An Accurate Evaluation of Water Balance to Predict Surface Runoff and Percolation

Problem and Research Objectives

Hawaii, like many other states, has a number of unlined landfills that are potential groundwater contamination sources. Infiltration control is a major means of reducing leachate generation at unlined landfill sites. Use of synthetic materials for the closure of landfills is quite expensive, especially for small rural communities. Use of alternate capping technologies, such as vegetation caps, may not be suitable in humid areas where the annual precipitation exceeds the evapotranspiration demand of growing crops. However, a combination of natural soil caps and runoff-enhancing structures can be a feasible capping method. Local plants growing on natural soil (clay) caps could transpire a large part of the percolating water. Making a portion of the landfill surface impervious (e.g., by use of rain gutters) and diverting the surface runoff offsite could reduce the entry of water through the landfill cap, thus reducing the potential for leachate generation. A recent demonstration by the U.S. Navy showed that, in tropical areas such as Hawaii, it is possible to cap landfills with natural soil cover if 20% to 40% of the surface area can be covered with rain gutters. However, the amount of error in the prediction was high. In addition to some simplifying assumption for water conduction in capping material, the model used daily water balance for calculating runoff and infiltration. In reality, rainfall in Hawaii occurs over a relatively short period of time. Higher-intensity rains cause significant surface runoff. Averaging a storm event over a day would significantly reduce the intensity, making it appear as if there is no runoff and all water is infiltrating the ground. For groundwater recharge studies, this overestimation of recharge may provide a false sense of security through modeling by implying that a large part of the rainwater is entering the soil in recharge areas and less water is lost through runoff. It is clear that an accurate estimate of the partitioning of rainwater to surface runoff and infiltration components and the subsequent movement of infiltrated water through subsoil media is quite important for a variety of applications.

The objectives of the study are to measure percolate and runoff at frequent intervals at the test plots from natural rain and sprinkler-applied water and to calibrate and test a recharge model and a runoff-producing model against the collected data. These models will provide some insight into the mechanisms of percolate and runoff production in response to specific storm events. They will also indicate if improvements in modeling strategy are needed to better calibrate these models against the collected data. An additional objective is to validate a regulatory model that is commonly used for the closure of landfill caps. The data will also help in the recalibration of the surface runoff and percolate production models and in the study of chemical transport through the soil. Since this is a multi-year study, the activities this year are closely related the previous two years' effort.

Methodology

The study site is located at the Marine Corps Base Hawaii in Kaneohe, Hawaii. The site, located near a landfill site, has six test plots—all instrumented to collect surface runoff, percolate at a depth of 2 to 3 feet, and soil moisture data. In addition, weather data such as temperature, relative humidity, wind velocity and direction, solar radiation, and rainfall are measured at the test site. The site is instrumented with pressure transducers, flow meters, soil moisture probes, and other sensors that are connected to data-logging devices to collect data at intervals ranging from a few minutes to twice daily. All collected data from the data loggers are downloaded to a computer (remotely located anywhere) via a modem and a cellular phone daily. Since the study is complete now, the site will be dismantled in summer 2005.

The following four tasks describe the methodology involved in the current study.

Task 1. Repair and replacement of aging and malfunctioning sensors and instruments, and instrument calibration (continuation of the previous years' activities)

In order for all instruments to function properly, replacement and recalibrations are continuously needed. Work involves replacement of flow counters, recalibration of pressure transducers, and replacement of level switches and multiplexers. In addition, work involves installing erosion control measures that are needed to prevent sliding of material in various areas of the experimental field and to prevent the material from offsite locations from entering the study area. To calibrate the pressure transducer, each tank is first emptied. Then, a known amount of water is introduced into the tank. The transducer response is recorded as a function of the volume of water that is expressed as the depth of water in the tank. Three separate measurements are made. A line of best fit is drawn to get the slope and the intercept to record the calibration constants. All these activities were carried out as needed.

Task 2. Additional soil hydraulic, vegetation, and evaporation data collection

To use computer models for water balance calculations, additional data (not counting the runoff and leachate data) need to be collected. Some examples include data on weather, soil-water retention, hydraulic conductivity, soil moisture, and leaf area index. Producing water retention curves for soil samples involves taking core samples from the field to the laboratory and measuring the equilibrated pressure and water content of the samples from –5 cm to 15 bars (-15,000 cm) using a combination of tension tables and pressure-plate apparatus. Altogether, 54 core samples were retrieved from various depths to obtain soil-water retention parameters.

A disc infiltrometer (from Soil Measurement Systems) is used to measure hydraulic conductivity at three locations per plot. Because surface soils are affected by cracks, root channels, and other macropore features, the measured hydraulic parameters at surface can be different from those at deeper depths. Thus, measurements are made first at the soil surface. Then similar measurements are made 15 to 20 cm below the land surface.

A vegetation survey is conducted using the point-frame method in which a frame, which has a groove at every 10-cm interval, spans the width of the plot. A thin metal rod is dropped in each of the grooves. The type of plants that the rod touches is then recorded. Also recorded is what the tip of the rod hits (e.g., soil, litter, or gutter). Approximately 600 points in each 6 m × 9 m plot is measured.

Leaf area index can be calculated using two methods. The first method is similar to the vegetation survey technique, except that it uses approximately 40 equally spaced points. The same frame and metal rod are used, but instead of recording which plants the rod touches, the number of live plants with which the rod makes contact is recorded. The 40 points are then averaged to get the leaf area index. The second technique involves tossing a 0.1 m × 0.1 m frame randomly onto the plot. All leaves found inside the frame are cut and bagged. The total area of the leaves divided by 0.01 m2 gives the leaf area index.

Biomass measurements are needed for each plot. By definition, biomass is the amount of living matter; however, for this project, biomass is defined as the amount of living and dead plants. To estimate the biomass, the 0.1 m × 0.1 m frame is randomly tossed onto the plot. All plant material within the frame is trimmed and bagged, leaving the roots behind. Each sample is dried at 70˚C in a plant-drying oven and then weighed. The weight of the dried biomass is divided by 0.01 m2 to get the average biomass per unit area.

A Class A Weather Bureau evaporation pan was setup near the meteorological station. A pressure transducer with fine resolution is used to continuously monitor the loss of water.

Duplicate soil cores from four locations outside the plots and from two locations within the plots are taken for the analysis of soil particle-size distribution. Both the mechanical sieve analysis and the hydrometer settling method are used to get the size distribution of these particles. Particle-size data are then related to soil hydraulic conductivity.

Task 3. Setup of an irrigation system to create artificial rain for water balance measurements

A sprinkler irrigation system was set up on three plots (control, 20% impervious, and 40% impervious) to make artificial rain at a given intensity for desired durations for water balance measurements. Before that, nine automated tensiometers in the three plots were installed to measure soil-water tension as a function of time.

Each plot has a nested tensiometer (at three depths) and four surficial tensiometers. Readings from these tensiometers are taken manually. Also, each plot has four automated (5 to 25 cm) and two manual (5 to 25 and 35 to 55 cm depths) time domain reflectometry (TDR) probes for reading water content. The manual probe readings are to be compared with the automated probe readings.

Task 4. Water balance simulations using a regulatory and two event-based (a runoff and an infiltration/percolation) models

The landfill water balance model (HELP-3, P.R. Schroeder, T.S. Dozier, P.A. Zappi, B.M. McEnroe, J.W. Sjostrom, and R.L. Peyton, 1994, The hydrological evaluation of landfill performance (HELP) model: Engineering documentation for version 3, EPA/600/R-94/168b, U.S. Environmental Protection Agency, Washington, D.C.) is used to calculate water balance on a daily basis. For the applied irrigation water or the rain from a natural storm, an infiltration/percolation model (HYDRUS-1D by J. Simunek, M. Sejna, and M. Th. van Genuchten, 1998, The HYDRUS-1D software package for simulating one-dimensional movement of water, heat, and multiple solutes in variably-saturated media, version 2.0, IGWMC-TPS-70, International Ground Water Modeling Center, Colorado School of Mines, Golden, Colo.) and a runoff model (KINEROS2, a modified version of the model by D.A. Woolhiser, R.E. Smith, and D.C. Goodrich, 1991, A kinematic runoff and erosion model: Documentation and user manual, ARS-77, U.S. Dept. of Agriculture, Agricultural Research Service, Washington, D.C.) are used. In the water balance equation, the amount of rain or irrigation water applied is known. In addition, the amount of percolation and runoff are directly measured. Pan evaporation data give an idea about evaporation. Also, the local weather data are used to calculate long-term potential evapotranspiration. Changes in soil-water storage are calculated from the tensiometer/TDR probe readings.

Principal Findings and Significance

Erosion control measures are periodically needed to ensure that water and sediments from offsite do not enter the test site where most of our leachate and runoff measuring devices are sitting in an excavated area adjacent to a slope. In the past, severe erosion resulted in the formation of gullies. After the addition of erosion cloth and riprap, the slope is stable and major erosion is not taking place and; all gullies have since been plugged.

With continuous repair and replacement, all sensors are working properly. Rainfall frequency data are now collected at 1-minute intervals during rain events, as a result of a modification made to the data logging program. During dry periods, rainfall data are collected only at 15-minute intervals (the same frequency as other sensors).

Retention data for more than 48 samples were developed between saturation and 15-bar pressure. Most soils appeared to be clayey, and the drainage time for the samples to attain 15 bars of pressure was more than six weeks. Surface hydraulic conductivity, measured using the disk infiltrometer, ranged between 10 and 30 cm/h, with an average of 20 cm/h. The deeper hydraulic conductivity values were close to 5 cm/h. While these values are significantly lower than those measured at the surface, they are much larger (at least one log order) than those used by the U.S. Navy in its earlier study based on core samples.

The leaf area index values were calculated using two techniques (see the “Methodology” section). The leaf area index varied between 0.96 and 2.08, depending on the plot.

The biomass measurements ranged between 210 and 900 g/m^2. This large range is understandable because of the varied nature of plant growth in each of the plots. Some areas of the plots have denser plant cover than other areas. Also, the presence of gutters reduces biomass in certain plots.

Eight rain and irrigation episodes were closely examined for water balance calculations. Most of the rain episodes were limited to three hours. Leachate and runoff were directly measured. Because of the short duration of the events, evaporation data are less likely to be in error. When we used water content changes, estimated from the responses of automated tensiometers, in the water balance equation, the terms do not balance out. Since the accuracy of measuring rain, runoff, leachate, and ET are better than measuring changes in soil water content, we suspect the conversion of pressure readings to water content using the retention curve could have brought in some errors to the water balance equation. Many fine soils exhibit hysteresis in soil-water retention. The retention curve developed in the laboratory was for the drying of samples. If there is hysteresis, then some discrepancy can be introduced in converting pressure to water content in the rain event using the drying curve.

We found that leachate amounts predicted using HELP-3 were off by as much as 100%. The underprediction of runoff was greatest for the 40% impervious plot. KINEROS-2 predicted surface runoff very well for the control plot. However, the predictions were off (-27% to 122%) for the partially impervious plots. A reason for this discrepancy is the improper accounting of runoff-producing areas in the model. Although the plots were supposed to be 20% and 40% impervious, in reality they were effective in producing on an average 5.3 % and 6.2% runoff (individual events ranged from 0 to 13%), due to interception of overhanging vegetation on the rain gutters. Also, runoff predicted using HELP-3 was lower than the measured runoff values. Leachate production simulation using HYDRUS-1D was better than that with HELP-3. However, the predicted leachate quantities obtained using HYDRUS-1D were still more than the observed values. HYDRUS-1D assumes instantaneous runoff once the rainfall exceeds the simulated infiltration capacity. Measurement errors for soil hydraulic conductivity and soil heterogeneity in the field are other possible types of error.

In 2004, two sets of three control irrigation episodes each were run, with 20 cm of irrigation applied at a constant rate of 1.7 cm/h during each 12-hour episode. For the first set of three episodes, performed between June 28 and July 8, the vegetation cover was completely cut and removed prior to the irrigation runs, which were performed consecutively with approximately 2.5 days between each. For the second set, performed between August 22 and 29 when all of the test plots were abundantly covered with vegetation, each run had a lag period of 1.5 days. During the June/July irrigation episodes, natural rainfall was minimal, with the third episode receiving 1.3 cm. More rainfall occurred during August, when 1.0 to 4.2 cm fell during the episodes, adding to the 20 cm of irrigation applied for each event.

The results of these long-duration irrigation events showed no major difference in leachate production between the non-vegetated (June/July runs) and vegetated (August runs) plots, which coincides with the antecedent soil water having been much lower in June/July than in August. Water was applied to almost dry soil in June, to somewhat wet soil in July, and to more wet soil in August. For the June/July events, leachate varied from 3% to 45% of the rainfall, whereas for the August events, it varied from 20% to 40%. Surface runoff in the initially dry soil was zero for the control plot, 6% for the 20% impervious plot, and 10% for the 40% impervious plot. However, under the subsequently wet conditions, runoff varied between 10% and 40%.

The present design of rain gutters as artificial diversion channels of rainwater does not seem to work effectively during irrigation and natural events. For practical reasons, a small number of wider gutters would work better because they would fill up with less vegetation debris, making them easier to clean. Splash can be minimized by placing some gravel inside these gutters. Another possible setup is to move all the gutters to one or two locations in the plots.

Measurement of water in the soil profile contributes most to the error in water balance, even if TDR probes instead of tensiometers are used over the entire depth of the profile. Soil heterogeneity, especially that for topsoil, contributes to 10% to 30% of the discrepancy. Tensiometers relying on the retention curve relationship can lead to inaccuracy due to hysteresis effects. This inaccuracy can also increase due to swelling of the soil, a phenomenon that was observed during all experiments. Entrapped air in soil could add an additional 10% to the inaccuracy. Errors of balancing outflow and runoff are in a range of a single percentage, due to the high sensitivity of the equipment used. Errors in evaporation can vary, depending on the method used for estimating and the duration of the water balance. However, having an on-site evaporation pan decreases this error to some extent.

Three papers, one project report, one technical report, and one seminar presentation provide the research results of this project. The three papers deal with different aspects of an alternative cover for landfill caps in a tropical setting: one on the general suitability aspects and the other two on the numerical modeling and water balance calculations. The seminar presentation focused on an accurate water balance study for the Kaneohe Marine Corps Base landfill test site.