EVALUATION OF HYDROLOGICAL BALANCE AT AN EXPERIMENTAL LANDFILL CAPPING SITE IN KANEHOE MARINE CORPS BASE HAWAII

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1 INTRODUCTION

1.1 Problem Identification

Landfilling is a method of waste disposal that has been used for many years. In 2001, 55.7% of municipal solid wastes, in the United States, were disposed of in landfills. In Hawaii alone, there were 8 municipal solid waste landfills in 1999 (Glenn 1999). Other methods of dealing with municipal solid waste include combustion and recycling. Combustion accounted for 14.7% and recycling accounted for 29.7% of MSW disposal in 2001 for the United States (EPA, 2001).

Prior to the passing of the Resource Conservation and Recovery Act (RCRA) of 1976, there was little regulation as to the design of new landfills. Landfill facilities were located in places of convenience, which may have been adjacent to sensitive ecosystems. There was little concern about the potential of environmental contamination of wetlands, aquifers, or other water bodies (McBean et al., 1995). A problem associated with landfills is the production of leachate, caused by water infiltrating into waste material, creating a liquid containing contaminants. This leachate can then migrate to aquifers or surface waters, including streams, lakes, and oceans, thus contaminating water resources.

1.2 Evaluation of Suitability of Landfill Cover

The Resource Conservation and Recovery Act of 1976 states guidelines that require safe disposal of waste materials. When the lifetime of an existing landfill expires, a landfill cover is designed and placed over the area. Landfill covers are one method to reduce leachate production by decreasing the water available for infiltration. Although landfill cover designs are site specific, RCRA recommends a minimum design cover
system. The RCRA landfill cover system consists of the following three layers: (1) a vegetation/soil top layer, (2) a drainage layer, and (3) a low permeability flexible membrane layer (FML)/soil layer. Figure 1.1 shows the RCRA recommended minimum landfill cover system. The vegetation/soil top layer has two purposes. The first is to reduce the amount of infiltrating water by using low permeability soil. The second is the accommodation of vegetation to increase the evapotranspiration. Increasing the evapotranspiration will reduce the amount of water available for infiltration through the soil top layer and increase its retention capacity for water. The purpose of the drainage layer is to remove water that infiltrates through the top layer, minimizing the amount of time the water is in contact with the low permeability layer. The purpose of the low permeability layer is to minimize infiltration of water into the waste.

![Diagram of RCRA Landfill Cover System](image)

Figure 1.1: RCRA Landfill Cover System (USEPA, 1991)

For each landfill soil cover, US Environmental Protection Agency (EPA) requires analysis and evaluation of the final cover by the computer model Hydrologic Evaluation of Landfill Performance Version 3 (HELP3) (Schroeder et al., 1994). One criteria that
must be met for an alternative landfill cover to be accepted is that, using HELP3 simulations, leachate production from the alternate cover must be equal to or less than that of the RCRA landfill cover system.

HELP3 often underpredicts amount of runoff and overpredicts the amount of leachate production (Fleenor et al., 1995). Therefore, HELP3 is a conservative model in terms of the prediction of leachate amounts. This can lead to the overdesign of landfill covers and unnecessary cost. One reason for the over prediction of runoff is the fact that daily rainfall values are used. HELP3 averages the daily amount evenly throughout the day, allowing the model to apply and infiltrate a given amount of water throughout the whole day, therefore in lower rain intensity, instead of the actual interval of the storm event, which may be much shorter and cannot infiltrate over a short time period, resulting in instant runoff. Lower intensity of rainfall allows more infiltration and reduces runoff. In Hawaii, typical rain events last for a few hours.

An additional reason for the overestimation of leachate production can be attributed to the assumption of 100% relative humidity assumed by the model on days when there is precipitation. This assumption leads to less water being removed through evaporation and more infiltrating into the soil (Young, 2000).

Also assumed by HELP3 is that the water in the soil/top layer is routed vertically downward under a unit hydraulic gradient using unsaturated hydraulic conductivity (Dwyer, 2003), which causes an overprediction in leachate. In reality, it is possible for the hydraulic gradient to be less than one, thus reducing the downward movement of water through the soil/top layer. HELP3 also assumes the low permeability/bottom layer is saturated, and uses saturated hydraulic conductivity ($K_{sat}$) in its calculations for
downward water movement through this layer. In reality, it is possible for this layer to be unsaturated, in which case unsaturated hydraulic conductivity ($K_{\text{unsat}}$), which is less than $K_{\text{sat}}$, should be used to determine water flow in the layer.

In arid environments, where annual precipitation is less than annual evapotranspiration, vegetated soil covers are adequate to prevent the production of leachate. In humid environments, where annual precipitation is greater than annual evapotranspiration, additional measures must be taken in order to reduce leachate production. One possibility to accomplish this is to use runoff-enhancing structures. By enhancing runoff, the amount of water available for infiltration is reduced.

1.3 Objective at Marine Base Corps Hawaii landfill site

The aim of the original study was to determine the amount of leachate through the soil layer made of site-specific soil material, which is planned to be used as a future cap for existing landfill. The study of leaching potential of a landfill cover at Marine Base Corps Hawaii was started in 1995 by the Naval Facilities Engineering Service Center in Port Hueneme, CA and the Los Alamos National Laboratory (Hakonson et al., 1999). Three cover designs were considered: (1) vegetated soil cover, (2) 20% of area covered by impervious runoff enhancing structures, (3) 40% of area covered by impervious runoff enhancing structures. For the impervious runoff enhancing structures, standard plastic rain gutters were used. While the plots with impervious runoff enhancing structures were found to produce larger quantities of runoff than the control (vegetated soil cover) plot, leachate estimates by HELP3 were much higher than the measured values and runoff predictions in HELP3 were lower than measured. Knowing that temporal averaging of rainfall by HELP3 (see section 1.2) can contribute to overestimation of leachate
production and underestimation of runoff, a new set of objectives were adopted to examine:

a) What would be the impact of storms of various duration and intensities on water balance for all three cover types?
b) For given rainfall intensities and durations, how would antecedent soil water conditions and vegetation stage affect the water balance?
c) How would the predictions of HELP3, that uses daily averaging of rainfall, compare with leachate and runoff quantities calculated from an event-based runoff and an event-based infiltration model?
d) Would closer monitoring of soil water content in the profile and accurate estimate of evapotranspiration affect the water balance calculations for the three cover designs?

1.4 Water Balance Equation and Collection of Data

The existing system of monitoring water balance was rebuilt at the test site in 2001, and was improved and enhanced in terms of precise monitoring of soil water balance and the implementation of an artificial irrigation system to produce infiltration to enable testing in naturally dry periods.

The site contained a 60 cm deep soil profile and water balance was calculated using the following equation:

\[ P = I + R + L + ET + \Delta S \]  \hspace{1cm} (1)

where \( P \) is precipitation amount, \( I \) is interception amount, \( R \) is runoff amount, \( L \) is leachate amount, \( ET \) is evapotranspiration amount, and \( \Delta S \) is the change of water content in the soil profile. Each term in the above equation was measured in the research except
for ET. In this thesis it was estimated based on known weather data, soil water pressure
data, and pan evaporation measurement utilizing a computer program, which calculates
potential ET, using Penman equation (Penman, 1963).

1.4.1 Modeling Assessment

The event-based models chosen for this thesis were KINEROS2, which is an updated version of KINEROS (Woolhiser et al., 1991), for runoff simulation and HYDRUS-1D (Simunek et al., 1998) for percolate simulation. These models are available in the public domain and have been tested for a wide variety of problems. These models, including HELP3, were calibrated using the collected data. Model predictions were compared to measured data and HELP3 were compared with KINEROS2 for runoff predictions and HELP3 and HYDRUS-1D were compared for leachate predictions.

The complementary objective was to validate water balance models (HELP3) and other event-based models: KINEROS2 (Woolhiser et al., 1991 for original model) and HYDRUS1-D (Simunek et al., 1998), using the collected data.
2 DESCRIPTION OF LANDFILL CAPPING EXPERIMENTAL SITE

2.1 Design, Instrumentation and Data Acquisition

Figure 2.1 shows a schematic plan view of the experimental area. The dimensions of experimental area are 44 m by 13 m. Six plots, each 6 m in width by 9 m in length (i.e. 54 m$^2$), were constructed. The area was leveled, and the top 0.6 m of soil was removed. A drain system was installed below each plot. Underdrains with dimensions of 0.3 m in height, 3 m in width, and 8 m in length, centered along the longer side of the plots, were constructed. The underdrain was lined with a plastic liner and filled with gravel for leachate collection. A 0.15 m diameter drain was installed on the downslope wall of the underdrain. Contrary to the methods used for runoff measurements (on the whole area of the plot), leachate passing through a 24 m$^2$ area (8 m by 3 m) under the middle part of each plot was collected and measured only. The reason for this design was to avoid the effects of flow across the plot boundaries which are difficult to account for. Similarly, the one meter gap in between the leachate collection area and the cutoff wall was to minimize the influence of the plot borders on the leachate production. For comparison, leachate, rainfall, irrigation, evapotranspiration and runoff amounts are all presented as values per unit area.

A 6 m plywood endwall, extending from the surface to the gravel layer, was installed on the downslope face of each plot. Previously removed soil of thickness 0.6 m was placed over the entire area and compacted to 95% Proctor. A runoff-collecting pipe, 0.20 m in diameter, was installed along the downslope edge of each plot. All plots were constructed with a 4% slope along its length. Seeds of native shrubs and grasses were
used to vegetate the area. A detailed construction plan describing the construction of the site can be found in Hakonson et al. (1999). Figure 2.2 is a schematic of runoff/leachate collection system.

Figure 2.1: Plan View of Experimental Area (Young, 2000)

Figure 2.2: Schematic of Runoff / Leachate Collection System (Young, 2000)
Three different types of plots, each with two replicating sets were used in this research. Types of the plots differ in the amount of surface area covered by gutters, with its purpose to enhance runoff. The enhancement of runoff reduces the amount of water that can leach into the soil profile. The first type has no gutters and serves as the control plot, called “ConA/B”. The second type has 20% of its area covered with gutters and is called “20A/B”. The third type has 40% of its area covered with gutters and is called “40A/B”. Each gutter is 0.12 m wide, 9 m long and, 0.08 m high. Gutters are placed along the length of the plot spaced evenly throughout it. They are fastened to the soil, using aluminum hooks and by filling with each gutter partially with gravel, and lay freely on the surface. Each gutter drains into the runoff-collecting pipe downslope of each plot.

Although the gutters are impervious, the soil directly below them may be wetted by lateral water flow from adjacent spaces in between the gutters. Rather than preventing leaching below them, the gutters prevent part of the incoming water from infiltrating by removing some water as runoff.

To prevent runoff from areas outside of the plots from entering the plots, barriers were constructed. The purpose of the barrier is to divert runoff from the upslope areas preventing their contribution into the experiment. It was constructed by a partial burial of the plywood sheets. A portion of the 0.50 m in height plywood sheet was buried into the soil, with 0.25 m left above ground level. Neighboring pieces of plywood had an overlap of 0.08 m, with joints filled with either silicone or foam to prevent leakage through the plywood barrier. The second barrier surrounded each plot. Plastic garden edging material was partially buried around three sides of the plot, excluding the downslope edge, which is bordered by the collection pipe. The edging material is 0.15 m high, of which 0.10 m
was buried, leaving 0.05 m of the edging material above ground level. The purpose of this barrier was to prevent runoff from crossing from one plot to another. This barrier was constructed to be shorter in height, because the plywood barrier blocked any runoff from the upslope areas. Runoff from the upslope areas is typically greater than the runoff that potentially would cross plots.

2.2 Data Acquisition

All measuring devices are currently connected to one of three Campbell Scientific 21X data loggers. The system is designed to allow each data logger to store 3 to 11 days worth of measured data. Each of the 21X loggers has 8 differential or 16 single ended channels that can be connected by various sensors. Such a system allows having 58 measuring instruments and multiplexors, which enhances the number of sensing capabilities for measurements of the same kind. For example, all pressure transducers are connected to one channel of the data logger, through the use of a multiplexor, AM416.

These three data loggers are connected to a cellular phone located at the research site, which connects them once a day with a personal computer, located at the University of Hawaii at Manoa, for recent data retrieval. The various types of data are distinguished by array numbers, which ease the data sorting and analysis.

All data loggers and the cellular phone are housed in fiberglass boxes and powered by 12-volt batteries, charged from solar panels.

2.3 Meteorological Measurements

A Campbell Scientific Meteorology Station, installed at the experimental site, was used to collect weather data. The system measures rain intensity, air temperature, soil
temperature at 0.15 and 0.30 m below surface, wind speed, wind direction, relative humidity and net radiation at fifteen-minute intervals. Meteorological data are used for processing parts of the hydrological cycle such as rainfall or evapotranspiration.

Meteorological data collected at the research site during period of irrigation episodes are present in Appendix A. The annual average values and standard deviations for 2003 are:

- air temperature 1 m above ground level: $24.7^\circ C \pm 2.0^\circ C$
- soil temperature at 0.15 m depth: $26.8^\circ C \pm 0.6^\circ C$
- relative humidity: $71.3\% \pm 12.6\%$
- wind speed: $3.1 \text{ m/s} \pm 1.4 \text{ m/s}$
- net radiation: $91.2 \text{ W/m}^2 \pm 32.1 \text{ W/m}^2$

### 2.3.1 Precipitation Measurement

Two TE525 tipping bucket counters, made by Texas Electronics, were used to measure precipitation at the site. The tipping buckets were placed at ground level and at 1 m above ground level. Theoretically, both should give the same readings. However, wind and interception, due to the difference in tipping bucket height, can alter the amount of rain collected in the tipping buckets.

Another advantage of having two tipping buckets was to mutually verify their performance. Often, it was found that one of the tipping buckets was malfunctioning due to debris settlements deposited by ants. At those times, the data from the other tipping bucket would be used to substitute the gap in measurement as the best available solution. The tipping buckets work with a precision of 0.0254 cm (0.01 inch). Previously the weather station data logger was programmed to collect fifteen-minute totals,
continuously. In 2002 it was reprogrammed to add a record of one minute rainfall totals when rainfall was occurring, giving more accurate data of the rainfall intensity.

Precipitation data from the 1 m high rain gage were used in the analysis because splash debris and vegetation surrounding the surface rain gage interfered with rainfall measurements. The cumulative natural rainfall values for years 2002 and for 2003, are 44.6 cm and 51.8 cm, respectively. The measured precipitation for those two years were low compared to the 50 year average annual rainfall of 101.4 cm.

2.3.2 Evapotranspiration

Evapotranspiration (ET) is the combination of evaporation from the soil surface and transpiration from vegetation (Chow et al., 1988).

ET was estimated using several methods. The first method is the pan evaporation method. A pan was filled with water, and equipped with a pressure transducer, which records the height of the water column above it. The drop in the water column corresponds to the amount of evaporated water from the pan.

The second method was to calculate potential ET using the Penman Method (Penman, 1963). Potential ET is the evapotranspiration that would occur from a well vegetated surface when moisture supply is not limiting. Penman’s equation is:

\[ E_o = \frac{(\Delta H + \gamma E_a)}{(\Delta + \gamma)} \]  

where \( E_o \) is open water evaporation (mm day\(^{-1}\)), \( \Delta \) is the slope of the saturation vapor pressure vs. temperature curve (mbar K\(^{-1}\)), \( H \) is net radiation (expressed as equivalent water depth), \( \gamma \) is the psychrometric constant, and \( E_a \) is an aerodynamic term.
This method requires wind speed, humidity, solar radiation, and air temperature data to obtain an estimate for potential ET. These data were collected by a meteorological station located at the experimental site.

The third method analyzed automated tensiometer data. After a rain event, a time comes when leachate is no longer produced, leaving only ET and soil water content loss as the only two processes occurring. During this time ET is equal to soil water content loss, according to water balance equation. By converting tensiometer data to soil water content amounts, the actual ET rate was determined.

The greatest value of ET obtained from the above three methods was the method of analyzing soil water content loss. As potential ET is the theoretical maximum of ET, this greatest value was assumed to be equal to potential ET.

ET for each episode was determined by assuming that the actual ET equaled the potential ET because with irrigation, and large storm events, the soil water content supply would not be limiting. Also, during all episodes, except episode 1, the site was well vegetated. The potential ET rate, obtained from determining the soil water content loss after a rain event, was multiplied by the duration of the interval to estimate the amount of ET. This rate was assumed to represent ET for the entire soil profile.

2.3.3 Runoff Measurement

Runoff from the plots was collected by a 0.20 m diameter collection pipe, located on the downslope edge of the plots. For each plot, the pipe runs to a collection tank, located in a trench, south of the experimental area. The location of the trench and collection tanks can be seen in figure 2.3. Runoff is determined by measuring the amount of water entering the collection tank, by means of two instruments:
1. Pressure transducer, which is able to measure precisely the water column in the tank. With the calibration of a pressure transducer and the tank volume, the transducers report the total volume of water in the tank. The transducers are programmed to collect data in fifteen-second intervals, which is stored in the intermediate logger storage for instant analysis prior to permanent data storage, because the volume of water can change significantly in the fifteen-minute collection interval. Data logger records minimum and
maximum values reached in the fifteen-minute interval. By examining the volume of water in the tank at two successive intervals, the amount of water entering or leaving the tank via pumping could be determined.

Situations occurred where the water was being pumped out of the tank, while runoff or leachate would be entering. Typical rate of runoff production from plots 20B and 40B is 50 liters per hour. Typical pumping rate of runoff tank is 50 liters per minute. Although this situation theoretically will cause an error, it is merely 2%.

2. Flow counters, which measure the amount of water pumped out of the tank. When the water level in the tank reaches a certain height, a switch activates a sump pump, which is located at the bottom of each runoff collection tank. The pump control box is housed in a plastic container. The water is pumped out of the tank through a 1.9 cm diameter PVC pipe with the flow counter mounted on its end and totalizing the flow over the fifteen-minute interval. The flow counters are equipped with a propeller, which turn when water flows through. Each quarter of revolution is equivalent to 5 mL of water. Both the transducer data and flow counter data, for the runoff collection tanks, were used to determine amount of runoff.

2.3.4 Leachate Measurement

Leachate is collected in the underdrain. On the downslope face of the underdrain, a 0.15 m diameter collection pipe collected the leachate and transported it to leachate collection tanks, located next to the runoff collection tanks. Each plot has its own leachate collection tank. Once in the leachate collection tank, the amount of leachate production is measured. The system for leachate measurement is designed identically to the system for runoff measurement, with an additional feature for flow measurement,
TE525 tipping bucket counter, the same device used to measure rainfall. This feature in the system is designed to be accurate for measuring the rate of leachate production, especially at small volumetric flow rates. However, during heavy rains, or irrigation runs, the leachate production from one plot overflows the tipping buckets, resulting in inaccurate measurements. Therefore these data are not used in the analysis.

Both the flow counter and pressure transducer supplied adequate information to determine leachate production. Prior to September 24, 2003, all leachate collection tanks were not equipped with flow counters. Leachate was calculated by transducer data of leachate collection tanks only. Because of the data collection scheme, gaps of inadequate data existed in the outflow hydrograph. However, the general shape of the leachate hydrograph could be observed from transducer data. Values for the gaps were linearly interpolated using adjacent data points. The area under the hydrograph was estimated resulting in a total value for leachate production. The original and corrected hydrograph for episode 5, plot 40B is presented in figure 2.5.
Figure 2.5: Leachate Hydrograph for Episode 5

Plot 40B – Original and Corrected

From September 24, 2003, leachate volumes were determined using flow counter and transducer data in the same way that runoff volumes were calculated. This method was compared to the hydrograph method used to calculate amounts for leachate prior to September 24, 2004 and was found to be within 15% of each other.
2.3.5 Soil Water Content Measurement

There are several different types of devices used to assess the soil moisture. Originally, the site was equipped with time domain reflectometry probes (TDR) operated by Tektronix 1502B Reflectometer to measure soil water content (Tektronix, 1992). TDR measures the apparent dielectric constant of the soil surrounding a waveguide. The soil dielectric constant is governed by the dielectric constant of liquid water and is an acceptable method for liquid soil water measurement (Warrick, 2002). The Tektronix device measures the response time of the electrical pulse sent to one electrode and received by the two remaining electrodes, arranged in a triplet on one probe. The shape of the response curve and the response time serve as information, from which the soil water content is determined.

Until August 2003, the 21X data logger was programmed to collect this TDR data twice a day. Starting on August 7, 2003, soil water content acquisition by means of TDR probes was reprogrammed for three-hour intervals. For this measurement, 24 electrodes were installed vertically into shallow soil horizon in all six plots, i.e. 4 electrodes/plot, at four locations over the plot. Their positioning can be seen in Appendix B. The length of a single probe is 0.15 m. All four probes were placed directly below the ground surface, and could only measure soil water content of the top 0.15 m of the soil profile. The TDR probes were tested and calibrated at the soils laboratory at the University of California at Santa Barbara soil laboratory. Being the only method used previously, Young (2000) and Hakonson et al. (1999) assumed that soil water content of the top 0.15 m of the artificial soil profile was representative of the entire 0.60 m profile. As found by analysis of undisturbed samples taken during 2003 from the depth 0-0.6 m, this assumption is
incorrect. This leads to inaccurate estimations for the soil water content gain/loss term in the water balance equation. In order to acquire more spatial knowledge of soil water content conditions and continuous record of soil water content and soil saturation essential for leaching, lower cost manual TDR and automated tensiometer systems were installed focusing on the B section (ConB, 40%B and 20%B), i.e. three plots only.

Two manual TDR probes were installed in each of the “B” plots and placed vertically at depths of 0.05-0.25 m and 0.25-0.55 m. The new TDR placement in each plot can be seen in Appendix B. These probes are of a different design than the original probes. They are 0.20 m long, with the middle electrode coated to prevent corrosion. A Model 6050X1 Water Content Measuring System device, made by Soil Moisture Equipment Corp, was used to manually measure these probes. As a cost effective, indirect soil water content measurement, soil water pressure by means of tensiometers is monitored.

A tensiometer is a device that measures soil capillary suction in a porous media. It is made of a ceramic tip, a plastic tube, and an airtight cap. The cap may be a rubber stopper or a screw cap. A pressure transducer may also be used for automated collection of data. Figure 2.6 shows the parts schematic construction of a tensiometer.

The most important portion of the tensiometer is the ceramic tip, buried at a desired distance below the ground surface. It bears unique properties, allowing water to pass through, but keeping air from entering the tensiometer. The whole tensiometer is filled with water and sealed with an airtight cap. Depending on the matric suction potential of the soil, water in the tensiometer reaches pressure equilibrium with the water
in the soil by allowing very small amounts of water to enter or leave the tensiometer via the porous cup.

The drier the soil, the higher the suction in soil and consequently in the tensiometer. With wetter soil, the suction decreases. With saturated soil, the suction in the tensiometer is equal to zero or the pressure is positive as a water table perches above the ceramic cup.

Four manual tensiometers at a depth of 0.10 m and three manual tensiometers at depths of 0.20 m, 0.30 m, and 0.50 m per plot, were installed in all six plots. Their positions can be seen in Appendix B. These tensiometers were measured manually with a Tensiometer (Marthaler et al., 1983), made by Soil Measurement Systems, Tucson, Arizona.
Three automated tensiometers at depths of 0.15 m, 0.30 m, and 0.45 m were installed in all “B” plots. The only additional feature of automated tensiometers is a pressure transducer connected to its body. The transducer automatically measures the suction in the tensiometer, which is reported to the data logger, storing such data at fifteen-minute intervals. Their location in the plots can be seen in Appendix B.

The transducers attached to automated tensiometers are calibrated to give results in centimeters (of water column) of suction. This cannot readily be used to determine soil moisture. Soil samples must be taken and retention curves analyzed in order to relate soil water pressure to soil water content.

Retention tests were conducted and will be discussed further in section 2.4.1. Using this retention curve, tensiometer data was converted to soil water content. The tensiometer at 0.15 m depth was assumed to represent soil at depths of 0-0.20 m, tensiometer at 0.30 m depth was assumed to represent soil at depths of 0.20-0.40 m, and the tensiometer at 0.45 m depth was assumed to represent soil at depths of 0.40-0.60 m. The water content reported by each tensiometer was multiplied by the thickness of the soil it represented to obtain subtotals soil water content. These subtotals were summed to determine the total amount of water in the profile.

2.3.6 Automation of Data Collection

As mentioned earlier, most of the instrumentation at the site has been automated. The data loggers collected data at either, one minute, fifteen minute, or three hour intervals, which are transferred daily to the University of Hawaii via cellular phone. The continuous collection and retrieval of data also helped in site maintenance.
Malfunctioning instruments could be determined by examining the recent data. Preparations for fixing the equipment could be made before going to the site.

2.4 Determination of Hydraulic Characteristics of Soil

2.4.1 Retention Curve of Soil Water

A retention curve describes the functional relationship between soil water content and matric potential under equilibrium conditions, and is a primary hydraulic property required for evaluation of water balance in soil and essential parameter for modeling water flow (Warrick, 2002). A retention curve is obtained by subjecting samples of soil to various negative pressures and weighing the samples to determine volumetric water content after it reaches equilibrium, for each specific negative pressure. A set of consecutively increasing pressure stages was applied and a related set of volumetric water content in soil is measured, allowing the construction of a retention curve.

Series of soil sampling events of undisturbed soil cores at different depths were performed to obtain retention curves. A total of 42 soil samples were collected.

Soil closer to the surface has different retention properties than deeper soils because of increasing compaction with depth, caused by overburden. As a result, soil samples at three depths (at the 10, 30 and 50 cm below the soil surface) were collected. Initially, three soil samples from each of the six plots at depth of 10 cm, were collected, resulting in a set of 18 samples. Later, a second set of 2x12 samples was collected between plots ConB and 20%-B, at a depth of 30 and 50 cm in two pits. All samples were collected into brass cylinders with dimension of 6 cm high and 5.4 cm in inside diameter. The samples were brought to the laboratory at the University of Hawaii, where the retention tests were conducted. Samples were first saturated and weighed. All samples
were subjected to a set of different pressures: 0.01, 0.10, 0.50, 1.00, 5.00, 10.00, 35.00, and 150.00 m of water column. For pressures of 0.01 and 0.10 m of water column, samples were placed on a clay/porous plate. This plate was connected by rubber tubing to a column of water, whose height was varied to have its water level at 0.01 and 0.10 m below the clay plate, thus subjecting samples to corresponding suctions. ASTM D-2325 and D-3152 was followed for pressures of 0.50 to 150.00 m of water column (ASTM, 2000). After reaching equilibrium for each pressure, where soil sample holds only water by capillary forces equal or higher than imposed by given suction, samples were weighed. Samples were subjected to the different pressures in ascending order, resulting in a drying process for the soil. Upon completion of all suctions, samples were completely dried and the volumetric water content for imposed sets of pressure, as well as, porosity, bulk density, and solids density were determined. Using the data, a retention curve, relating soil suction to water content could be graphed. Figure 2.7 shows a sample retention curve.
Figure 2.7: Measured Points of Soil Water Retention and Retention Curve for Sample Data

After conducting the retention tests, the soil water retention data were inputted into the ARC-RETC (Vogel et al., 1991) program, and fitted to the van Genuchten equation (van Genuchten, 1980).

\[
\theta = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + (\alpha h)^n\right)^m}
\]

The parameters obtained from the fitting are residual water content (\(\theta_r\)), saturated water content (\(\theta_s\)), \(\alpha\), and \(n\), which are fitting parameters. This equation is used to relate soil
water pressure data to actual volumetric soil water content data, used here for the purpose of calculating mass balance of water and for computer modeling. For these purposes the set of retention curves have been scaled in order to find a reference retention curve for each soil horizon. Scaling of retention curves is an advanced way of their averaging (Vogel et al., 1991). As each fitted retention curve has its $\theta_s$, $\theta_r$, $\alpha$, and $n$, which best fit the measured data according to van Genuchten’s formula, scaling is a way of finding adequate transformation parameters for each single curve when related to averaged reference retention curve.

Overall scaling factors, $\alpha$, are computed for each pair of soil hydraulic characteristics from the relationships

$$\alpha_s = \frac{(\theta_s - \theta_r)}{(\theta^* - \theta^*_r)}$$

$$\alpha_h = \frac{h_s}{h^*_c}$$

where $\theta_s$ is saturated water content, $\theta_r$ is residual water content, $h_c$ is suction, and $^*$ denotes arithmetic means of the respective values (Vogel et al., 1991). The procedure of scaling is beneficial in several ways:

1. by relating scaled measured points to reference retention curve, one may visually check the bandwidth of the measured data, which relate to a new single curve, thus to evaluate the heterogeneity of soil properties or quality of measurement, and

2. scaling is important in nondimensional solution of Richard's equation of flow in porous media, which can be solved only once for a very narrow class of geometrical and material parameters as well as boundary and initial conditions. By scaling, one can introduce a heterogeneity of properties into the mathematical solution.
Table 2.1: Reference Parameters of Soil Water Retention Curves by ARC-RETC

<table>
<thead>
<tr>
<th>Depth</th>
<th>$\Theta_r$</th>
<th>$\Theta_s$</th>
<th>$\alpha$ (cm$^{-1}$)</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20 cm</td>
<td>0.289</td>
<td>0.654</td>
<td>0.113</td>
<td>1.231</td>
</tr>
<tr>
<td>20-40 cm</td>
<td>0.305</td>
<td>0.569</td>
<td>0.083</td>
<td>1.193</td>
</tr>
<tr>
<td>40-60 cm</td>
<td>0.318</td>
<td>0.556</td>
<td>0.026</td>
<td>1.217</td>
</tr>
</tbody>
</table>

The results of ARC-RETC are presented in table 2.1. Porosity, which is the soil water content at saturation ($\Theta_s$), decreases with depth due to the increasing soil compaction.

Analysis of the 18 surface soil samples, 12 samples at 30 cm depth, and 12 samples at 50 cm depth results in reference parameters representing soil depths of 0-20 cm, 20-40 cm, and 40-60 cm respectively. These parameters, along with van Genuchten’s equation, allow the conversion from soil water pressure to soil water content. The retention curves for all soil samples and the scaled curves are presented in Appendix C.1.

2.4.2 Saturated Hydraulic Conductivity

Saturated hydraulic conductivity is an essential soil parameter that describes allowance of soil to permeate water under unit pressure gradient. Darcy’s Law describes the flow of a liquid through a porous media and is written as:

$$ q = K_s \cdot \frac{\Delta H}{L} $$

(5)

where $q$ is Darcy velocity, $\frac{\Delta H}{L}$ is hydraulic gradient, and $K_s$ is saturated hydraulic conductivity. The hydraulic conductivity at zero suction is the saturated hydraulic conductivity.
conductivity. Darcy’s Law also applies to unsaturated flow, with the difference of using unsaturated hydraulic conductivity \( K_{\text{unsat}} \) instead of saturated hydraulic conductivity. 

\( K_{\text{unsat}} \) is less than or equal to \( K_s \) because in unsaturated flow, only a fraction of the total pores are filled, and thus able to transport water. \( K_{\text{unsat}} \) is a function of water content. Higher water content relates to higher \( K_{\text{unsat}} \), with eventually \( K_s = K_{\text{unsat}} \) when the soil is saturated. At higher negative pore pressure or suction, the unsaturated hydraulic conductivity is lower, because at high negative pore pressure, the soil is relatively drier. Drier soil conducts less water because only the small pores are filled water, while the larger pores, which are able to conduct a higher volume of water, remain empty.

For the field measurement of soil hydraulic conductivity, a disc infiltrometer (Ankeny et al., 1988) was used at the surface and at 20 cm depth. The infiltrometer setup can be seen in figure 2.8. The locations of the tests are present in Appendix B.

Figure 2.8: Disc Infiltrometer Setup (Wyseure et al., 1998)
A water pressure in the disc can be set with the water level tension valve and water is allowed to flow out of the water reservoir into the soil below. After reaching water pressure equilibrium between the infiltrometer and soil, steady state of flow is also reached, i.e. the amount of water leaving the water reservoir per unit time will be constant and is recorded. Given the disc diameter, the water reservoir diameter, and the constant dropping rate of the level in the water reservoir, saturated hydraulic conductivity for a pressure was determined. Repeating this process for a series of different water pressures including water pressure equal to zero, corresponding to saturated conditions, a curve relating soil water pressure to hydraulic conductivity was found.

The results of the infiltrometer tests for soil at the research site are presented in figure 2.9. The saturated hydraulic conductivity is higher (see figure 2.9) for the surface soil layers because of greater cracking in the soil, less compaction, and greater effect of root zones for water flow.

![Figure 2.9: Results of Infiltrometer Test for Surface and Deeper Horizons-MCBH Soil](image-url)
Also conducted was a laboratory test to determine saturated hydraulic conductivity. Two soil samples were first saturated, then subjected to increasing pressures, similar to the method used in determining soil water retention parameters. In addition, a pressure transducer was used to determine the pressure in the soil sample in relation to time. Continuous data for pressure and soil water content was obtained, which were inputted into HYDRUS-1D, and inverse modeling was conducted. Based on the continuous data, a value for saturated hydraulic conductivity was obtained and is presented in table 2.2.

Table 2.2: Saturated Hydraulic Conductivity Results-MCBH Soil

<table>
<thead>
<tr>
<th>Saturated hydraulic conductivity [cm/sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disc Infiltrometer Test</td>
</tr>
<tr>
<td>Surface</td>
</tr>
<tr>
<td>18 cm depth</td>
</tr>
<tr>
<td>Lab Test*</td>
</tr>
</tbody>
</table>

*by inverse modeling with HYDRUS-1D
** by falling head permeameter test

Values of hydraulic conductivity reported in Hakonson, which used soil cores from the same site was 5x10^{-7} cm/sec. Field tests using a tension disc infiltrometer results in values of 5x10^{-3} cm/sec for surface soil and 2x10^{-3} cm/sec for soil at 0.18 m depth. Laboratory tests using inverse modeling result in values ranging from 6x10^{-6} cm/sec to 2x10^{-7} cm/sec. A possible explanation for the lower saturated hydraulic conductivities reported by Hakonson and from the inverse modeling is that the lab tests typically result
in lower values in saturated hydraulic conductivity because they do not account for root
channels, cracks, and lateral spreading of water through the soil while conducting tension
disk infiltrometer experiments close to saturation.

Soil hydraulic properties can vary over time because of soil disturbance, shrinking
and swelling of fine textured soil, wetting and drying cycle, and the effect of particle
dispersion and soil crusting (van Genuchten et al., 1995). An investigation of a final
cover on a Uranium Mill Tailings Disposal Site (Waugh et al., 1997) reported that the
hydraulic conductivity of the clay barrier increased by three orders of magnitude from
1x10^-7 cm/sec in 1987 to 1x10^-4 cm/sec in 1996.

Keeping this in mind, it was realized that the saturated hydraulic conductivity for
the soil cover could vary in time and space. A range of values for $K_{sat}$ was used for
comparing RCRA landfill cover with alternate covers.

**2.4.3 Particle Size Analysis**

Particle size analysis is the determination of the size range of particles present in a
soil, expressed as a percentage of the total dry weight (Das, 1998).

Appendix B shows the location where soil was sampled to conduct particle size
analysis. A brass cylinder, 0.04 m in diameter and 0.15 m in length, was used to collect
the sample. ASTM D-422 method was followed for the sieve analysis and ASTM D-1140
was followed for the hydrometer analysis (ASTM, 1995). Using the textural classification
system developed by the U.S. Department of Agriculture (USDA), the soil is classified as
a loam. The particle size curve is presented in Appendix C.2. The test resulted in an
effective size ($D_{10}$) of 0.004 mm, uniformity coefficient ($D_{60}/D_{10}$) of 17.5, and coefficient
of gradation ($D_{30}^2/D_{60}*D_{10}$) of 1.4.
2.5 Vegetation Monitoring

2.5.1 Vegetation Survey

A vegetation survey is a procedure in which the amounts and types of plants in an area are recorded. Any new species of vegetation may be found by a comparison of the previous survey to the results of the current survey. Also, the results of the survey give an idea of the types of plants at the site. This information could be used for estimates of interception and water uptake.

The experimental area was vegetated by seeding in 1994 with plants that existed in the surrounding area. In January of 2003, a vegetation survey was conducted. The survey used the point frame method that utilized a frame with 61 equidistant notches (Pieper, 1973). An aluminum rod 0.5 cm in diameter and 1.5 m long was dropped into each notch. The frame was moved at 60 cm intervals across each plot. The type of plant that touched the aluminum rod was recorded.

2.5.2 Ground Cover Survey

Ground cover is a way of estimating the health of the vegetation. A lot of litter on the surface indicates that many plants have died.

In January 2003, a ground cover survey was conducted. This survey used the same frame and aluminum rod that was used in the vegetation survey. The modification of the test this time was in recording the type of cover that the tip hit. The possible categories were ground, gutter, or litter. Table 2.3 is a summary of the percentage of cover of each category for each plot.
Table 2.3: Ground Cover Data – MCBH Experimental Site

<table>
<thead>
<tr>
<th>Plot</th>
<th>% of cover</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bare Soil</td>
<td>Litter</td>
<td>Gutter</td>
</tr>
<tr>
<td>CA</td>
<td>2.3</td>
<td>97.7</td>
<td>0.0</td>
</tr>
<tr>
<td>20A</td>
<td>0.3</td>
<td>80.5</td>
<td>19.2</td>
</tr>
<tr>
<td>40A</td>
<td>4.1</td>
<td>38.0</td>
<td>57.9</td>
</tr>
<tr>
<td>CB</td>
<td>0.8</td>
<td>99.2</td>
<td>0.0</td>
</tr>
<tr>
<td>20B</td>
<td>0.2</td>
<td>81.3</td>
<td>18.5</td>
</tr>
<tr>
<td>40B</td>
<td>0.0</td>
<td>61.8</td>
<td>38.2</td>
</tr>
</tbody>
</table>

The most common species of vegetation was buffel grass and blue panic. Knowing the common species of plant allowed for an estimation of interception amounts, which is based on the assumption of a single type of plant species.

2.5.3 Leaf Area Index Measurement

Leaf area index is a measure of the surface of area of leaves per unit area (Schroeder et al., 1994) and is described in the following equation,

$$LAI = \frac{\text{surface area of live leaves}}{\text{horizontal area}}$$

This index is used in estimating interception and evapotranspiration. Higher LAI results in greater interception and plant transpiration. LAI is used by HELP3 model in its calculation for evapotranspiration.

In January of 2003, a leaf area index measurement was conducted. This survey used the same frame and rod that was used in the vegetation survey. However, all 61 notches were not used to do this survey. Instead, five notches of the 61 total notches were used. To determine the leaf area for that point, the number of live plants in contact with the rod, were counted. This number was the corresponding leaf area index for that point.
In addition to the above method, a manual method was conducted. A 0.1 m$^2$ plastic square frame was randomly thrown onto a plot. All the plants were then cut at the ground surface and collected in an airtight bag. The bags were brought to the University of Hawaii where, each green leaf/plant was entered into a portable leaf area meter, made by LiCor (LiCor). The output of this meter is the total area of leaves. (Cramer et al., 2000).

The leaf area indexes found in January 2003 were 2.08 for ConB, 1.94 for 20-B, and 0.96 for 40-B.

2.5.4 Biomass Measurement

In January of 2003, a biomass measurement was conducted at the site. Biomass consisted of live plants, standing dead plants, and litter. A 0.1 m$^2$ square plastic frame was randomly thrown three times over each plot. All biomass inside the square was collected and placed into airtight bags. All bags were taken to the University of Hawaii and dried. The dry mass was measured and recorded.

In October of 2003, another biomass measurement was conducted. An irrigation system had been installed three months prior, resulting in tremendous plant growth. This measurement was performed at this time to estimate possible maximum biomass for this site. The measurement followed the same procedure applied in January 2003.

The biomass results can be seen in table 2.4. Biomass results give an idea as to the health of the vegetation.
Table 2.4: Biomass Data – MCBH Experimental Site

<table>
<thead>
<tr>
<th>Date</th>
<th>Plot</th>
<th>avg dried biomass (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-03</td>
<td>40B</td>
<td>744.3</td>
</tr>
<tr>
<td>Jan-03</td>
<td>20B</td>
<td>759.3</td>
</tr>
<tr>
<td>Jan-03</td>
<td>CB</td>
<td>744.3</td>
</tr>
<tr>
<td>Oct-03</td>
<td>40B</td>
<td>574.5</td>
</tr>
<tr>
<td>Oct-03</td>
<td>20B</td>
<td>584.0</td>
</tr>
<tr>
<td>Oct-03</td>
<td>CB</td>
<td>605.5</td>
</tr>
</tbody>
</table>

2.5.5 Root Zone Depth

Root zone depth is the distance from the surface to which the roots of vegetation extend and is related to the depth which transpiration of soil water can occur. Deeper roots allow plants to transpire water from deeper horizons in the soil profile. Root zone depth is a parameter used in the HELP3 and HYDRUS-1D computer programs as part of its calculation of evapotranspiration.

In order to estimate root zone depth, a soil pit, approximately 60 cm deep was dug, 2 m to the west of our experimental area. This was determined to be adequate because the experimental area was vegetated with natural, surrounding vegetation. The excavation found that roots extend to the bottom of the 0.60 m pit. Therefore, it was estimated that the root zone depth for the site is 0.60 m, ie. through the entire soil profile.

2.5.6 Visual evaluation

During the tests, photographs were taken before each irrigation run, for a visual examination for the estimation of plant height resulting in interception on vegetation, which is a necessary parameter for water balance. Photographs of the site during irrigation events are presented in Appendix G.
2.6 Irrigation System

Rainfall totals for 2002 and 2003 are 44.6 cm and 51.8 cm respective, significantly less than the 50 year average of 101.4 cm/yr. As precipitation is the catalyst for the runoff, infiltration and leachate, and soil water content change processes, rain is an essential factor in the entire study. In order to study the desired effect of a rainfall event with higher intensity, which has a low probability of occurrence, and higher likelihood to produce runoff and leachate, an irrigation system was installed to produce artificial rainfall.

2.6.1 Installation of the System

Approximately 150 m south of our experimental site, an existing tap that feeds the irrigation system was reconstructed. The existing high water pressure at the tap was reduced by a pressure reducing valve, followed by a backflow preventer. PVC pipes with 0.0381 m (1.5") diameter were used to span the 150 m distance to transport the water to the experimental area. Just before the site, a dynamic pressure reducing valve, dropping the water pressure from 75psi to 35psi (psi=pound per square inch=6.89kPa), water meter, pressure gauge, and sprinkler timer were installed. The water meter was connected to one of the dataloggers for automatic collection of data of flow (1 impulse per 10 gallons, 1 gal=3.785 liter). However, a manual meter, which was on the face of the flow counter, was used to determine the amount of the water transported through the sprinkler system.

The sprinkler heads by LR Nelson Corporation (Nelson Corp., 2000) were used. These sprinklers have a feature of rotation, with the capability to define the horizontal angle of sprinkling. Depending on their locations in the plot, some sprinkler heads were
set to turn 180 degrees, while others were set to rotate 360 degrees. A total of 18 sprinkler heads were used, evenly spaced at 4.57 m (15 ft) intervals. All three plots in the B section were irrigated, while the three plots in section A was left to natural conditions. Figure 2.11 and 2.12 shows the positions of the sprinklers.

The original design of the irrigation system had the sprinkler heads placed at 0.08 m above the ground. However, after two months of irrigation, the plants grew up to a height of over 1 m. This caused the sprinkler heads to be blocked. Clearing a 1 m diameter area around blocked sprinkler heads was done to minimize the effect of the plants blocking the sprinkler heads. This seemed inadequate, thus raising the sprinkler heads to 0.94 m was performed after three months of operating the system. This arrangement prevents plants from blocking the sprinkler heads.

2.6.2 Uniformity Test

Uniformity test was used to verify that sprinkler application is even throughout an area, and was done before any rainfall events were simulated. This test was used to ensure that the areas of simulated rainfall application would be wetted evenly.

To conduct the uniformity test, the existing plants had to be cut and cleared. Aluminum cans with diameter of 0.089 m and 0.051 m high were placed at 1.5 m intervals throughout the entire irrigation layout. The sprinklers were run for 30 minutes. The amount of water in each can was collected and measured with a graduated cylinder. Sprinklers were then adjusted to decrease imperfections in the spatial delivery of water.

After raising the sprinkler heads to 0.94 m, another uniformity test was conducted due to change in the travel destination of sprinkled water after raising the sprinkler heads. The existing plants were again cut and cleared. By raising the sprinkler heads, the wind
affected the destination of water greatly. Only with minimal wind, the uniformity test would be acceptable. This limits the times when an irrigation test could be run. Only on days with negligible or no wind, would the sprinkler settings uniformly apply water to the plots.

To determine if the irrigation had adequate uniformity, a uniformity index for sprinklers was calculated as:

\[
\text{Uniformity index} = \frac{\text{average of data set lowest quartile}}{\text{average of entire data set}}
\]  

An index of 0.85 is considered adequate uniformity. The uniformity index achieved for the surface sprinkler system was 0.75 and it was 0.82 for the raised sprinkler system.

Photos of the plots during the uniformity test can be seen in figure 2.10. Irrigation uniformity maps can be seen in figure 2.11 and figure 2.12. The surface sprinkler test reveals areas on the northern portions of the plot where more water is applied, resulting in the slightly lower uniformity index as compared to the raised sprinkler system, where the water is applied quite evenly throughout. On August 7th 2003, the installation of the irrigation system was completed.
Figure 2.10: Collection Cans During Uniformity Test

Figure 2.11: Uniformity Test Results, 08/14/03 Sprinklers 0.08 m Above the Soil Surface
Figure 2.12: Uniformity Test Results, 10/31/03 Sprinklers 0.94 m Above the Soil Surface

2.6.3 Irrigation Amounts

The irrigation system was equipped with a flow counter recording the volume of applied water. While conducting uniformity tests, based on the volumes captured in cans, it was found that 80% of total volume passing through the water meter, for sprinkler heads located 0.08 m above ground, and 77% for sprinkler heads located 0.94 m above ground, was applied to plots. The reduction in volume that is actually applied to the plots, as compared to the volume passing through the water meter, was due to the fact that some sprinklers were set to apply water outside of the plots and wind caused some water to be blown outside of the plots. Respective percentages, of the total volumes, were used in calculating amount of simulated rain applied. This rain was referred to as effective
simulated rainfall. The amount of effective simulated rainfall, from August 7, 2003 to December 31, 2003, was 84.0 cm, while the natural rainfall during this same period was 22.8 cm, about one fourth of the simulated rainfall. A cumulative plot of the natural rainfall and effective simulated rainfall during irrigation episodes is present in figure 2.13. With the addition of the irrigation system, simulated rainfall events were conducted, ranging in duration from 1 hour to 3 hours. Eight episodes, due to both natural and irrigated events were chosen to be analyzed in terms of water balance.

Figure 2.13: Natural and Effective Simulated Rainfall from 8/1/2003 to 12/31/2003
3 MODELING

Based on the measured field data, models were used to simulate hydrologic events using the HELP3, KINEROS2, and HYDRUS-1D models. The results of more advanced models: KINEROS2 and HYDRUS-1D were compared against HELP3 to determine the limits of expectation of predictive performance of HELP3.

3.1 Hydrologic Evaluation of Landfill Performance Version 3 (HELP3)

3.1.1 Model Overview

The computer simulation model, Hydrologic Evaluation of Landfill Performance version 3 (HELP3), was developed by the U.S. Army Engineer Waterways Experiment Station for the U.S. Environmental Protection Agency (Schroeder et al., 1994). HELP3 was developed to provide regulators a tool to evaluate the hydrologic performance of proposed landfill designs. The model uses weather, soil, and design data as inputs to estimate runoff, evapotranspiration, leakage through soil layers, and soil water content storage. HELP3 is a quasi-two-dimensional model for determining water balances (Schroeder et al., 1994).

The program accepts meteorological data, including daily values for precipitation, temperature, and solar radiation, an annual value for average wind speed, and a quarterly average for relative humidity. Soil characteristics, including porosity, field capacity, wilting point, and saturated hydraulic conductivity are required as well. Vegetation inputs include leaf area index and evaporative zone depth. As an output, the model predicts daily water balance values for surface runoff, evapotranspiration, leachate production, and soil water content storage.
In the logic of the model design, surface runoff is the portion of incoming precipitation that flows along the soil surface. Runoff is calculated by the following equation:

\[
\frac{Q}{S} = \frac{P}{S} - 1.2 - \frac{1.0}{\frac{P}{S} + 0.8}
\]

(8)

where \(Q\) is runoff, \(P\) is precipitation, \(S = \frac{1000}{CN} - 10\), and \(CN\) is the runoff curve number.

HELP3 uses the Soil Conservation System (SCS) runoff curve number technique to partition between runoff and infiltration. Curve numbers have been tabulated by the SCS based on soil type, land use, and soil classification. A higher runoff curve number will result in more runoff. HELP3 can modify the entered curve number based on surface slope and surface length (Chow et al., 1988).

Potential evapotranspiration, in HELP3 is understood as the evapotranspiration that would occur from a well-vegetated surface when soil water supply is not limited and is estimated by the Penman method, which requires relative humidity, solar radiation, and wind speed. Actual evapotranspiration drops below this potential level as the soil dries (Chow et al., 1988).

Infiltration is the process of water penetrating from the ground surface into the soil (Chow et al., 1998). It is calculated by the following equation:

\[
INF_i = PRE_i + GM_i - INT_i - Q_i
\]

(9)

where \(INF\) is infiltration, \(PRE\) is precipitation, \(GM\) is groundmelt, \(INT\) is interception, and \(Q\) is runoff.

To determine subsurface water routing and storage, HELP3 utilizes saturated hydraulic conductivity (\(K_s\)), field capacity, which is defined as the soil water content at a
suction of 0.33 bar, and wilting point, which is defined as the soil water content at 15 bar. These values are used to determine such processes as plant transpiration, vertical drainage, surface and subsurface evaporation.

### 3.1.2 Input Parameters for Simulating Experimental Plots

Input parameters for HELP3 plot 40B is presented in Appendix E.1. All plots were simulated by a three layer soil, each with a depth of 0.20 m because retention data and hydraulic conductivity data for soil at depths 0-20 cm, 20-40 cm, and 40-60 cm was obtained from soil sampling and infiltrometer tests. Saturated hydraulic conductivity values from the disc infiltrometer test and soil water characteristics from retention curves were entered for each layer.

Daily values for rainfall (natural plus irrigated), net solar radiation, and temperature were obtained from the meteorological station and used as input. Required quarterly humidity and annual average wind speed was obtained from the meteorological station.

Field measurements of leaf area index ranging from 0.96 to 2.08, has been evaluated in January of 2003. However, these measurements were taken prior to the installation of the irrigation system, which greatly increased the amount of live plants. It was assumed that the leaf area index was much greater and a LAI=5, which is the maximum allowed by HELP3, was used in the simulation. An evaporative zone depth of 0.60 m, the entire soil profile, was also entered.

The above parameters were identical for simulation of water balance for all three plots. The only difference between the simulation of the three plots is in the runoff curve number. HELP3 does not allow the input of gutters, which effect was substituted by an
increase in the runoff curve number. Increasing the runoff curve number increases the runoff production, which is the role of the gutters. Plot 40B had the highest curve number followed by plot 20B and CB. Table 3.1 shows the curve numbers used in the HELP3 simulation.

Table 3.1: HELP3 Simulation Curve Numbers

<table>
<thead>
<tr>
<th>Plot</th>
<th>Runoff Curve Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>65</td>
</tr>
<tr>
<td>20B</td>
<td>70</td>
</tr>
<tr>
<td>40B</td>
<td>71</td>
</tr>
</tbody>
</table>

Figure 3.1 shows the relation between curve number, soil texture, and vegetation level. An excellent stand of grass with a loam soil, which is the soil classification from particle size analysis, results in a curve number of 65. This was used to simulate ConB. Curve numbers for 20B and 40B were chosen by trial and error. By examining runoff data, a trend of increasing runoff with increasing gutter cover is present. Ratio of runoff amounts from the field measure for 20B to runoff for 40B was examined and the curve numbers chosen result in a similar ratio for runoff predictions by HELP3.
3.1.3 Input Parameters for RCRA and 40% Cover Plots

Regulatory agencies require that alternate landfill covers produce equal or less leachate than RCRA landfill covers as predicted by HELP3. By analyzing water balance for plot 40B it was found that 40% of rainfall did not become runoff, instead 6.2% became runoff. However, the performance of theoretical landfill covers, where 40% of the area is impervious and all rainfall contacting this impervious area is totally produced as runoff, was compared with the RCRA cover.

The RCRA cover was simulated with three layers, a 60 cm vegetated layer with a $K_{sat}$ ranging from $10^{-5}$ cm/sec to $10^{-7}$ cm/sec, a 30 cm lateral drainage layer with a $K_{sat}$ of
0.3 cm/sec, and a 30 cm layer of compacted clay with a $K_{\text{sat}}$ of $10^{-7}$ cm/sec. Input parameters for the RCRA cover is presented in table 3.2.

Theoretical landfill covers were simulated with a soil/top layer with depths ranging from 0.60 m to 1.2 m. The $K_{\text{sat}}$ ranged from $10^{-5}$ cm/sec to $10^{-7}$ cm/sec. The area was split into two parts to simulate the theoretical cover, where all rainfall contacting the 40% impervious area is totally produced as runoff. The first part simulated the pervious area, with a runoff curve number of 65 (based on vegetation stage and soil classification) and with a total area 60% that of the entire plot. The second part simulated the impervious area, with a runoff curve number of 100, which results in all rainfall being produced as runoff or as surface evaporation and had a total area 40% that of the entire plot.

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Type</th>
<th>top/soil layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curve Number</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Thickness [cm]</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>0.654</td>
<td></td>
</tr>
<tr>
<td>Field Capacity</td>
<td>0.447</td>
<td></td>
</tr>
<tr>
<td>Wilting Point</td>
<td>0.328</td>
<td></td>
</tr>
<tr>
<td>$K_{\text{sat}}$ [cm/sec]</td>
<td>$10^{-5}$ to $10^{-7}$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Layer 2</th>
<th>Type</th>
<th>lateral drainage layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness [cm]</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>0.397</td>
<td></td>
</tr>
<tr>
<td>Field Capacity</td>
<td>0.032</td>
<td></td>
</tr>
<tr>
<td>Wilting Point</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>$K_{\text{sat}}$ [cm/sec]</td>
<td>$3 \times 10^{-1}$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Layer 3</th>
<th>Type</th>
<th>barrier soil layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness [cm]</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>0.427</td>
<td></td>
</tr>
<tr>
<td>Field Capacity</td>
<td>0.418</td>
<td></td>
</tr>
<tr>
<td>Wilting Point</td>
<td>0.367</td>
<td></td>
</tr>
<tr>
<td>$K_{\text{sat}}$ [cm/sec]</td>
<td>$10^{-7}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2: Input Parameters for HELP3 Simulation of RCRA Cover
Weather data for the year 2003 were used as inputs for these simulations. The leachate predictions for the RCRA cover and theoretical landfill cover were compared for the year 2003.

3.2 Kinematic Runoff and Erosion Model Version 2 (KINEROS2)

3.2.1 Model Overview

The kinematic runoff and erosion model, version 2, (KINEROS2) is an event-oriented model, describing the processes of interception, infiltration, and surface runoff of watersheds. The watershed is represented by a series of planes and channels. As the model is event based, it does not consider long term changes in soil water content and plant growth.

KINEROS2 calculates overland flow by solving the kinematic wave equation using finite difference method.

KINEROS2, assumes that the overland flow can be described by the equation

\[ Q = \alpha h^m \]  

where \( Q \) is the discharge per unit width, \( h \) is the head, and \( \alpha \) and \( m \) are related to slope and surface roughness. This equation, along with the equation of continuity, results in the kinematic wave equation below

\[ \frac{\partial h}{\partial t} + \alpha m h^{m-1} \frac{\partial h}{\partial x} = q(x,t) \]  

where \( h \) is the head, \( t \) is time, \( x \) is distance along slope direction, \( \alpha \) and \( m \) are coefficients related to slope and surface roughness, and \( q \) is lateral inflow rate.

The output includes interception, surface runoff, and infiltration. KINEROS2 does not predict water movement and storage in the soil profile.
Two input files required by KINEROS2 are the parameter file and the rainfall file. The parameter file consists of watershed geometry and soil surface/subsurface characteristics. The soil surface parameters include Manning's roughness coefficient and maximum interception. Subsurface parameters include saturated hydraulic conductivity ($K_s$), capillary drive ($G$), porosity, and initial degree of soil saturation. Geometry parameters include type of element (plane or channel), dimensions of element, and slopes of sides for channels, which must be trapezoidal.

The rainfall file provides information on the intensity of rainfall throughout the interval, which is being modeled. Rainfall data can be entered as time vs. intensity or time vs. accumulated depth.

3.2.2 Input Parameters and Calibration

The input file for KINEROS2 plot 40 B for a selected hydrologic episode is presented in Appendix E.2. ConB consisted of one plane, representing vegetated soil, and a collection channel, while plots 20B and 40B consisted of two planes, representing vegetated soil and the gutters, and a collection channel. All elements have a slope of 4%.

For the plane representing vegetated soil, a Manning's coefficient of 0.24 and an interception depth of 0.003 m were chosen based on the observed type of vegetation that consisted mainly of dense grass (USDA, 1990).

Two options for soil layer thickness are available. The first is simulating a two layer soil profile, in which case, the lower layer is infinitely deep. The second is to have a single layer soil profile, which is infinitely deep. Because KINEROS2 is a runoff model, which cannot produce information about leachate, and for the purpose of decreasing number of unknowns in the simulation, a single soil layer profile was chosen as adequate.
for calibrating model with surface runoff data. A porosity of 0.654 was chosen based on results of the retention tests. Hydraulic conductivity ($K_s$) of 0.17 m/hr as measured by the disc infiltrometer in field tests was used. Capillary drive ($G$) was calculated as 0.11 m based on the following equation

$$G = \frac{2 + 3\lambda}{1 + 3\lambda} \phi_b$$

(12)

where $\lambda$ is “n” from the RETC output, and $\phi_b$ is “$a^{-1}$” from the RETC output.

$K_s$ and $G$ are influential factors in the prediction of surface runoff by KINEROS, and were slightly modified from above values to obtain satisfactory agreement in runoff predictions and real measured data.

The only episode producing a significant amount of runoff for plot ConE, episode 8, was used to calibrate $K_s$ and $G$.

The best fit of $K_s$ and $G$, when measured and simulated runoff on ConE is $K_s$ equal to 0.06 m/hr and $G$ equal to 0.15 m. These values are in the same order of magnitude as the measured $K_s$ and calculated $G$ value.

For the plane representing the gutters, a Manning’s coefficient of 0.02 was used (USDA, 1990). A saturated hydraulic conductivity ($K_s$) equal to 0 was used to represent the gutters. KINEROS2 assumes that because the surface is impermeable, the area below the surface is also impermeable, resulting in less area that water can store in soil.

However, in reality, the gutters lay freely on the surface, allowing water from adjacent vegetated soil cover areas to seep under the area of the gutters. The width of the soil plane must be increased to account for this. The width of the gutter plane is decreased in order to keep the total width at 6 m. Also, in reality, vegetation overhangs the gutters, intercepting incoming precipitation and routing it to the soil, via stem. In reality, this
diminishes the effect of the runoff enhancement, as the gutters are avoided. Thus the gutter plane must be further reduced to account for this. Therefore, the percent of area represented by this plane was not 20% for plot 20B and 40% for 40B, as the actual surficial area covered by gutters. Instead, total width of soil plane and gutter plane was held constant at 6 m, and the widths of each were modified to obtain satisfactory results. Calibration of impermeable plane width and vegetated soil plane width with runoff data from episodes 1, 2, and 3, which were irrigated events lasting from 2 to 3 hours, resulted in percentage of impermeable surface equal to 4.6% for plot 20B and 5.7% for plot 40B. These percentages, along with $K_s$ of 0.06 m/hr and $G$ of 0.15 m were used to simulate all other episodes.

Initial degree of soil saturation (SAT) was obtained from automated tensiometer data, and varied for each episode.

3.3 HYDRUS-1D

3.3.1 Model Overview

HYDRUS-1D is a public domain Windows-based modeling environment for analysis of one dimensional water flow and solute transport in variably saturated porous media (Simunek et al., 1998). Only water flow is simulated for this thesis. The model is supported by an interactive graphics-based interface for date-preprocessing, discretization of the soil profile, and graphic presentation of the results (Simunek et al., 1998).

HYDRUS-1D solves the one-dimensional form of Richard's equation (14), which is a combination of Darcy's law (12) and continuity equation (13)

$$q = -K(\theta) \text{ grad } H$$

(13)
where $q$ is the Darcy flux, $K$ is the unsaturated hydraulic conductivity, and $\text{grad}H$ is the hydraulic gradient. The continuity equation can be mathematically expressed as

$$\frac{\partial (\theta \rho)}{\partial t} + \text{div}(\theta \rho \mathbf{v}) = 0$$

(14)

where $\theta$ is the volumetric water content, $\rho$ is density, and $\mathbf{v}$ is the velocity.

Richard's equation is then

$$C(h) \frac{\partial h}{\partial z} = -\frac{\partial}{\partial z} \left( K(h) \frac{\partial h}{\partial z} \right) + \frac{\partial K(h)}{\partial z}$$

(15)

where $C$ is soil-water capacity, $h$ is the head, $K$ is unsaturated hydraulic conductivity, and $z$ is the depth.

HYDRUS-1D accepts saturated hydraulic conductivity and soil retention values given from RETC using van Genuchten retention parameters, which are $\theta_s$, $\theta_r$, $\alpha$, and $n$.

3.3.2 Input Parameters

HYDRUS-1D discretizes the 0.60 m soil profile into 100 nodes, chosen arbitrarily, with the top of the profile containing shorter distances between nodes and the lower horizons containing larger distances.

In addition the 0.60 m soil profile was divided into three layers, each 0.20 m in depth, allowing separate saturated hydraulic conductivity and retention parameters to be inputted for each layer and is present in table 3.3. Input parameters for a HYDRUS-1D simulation are presented in Appendix E.3.

The boundary condition for the top surface is atmospheric, where rainfall adds water into the profile, evaporation removes water from the surface, and root water uptake removes water from deeper horizons. The bottom boundary condition is a seepage face,
where water flows according to Darcy's Law when saturated and no flow occurs when soil is unsaturated. The initial soil water content is entered as -700 cm throughout the 0.60 m profile, which applies to the start of the simulation of August 1, 2003. Because the first episode begins on August 20, 2003, the program is allowed to equalize the amount of water in the simulated profile for 20 days.

Table 3.3: Soil Retention Input Parameters for HYDRUS-1D

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth [m]</th>
<th>K_s [cm/d]</th>
<th>( \theta_r )</th>
<th>( \theta_s )</th>
<th>( \alpha [cm^{-1}] )</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 - 0.20</td>
<td>800</td>
<td>0.289</td>
<td>0.654</td>
<td>0.113</td>
<td>1.231</td>
</tr>
<tr>
<td>2</td>
<td>0.20 - 0.40</td>
<td>400</td>
<td>0.305</td>
<td>0.569</td>
<td>0.083</td>
<td>1.193</td>
</tr>
<tr>
<td>3</td>
<td>0.40 - 0.60</td>
<td>100</td>
<td>0.312</td>
<td>0.5625</td>
<td>0.0545</td>
<td>1.205</td>
</tr>
</tbody>
</table>

Required data include rainfall and evapotranspiration data. Rainfall data, combining natural rainfall and irrigated rainfall, of 15 minute intervals were entered. Root water uptake distribution was calibrated based on automated tensiometer data.

Original evapotranspiration data was obtained by observing the drying of the soil through the use of automated tensiometers. Approximate values for ET during different time intervals was estimated.

3.3.3 Model Calibration

Simulation of ConB was done using total rainfall (natural plus irrigated) as the input. HYDRUS-1D does not allow the input of gutters, with its purpose to enhance runoff. From measured data, the percentage of incoming rainfall as runoff was calculated for the eight episodes and averaged, resulting in an average of 4.8% and 5.5% of rainfall being taken out of the plots by the gutters for 20B and 40B respectively. A decrease in
the total rainfall by respective percentages was used to simulate the role of the gutters for 20B and 40B.

As was reported, three automated tensiometers in each plot record the soil water pressure continuously. To calibrate the model, the soil water pressure data was compared to soil water pressure predictions of HYDRUS-1D. During this process, ET values were increased from original estimates to achieve satisfactory soil water pressure predictions, as raising ET results in a reduction of the water pressure. The ET increases ranged from 1.3 to 2.5 times the estimate from soil drying.
4 RESULTS AND DISCUSSION

4.1 Water Balance

With the irrigation system, 19 simulated rainfall events were conducted. The duration of the simulated events varied from 1 hour to 3 hours, with three hours being the typical length of irrigation. Eight episodes, due to both natural and irrigated events were chosen. Episodes began with the initiation of rainfall, with the ending of episodes determined to be when leachate production had ceased. Initially all components of the water balance equation were found. However, significant amounts of water was unaccounted for. It was assumed that all components excluding soil water content change was well estimated. Therefore, soil water content change was calculated by solving the water balance equation rather than by converting soil water pressure to soil water content, as will be discussed in section 4.1.4.

4.1.1 Precipitation and Irrigation Data

Due to lack of natural rain, as reported in section 2.3.1, to study leachate formation, intermittent simulated precipitation was applied starting August 7, 2003 with the installation of the irrigation. A total of 19 hydrologic events, including both irrigated and natural events, occurred from the installation of the irrigation system until the end of 2003. The simulated events typically lasted for three hours. Eight, of the nineteen episodes, varying in the amount of antecedent rain received, were chosen for analysis of water balance. Episodes were initiated by rainfall, either natural or simulated and conclusions of episodes were when leachate production ceased. Events were chosen for analysis when a minimum of 3 cm of natural or simulated rain occurred and sensing
instruments were all properly functioning. Events covered varying vegetation growth stages and antecedent precipitations. Summary of the eight events is present in table 4.1.

Table 4.1: Summary of Hydrologic Events

<table>
<thead>
<tr>
<th>Episode</th>
<th>Date / Time</th>
<th>Natural or irrigated</th>
<th>5day antecedent rain [cm]</th>
<th>Sprinkler height [m]</th>
<th>% of max vegetation height*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start</td>
<td>End</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8-20 9:00</td>
<td>8-20 12:00</td>
<td>Irrigated</td>
<td>0</td>
<td>0.08</td>
</tr>
<tr>
<td>2</td>
<td>9-17 9:00</td>
<td>9-18 0:00</td>
<td>Irrigated</td>
<td>5.77</td>
<td>0.08</td>
</tr>
<tr>
<td>3</td>
<td>10-8 9:00</td>
<td>10-9 11:00</td>
<td>Irrigated</td>
<td>6.16</td>
<td>0.08</td>
</tr>
<tr>
<td>4</td>
<td>10-10 9:30</td>
<td>10-11 17:30</td>
<td>Irrigated</td>
<td>12.65</td>
<td>0.08</td>
</tr>
<tr>
<td>5</td>
<td>10-15 10:00</td>
<td>10-16 5:00</td>
<td>Irrigated</td>
<td>5.87</td>
<td>0.08</td>
</tr>
<tr>
<td>6</td>
<td>11-28 9:00</td>
<td>11-29 3:00</td>
<td>Irrigated</td>
<td>5.18</td>
<td>0.94</td>
</tr>
<tr>
<td>7</td>
<td>11-29 12:00</td>
<td>11-30 10:00</td>
<td>Natural</td>
<td>10.36</td>
<td>NA</td>
</tr>
<tr>
<td>8</td>
<td>11-30 12:00</td>
<td>12-2 14:00</td>
<td>Natural</td>
<td>8.4</td>
<td>NA</td>
</tr>
</tbody>
</table>

*Determined by examination of photographs during irrigation. Maximum vegetation height assumed to be 1m.

Runoff, leachate, and simulated rainfall + natural rainfall intensities for the episodes are presented in Appendix D.1. Cumulative amounts for runoff, leachate, and runoff are presented in Appendix D.2.

Episodes 1 through 6 were simulated rainfall events, with average intensities of 1.8 cm/hr. Irrigation for episode 1 lasted 2 hours, while irrigation for episodes 2 through 6 lasted for three hours. Episode 1 differed from the others, by having vegetation at 5% of its maximum height, while the others varied from 70% to 100%.
Episodes 7 and 8 were natural rainfall events. Episode 7 produced 2.82 cm of rain, while episode 8 produced 7.38 cm of rain. These events also differed in maximum intensities of the events. Episode 7 had a maximum of 4.8 cm/hr (0.08 cm/min) and episode 8 had a maximum intensity of 12 cm/hr (0.20 cm/min), over two times that of episode 7.

4.1.2 Runoff Data

Runoff volumes were measured by flow counters and pressure connected to the runoff tanks (see Fig 2.2). Total runoff for ConB, 20B and 40B in 2003 were 0.23 cm, 5.53 cm, and 6.63 cm respectively. A summary of runoff is presented in Table 4.2.

Table 4.2: Summary of Runoff for Eight Episodes*

<table>
<thead>
<tr>
<th>Episode</th>
<th>Rain [cm]</th>
<th>Runoff [cm]</th>
<th>% of rainfall as runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Con B</td>
<td>20B</td>
</tr>
<tr>
<td>1</td>
<td>3.86</td>
<td>0.00 / 0.0</td>
<td>0.24 / 6.3</td>
</tr>
<tr>
<td>2</td>
<td>5.42</td>
<td>0.00 / 0.0</td>
<td>0.24 / 5.6</td>
</tr>
<tr>
<td>3</td>
<td>6.13</td>
<td>0.00 / 0.0</td>
<td>0.21 / 4.5</td>
</tr>
<tr>
<td>4</td>
<td>5.48</td>
<td>0.00 / 0.0</td>
<td>0.22 / 5.5</td>
</tr>
<tr>
<td>5</td>
<td>5.42</td>
<td>0.01 / 0.2</td>
<td>0.21 / 5.2</td>
</tr>
<tr>
<td>6</td>
<td>5.03</td>
<td>0.01 / 0.2</td>
<td>0.25 / 5.8</td>
</tr>
<tr>
<td>7</td>
<td>2.82</td>
<td>0.01 / 0.5</td>
<td>0.14 / 5.6</td>
</tr>
<tr>
<td>8</td>
<td>7.38</td>
<td>0.23 / 3.8</td>
<td>0.73 / 25.2</td>
</tr>
</tbody>
</table>

*See Table 4.1 for event descriptions

Runoff, leachate, and simulated rainfall + natural rainfall intensities for episodes are presented in Appendix D.1. The maximum intensities for runoff occurred in episode 8
and was 0.72 cm/hr, 1.26 cm/hr, and 2.22 cm/hr for plots ConB, 20B, and 40B, respectively. Cumulative amounts for runoff, leachate, and runoff are present in Appendix D.2.

Runoff from ConB plot was nearly zero for all episodes except episode 8. Episode 8 consisted of a short interval of high intensity natural rain, with an intensity of 12 cm/hr (0.2 cm/min) for a five minute interval, which is over five times higher than the intensity of the average simulated rainfall of 2.1 cm/hr (0.034 cm/min). Only such a high intensity of rainfall produced runoff for the ConB plot. Surface runoff occurs when the rainfall intensity is higher than the infiltration capacity of the soil.

For all episodes on plots 20B and 40B, runoff production started a few minutes after the start of the rain event, and ended a few minutes after the end of simulated rain, with a relatively constant runoff rate in between those times. Relatively constant rate of runoff was produced, during simulated rain events, because the application of rain was also constant.

An interesting finding from the simulations was that rainfall directly above gutters can be intercepted by leaves or stems and transported to the soil via plant stem, resulting in less runoff production than would occur without the interception. Therefore, 20% of incoming rainfall does not become runoff for plot 20B and 40% does not become runoff for plot 40B. Instead, an average for the eight episodes of 5.3% and 6.2% of incoming rainfall becomes runoff for plots 20B and 40B, respectively.

In terms of percentage of rainfall, for 20B and 40B, runoff amounts are similar for events 2 through 6. Events 1 and 8 have significantly higher percentage of rainfall occurring as runoff. The vegetation height during event 1 was 5% of its maximum height,
with its maximum height assumed to be 1 m, which is significantly less than the growth stage during all other episodes. Less vegetation overhanging the gutters would allow more incoming rainfall to be caught by the gutters, causing an increase in runoff production.

Episode 8, like episode 7 was a natural rain event. However, the amount of rainfall during episode 8 is over two times higher than that of episode 7. A possible explanation for the increased runoff could be the storing capacity of the gutters. Because gutters are filled with debris, consisting of gravel, soil, and vegetation litter, some water can be stored in the gutters before it starts to flow toward the collection pipe. Assuming the debris fills 0.04 m of the gutters, half of the gutter height, and assuming the porosity of the debris to be 0.30, the water storage capacity of the gutters, per unit area, are 0.003 m and 0.006 m for plots 20B and 40B respectively. This amount is typically 5%-10% of the simulated precipitation. A high volume of rainfall fills this storing capacity of the gutters quickly, allowing all subsequent incoming rainfall into the gutters to flow freely toward the collection pipe. This phenomenon causes an increase in runoff, in terms of percentage of rainfall.

4.1.3 Leachate Data

Leachate volumes were measured by flow counters and pressure transducers attached to leachate storage tanks (see Fig. 2.2). Prior to September 24, 2003, leachate collection tanks were not equipped with flow counters. Leachate was determined by analysis of leachate hydrograph (see Fig. 2.4), which was obtained from transducer data. A summary of leachate is present in Table 4.3.
### Table 4.3. Summary of Leachate for Eight Episodes*

<table>
<thead>
<tr>
<th>Episode</th>
<th>Rain [cm]</th>
<th>Leachate [cm] / % of rainfall as leachate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ConB</td>
</tr>
<tr>
<td>1</td>
<td>3.86</td>
<td>0.00 / 0.0</td>
</tr>
<tr>
<td>2</td>
<td>5.42</td>
<td>2.65 / 61.5</td>
</tr>
<tr>
<td>3</td>
<td>6.13</td>
<td>1.75 / 37.4</td>
</tr>
<tr>
<td>4</td>
<td>5.48</td>
<td>2.82 / 69.7</td>
</tr>
<tr>
<td>5</td>
<td>5.42</td>
<td>1.82 / 45.3</td>
</tr>
<tr>
<td>6</td>
<td>5.03</td>
<td>1.55 / 36.0</td>
</tr>
<tr>
<td>7</td>
<td>2.82</td>
<td>1.29 / 51.1</td>
</tr>
<tr>
<td>8</td>
<td>7.38</td>
<td>4.09 / 66.8</td>
</tr>
</tbody>
</table>

*See Table 4.1 for event descriptions

Runoff, leachate, and simulated rainfall + natural rainfall intensities for episodes are presented in Appendix D.1. The maximum intensities for leachate occurred in episode 8 and were 1.22 cm/hr, 0.34 cm/hr, and 0.29 cm/hr for plots ConB, 20B, and 40B respectively. Cumulative amounts for runoff, leachate, and runoff are presented in Appendix D.2.

Production of leachate occurs when the wetting front in soil reaches the bottom of the 0.60 m soil profile. Therefore, leachate production is dependent not only on the amount of rainfall, but also on the level of soil water content. With higher soil water content, less rainfall is required to produce leachate than a soil with lesser amounts of water. Therefore, the production of leachate is dependent upon antecedent rain, the amount of rain in a specified time before the rain event of interest, which causes an increase in the soil moisture. Figure 4.1 shows the relationship between a 5-day antecedent rain event and leachate production. Larger amounts of antecedent rain
correspond to increased leachate production. A time period of 5 days for antecedent rain was arbitrarily chosen. Leachate, as percentage of rainfall, increases with greater 5-day antecedent rain.

![Graph showing correlation between 5-day antecedent rain and leachate as percentage of rainfall.](image)

Figure 4.1: Correlation Between 5-Day Antecedent Rain and Leachate as Percentage of Rainfall

Leachate was produced during all episodes except episode 1, where the simulated rain was applied for two hours into very dry soil (5-day antecedent rain total was 0 and the average soil water pressures, obtained from automated tensiometer readings, were -616 cm, -508 cm, and -738 cm for plots ConB, 20B, and 40B, respectively). Leachate production for other simulated rainfall episodes began at varying times, but always started within the simulated event (see Appendix D1). The production then increased sharply and typically peaked near the end of the event, slowly decreasing to zero.
production with time. Episodes 7 and 8, which cover natural rainfall events, also showed the slow reduction of leachate production after the rainfall stopped.

Plot ConB typically produced the most leachate, with plots 40B and 20B producing similar amounts of leachate. The average percentage of rainfall as leachate is 46.0%, 29.3%, and 33.9% for plots ConB, 20B, and 40B respectively. Theoretically, leachate production from 20B should be greater than that for 40B. However, due to decreased efficiency of gutters (possibly due to vegetation overhang) and heterogeneity of soil, leachate production for plot 40B is the greater than leachate production for plot 20B.

**4.1.4 Automated Soil Water Monitoring Results**

Soil water pressure was measured by automated tensiometers at 15 cm, 30 cm, and 45 cm depths. The soil water pressure for the period from August 2003 through December 2003 is presented in Appendix D.2. Soil water pressure was converted to volumetric water content using the retention curve (see Appendix C1) with fitted parameters obtained for retention curve measurement (van Genuchten, 1980). Originally, the amount of water in each layer was combined to determine the total amount of water in the 60 cm soil profile and is presented in Appendix D2. However, during water balance analysis, it was discovered that significant amounts of water was unaccounted for. A possible reason for this is soil water pressure hysteresis. A sample retention curve showing both the wetting and drying retention curve is presented in figure 4.2.
Figure 4.2: Example of Retention Curve With Hysteresis (Finsterle, et al. 1998)

The retention curve constructed for this research is a drainage curve. Assuming hysteresis occurring when soil is being wetted, it will not follow the same curve as the drainage curve. Instead, it will follow another curve called the wetting curve. Because a wetting curve was not constructed for this project, soil water content was not obtained from soil suction data, but by solving the water balance equation. Other possible reasons for the unaccounted water are discussed later in this thesis. An alternative method, solving the water balance equation with known values for rainfall, runoff, leachate, and ET, was used to determine soil water content change. Soil water content change as reported in Appendix D3 and D4 was obtained in this manner. A summary of soil water content gain is presented in Table 4.4.
Table 4.4: Summary of Soil Water Content Gain for Eight Episodes*

<table>
<thead>
<tr>
<th>Episode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain [cm]</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
</tbody>
</table>

*See Table 4.1 for event descriptions

Soil water content gain, as percentage of rainfall, ranged from 99%, 93%, and 91%, for plots ConB, 20B, and 40B, respectively during episode 1 to 55%, 38%, and 40% for plots ConB, 20B, and 40B, respectively during episode 8. A major factor in determining the amount of soil water content gain is the initial condition of the soil. Drier soil has a greater capacity to store water. Episode 1 had the driest initial condition with a soil water pressure of -616 cm, -508 cm, and -738 cm for plots ConB, 20B, and 40B, respectively. Episode 8 had the wettest initial condition with soil water pressures of -78 cm, -65 cm, and -73 cm for plots ConB, 20B, and 40B, respectively.

4.1.5 Manual Soil Water Monitoring

Before conducting the test, soil water pressure in all manual tensiometers and soil moisture, by means of manual TDR probes were measured. After the irrigation run was completed, soil pressure in all manual tensiometers and soil moisture, by means of
manual TDR probes were measured once again. However, data obtained from manual TDR and manual tensiometer was not used in analysis of water content gain in the soil because the amount of the manually collected tensiometer data is limited. It simply gave an idea as to the condition of the soil before and after simulated rainfall events.

4.1.6 Evapotranspiration

Calculated evapotranspiration values for the eight episodes are presented in table 4.5. Of the three methods used to estimate potential ET (see section 2.3.2), the method that resulted in the maximum value was the analysis of automated tensiometer data while soil was drying. This rate was estimated for each episode, and multiplied by the duration of the episode to obtain an estimate for actual ET. It was assumed that potential ET was equivalent to actual ET because water was in abundance during irrigation events.

Table 4.5: Summary of Evapotranspiration for Eight Episodes*

<table>
<thead>
<tr>
<th>Episode</th>
<th>Duration [days]</th>
<th>ET rate [cm/day]</th>
<th>Total ET [cm]</th>
<th>% of rainfall as ET</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.125</td>
<td>0.43</td>
<td>0.05</td>
<td>1.4</td>
</tr>
<tr>
<td>2</td>
<td>0.625</td>
<td>0.43</td>
<td>0.27</td>
<td>5.0</td>
</tr>
<tr>
<td>3</td>
<td>1.083</td>
<td>0.43</td>
<td>0.47</td>
<td>7.6</td>
</tr>
<tr>
<td>4</td>
<td>1.333</td>
<td>0.43</td>
<td>0.57</td>
<td>10.5</td>
</tr>
<tr>
<td>5</td>
<td>0.792</td>
<td>0.43</td>
<td>0.34</td>
<td>6.3</td>
</tr>
<tr>
<td>6</td>
<td>0.750</td>
<td>0.32</td>
<td>0.24</td>
<td>4.8</td>
</tr>
<tr>
<td>7</td>
<td>0.917</td>
<td>0.32</td>
<td>0.29</td>
<td>10.4</td>
</tr>
<tr>
<td>8</td>
<td>2.083</td>
<td>0.32</td>
<td>0.67</td>
<td>9.0</td>
</tr>
</tbody>
</table>

*See Table 4.1 for event descriptions
The potential ET rate for episodes 6, 7, and 8 are lower than that of all other episodes. The rate is dependent upon the amount of solar radiation, and summer months have greater solar radiation, resulting in higher potential ET rates.

4.1.7 Interception

Interception is the “segment of gross precipitation input which wets and adheres to aboveground objects until it is returned to the atmosphere through evaporation” (Viessman et al., 2003). When water is applied at a rate of 0.0127 m per 0.5 hr (0.0254 m/hr), the percentage of water intercepted for buffel grass is 31% (Viessman et al., 2003), with grass heights of up to 1 m. Buffel grass is the most common plant according to the vegetation survey and the rate of application of simulated rain is approximately 0.01 m per 0.5 hr (0.02 m/hr). A ratio of actual height to the maximum height of 1 m was estimated from photographs of the plots for each episode. For water balance analysis, the total amount of natural and simulated rain was reduced by the above ratio multiplied by 31% of 0.0127 m. For water balance analysis, it was assumed that this amount of incoming rainfall would be first intercepted, and all subsequent amounts of rain would reach the soil surface. Other plants also exist, which could result in slightly different values for interception, however the above method was assumed to adequately estimate interception for the experimental site.

4.1.8 Water Balance Summary

Data produced by the irrigation runs resulted in acquiring valuable data sets to evaluate leaching in the projected landfill cap. The results of the water balance analysis are presented in Appendix D.3. The amount of each term, as a percentage of rainfall is present in pie chart form in Appendix D.4. All components of water balance, excluding
soil water content change, was determined and reported in Appendix D.3 and D.4. Soil water content change was back calculated by solving the water balance equation.

The soil condition was dry for the first episode (the average soil water pressure was -616 cm, -508 cm, and -738 cm for plots ConB, 20B, and 40B, respectively), which is why no leachate was produced. As the soil wetted, leachate production began increasing. Subsequent episodes produce leachate, with ConB typically producing the most leachate, followed by plot 20B and 40B.

Runoff for ConB only occurred in episode 8, which was a natural rain event with high intensity over a short (5 minute) interval. Plots 20B and 40B during episode 8 also produced the most runoff, as the high volume of rain filled up the storing capacity of the gutters, allowing all subsequent rainfall to flow freely to the runoff collection tanks. All irrigated events produced similar results for runoff as a percentage of rainfall for all three plots. Runoff, as a percentage of rainfall, averaged for the eight episodes were 0.6%, 5.3%, and 6.2% for plots ConB, 20B, and 40B respectively. Increased gutter cover resulted in increased runoff production.

The episode in which the largest soil water content gain occurred was episode 1, where the initial soil conditions were the driest, allowing the soil profile to absorb most of the rainfall. The smallest soil water content gain occurred in episode 8, where the initial soil conditions were the wettest. The already wet soil did not have a large capacity to store additional water.

Evapotranspiration varied from 1% of total incoming precipitation during episode 1, the shortest episode, to 11% for episode 8, the longest episode.
4.2 Modeling Results

4.2.1 HELP3 Results of Simulating Hydrologic Episodes

As the output, HELP3 gives the values of runoff, leachate, ET, and soil water content for each day. The resulting prediction of runoff and leachate are presented in table 4.6. The end of episode 7 and start of episode 8 occurred on the same day, therefore these two episodes were combined, due to the fact that HELP3 can handle daily totals only. The figures comparing HELP3 output for runoff and leachate versus field data are presented in Appendix F.1.

The results show, that typically, HELP3 underpredicts runoff. The most severe underprediction of runoff occurs in episode 8, which is a natural rain event with a short interval of high intensity rain. The effect of averaging the rainfall for the entire day, which HELP3 does, is evident in these results. Instead of simulating the high intensity rain for the short interval, the rainfall is distributed evenly throughout the 24 hours, thus reducing the intensity of the rain, nearly 100 times in this case.

Also shown is that the HELP3 prediction of leachate is greater than the measured leachate. HYDRUS-1D was also used to simulate this experimental area. Both models overpredict leachate. Possible reasons for this are discussed in later sections (section 4.3.2).
Table 4.6: Predicted Runoff and Leachate by HELP3 vs. Actual Runoff and Leachate

<table>
<thead>
<tr>
<th>Episode</th>
<th>Plot</th>
<th>Actual Runoff [mm]</th>
<th>Actual Leachate [mm]</th>
<th>Predicted Runoff [mm]</th>
<th>Predicted Leachate [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CB</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>CB</td>
<td>0</td>
<td>26.6</td>
<td>0.0</td>
<td>42.8</td>
</tr>
<tr>
<td>3</td>
<td>CB</td>
<td>0</td>
<td>17.6</td>
<td>0.3</td>
<td>45.1</td>
</tr>
<tr>
<td>4</td>
<td>CB</td>
<td>0</td>
<td>28.4</td>
<td>0.2</td>
<td>67.3</td>
</tr>
<tr>
<td>5</td>
<td>CB</td>
<td>0.1</td>
<td>18.2</td>
<td>0.0</td>
<td>35.8</td>
</tr>
<tr>
<td>6</td>
<td>CB</td>
<td>0.1</td>
<td>15.5</td>
<td>0.0</td>
<td>20.0</td>
</tr>
<tr>
<td>7,8</td>
<td>CB</td>
<td>2.3</td>
<td>53.8</td>
<td>0.0</td>
<td>100.7</td>
</tr>
</tbody>
</table>

**Total**

<table>
<thead>
<tr>
<th>Episode</th>
<th>Plot</th>
<th>Actual Runoff [mm]</th>
<th>Actual Leachate [mm]</th>
<th>Predicted Runoff [mm]</th>
<th>Predicted Leachate [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20B</td>
<td>2.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>20B</td>
<td>2.4</td>
<td>20.0</td>
<td>0.8</td>
<td>31.3</td>
</tr>
<tr>
<td>3</td>
<td>20B</td>
<td>2.1</td>
<td>9.0</td>
<td>2.0</td>
<td>43.6</td>
</tr>
<tr>
<td>4</td>
<td>20B</td>
<td>2.2</td>
<td>17.6</td>
<td>1.4</td>
<td>67.8</td>
</tr>
<tr>
<td>5</td>
<td>20B</td>
<td>2.1</td>
<td>9.5</td>
<td>0.1</td>
<td>39.6</td>
</tr>
<tr>
<td>6</td>
<td>20B</td>
<td>2.5</td>
<td>5.6</td>
<td>0.2</td>
<td>19.2</td>
</tr>
<tr>
<td>7,8</td>
<td>20B</td>
<td>16.8</td>
<td>43.2</td>
<td>0.4</td>
<td>102.0</td>
</tr>
</tbody>
</table>

**Total**

<table>
<thead>
<tr>
<th>Episode</th>
<th>Plot</th>
<th>Actual Runoff [mm]</th>
<th>Actual Leachate [mm]</th>
<th>Predicted Runoff [mm]</th>
<th>Predicted Leachate [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40B</td>
<td>2.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>40B</td>
<td>3</td>
<td>15.8</td>
<td>1.1</td>
<td>31.2</td>
</tr>
<tr>
<td>3</td>
<td>40B</td>
<td>2.7</td>
<td>8.8</td>
<td>2.8</td>
<td>47.7</td>
</tr>
<tr>
<td>4</td>
<td>40B</td>
<td>3</td>
<td>25.2</td>
<td>1.7</td>
<td>67.3</td>
</tr>
<tr>
<td>5</td>
<td>40B</td>
<td>3.3</td>
<td>13.1</td>
<td>0.3</td>
<td>36.9</td>
</tr>
<tr>
<td>6</td>
<td>40B</td>
<td>2.3</td>
<td>7.4</td>
<td>0.4</td>
<td>19.2</td>
</tr>
<tr>
<td>7,8</td>
<td>40B</td>
<td>10.9</td>
<td>52.0</td>
<td>0.5</td>
<td>104.4</td>
</tr>
</tbody>
</table>

**Total**

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.3</td>
<td>633.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.4</td>
<td>618.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.0</td>
<td>615.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Total is sum for leachate prediction during entire simulation period of 8-1-2003 to 12-31-2003

The value for leachate prediction of ConB should be greater than 20B, which should be greater than 40B. However, at times this trend is not found from HELP3 simulations. Part of the reason for this is because of the daily averaging and output of daily totals by HELP3. Leachate prediction by HELP3 could be spread over two days. Instead of HELP3 predicting leachate during the same day of the episode, the daily averaging of the rainfall could lead HELP3 to predict some leachate to be produced the next day. This can cause some error in the leachate prediction and at times allow HELP3...
to predict more leachate for 40B and 20B than ConB. Leachate prediction by HELP3 is present in figure 4.3.

![HELP3 prediction for leachate](image)

**Figure 4.3: Leachate Prediction for Episodes – HELP3**

### 4.2.2 HELP3 Results of RCRA and Theoretical Alternate Landfill Cover

To compare the performance of the RCRA landfill cover and the theoretical landfill covers, where 40% of the surface is impervious and all water contacting it is totally produced as runoff, the total amounts of runoff and leachate for the entire year of 2003 were analyzed.

Two simulations involving the RCRA covers were performed and differed in terms of the $K_{sat}$ value, $10^{-5}$ cm/sec and $10^{-7}$ cm/sec, for the top/soil layer.

A total of six simulations involving the theoretical 40% impervious covers were simulated. Three simulations were run with a $K_{sat}$ of $10^{-5}$ cm/sec and the other three with $K_{sat}$ of $10^{-7}$ cm/sec. For each simulation involving a specific $K_{sat}$, total soil depths of 0.60 m, 0.80 m, and 1.20 m were used.
A summary of the HELP3 predictions for the RCRA covers and the theoretical 40% impervious covers are presented in table 4.7.

<table>
<thead>
<tr>
<th>RCRA cover</th>
<th>Ksat [cm/sec] of top layer</th>
<th>HELP3 prediction for year 2003</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Runoff [cm]</td>
</tr>
<tr>
<td>10⁻³</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>10⁻⁵</td>
<td></td>
<td>35.0</td>
</tr>
<tr>
<td>10⁻⁷</td>
<td></td>
<td>108.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>40% theoretical cover</th>
<th>Ksat [cm/sec]</th>
<th>thickness of soil [cm]</th>
<th>Leachate [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10⁻⁵</td>
<td>60</td>
<td>136.9</td>
<td>51.6</td>
</tr>
<tr>
<td>10⁻⁵</td>
<td>80</td>
<td>136.3</td>
<td>51.8</td>
</tr>
<tr>
<td>10⁻⁵</td>
<td>120</td>
<td>136.2</td>
<td>51.2</td>
</tr>
<tr>
<td>10⁻⁷</td>
<td>60</td>
<td>173.4</td>
<td>16.6</td>
</tr>
<tr>
<td>10⁻⁷</td>
<td>80</td>
<td>172.8</td>
<td>15.5</td>
</tr>
<tr>
<td>10⁻⁷</td>
<td>120</td>
<td>172.5</td>
<td>15.0</td>
</tr>
</tbody>
</table>

As shown in table 4.7, the leachate prediction for the RCRA cover does not significantly change when varying the \( K_{sat} \) of the top/soil layer. With a top/soil layer of high conductivity, water infiltrates through it, however, the lateral drainage layer drains most of the water out, resulting in minimal amounts of leachate. With a top/soil layer of low conductivity, most of the incoming water is produced as runoff.

The results of the simulations of the theoretical landfill covers suggest that increasing the thickness of the soil does not have a significant effect on leachate production. Decreasing the \( K_{sat} \) from \( 10^{-5} \) cm/sec to \( 10^{-7} \) cm/sec did have a significant effect on leachate production, resulting in a leachate decrease of approximately 3.4 times. Although increasing the soil layer will increase the soil water storage capacity, evapotranspiration from deeper horizons is typically minimal, thus not removing water from the system but storing it for future leaching.
The decrease in $K_{sat}$ for the theoretical cover resulted in a significant decrease in leachate production, however it is still an order of magnitude higher than that of the RCRA cover. This suggests that a landfill cover with 40% impervious area, where all water contacting the impervious area totally becomes runoff, may be inadequate as an alternative to the RCRA landfill cover, especially in conditions expected in wet humid conditions.

4.2.3 KINEROS2 Results

The results of KINEROS2 simulation is present in table 4.7. Runoff is underpredicted for episodes 1 and 8 for both 20B and 40B. During episode 1, the vegetation was at 5% of its maximum growth stage (assumed to be 1m), causing most of the rainfall to fall directly onto the gutters. The amount of runoff collected in the field increases, causing an underprediction of runoff by KINEROS2. The rainfall for episode 8 was a natural rain event, with a short interval of high intensity rain. This high intensity of short duration caused most of the runoff for episode 8. The gutters are filled with gravel and some debris, giving plot 20B the capacity to store 0.003 m and 40B the capacity to store 0.006 m of incoming rainfall before flowing into the collection pipes. The high volume of rainfall filled this storing capacity quickly, causing all subsequent incoming rainfall to flow into the collection pipe. This phenomenon increases the fraction of incoming rainfall that flows into the collection pipe, thus causing an underprediction of runoff. This data suggests that the gutters are more efficient during rain events of high intensity.
Table 4.8: Predicted Runoff by KINEROS2 vs. Actual Runoff

<table>
<thead>
<tr>
<th>Episode</th>
<th>Plot</th>
<th>Predicted runoff [mm]</th>
<th>Actual runoff [mm]</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ConB</td>
<td>0.0</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>ConB</td>
<td>0.0</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>ConB</td>
<td>0.0</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>ConB</td>
<td>0.0</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>ConB</td>
<td>0.0</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>ConB</td>
<td>0.0</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>ConB</td>
<td>0.0</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>ConB</td>
<td>2.3</td>
<td>2.3</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>20B</td>
<td>1.8</td>
<td>2.4</td>
<td>-26.8</td>
</tr>
<tr>
<td>2</td>
<td>20B</td>
<td>2.6</td>
<td>2.4</td>
<td>9.2</td>
</tr>
<tr>
<td>3</td>
<td>20B</td>
<td>3.0</td>
<td>2.1</td>
<td>41.4</td>
</tr>
<tr>
<td>4</td>
<td>20B</td>
<td>2.7</td>
<td>2.2</td>
<td>21.9</td>
</tr>
<tr>
<td>5</td>
<td>20B</td>
<td>2.7</td>
<td>2.1</td>
<td>26.5</td>
</tr>
<tr>
<td>6</td>
<td>20B</td>
<td>2.4</td>
<td>2.5</td>
<td>-3.1</td>
</tr>
<tr>
<td>7</td>
<td>20B</td>
<td>1.4</td>
<td>1.4</td>
<td>1.7</td>
</tr>
<tr>
<td>8</td>
<td>20B</td>
<td>5.7</td>
<td>15.4</td>
<td>-62.9</td>
</tr>
<tr>
<td>1</td>
<td>40B</td>
<td>2.2</td>
<td>2.9</td>
<td>-24.4</td>
</tr>
<tr>
<td>2</td>
<td>40B</td>
<td>3.3</td>
<td>3.0</td>
<td>9.0</td>
</tr>
<tr>
<td>3</td>
<td>40B</td>
<td>3.7</td>
<td>2.7</td>
<td>37.2</td>
</tr>
<tr>
<td>4</td>
<td>40B</td>
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<td>3.0</td>
<td>11.6</td>
</tr>
<tr>
<td>5</td>
<td>40B</td>
<td>3.3</td>
<td>3.3</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>40B</td>
<td>3.0</td>
<td>2.3</td>
<td>31.5</td>
</tr>
<tr>
<td>7</td>
<td>40B</td>
<td>1.8</td>
<td>0.8</td>
<td>122.0</td>
</tr>
<tr>
<td>8</td>
<td>40B</td>
<td>6.6</td>
<td>10.1</td>
<td>-35.1</td>
</tr>
</tbody>
</table>

4.2.4 HYDRUS-1D Results

The HYDRUS-1D predicted soil water pressure versus soil water data for plot ConB can be seen in figure 4.4. The comparisons with HYDRUS-1D predicted soil water pressure for plots 20B and 40B is presented in Appendix F.2.
It is shown that the HYDRUS-1D prediction of leachate is greater than measured leachate. This finding is relatively consistent with the HELP3 leachate prediction which is also greater than measured leachate. The HYDRUS-1D predicted leachate versus leachate data is present in table 4.8.

The HYDRUS-1D leachate prediction is present in figure 4.5. The highest prediction for leachate is for plot ConB followed by 20B and 40B. More water is available for leaching in ConB because no rainfall is diverted, as there are no gutters. Increasing the percent of gutter cover means more runoff, reducing the amount of water available for leaching.
Table 4.9: Predicted Leachate by HYDRUS-1D vs. Actual Leachate

<table>
<thead>
<tr>
<th>Plot</th>
<th>Episode</th>
<th>Actual leachate [cm]</th>
<th>HYDRUS-1D predicted leachate [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ConB</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.66</td>
<td>4.70</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.76</td>
<td>4.70</td>
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<tr>
<td></td>
<td>4</td>
<td>2.84</td>
<td>4.80</td>
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<tr>
<td></td>
<td>5</td>
<td>1.82</td>
<td>3.10</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.55</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1.28</td>
<td>1.80</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>4.10</td>
<td>5.70</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>42.0</td>
</tr>
<tr>
<td>20B</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.00</td>
<td>3.96</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.90</td>
<td>4.40</td>
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<tr>
<td></td>
<td>4</td>
<td>1.76</td>
<td>4.70</td>
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<td>5</td>
<td>0.95</td>
<td>3.00</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.56</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.81</td>
<td>1.70</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3.51</td>
<td>5.40</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>34.1</td>
</tr>
<tr>
<td>40B</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.58</td>
<td>3.67</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.88</td>
<td>3.98</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.52</td>
<td>4.40</td>
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<td>5</td>
<td>1.31</td>
<td>2.30</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.74</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.77</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>4.43</td>
<td>5.30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>30.3</td>
</tr>
</tbody>
</table>

*Total is sum for leachate prediction during entire simulation period 8-1-2003 to 12-31-2003

The HYDRUS-1D prediction of leachate amount for plot 20B is only slightly greater than prediction of leachate amount for ConB. Leachate production for 40B is only slightly less than for 20B. This is due to the method which gutters were simulated in HYDRUS-1D. Because gutters cannot explicitly be entered in HYDRUS-1D, effects of the gutters were simulated by reducing the amount of rainfall used. For simulating ConB, the total rainfall was used. However, for simulating 20B and 40B, rainfall was reduced by
5.3% and 6.2% respectively, because those are the average percent of rainfall occurring as runoff, according to measured data. Because the only difference between simulating ConB, 20B, and 40B is slight modification in rainfall input, the leachate predictions are also only slightly varied. In reality, the percent reduction of rainfall used for 20B and 40B should not be the same for all storm events, which should differ depending on storm intensity and duration. Practical considerations, when modeling, require one value for the reduction of rainfall to simulate the effect of gutters.

![HYDRUS-1D predicted leachate](image)

**Figure 4.5: Leachate Prediction for Episodes – HYDRUS-1D**

### 4.3 Model Comparisons

#### 4.3.1 HELP3 vs. KINEROS2

Because KINEROS2 predicts surface runoff, and not leachate production, its results were compared with the HELP3 predicted runoff. Figure 4.6 shows the runoff predictions by HELP3 and KINEROS.
Figure 4.6: Runoff Prediction by HELP3 and KINEROS2

In nearly all cases, HELP3 predicts less runoff than KINEROS2. As theorized, the averaging of daily rainfall reduces the prediction of runoff by HELP3. KINEROS2 predicts runoff amounts greater than HELP3 and amounts similar to runoff data. A reason for the values being similar to measured runoff data is that the KINEROS2 simulations were calibrated, by modifying the percent of cover to be simulated as gutters, to match its runoff prediction with runoff data. This calibration allows KINEROS2 predictions to be very near the runoff data.
4.3.2 HELP3 vs HYDRUS-1D

The soil geometry, soil retention characteristics, and saturated hydraulic conductivity parameters for both HELP3 and HYDRUS-1D simulations were similar. Both models had three layers, first layer 0-0.20 m, second layer 0.20-0.40 m, and third layer 0.40-0.60 m, making up the 0.60 m soil profile, with $K_s$ analyzed from the infiltrometer tests and soil retention parameters from the retention tests. The $K_s$ and retention curve parameters for the bottom layer were slightly modified in HYDRUS-1D to provide satisfactory soil water pressure predictions. Because HYDRUS-1D models subsurface flow, its leachate prediction were compared with the HELP3 predicted leachate. Figure 4.7. shows leachate prediction by HELP3 and HYDRUS-1D. HELP3 consistently overpredicted leachate, as compared to HYDRUS-1D. With daily averaging of rainfall, in HELP3, less water runs off the surface, and more water was available for leachate production.

The simulation for plots 20B and 40B resulted in similar predictions of leachate by both HELP3 and HYDRUS-1D. One reason for this is that both plots produce similar amounts of runoff. The KINEROS2 calibration results show that the simulated gutter size to be 4.6% for plot 20B and 5.7% for plot 40B. The similar values are caused by overhanging vegetation which intercepts rainfall and channels it directly to the soil surface via stem, reducing the efficiency of a 40% gutter cover, resulting in similar runoff enhancement for plots 20B and 40B.
Although HELP3 consistently predicts more leachate than HYDRUS-1D, both significantly overpredict leachate compared to real measured leachate data. Several factors could be the cause of this overprediction. One possible explanation for the models overprediction is that both use soil retention values for the drainage branch of retention curve. In reality, hysteresis, can play a major role in determining soil water content change. In a soil profile of 0.60 m and a porosity of 0.654, 0.39 m of the profile is
allowed to hold water. If 0.03 m of water was unaccounted for, that would be less than 10% of the total area allowed to hold water. Hysteresis could be the cause of the overprediction by both models of leachate production.

Another possible explanation of the overprediction of leachate by both models is that the leachate collection design could have been damaged due to aging. The experimental area was constructed in 1994, ten years ago, and the lining under the gravel drainage could be deteriorated, causing leachate to bypass the collection pipe and seep in the soil below, where it cannot be measured. Also, the gravel may have an ability, to store some leachate instead of directly depositing all incoming leachate to the leachate collection tank. A possible check for this would be to run the irrigation for a long time (approximately 12 hours), as to fill this storage ability of the gravel and soil profile. Upon the storage ability being used up, the amount of leachate production should be equal to incoming rainfall minus runoff for a certain time interval.

Another possible explanation for the overprediction of leachate by both HELP3 and HYDRUS-1D is that more interception is occurring than is accounted for. In this thesis, interception by plants is assumed to be 0.004 m (4mm) at maximum plant growth stage. Because this value is approximated from Viessman et al. (2000) assuming that the entire plot is vegetated with buffel grass and the reality that other species of plant also grow in the experimental plots, 0.004 m of interception could be an underestimation. Other plants, most notably broad leaf plants, could have the ability to intercept and retain more water than buffel grass. A possible check for this would be to install a raingage, near the soil surface and run the irrigation system. The amount of water applied could be compared to the amount of water captured by the raingage, thus allowing one to
determine the amount of intercepted water by the vegetation. This amount could then be compared to the assumed 0.004 m of interception that was used in this thesis.
5 CONCLUSIONS

The percentage of rainfall becoming leachate was 29.3% and 33.9% for plots 20B, and 40B, respectively. Theoretically 20B should produce more leachate than 40B, however due to soil heterogeneity and decreased efficiency of gutters (possibly due to vegetation overhang) this can be reversed. The percentage of rainfall becoming leachate for plot ConB was 46.0%.

In the present design, gutters do not play major role in reducing of leachate, due to the fact that vegetation cover controls transfer of water from the rainfall into the soil. Although our storm intensities varied from 1.8 to 12.0 cm/h and the durations varied from 3.1 to 50.4 hrs, 20B and 40B never captured 20% and 40% of the rainfall as runoff. If all the gutters in 20B and 40B were placed in one place in the plot, the runoff percentages would have been higher. However, simulations involving the RCRA landfill covers and theoretical landfill covers with 40% of its area as impervious, where all water contacting this impervious surface totally becoming runoff, suggest that 40% impervious cover may not be an adequate alternative to a RCRA landfill cover. The RCRA cover with a $K_{sat}$ of $10^{-7}$ cm/sec for the top/soil layer predicted 1.8 cm of leachate for 2003, while the theoretical cover with a $K_{sat}$ of $10^{-7}$ cm/sec and a total depth of 1.20 m predicted 15 cm of leachate for 2003.

In earlier work, all terms of water balance except for evapotranspiration, were measured. Evapotranspiration was calculated as the difference of all other components of hydrological balance, resulting occasionally in amounts completely out of range of reality. In the earlier approach, the changes in soil-water storage were calculated from the soil water content measurements by means of TDR in the top 20-cm profile. This was
found to be greatly imprecise and not representative of the whole 60 cm of the soil profile.

In this research, all components of water balance were analyzed individually. We found that calculation of changes in water storage in the 60-cm soil layer was the least accurate component of the water balance equation. Therefore it was calculated by solving the water balance equation with known or accurately estimated irrigation + natural rain, evapotranspiration, interception, runoff and leachate data.

Possible reasons for the discrepancy in water balance in the soil layer include:

a) hysteresis of the soil water retention curve, where the drainage and wetting branches of retention curve may differ. Hysteresis of the retention curve was not considered when determining soil water content change, only drainage branch of retention curve was measured. Traditionally, the drainage branch of the retention curve is used in water flow modeling. Because the wetting curve may differ from the drainage curve, our original estimates of soil water content change could be inaccurate.

b) entrapped air in the profile during infiltration. This may result in incorrect transformation of recorded pressure to water content using the existing soil-water retention curve. With rain or irrigation, the surface soil layer wets and swells, acting as a seal for the air below. The bottom of the soil profile, due to its compaction serves as partial bottom seal for the air as well. The soil water pressure within the profile is increased, partly due to the compression of the air during the infiltration event. Consequently,
water content amounts, which are determined by the soil-water retention curve, could be inaccurate.

c) leakage of the leachate collection system. The leachate collection system includes a plastic liner below the gravel layer that lies beneath the 60-cm soil layer. Inspection of the liner was not possible. Since the experimental site is almost ten years old, the liner integrity can be an issue.

d) the gravel underdrain storing some water. This allows soil-water leachate to stay in the man-made profile, thus not accounting for it.

e) the increased interception and evaporation from plant surfaces. Results of the vegetation survey revealed that most common plant is buffel grass. Viessman et al. (2003) suggests 0.004 m (4 mm) of the initial 0.01 m of incoming precipitation is intercepted, for buffel grass of height 1m. Although buffel grass is the most common plant, other types of plants appeared. Also, plants with broader leaves, not present before irrigation events, grew as irrigation events continued, thus having higher interception rates. Improvement in measurement of the water amount entering the soil in plots is advised.

The difference in runoff production between plots 20B and 40B is minimal. The percentage of rainfall produced as runoff was 5.3% and 6.2% for plots 20B and 40B, respectively. These values were average for the 8 events studied. The range of percentage of rainfall produced as runoff was 0 – 13.7%.

Gutters are found to be most effective for large storms and storms with high intensity. Episode 8, which consisted of a high intensity natural rain event and highest
volume, produced the most runoff. The high intensity rain filled the water storage capacity (in the pores of filled gravels and debris) of the gutters quickly and allowed all subsequent rainfall to flow down in the gutters. This improved the efficiency of the gutters to take runoff water out of the plots.

Comparing modeling results, it was found that HELP3 predicts higher values for leachate than HYDRUS-1D. This agrees with the hypothesis that daily averaging of rainfall amounts, (i.e. decreasing the rainfall intensity by HELP3) increases the amount of water available for leaching. HYDRUS-1D predicts less leachate and provides higher accuracy in modeling physical processes with more precise division of inputs such as time definition of rain events.

Comparing results of HELP3 and KINEROS2 it was found that HELP3 underpredicts runoff. This agrees with the hypothesis that daily averaging of rainfall reduces amount of calculated runoff, as the intensity of the rain event is reduced evenly throughout 24 hours.

Both HELP3 and HYDRUS-1D predict more leachate than that is measured, supporting the fact found in simple hydrological balance, despite our efforts, we were unable to accurately measure soil water content change. Instead it was calculated by solving the water balance equation.
APPENDICES
Appendix A: Measured Weather Data and Irrigation at Test Site During the Period of Irrigation Episodes

natural rainfall - MCBH research site

![Graph showing natural rainfall at 1m above ground and rainfall at the surface over time]

rain and irrigation - MCBH research site

![Graph showing natural rainfall, rainfall at 1m above ground, and sprinkler irrigation over time]

temperature - MCBH research site

![Graph showing air temperature at 1m, air temperature at 2m, soil temperature 15cm, and soil temperature 30cm over time]
Appendix A: Measured Weather Data and Irrigation at Test Site During the Period of Irrigation Episodes

1. Air humidity - MCBH research site

2. Wind speed - MCBH research site

3. Net radiation - MCBH research site
Appendix B: Instrumentation of the Experimental Site at MCBH

Instrumentation of the experimental site at Marine Base Corps Hawaii

Equipment for data acquisition:
- * weather station
- ▲ automatic tensiometers
- • manual tensiometers
- ◊ manual tensiometers - shallow
- ● automatic TDR
- ○ manual TDR

Sampling at the experimental site:
- ■ particle size analysis
- ○ surface tension infiltration
- ● deeper tension infiltration
- □ surface samples for soil-water retention function
- ■ deeper samples for soil-water retention function
- * root zone pit
Appendix C1: Retention Curves for All Soil Samples

measured points of soil water retention and fitted retention curves

- points of soil water retention (0-30 cm)
- points of soil water retention (30-45 cm)
- points of soil water retention (45-60 cm)
- soil water retention curves (0-30 cm)
- soil water retention curves (30-45 cm)
- soil water retention curves (45-60 cm)

scaled points of soil water retention and reference retention curves

- scaled points of measurement (samples 0-30 cm)
- scaled points of measurement (samples 30-45 cm)
- scaled points of measurement (samples 45-60 cm)
- reference retention curve for 0-30 cm
- reference retention curve for 30-45 cm
- reference retention curve for 45-60 cm
Appendix C2: Particle Size Distribution for the Soil at the Research Site

 particle size distribution for soil at MCBH research site

USDA particle size limits:
sand: 2.0 to 0.05 mm in grain size diameter
silt: 0.05 to 0.002 mm in grain size diameter
clay: smaller than .002 mm in grain size diameter

class | %
sand  | 50
silt   | 39
clay   | 11

Textural classification: LOAM
Appendix D1: Soil Water Pressure and Intensity of Rainfall, Runoff, and Leachate for Episode 1

![Soil Water Pressure Graphs](image)

![Runoff and Leachate Intensity Graph](image)
Appendix D1: Soil suction and Intensity of Rainfall, Runoff, and Leachate for Episode 2

**automated soil suction measurement - 20B episode 2**

- T4 -20 cm
- T5 -35 cm
- T6 -50 cm

**automated soil suction measurement - 40B episode 2**

- T1 -21 cm
- T2 -36 cm
- T3 -51 cm

**automated soil suction measurement - ConB episode 2**

- T1 -21 cm
- T2 -36 cm
- T3 -51 cm

**runoff and leachate intensity - episode 2**

- ConB runoff intensity
- ConB leachate intensity
- 20B runoff intensity
- 20B leachate intensity
- 40B runoff intensity
- 40B leachate intensity
- rain + irrigation
Appendix D1: Soil suction and Intensity of Rainfall, Runoff, and Leachate for Episode 3

**Automated Soil Suction Measurement - 20B Episode 3**

- **T4 - 20 cm**
- **T5 - 35 cm**
- **T6 - 50 cm**

**Automated Soil Suction Measurement - 40B Episode 3**

- **T1 - 20 cm**
- **T2 - 36 cm**
- **T3 - 51 cm**

**Automated Soil Suction Measurement - ConB Episode 3**

- **T1 - 21 cm**
- **T2 - 36 cm**
- **T3 - 51 cm**

**Runoff and Leachate Intensity - Episode 3**

- **ConB Runoff Intensity**
- **ConB Leachate Intensity**
- **20B Runoff Intensity**
- **20B Leachate Intensity**
- **40B Runoff Intensity**
- **40B Leachate Intensity**
- **Rain + Irrigation Intensity**
Appendix D1: Soil suction and Intensity of Rainfall, Runoff, and Leachate for Episode 4

automated soil suction measurement - 20B episode 4

automated soil suction measurement - 40B episode 4

automated soil suction measurement - ConB episode 4

runoff and leachate intensity - episode 4
Appendix D1: Soil suction and Intensity of Rainfall, Runoff, and Leachate for Episode 5

automated soil suction measurement - 20B episode 5

automated soil suction measurement - 40B episode 5

automated soil suction measurement - ConB episode 5

runoff and leachate intensity-episode 5
Appendix D1: Soil suction and Intensity of Rainfall, Runoff, and Leachate for Episode 6

automated soil suction measurement - 20B episode 6

automated soil suction measurement - 40B episode 6

automated soil suction measurement - ConB episode 6

runoff and leachate intensity-episode 6
Appendix D1: Soil suction and Intensity of Rainfall, Runoff, and Leachate for Episode 7

automated soil suction measurement - 20B episode 7

- T4 -20 cm
- T5 -35 cm
- T6 -50 cm

automated soil suction measurement - 40B episode 7

- T1 -20 cm
- T2 -36 cm
- T3 -51 cm

automated soil suction measurement - ConB episode 7

- T1 -21 cm
- T2 -36 cm
- T3 -51 cm

runoff and leachate intensity-episode 7

- ConB runoff intensity
- ConB leachate intensity
- 20B runoff intensity
- 20B leachate intensity
- 40B runoff intensity
- 40B leachate intensity
- rain + irrigation
Appendix D1: Soil suction and Intensity of Rainfall, Runoff, and Leachate for Episode 8a

automated soil suction measurement - 20B episode 8a

automated soil suction measurement - 40B episode 8a

automated soil suction measurement - ConB episode 8a

runoff and leachate intensity - episode 8a
Appendix D1: Soil suction and Intensity of Rainfall, Runoff, and Leachate for Episode 8b

**automated soil suction measurement - 20B episode 8b**

- T4 -20 cm
- T5 -35 cm
- T6 -50 cm

**automated soil suction measurement - 40B episode 8b**

- T1 -20 cm
- T2 -36 cm
- T3 -51 cm

**automated soil suction measurement - ConB episode 8b**

- T1 -21 cm
- T2 -36 cm
- T3 -51 cm

**runoff and leachate intensity -episode 8b**

- ConB runoff intensity
- ConB leachate intensity
- 20B runoff intensity
- 20B leachate intensity
- 40B runoff intensity
- 40B leachate intensity
- rain + irrigation

12/1/03 10:00 to 12/1/03 19:00
Appendix D2: Soil Water Content and Cumulative Rainfall, Runoff, and Leachate - Episode 1

**Total Soil Water Content by Means of Tensiometers - Episode 1**

- Con B total water in soil profile 0-60 cm depth [cm]
- 40 B total water in soil profile 0-60 cm depth [cm]
- 20 B total water in soil profile 0-60 cm depth [cm]

**Cumulative Leachate - Episode 1**

- ConB from hydrograph [cm]
- 40B from hydrograph [cm]
- 20B from hydrograph [cm]
- Rain + irrigation

**Cumulative Runoff - Episode 1**

- ConB from flowcounters [cm]
- 40B from flowcounters [cm]
- 20B from flowcounters [cm]
- ConB from hydrograph [cm]
- 40B from hydrograph [cm]
- 20B from hydrograph [cm]
Appendix D2: Soil Water Content and Cumulative Rainfall, Runoff, and Leachate - Episode 3

**Total Soil Water Content by Means of Tensiometers - Episode 3**

- ConB total water in soil profile 0-60 cm depth [cm]
- 40B total water in soil profile 0-60 cm depth [cm]
- 20B total water in soil profile 0-60 cm depth [cm]

**Cumulative Leachate - Episode 3**

- ConB from flowcounters [cm]
- 40B from flowcounters [cm]
- 20B from flowcounters [cm]
- ConB from hydrograph [cm]
- 20B from hydrograph [cm]
- 40B from hydrograph [cm]
- Rain + Irrigation

**Cumulative Runoff - Episode 3**

- ConB from flowcounters [cm]
- 40B from flowcounters [cm]
- 20B from flowcounters [cm]
- ConB from hydrograph [cm]
- 20B from hydrograph [cm]
- 40B from hydrograph [cm]
Appendix D2: Soil Water Content and Cumulative Rainfall, Runoff, and Leachate - Episode 4

total soil water content by means of tensiometers - episode 4

cumulative leachate-episode 4

cumulative runoff-episode 4
Appendix D2: Soil Water Content and Cumulative Rainfall, Runoff, and Leachate - Episode 5

**Total Soil Water Content by Means of Tensiometers - Episode 5**

- ConB total water in soil profile 0-60 cm depth [cm]
- 40B total water in soil profile 0-60 cm depth [cm]
- 20B total water in soil profile 0-60 cm depth [cm]

**Cumulative Leachate - Episode 5**

- ConB from flowcounters [cm]
- 40B from flowcounters [cm]
- 20B from flowcounters [cm]
- ConB from hydrograph [cm]
- 40B from hydrograph [cm]
- 20B from hydrograph [cm]
- Rain + Irrigation

**Cumulative Runoff - Episode 5**

- ConB from flowcounters [cm]
- 40B from flowcounters [cm]
- 20B from flowcounters [cm]
- ConB from hydrograph [cm]
- 40B from hydrograph [cm]
- 40B from hydrograph [cm]
Appendix D2: Soil Water Content and Cumulative Rainfall, Runoff, and Leachate - Episode 6

1. Total soil water content by means of tensiometers - episode 6

2. Cumulative leachate - episode 6

3. Cumulative runoff - episode 6
Appendix D2: Soil Water Content and Cumulative Rainfall, Runoff, and Leachate - Episode 7

**Total Soil Water Content by Means of Tensiometers - Episode 7**

- ConB total water in soil profile 0-60 cm depth [cm]
- 40B total water in soil profile 0-60 cm depth [cm]
- 20B total water in soil profile 0-60 cm depth [cm]

**Cumulative Leachate - Episode 7**

- ConB from flowcounters [cm]
- 40B from flowcounters [cm]
- 20B from flowcounters [cm]
- ConB from hydrograph [cm]
- 40B from hydrograph [cm]
- 20B from hydrograph [cm]
- Rain + Irrigation

**Cumulative Runoff - Episode 7**

- ConB from flowcounters [cm]
- 40B from flowcounters [cm]
- 20B from flowcounters [cm]
- ConB from hydrograph [cm]
- 40B from hydrograph [cm]
- 20B from hydrograph [cm]
Appendix D2: Soil Water Content and Cumulative Rainfall, Runoff, and Leachate - Episode 8

**Total Soil Water Content by Means of Tensiometers - Episode 8**

- ConB total water in soil profile 0-60 cm depth [cm]
- 40B total water in soil profile 0-60 cm depth [cm]
- 20B total water in soil profile 0-60 cm depth [cm]

**Cumulative Leachate - Episode 8**

- ConB from flowcounters [cm]
- 40B from flowcounters [cm]
- 20B from flowcounters [cm]
- ConB from hydrograph [cm]
- 40B from hydrograph [cm]
- 20B from hydrograph [cm]
- Rain + irrigation

**Cumulative Runoff - Episode 8**

- ConB from flowcounters [cm]
- 40B from flowcounters [cm]
- 20B from flowcounters [cm]
- ConB from hydrograph [cm]
- 40B from hydrograph [cm]
- 20B from hydrograph [cm]
### Appendix D.3. Water balance values for episodes 1-4

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Appendix D.3. Water balance values for episodes 5-8

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<td>% of precipitation as gain in soil moisture</td>
<td>0.1</td>
<td>6.4</td>
<td>18.4</td>
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<tr>
<td>% of precipitation as ET</td>
<td>11.0</td>
<td>11.0</td>
<td>11.0</td>
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</table>
Appendix D4. Water balance charts—episodes 1 & 2

episode 1 - ConB

ET 1%

gain in soil moisture 99%

episode 1 - 20B

ET 1%
runoff 6%

gain in soil moisture 93%

episode 1 - 40B

ET 1%
runoff 8%

gain in soil moisture 91%

episode 2 - ConB

ET 5%

gain in soil moisture 34%

leachate 61%

episode 2 - 20B

ET 5%
runoff 6%

gain in soil moisture 45%

leachate 44%

episode 2 - 40B

ET 5%
runoff 7%

leachate 37%

gain in soil moisture 51%
Appendix D4. Water balance charts—episodes 3 & 4

**Episode 3 - ConB**
- ET 8%
- Leachate 37%
- Gain in soil moisture 55%

**Episode 3 - 20B**
- ET 8%
- Runoff 5%
- Leachate 19%
- Gain in soil moisture 68%

**Episode 3 - 40B**
- ET 8%
- Runoff 6%
- Leachate 19%
- Gain in soil moisture 67%

**Episode 4 - ConB**
- ET 11%
- Leachate 70%
- Gain in soil moisture 19%

**Episode 4 - 20B**
- ET 11%
- Runoff 6%
- Leachate 42%
- Gain in soil moisture 41%

**Episode 4 - 40B**
- ET 11%
- Runoff 7%
- Leachate 63%
- Gain in soil moisture 19%
Appendix E1: Input Parameters for HELP3 Simulation of 40B

***********************************************************************
** HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE
** HELP MODEL VERSION 3.07 (1 NOVEMBER 1997)
** DEVELOPED BY ENVIRONMENTAL LABORATORY
** USAE WATERWAYS EXPERIMENT STATION
** FOR USEPA RISK REDUCTION ENGINEERING LABORATORY
***********************************************************************

PRECIPITATION DATA FILE: C:\HELP3\DATA4.D4
TEMPERATURE DATA FILE: C:\HELP3\DATA7.D7
SOLAR RADIATION DATA FILE: C:\HELP3\DATA13.D13
EVAPOTRANSPIRATION DATA: C:\HELP3\DATA11.D11
SOIL AND DESIGN DATA FILE: C:\HELP3\DATA10.D10
OUTPUT DATA FILE: C:\HELP3\out.OUT

TIME: 10:0 DATE: 4/14/2004

********************************************************************************
NOTE: INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER WERE COMPUTED AS NEARLY STEADY-STATE VALUES BY THE PROGRAM.

LAYER 1
--------

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 0
THICKNESS = 8.00 INCHES
POROSITY = 0.6540 VOL/VOL
FIELD CAPACITY = 0.4470 VOL/VOL
WILTING POINT = 0.3280 VOL/VOL
INITIAL SOIL WATER CONTENT = 0.4271 VOL/VOL
EFFECTIVE SAT. HYD. COND. = 0.400000019000E-02 CM/SEC

LAYER 2
--------

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 0
THICKNESS = 8.00 INCHES
POROSITY = 0.5690 VOL/VOL
FIELD CAPACITY = 0.4470 VOL/VOL
WILTING POINT = 0.3450 VOL/VOL
INITIAL SOIL WATER CONTENT = 0.3458 VOL/VOL
EFFECTIVE SAT. HYD. COND. = 0.200000009000E-02 CM/SEC

LAYER 3
--------

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 0
THICKNESS = 8.00 INCHES
POROSITY = 0.5550 VOL/VOL
FIELD CAPACITY = 0.4400 VOL/VOL
WILTING POINT = 0.3180 VOL/VOL
INITIAL SOIL WATER CONTENT = 0.3545 VOL/VOL
EFFECTIVE SAT. HYD. COND. = 0.100000005000E-02 CM/SEC

GENERAL DESIGN AND EVAPORATIVE ZONE DATA
---------------------------------------------

NOTE: SCS RUNOFF CURVE NUMBER WAS USER-SPECIFIED.

SCS RUNOFF CURVE NUMBER = 71.00
FRACTION OF AREA ALLOWING RUNOFF = 100.0 PERCENT
AREA PROJECTED ON HORIZONTAL PLANE = 0.013 ACRES
EVAPORATIVE ZONE DEPTH = 24.0 INCHES
INITIAL WATER IN EVAPORATIVE ZONE = 9.016 INCHES
UPPER LIMIT OF EVAPORATIVE STORAGE = 14.220 INCHES
LOWER LIMIT OF EVAPORATIVE STORAGE = 7.925 INCHES
INITIAL SNOW WATER = 0.000 INCHES
INITIAL WATER IN LAYER MATERIALS = 9.020 INCHES
TOTAL INITIAL WATER = 9.020 INCHES
TOTAL SUBSURFACE INFLOW = 0.00 INCHES/YEAR

EVAPOTRANSPIRATION AND WEATHER DATA
-------------------------------------

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
Honolulu Hawaii

STATION LATITUDE = 21.27 DEGREES
MAXIMUM LEAF AREA INDEX = 5.00
START OF GROWING SEASON (JULIAN DATE) = 0
END OF GROWING SEASON (JULIAN DATE) = 367
EVAPORATIVE ZONE DEPTH = 60.9 CM
AVERAGE ANNUAL WIND SPEED = 11.20 KPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY = 72.90 %
AVERAGE 2ND QUARTER RELATIVE HUMIDITY = 70.30 %
AVERAGE 3RD QUARTER RELATIVE HUMIDITY = 68.70 %
AVERAGE 4TH QUARTER RELATIVE HUMIDITY = 71.10 %

NOTE: PRECIPITATION DATA FOR HONOLULU HAWAII WAS ENTERED FROM AN ASCII DATA FILE.

NOTE: TEMPERATURE DATA FOR HONOLULU HAWAII WAS ENTERED FROM AN ASCII DATA FILE.

NOTE: SOLAR RADIATION DATA FOR HONOLULU HAWAII WAS ENTERED FROM AN ASCII DATA FILE.
Appendix E.2: Input Parameters for KINEROS2 Simulation of 40B, Episode 3

BEGIN GLOBAL
  CLen = 9, UNITS = METRIC
  Nele = 3
END GLOBAL

BEGIN PLANE !plot
  ID = 1  LEN = 9  WID = 5.658  SL = 0.04  MANNING = 0.24
  CV = 0.07  SAT = 0.779  PR = 3  File = c:\seethis.txt
  Canopy = 1  Interception = 3.0
  KS  G  DIST  POR  ROCK
  58  15  0.147  0.65  0  !soil layer
END PLANE

BEGIN PLANE !gutters
  ID = 2  LEN = 9  WID = 0.342  SL = 0.04  MANNING = 0.02
  PR = 2
END PLANE

BEGIN CHANNEL !runoff collection pipe
  ID = 3  UP = 1,2  LEN = 6  PR = 2
  WIDTH  RWIDTH  SS1  SS2  SLOPE  MANNING
  0.15  0.00  1.7  1.7  0.04  0.005
  Plot = H
END CHANNEL
Appendix E.3: Input Parameters HYDRUS-1D Simulation

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<th>Retention parameters</th>
<th>Saturated hydraulic conductivity</th>
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<td>0.5625</td>
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*** BLOCK A: BASIC INFORMATION ************************************************

Heading
Landfill 2003 season inverse
LUnit TUnit MUnit (indicated units are obligatory for all input data)
cm days g
lWat lChem lTemp lSink lShort lWDep lScreen lVariabBC lEquil lInverse
t f f t f f t t t f
NMat NLay CosAlpha
3 3 1

*** BLOCK B: WATER FLOW INFORMATION ****************************************

MaxIt TolTh TolH (maximum number of iterations and tolerances)
1000 1e-005 0.01
TopInf WLayer KodTop InitCond
t f -1 f
BotInf qGWL F FreeD SeepF KodBot DrainF
t f f -1 f
hTab1 hTabN
1e-006 10000
Model Hysteresis
1 0
thr ths Alfa n Ks l thm thta thk
Kk
0.289 0.654 0.113 1.231 800 0.5 0.6545 0.2885 0.654 800
0.305 0.569 0.083 1.193 400 0.5 0.5695 0.3045 0.569 400
0.3115 0.5625 0.0545 1.205 100 0.5 0.563 0.311 0.5625 100

*** BLOCK C: TIME INFORMATION **********************************************

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TPrint(1), TPrint(2), ..., TPrint(MPL)
232.375 232.5 260.375 261 281.375 282.458
283.396 284.729 288.417 289.208 332.375 333.125
333.5 334.417 334.5 336.583 366

*** BLOCK G: ROOT WATER UPTAKE INFORMATION **********************************

Model (0 - Feddes, 1 - S shape) cRootMax
0
P0 P2H P2L P3 r2H r2L
-10 -200 -800 -1000 0.25 0.1
POptm(1), POptm(2), ..., POptm(NMat)
-25 -25 -25

*** END OF INPUT FILE 'SELECTOR.IN' ******************************************
Appendix F1: HELP3 Predicted Runoff and Measured Leachate

HELP3 predicted runoff vs. actual runoff - ConB

HELP3 predicted runoff vs. actual runoff - 20B

HELP3 predicted runoff vs. actual runoff - 40B
Appendix F1: HELP3 Predicted Leachate and Measured Leachate

HELP3 predicted leachate vs. actual leachate - ConB

HELP3 predicted leachate vs. actual leachate - 20B

HELP3 predicted leachate vs. actual leachate - 40B
Appendix F2: HYDRUS 1-D Predicted Leachate and Measured Leachate Data

HYDRUS-1D predicted leachate vs actual leachate-ConB

HYDRUS-1D predicted leachate vs actual leachate-20B

HYDRUS-1D predicted leachate vs actual leachate-40B

HYDRUS-1D predicted leachate
Appendix F.2: HYDRUS-1D Predicted Soil Water Pressure and Measured Soil Water Pressure

soil water pressure, field measurement - ConB

soil water pressure, predicted by HYDRUS-1D - ConB
Appendix F.2: HYDRUS-1D Predicted Soil Water Pressure and Measured Soil Water Pressure
Appendix F.2: HYDRUS-1D Predicted Soil Water Pressure and Measured Soil Water Pressure

soil water pressure, field measurement - 40B

soil water pressure, predicted by HYDRUS-1D - 40B
Appendix G: Photos of Research Site and Equipment

21X Campbell data logger and MD9 unit

Disc infiltrometer

Evaporation pan

Automated tensiometers
Appendix G: Miscellaneous Photos of Research Site and Equipment

ConB before irrigation events

40B before irrigation events

20B after 9 weeks of irrigation (notice gutters are covered by vegetation)

20B during uniformity test

All three plots after 9 weeks of irrigation
Appendix H: Sample Calculation for Saturated Hydraulic Conductivity

<table>
<thead>
<tr>
<th>Test #</th>
<th>Depth [cm]</th>
<th>Simulated soil water pressure [cm of water column]</th>
<th>Drop in water level of water supply tube at steady state [mm]</th>
<th>Time for water level drop in water supply tube [min]</th>
<th>Equivalent rate of water leaving disc [mm/min]</th>
<th>K [m/sec]</th>
<th>K [cm/sec]</th>
<th>K [cm/hr]</th>
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* Hydraulic conductivity at 0 water pressure is the saturated hydraulic conductivity
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