graphical user interface ModelMuse would be used, which would allow for more user-friendly inputs and three-dimensional graphical results. This method will be much simpler than creating text files and importing them into a postprocessor. ModelMuse can create a three-dimensional representation of the leachate plume in relation to the underlying aquifer, which is the desired result from the client. The team must learn how to properly use ModelMuse due to no prior experience with three-dimensional graphical user interfaces. Some tutorials are available for inputting data into ModelMuse, which would be useful to assist the team in developing a sufficient understanding of the interface.

MODFLOW-NWT can model the problems involving the drying and rewetting nonlinearities of the standard groundwater flow equation. The model is able to let the team input various hydraulic conductivities and transmissivities for any layer that may differ spatially and be anisotropic (restricted to having the principle directions aligned with the grid axes) [7]. There are limitations to MODFLOW-NWT such that it only solves 3-D problems in the saturated zones, but not the unsaturated zone. In addition, since the model does not allow non-orthogonal anisotropies, the accurate evaluation of flow through fractures cannot be assessed [7]. Since the team assumes there may be various fractures beneath the landfill, this model will most likely not represent the actual flows of leachate occurring. When using NWT in the unsaturated zone, it uses a more stable and simplistic approach that is more adequate for large regional scale models. The best this model could be used for in the landfill scenario is creating 2-D cross-sectional plume visualization graphs below the landfill. This model can also be run on ModelMuse. This would be the very beneficial for the team to use, as the team is not familiar with text-based inputs.

5.1.2 Cost Comparison

Out of the three modeling programs found, only PetraSim has an associated cost, which is the graphical user interface to run TOUGH2. This program can be purchased for one month for $200. The software would cost $1,200 to purchase for one year [9]. If the software were to be purchased permanently, it would cost $2,500 [9]. ModelMuse, which runs SUTRA3.0 and MODFLOW-NWT, is free to download and has no cost associated with it since USGS provides it to the public.

5.2 Model Selection Decision Matrix

The selection of the best model is based on three criteria: cost, user interface complexity, and graphical output capability for leachate. The user interface complexity was scored based on how difficult the team estimated the software will be to learn and implement. The graphical output ability was scored based on each model's ability to provide three-dimensional graphical outputs. The importance of all the criteria were weighted equally. The models were scored for each parameter from 1-10 with 1 being the worst and 10 being the best. Table 5-3 shows the decision matrix with the weighted values for each parameter and the total score each model received from the decision matrix

Table 5-3: Decision Matrix for Unsaturated Zone Models

Model	Cost	User Interface Complexity	Graphical Output Capability	Total
TOUGH2/PetraSim	1	5	10	16
SUTRA3.0/ModelMuse	10	3	10	23
MODFLOW-NWT/ModelMuse	10	5	5	20

As seen in Table 5-3, SUTRA3.0 scored the highest in the decision matrix with a score of 23. SUTRA3.0 scored the highest because it is free to use and provides three-dimensional graphical outputs in the unsaturated zone, which is the desired result of the client. MODFLOW-NWT was also free to use, but it only provides two-dimensional graphical outputs in the unsaturated zone, which resulted in a lower graphical output capability score. Although MODFLOW-NWT provides more tutorials than SUTRA3.0 on running a model and gaining familiarity with the graphical user interface, SUTRA3.0 still meets the modeling needs of a 3-D model. TOUGH2 provides three dimensional graphical output capabilities, but it is expensive to purchase. Due to the amount of simplifying assumptions that will be made to obtain graphical results, the team could not justify spending money to run a model that will not be entirely indicative of the actual leachate flow underlying the landfill. The team will proceed with creating a 3-D graphical representation of the landfill leachate plume by running a SUTRA3.0 model within the ModelMuse graphical user interface.

6.0 Develop 3-D Vadose Zone Plume Visualization

Before the team began using the SUTRA3.0 code with ModelMuse to create the 3-D plume, three simplified plume scenarios were considered to estimate the time it would take for the leachate to reach the C-Aquifer. The time estimates are used as a guide to what the team would expect in the 3-D SUTRA3.0 model for the leachate to reach the C-Aquifer.

6.1 Calculations for Leachate to Reach Aquifer

The first scenario shown in Figure 6-1 considers that the entire landfill footprint of 108 acres will percolate the 100-year average of 2.48 in/yr found from the HELP model into unsaturated ground, where liquid drains from pores more quickly than it comes in and flows downward faster than it comes in. The second scenario will consider that the entire landfill footprint of 108 acres percolates 2.48 in/yr of leachate into saturated ground, where liquid drains from pores more slowly than it comes in and flows downward at the same rate it comes in. The third scenario will consider that 0.1% of the landfill footprint accepts all the leachate that the landfill produces to simulate a preferential flow pattern. These scenarios used soil layers gathered from previous borehole drilling activities. Therefore, the team relied more heavily on Figure D-1 for layer types and depths because the borehole was taken at the landfill. Figure D-2 shows borehole data taken from Doney

Park, which was used to determine that sandstone is present below the limestone. The moisture content for each soil layer was taken from the hydroprobe data at the observed depth of the soil layer. The porosities of the soil layers were found in previous geotechnical investigations, which took place at the landfill.

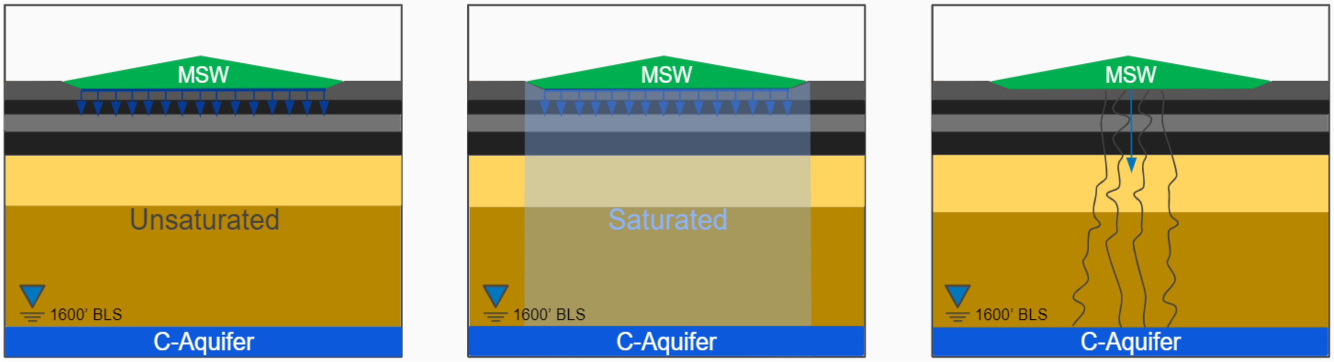


Figure 6-1: Cross-Sectional Plume Scenarios

Table 6-1 shows the calculated hypothetical time for leachate to pass through the unsaturated and saturated zone scenarios as well as the crack scenario to reach the underlying C-Aquifer. The unsaturated scenario accounts for the individual soil layer moisture contents and is the most likely case. The saturated scenario assumes that all of the underlying soil and rocks are entirely saturated and is the least likely case. However, this could still be a possibility because these time calculations are conducted based on post closure conditions in which the estimated 90 years of landfill operations could have already leached into the soil and saturated the whole area under the landfill. The third scenario assumes that 0.1% of the area of the landfill consists of cracks, and all of the leachate from the landfill flows through only these cracks. This is the worst-case and an extreme scenario. The calculations for each scenario can be seen in Appendix E.

Table 6-1: Time Calculations for Leachate to Reach Aquifer

Scenario	Time for Leachate to Reach Aquifer (years)
Unsaturated Flow	93
Saturated Flow	1692
Flow only through cracks	0.09

Table 6-1 shows that assuming an area of cracks is unlikely because contamination would have already been found in city and county monitoring wells located less than two miles north of landfill in the direction of groundwater flow as shown in Figure 1-4. The saturated flow scenario is encouraging because the leachate would take thousands of years to reach the aquifer if all soil and rock voids have to fill with leachate with water. However, this is unlikely considering the average moisture content of the soil underlying the landfill was measured at 18.2%. The unsaturated flow scenario is the most likely because it applied actual and estimated moisture content data of the underlying soil and rock layers to predict the leachate flow.

6.2 Develop 3-D Plume Visualization

The team utilized the simplified borehole as the layers within the model. Solute transport in the unsaturated zone was modeled using transient flow and transient transport conditions. No adsorption parameters were considered. The team then utilized ModelMuse, the graphical user interface with SUTRA3.0, to create a 3-D migration model of the leachate in the vadose zone beneath the landfill. The team used the one-dimensional flow of 2.48 in/yr determined by the HELP model for the flow out of the landfill and into the vadose zone. The SUTRA3.0 model was ran for 50 years, which was chosen because increasing the number of years did not notably change the results, but it did increase the computer run time. The team used the same layers and associated thickness used in the hand calculations.

Table 6-2 shows the SUTRA3.0 input parameters.

Table 6-2: SUTRA3.0 Input Parameters

Flow Angle (degrees)	0
Initial Concentration (mg/L)	1073
Initial Pressure (psf)	1229
Longitudinal Dispersivity (ft/yr)	0.5
Permeability (yr/ft)	$1E^{-10}$
Nodal Porosity (vol/vol)	0.1
Transverse Dispersivity (ft/yr)	0.5
Inlet Flow (kg/s)	0.872
Fluid Compressibility (psi)	$4.47E^{-10}$
Fluid Density (kg/m^3)	1000
Fluid Viscosity (poise)	0.001
Number of Nodes	250

Flow angle, longitudinal dispersivity, permeability, transverse dispersivity, fluid compressibility, fluid density, and fluid viscosity were all left at the typical default values given by the model. These values were not changed because of insufficient data to determine each value. However, these default values are typical values for unsaturated flow. The initial concentration input is the highest concentration of chloride found in previous leachate tests from Cinder Lake Landfill [14]. Chloride was used as an indicator for solute flow in the leachate because it is the most transportable contaminant in leachate. The initial pressure input was assumed based on report pressure values from another landfill, but Cinder Lake Landfill did not have this data available [15]. The inlet flow input is the 2.48 in/yr of leachate obtained from the HELP model converted to kg/s, assuming the density of the leachate is the same as the density of water. The number of nodes indicates the number of sections that the landfill is divided into, and the model evaluates the flow at each individual node.

Figure 6-2 shows the top view of the landfill created using the SUTRA3.0 input parameters from Table 6-2. The associated negative numbers indicate z-velocity downward through the landfill in ft/yr. The legend shows that areas with blue flow are the highest and areas with red flow are the lowest. The areas with red flow are along the edges of the landfill, and the flow rate is essentially negligible. Therefore, the model shows that the edges of the landfill with red flow should not be of concern.

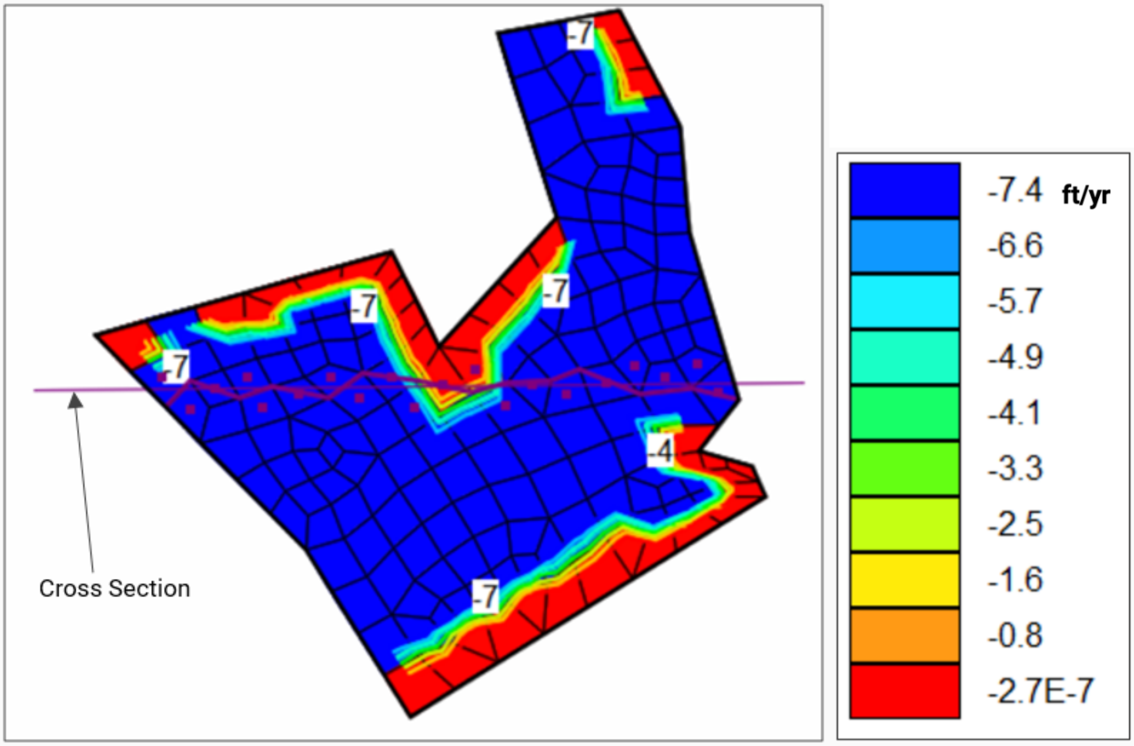


Figure 6-2: Base SUTRA3.0 Model Top View with Legend

Figure 6-2 indicates that most of the leachate flow is the same towards the middle of the landfill, but there is a decreasing flow gradient towards some edges of the landfill.

Figure 6-3 shows the cross-sectional view of the model as indicated by the purple cross-section line seen in Figure 5-2.

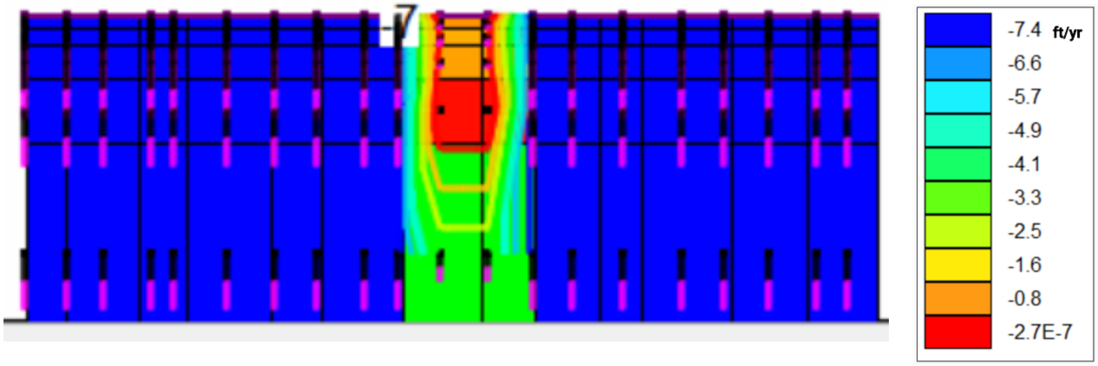


Figure 6-3: Base SUTRA3.0 Model Cross-sectional View with Legend

Figure 6-3 suggests that the vertical flow seen in blue does not change over the entire depth of the landfill. However, the flow gradient does change over depth at the edges of the landfill as seen in the middle of Figure 6-3. The purple lines pointing straight down indicate that the leachate flow is moving directly downward.

Figure 6-4 shows the 3-D view of the SUTRA3.0 model.

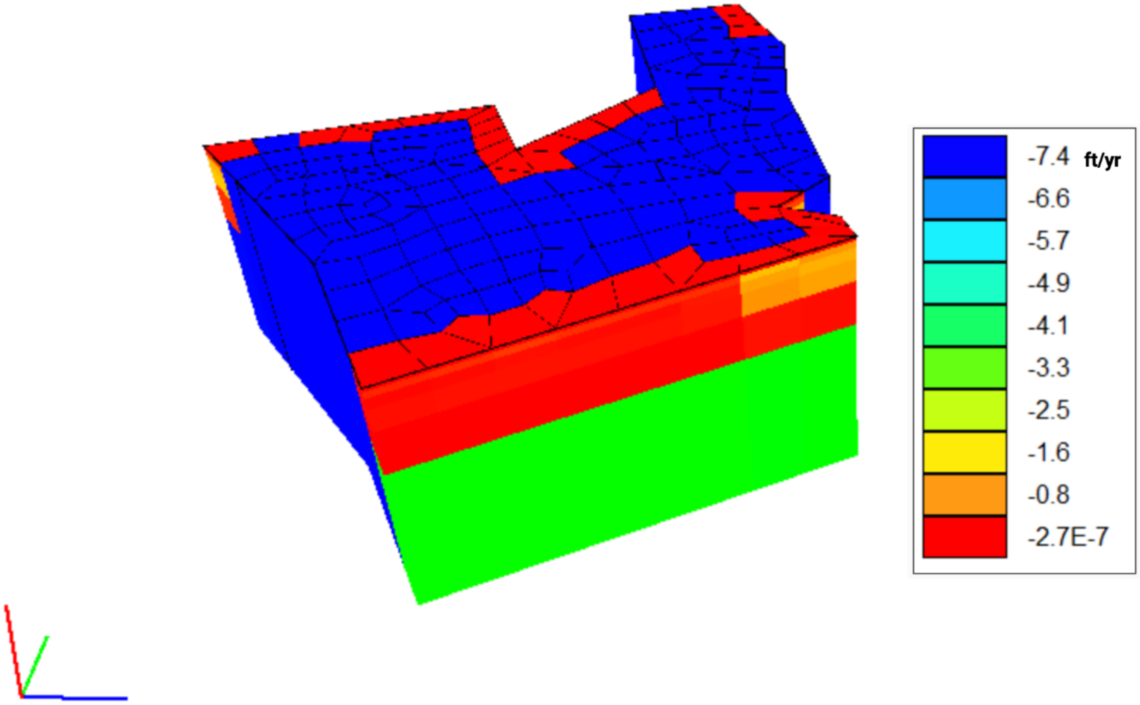


Figure 6-4: Base SUTRA3.0 Model 3-D View with Legend

Figure 6-4 shows that the flow gradient remains constant in the middle of the model, but fluctuates around some of the landfill boundaries. The middle of the model is of the highest concern because the flow indicated in blue is the highest, which is shown in Figure E-1.

The areas with blue flow take up the majority of the landfill and have a flow of 7.4 feet per year. Based on this percolation rate, the leachate would take 217 years to travel reach the underlying aquifer 1600 feet under the landfill.

Figure 6-5 shows the top view of the landfill with a large area surrounding it. This model was ran to determine how far leachate is expected to flow horizontally from the boundaries of the landfill.

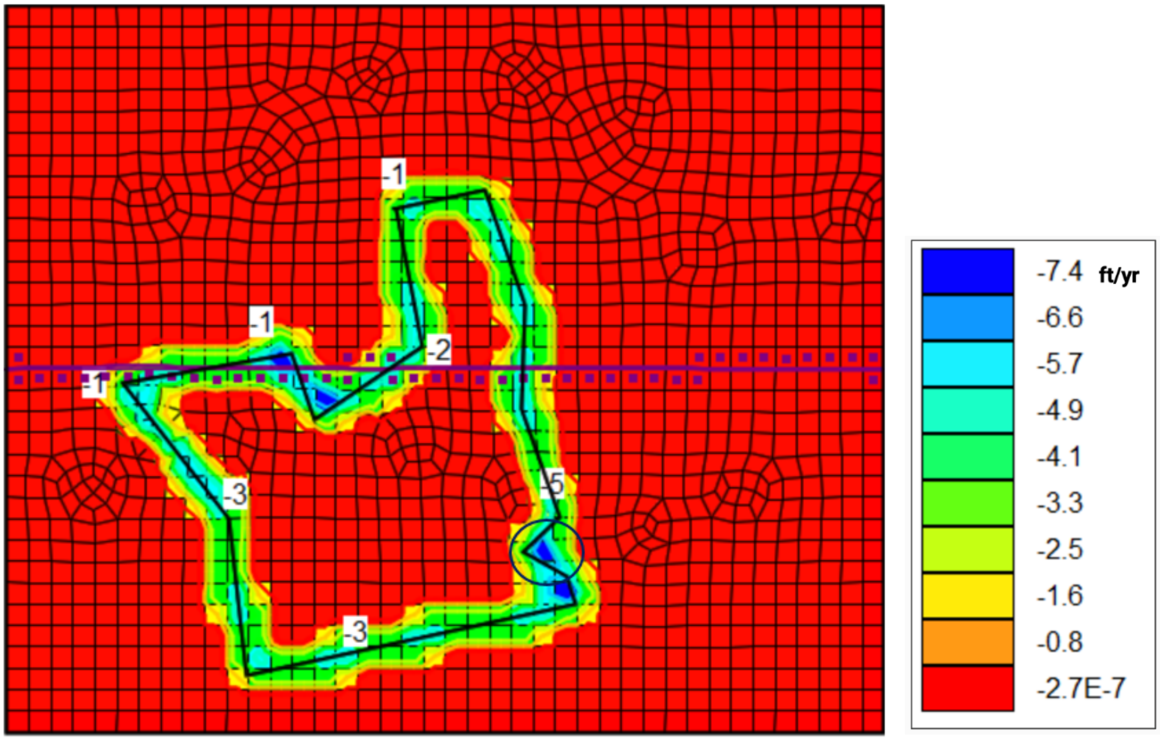


Figure 6-5: Top View of Landfill with Extended Area with Legend

The black circle seen towards the bottom right of the landfill is the farthest that leachate would travel horizontally from the landfill, which is 1,100 feet. This indicates that it is unlikely for the leachate to flow a long distance from the landfill, unless it reaches the C-Aquifer below.

6.3 Sensitivity Analysis for Leachate Potential to Reach Aquifer

The input parameters in Table 6-2 were altered to determine which parameters had the biggest impact on the results. The sensitivity analysis is intended to inform the client which parameters they should focus their efforts for further data collection to create a more accurate model.

Table 6-3 shows the input parameters from Table 6-3 that had an impact on the time it would take the leachate to reach the aquifer compared to the base result of 217 years.. The model was ran for 50 years to analyze the sensitivity of each parameter. An example of the 3-D model results and associated color legend for increasing the permeability by a factor of 10 can be seen in Appendix F. This process was repeated for each parameter.

Table 6-3: ModelMuse Sensitivity Analysis

Initial Concentration (mg/L)	**Permeability (yr/ft)**	**Fluid Viscosity (poise)**	**Nodal Porosity (vol/vol)**	**Years to Reach Aquifer (yr)**	**Percent Change (%)**
1073	1E^{-10}	0.001	0.1	217	0
5000	1E^{-10}	0.001	0.1	190	-12.30
1073	1E^{-9}	0.001	0.1	22	-90.00
1073	1E^{-10}	0.002	0.1	434	+100
1073	1E^{-10}	0.001	0.2	434	+100

As seen in Table 6-3, increasing the permeability by a factor of ten significantly decreased the time for leachate to reach the aquifer. Increasing the chloride concentration to 5000 mg/L moderately decreased the time to reach the aquifer, and doubling the fluid viscosity and nodal porosity both doubled the time it would take the leachate to reach the aquifer.

6.4 Analysis of Landfill Excavation Requirements

According to prior research by the landfill, it will cost them $40 per cubic yard on average to excavate the buried MSW. Following the results of the model, the team's goal was to identify regions below the landfill that show an EPA exceedance moisture content of 21%. These problem source areas would need to be excavated (at $40/cy) to get moisture content back under 21%. However, the team was not able to get any reliable results regarding the saturation levels within the vadose zone. Therefore, no specific excavation recommendations can be made.

7.0 Final Design Recommendations

The hand calculation results indicate that the time range for the leachate to reach the aquifer is 93-1692 years (Table 6-1). The SUTRA3.0 model gave a time to reach aquifer of 217 years, which is within the range calculated by hand. The results suggest that the leachate has not reached the underlying aquifer and will likely not reach the underlying aquifer for a long period of time after closure. The SUTRA3.0 results did not offer any reliable results regarding the saturation of the underlying soil and rock layers. Therefore, no specific excavation recommendations can be made.

To develop a more accurate SUTRA3.0 model for leachate, further data collection is recommended. The initial concentration of chloride in leachate, permeability, fluid viscosity, and nodal porosity should be determined at the landfill because these parameters have the higest impacts on the outputs of the model. Furthermore, the leachate flow and change in pressure with depth needs to be determined at the boundaries of the landfill. Additionally, the landfill should acquire further borehole data in order to obtain a less simplified version of the vadose zone soil and rock layers. Further data collection will aid in the development of a more accurate model to determine the time for the leachate to reach the aquifer and leachate saturation levels within the landfill.

8.0 Analysis of Project Impacts

The project impacts from this project were assessed in two ways. The first is if the landfill acts on mitigating or remediating the leachate migration. This will in turn prevent multiple negative social, economic, environmental and human health impacts but will also create some positive impacts. The second way the impacts were assessed is if the landfill proceeds forward in current operations and waits for better technology to become available for future geophysical monitoring of the leachate.

8.1 Social Impacts

The modeling results suggest that migration of the leachate to the C-aquifer will take hundreds of years, which provides confidence in landfill operation and safety. However, if future modeling shows a faster migration, this can decrease the confidence and require mitigation such as landfill excavation and/or groundwater pump and treat. If the landfill chooses to excavate any problem areas of the landfill found to be a large contribution to the leachate, then there are associated social impacts. A large social impact of the excavation could lead to increased littering and blowing of the mined trash or the potential for unwanted smells in the area. If excavation or pump and treat remediation is chosen and the leachate migration problem is solved, then the nearby community will have peace of mind going forward in that groundwater contamination is highly unlikely.

8.2 Economic Impacts

The economic impacts of the project include the potential for increased landfill operations if excavation of mined trash is conducted or if pump and treating of groundwater is selected. If needed, any mitigation would lead to increased landfill costs for the city and these cost would be passed on to customers. Mining buried waste is counterproductive and thus would increase the costs of labor and the wear and tear on heavy equipment and machinery. Any additional sampling and/or modeling that is needed will also increase costs because third parties would have to be contracted. If the leachate migration issue is not solved, then the local area may potentially experience housing and property values decreases in the future depending on the distance from the landfill. Additionally, if the landfill chooses to wait for better monitoring technologies and to run a more accurate model in the future, the cost of remediation may be significant. However, money spent to improve the model could further confirm that no expensive mitigation is needed.

8.3 Environmental Impacts

If further study of the leachate indicates that mitigation is needed, then there could be environmental impacts based on the chosen remediation. Those impacts would range based on the chosen remediation, but if excavation is selected, then there may be some land surface disturbance nearby the landfill contributing to the loss of animal habitats. Additionally, if groundwater is pumped and treated in-situ, then pumping of the groundwater to the ground surface could potentially expose wildlife to contamination if proper boundaries are not set in place during remediation.

8.4 Human Health Impacts

If further study indicates that mitigation is needed, then the community members nearby could potentially face possible future health impacts by drinking or coming into dermal contact of leachate contaminated groundwater. The typical leachate contains heavy metals such as lead, mercury and cadmium, which can cause serious health effects like abdominal pain, skin irritation, diarrhea and even kidney damage. If the landfill decides to excavate the buried trash, it is important to note that it is partially digested, and it may release additional moisture, gases and smells that are locked up in the landfill into the atmosphere thus leading to a decrease in air quality for the local community. If further studies show that mitigation is not needed, then the potential for health impacts of the coming into contact with contaminated groundwater decreases substantially.

9.0 Summary of Engineering Work

The project had a few changes to the scope and schedule due to loss of a group member entering the second semester of the senior design capstone class. The team omitted Task 4: Research and Compare Geophysical Monitoring Methods entirely to ensure the scope of the project was not too large for only two team members. This task was not on the critical path for project completion and did not affect the final modeling results.

The original Gantt chart the team created prior to conducting any research or technical work is located in Appendix G. The final modified Gantt chart is also located in Appendix G. Some of the changes the team made to the original Gantt is that the team decided to expand Task 1: Site Investigation to include two sub tasks that detailed the site visit and the procurement of site-specific data. Originally, the team had one task for the site investigation but since it encompasses a few steps, the task was expanded out for proper documentation of the teams work. Additionally the team decided to change the titles of some tasks to better represent the technical conducted For instance, "Task 3.4.1 Efficiency Analysis" of the HELP Model was retitled to "Task 3.4.1 Model Ease of Use" since the team was more concerned about the complexity of running the models rather than its efficiency.

A number of changes were made in Task 4: Develop 3-D Plume Visualization since the team was limited on data. Originally Task 4.1: Interpolate 2-D Geophysical Data was going to be conducted, but the team was limited on data to draw conclusions of the makeup beneath the landfill from provided geotechnical documents. After further discussion with professional groundwater modeler Clifford Voss from the USGS, the team decided to start the modeling process by conducting simple hand calculations to determine time estimates for the leachate to reach the aquifer. Therefore, the team renamed the task to Task 4.1: Calculations for Leachate to Reach Aquifer. The team also underestimated the time it would take to create and run the 3-D model from Task 5.2. The team originally planned that the 3-D modeling would take 9 days to complete, but the team spent 30 days completing this task.

10.0 Summary of Engineering Costs

The team's original project proposal for the total cost of engineering services was estimated to cost $52,283 as shown in Table 10-1. The cost breakdown entailed the cost of the employees' hourly wage on the project, the cost of travel to conduct the initial site investigation, as well as the expected cost of modeling software. The detailed estimate of hours associated with each task is located in Appendix H in Figure H-1.

Table 10-1: Proposed Cost Breakdown

1.0 Personnel	Classification	Hours	Rate, $/hr	Cost
	SENG	62	194	$ 12,058
	ENG	278	98	$ 27,244
	INT	170	26	$ 4,342
	ADM	92	39	$ 3,618
	Total Personnel			$ 47,262
2.0 Travel	2 meetings @ 26 mi/meeting	$0.40/mi		$ 21
3.0 Supplies	Modeling Software	$5,000		$ 5,000
4.0 Subcontract	N/A	N/A		N/A
5.0 Total				$ 52,283

The final cost breakdown of the project is shown in Table 10-2. The final cost of engineering services was calculated to be $25,069. The difference between the proposed hours cost and the completed hours cost reflects the loss of a team member and the change to the project scope. The team also selected a free modeling software, so the cost of modeling software was omitted and reduced the final cost by an additional $5,000.

Table 10-2: Final Cost Breakdown

1.0 Personnel	Classification	Hours	Rate, $/hr	Cost
	SENG	63.5	194	$ 12,319
	ENG	93	78	$ 7,254
	INT	110.5	26	$ 2,873
	ADM	67	39	$ 2,613
	Total Personnel			$ 25,059
2.0 Travel	1 meeting @ 26 mi/meeting	$0.40/mi		$ 10
3.0 Supplies	Modeling Software	N/A		$ -
4.0 Total				$ 25,069

The majority of the omitted came from the environmental engineer's hours since that employee contributed the most to all the technical work in the omitted task. The engineering team also found that the intern was highly capable of completing the tasks assigned, so they were able to take on more during project implementation. The senior environmental engineer was able to perform all tasks allocated in the proposal phase and was able to provide the client with a 3-D model and recommendations for running a better model in the future if the landfill chooses to do so. The administrative assistant was able to contribute greatly to the creation of reports, presentations, and project management. The administrative assistant hours after project completion were lower than proposed since the engineers and intern helped in the creation of those reports and presentations. The administrative assistant does not have any engineer background, so they were helped to ensure the teams technical work could be effectively communicated to any audience.

11.0 Conclusion

The team collected necessary data for input into the HELP model to determine the percolation rate of leachate at closure of the landfill at worst case scenario, which was 2.48 in/yr. Subsequently, 3-D models were researched to determine the most suitable model for the project, which was found to be SUTRA using ModelMuse as the graphical user interface to generate graphical outputs. Simplified hand calculations were done for various flow scenarios through the vadose zone to estimate that the leachate would take between 93-1692 years to reach the underlying aquifer. Literature review was conducted to estimate the input parameters for SUTRA3.0 as well as several simplifying input assumptions due to lack of available data. Results showed that the leachate would take 217 years to reach the underlying aquifer, which is within the range found from the hand calculations. Further data collection is recommended to create a model that more accurately represents the landfill.

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Appendices

Appendix A: Hydroprobe Soil Moisture Data

Table A-1: Moisture Content Data from Hydroprobe V-1

Well Identification	Date	Average Soil Moisture Content (%)
V-1	3/18/16	17.7
V-1	6/29/16	17.61
V-1	9/19/16	18.01
V-1	12/14/16	18.21
V-1	3/1/17	18.23
V-1	6/16/17	18.18
V-1	9/6/17	18.06
V-1	12/8/17	17.95
V-1	3/16/18	17.99
V-1	6/18/18	17.94
V-1	9/19/18	17.97
V-1	12/17/18	18.04
V-1	3/12/19	17.75
V-1	6/26/19	17.76
V-1	9/13/19	17.74
V-1	12/14/19	18.06
V-1	3/11/20	17.91
V-1	6/19/20	17.85
V-1	9/15/20	17.95
V-1	12/7/20	18.16

Table A-2: Moisture Content Data for Hydroprobe V-3

Well Identification	Date	Average Soil Moisture Content (%)
V-3	3/13/15	18.35
V-3	7/28/15	20.46
V-3	9/23/15	20.44
V-3	12/11/15	20.11
V-3	3/18/16	20.12
V-3	6/29/16	19.97
V-3	9/19/16	19.95
V-3	12/15/16	13.97

Table A-3: Moisture Content Data for Hydroprobe V-4

Well Identification	Date	Average Soil Moisture Content (%)
V-4	3/18/16	17.64
V-4	6/29/16	17.6
V-4	9/19/16	17.62
V-4	12/15/16	17.64
V-4	3/20/17	17.73
V-4	6/1/17	17.78
V-4	9/1/17	17.78
V-4	12/8/17	17.62
V-4	3/16/18	17.63
V-4	6/18/18	17.73
V-4	9/19/18	17.63
V-4	12/17/18	17.59
V-4	3/12/19	17.76
V-4	6/26/19	17.73
V-4	9/13/19	17.74
V-4	12/14/19	17.58
V-4	3/11/20	17.86
V-4	6/19/20	17.56
V-4	9/15/20	17.75
V-4	12/7/20	17.82

Table A-4: Moisture Content Data from Hydroprobe V-5

Well Identification	Date	Average Soil Moisture Content (%)
V-5	3/18/16	18.91
V-5	6/29/16	18.91
V-5	9/19/16	18.75
V-5	12/15/16	18.72
V-5	3/21/17	18.75
V-5	6/16/17	18.65
V-5	9/6/17	18.66
V-5	12/8/17	18.68
V-5	3/16/18	18.52
V-5	6/18/18	18.59
V-5	9/19/18	18.59
V-5	12/17/18	18.56
V-5	3/12/19	18.4
V-5	6/26/19	18.57
V-5	9/13/19	18.57
V-5	12/14/19	18.54
V-5	3/11/20	18.39
V-5	6/19/20	18.46
V-5	9/15/20	18.38
V-5	12/7/20	18.41

Appendix B: HELP Model Inputs

Table B-1: HELP Model Data Inputs: Cover Layer

Bottom Elevation (ft)	6648
Layer Thickness (ft)	2
Surface Slope (%)	0
Porosity (vol/vol)	0.471
Field Capacity (vol/vol)	0.342
Wilting Point (vol/vol)	0.21
Saturated Hydraulic Conductivity (cm/sec)	4.2E^-5
Initial Moisture Content (vol/vol)	0.105

Table B-2: HELP Model Data Inputs: Waste Layer

Bottom Elevation (ft)	6620
Layer Thickness (ft)	28
Surface Slope (%)	0
Porosity (vol/vol)	0.671
Field Capacity (vol/vol)	0.292
Wilting Point (vol/vol)	0.077
Saturated Hydraulic Conductivity (cm/sec)	0.001
Initial Moisture Content (vol/vol)	0.294

Table B-3: General HELP Model Input Data

Area (acres)	108
Runoff Area (%)	80
Vegetation Class	Bare soil

Table B-4: HELP Model Input Precipitation and Temperature Data

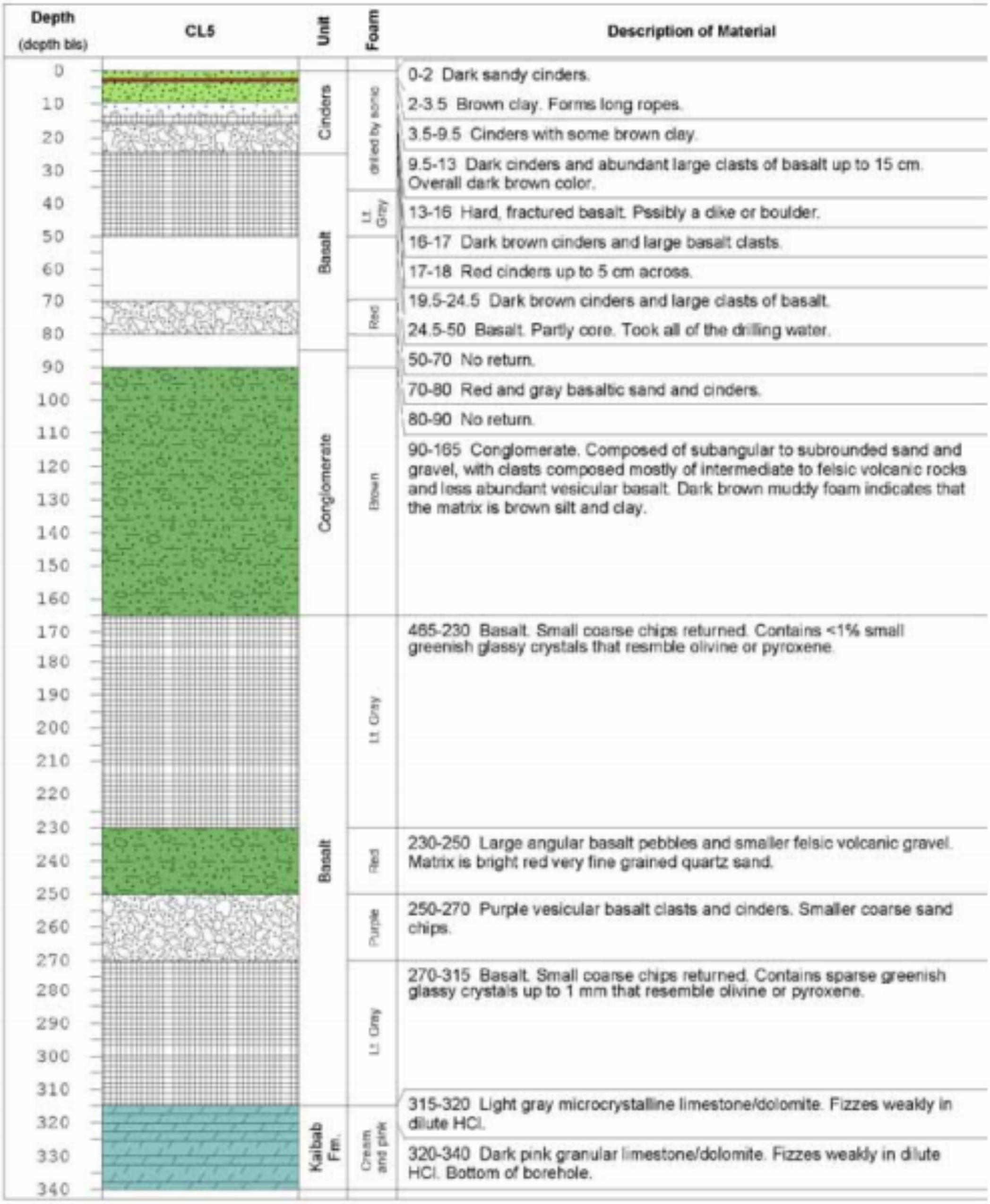
Month	Precipitation (in)	Temperature (F)
January	2.1	28.2
February	1.95	30.7
March	2.13	34.5
April	1.35	41.6
May	0.75	49.9
June	0.57	59.2
July	2.47	66.1
August	2.62	63.8
September	1.47	57.5
October	1.54	47.2
November	1.65	36.3
December	2.26	29.6

Appendix C: HELP Model Sensitivity Analysis

Table C-1: Sensitivity Analysis Results

Poor Stand of Grass							
Year	1	2	3	4	5	**Total**	**Average (in/yr)**
Percolation Through Layer 2 (in)	2.4	1.36	2.23	3.04	2.07	11.1	2.22
5 % Slope							
Year	1	2	3	4	5	**Total**	**Average (in/yr)**
Percolation Through Layer 2 (in)	2.4	0.15	1.3	1.58	1.41	6.84	1.368
3% Slope							
Year	1	2	3	4	5	**Total**	**Average (in/yr)**
Percolation Through Layer 2 (in)	2.4	0.154	1.32	1.59	1.39	6.854	1.3708
0.01 cm/sec hydraulic conductivity							
Year	1	2	3	4	5	**Total**	**Average (in/yr)**
Percolation Through Layer 2 (in)	2.64	1.186	2.366	2.83	2.26	11.282	2.2564
0.0001 cm/sec hydraulic conductivity							
Year	1	2	3	4	5	**Total**	**Average (in/yr)**
Percolation Through Layer 2 (in)	0.133	0.332	0.03	0.03	0.054	0.579	0.1158
18.2 % Moisture Content							
Year	1	2	3	4	5	**Total**	**Average (in/yr)**
Percolation Through Layer 2 (in)	0	2.69E-05	0	0	0	2.69E-05	5.38E-06

Appendix D: Borehole Data



0-2 Dark sandy cinders.

2-3.5 Brown clay. Forms long ropes.

3.5-9.5 Cinders with some brown clay.

9.5-13 Dark cinders and abundant large clasts of basalt up to 15 cm. Overall dark brown color.

13-16 Hard, fractured basalt. Pssibly a dike or boulder.

16-17 Dark brown cinders and large basalt clasts.

17-18 Red cinders up to 5 cm across.

19.5-24.5 Dark brown cinders and large clasts of basalt.

24.5-50 Basalt. Partly core. Took all of the drilling water.

50-70 No return.

70-80 Red and gray basaltic sand and cinders.

80-90 No return.

90-165 Conglomerate. Composed of subangular to subrounded sand and gravel, with clasts composed mostly of intermediate to felsic volcanic rocks and less abundant vesicular basalt. Dark brown muddy foam indicates that the matrix is brown silt and clay.

465-230 Basalt. Small coarse chips returned. Contains <1% small greenish glassy crystals that resmble olivine or pyroxene.

230-250 Large angular basalt pebbles and smaller felsic volcanic gravel. Matrix is bright red very fine grained quartz sand.

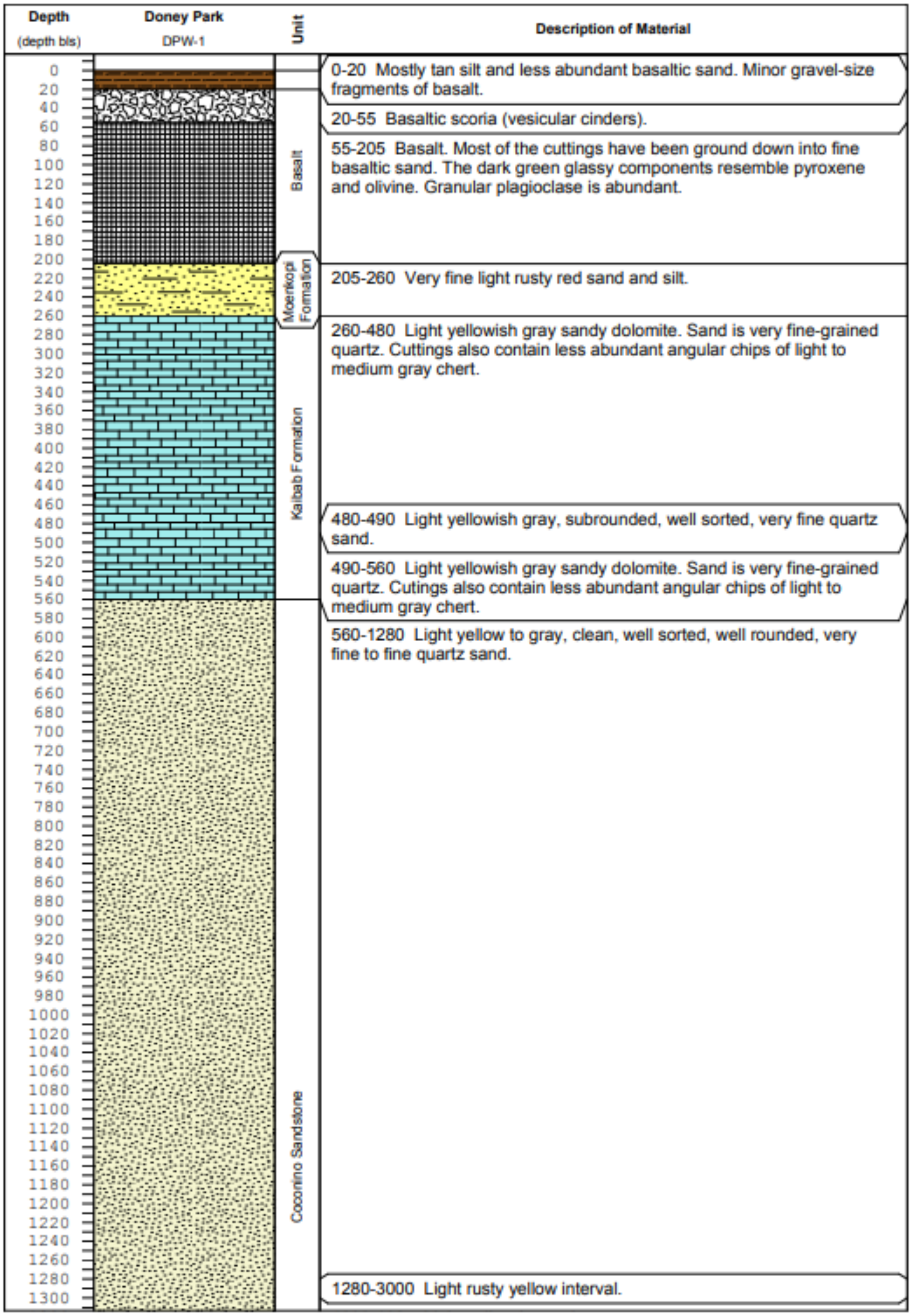
250-270 Purple vesicular basalt clasts and cinders. Smaller coarse sand chips.

270-315 Basalt. Small coarse chips returned. Contains sparse greenish glassy crystals up to 1 mm that resemble olivine or pyroxene.

315-320 Light gray microcrystalline limestone/dolomite. Fizzes weakly in dilute HCl.

320-340 Dark pink granular limestone/dolomite. Fizzes weakly in dilute HCl. Bottom of borehole.

Figure D-1: Landfill Deep Borehole Log [12]



0-20 Mostly tan silt and less abundant basaltic sand. Minor gravel-size fragments of basalt.

20-55 Basaltic scoria (vesicular cinders).

55-205 Basalt. Most of the cuttings have been ground down into fine basaltic sand. The dark green glassy components resemble pyroxene and olivine. Granular plagioclase is abundant.

205-260 Very fine light rusty red sand and silt.

260-480 Light yellowish gray sandy dolomite. Sand is very fine-grained quartz. Cuttings also contain less abundant angular chips of light to medium gray chert.

480-490 Light yellowish gray, subrounded, well sorted, very fine quartz sand.

490-560 Light yellowish gray sandy dolomite. Sand is very fine-grained quartz. Cutings also contain less abundant angular chips of light to medium gray chert.

560-1280 Light yellow to gray, clean, well sorted, well rounded, very fine to fine quartz sand.

1280-3000 Light rusty yellow interval.

Figure D-2: Doney Park Deep Borehole Log [12]

Appendix E: Time for Leachate to Reach Aquifer Calculations

The general soil/rock layers were selected based on the borehole log see in Figure D-1. The porosities were estimated based on USGS cinder deposit borehole data for the cinders, basalt, and conglomerate [10]. The limestone porosity of 0.26 was provided by the client [11].

Table E-1: Calculations for Unsaturated Scenario

Entire Landfill Area Unsaturated					
Rock Type	**Porosity (vol/vol)**	**Percolation (in/yr)**	**Layer Moisture Content (%)**	**Layer Depth (ft)**	**Time to pass layer (yr)**
Cinders	0.51	4.86	17.57	24.5	3
Upper Basalt	0.28	8.86	18.07	45.5	3
Conglomerate	0.38	6.53	18.94	75	7
Lower Basalt	0.28	8.86	18.2	150	11
Limestone	0.26	9.54	18.2	300	21
Sandstone	0.175	14.17	18.2	1005	47

Table E-2: Calculations for Crack Scenario

Crack Scenario					
Soil/Rock Type	**Porosity (vol/vol)**	**Percolation (in/yr)**	**Layer Moisture Content (%)**	**Layer (ft)**	**Time to pass layer (yr)**
Cinders	0.51	4859.00	17.57	24.5	0.0034
Upper Basalt	0.28	8850.31	18.07	45.5	0.0034
Conglomerate	0.38	6521.28	18.94	75	0.0073
Lower Basalt	0.28	8850.31	18.2	150	0.0112
Limestone	0.26	9531.11	18.2	300	0.0208
Sandstone	0.175	14160.50	18.2	1005	0.0468

Table E-3: Calculations for Saturated Scenario

Entire Landfill Area Saturated					
Soil/Rock Type	**Porosity (vol/vol)**	**Percolation (in/yr)**	**Layer Moisture Content (%)**	**Layer Depth (ft)**	**Time to pass layer (yr)**
Cinders	0.51	4.86	100	24.5	60
Upper Basalt	0.28	8.86	100	45.5	62
Conglomerate	0.38	6.53	100	75	138
Lower Basalt	0.28	8.86	100	150	203
Limestone	0.26	9.54	100	300	377
Sandstone	0.175	14.17	100	1005	851

Appendix F: SUTRA Modeling Results

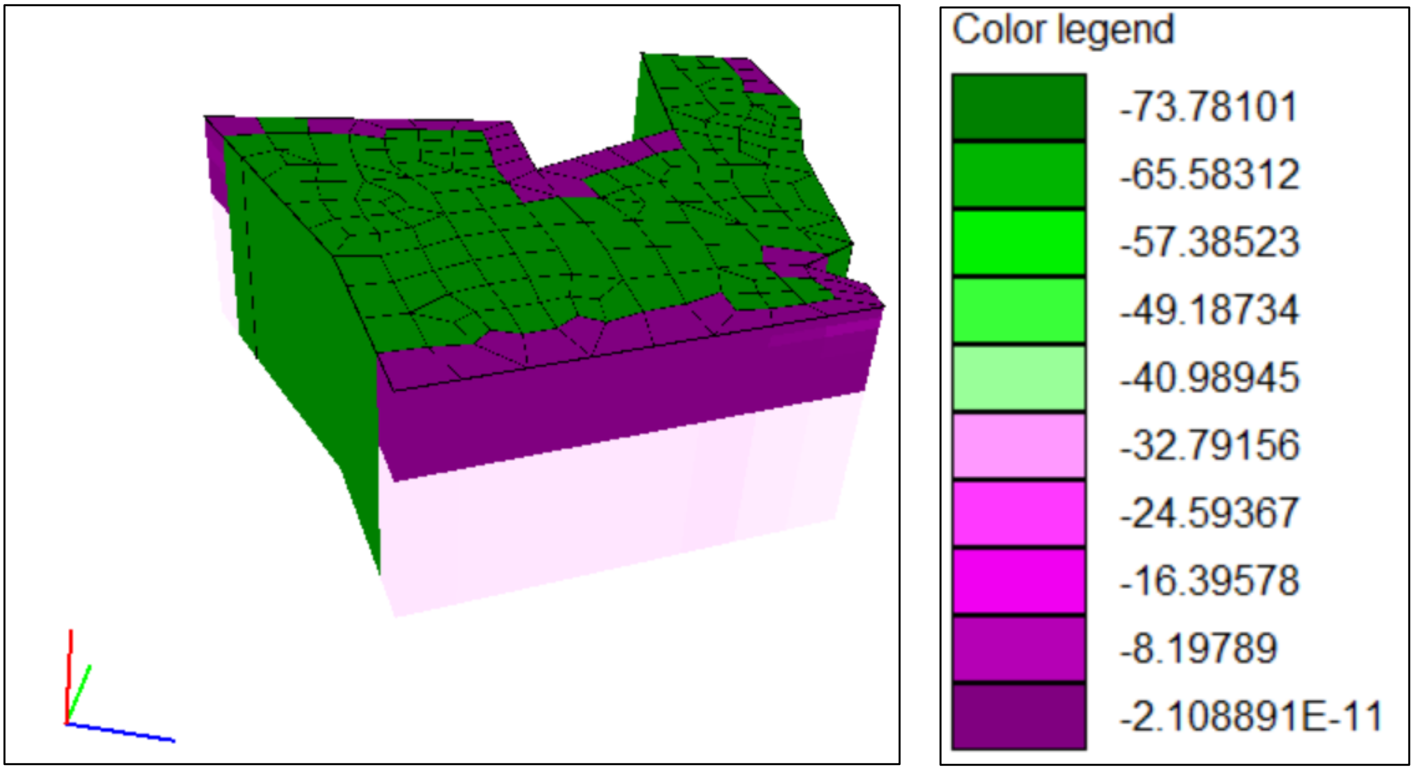
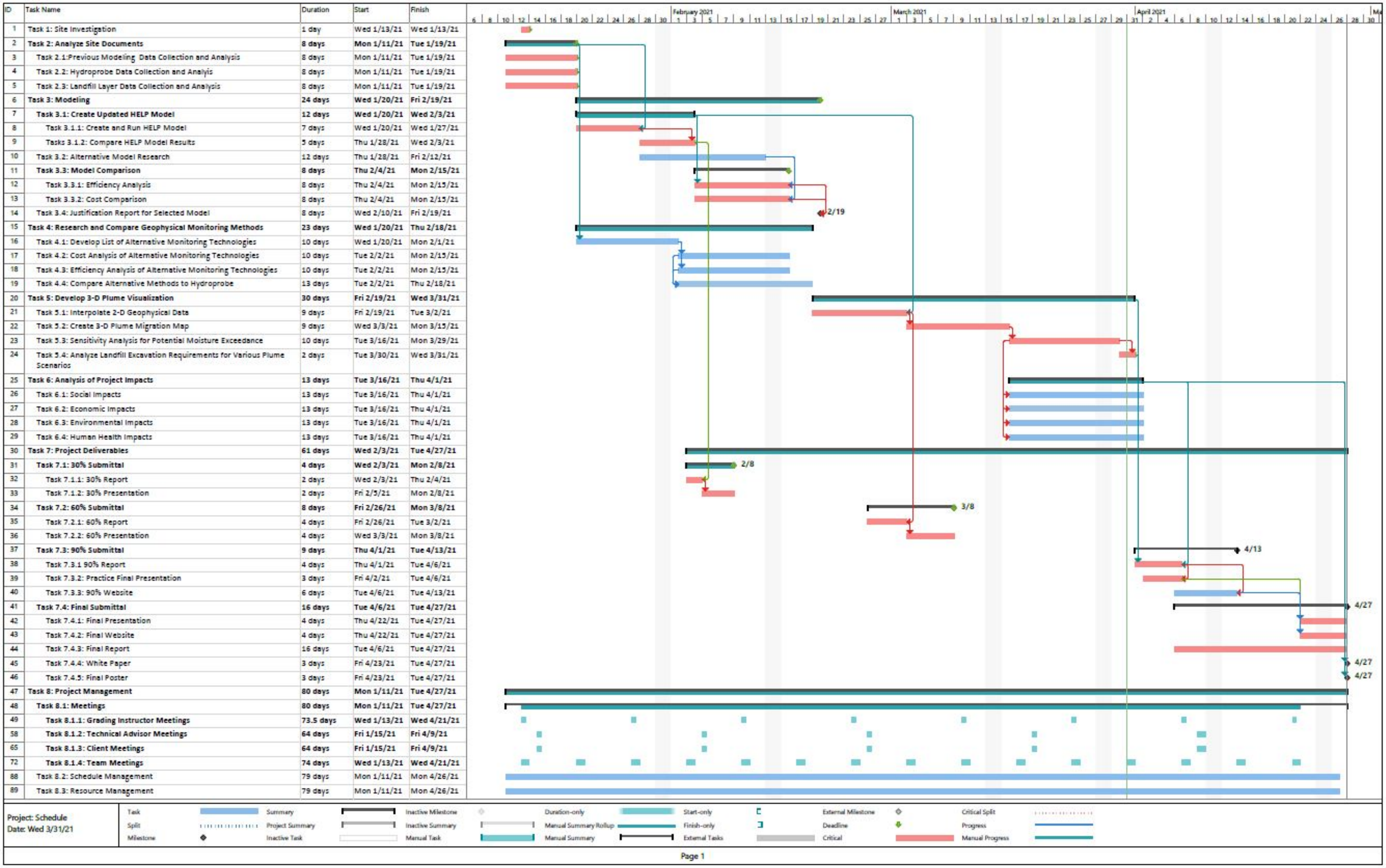


Figure F-1: Permeability Sensitivity Analysis Results 3-D View with Legend

Appendix G: Original and Final Gantt Charts



ID	Task Name	Duration	Start	Finish
1	Task 1: Site Investigation	1 day	Wed 1/13/21	Wed 1/13/21
2	**Task 2: Analyze Site Documents**	**8 days**	**Mon 1/11/21**	**Tue 1/19/21**
3	Task 2.1:Previous Modeling Data Collection and Analysis	8 days	Mon 1/11/21	Tue 1/19/21
4	Task 2.2: Hydroprobe Data Collection and Analyis	8 days	Mon 1/11/21	Tue 1/19/21
5	Task 2.3: Landfill Layer Data Collection and Analysis	8 days	Mon 1/11/21	Tue 1/19/21
6	**Task 3: Modeling**	**24 days**	**Wed 1/20/21**	**Fri 2/19/21**
7	**Task 3.1: Create Updated HELP Model**	**12 days**	**Wed 1/20/21**	**Wed 2/3/21**
8	Task 3.1.1: Create and Run HELP Model	7 days	Wed 1/20/21	Wed 1/27/21
9	Tasks 3.1.2: Compare HELP Model Results	5 days	Thu 1/28/21	Wed 2/3/21
10	Task 3.2: Alternative Model Research	12 days	Thu 1/28/21	Fri 2/12/21
11	**Task 3.3: Model Comparison**	**8 days**	**Thu 2/4/21**	**Mon 2/15/21**
12	Task 3.3.1: Efficiency Analysis	8 days	Thu 2/4/21	Mon 2/15/21
13	Task 3.3.2: Cost Comparison	8 days	Thu 2/4/21	Mon 2/15/21
14	Task 3.4: Justification Report for Selected Model	8 days	Wed 2/10/21	Fri 2/19/21
15	**Task 4: Research and Compare Geophysical Monitoring Methods**	**23 days**	**Wed 1/20/21**	**Thu 2/18/21**
16	Task 4.1: Develop List of Alternative Monitoring Technologies	10 days	Wed 1/20/21	Mon 2/1/21
17	Task 4.2: Cost Analysis of Alternative Monitoring Technologies	10 days	Tue 2/2/21	Mon 2/15/21
18	Task 4.3: Efficiency Analysis of Alternative Monitoring Technologies	10 days	Tue 2/2/21	Mon 2/15/21
19	Task 4.4: Compare Alternative Methods to Hydroprobe	13 days	Tue 2/2/21	Thu 2/18/21
20	**Task 5: Develop 3-D Plume Visualization**	**30 days**	**Fri 2/19/21**	**Wed 3/31/21**
21	Task 5.1: Interpolate 2-D Geophysical Data	9 days	Fri 2/19/21	Tue 3/2/21
22	Task 5.2: Create 3-D Plume Migration Map	9 days	Wed 3/3/21	Mon 3/15/21
23	Task 5.3: Sensitivity Analysis for Potential Moisture Exceedance	10 days	Tue 3/16/21	Mon 3/29/21
24	Task 5.4: Analyze Landfill Excavation Requirements for Various Plume Scenarios	2 days	Tue 3/30/21	Wed 3/31/21
25	**Task 6: Analysis of Project Impacts**	**13 days**	**Tue 3/16/21**	**Thu 4/1/21**
26	Task 6.1: Social Impacts	13 days	Tue 3/16/21	Thu 4/1/21
27	Task 6.2: Economic Impacts	13 days	Tue 3/16/21	Thu 4/1/21
28	Task 6.3: Environmental Impacts	13 days	Tue 3/16/21	Thu 4/1/21
29	Task 6.4: Human Health Impacts	13 days	Tue 3/16/21	Thu 4/1/21
30	**Task 7: Project Deliverables**	**61 days**	**Wed 2/3/21**	**Tue 4/27/21**
31	**Task 7.1: 30% Submittal**	**4 days**	**Wed 2/3/21**	**Mon 2/8/21**
32	Task 7.1.1: 30% Report	2 days	Wed 2/3/21	Thu 2/4/21
33	Task 7.1.2: 30% Presentation	2 days	Fri 2/5/21	Mon 2/8/21
34	**Task 7.2: 60% Submittal**	**8 days**	**Fri 2/26/21**	**Mon 3/8/21**
35	Task 7.2.1: 60% Report	4 days	Fri 2/26/21	Tue 3/2/21
36	Task 7.2.2: 60% Presentation	4 days	Wed 3/3/21	Mon 3/8/21
37	**Task 7.3: 90% Submittal**	**9 days**	**Thu 4/1/21**	**Tue 4/13/21**
38	Task 7.3.1 90% Report	4 days	Thu 4/1/21	Tue 4/6/21
39	Task 7.3.2: Practice Final Presentation	3 days	Fri 4/2/21	Tue 4/6/21
40	Task 7.3.3: 90% Website	6 days	Tue 4/6/21	Tue 4/13/21
41	**Task 7.4: Final Submittal**	**16 days**	**Tue 4/6/21**	**Tue 4/27/21**
42	Task 7.4.1: Final Presentation	4 days	Thu 4/22/21	Tue 4/27/21
43	Task 7.4.2: Final Website	4 days	Thu 4/22/21	Tue 4/27/21
44	Task 7.4.3: Final Report	16 days	Tue 4/6/21	Tue 4/27/21
45	Task 7.4.4: White Paper	3 days	Fri 4/23/21	Tue 4/27/21
46	Task 7.4.5: Final Poster	3 days	Fri 4/23/21	Tue 4/27/21
47	**Task 8: Project Management**	**80 days**	**Mon 1/11/21**	**Tue 4/27/21**
48	**Task 8.1: Meetings**	**80 days**	**Mon 1/11/21**	**Tue 4/27/21**
49	**Task 8.1.1: Grading Instructor Meetings**	**73.5 days**	**Wed 1/13/21**	**Wed 4/21/21**
58	**Task 8.1.2: Technical Advisor Meetings**	**64 days**	**Fri 1/15/21**	**Fri 4/9/21**
65	**Task 8.1.3: Client Meetings**	**64 days**	**Fri 1/15/21**	**Fri 4/9/21**
72	**Task 8.1.4: Team Meetings**	**74 days**	**Wed 1/13/21**	**Wed 4/21/21**
88	Task 8.2: Schedule Management	79 days	Mon 1/11/21	Mon 4/26/21
89	Task 8.3: Resource Management	79 days	Mon 1/11/21	Mon 4/26/21

Project: Schedule
Date: Wed 3/31/21

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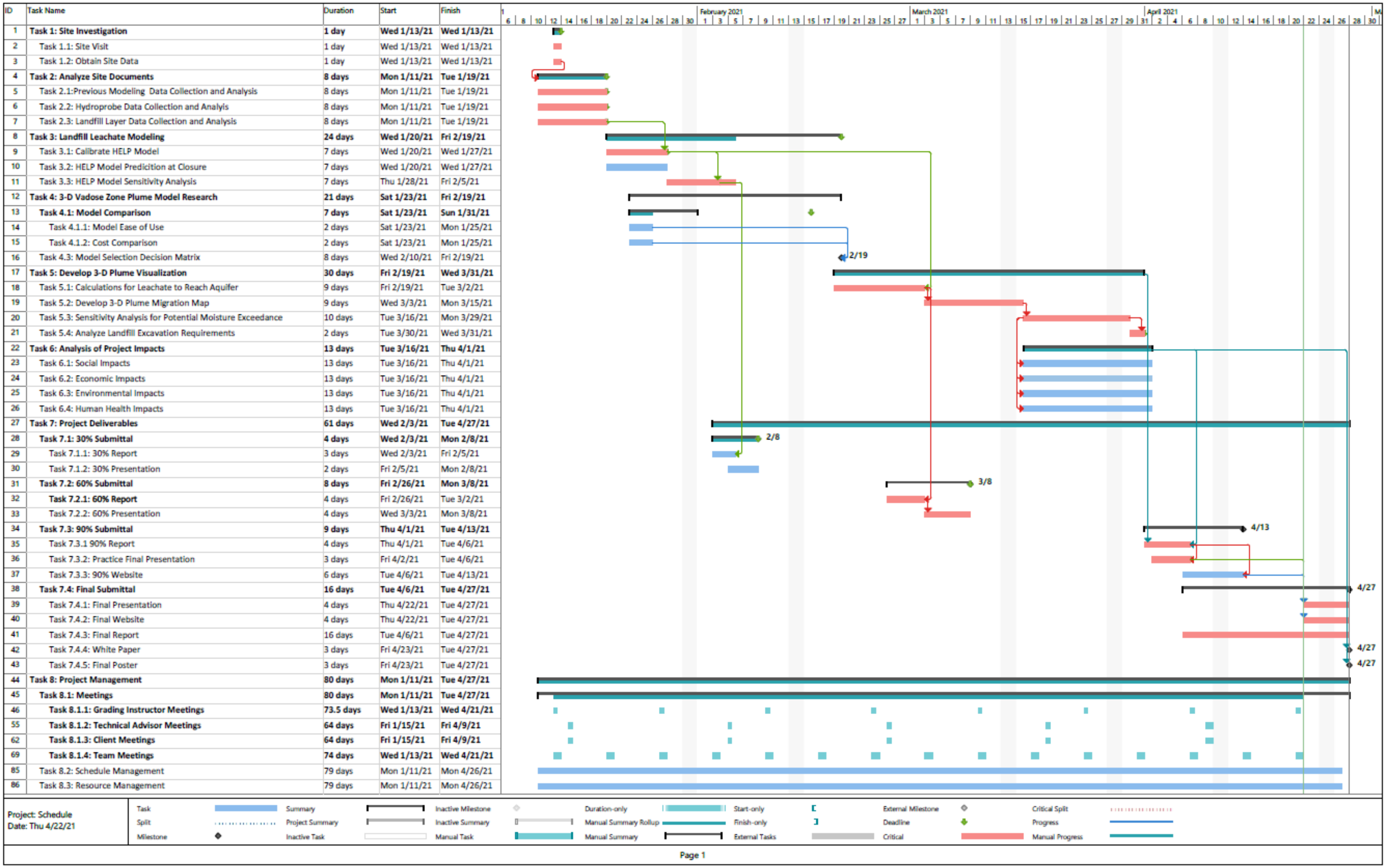
Figure G-1 : Original CENE-476C Gantt Chart



ID	Task Name	Duration	Start	Finish
1	**Task 1: Site Investigation**	**1 day**	**Wed 1/13/21**	**Wed 1/13/21**
2	Task 1.1: Site Visit	1 day	Wed 1/13/21	Wed 1/13/21
3	Task 1.2: Obtain Site Data	1 day	Wed 1/13/21	Wed 1/13/21
4	**Task 2: Analyze Site Documents**	**8 days**	**Mon 1/11/21**	**Tue 1/19/21**
5	Task 2.1:Previous Modeling Data Collection and Analysis	8 days	Mon 1/11/21	Tue 1/19/21
6	Task 2.2: Hydroprobe Data Collection and Analyis	8 days	Mon 1/11/21	Tue 1/19/21
7	Task 2.3: Landfill Layer Data Collection and Analysis	8 days	Mon 1/11/21	Tue 1/19/21
8	**Task 3: Landfill Leachate Modeling**	**24 days**	**Wed 1/20/21**	**Fri 2/19/21**
9	Task 3.1: Calibrate HELP Model	7 days	Wed 1/20/21	Wed 1/27/21
10	Task 3.2: HELP Model Predicition at Closure	7 days	Wed 1/20/21	Wed 1/27/21
11	Task 3.3: HELP Model Sensitivity Analysis	7 days	Thu 1/28/21	Fri 2/5/21
12	**Task 4: 3-D Vadose Zone Plume Model Research**	**21 days**	**Sat 1/23/21**	**Fri 2/19/21**
13	**Task 4.1: Model Comparison**	**7 days**	**Sat 1/23/21**	**Sun 1/31/21**
14	Task 4.1.1: Model Ease of Use	2 days	Sat 1/23/21	Mon 1/25/21
15	Task 4.1.2: Cost Comparison	2 days	Sat 1/23/21	Mon 1/25/21
16	Task 4.3: Model Selection Decision Matrix	8 days	Wed 2/10/21	Fri 2/19/21
17	**Task 5: Develop 3-D Plume Visualization**	**30 days**	**Fri 2/19/21**	**Wed 3/31/21**
18	Task 5.1: Calculations for Leachate to Reach Aquifer	9 days	Fri 2/19/21	Tue 3/2/21
19	Task 5.2: Develop 3-D Plume Migration Map	9 days	Wed 3/3/21	Mon 3/15/21
20	Task 5.3: Sensitivity Analysis for Potential Moisture Exceedance	10 days	Tue 3/16/21	Mon 3/29/21
21	Task 5.4: Analyze Landfill Excavation Requirements	2 days	Tue 3/30/21	Wed 3/31/21
22	**Task 6: Analysis of Project Impacts**	**13 days**	**Tue 3/16/21**	**Thu 4/1/21**
23	Task 6.1: Social Impacts	13 days	Tue 3/16/21	Thu 4/1/21
24	Task 6.2: Economic Impacts	13 days	Tue 3/16/21	Thu 4/1/21
25	Task 6.3: Environmental Impacts	13 days	Tue 3/16/21	Thu 4/1/21
26	Task 6.4: Human Health Impacts	13 days	Tue 3/16/21	Thu 4/1/21
27	**Task 7: Project Deliverables**	**61 days**	**Wed 2/3/21**	**Tue 4/27/21**
28	**Task 7.1: 30% Submittal**	**4 days**	**Wed 2/3/21**	**Mon 2/8/21**
29	Task 7.1.1: 30% Report	3 days	Wed 2/3/21	Fri 2/5/21
30	Task 7.1.2: 30% Presentation	2 days	Fri 2/5/21	Mon 2/8/21
31	**Task 7.2: 60% Submittal**	**8 days**	**Fri 2/26/21**	**Mon 3/8/21**
32	**Task 7.2.1: 60% Report**	4 days	Fri 2/26/21	Tue 3/2/21
33	Task 7.2.2: 60% Presentation	4 days	Wed 3/3/21	Mon 3/8/21
34	**Task 7.3: 90% Submittal**	**9 days**	**Thu 4/1/21**	**Tue 4/13/21**
35	Task 7.3.1 90% Report	4 days	Thu 4/1/21	Tue 4/6/21
36	Task 7.3.2: Practice Final Presentation	3 days	Fri 4/2/21	Tue 4/6/21
37	Task 7.3.3: 90% Website	6 days	Tue 4/6/21	Tue 4/13/21
38	**Task 7.4: Final Submittal**	**16 days**	**Tue 4/6/21**	**Tue 4/27/21**
39	Task 7.4.1: Final Presentation	4 days	Thu 4/22/21	Tue 4/27/21
40	Task 7.4.2: Final Website	4 days	Thu 4/22/21	Tue 4/27/21
41	Task 7.4.3: Final Report	16 days	Tue 4/6/21	Tue 4/27/21
42	Task 7.4.4: White Paper	3 days	Fri 4/23/21	Tue 4/27/21
43	Task 7.4.5: Final Poster	3 days	Fri 4/23/21	Tue 4/27/21
44	**Task 8: Project Management**	**80 days**	**Mon 1/11/21**	**Tue 4/27/21**
45	**Task 8.1: Meetings**	**80 days**	**Mon 1/11/21**	**Tue 4/27/21**
46	**Task 8.1.1: Grading Instructor Meetings**	**73.5 days**	**Wed 1/13/21**	**Wed 4/21/21**
55	**Task 8.1.2: Technical Advisor Meetings**	**64 days**	**Fri 1/15/21**	**Fri 4/9/21**
62	**Task 8.1.3: Client Meetings**	**64 days**	**Fri 1/15/21**	**Fri 4/9/21**
69	**Task 8.1.4: Team Meetings**	**74 days**	**Wed 1/13/21**	**Wed 4/21/21**
85	Task 8.2: Schedule Management	79 days	Mon 1/11/21	Mon 4/26/21
86	Task 8.3: Resource Management	79 days	Mon 1/11/21	Mon 4/26/21

Project: Schedule
Date: Thu 4/22/21

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Figure G-2: Final CENE- 486C Gantt Chart

Appendix H: Cost of Engineering Services

Table H-1: Proposed Hours

Task	SENG Hours	ENG Hours	INT Hours	ADM Hours
Task 1: Site Investigation	4	4	8	4
Task 2: Analyze Site Documents	-	12	24	-
Task 2.1: Geotechnical Data Collection and Analysis		4	8	
Task 2.2: Hydroprobe Data Collection and Analysis		4	8	
Task 2.3: Landfill Layer Data and Analysis		4	8	
Task 3: Modeling	8	58	36	4
Task 3.1: Create Updated HELP Model	2	12	4	
Task 3.1.1 : Create and Run Updated HELP Model	2	8		
Task 3.1.2: Compare HELP Model Results		4	4	
Task 3.2: Alternative Model Research		6	8	
Task 3.3: Model Comparison	6	32	16	
Task 3.3.1: Sensitivity Analysis	4	16	8	
Task 3.3.2: Cost Estimate Comparison	2	16	8	
Task 3.4: Justification Report for Selected Model		8	8	4
Task 4: Research and Compare Geophysical Methods	6	44	24	-
Task 4.1: Develop List of Alternative Modeling Technologies	2	8	8	
Task 4.2: Cost Analysis of Alternative Modeling Technologies	2	16	4	
Task 4.3: Efficiency Analysis of Alternative Modeling Technologies	2	16	4	
Task 4.4: Compare Alternative Methods to Hydroprobe		4	8	
Task 5: Develop 3-D Plume Visualization	8	80	16	
Task 5.1: Interpolate 2-D Geophysical Data	2	20	4	
Task 5.2: Create 3-D Plume Migration Map	2	24	4	
Task 5.3: Sensitivity Analysis for Potential Moisture Exceedance	2	24	4	
Task 5.4: Identify Portions of Landfill Requiring Excavation	2	12	4	
Task 6: Analysis of Project Impacts	-	24	16	16
Task 6.1: Social Impacts		6	4	4
Task 6.2: Economic Impacts		6	4	4
Task 6.3: Environmental Impacts		6	4	4
Task 6.4: Human Health Impacts		6	4	4
Task 7: Project Deliverables	24	44	24	48
Task 8: Project Management	12	12	22	20
Total Expected Hours	62	278	170	92

Table H-2: Completed Hours

Task	SENG Hours	ENG Hours	INT Hours	ADM Hours
Task 1: Site Investigation	**3**	**3**	**3**	**0**
Task 1.1: Site visit	2	2	2	
Task 1.2: Obtain Past Sampling Data	1	1	1	
Task 2: Analyze Site Documents	**1.5**	**5.5**	**6**	**0**
Task 2.1: Geotechnical Data Collection and Analysis		3	3	
Task 2.2: Hydroprobe Data Collection and Analysis		1	1	
Task 2.3: Landfill Layer Data and Analysis	1.5	1.5	2	
Task 3: Landfill Leachate Modeling	**8**	**22**	**22**	**0**
Task 3.1 Calibrate HELP Model	0	8	8	
Task 3.2:HELP Model Prediction at Closure	6	8	8	
Task 3.2: HELP Model Sensitivity Analysis	2	6	6	
Task 4: 3-D Vadose Zone Plume Model Research	**1**	**11**	**11**	**0**
Task 4.1: Model Comparison	**0**	**5**	**6**	
Task 4.1.1: Model Ease of Use		4	5	
Task 4.1.2: Cost Estimate Comparison		1	1	
Task 4.2: Model Selection Decision Matrix	1	2	1	2
Task 5: Develop 3-D Plume Visualization	**24**	**21.5**	**20.5**	**0**
Task 5.1: Calculations for Leachate to Reach Aquifer	4	4	4	
Task 5.2: Develop 3-D Plume Migration Map	15	12.5	12.5	
Task 5.3: Sensitivity Analysis for Potential Moisture Exceedance	3	3	2	
Task 5.4: Analyze Landfill Excavation Requirements	2	2	2	
Task 6: Analysis of Project Impacts	**0**	**4**	**4**	**4**
Task 7: Project Deliverables	**8**	**10**	**24**	**35**
Task 8: Project Management	**18**	**16**	**20**	**28**
Total Hours Worked	63.5	93	110.5	67