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A Seven-Year Water Balance Study of an Evapotranspiration Landfill Cover Varying in Slope for Semiarid Regions

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ABSTRACT

The goal of radioactive and hazardous waste disposal in shallow landfills is to reduce risk to human health and to the environment by isolating contaminants until they no longer pose a hazard. To achieve this for a semiarid region, we studied a landfill cover containing a gravel layer, an evapotranspiration (ET) cover, in the field for 7 yr. We measured total water balance at 6-h intervals for this landfill cover design in four 1.0- by 10.0-m plots with downhill slopes of 5, 10, 15, and 25%. During the 7 yr of the field study, runoff accounted for 1.4 to 3.8% of the precipitation losses on these unvegetated landfill cover designs, whereas similar values for evaporation ranged from 88 to 95%. Evaporation usually increased with increases in slope in our field plots; for example, the ET Cover at slopes of 5 and 15% displayed 274 and 296 cm of evaporation, respectively. Interflow and seepage usually decreased with increasing slope; for example, as slope increased from 10 to 25%, interflow decreased from 18.4 to 8.8 cm. Seepage consisted of up to 1.7% of the precipitation on the ET cover, showing a maximum value of 5.3 cm on the ET cover with the slope of 5%.

Institutional control and maintenance of low-level radioactive-waste repositories are assumed to end 100 yr after the closure of a waste site. After this time the repository's engineered barriers and geohydrologic conditions need to act passively to isolate the radionuclides for an additional 300 to 500 yr (USNRC, 1982; Garrick, 2002). Despite this intent, there are neither experimental nor experiential real-time bases for long-term projections on the effectiveness of engineered barriers in conventional landfill covers for long-term containment of either radionuclides (Bedinger, 1989) or other waste forms. The operators of municipal solid waste and hazardous waste landfills may use ET covers (Hauser et al., 2001; McGuire et al., 2001; Madalinski et al., 2003) if they display equivalent performance to conventional Resource Conservation and Recovery Act (RCRA) final covers (Madalinski et al., 2003). Unlike expensive conventional cover designs that use materials with low hydraulic permeability (barrier layers) to minimize the downward migration of water from the cover to the waste (seepage) ET covers use water balance to minimize seepage. These covers rely on the properties of soil to store water and evaporation and plant transpiration to pump water out of the landfill cover.

Operators of remediation and landfill sites have proposed, tested, or installed ET covers in increasing numbers with time, including at several Superfund sites (Madalinski et al., 2003). This is happening despite both limited field performance data and design guidance and "the negative implications of one 'flawed' field study" (Koerner, 2002) of soil-only landfill covers performed in Albuquerque, NM. The online database of the USEPA contains information about specific projects using ET covers at demonstration and full-scale applications (USEPA, 2003). The two types of ET covers are monolithic covers and capillary barriers. Monolithic covers have a single, fine-grained vegetated soil layer, which holds water for evapotranspiration. Capillary barriers have a similar top layer underlain by a coarser-textured layer (sand or gravel), such as used in the current study. In October 2003 (Madalinski et al., 2003), waste site operators at 64 sites proposed, tested, or installed ET covers throughout the United States on 56 projects with monolithic covers and 20 projects with capillary barrier covers. In June 2004, operators at 74 sites proposed, tested, or installed ET covers on 58 projects with monolithic covers and 21 projects with capillary barrier covers.

The successful performance of a landfill is a function of interactive water balance processes (Paige et al., 1996), which traditional remedial engineering solutions have ignored. This, in turn, led to many landfill failures (Jacobs et al., 1980; Hakonson et al., 1982). Even soil microbes can influence the long-term performance of capillary barriers in landfills (Lehman et al., 2004). Several recent modeling studies have taken on hydrologic performance evaluations of landfill covers (Katsumi et al., 2001; Chai and Miura, 2002; Yalcin and Demirer, 2002; Ho et al., 2004). Several investigators studied seepage production (Elshorbagy and Mohamed, 2000; Dho et al., 2002; Ham, 2002; Shan and Lai, 2002). However, evaporation studies are more numerous (Simunek et al., 1998; Nassar and Horton, 1999; Qiu et al., 1999; Wythers et al., 1999; Bachmann et al., 2001; Shangning and Unger, 2001; Suleiman and Ritchie, 2003; Yanful and Mousavi, 2003; Yanful et al., 2003). One stress test evaluated the hydrologic behavior of two cover designs with no vegetation following extreme wetting before and for 2 yr after irrigation to breakthrough (Porro, 2001). However, few total water balance data for landfill cover designs exist (Nyhan et al., 1990a, 1997, 1998; Benson et al., 1993, 1994; Hakonson et al., 1993; Gee et al., 1994; O'Donnell et al., 1994) to enable the site operator to define and engineer suitable barriers that prevent waste material migration out of the landfill.

We used the results of 10 yr of individual shallow land burial studies at Los Alamos and Utah (Hakonson et al., 1982; Nyhan et al., 1984, 1990a, 1990b; Pertusa,

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Abbreviations: ET, evapotranspiration; RCRA, Resource Conservation and Recovery Act.

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1980) to develop an effective landfill cover technology. These studies were used to design and emplace the Protective Barrier Landfill Cover Demonstration at the Los Alamos National Laboratory in Los Alamos, NM. The major purpose of this field demonstration was to study water balance on the ET cover in a semiarid temperate mountain climate as a function of slope (Nyhan et al., 1997). The data that were published in 1997 contained water balance data for landfill cover designs from 1 Dec. 1991 through 31 July 1995. While the 1997 paper included only three full hydrologic years, the power of the statistical tests really increased in the current paper as a result of the many more days of data from the 7 yr covered here.

MATERIALS AND METHODS

Plot Construction, Design, and Rationale

We built the Protective Barrier Landfill Cover Demonstration to study water balance on the ET cover design at dominant downhill slopes of 5, 10, 15, and 25% on field plots without vegetation. We installed these plots in 1991 in our 8-ha field test facility (Nyhan et al., 1997; Fig. 1) and instrumented them to account for what happened to precipitation falling on the plots. Accounting for precipitation on the plots involved measures of runoff and interflow, as well as seepage and soil water storage as a function of slope length.

The 1.0- by 10.0-m field plots in the Protective Barrier Landfill Cover Demonstration were built on an east-facing slope, using design, surveying, field and laboratory compaction tests, and construction techniques described previously (Nyhan et al., 1997). We placed metal pans (2.02 by 0.76 m with a depth of 0.30 m) in the bottom of each of the plots as part of the seepage collection system. Each pan and the rest of the bottom of each plot were filled with medium gravel (8.0–25 mm diam). A high-conductivity (0.024 m s^{-1}) geotextile (600X Brand, MIRAFI, El Toro, CA) preserved a sharp boundary between this gravel layer and the soil layers above (Fig. 2). This geotextile had a range in apparent opening size of 300 to 850 μm between the polypropylene strands of the fabric.

Hydrologic properties were characterized using van Genuchten's RETC model (van Genuchten et al., 1991). Specific analyses were porosity and hanging column and thermocouple psychrometric moisture retention characteristics (Klute, 1986). Constant head determinations of saturated hydraulic conductivity and pressure plate extractor determinations of moisture retention characteristics were also performed (Nyhan et al., 1997).

The technology for controlling soil water erosion on the field plots without plant cover consisted of applying a 70% surface cover of medium gravel (8.0–25 mm diam). The plots with the ET covers contained 15 cm of a loam topsoil described previously (Nyhan et al., 1997) underlain by 76 cm of crushed tuff backfill described previously (Nyhan et al., 1984, 1990a).

We performed a statistical analysis (two-factor ANOVA without replication, 95% confidence level) on all the daily water balance parameters from each field plot to discover if slope significantly influenced each water balance parameter. These comparisons also involved field data from each year and for all the years of the field experiment.

Measurement of Water Balance Parameters

We collected runoff, interflow, and seepage in 100-L tanks housed in instrument trailers. This involved hourly measurements of the water level in each tank, using microprocessor-controlled ultrasonic liquid level sensors and a multiplexed, automated system, as described previously (Nyhan et al., 1993, 1997).

An automated and multiplexed measurement system (Nyhan et al., 1993, 1997) routinely collected soil water content data every 6 h at each of 48 locations throughout the four plots using TDR techniques. We performed site-specific TDR calibrations as suggested recently (Masbruch and Ferre, 2003). Waveguides buried horizontally at the 5- to 10-cm depth at slope lengths of 2.63, 4.65, 6.62, and 8.69 m allowed us to determine topsoil water inventory. We positioned more waveguides vertically in the crushed tuff at depths of 20 to 80 and 80 to 86 cm at slope lengths of 3.64, 5.66, 7.68, and 9.70 m. These locations matched positions that were 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 plot close to the boundaries of the gravel within the seepage pans. We calculated soil water inventories from the average daily volumetric water content for all 12 waveguide positions in each field plot (Nyhan et al., 1993, 1997).

After calculating the daily change in soil water inventory, we totaled daily amounts of precipitation, seepage, interflow, and runoff. The last water balance component, evaporation, was then calculated by difference.

RESULTS AND DISCUSSION

Measurements of Precipitation and Evaporation Estimates

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 normally the rainiest months, with 48% of the annual precipitation falling as intense thundershowers. There were 581 precipitation events during 1992 through 1998, with the largest number of events occurring in the summer months; about the same number of events occurred in all the other 9 mo (Fig. 3–6). Warm temperatures and high evaporation also characterize the summer months, unlike during the winter and spring when snowmelt results in seepage production within landfill covers (Nyhan et al., 1990a, 1990b).

An understanding of the spatial and temporal variation of precipitation around Los Alamos (Bowen, 1990) led us to an understanding of the overall significance of each year's water balance data. Going from the Jemez Mountains on the western border of Los Alamos County to the Rio Grande to the east, Bowen showed that mean annual precipitation decreases from 45.3 cm at Los Alamos to only 33.7 cm at White Rock. These are the only two stations close to the Protective Barrier Landfill Cover Demonstration with a much longer database than our 7-yr record of daily precipitation. We discovered that 1997 displayed average precipitation (2-yr event: 46.2 cm) using the Bowen database and the methods described previously (Nyhan et al., 1997). Five of the 7 yr were drier years than this: 1.3-yr, 1.4-yr, 1.6-yr, 1.7-yr, and 1.8-yr events occurred in 1998 (36.2 cm), 1992 (37.9 cm), 1996 (40.3 cm), 1995 (42.1 cm), and 1993 (43.7 cm), respectively. Only one year ended being a 6.9-yr event: the plots received 63.9 cm of precipitation

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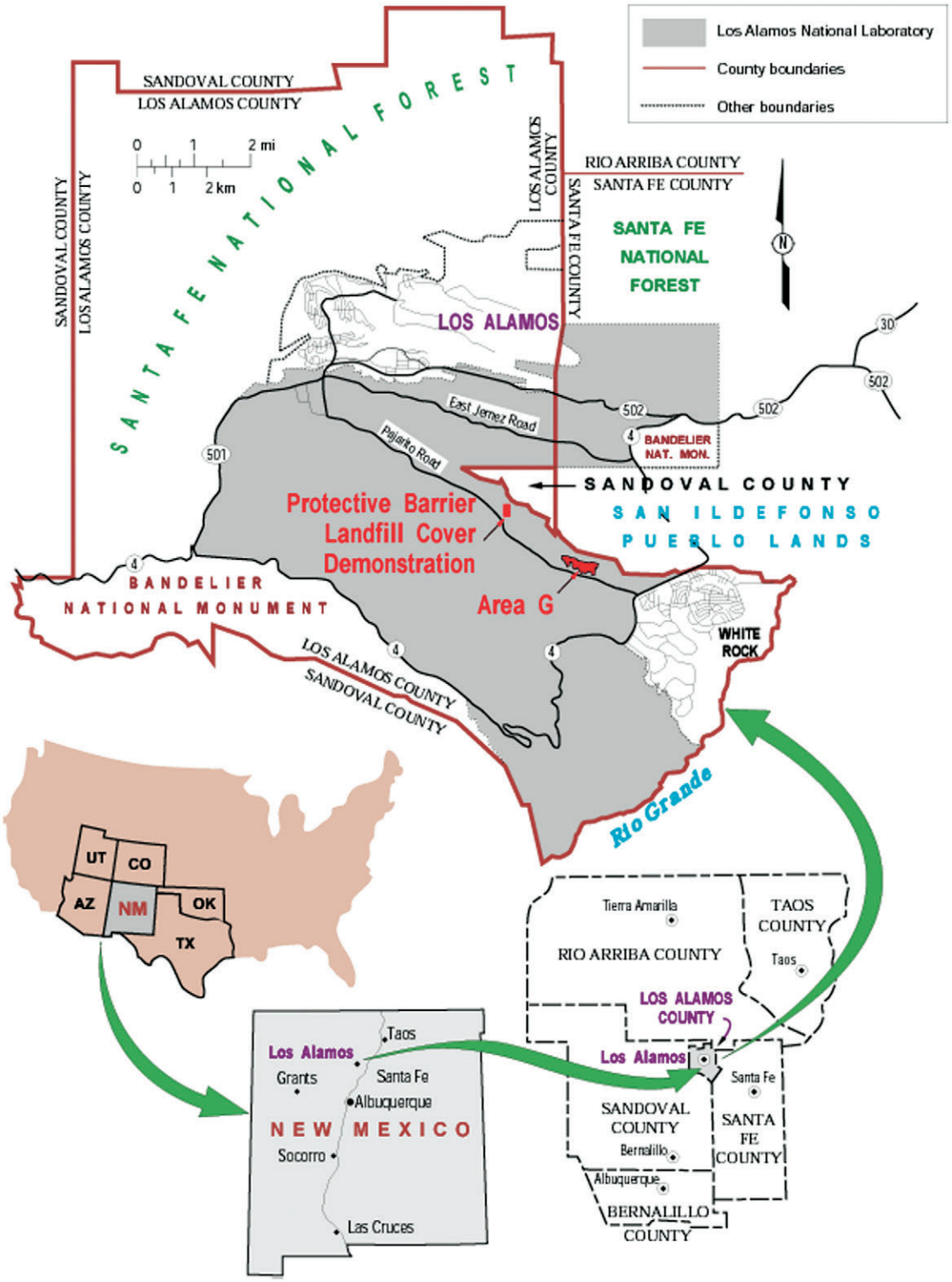

Fig. 1. The location of the Protective Barrier Landfill Cover Demonstration at the Los Alamos National Laboratory.

in 1994 (a special crushed ice addition made up 9.5 cm of this total: see Nyhan et al., 1993, 1997). We compared this with the hundred-year event for the years 1911 through 1986 of 83.6 cm precipitation (Nyhan et al., 1989).

Evaporation estimates were made for each field plot (Fig. 3–6). For most of the years in this study and for all the plots studied, evaporation usually displayed negative values during the first portion of the winter. This phenomenon also occurred in the winter in other landfill cover studies where the field plots contained large shrubs, forbs, and grasses at Los Alamos (Nyhan et al., 1986, 1998). The explanation for this is that the rain gauge accurately reflects the additions of precipitation

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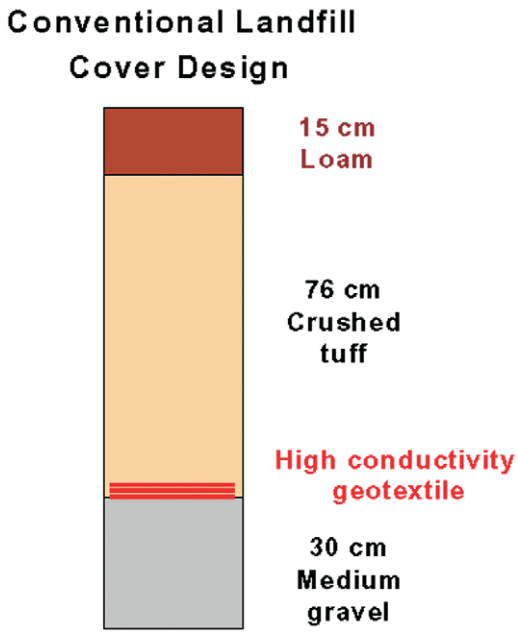

Fig. 2. Descriptions of soil layers in the ET cover design at the Protective Barrier Landfill Cover Demonstration.

as snow and rainstorms during these time periods, but sublimation of snow precludes these precipitation events from forming water that can migrate into the topsoil and be detected by the TDR probes. Thus, the water balance equation really needs a sublimation term in it to properly express this process, but we opted to express the data as negative evaporation in this study.

In the previous studies involving plants, the vegetation not only intercepted the snow from reaching the topsoil, the snow on the vegetation was frequently observed undergoing sublimation. The extent and timing of all of our field observations agree with a snow sublimation study performed on the Colorado Front Range (Hood et al., 1999). The latter field study showed that total net sublimation for the snow season amounted to 15% of maximum snow buildup, and most of the sublimation occurred during the snow collection season.

The largest amounts of annual evaporation occurred during the late spring and summer of all 7 yr of the study (Fig. 3–6). Maximum annual evaporation was measured on the landfill cover with the 10% slope in 1997, when 53 cm of evaporation occurred. There is a trend for annual evaporation to increase with increasing slope yearly (Fig. 3–6). However, an ANOVA displayed a significant (95% confidence level) relationship of daily evaporation with time, but not with slope. The slope of landfill covers did not significantly affect daily evaporation, and this was true for both the entire 7-yr time period and each individual year of record.

Soil Water Inventory

The daily soil water inventory was calculated from the soil water content data for the ET cover studied at slopes of 5, 10, 15, and 25% (Fig. 3–6). The seasonal trends typically started out with large water inventories in the topsoil and the crushed tuff in the spring and gradually decreased to a minimum during the fall. Starting in the spring, the constant-rate stage of evaporation occurs, followed by the falling-rate stage. The upper portions of the profile gradually dry out, and water starts moving upward in response to increasing evaporation-induced gradients (Hillel, 1971; Suleiman and Ritchie, 2003). As an example, in 1992, the ET cover with the 5% slope displayed inventories of water in the topsoil and the crushed tuff at the 15- to 75- and 75- to 91-cm depths of 3.66 (May 29), 20.84 (June 1), and 7.06 cm (July 6), respectively (Fig. 3). By November 10, these three profile layers had dramatically dropped to 0.87, 2.39, and 1.39 cm (Fig. 3). The downward movement of a drying front or drying zone into the profile sometimes accompanies this phenomenon, so evaporation may take place at some depth and the water must move through the desiccated zone by vapor diffusion (Hillel, 1971).

An ANOVA was performed to discover if there were significant relationships with time (seasonality of inventory) and slope daily: sometimes it initially appeared there were none. The ANOVA displayed a significant (95% confidence level) relationship for the daily soil water inventories for the topsoil and two tuff depths with both time and slope. This held true for both the entire 7-yr period and each individual year of record, with only a few exceptions.

The topsoil water inventories in all four field plots consistently centered around 1.9 to 2.2 cm for the 7 yr of the study (Fig. 3–6). The coefficients of variation (standard deviation multiplied by 100 and divided by mean) calculated with 2557 daily average values ranged from 29 to 32% for the four field plots. Despite this low CV, topsoil water inventories varied with time much more than the similar water inventories in the crushed tuff (Fig. 3–6).

The 15- to 75-cm sampling depth in the crushed tuff layer showed large changes in soil water inventory with time in all the ET covers (Fig. 3–6). Since this layer was the thickest layer, it accounted for most of the changes in soil water inventory calculated for the entire landfill cover profile. Field plots with slopes of 5 and 10% had slightly larger inventories of water than the ET covers with slopes of 15 and 25% (Fig. 3–6). The plots with the lower slopes had average daily inventories of 13 cm, whereas the two designs with the larger slopes showed similar values of 10 cm. The daily water inventory data collected in the crushed tuff at the 15- to 75-cm depth displayed CV values that ranged from 33 to 38%.

The water inventories in the bottom tuff layer (75–91 cm) usually were reduced as the summer advanced (Fig. 3–6). The suggestion has been made that this was an artifact because of the fact the water in the pans of gravel were dried out by the air in the water collection system, which day-lighted in the tanks of the collection system. The author thinks this is unlikely because there was always water in the closed collection tank where the flow day-lighted and because there was nominal airflow through this system because of small temperature and barometric pressure gradients.

The water inventory in this layer (75–91 cm) also displayed the trend of larger daily inventories (1992–

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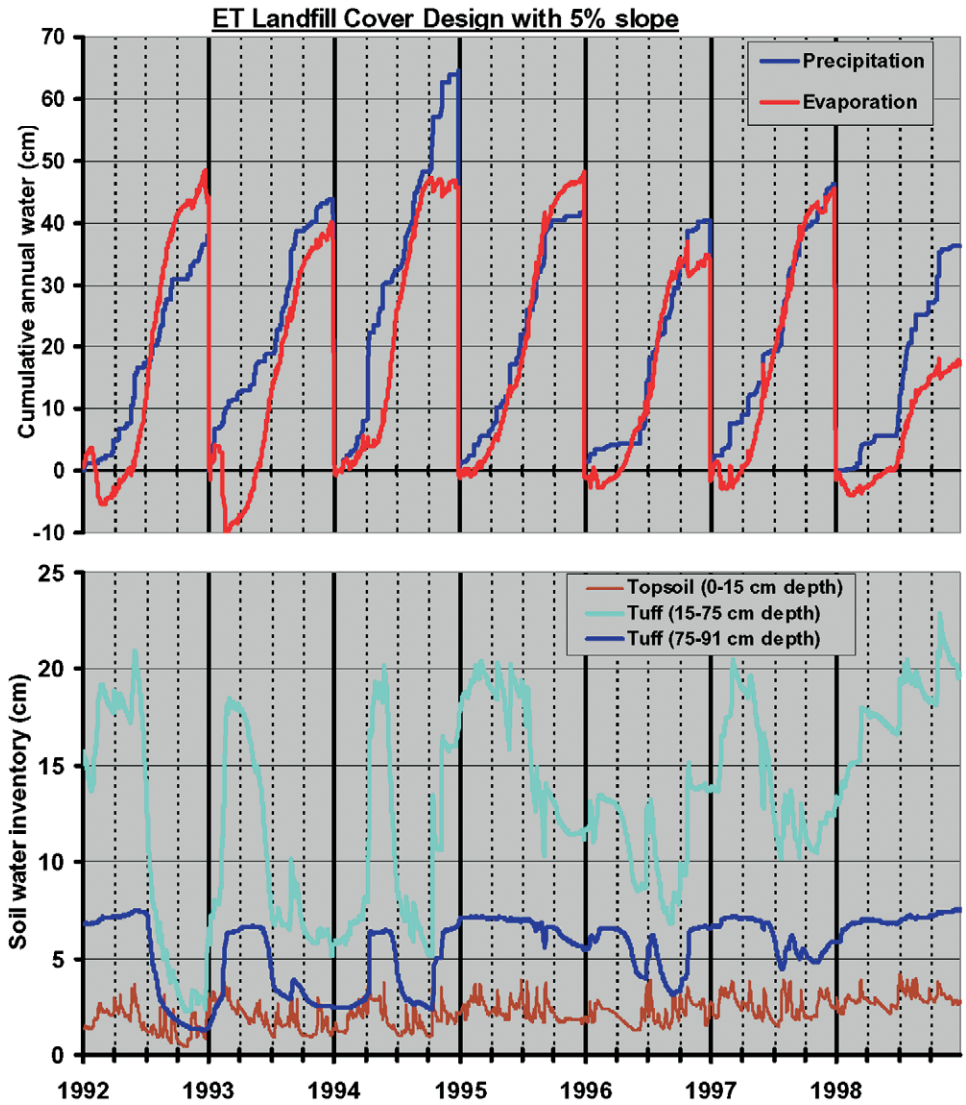

Fig. 3. Daily precipitation, evaporation, and soil water inventories for the ET cover design with 5% slope from 1992 through 1998.

1998) for field plots with low slopes (Fig. 3–6). For the ET cover with a slope of 5%, this value was 5.5 cm, and for the plots with slopes of 10 and 15%, these values were 4.5 cm. The ET plots with 25% slope showed average daily water values of only 3.9 cm. Daily inventories at this depth usually increased in the winter and spring with snowmelt events and then decreased starting in late spring and summer, as seepage, interflow, and evaporation losses occurred throughout the landfill profiles (Fig. 3–6). As a result, the soil water inventories for the 75- to 91-cm tuff layer showed large CV values, ranging from 33% to 51%, compared with similar data for the other profile depths.

Both interflow and seepage occurred in the ET cover with the 5% slope when the daily average inventory of water in the tuff at the 75- to 91-cm depth was ≥6.4 cm. However, this was not true for the entire data set. Simultaneous interflow and seepage did not occur every time the soil water inventory was ≥6.4 cm. Slightly larger water inventories were required for seepage to occur than for interflow in the other three plots. For slopes of 10, 15, and 25%, interflow occurred at water inventories ≥6.7, 6.7, and 4.8 cm, respectively, and seepage occurred at water inventories ≥7.4, 6.8, and 5.9 cm, respectively.

Seepage, Interflow, and Runoff

The yearly seasonality of daily runoff, interflow, and seepage from 1992 through 1998 is shown in Fig. 7 through 10. The same daily events were summed across all years monthly (Fig. 11–13).

The ANOVA of the amounts of daily runoff, interflow, and seepage displayed a significant (95% confidence level) relationship with both time (seasonality of flow) and slope. This was true for both the entire 7-yr time period and each individual year of record. Exceptions to this theme, where no significant relationships with slope were found, were as follows: daily runoff for 1992 and 1994 (similar amounts of runoff occurred on all four plots; Fig. 7–10), and daily interflow for 1993 (similar amounts of interflow occurred on all four plots;

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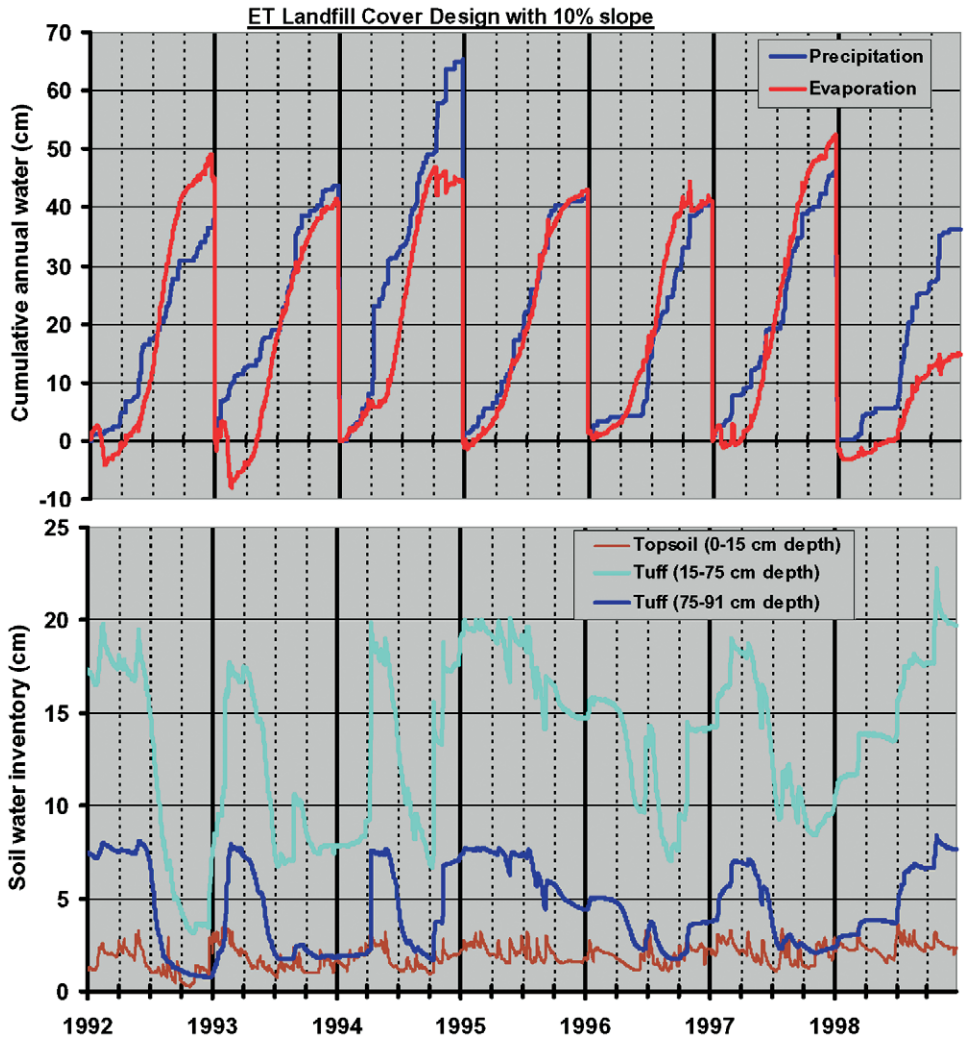

Fig. 4. Daily precipitation, evaporation, and soil water inventories for the ET cover design with 10% slope from 1992 through 1998.

Fig. 7–10) and 1996 (all four plots had zero to insignificant amounts of interflow; Fig. 7–10). Finally, daily seepage for 1993 and 1997 did not display a significant relationship with time (all four plots had zero to insignificant amounts of seepage; Fig. 7–10).

The largest daily runoff event in the 7-yr record occurred on the cover with the 25% slope on 27 Aug. 1993 (Fig. 10). This runoff occurred during a 3.6-cm precipitation event and generated 1.3 cm of flow. This same event also produced the maximum runoff events measured on the plots with the 5 and 10% slopes, amounting to 1.0 and 0.91 cm of runoff, respectively (Fig. 7 and 8). In contrast, no runoff occurred during 1996 and 1997 on the ET covers with 5 and 10% slopes (Fig. 7 and 8). In addition, no runoff occurred on the ET cover plot with the 15% slope in 1997 (Fig. 9).

Runoff occurred throughout the year on these unvegetated plots because of snowmelt and thunderstorms (Fig. 7–10). The amounts of daily runoff on the four plots varied by three orders of magnitude. On the watershed scale, runoff from snowmelt in the spring usually occurs over several weeks to several months with a low discharge (Purtymun et al., 1990). However, on our ET cover plots, runoff from snowmelt was normally intermittent. Snowmelt runoff occurred for a maximum of two to four concurrent days in the winter (Fig. 7–9). No runoff occurred when the air temperatures dropped below freezing in the early morning hours and at night. On the watershed scale, runoff from summer storms usually reaches a maximum discharge in <2 h, with total flow lasting <24 h (Purtymun, 1974). At our field plot scale, summer runoff was also intermittent, and daily runoff events normally lasted for about an hour. These events usually occurred for a maximum of two to four concurrent days (Fig. 7–10).

From 1992 through 1998, there were 30, 57, 47, and 67 runoff events measured on the ET Covers with 5, 10, 15, and 25% slopes, respectively (Fig. 11). The total number of runoff events for all the ET covers peaked in July for the plots with the 15 and 25% slopes and in August for the plots with slopes of 5 and 10% (Fig. 11). When the amounts of runoff were summed for each month from 1992 to 1998, runoff for all plots peaked in August and increased with increasing slope. The only exception to this was that there was more runoff produced in August by the field plot with the 10% slope

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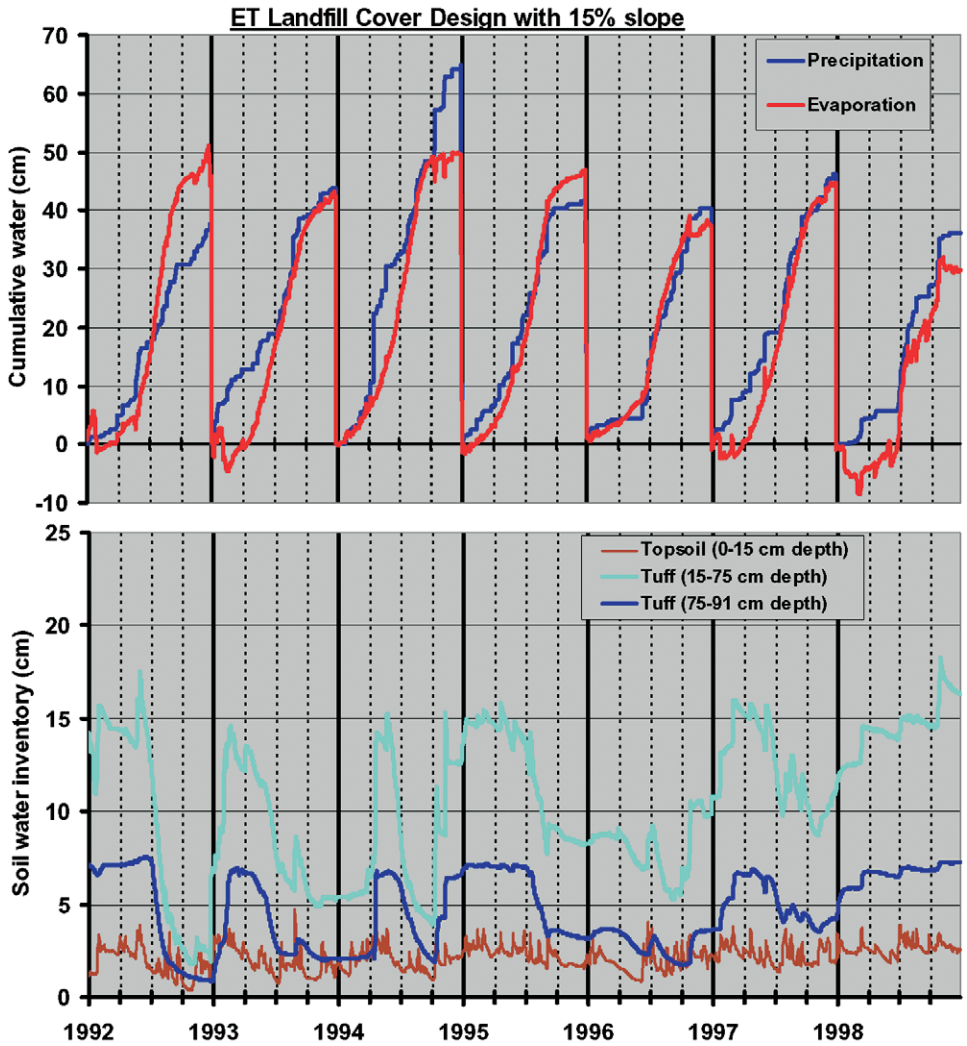

Fig. 5. Daily precipitation, evaporation, and soil water inventories for the ET cover design with 15% slope from 1992 through 1998.

than the plot with the 15% slope. The plot with the 10% slope had seven more runoff events in August (1992–1998) than the plot with the 15% slope, resulting in more total runoff. Differences in antecedent moisture conditions were investigated as a cause for this exception, but no significant differences were found in the topsoil water inventory across all plots in August, leaving us without an explanation at this time.

Interflow occurs in the bottom portions of the 76-cm-thick crushed tuff layer, probably immediately above the high-conductivity geotextile–gravel layer (Fig. 2). The TDR probes were positioned 5 cm above this boundary (75–91 cm depth) to capture this hydrologic process. Interflow occurs when the rate of infiltration of water into this lower crushed tuff layer was less than the crushed tuff's capacity to conduct water laterally. Seepage occurs when matric potential forces are not able to hold the water within the crushed tuff at the boundary between the crushed tuff and the medium gravel. Thus, interflow always occurs before seepage starts (if it starts) and continues for much longer times than seepage. From 1992 through 1998, there were 387, 397, 363, and 371 d of interflow measured on the ET Covers with 5, 10, 15, and 25% slopes, respectively (Fig. 7–10).

Interflow is important in the hydrologic behavior of landfill covers. Starting in February 1992, interflow occurred continuously for 69, 105, 101, and 102 d on the 5, 10, 15, and 25% slopes, respectively (Fig. 7–10). Interflow events gradually increased in number from January through February and occurred most often in March (Fig. 12). The number of events then decreased until a secondary peak occurred in November because of additions of rain and snow in the middle of fall (Fig. 12). There was no consistent relationship between the number of interflow events and the slope of the landfill cover plots (Fig. 12).

The largest daily interflow event measured in our data set happened 29 May 1992 on the 5% slope cover (Fig. 7) when 0.51 cm of interflow took place. The next day, the largest amount of interflow (0.14 cm) developed on the plot with the 15% slope (Fig. 9). The soil water inventory on both of these plots gradually increased between 20 and 25 May 1992, when 4.2 cm of precipita-

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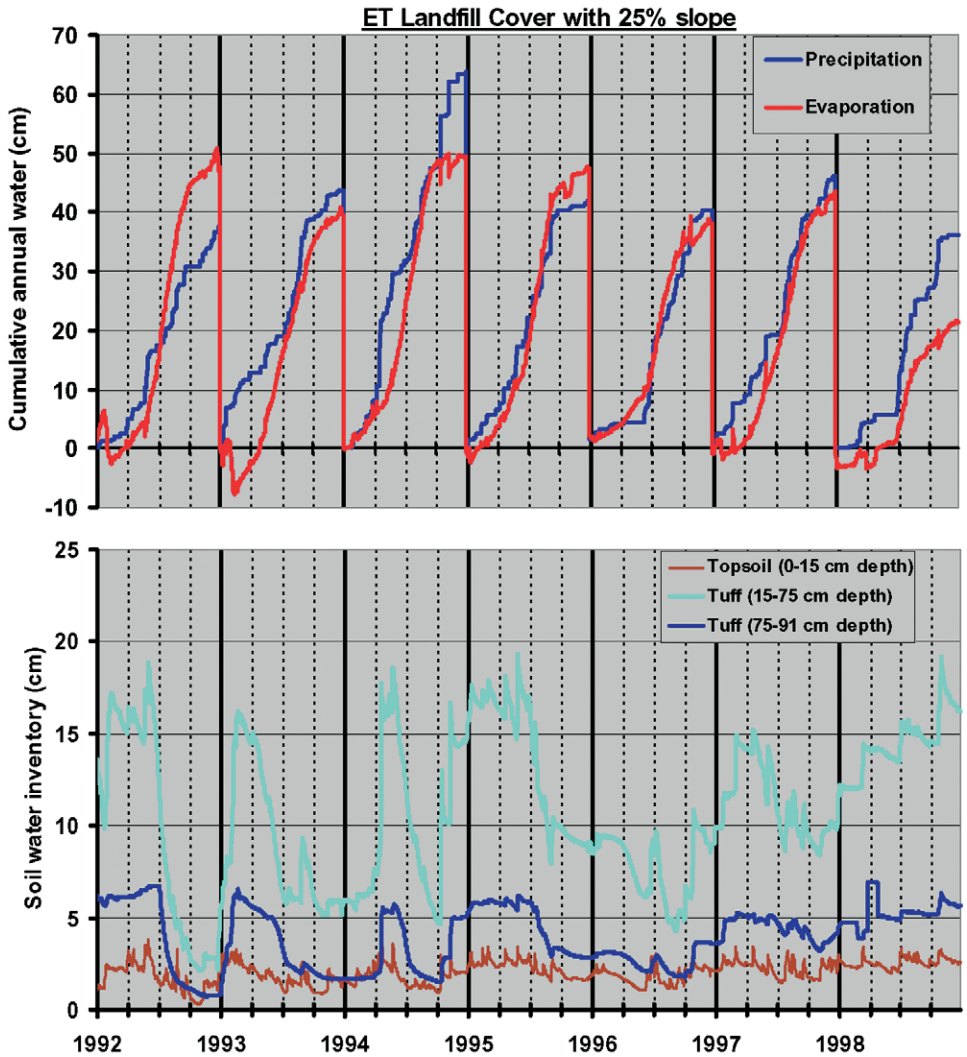

Fig. 6. Daily precipitation, evaporation, and soil water inventories for the ET cover design with 25% slope from 1992 through 1998.

tion happened, followed by 3.1 cm of precipitation on 29 through 30 May. However, for the 7 yr of data, the maximum amounts of interflow occurred in February on the plots with the 5% slope and during March for the plots with the 25% slope (Fig. 12). This happened during May on the plots with slopes of 10 and 15%.

Seepage occurred on all the ET covers (Fig. 7–10). In comparison with interflow, seepage was typically intermittent, like runoff. Seepage only occurred during 1992 through 1998 for 81, 25, 31, and 16 d on the ET covers with 5, 10, 15, and 25% slopes, respectively (Fig. 7–10). Thus, as the slope of the landfill covers increased, the number of seepage events decreased: there were 81 and 16 seepage events on the landfill covers with 5 and 25% slopes, respectively. No seepage was noted on ET cover plots with slopes of 10 to 25% in 1996 and 1997, and the field plots with slopes of 5 and 10% displayed no seepage during 1995 and 1996, and 1993 and 1995, respectively.

Seepage did not occur on any plot during January, as well as during July, August, September, and December on the landfill designs with slopes ranging from 10 to 25%. In contrast, the field plot with the 5% slope displayed seepage on every month except January, even during the summer months, with peak numbers of events in May and November (Fig. 13). Although there was negligible seepage on the landfill cover with the 25% slope, the largest number of seepage events occurred in March and November for this plot (Fig. 13). The plots with slopes of 10 and 15% had the maximum number of seepage events during May and June, respectively (Fig. 13).

The largest daily seepage event measured in all of our plots happened 1 Nov. 1998, on the ET cover with the 5% slope (Fig. 7). This event amounted to 0.56 cm of seepage during this day, which happened after 3.9 cm of precipitation as snow occurred on the plots during the two previous days. On this same day, 0.069 cm of seepage developed on the plot with the 25% slope (Fig. 10), which was the largest seepage event noted on this plot as well. For the field plots with slopes of 5 and 10%, the largest amounts of daily seepage happened during October and May, respectively (Fig. 13). The plot with the 15% slope had the largest number of events in June, but the largest amounts of daily seepage in March.

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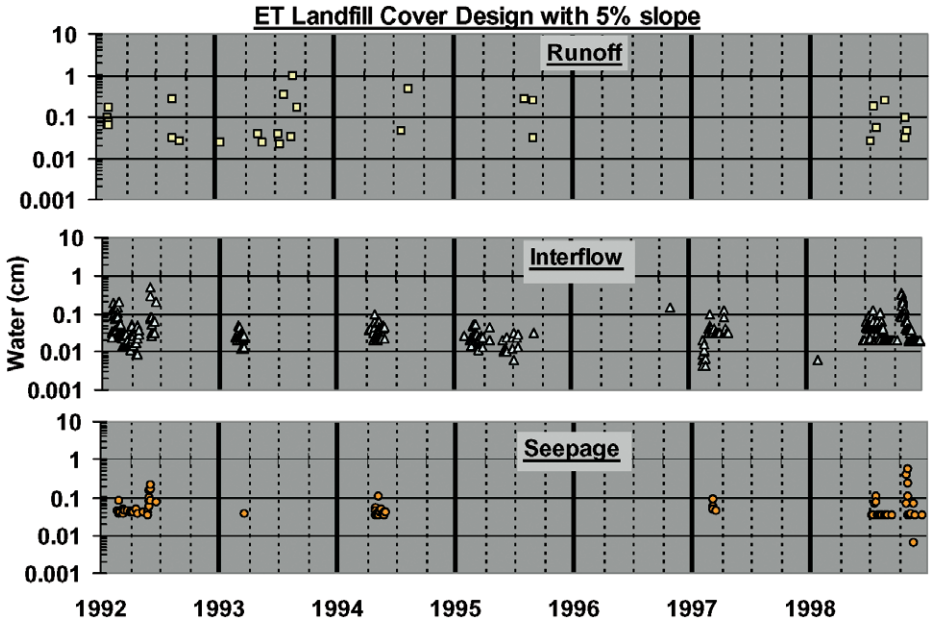

Fig. 7. Daily runoff, interflow, and seepage for the ET cover design with 5% slope from 1992 through 1998.

Water Balance Summaries

The most practical comparisons among the four field plots containing the ET covers for their usefulness to the burial site operator should be the overall performance comparison of the water balance features (Table 1). As expected in a semiarid environment, 88 to 95% of the precipitation received by all the ET covers evaporated from these unvegetated ET covers. There was an annual trend for evaporation to increase with slope of the landfill cover, probably because plots with large slopes can intercept more solar radiation than plots with smaller slopes (Nyhan et al., 1997). Thus, interflow and seepage usually decreased with increasing slope for each landfill cover plot (Table 1).

Runoff significantly increased with increasing slope during the 7 yr of this study. Runoff accounted for about 1 to 4% of the precipitation losses across all the plots studied. Runoff for the 7 yr of experimentation accounted for a minimum of 4.25 cm of runoff on the ET cover with the 5% slope to a maximum of 11.8 cm of runoff on the plot with the 25% slope (Table 1).

Minimal seepage is also an objective for landfill covers. Seepage decreased with the presence of the underlying gravel layer in this study, which was able to divert about 5.9% of the precipitation (plot with the 10% slope) received at the site to interflow (Table 1). If the gravel layer had not been there, the amounts of seepage would have amounted to the sum of the seepage and interflow values in Table 1. This may not be acceptable to the site operator, but would need to be used as an

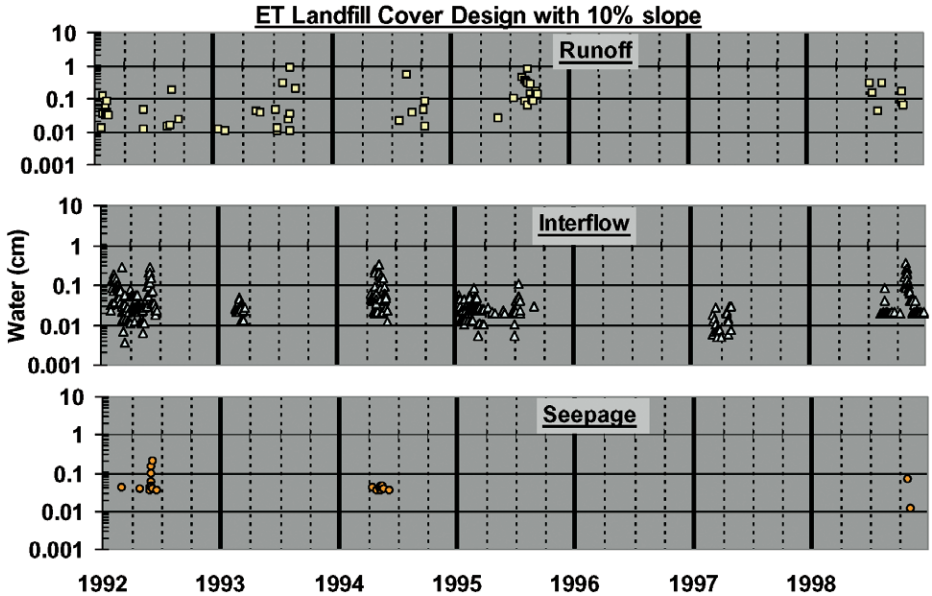

Fig. 8. Daily runoff, interflow, and seepage for the ET cover design with 10% slope from 1992 through 1998.

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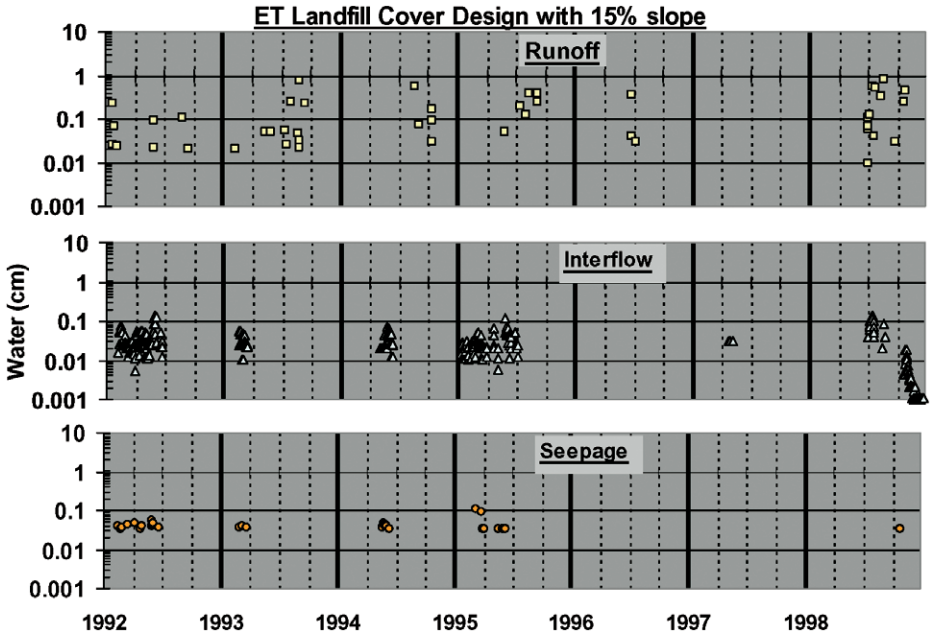

Fig. 9. Daily runoff, interflow, and seepage for the ET cover design with 15% slope from 1992 through 1998.

input term for a risk assessment model to decide if this was an acceptable institutional risk.

The original idea for field-testing these ET covers was to gather hydrologic data on their performance with and without vegetation present on the field plots. Although we were unable to perform the former part of the study, vegetation would occur on landfill covers given regulatory periods of up to 500 yr and would have effects on landfill hydrology, such as plant transpiration, seepage, and soil erosion. The EPA only recommends ET covers for arid or semiarid climates (USEPA, 2003). Evaporation is the dominant water-loss process here, but plant transpiration also contributes (Nyhan et al., 1986). The ideal plant community for an ET cover would be active year-round and have roots throughout the cover. It could contain evergreen shrubs such as those tested at Materials Disposal Area B at Los Alamos (Nyhan et al., 1998) aimed at reducing seepage that results from large snow melts. Our field plots contained partial covers of gravel to reduce erosion. There is an inverse relationship between vegetation cover and overland flow in semiarid landscapes (Wilcox et al., 2003), so the presence of vegetation could have led to reduced overland flow on our plots. However, given the extreme drought occurring in the last decade across the southwestern portions of the United States, the helpful losses

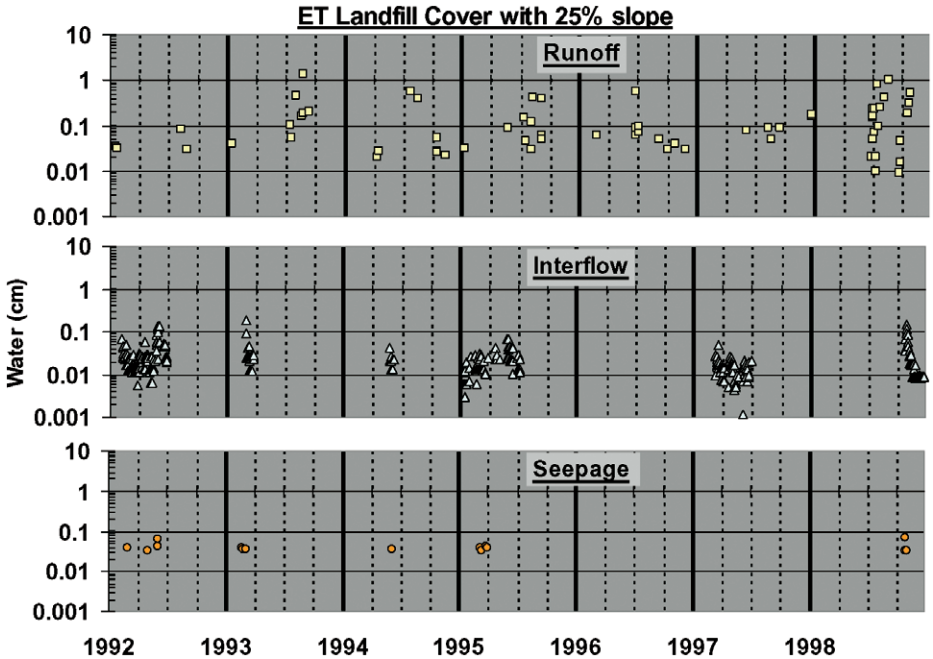

Fig. 10. Daily runoff, interflow, and seepage for the ET cover design with 25% slope from 1992 through 1998.

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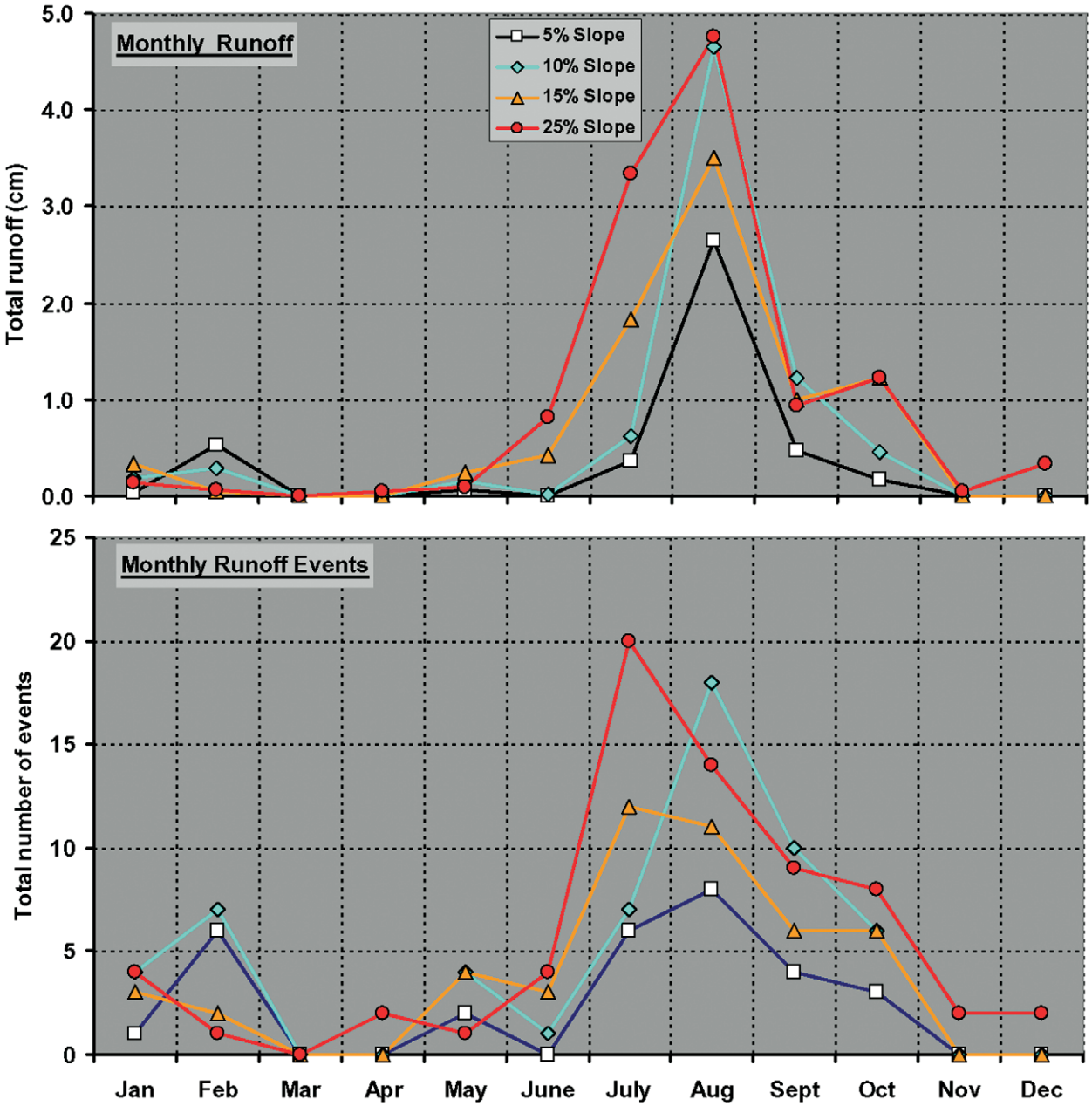

Fig. 11. Total monthly runoff and runoff events measured during the entire 1992 through 1998 period for the ET cover design as a function of slope.

of water from the ET cover because of plant transpiration (resulting in reduced seepage) would currently be negligible. Drought, forest fires, and bark beetles reduced grass, shrub, and tree biomass in many mesa-top locations containing landfills at Los Alamos. This also would mean that reduced plant cover would result in increased soil erosion.

EQUIVALENCE AND OPTIMIZATION OF LANDFILL COVER DESIGNS

Unlike expensive RCRA landfill covers containing hydraulic barriers to limit seepage into the underlying wastes, ET covers are able to use water balance to minimize seepage. Under RCRA, the landfill operator can propose an alternative design, such as an ET cover. This can be done only if it can be shown the alternative provides equivalent performance with decrease in seepage and with erosion resistance and gas control (USEPA, 2003). The information provided in this paper (Table 1) should help operators better defend equivalency arguments.

Once an ET cover is found to be acceptable, the site operator wants a design for a specific slope and slope length that minimizes long-term runoff and seepage and maximizes interflow and evaporation. Increased solar energy would be helpful in increasing evaporation from the landfill (Nyhan et al., 1997), especially in the late winter, spring, and late fall. With this in mind, we could match the aspect of the landfill cover with the sun's altitude and angle at the landfill site for these seasons.

The last step might be to decide the slope of the

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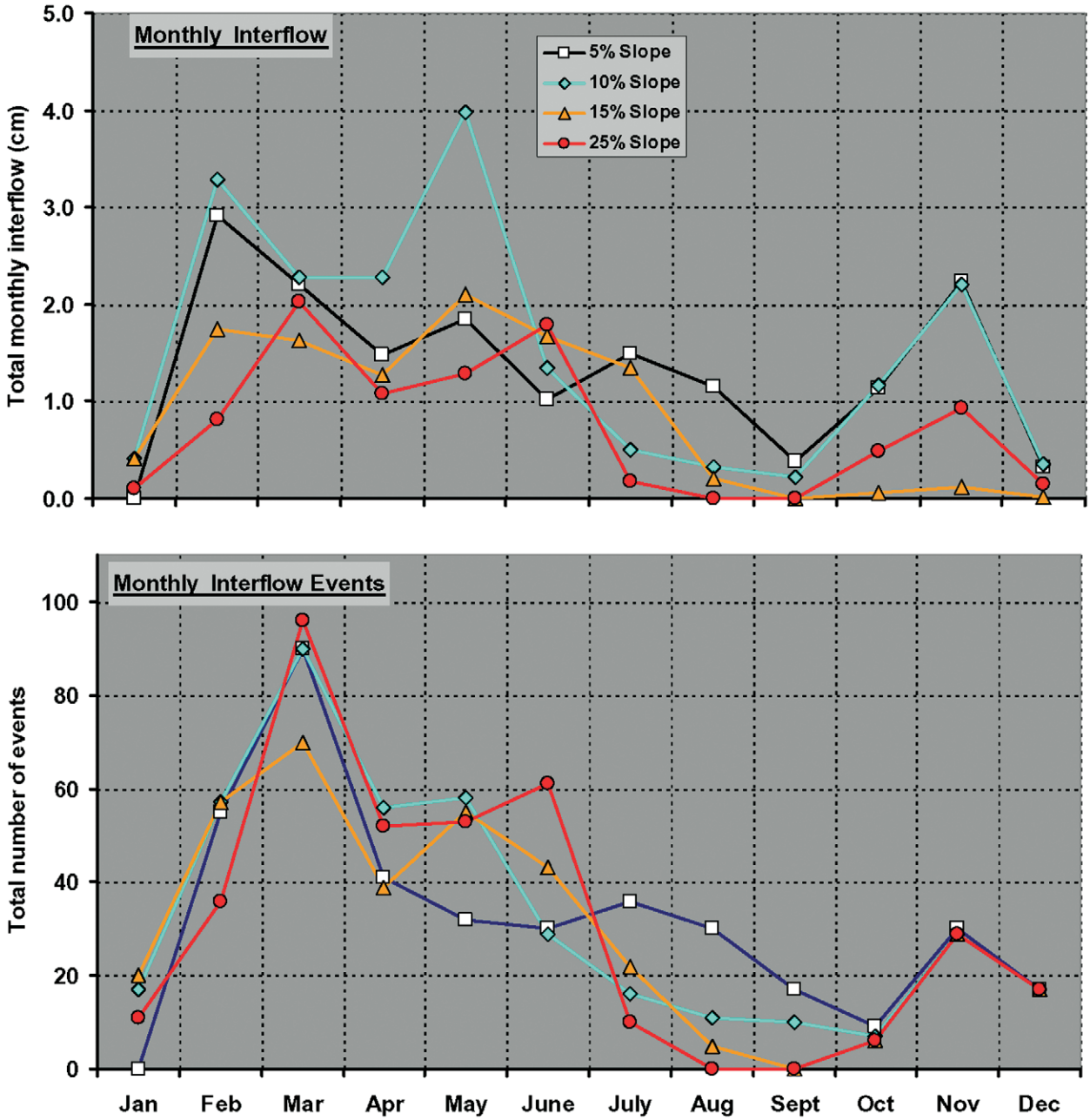

Fig. 12. Total monthly interflow and interflow events measured during the entire 1992 through 1998 period for the ET cover design as a function of slope.

landfill cover. For the water balance data presented in Table 1, for example, a landfill cover with a slope from 10 to 15% might be a good alternative. There is not a large increase in runoff by increasing the landfill cover slope from 10 to 15%, so perhaps extra measures to control erosion could be used. With 95% evaporation and low seepage, the plot with the 15% slope would be recommended. The site operator's final landfill cover design would incorporate a method of collecting interflow water and diverting it away from the underlying wastes at the waste site.

For arid and semiarid locations, the bare soil evaporation depth is useful in modeling ET covers needing maximum evaporation. In the piñon (*Pinus edulis* Engelm.)–juniper [*Juniperus monosperma* (Engelm.) Sarg.] woodland adjacent to our plots, stable isotope techniques showed evaporation to occur mainly in the upper 10 cm of the soil profile (Newman et al., 1997). The latter soil profile contained a B_t horizon, which probably limited evaporation to shallow depths compared with our soil cover profiles (Fig. 2). This variable is also important in modeling evaporation from soil in the CREAMS water balance model (Hakonson et al., 1984) and in the SPUR hydrologic model (Wilcox et al., 1989). Lane and Stone (1983) quantified this effective depth influenced by bare soil evaporation (Y) as

$$Y(\mathrm{FC} - \mathrm{WP}) = (1 + A)u \qquad [1]$$

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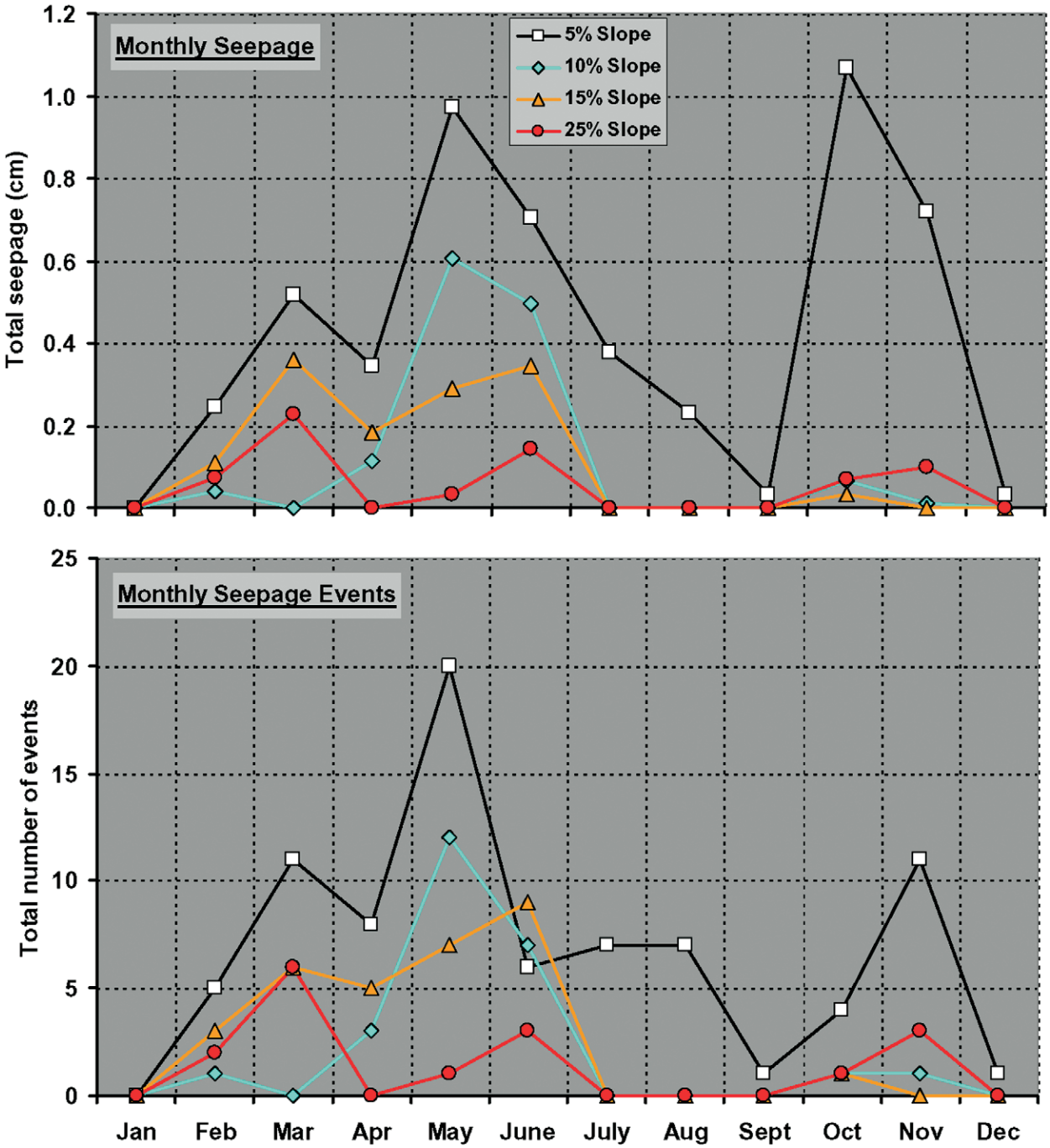

Fig. 13. Total monthly seepage and seepage events measured during the entire 1992 through 1998 period for the ET cover design as a function of slope.

Thus, Y is expressed as a function of soil moisture content at field capacity (FC) and wilting point (WP), the ratio of Stage 2 to Stage 1 evaporation volume (A), and the volume of evaporation during Stage 1 evaporation (u).

This information needs to be determined for the highly disturbed landfill covers at our site, using data presented in this paper, as well as the sublimation process discussed earlier. This field data can thus be used to develop field-calibrated hydrologic models to evaluate future performance of landfill cover designs, such as the effect of a 100-yr precipitation event on the ET cover. Finally, we will choose the final closure design for each waste site landfill cover after evaluating the human and ecological risk, cost-effectiveness, and practicality of various landfill cover designs.

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Table 1. Water balance data for ET cover design as a function of slope from 1992 through 1998. Total precipitation for this time period was 311.14 cm.

Landfill cover slope	Water balance parameter					Evaporation/ precipitation
	Evaporation	Interflow	Seepage	Runoff	Change in soil water inventory	
%	cm					
5	273.77	16.22	5.25	4.25	11.65	0.88
10	280.50	18.35	1.33	7.57	3.39	0.90
15	296.13	10.57	1.32	8.58	−5.46	0.95
25	287.40	8.82	0.64	11.79	2.49	0.92

Group at Los Alamos. Thanks to J. Leo Martinez and T. G. Schofield for helping with the design, construction, and emplacement of the field experiment and to Gary J. Langhorst for all the help in computer software and hardware support for the field study. Research performed for the USDOE Environmental Restoration Program by the Los Alamos National Laboratory operated by the Univ. of California under contract W-7405-ENG-36.

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