LA-UR- 96- 4093

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Submitted to: Journal of Environmental Quality

4019

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Form 836 (10/95)

A Water Balance Study of Four Landfill Cover Designs Varying in Slope for Semiarid Regions

J.W. Nyhan*, T.G. Schofield, and R.H. Starmer

ABSTRACT

The goal of waste disposal in landfills is to reduce risk to human health by isolating contaminants until they no longer pose a hazard. In order to achieve this, the performance of a landfill cover design without an engineered barrier (Conventional Design) was compared with designs containing either a hydraulic barrier (EPA Design) or two capillary barriers (Loam and Clay Loam Capillary Barrier Designs). Water balance parameters were measured at six-hour intervals for these designs in 1.0- by 10.0-m plots with downhill slopes of 5, 10, 15, and 25%. Whereas runoff generally accounted for only 2-3% of the precipitation losses on these designs from December 1991 through July 1995, similar values for evaporation ranged from 86% to 91%. Evaporation usually increased with increases in slope in our field plots; the Conventional Design at slopes of 5% and 25% exhibited 139 and 162 cm of evaporation, respectively. Consequently, interflow and seepage usually decreased with increasing slope: interflow decreased from 10.7 to 1.5 cm for the Clay Loam Capillary Barrier Design at slopes of 5 and 25%. Although seepage comprised up to 10% of the precipitation on the Conventional Design, seepage did not occur in either the EPA Design or the capillary designs at the larger slopes.

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Research performed for the US Department of Energy Environmental Restoration Program by the Los Alamos National Laboratory operated by the U. of California under contract W-7405-ENG-36. *Corresponding author.
Abbreviations: TDR, time domain reflectometry; ANOVA, analysis of variance; CV, coefficient of determination.

INTRODUCTION

Institutional control and maintenance of low-level radioactive-waste repositories are expected to cease 100 years after the closure of a waste site, after which time the repository's engineered barriers and geohydrologic conditions need to act passively to isolate the radionuclides for an additional 300 to 500 years (US NRC, 1982). In spite of the intent of these regulations, experimental data bases regarding the effectiveness of engineered barriers in landfill covers do not exist for long-term projections of containment of either radionuclides (Bedinger, 1989) or other waste forms.

Even though the successful performance of the entire landfill is very much a function of interactive water balance processes (Paige et al., 1996), traditional remedial engineering solutions have ignored these processes, leading to numerous landfill failures (Jacobs et al., 1980; Hakonson et al., 1982). Field water balance data for landfill cover designs do not exist to enable the site operator to adequately define and engineer suitable barriers to prevent the migration of waste materials out of the landfill.

Our approach to developing effective landfill cover technology is based on the results of ten years of individual shallow land burial studies at Los Alamos and Utah (Abeele, 1986a, 1986b; DePoorter, 1981; Hakonson et al., 1982; Nyhan et al., 1984, 1990a, 1990b). These studies were combined with current European research (Nyhan et al., 1993) to design and emplace the Protective Barrier Landfill Cover Demonstration at the Los Alamos National Laboratory in Los Alamos, New Mexico. The objectives of the present study are: (i) to determine if hydraulic and capillary barriers in three landfill cover designs can change water balance relationships over those

observed in landfill covers without engineered barriers; and (ii) to determine how the slope of the landfill cover influences water balance parameters.

MATERIALS AND METHODS

Site Description

Los Alamos has a semiarid, temperate mountain climate with an average total annual precipitation of 46.9 cm for the years 1911 through 1986 (Nyhan et al., 1989). July and August are the wettest months, with 48% of the annual precipitation falling at this time as intense thundershowers. These months are also characterized by warm temperatures and high evapotranspiration, with the net result that only precipitation occurring in the winter and spring results in seepage within landfill covers (Nyhan et al., 1990a, 1990b).

Plot Construction, Design and Rationale

The Protective Barrier Landfill Cover Demonstration was constructed to compare water balance on the conventional landfill cover design, similar to that used in Los Alamos and the waste management industry for waste disposal (Jacobs et al., 1980), with that on three other designs containing engineered barriers (Fig. 1). The performance of all four designs was evaluated at dominant downhill slopes of 5, 10, 15 and 25% on plots without vegetation. These plots were installed in 1991 in our 8-ha field test facility (DePoorter, 1981) and were instrumented so that a complete accounting of precipitation falling on the plots could be made. The plots were constructed and instrumented to provide measures of runoff and interflow, as well as seepage and soil water storage as a function of slope length.

The Protective Barrier Landfill Cover Demonstration was emplaced on an east-facing slope similar to the aspect of many of the local landfills where this technology will be applied.

The area was surveyed into four pads, each of which received crushed tuff to establish the varying downhill slopes. Four 1.0- by 10.0-m plots with common sidewalls were then constructed on the center of each pad. The plot walls were fabricated (Nyhan et al., 1993) using plywood emplaced within a framework consisting of vertically placed iron I beams. The metal endplates had steel half couplings welded into the endplate wall to connect schedule 40 PVC pipe for the collection of seepage, interflow and runoff. The interflow and runoff collection systems consisted of metal troughs welded to the inside and top of the plot's endplate, respectively. A seepage collection system was installed in the bottom of each of the plots to collect water percolating vertically through all of the soil layers in each landfill cover design. This system consisted of four metal pans filled with medium gravel (8.0- to 25-mm diam) overlain with a high conductivity MIRAFI geotextile used in previous field studies (Nyhan et al., 1990a); an 11-cm-wide space was left between the sidewalls of the plot and the pan to minimize sidewall effects.

The hydrologic properties of soils used in the field study are presented in Table 1 (data represent assays on disturbed soil samples compacted to the same dry unit weight as found in the field plots). The soils were analyzed for porosity and for hanging column and thermocouple psychrometric moisture retention characteristics (Klute, 1986). Constant head determinations of saturated hydraulic conductivity were performed as well as pressure plate extractor determinations of moisture retention characteristics (ASTM, 1993). Based on this data, the RETC code (van Genuchten, 1991) was employed to determine the van Genuchten parameters for each soil (Mualem, 1976; van Genuchten, 1980).

The technology for controlling soil water erosion on all cover designs consisted of applying a 70% surface cover of medium gravel (8.0- to 25-mm diam). The plots with the

Conventional Design, similar to that used at Los Alamos waste sites, contained 15 cm of a loam surface layer (Fig. 1) consisting of a 2:1:1 (V:V:V) mixture of an uncharacterized topsoil, sand, and aged sawdust (<9.5-mm diam). This surface layer was not underlain by an engineered barrier, only by 76 cm of crushed tuff (Nyhan et al., 1984, 1990a).

One set of plots contained the EPA-recommended (US EPA, 1989) final cover design (Fig. 1). These plots contained 61 cm of the loam surface layer described previously emplaced on top of 30 cm of a medium sand (0.25 to 0.5-mm diam) made in a sand classifying/blending tank system (Portec Kolberg Division, Yankton, SD). The medium sand layer corresponds to the EPA "drainage layer" and was overlain with the MIRAFI geotextile to provide the EPA-recommended filter layer necessary to prevent fine soil particles from migrating into the drainage layer. The bottom layer in the EPA-recommended final cover, called the "low-permeability layer," usually consists of a 20 mil (0.5 mm) minimum thickness flexible membrane liner (FML) on top of a 60-cm-thick layer of soil with an in-place saturated hydraulic conductivity of $<1\times10^{-7}$ cm/s. Since the plastic FML would last less than 35 years (US EPA, 1989), this feature of the EPA design was omitted in our study. The results of previous research on mixtures of local crushed tuff and sodium-saturated bentonite (Abeele, 1986a, 1986b) indicated that a 1:10 (W:W) dry mixture of finely ground Aquagel (Baroid Drilling Fluids, Farmington, NM) and crushed tuff (called the clay-tuff mixture) should easily provide the low saturated hydraulic conductivity required for this layer (Table 1). Each layer of this mixture was covered after it was compacted in the plot to prevent drying, and each layer was sprayed with water before adding the next layer to promote the uniformity of the entire 61-cm layer.

Two designs contained capillary barriers varying only in surface layer (Fig. 1). One of the designs contained 61 cm of the loam surface layer used in the previous designs, whereas the other design contained 61 cm of a Hackroy clay loam classified (Nyhan et al., 1978) as a Lithic Aridic Haplustalf (clayey, mixed, mesic family) and used in two previous studies (Nyhan et al., 1984, 1990a). These soils were emplaced on top of 76 cm of a fine sand (0.05-to 0.425-mm diam) made in the sand classifier/blender described previously. The fine sand was specifically chosen to complement the underlying medium-sized gravel in terms of optimizing the relationship between the hydraulic conductivity and the water-holding properties of the capillary barrier (Wohnlich, 1990).

All of the soil materials used in each landfill cover design except the medium gravel (Fig. 1) were compacted in 15-cm-layers (Nyhan et al., 1993). Laboratory compaction tests were performed on the sands using Standard Test Methods for Maximum Index Density of Soils Using a Vibratory Table (ASTM, 1979; Test Method D4253-83) and on the other soils using the Modified Proctor Method (ASTM, 1979; Test Method D1557). After the first layer of each type of soil material was added to a plot and compacted, a set of 13 Proctor measurements of soil water content and bulk density was collected over the depth of the layer every 0.6 m down the length of the plot. A semivariogram analysis of this data was performed to show that only 5 Proctor determinations were necessary to characterize the compaction of each layer of soil. The loam surface layer (30 layers in 12 plots) and the clay loam surface layer (14 layers in 4 plots) were compacted to averages of 87 (CV = 3.6%) and 92% (CV = 3.3%) of the maximum dry unit weight from standard Proctor compaction, respectively. Average values for the fine sand,

medium sand, clay-tuff mixture and tuff were 96, 97, 90, and 90%, respectively, with CV's ranging from 1.5 to 2.7%.

Measurement of Seepage, Interflow, Runoff, and Precipitation

Runoff, precipitation, and seepage were collected year-round from December 1991 through July 1995, as well as interflow (flow occurring along the length of each plot through the medium sand layer in the EPA Design, the fine sand layer in the two designs with capillary barriers, and the crushed tuff layer of the Conventional Design). Water levels in each 100-liter tank used to collect these data were measured with a microprocessor-controlled ultrasonic liquid level sensor (model DCU-7, Lundahl Instruments, Logan, UT) connected to a multiplexed, automated system described previously (Nyhan et al., 1993). The water levels in the tanks were routinely recorded hourly, but much more frequently when the tank was either emptying or when it was nearly full.

Precipitation was measured using a weighing rain gauge and a long-term event recorder (Weathermeasure Corp., Sacramento, CA).

Measurement of Soil Water Content

Soil water content was routinely monitored once every six hours from December 1991 through July 1995, at each of 212 locations throughout the 16 plots using Time Domain Reflectometry (TDR) techniques (Topp et al., 1980) with the help of an automated and multiplexed measurement system. Volumetric water content was measured with a pair of stainless steel waveguides (60-cm long, 3-mm diam soil moisture probes; model number 6860, Campbell Scientific, Logan, UT), which were buried parallel and 5 cm apart in the soil and connected to a 26-m length of RG-8/U coaxial cable. TDR waveguides were emplaced in the Conventional

Design at depths of 5-10, 20-80, and 80-86 cm, in the EPA Design at depths of 1-61, 61-91, 96-102, and 92-152 cm, and in the two designs containing capillary barriers at depths of 1-61, 66-126, and 126-132 cm. These TDR waveguides were normally emplaced at downslope locations of 2.63, 4.65, 6.62, and 8.69 m for each soil depth, except at the deepest depths in the Conventional Design and the designs containing the capillary barriers, where they were emplaced at downslope locations of 3.64, 5.66, 7.68 and 9.70 m (to coincide with the bottom end of each of the four seepage pans installed in the bottom of each field plot).

A computerized TDR system captured and stored the 251-point waveform data (which represented an average of 64 replicate waveform determinations for each TDR waveguide pair at each sampling time), which was then used to determine the apparent dielectric constant and the water content of the soil (Topp et al., 1980). Soil water inventories were calculated from the average daily volumetric water content for each soil depth (Fig. 1) across the four downslope locations, as described previously (Nyhan et al., 1990a).

Water Balance Calculations

Daily water balance calculations were performed by determining the daily change in soil water inventory, by summing the daily amounts of precipitation, seepage, interflow, and runoff, and then determining the amount of daily evaporation by difference. As an independent check on these evaporation estimates, evaporation was also estimated from eddy heat flux data collected from a fast-response hygrometer mounted at a height of 12 m on a 92-m meteorological tower at Los Alamos; daily values were estimated from field data collected at 15-minute intervals.

In order to further evaluate the water balance data, daily shortwave radiative energy received by field plots with slopes of 5, 10, 15, and 25% was estimated from pyranometer data

collected at a height of 1.2 m from the same meteorological tower described above at the same sampling frequencies. The influences of slope and seasonality of shortwave radiative energy were calculated using the SOLARFLUX model (Rich et al., 1995).

RESULTS AND DISCUSSION

Estimates of Precipitation and Soil Water Inventory

The overall significance of each year's water balance data can best be explained by understanding the spatial and temporal occurrence of precipitation around Los Alamos (Bowen, 1990). Bowen showed that mean annual precipitation is 32.8 cm at White Rock, the only station close to the Protective Barrier Landfill Cover Demonstration with a data base longer than the data collected in this field study (Table 2). From this analysis, we determined that 2.94-year, 5.56-year, and 20-year events occurred in 1992, 1993, and 1994, respectively.

The daily soil water inventory calculations are presented in Figs. 2-5 for each of the landfill cover designs with 5% slopes. Field plots with 5% slopes provided examples of engineered barriers that failed (produced seepage), compared with plots at slopes of 15 and 25%, which usually exhibited smaller changes in soil water inventories with time and engineered barriers that did not fail.

Soil water inventory data are presented for several layers of the Conventional Design (Fig. 2). The inventory data for the loam topsoil represents the daily average readings of horizontally-emplaced waveguide pairs at a depth of 5 to 10 cm at downslope locations of 2.63, 4.65, 6.62, and 8.69 m. The frequent variations in the TDR measurements at this depth occurred because soil water content usually increased with precipitation events as small as 0.5 cm. Similar data collected at the 15-75 cm depths exhibited less frequent fluctuations because the small

precipitation events did not penetrate to the maximum depths over which the measurements were integrated.

Large changes in soil water inventory were observed at both sampling depths in the crushed tuff layer monitored with time in the Conventional Design with the 5% slope (Fig. 2), typical of the changes observed on the three field plots containing this design with larger slopes. The soil water inventories presented for the 15-75 cm depth decrease throughout the summer and fall of each year and increase during the cooler winter and spring months with snowmelt additions. The data collected at the 75-91 cm depth of the tuff layer (Fig. 2) shows that soil water inventories remained at values greater than 2.9 cm (corresponding to field capacity volumetric water content of 18%) over 69% of the time. Since soil water inventory values greater than 2.9 cm for the tuff correspond to soil water regimes dominated by gravity flow, these time periods represent periods when seepage was observed to occur beneath this lower tuff layer with additions of water from upper layers.

Soil water inventory data are presented in Fig. 3 for the EPA Design with the 5% dominant downhill slope. TDR data are presented for the 61-cm-deep loam topsoil layer in this design, representing the measurements collected from a pair of 60-cm-long waveguides emplaced vertically in this soil layer. Many of the same snowmelt relationships shown for the Conventional Design (Fig. 2) were also observed in this plot (Fig. 3). Soil water in the topsoil decreased as water drained into the medium sand layer (the EPA "drainage layer") at a depth of 61-91 cm. The horizontally-emplaced waveguides in the medium sand layer demonstrated increased soil water inventories as interflow occurred in January, May, and June 1992.

Using a Single-Factor ANOVA on all of the plots with the EPA Design ($P < 0.05$; Steel and Torrie, 1960), there was a small but significant increase in the soil water inventory of the 97-146 cm depth of the hydraulic barrier (clay/tuff mixture) during March 1992, compared with similar data collected either before (December 1, 1991, through December 30, 1991) or after (July 2, 1995, through July 31, 1995) this time period. This data (Fig. 3) and those collected from the other three field plots containing this design showed similar results, indicating that this hydraulic barrier was permitting very little water penetration to occur, as expected due to the very low saturated hydraulic conductivity of the clay/tuff mixture (Table 1).

The soil water inventory data presented for the Loam Capillary Barrier Design demonstrates the dynamics of water movement through the loam surface layer and underlying fine sand layers (Fig. 4). Soil water inventories in the loam surface layer increased dramatically in June 1992, causing the inventories of water in the fine sand layers to increase for a short time period. As a result of this sudden increase in the fine sand water inventory, only 0.06 cm of interflow occurred along the length of the fine sand layer, with 0.48 cm of seepage moving vertically into the seepage pans during this time period. However, during the snowmelt of 1993 (a 5.66-year event; see Table 2), the soil water inventory again increased dramatically up to February 16, resulting in sudden increases in the inventories of water in the fine sand layer. In this case, these inventory increases resulted in 6.24 cm of seepage and 4.02 cm of interflow occurring in this plot. Thus, in both of these cases, the rate of infiltration of water into the fine sand layer was greater than the capillary barrier's ability to conduct water laterally: matric potential forces, which were probably close to 0 kPa near the bottom of this layer, were not able to hold the water

within the fine sand at the interface between the fine sand and the medium gravel. This effect was not observed for the Loam Capillary Barrier Design at slopes of 15 and 25%, and minimally at a slope of 10%.

The soil water inventory data for the Clay Loam Capillary Barrier Design with the dominant downhill slope of 5% is presented in Figure 5. Soil water inventory changes were much smaller on this plot than the Loam Capillary Barrier Design (Fig. 4) probably due to the effect of a low-conductivity surface layer (Table 1) on capillary barrier dynamics. Whereas interflow and seepage were observed with the Loam Capillary Barrier Design on June 22 and 23, 1992, there was a negligible increase in soil water inventories for the Clay Loam Capillary Barrier Design (Fig. 5), resulting in no interflow and no seepage. However, from February 17 to March 29, 1993, the fine sand water inventory did increase in the Clay Loam Capillary Barrier Design (Fig. 5) and 5.59 cm of seepage and 4.50 cm of interflow did occur on this plot. No seepage occurred on the 10,15, and 25% slopes of this design, indicating a very slow drainage rate of water from the clay loam layer into the underlying fine sand layer and more water available for evaporation than the plots containing the loam surface layer at each slope (Table 3).

Seepage, Interflow and Runoff Data

Seepage occurred on all of the landfill cover designs at a slope of 5% except for the EPA Design (Table 3). Seepage occurred sporadically in the Spring of 1992, 1993, and 1994, as observed in previous field studies (Nyhan et al., 1990a, 1990b). Interflow occurred continuously for longer time periods than seepage and during other seasons as well. Of the 1339 days of the field study, seepage occurred on 49, 27, and 9 days for the Conventional, Loam Capillary Barrier, and Clay Loam Capillary Barrier designs with slopes of 5%, respectively; interflow occurred on

243, 339, and 220 days during this time period for these plots. Although no seepage occurred on the EPA Design with the 5% slope, interflow occurred on 262 days.

The magnitude of the seepage and interflow rates varied widely from one design to another on the 5% slopes. The largest daily seepage rate (1.37 cm) occurred on the Conventional Design, which had a maximum daily interflow of 0.51 cm. The capillary barrier design with the loam topsoil exhibited maximum daily interflow production rates up to 0.37 cm, with 1.20 cm of seepage occurring in February 1993. During this same period, the design with the clay loam topsoil exhibited maximum daily interflow and seepage rates of 0.39 and 1.36 cm, respectively. We had expected a much smaller amount of interflow to occur on the Clay Loam Capillary Barrier Design than on the Loam Capillary Barrier Design because the clay loam has a lower saturated hydraulic conductivity (see Table 1 and Nyhan et al., 1984), compared to the loam surface layer, which limited the flow of soil water into the fine sand layer in this design.

Runoff occurred throughout the year on these unvegetated plots as a result of snowmelt and thunderstorm activity. Only 18% of the total runoff between 1992-1994 came from snowmelt events, with 82% of the runoff generated on the study plots being generated during summer thunderstorms. On an individual precipitation basis, no consistent relationship was detected between slope and runoff for either the clay loam topsoil or the loam topsoil, because of the large spatial and temporal variation in runoff observed for both of these soils. For example, the largest daily runoff observed during our field study (1.34 cm) occurred on the Conventional Design with the 25% slope during a record-breaking 3.56-cm precipitation event on August 27, 1993. However, on this same day, the Conventional Design plots with slopes of 5, 10, and 15% exhibited 1.03, 0.91, and 0.78 cm of runoff, respectively.

Water Balance Summaries

The most practical comparisons among the four landfill cover designs for a semiarid region, in terms of their usefulness to the burial site operator, should be the overall performance comparison of the water balance parameters for the duration of this field study (Table 3). The data listed in Table 3 represents the only comprehensive field test of the EPA Design in the literature, besides the experiment performed by Los Alamos personnel at Hill Air Force Base (Paige et al., 1996). Using a Two-Factor ANOVA without replication ($P < 0.05$; Steel and Torrie, 1960), there was a significant effect of both landfill cover design and slope on all of the individual water balance parameters listed in Table 3.

As might have been expected in a semiarid environment, 86 to 91% of the precipitation received by all of the landfill cover designs was evaporated from these unvegetated landfill cover designs. Since the soil in the vicinity of the meteorological tower was similar to the Conventional Landfill Cover Design with the 5% slope, we were able to compare the tower hygrometer estimates of water flux with the amounts of evaporation observed in this plot and found that these two estimates agreed quite well (138.9 and 131.1 cm, respectively, for the period December 1991 through July 1995; Table 3). For the years 1992, 1993, and 1994, the meteorological tower estimates were 36.5, 36.2, and 32.7 cm water, respectively, compared with evaporation estimates from the Conventional Landfill Cover Design with the 5% slope of 33.8, 39.6, and 34.7 cm water for the same years.

Evaporation usually increased with slope gradient within each landfill cover design (Table 3) on our east-facing study site, because plots with large slopes intercepted more shortwave radiative energy than plots with lower slope gradients (Fig. 6). This effect was dominant during the first and fourth quarters of each year, during times when seepage occurred; e.g., during the fourth quarter of 1993, plots with a 5% slope received 1339 MJ/m^2 shortwave radiative energy compared with the 1561 MJ/m^2 received by the plots with a slope of 25% (Fig. 6). Consequently, the sum of the interflow and seepage usually decreased with increasing slope for each landfill cover design (Table 3).

Evaporation also varied inversely with the ability of each cover design to conduct water into the soil layers in the design (Fig. 1). The smallest amounts of evaporation generally occurred on the field plots with the Loam Capillary Barrier Design (Table 3), where water could quickly move through the loam topsoil and the fine sand layers, which had saturated hydraulic conductivities of 0.0057 and 0.012 cm/s, respectively (Table 1). Slightly larger amounts of evaporation occurred on the plots with the Conventional Design than on those with the Loam Capillary Barrier Design, because water had to move through the loam topsoil in the Conventional Design, but then migrated more slowly through the crushed tuff layer which had a saturated hydraulic conductivity of 0.00082 cm/s (Table 1). The plots with the EPA Design and the Clay Loam Capillary Barrier Design generally had larger amounts of evaporation than the plots with the other designs, due to the low saturated hydraulic conductivities of the clay/tuff mixture in the former and of the clay loam topsoil in the latter, as well as the large water-holding capacity in the surface layer of the latter.

Although runoff did not seem to be related to surface slope on a per-event basis, runoff did increase with increasing slope over the 44-month duration of this study for each of the designs. Runoff generally accounted for about 2-3% of the precipitation losses across all of the plots studied (Table 3).

Seepage was definitely decreased with engineered barriers in this study over that observed in the Conventional Design, which did not contain an engineered barrier. Although 9.86 cm of interflow occurred on the Conventional Design with the 5% slope, 17.4 cm of seepage occurred over the life of the field study. This amount of seepage represents 10% of the precipitation that could be added directly to the wastes underlying the landfill cover at an actual waste site. The hydraulic barrier in the EPA Design effectively controlled seepage at all slopes, and both of the capillary designs worked effectively to eliminate seepage at the higher slopes (Table 3), many of which are commonly used on waste sites at Los Alamos and throughout the waste management community.

OPTIMIZATION OF LANDFILL COVER DESIGNS

The best landfill cover design for a specific site depends on the specific needs and characteristics of the site, the types of wastes present at the site and how they are stored, the potential long-term risks and costs, and the pertinent state and federal regulations. After collecting most of this information, the waste site operator is usually asked to use the HELP model (Schroeder et al., 1994) to justify the validity of the proposed landfill cover design, since this model is recommended by the US EPA for solid waste landfill design. The HELP model was even used in the Prototype Decision Support System for selecting these designs (Paige et al., 1996). However, the HELP model is a one-dimensional flow model and, as such, is incapable of

adequately describing the three-dimensional flow of water through landfill cover designs containing engineered barriers, such as those used in the current field study.

Ultimately, the waste site operator wants a landfill cover design for a specific slope that keeps the wastes beneath the landfill cover dry, that is, a design that minimizes seepage and maximizes interflow and evaporation. Since the design must also keep the wastes covered, it must also minimize erosion. However, a few parameters, such as slope, are generally predetermined by site characteristics. The data presented in Table 3 would suggest that the best approach for the waste site operator might be to select a combination of a surface layer (with erosion control technology included) and a slope for a landfill cover design that would result in minimal runoff, realizing that larger amounts of runoff occurred on plots with larger slopes.

The site operator could then choose a landfill cover design that would minimize seepage. This field study has shown that appreciable seepage can occur on a landfill cover that does not contain an engineered barrier, i.e., the Conventional Design in this study (Table 3). Our field plots had to contain a layer of medium gravel beneath them to collect seepage, a layer that is not present in old, inactive landfills at Los Alamos that contain this design. The presence of this gravel layer thus promoted interflow to occur in this design, so that the amounts of seepage that would have occurred without the gravel layer present could be estimated by adding the seepage and the interflow terms in the current study.

Current state and federal regulations usually require an engineered barrier to be present in the landfill cover design, a design criterion that is also impacted by risk assessments and cost considerations. Capillary barriers can be used as alternative designs to the EPA Design, with the realization that seepage did occur at 5 and 10% slopes in the Loam Capillary Barrier Design and

in the Clay Loam Capillary Barrier Design with a slope of 5% (Table 3). Although the EPA Design does seem to eliminate seepage in field plots with 5 and 10% slopes (Table 3), the EPA design is probably more expensive than alternative designs (Paige et al., 1996). In the case of either engineered barrier, other field data sets similar to that collected in this study are needed in a variety of climates and with slope lengths longer than 10 m to validate hydrologic models that can be used in design selection.

ACKNOWLEDGMENTS

The DOE Environmental Restoration Program funded this program as part of a landfill cover pilot study to help remediate waste sites at the Los Alamos National Laboratory. The DOE International Technology Exchange Program also helped by sponsoring exchange of scientific information between the major author and scientists in Germany and UK Special thanks are extended to J. Leo Martinez for helping with the design, construction, and emplacement of the field experiment and to Gary J. Langhorst for his help with computer software and hardware for the field study.

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Table 1. Hydrologic properties of soils used in field study as determined with van Genuchten's RETC model (van Genuchten et al., 1991) and laboratory analyses.

Soil description	van Genuchten factors			θ_r	θ_s	Saturated conductivity
	α	n	m	(cm^3/cm^3)		(cm/s)
Loam topsoil	0.0271	1.539	0.3504	0.0692	0.4209	5.7×10^{-3}
Hackroy clay loam	0.0100	1.548	0.3541	0.0730	0.4839	2.5×10^{-4}
Fine sand (0.05-0.425 mm diam)	.0334	5.472	0.8173	0.0700*	0.4180	1.2×10^{-2}
Medium sand (0.25-0.5 mm diam)	0.0288	3.766	0.7344	0.0376	0.4184	1.3×10^{-1}
Crushed tuff	0.0104	1.707	0.4140	0.0031	0.4079	8.2×10^{-4}
Clay-tuff mix	0.00014	3.992	0.7495	0.0000*	0.4415	6.3×10^{-8}
Medium gravel	-	-	-	-	-	2.0

* Constrained parameter in van Genuchten model.

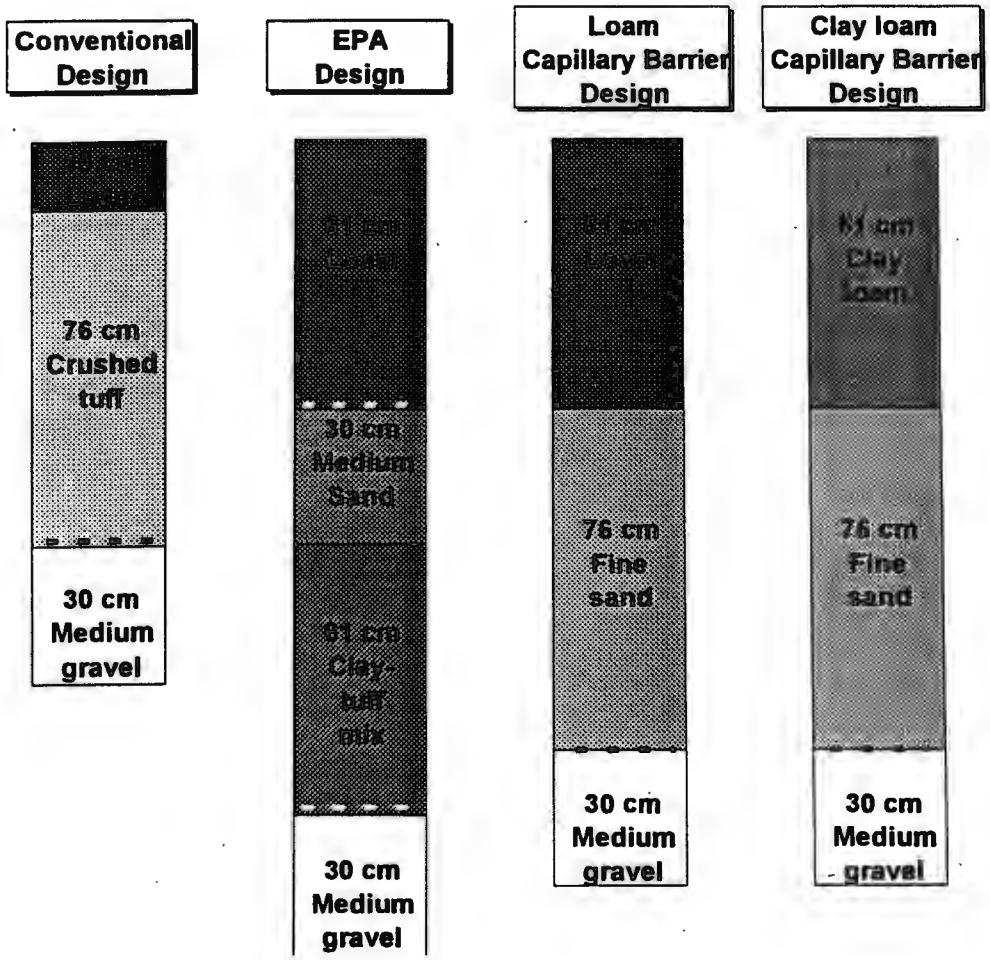
Table 2. Annual precipitation probabilities for the Protective Barrier Landfill Cover Demonstration site.

Percentage	Frequency of event	Annual precipitation (cm)	Year of study
≤ 5	1.05-year	22.2	
≤ 10	1.11-year	23.5	
≤ 50	2.00-year	32.8	
≤ 66	2.94-year	37.9	1992
≤ 82	5.56-year	43.7	1993
≤ 90	10-year	48.0	
≤ 95	20-year	48.8	1994[†]

[†] 9.5 cm of precipitation was added as crushed ice to all field plots in April 1994 in addition to this natural precipitation.

Table 3. Water balance data for all landfill cover designs from December 1, 1991 through July 31, 1995. Total precipitation for this time period was 171 cm.

Landfill cover Design and slope	Water balance parameter (cm)				
	Evapor-ation	Interflow	Seepage	Runoff	Change in soil water inventory
Conventional Design					
5%	138.9	9.86	17.40	3.04	2.52
10%	143.8	15.12	8.16	3.19	0.45
15%	152.8	10.05	8.60	3.32	-4.57
25%	161.7	6.72	3.09	4.34	-5.69
EPA Design					
5%	154.1	17.07	0.00	1.83	-1.12
10%	154.1	16.02	0.00	1.73	0.00
15%	154.4	15.10	0.00	3.94	-2.23
25%	154.4	12.95	0.00	6.14	-2.27
Loam Capillary Barrier Design					
5%	143.0	14.59	9.64	1.41	2.09
10%	137.9	20.62	3.61	4.75	3.87
15%	150.6	17.85	0.00	3.37	-0.59
25%	155.9	10.69	0.00	5.66	-2.08
Clay loam Capillary Barrier Design					
5%	149.5	10.71	5.59	2.95	2.03
10%	152.5	12.77	0.00	4.44	1.06
15%	156.9	6.83	0.00	6.19	0.21
25%	163.7	1.50	0.00	7.43	-1.39



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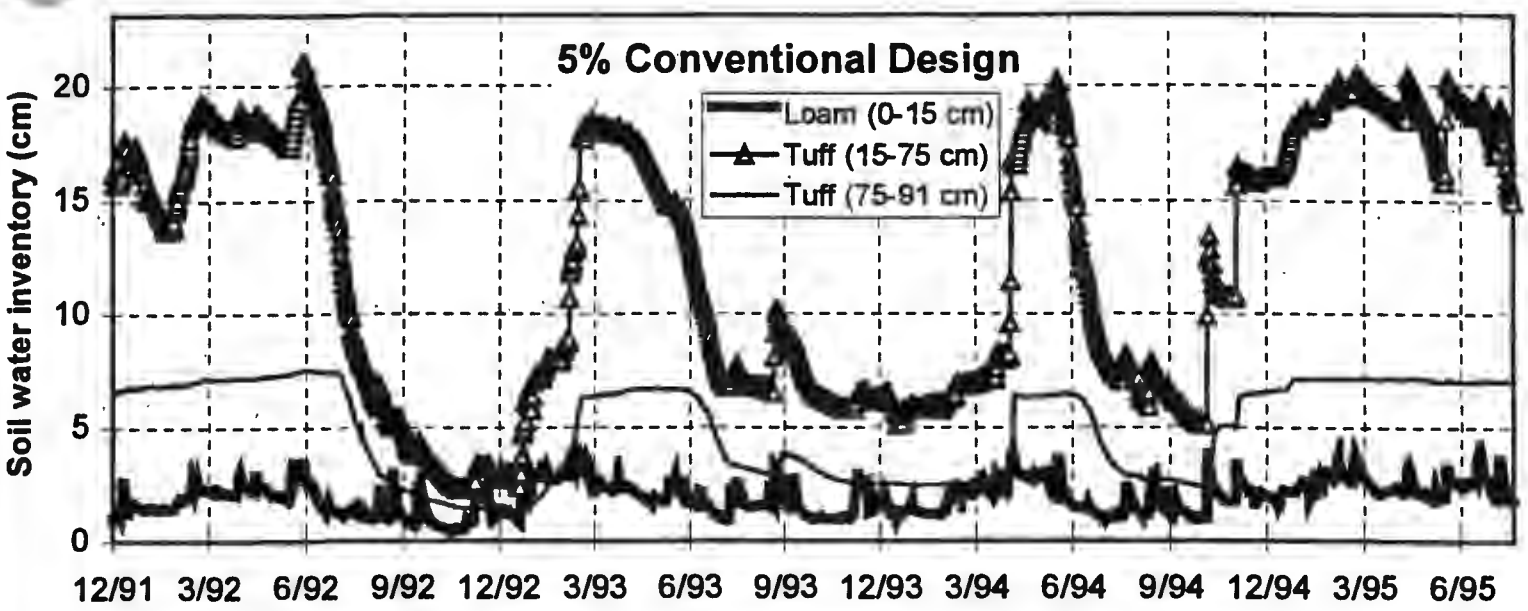


Figure 2. Daily soil water inventory as a function of time for the Conventional Landfill Cover Design with the dominant downhill slope of 5%.

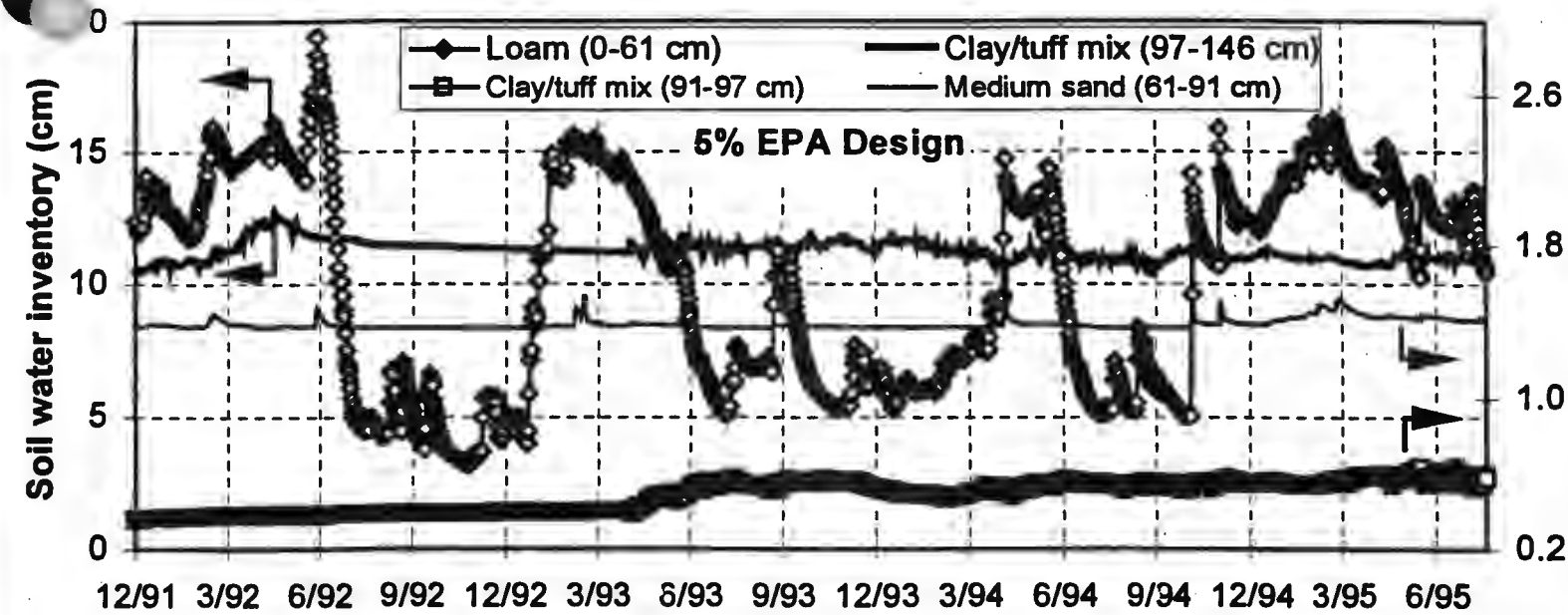


Figure 3. Daily soil water inventory as a function of time for the EPA Design with the dominant downhill slope of 5%. Arrows indicate which axis corresponds to the data.

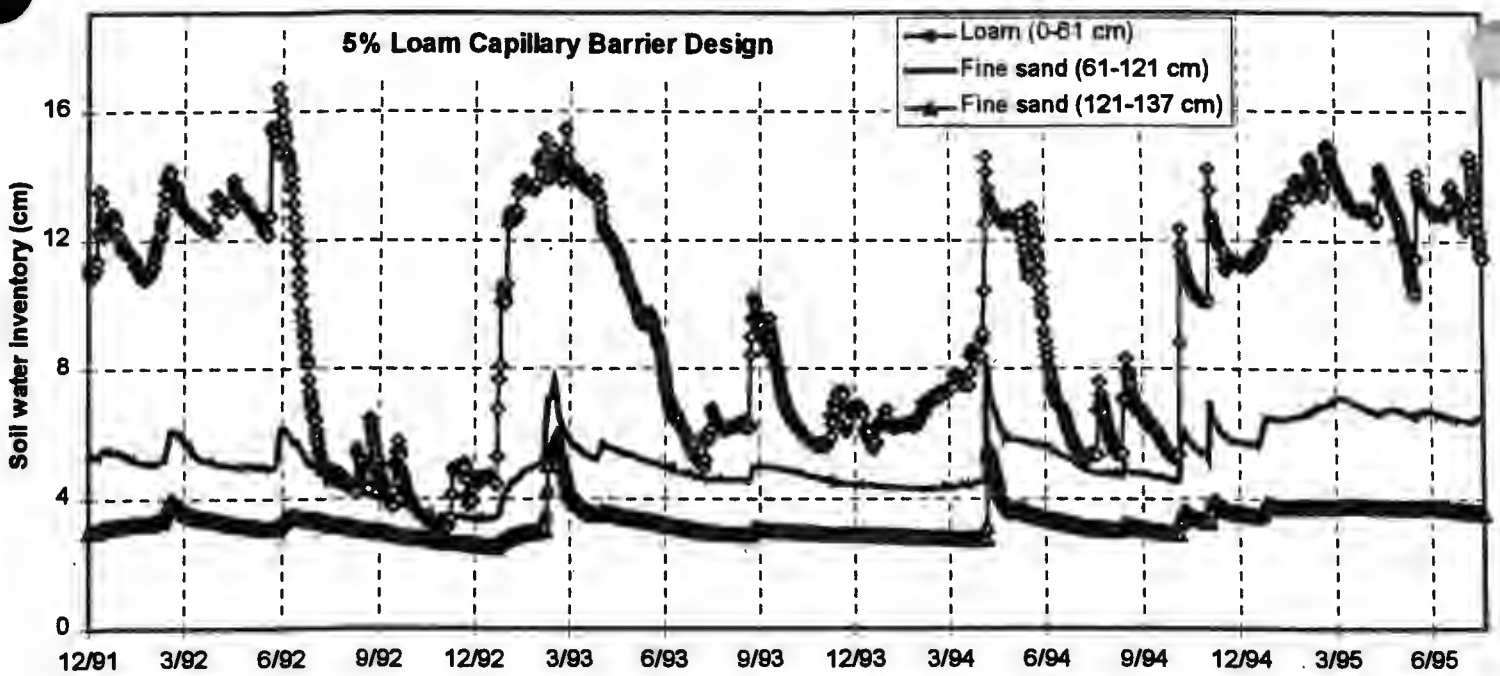


Figure 4. Daily soil water inventory as a function of time for the Loam Capillary Barrier Design with the dominant downhill slope of 5%.

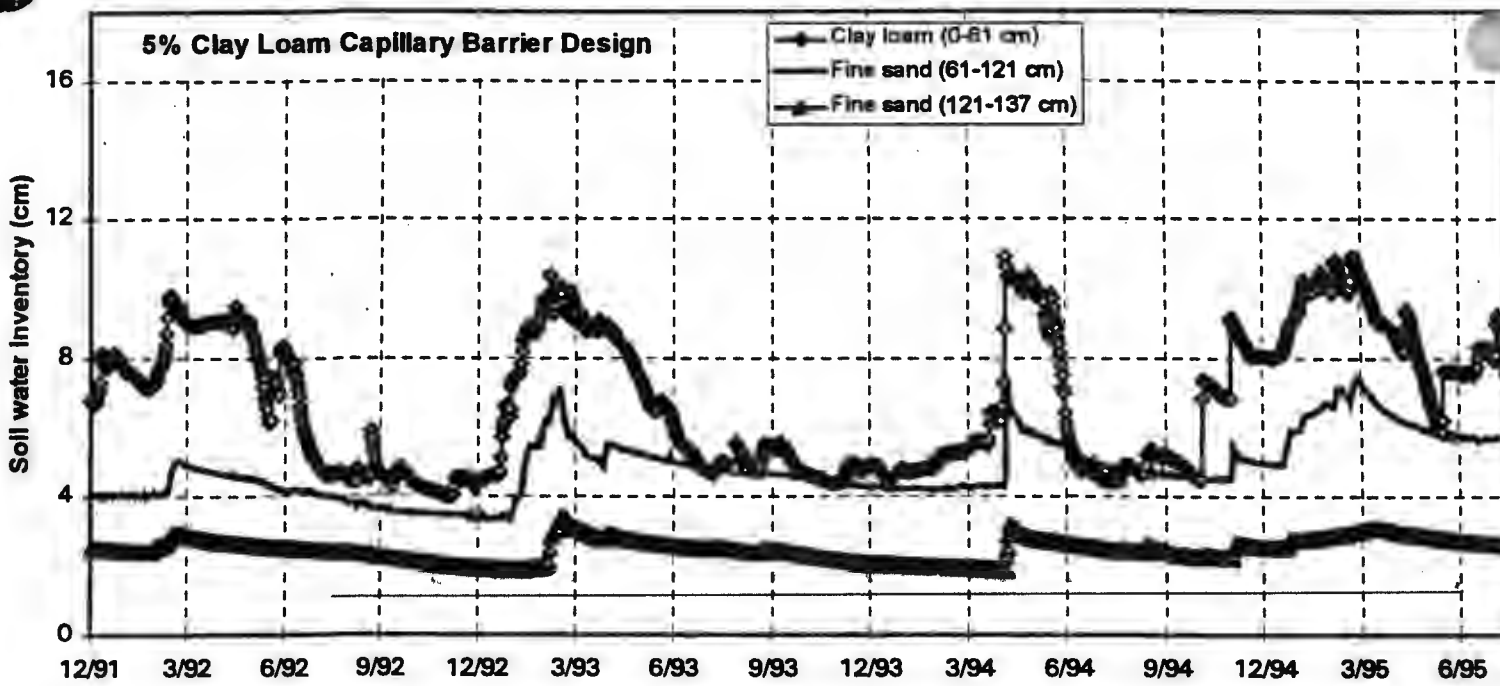
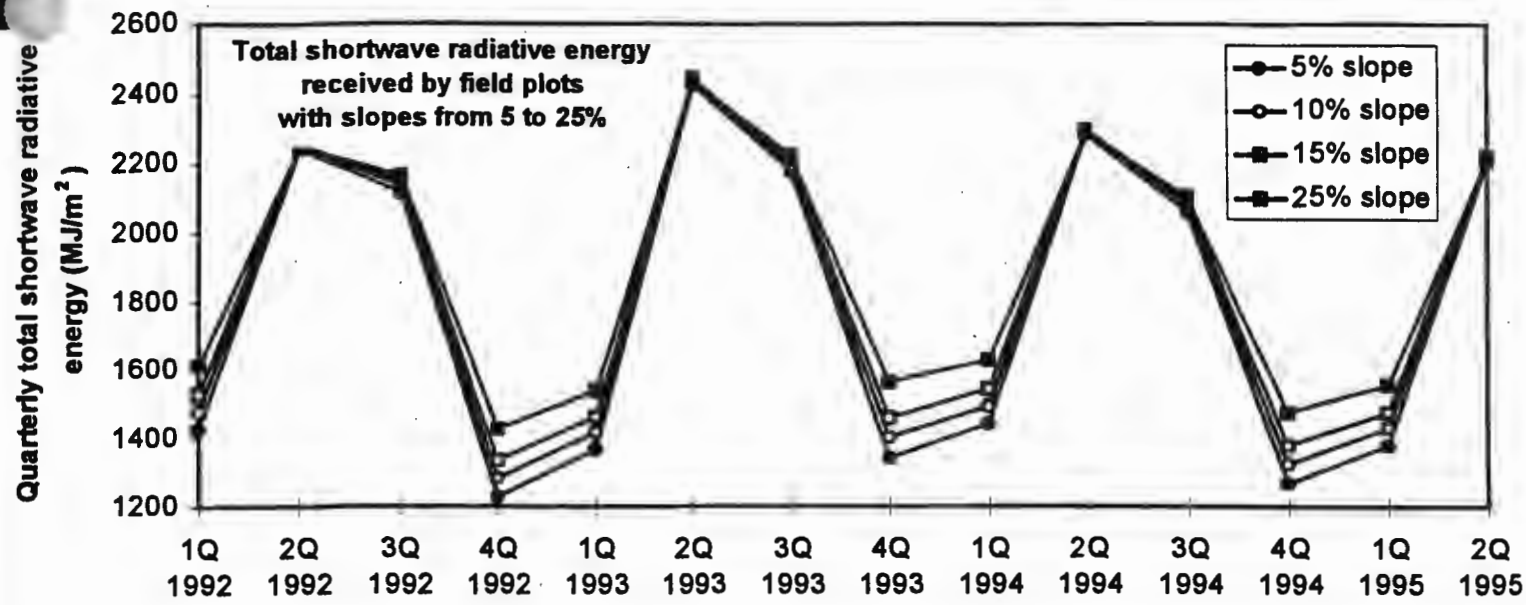


Figure 5. Daily soil water inventory as a function of time for the Clay Loam Capillary Barrier Design with the 5% dominant downhill slope.



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