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FIELD STUDIES OF ENGINEERED BARRIERS FOR CLOSURE OF LOW LEVEL RADIOACTIVE WASTE LANDFILLS AT LOS ALAMOS, NEW MEXICO, USA

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ABSTRACT

The Los Alamos National Laboratory examined water balance relationships for four different landfill cover designs containing engineered barriers. These field experiments were performed at Los Alamos, New Mexico, USA, in 1.0- by 10.0-m plots with downhill slopes of 5, 10, 15, and 25%. This plot size and these slopes were chosen to complement similar experiments currently being performed at the Universities of Hamburg, Munchen, Darmstadt, and Karlsruhe, Germany, as part of the US Department of Energy's International Technology Exchange and Environmental Restoration programs.

Field measurements of seepage, precipitation, interflow, runoff, and soil water content were collected in each of the 16 plots representing four slopes each with four cover designs: Conventional, EPA, Loam Capillary Barrier and Clay Loam Capillary Barrier. A seepage collection system was installed beneath each cover design to evaluate the influence of slope length on seepage using a series of four metal pans filled with medium gravel that were placed end-to-end in the bottom of each field plot. An automated waterflow datalogging system was used to collect hourly seepage, interflow and runoff data and consisted of 100 100-liter tanks, each of which was equipped with an ultrasonic liquid-level sensor and a motor-operated ball valve used to drain the tank. Soil water content was routinely monitored every six hours at each of 212 locations throughout the 16 plots with time domain reflectrometry (TDR) techniques using an automated and multiplexed measurement system.

Field data is presented to show the effects of slope and slope length on the performance of each landfill cover design for the first 15 months of this field experiment.

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). There are currently neither experimental nor experiential real-time bases for long-term projections regarding the effectiveness of engineered barriers in landfill covers for long-term 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, 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 do not exist to enable the site operator to define and engineer suitable barriers to prevent the migration of waste materials out of the landfill.

Our approach to developing an 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; Pertusa, 1980). These studies were combined (with the help of the US Department of Energy's International Technology Exchange Program) with current European research (Anonymous, 1988; Berger et al., 1991; Gregersen et al., 1991; Hotzl and Wohnlich, 1992; von der Hude, 1991a,1991b; Matter, 1991; Melchior et al., 1990a,1990b, 1991,1992; Melchoir and Miehlich, 1988; Mielich and Melchoir, 1992; Mock et al., 1991; Wohnlich 1990,1991) to design and emplace the Protective Barrier Landfill Cover Demonstration at the Los Alamos National Laboratory in Los Alamos, New Mexico, USA. The purpose of this field demonstration was to monitor and compare water balance relationships on four landfill cover designs in a semiarid temperate mountain climate as functions of slope and slope length. This field data was to be used to calibrate several hydrologic models that will be used to design landfill covers.

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MATERIALS AND METHODS

Plot Construction, Design and Rationale

The purpose of the Protective Barrier Landfill Cover Demonstration was to monitor and 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. The performance of all four designs was evaluated at dominant downhill slopes of 5, 10, 15 and 25%. These plots were installed during the spring, summer and fall of 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 measured. 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 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). Dominant downhill slopes up to 25% were used on the plot surfaces to insure a range of slopes up to the maximum slope that would be allowable for the safe operation of large earth-moving equipment at a landfill.

The Protective Barrier Landfill Cover Demonstration was emplaced on an east-facing 10.7- by 37.5-m parcel of land with crushed tuff backfill on the surface (Nyhan et al., 1984). This backfill is used in landfills at Los Alamos as a result of excavating disposal trenches in local Bandelier Tuff, which is then crushed and emplaced around the waste materials. This area was surveyed into four 10.7- m-long areas, each of which received additional crushed tuff to establish the varying downhill slopes. The crushed tuff on each of these pads was then compacted and resurveyed to confirm the desired slopes. A south-facing 4.6-m-wide, 40-m-long ramp that abutted the lower ends of these four east-facing pads was constructed similarly, only with a 2% dominant downhill slope. A set of four 1.0- by 10.0-m plots with common sidewalls was then constructed on the center of each pad, with a distance of 3.05 m between each set of plots. All of the plot walls except the downhill endplates were fabricated using two pieces of plywood (1.27 cm by 1.88 m by 1.22 m) emplaced within a framework consisting of vertically placed iron I beams (2.5 by 5.1 by 0.32 cm) on 1.22 m centers, with channel iron (2.5 by 5.1 by 0.32 cm) top and bottom framing. The endplates were fabricated from 14 gauge sheet metal, and had 7.62-cm and 10.2-cm diam steel half couplings welded into the endplate wall to connect plumbing used for the collection of seepage and interflow, respectively. The interflow collection system consisted of a 1.0-m long, 30.5-cm-deep, 30.5-cm-wide 14 gauge metal trough welded to the inside of the plot's endplate. The runoff collection system was also fabricated using 14 gauge sheet metal and consisted of a 1.0-m long, 15.2-cm-wide trough with a floor that sloped to divert runoff (30.5-cm deep at the low end and only 25.4 cm deep at the high end); this trough was welded to the top of each endplate and had a 15.2-cm-diam steel half coupling welded into the trough wall to connect plumbing used to collect runoff.

A seepage collection system was installed in the bottom of each of the plots and was designed to evaluate seepage as a function of slope length. Sixty-eight 2.02- by 0.76 m pans with a depth of 0.30 m were fabricated from 14 gauge sheet metal. Each pan was designed with a 5.0-cm-tall, 2.02-m-long channel iron foot that was welded to the bottom of the pan; this foot insured a slope on the bottom of the pan for seepage water to flow out of the pan through a standard 1.3-cm-diam standard pipe coupling which was welded into a corner of the pan. Four of these pans were placed end-to-end in the bottom of each plot, and were attached to each other at the top of each pan using a sheet metal clip. An 11.4-cm-wide space was purposely left between each sidewall of the plot and the pan to minimize sidewall effects in this experiment, which might allow water to migrate down the sidewalls of the plot and be incorrectly measured as seepage. Each pan and the rest of the bottom of each plot were then filled with medium gravel (8.0- to 25-mm diam). A sharp interface between this gravel layer and the above-lying soil layers was maintained with a high conductivity (0.024 m/s) geotextile (600X Brand, manufactured by MIRAFI, El Toro, CA) with a range in apparent opening size of 300 to 850 μm between the polypropylene strands of the fabric.

After every plot corner was resurveyed to make sure of the final slopes, 15 cm of backfill was emplaced around the outside of each of the four sets of plots and compacted with a walk-behind dual drum trench roller with a cleated drum width of 0.38 m capable of exerting 3.08 metric tons of applied force (Model MDR-T38S, Mikasa USA, Multiquip, Carson, CA) and a vibratory plate compactor with a 0.50 by 0.56 m plate capable of exerting 1.52 metric tons of applied force (Model MVC-90A, Mikasa USA, Multiquip, Carson, CA). The next step involved emplacing 15 cm of various soils materials inside each of the plots using a Clark Bobcat Model 975 skid-steer trencher (American Trencher Inc., Delhi, IA) and a 15.9-m long Model HSDU-52 conveyor with a hydraulic cleated belt (Clearfield Conveyors Corp., Clearfield, UT). These two consecutive steps were repeated until the last soil layer was added to the plots.

All of the soils materials used in each landfill cover design except the medium gravel were compacted using the equipment described above for each 15-cm lift of soil emplaced in each plot. Laboratory compaction tests were performed on the sands using Standard Test Methods for Maximum Index Density of Soils Using a Vibratory Table (American Society for Testing and Materials, 1979; Test Method D4253-83) and on the other soils using the Modified Proctor Method (American Society for Testing and Materials, 1979; Test Method D1557). After the first lift of each type of soil material was added to a plot and compacted, a set of 13 nuclear gauge readings of soil water content and bulk density was collected over the depth of the lift every 61 cm down the length of the plot. A semivariogram analysis of this data was performed to determine how many Proctor determinations would be necessary to characterize the compaction of each lift of soil added to the plots. For a specified range of soil water content, our typical construction specifications required that our soils materials be compacted to a minimum dry unit weight. These values were 85%, 95% and 90% of the maximum dry unit weight from standard Proctor compaction for the two topsoils, the sands, and the tuff-clay mixture, respectively.

Schedule 40 PVC pipe was used to connect the water collection systems for runoff, interflow and seepage to the automated water flow datalogging system. Each of the four pans of the seepage collection system was plumbed with 2.5-cm diam pipe, which were then emplaced in a 7.62-cm diam pipe outside the plot endplate for added protection against crushing as the pipes were buried with additional backfill. The interflow and runoff collection systems were plumbed with 10.2- and 15.2-cm diam pipe, respectively. All of this pipe was initially laid on the 4.6-m wide ramp at the bottom of the plots to insure the gravity flow of water with a minimal 2% slope.

The plots with the conventional landfill cover design contained 15 cm of a loam topsoil consisting of a 2:1:1 (V:V:V) mixture of an uncharacterized topsoil with a large organic matter content, sand, and aged sawdust (<9.5-mm diam). This topsoil was underlain by 76 cm of crushed tuff backfill described previously (Nyhan et al., 1984 and 1990a). The crushed tuff backfill beneath a depth of about 1 m in a profile like this would normally contain wastes in an actual waste disposal site at Los Alamos.

One set of plots contained the EPA-recommended final cover design (US EPA, 1989). These plots contained 61 cm of the loam topsoil described previously (this corresponds to the EPA "vegetated topsoil layer"), emplaced on top of 30 cm of a medium sand (8.0- to 25-mm diam) made in a sand classifying/blending tank system (Portec Kolberg Division, Yankton, SD). The latter layer corresponds to the EPA "drainage layer" and was overlain with the MIRAFI geotextile layer described above 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 $<1\times10^{-9}$ m/s. Since the plastic FML would last less than 35 years (Pertusa, 1980), this feature of the EPA design was omitted in our EPA design to evaluate the worst possible case. The results of previous research on mixtures of local crushed tuff and sodium-saturated bentonite (Abeele, 1986a and 1986b) indicated that a 1:10 (W:W) mixture of finely ground Aquagel (Baroid Drilling Fluids, Farmington, NM) and crushed tuff should easily provide us with the low conductivity required for this layer. This mixture was prepared in a cement truck by adding 10 45.4-kg bags of dry Aquagel to 4.54 metric tons of <6.4-mm diam crushed tuff that had been screened and dried using an asphalt batch plant. This dry mixture was mixed for 40 minutes, approximately 200 liters of water was added (for dust control and to optimize compaction), followed by an additional 30 minutes of mixing. A 15-cm-deep lift of mixture was finally added to each plot. After compaction this lift was covered to prevent the mixture from drying, and this lift was sprayed with water before adding the next 15-cm lift of mixture to promote the uniformity of the entire 61-cm layer.

Two designs contained capillary barriers varying only in the type of soil used in the uppermost layer. One of the designs contained 61 cm of the same loam mixture used in the previous designs, whereas the other design contained 61 cm of a local clay loam backfill classified (Nyhan et al., 1978) as a Lithic Aridic Haplustalf (clayey, mixed, mesic family) and used in two previous studies (Nyhan et al., 1984 and 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 both the hydraulic conductivity and water-holding properties of the capillary barrier (Wohnlich, 1991).

Measurement of Seepage, Interflow, Runoff, and Precipitation

Runoff, interflow, and seepage were collected in 100 100-liter tanks housed in two instrument trailers that were heated in the winter to allow year-round hydrologic measurements. Water levels in each tank was measured with a microprocessor-controlled ultrasonic liquid level sensor (model DCU-7, Lundahl Instruments, Logan, UT) mounted in the top end of a 1.5-m-long stilling well (5.1-cm diam PVC pipe) attached to the inside of the tank. The sensor output was connected to one of five multiplexer boards (model CIO-MUX32, CyberResearch, New Haven, CT) located in five junction boxes. This multiplexer board was organized as a pair of 16-to-1 multiplexers. The output of each multiplexer was connected by way of shielded flat cable to a digitizer card (model CIO-AD08, CyberResearch, New Haven, CT) in a computer with a widely used personal computer motherboard (model 386N33, Hauppauge Computer Works, Inc., Commack, NY) and a 200 megabyte hard drive (model ST1239A, Seagate Technology, Scotts Valley, CA). Two digitizer cards served the ten multiplexers in this system, in which the digitizer cards accepted 4 and 6 analog inputs, one from each multiplexer.

The computer was used to capture and store the water level data from each tank and to activate the draining of the tank when it was nearly full by actuating a 5.1-cm-diam electrically-actuated ball valve (115 volt alternating current Electromni model, Asahi/America Inc., Medford, MA) mounted in the bottom of the tank. The digital output card in the computer (model PCL 722, CyberResearch, New Haven, CT) was organized as six channels of 24 bits each, with five channels being connected to five relay driver boards (model DB-3737, PERX, Inc., San Mateo, CA) located in the junction boxes. Thus, the computer read the water levels in the 100 tanks and made the decision to actuate the valves and repeated this loop at a rep rate of approximately 1.5 hertz. The water levels in the tanks were routinely recorded hourly, but much more frequently when the tank was emptying and when it was nearly full. This data was routinely copied into a single large file every 24 hours.

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

Measurement of Soil Water Content

Since the goals of this experiment were to provide field data to calibrate several hydrologic models and to collect water balance data, it was necessary to measure soil water content at multiple points in space and time. Thus, soil water content was routinely monitored once every six hours at each of 212

locations throughout the 16 plots using Time Domain Reflectrometry (TDR) techniques 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 are buried parallel and 5 cm apart in the soil. One set of waveguides was emplaced vertically in every soil layer above the bottom end of each of the metal pans in the seepage collection system; these waveguides allowed us to determine soil water inventory in four locations in each field plot. A second set of waveguides was emplaced horizontally in several soil layers to provide us with a more detailed picture of soil water dynamics close to the interfaces of a few soil layers.

Each set of waveguides was connected to 4.6 m of shielded twin-lead antenna cable that was connected to a molded balun connected to a 26-m length of RG-8/U coaxial cable. An instrument trailer housed a 256-to-1 coaxial switch that connected one set of waveguides at a time to a TDR cable tester (model 1502B, Tektronix Inc., Beaverton, OR) through a system of 37 8-to-1 coaxial switches (model 610-007A, Autek Systems Corp., Santa Clara, CA). The computerized TDR system captured and stored the information from each pair of waveguides as a 220-point waveform (which represented an average of 16 waveform determinations). The personal computer (model 386-20, Compaq Computer Co., Austin, TX) stored the waveform data on a hard disk, which was then used to determine the water content of the soil through a calibration curve relating water content to measured dielectric constant (Topp et al., 1980).

RESULTS AND DISCUSSION

Estimates of Precipitation

In New Mexico, average annual precipitation ranges from less than 25 cm over much of the southern desert and the Rio Grande valley to more than 50 cm at higher elevations in the state. 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 rainiest months, with 48% of the annual precipitation falling at this time in Los Alamos as intense thundershowers. These months are also characterized by warm temperatures and high evapotranspiration, with the net result that precipitation occurring in the winter and spring result in seepage production within landfill covers (Nyhan et al., 1990a,1990b).

Precipitation data collected at the Protective Barrier Landfill Cover Demonstration (Fig. 1) show that 37.4 cm of precipitation occurred during 1992, with a total of 53.0 cm occurring between November 1991 through January 1993. The precipitation received during the winter of 1991-1992 amounted to 4.65 cm, making this a dry winter compared with the 1911-1986 average of 6.71 cm for winter (Nyhan et al., 1989). However, this was followed by a wet spring in which 12.4 cm of precipitation occurred compared with the long-term average of 9.37 cm. The precipitation during the dry summer of 1992 amounted to 13.3 cm, only 59% of the long-term summer average precipitation.

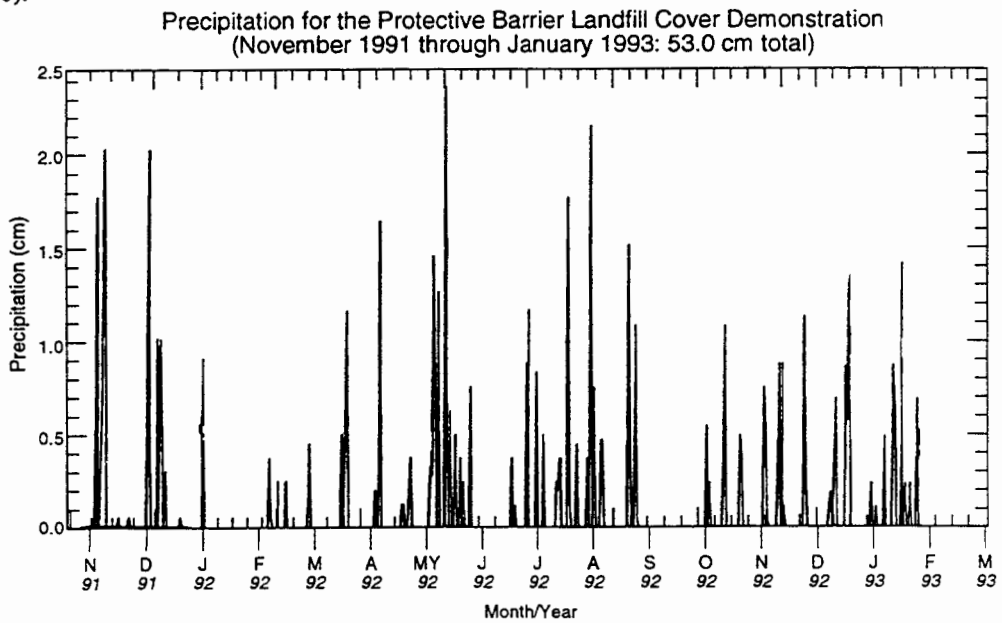

Fig. 1. Precipitation Data Collected at the Protective Barrier Landfill Cover Demonstration In Los Alamos, NM From November 1991 Through January 1993.

Seepage, Interflow, and Runoff Data

Very little field data are available on the flow of water through landfill cover designs, making the data gathered in this field study unique. Each of the 100 different estimates of seepage, interflow, and runoff in our experiment resulted in a hydrograph chart with flow data for approximately 14,000 sampling times (a computer file of about 0.6 megabytes) for the 15 months of this study. This hourly data was reduced to daily flow estimates (Fig. 2), which represent interflow estimates for two of the capillary barrier designs with dominant downhill slopes of 5%. The capillary barrier design with the loam topsoil exhibited maximum daily interflow production rates approaching 0.24 cm, with 3.45 cm of total interflow occurring from February through April of 1992. The design with the clay loam topsoil exhibited maximum daily interflow rates of only 0.034 cm with only 0.71 cm of interflow occurring during this time period. Most of this large difference in interflow can probably be attributed to the fact that the clay loam has a low conductivity (Nyhan et al., 1984), compared to the loam topsoil, which limited the flow of soil water into the fine sand layer in this design.

The estimates of interflow and seepage on all 16 plots for the 15 months of this study are summarized in Table 1. This data shows that all of the capillary and hydraulic barriers are preventing seepage at all slopes and slope lengths tested in the study. Total interflow for the 15 months of the study ranged from 3.4 to 6.1 cm on all of the EPA and capillary barrier designs containing the loam topsoil. In contrast, the conventional design, which did not contain an engineered barrier, produced seepage in almost every case tested and most of this seepage occurred from February through April of 1992, during and following a relatively dry winter (Fig. 1).

For the Conventional design evaluated on the 5% slope, this 15-month total seepage occurred in the seepage collection system located 3.64-5.66 m downslope (0.21 cm), 5.66-7.68 m downslope (0.37 cm), and 7.68-9.70 m downslope (2.86 cm). This design only produced seepage 5.66 to 9.70 m downslope with a 15% slope, and 7.68 to 9.70 m downslope with a 25% slope.

Runoff occurred on these unvegetated plots from December 1991 through February 1992, as a result of snowmelt and during May and August 1992, as a result of thunderstorm activity. The total runoff from all 16 plots is summarized in Table 2 for the 15 months of the study. The largest daily runoff (0.54 cm) occurred on the EPA design with the 25% slope after a 2.16-cm precipitation event on August 24, 1992.

No consistent relationship exists between slope and runoff for either the clay loam topsoil used on the Clay Loam Capillary Barrier design or the loam topsoil used on all the other designs. Less than 15% of this total runoff (Table 2) usually came from snowmelt events during the first winter of the study, but this is not surprising since almost 30% of the total precipitation for the entire 15 months was received in May and August, 1991 (Fig. 1).

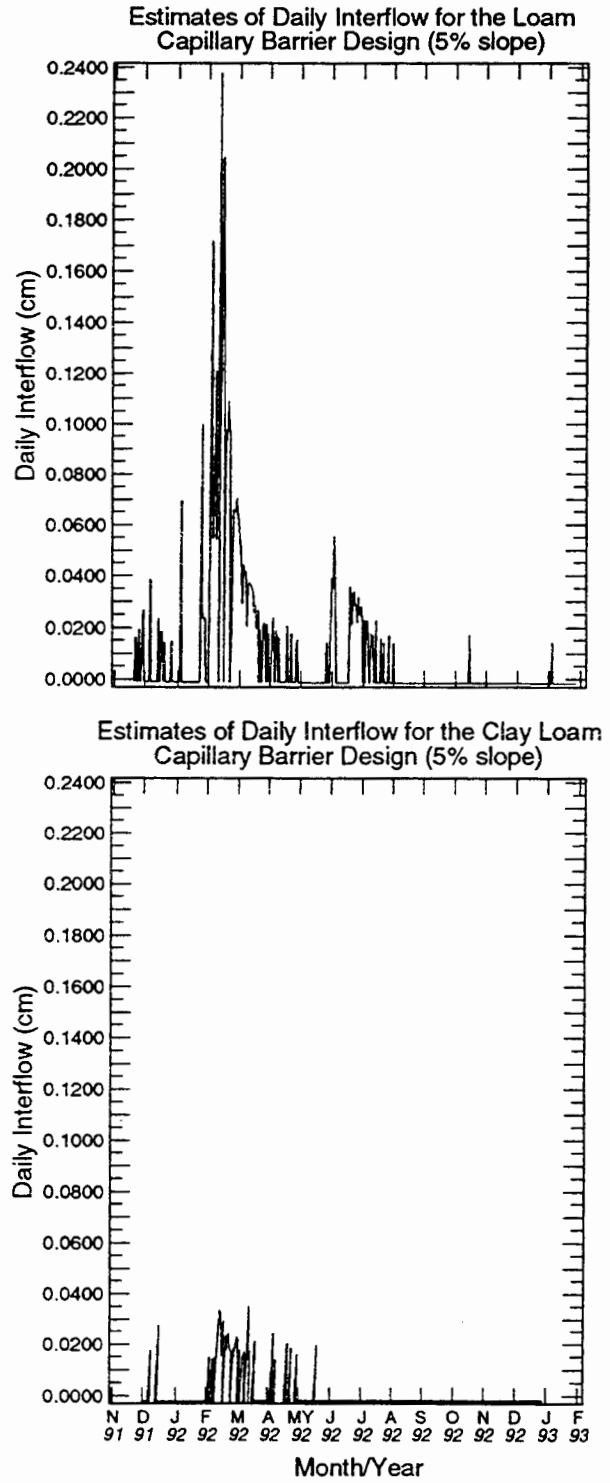

Fig. 2. Estimates of Daily Inteflow for the Loam and Clay Loam Capillary Barrier Designs (5% Slope) At the Protective Barrier Landfill Cover Demonstration in Los Alamos, NM.

TABLE 1
Interflow and Seepage Estimates for the Protective Barrier Landfill Cover Demonstration at Los Alamos, NM (November 1991 through January 1993)

Landfill Cover Design	Interflow (Seepage) (cm) for Dominant Downhill Slopes of 5%	10%	15%	25%
Conventional	3.2 (3.4)	8.8 (0)	5.8 (4.0)	4.6 (0.41)
EPA	5.4 (0)	6.1 (0)	4.3 (0)	4.5 (0)
Loam Capillary Barrier	4.8 (0)	5.1 (0)	3.4 (0)	3.9 (0)
Clay Loam Capillary Barrier	0.78 (0)	3.2 (0)	0.12 (0)	0.36 (0)

TABLE 2
Runoff Estimates for the Protective Barrier Landfill Cover Demonstration at Los Alamos, NM. (November 1991 through January 1993)

Landfill Cover Design	Runoff (cm) for Dominant Downhill Slopes of 5%	10%	15%	25%
Conventional	1.3	0.48	0.87	0.10
EPA	0.27	0.50	0.72	0.74
Loam Capillary Barrier	0.31	2.6	0.79	1.6
Clay Loam Capillary Barrier	0.88	2.1	1.7	3.3

Soil Water Data

Each of the 212 locations throughout the 16 plots was monitored for soil water content once every six hours from November 1991 through December 1992, resulting in several 60-megabyte monthly computer files of TDR waveforms. This waveform data was then reduced to soil water content data.

Soil water data is presented for several layers of the Conventional design evaluated at a position 9.7 m downslope in the plots with dominant downhill slopes of 5% (Fig. 3) and 15% (Fig. 4). The water content of the loam topsoil is presented in the top half of each of these two figures, representing the readings of a horizontally-emplaced pair of waveguides within the 15-cm deep topsoil (at an actual depth of 5 to 10 cm).

The topsoil water content data from these two plots can be used to demonstrate the influence of aspect on snowmelt dynamics during the short daylight periods of the winter when the sun is at a low angle on the horizon. For the plot with the 15% slope (Fig. 4), the volumetric water content rises from 14.2% on December 10, 1991 (at 6:20 am), to 27.9% on December 11 (at 2:44 PM), as a result of a snow event that accounted for 2.4 cm of precipitation added to the surface of the site. The volumetric water content steadily decreased to 7.1% on December 15 (at 5:08 am). All of this happened as the snow melted on the surface of this high-aspect plot, unlike what happened on the plot with the 5% slope (Fig. 3). This plot retained snow cover and only demonstrated a small increase in volumetric water content to 19.0% on December 11, 1991 (at 2:44 PM).

The bottom portions of Figures 3 and 4 contain the soil water content data for the crushed tuff layer of the Conventional design at a depth of 15 to 91 cm. The vertically-emplaced waveguides were used to measure the average tuff water content from 20 to 80 cm and the horizontally-emplaced waveguides measure the water content at the bottom of the crushed tuff layer (80 to 86 cm depth). This latter data, collected at the bottom and toward the end of the plot (9.7 m downslope), gives a good representation of the influence of slope and seepage on water dynamics in these two plots. Seepage occurred in January, April, May, and June of 1992 on the plot with the 15% slope, and finally stopped, resulting in an enormous decrease in volumetric water content (Fig. 4). The Conventional design on the 5% slope demonstrated a gradual increase in tuff water content resulting in seepage starting in February 1991 (Fig. 3) instead of January 1991 (Fig. 4). The average tuff water content of the 20-80-cm depth was also significantly larger in the plot with the 5% slope than in the plot with the larger slope (Fig. 4).

Soil water content data is presented in Fig. 5 for the EPA design with the 25% dominant downhill slope. The TDR data presented in the top portion of the curve represents 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 topsoil in the Conventional design with the 15% slope (Fig. 4) can also be observed for this plot in December 1991. 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 this medium sand layer demonstrated increased soil water content as interflow occurred in December 1991, as well as in the succeeding months of January, and late May through June. During the time that the interflow was occurring, the water content of the top portion (96-102 cm depth) of the hydraulic layer (the clay-tuff mixture) gradually increased from 10% to 20%, followed by a substantial increase to 36% by the end of the summer of 1992, as water from thunderstorms infiltrated the highly conductive loam topsoil (Fig. 5). The water content of both the medium sand layer and the top of the underlying hydraulic layer then decreased with reduced precipitation events in the fall of 1992.

The TDR data presented for the Loam Capillary Barrier designs at slopes of 5% (Fig. 6) and 25% (Fig. 7) is meant to demonstrate the dynamics of three-dimensional water movement through the loam topsoil and underlying fine sand layers. Since no seepage occurred in either of these two designs the soil water content data presented here can be used to understand why the barrier was a success hydrologically and will be used to field validate several hydrologic models. The interflow data presented in Fig. 2 corresponds with the TDR data presented in Fig. 6 for the Loam Capillary Barrier

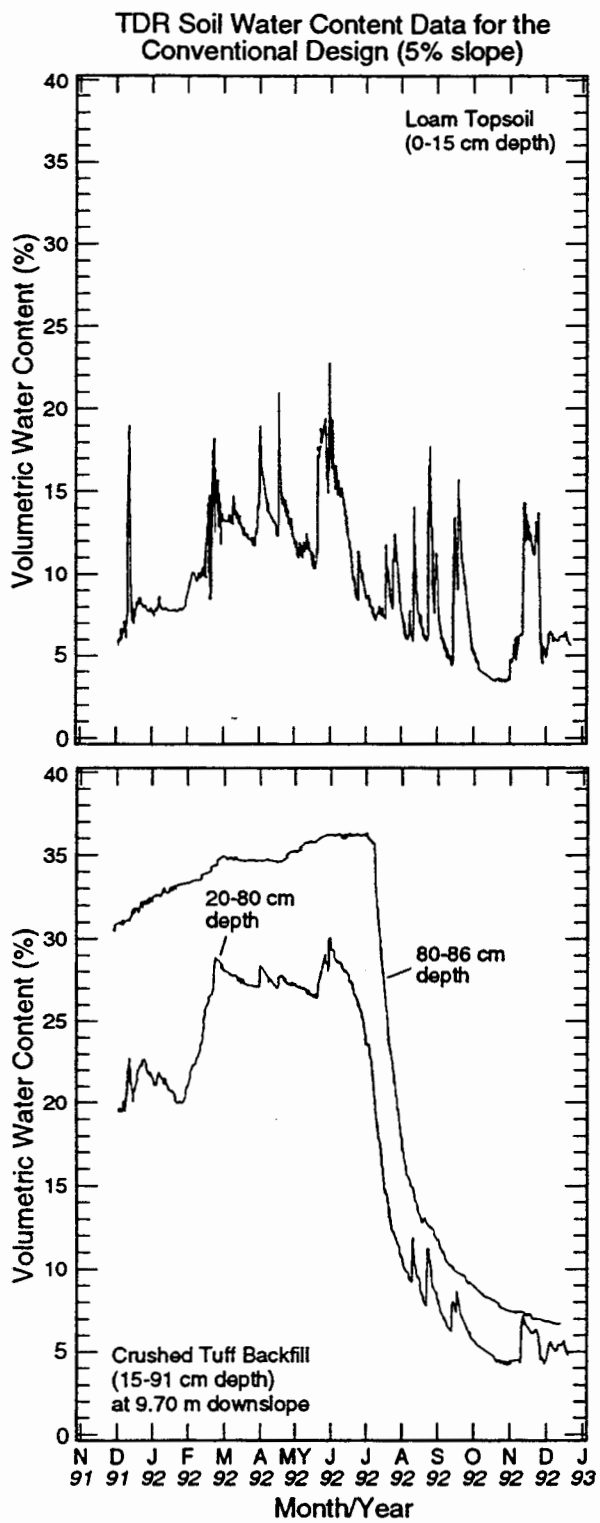

Fig. 3. TDR Soil Water Content Data Collected For the Conventional Landfill Cover Design With the 5% Dominant Downhill Slope At the Protective Barrier Landfill Cover Demonstration in Los Alamos, NM.

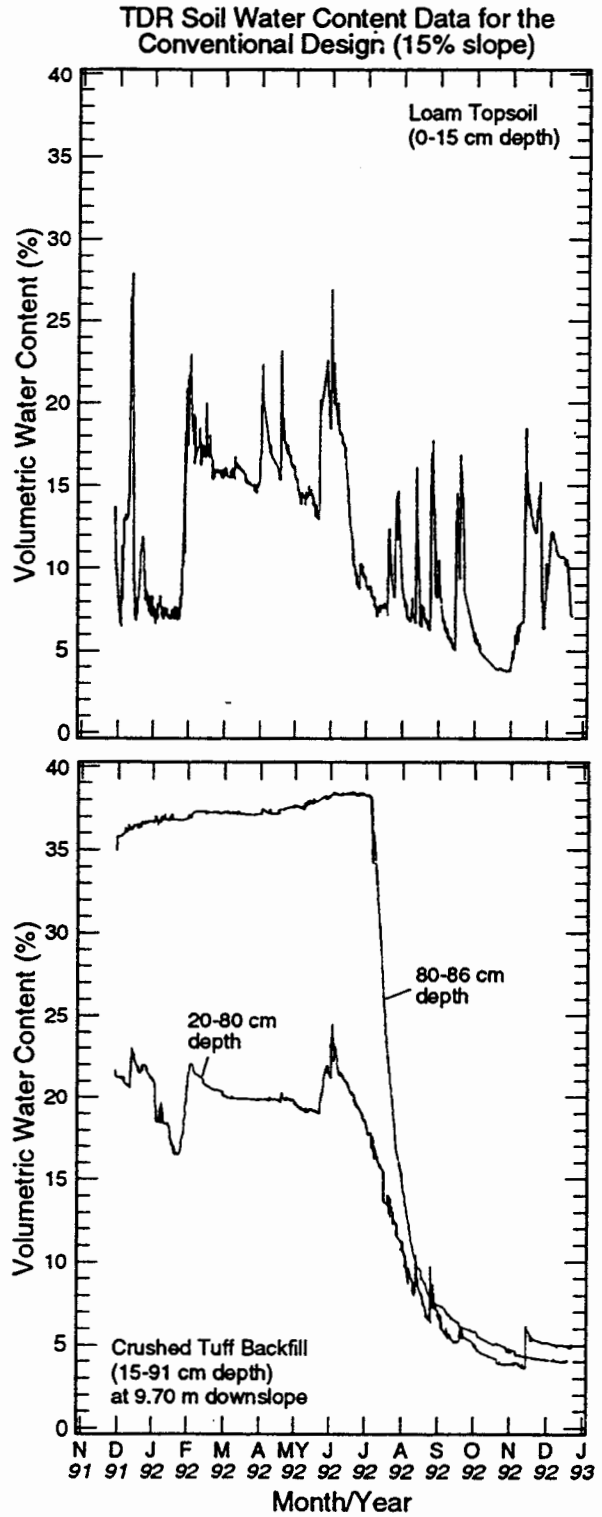

Fig. 4. TDR Soil Water Content Data Collected For the Conventional Landfill Cover Design With the 15% Dominant Downhill Slope At the Protective Barrier Landfill Cover Demonstration in Los Alamos, NM.

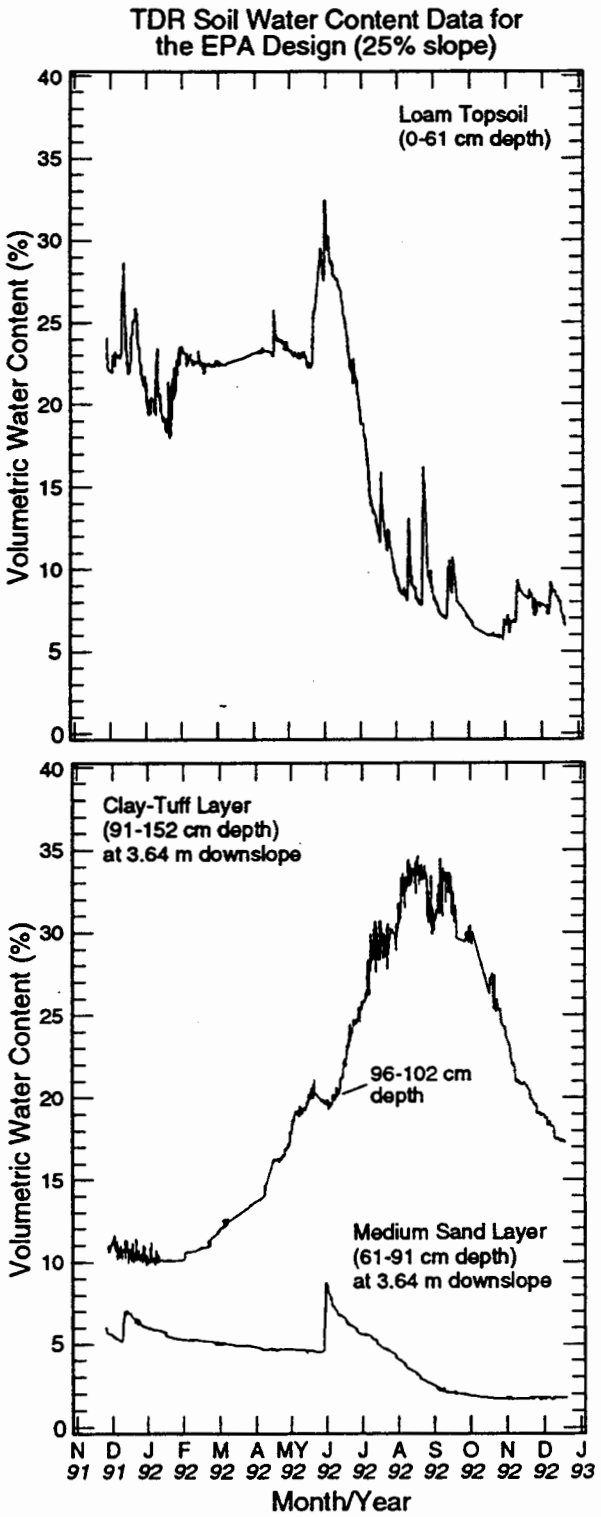

Fig. 5. TDR Soil Water Content Data Collected For the EPA Landfill Cover Design With the 25% Dominant Downhill Slope At the Protective Barrier Landfill Cover Demonstration in Los Alamos, NM.

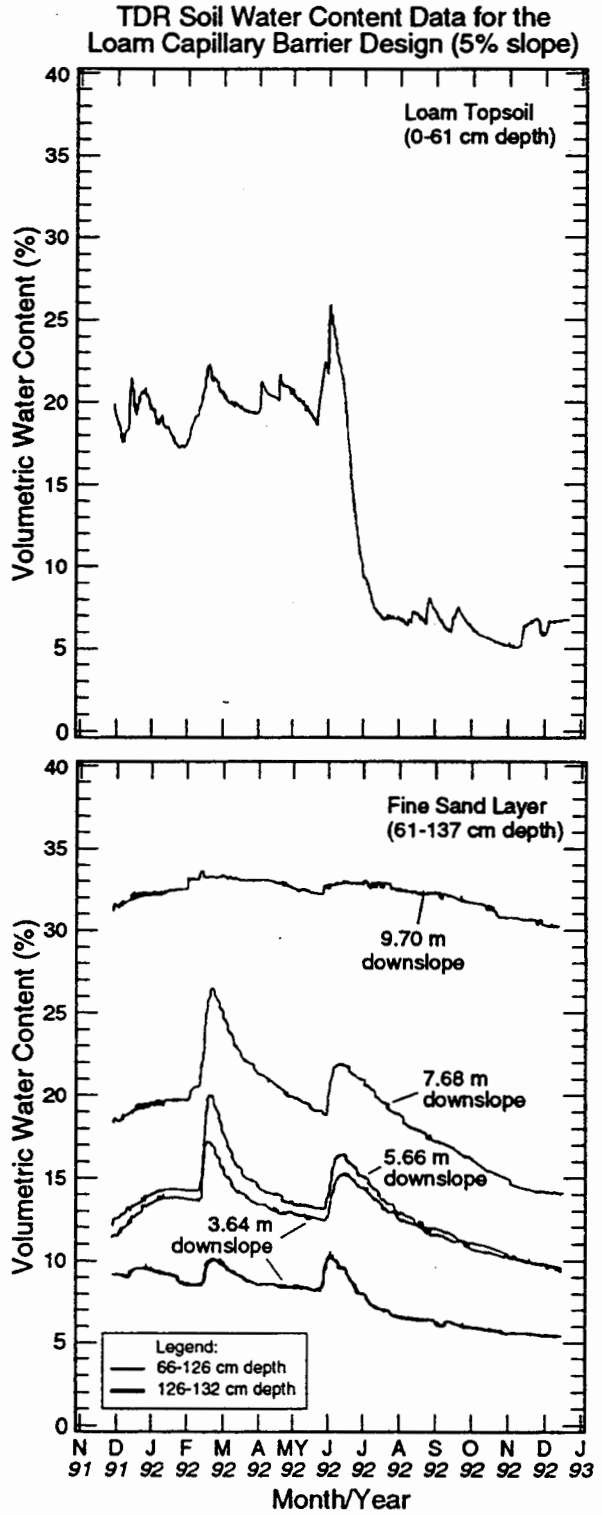

Fig. 6. TDR Soil Water Content Data Collected For the Loam Capillary Barrier Landfill Cover Design With the 5% Dominant Downhill Slope At the Protective Barrier Landfill Cover Demonstration in Los Alamos, NM.

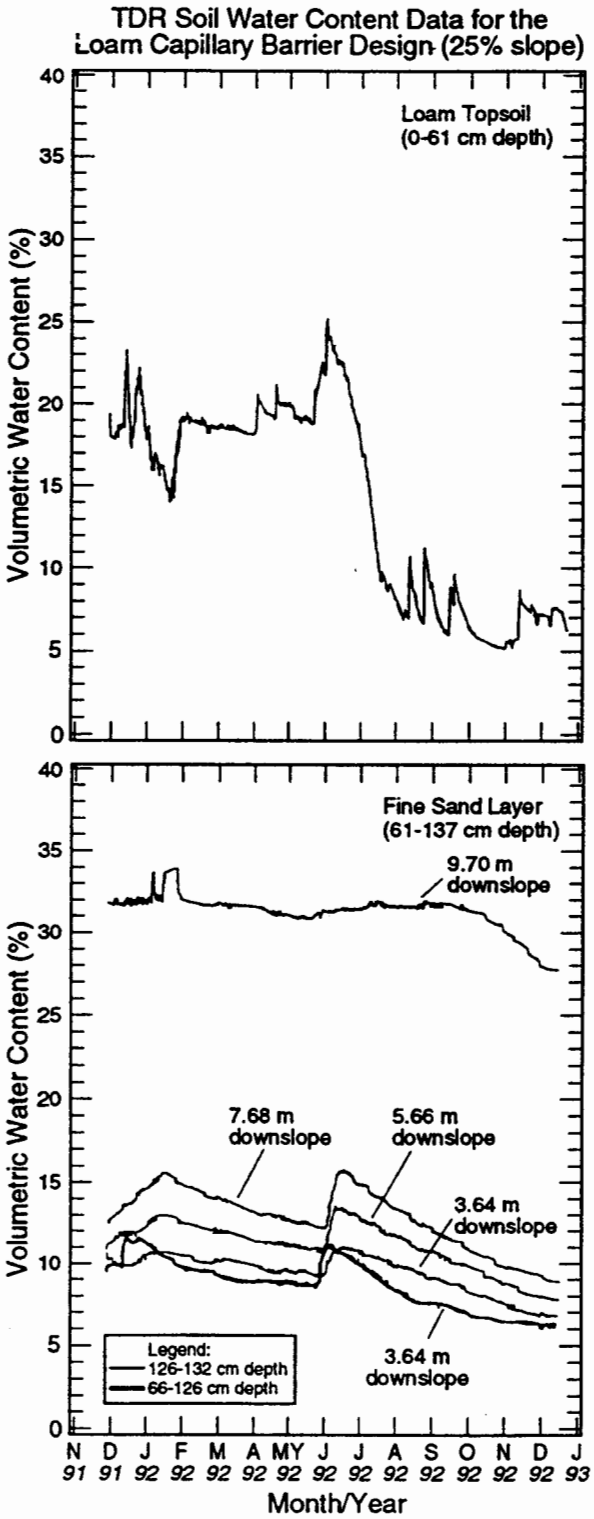

Fig. 7. TDR Soil Water Content Data Collected For the Loam Capillary Barrier Landfill Cover Design With the 25% Dominant Downhill Slope At the Protective Barrier Landfill Cover Demonstration in Los Alamos, NM.

design with the 5% slope. Approximately 3.5 cm of water moved out of the topsoil in this plot from January through March 1992 resulting in a dramatic increase in the water content of the underlying fine sand layer. TDR data (bottom portion of Fig. 6) was collected to evaluate the water status of the entire 66-126 cm layer of fine sand, as well as of the bottom of the fine sand layer (126-132 cm depth) for four downslope positions within the plot. This data shows that the water content at the bottom of the fine sand layer is considerably larger than the average water content of the entire layer. The TDR data also demonstrates that the water content at the bottom of the fine sand layer increased during interflow as a function of slope length, resulting in volumetric water content values observed at the maximum slope length (9.7 m downslope) in excess of 33% (Fig. 6). Thus, even at this location in the capillary barrier, the rate of infiltration of water into the fine sand layer was less than the capillary barrier's ability to conduct water laterally: matrix potential forces were still able to hold the water within the fine sand at the interface between the fine sand and the medium gravel.

The TDR data presented for the Loam Capillary Barrier with the 25% slope (Fig. 7) shows several of the same relationships discussed above for the same design evaluated on a 5% slope. Due to a much larger slope, probably resulting in enhanced lateral flow rates, smaller differences were observed in the water content of the fine sand as a function of slope length than for the data from the 5% plot (Fig. 6). However, the same conclusions can be made for both plots for the data collected at the bottom of the fine sand layer at the maximum slope length tested (9.7 m downslope).

The TDR data for the Clay Loam Capillary Barrier design with the dominant downhill slope of 25% is presented in Fig. 8 to demonstrate the effect of a low-conductivity topsoil on capillary barrier dynamics. The daily interflow data presented in Fig. 2 for this design evaluated on a 5% slope is typical for this design compared with similar data from the plots on the other three slopes. The soil water content data for the bottom of the fine sand layer (25% slope) do not demonstrate multiple large pulses of water coming through the clay loam topsoil (Fig. 8), in contrast to what happened on the capillary and hydraulic barrier plots with the highly conductive loam topsoil (Figs. 5-7). Instead, we observed a pattern indicating a very slow drainage rate of water from the clay loam layer into the underlying fine sand layer, whose soil water content dramatically decreased from September through December 1992 (notice the TDR data at the 9.70 m downslope position), following the decrease in soil water content of the soil layer about 1 month previous to this time period (top portion of Fig. 8).

USEFULNESS OF STUDY AND FUTURE RESEARCH

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. Ultimately, the site operator wants a design for a specific slope and slope length that minimizes long-term runoff and seepage and maximizes interflow and

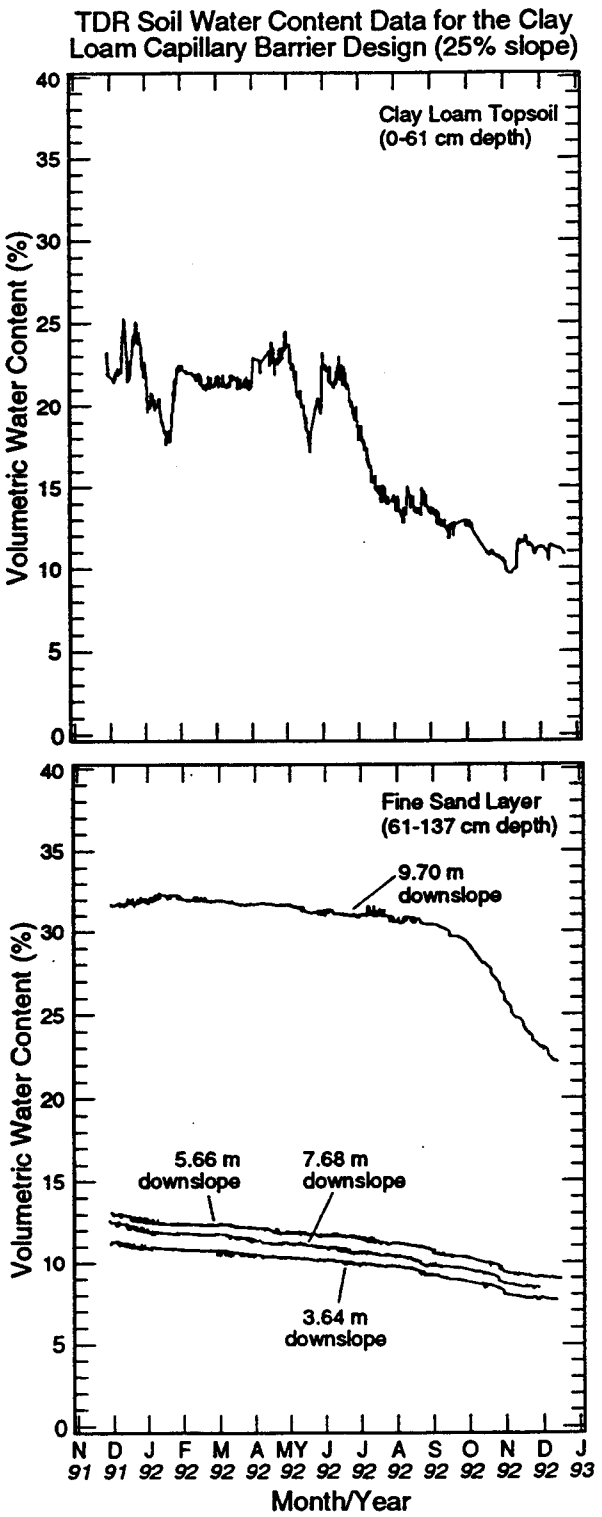

Fig. 8. TDR Soil Water Content Data Collected For the Clay Loam Capillary Barrier Landfill Cover Design With the 25% Dominant Downhill Slope At the Protective Barrier Landfill Cover Demonstration in Los Alamos, NM.

evapotranspiration. These water balance parameters are interdependent and need to be evaluated in the field using techniques and field data similar to those in this study.

Only 15 months of data is presented in this manuscript for this study, yet we are already struggling to keep up with data analysis. Many of the commonly used computer software programs and hardware do not have the capacities to handle such large data sets, so we are in the process of connecting our measurement systems for water flow and TDR to a local area net of computers to solve this problem. This will allow us to perform routine system diagnostic checks on our hydrologic sensors and to calculate water balance estimates on this entire data set. Once this is accomplished, we can evaluate important issues such as the time scale necessary to adequately describe a landfill cover design for waste management purposes. Coupled with this effort will be a major activity to develop field-calibrated hydrologic models that then can be used to evaluate future performance of the designs, such as the effect of a 100-year precipitation event on the design. The cost effectiveness and practicality of various designs can then be evaluated with the help of burial site operators and regulators, who will have major inputs into the selection of a final closure design for low-level radioactive and hazardous waste sites.

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