LA-13457-MS

#71345

A Water Balance Study of Four Landfill Cover Designs at Material Disposal Area B in Los Alamos, New Mexico

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory is operat...
for the United States Department of Ener...

A WATER BALANCE STUDY OF FOUR LANDFILL COVER DESIGNS AT MATERIAL DISPOSAL AREA B IN LOS ALAMOS, NEW MEXICO

by

John W. Nyhan, Johnny A. Salazar,
David D. Breshears, and Fairley J. Barnes

ABSTRACT

The goal of disposing of low-level radioactive and hazardous waste in shallow landfills is to reduce risk to human health and the environment by isolating contaminants until they no longer pose an unacceptable hazard. In order to achieve this, the Department of Energy (DOE) Environmental Restoration (ER) Program is comparing the performance of several different surface covers at Material Disposal Area (MDA) B in Los Alamos. Two conventional landfill designs, consisting only of layers of topsoil seeded with grasses, were compared with an improved cover designed to minimize plant and animal intrusion and to minimize water infiltration into the underlying wastes. The conventional covers varied in depth and both conventional and improved designs had different combinations of vegetation (grass verses shrub) and gravel mulch (no mulch verses mulch). These treatments were applied to each of 12 plots and water balance parameters were measured from March 1987 through June 1995. This has been the longest-term study of water balance on a remediated site.

Field results document several improvements for conventional landfill surface covers. Adding a gravel mulch significantly influenced the plant cover: field plots receiving no gravel mulch averaged 21.2% shrub cover, while plots with gravel had a 20% larger percent cover of shrubs. However, the influence of gravel mulch on the grass cover was even larger than the influence on shrub cover: average grass cover on the plots with no gravel was 16.3%, compared with a 42% increase in grass cover due to gravel mulch. These cover relationships are important to reduce runoff on the landfill cover, as shown by a regression model that predicts that as ground cover is increased from 30 to 90%, annual runoff is reduced from 8.8 to 0.98 cm—a nine-fold increase. We also found that decreasing the slope of the landfill cover from 6 to 2% reduced runoff from the landfill cover by 2.7-fold.

To minimize the risk of hazardous waste from landfills to humans, runoff and seepage need to be minimized and evapotranspiration maximized on the landfill cover. This has to be accomplished for dry and wet years at MDA B. Seepage consisted of 1.9% and 6.2% of the precipitation in the average and once in ten year events, respectively, whereas corresponding values for runoff were 13% and 16%; these changes were accompanied by corresponding decreases in evapotranspiration, which accounted for 86% and only 78% of the precipitation occurring on the average and once in ten year event, respectively. We found that doubling the percent shrub plus grass cover (25% verses 50%) on the landfill cover increases lifetime evapotranspiration by 28%. Since our evergreen shrubs could transpire during the seasons when seepage usually occurs, we found seasonal differences in seepage: as shrub cover increased from 0.13 to 23%, seepage occurring in the winter and spring decreased from 5.73 to 1.19 cm.

1. INTRODUCTION

The goal of disposing of low-level radioactive and hazardous waste in shallow landfills is to reduce risk to human health and the environment by isolating contaminants until they no longer pose an unacceptable hazard. 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 landfill cover needs to act passively to isolate the radionuclides for an additional 300 to 500 years (US NRC, 1982; US DOE, 1988). Disposal in shallow landfills can minimize both costs and the problems of excavating, transporting, and reburying large quantities of slightly contaminated material. However, to be cost-effective and reduce risk associated with the movement of contaminants in the environment, landfills must be designed to minimize long-term maintenance and to maximize the integrity of the landfill cover.

Vegetation can play a critical role in precluding water received as precipitation from reaching buried wastes (Anderson et al., 1993). Plants can extract water from the entire soil profile, whereas the physical process of soil evaporation only removes water from relatively shallow soil depths. On an annual basis in arid and semiarid climates, potential evapotranspiration is far greater than the amount of water received as precipitation (Chang, 1971). Consequently, if a landfill cover is deep enough to store precipitation received while vegetation is dormant, and if sufficient vegetation is present to use all of the stored moisture each growing season, then no water will drain into the underlying wastes. Conversely, if vegetation is sparse or absent, has insufficient rooting depth, or is physiologically inactive during several seasons, the landfill cover may become very wet and water will seep into the buried wastes.

Vegetation has many other influences on the landfill topsoil (Dadkhah and Gifford, 1980). Vegetation plays a major role in soil erosion as a component of the Cover Management Factor (Nyhan and Lane, 1986) of the Universal Soil Loss Equation (USLE). The US EPA-recommended approach to reducing soil erosion on landfills is based on control using plant cover (US EPA, 1989), as opposed to approaches based on the use of gravel and other materials to control erosion (Lopez et al., 1988, 1989; Nyhan et al., 1984; Nyhan and Lane, 1986). Plant cover influences many other hydrological processes, including interception, infiltration, evaporation, transpiration, and soil water storage, and plants are also involved in contaminant uptake.

Two primary factors that can reduce the integrity of the cover and increase the risks associated with the movement of contaminants are surface erosion of the cover and infiltration of water through the cap and into the waste (Jacobs et al., 1980; Luxmoore and Tharp, 1993; Suter et al., 1993). Erosion rates are related to amounts of runoff that leave the surface area and are reduced when more water infiltrates into the soil profile. Properties of the surface cover such as vegetation and organic matter or rock mulches can increase the infiltration capacity of a site (Nyhan and Lane, 1986). However, increased infiltration into the cover can potentially lead to more water reaching the waste, so there are tradeoffs in cover design to optimize both the amounts of runoff and leachate that are generated from precipitation.

Vegetation can modify soil moisture profiles, suggesting a hypothesis for the tradeoff between runoff and soil moisture storage: runoff and erosion rates can be reduced to acceptably low levels by maintaining a high percentage of ground cover from vegetation and gravel mulch, and seepage can be reduced by using vegetation that is deep-rooting and evergreen. In addition, problems with root penetration into the waste can be minimized using biobarriers. This hypothesis has been the focus of a long-term study at Material Disposal Area B (MDA B) at Los Alamos National Laboratory between 1987 and 1995. A field study was designed to test the interactive effects of soil surface mulches made of gravel and type of vegetation cover on components of water balance under natural precipitation. One of the two major vegetation types tested was an overstory of rubber rabbitbrush (*Chrysothamnus nauseosus*), an evergreen shrub (Mielke, 1993) observed to be growing year-round at Los Alamos and having maximum rooting depths of 4.5 m (Tierney and Foxx, 1987). Rabbitbrush is not an evergreen plant such as a plant like a ponderosa pine, but even if rabbitbrush loses its leaves in the early winter, this plant can still transpire because it has green stems. The other vegetation type established on the plots was a plant cover of mixed grasses and forbs, observed to be actively growing predominantly during the spring and summer. Testing this hypothesis requires a long-term data set, not only because regulations for radioactive wastes require long-term containment, but because of (1) high variability in precipitation among seasons and across years, and (2) changes in vegetation through time.

MDA B was selected for this study for several reasons. This disposal area is located on a mesa top similar to several other landfills that were closed in the 1940s at Los Alamos National Laboratory (LANL). MDA B has been the object of a previous field study of biobarriers in landfill covers (Nyhan et al., 1986). In addition, current regulations prevent the installation of different covers on the same waste site, so this study represents a unique opportunity for a controlled comparison of different cover treatments.

The following sections of this report describe the history of waste disposal and previous field studies at MDA B, document the methodologies used by members of the Environmental Science Group, present the field data collected for the Department of Energy (DOE) Environmental Restoration Program between 1987 and 1995, and demonstrate the utility of this field data for improving the application of landfill cover technology at Los Alamos.

A. History of Waste Use at MDA B

MDA B was probably the first common solid waste burial ground used by Los Alamos National Laboratory (Rogers, 1977). This disposal area is located on a narrow eastward-trending mesa whose south side is approximately 30 m from a canyon tributary to Los Alamos Canyon (see Figure 1). More specifically, it located on the south side of DP road, approximately 488 m east of the intersection of DP Road and Trinity Drive (SE 1/4 sec. 15, T. 19 N., R. 6E., and SW 1/4 sec. 14, T. 19., R. 6E.). Approximate acreage is 6.03, the western two thirds of which is presently covered by a layer of asphalt. Elevation of the area ranges from 7150 ft at the east end to 7230 ft at the west end. The MDA B waste disposal pits were cut in Unit 3a of the Tsierege Member of the Bandelier tuff and the thickness of the tuff beneath the disposal pits is estimated to exceed 240 m (Nyhan et al., 1986). Depth to the water table is estimated to be 365.8 m beneath the surface of the mesa.

Based on memos dated July 5, 1945 through January 31, 1952, and on aerial photographs, Rogers (1977) reported that a series of pits was used at MDA B (see Figure 2). Chemical wastes were buried in trenches 0.91 to 1.22 m deep, 0.61 m wide to 4 ft deep, and of varying lengths. Trenches of other sizes were also used (3.66 m deep, 4.57 m wide, 91.44 m long). Total volume of the pits, after deducting three feet of cover material was estimated to be 21,400 cubic meters (Meyer, 1971).

The contamination of materials in these pits consists of all types of radioactive materials used at Los Alamos but contain very little plutonium: less than 100 g of Pu^{239} for the entire area (Meyer, 1951). Approximately 90% of the waste consisted of paper, rags, rubber gloves, glassware, and small apparatus placed in cardboard boxes and sealed with masking tape by the waste originator. At least one truck contaminated with fission products from the Trinity test is also buried at MDA B.

Unlike current practices of layering waste in pits, the MDA B waste filled the depth and width of the pits before they were covered with backfill. As a result, shortly after MDA B was closed in 1947 subsidence occurred. The cover over the pits then was remediated by using the area for disposal of noncontaminated concrete and soil from construction sites (Rogers, 1977). Around 1966 or 1967, the western two-thirds of MDA B was covered with a layer of asphalt.

A more detailed history of material disposal is presented in Appendix Q of the Los Alamos National Laboratory Environmental Restoration Work Plan for November 1991 (LANL, 1991).

B. Previous Studies at MDA B

Several previous studies have occurred at MDA B. These provide valuable data for analyzing the current study and for designing waste covers. In 1966, the US Geological Survey investigated the distribution of subsurface moisture and potential migrating contaminants in the soil and tuff around the perimeter of the site (Purtymun and Kennedy, 1966). They found that the moisture content of all layers was below saturation, that there was no evidence of lateral migration of contaminants, and that a slight increase in soil moisture at depths of 3.7 to 7.3 m along the upgradient side of the site indicated slight lateral moisture movement.

In 1970, concentrations of plutonium and strontium in soil in and adjacent to Technical Area (TA) 21 (where MDA B is located) were estimated to determine deposition of plutonium from ventilation stack emission (Kennedy and Purtymun, 1971). These data quantify a significant, input source of Pu^{239} in surface soils, independent from that disposed of in the trenches at MDA B. In the late 1970s, above-background concentrations of Am^{241}, Pu^{238}, Pu^{239}, Cs^{137}, and U were measured in surface soils and vegetation at MDA B (Trocki, 1977) and were attributed to deposition of stack emissions from a source near MDA B and from subsidence and erosion, rodent burrowing, and plant uptake taking place within MDA B.

In 1981, vegetative cover and root distributions were estimated at MDA B (Tierney and Foxx, 1982). Numerous native species had recolonized the waste site, including many ponderosa pines (*Pinus ponderosa*), the larger of which were 16–27 years old. Several plant species that are associated with disturbed areas were also prevalent. The disturbance was related to soil slumping and burrowing by gophers. At this time, radionuclide concentrations in plants, soil, and rodents were also estimated (Wenzel et al., 1987). The radionuclide concentrations in plants were elevated above world-wide fallout concentrations, consistent with observations that plant roots had penetrated the cover and had accessed the wastes.

In 1982, the cover of the vegetated portion MDA B (the eastern third of the entire MDA B site) was modified as part of a remedial action (Nyhan et al., 1986). The study tested a conventional waste cover (the control) against an improved cover that included a biobarrier designed to prevent penetration into the waste by plant roots and burrowing animals and to serve as a barrier to moisture flow (Figures 2a and 2b). The profile of the control plot consisted of about 75 cm of crushed tuff covered with 15 cm of topsoil. The improved design consisted of 75 cm of 10- to 30-cm diameter cobble covered with 25 cm of 2-cm of gravel. The surface of the entire area was seeded with a mixture of native grasses and covered with a straw mulch to minimize erosion during seedling establishment (Barnes and Warren, 1988; Nyhan et al., 1986; Nyhan, 1989).

The effectiveness of the covers that were installed in 1982 was studied by measuring soil moisture and plant root penetration through the covers. The results of a three year study indicated that (1) all three cap designs prevented plant root intrusion to the simulated waste underlying the caps: (2) most of the increase in soil water storage within the covers, and all of the seepage through the covers was associated with snowmelt; (3) the biobarrier functioned effectively as a capillary barrier and reduced the incidence of percolation; and (4) evapotranspiration effectively prevented percolation into backfill during the summer months regardless of cap design (Nyhan et al., 1986; Nyhan, 1989).

Since the vegetative cover established in 1982 resulted in heterogeneous mixture of grasses and clover with several areas of bare soil across the western portion of MDA B, the entire site was disked in 1984 at the start of an EPA-sponsored project (Barnes and Rodgers, 1988). Twelve study plots were established on the site at the locations of the plots in the current study (Figure 2a). The site had plo with three different soil profiles (Figure 2b) and four different surface treatments. Two treatments consisted of rabbitbrush (1-gal. size) planted at different densities. Besides the bare soil treatment, the fourth treatment consisted of a vegetated cover of sand dropseed (*Sporobolus cryptandrus*), which were planted as 2.5-cm by 8-cm plugs. This two-year study demonstrated several differences in soil water withdrawal on the plots as a function of vegetative cover and compared predictions of soil moisture on the site using the CREAMS and HELP models (Barnes et al., 1986; Barnes and Rodgers, 1987, 1988; Barnes and Warren, 1988; Lopez et al., 1988, 1989

C. Current Study

The experimental design of the long-term water balance study at MDA B is documented in detail in the work plan for TA-21 (LANL, 1991). Briefly, the experimental desig consisted of applying new surface treatments to the 12 study plots (3.05 m by 10.7 m) used for the EPA-funded study. Four surface treatments (grass with gravel cover, grass with no gravel cover, shrub with gravel cover, and shrub with no gravel cover) were used on plots at each of three locations on the site (Figure 2). Soil moisture, runol precipitation, and surface conditions have been monitore since 1987 and sediment transport was monitored betwee 1987 and 1989. The objective of this study was to determine the interactive effects of vegetation cover and use o gravel mulches on runoff, erosion, and soil moisture storage.

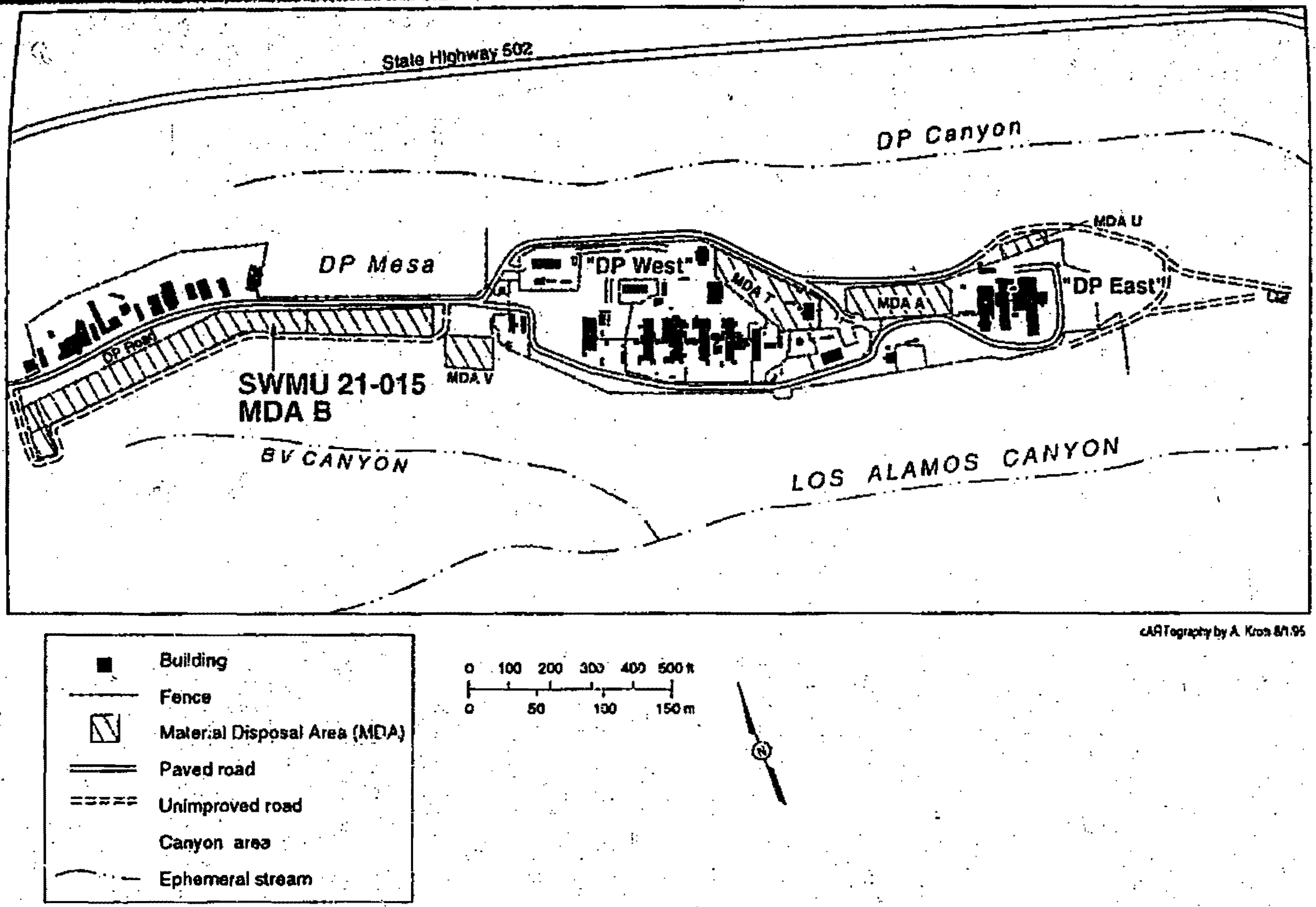


Figure 1a. Location of Materials Disposal Area B (MDA-B) in Los Alamos, NM.

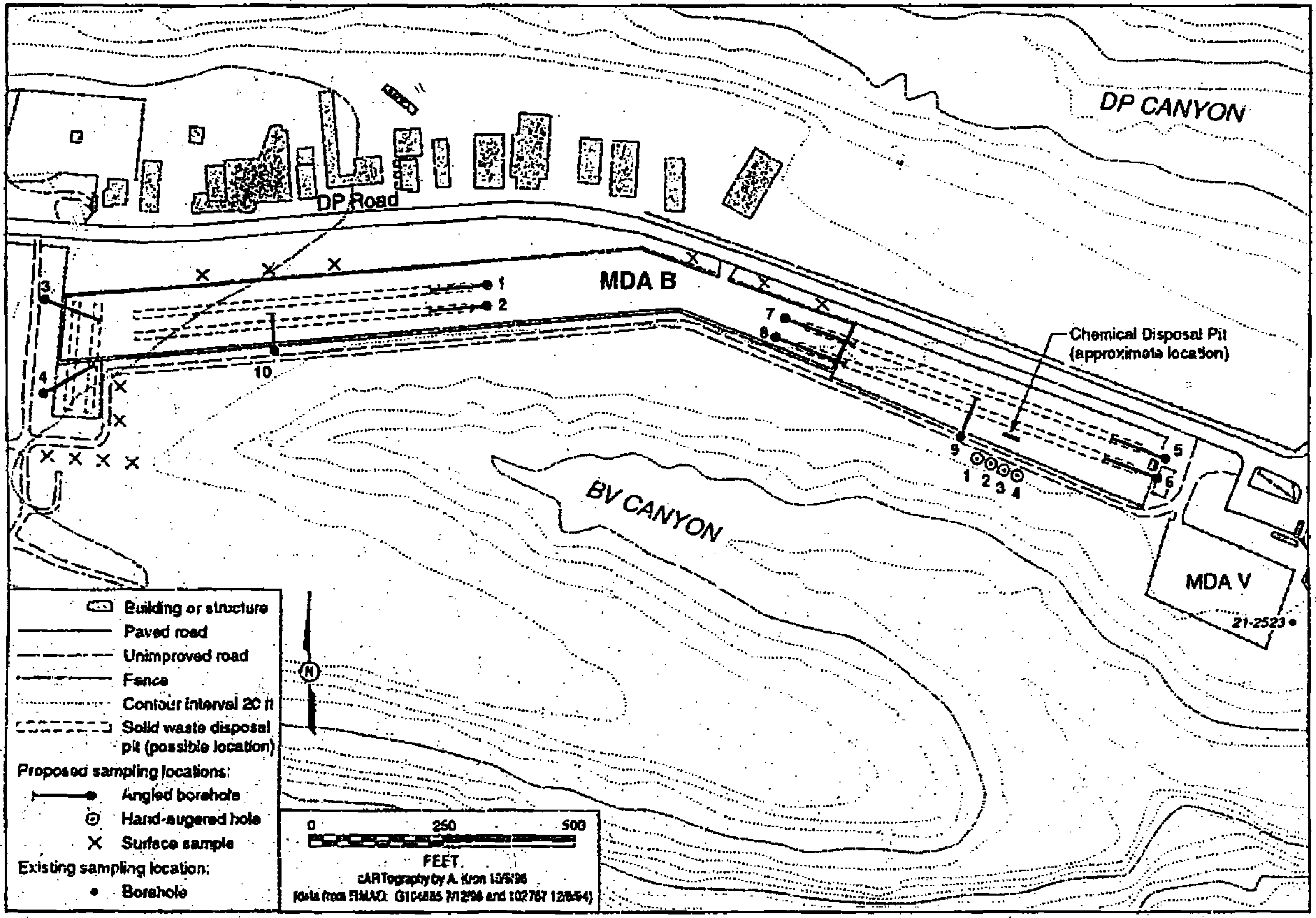


Figure 1b. Location of solid waste disposal pits at MDA-B.

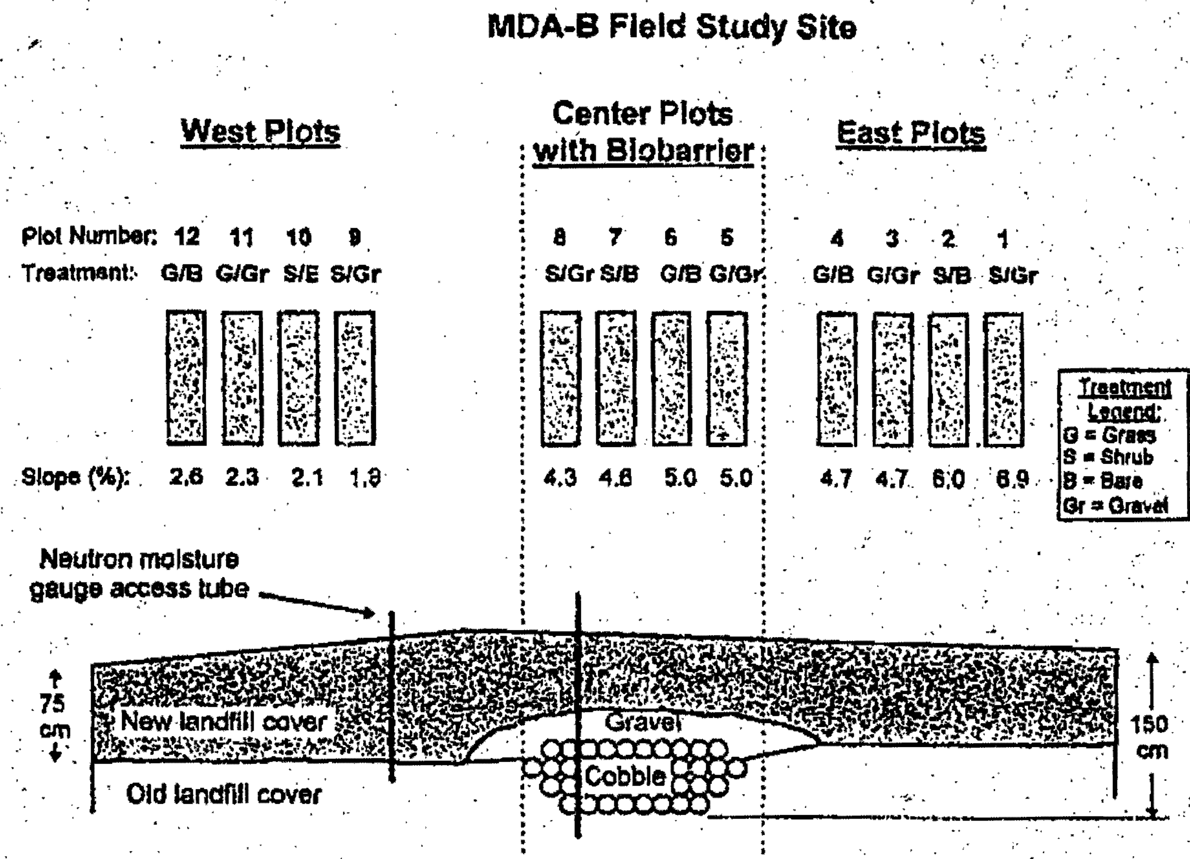


Figure 2a. *Plot locations, surface treatments, and average percent downhill slope for study plots at MDA-B (top), and a cross section of soil profile characteristics (bottom). For further details refer to plot map in Appendix A.*

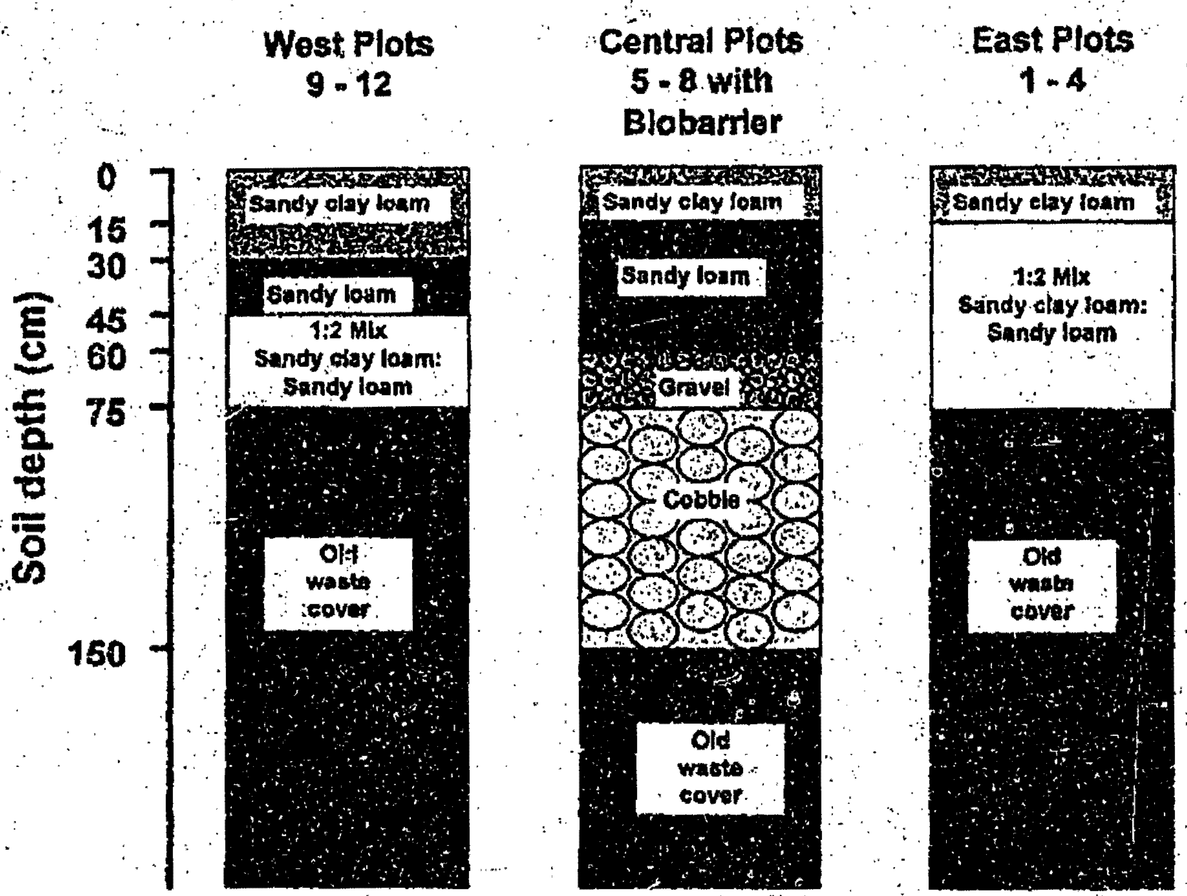


Figure 2b. Soil profiles on the east (Plots 1–4), central (Plots 5–8), and west (Plots 9–12) portions of the MDA-B study site. The central profile contains the gravel/cobble biobarrier.

A. Plot Construction

The soil and vegetation covers from the 1982 study were modified at shallow depths to create three soil profiles (Figure 2). The east and west portions of the site surface were replaced with a standard trench cover consisting of 147 cm of crushed tuff overlain by 75 cm of topsoil. The topsoil profile for the east portion was sandy clay loam (0–30 cm), sandy loam (30–45 cm), and a mixture of one part sandy clay loam to one part sandy loam (30–45 cm); the west profile was sandy clay loam (0–15 cm) and a mixture of one part sandy clay loam to two parts sandy loam (15–75 cm). Both the east and the west profiles were underlain by 147 cm of crushed tuff from the old waste cover. The central profile included a biobarrier, designed to prevent penetration into the waste by plant roots and burrowing animals to serve as a barrier to moisture flow. This center profile consisted of sandy clay loam (0–15 cm), sandy loam (15–60 cm), 25-cm diameter gravel (60–75 cm), and 10- to 30-cm diameter cobble (75–150 cm), underlain by 72 cm of crushed tuff from the old waste cover.

Four cover treatment plots were installed on each of the three soil profiles (Figure 2). These were shrub/gravel (shrub cover with gravel mulch), shrub/bare (shrub cover without gravel mulch), grass/gravel (grass cover with gravel mulch), and grass/bare (grass cover without gravel mulch). Each plot (3 m x 11 m) was oriented with the long axis parallel to the south-facing slope of the site. Downhill slopes (along the length of the plot) ranged from 1.9 to 6.9% (Figure 2), with the slopes across the width of the plots being less than 0.7% (Lopez et al. 1988).

B. Hydrologic Measurements

Throughout the entire study, precipitation was measured using a Universal Weighing Rain Gauge. The location and data collected daily from this gauge is presented in Appendices A and B, respectively. In 1987, an Omnidata meteorological station was installed so that we could also measure solar insulation, air temperature, and wind speed and direction. This data base is currently maintained in the Environmental Science Group data archives.

Measuring volumetric water content was performed using a Campbell Pacific Model 503 neutron moisture probe (CPN Corporation, Pacheco, California 94553; Serial Number 4519). All of the aluminum access tubes were 5.1 cm diameter, as specified in the calibration of each of the soils in the study area (Nyhan et al., 1994). Three access tubes were installed along the long central axis of each plot to a maximum depth of 100 cm on the east and west profiles and to 60 cm on the central profile to measure soil moisture with a neutron probe (these tubes are numbered 1 through 36). Soil moisture was also measured in tubes that were still in place from the 1982 study (these tubes were numbered in the 600s), for which the maximum depth was 180 cm. In general, soil moisture was measured at depths of 20, 40, 60, 80, and 100 cm for plots on the east (Plots 1–4) and west (Plots 9–12) profiles; and at depths of 20, 40, and 60 cm for plots on the central profile (Plots 5–8). The location of the access tubes is shown on a map presented in Appendix A, and the entire soil moisture data base is presented in Appendix D.

The plots were bordered with metal strips to prevent overland flow of runoff from entering the plot. The borders were made of 25 cm wide metal strips installed so that 16 cm was inserted in the soil and 9 cm extended above the soil surface. On the downslope end of each plot, a 40 cm-wide, 14 gauge metal end plate with a 5-cm lip was inserted into the soil so that the lip was flush with the soil surface. Total runoff from each of the 12 study plots was collected by a gutter system at the lower end of the plot and diverted through a buried drain pipe into collection tanks. The daily runoff data is summarized in Appendix E. Runoff volume (l) was initially estimated by measuring water depth in the collection tanks. Calibration curves were used to estimate water volume in the collection tanks as a function of depth. In May 1993, an automated system was installed to measure runoff volumes from the plots, using a computerized system of pressure transducers to measure water level in the runoff collection tanks located on the south side of the pilot study area.

Each of these runoff tanks is now equipped with a submersible pressure detector to continuously measure the water pressure and thus the water depth occurring during snowmelt and summer runoff events. A submersible sump pump in the bottom of the tank pumps water from this tank to a second large tank for backup and overflow measurement. Pressure monitoring, data logging, and pump control are performed by a personal computer in a weatherproof enclosure mounted on the south fence of MDA B.

Druck Incorporated depth transducers (model 940) were placed horizontally on the bottom of the tanks. This sensor is a temperature-compensated balanced bridge that is excited by 9 v DC and has a nominal output of zero volts. The device output is rationetric; the output is proportional to the excitation. In order to accurately measure the excitation over a 50 ft cable, the excitation was provided by one pair of wires and was measured using a second pair of wires connected directly to the device. This arrangement eliminates errors due to excitation voltage loss in the 50 ft cable. Volume data was logged to disk storage hourly as well as for any time that a significant event occurred. When the water level neared the top of the tank, the pump was turned on for approximately 20 seconds to return the water level to near the bottom of the tank. Water volume calibration was achieved by logging pressure sensor output at five levels of manually measured water volume.

The power sources for the instruments, computer, and pumps were twelve volt batteries, which were recharged and maintained by a conventional charger and small transformers. In case of AC power interruption, the electronics and pumps will operate for more than one hour on a full charge. The water heaters for freeze protection operated at 28 v AC.

Campbell Scientific temperature probes (model 107B) were placed alongside the pressure sensors, as well as in the personal computer, the battery charger enclosure, and external to the enclosure for measurement of ambient temperature. These devices incorporated a thermistor and resistor in series with a 1K ohm sensing resistor. Excitation of minus nine volts was applied to the device. The voltage drop across the 1K ohm sensing resistor indicated the current through the device, and therefore the resistance of the thermistor. Since the output was ratiometric, it was necessary to measure the excitation voltage accurately.

A Smith-Gates watertight automatic water warmer (model 450-50A2) was placed in the bottom of each runoff tank to keep the runoff from freezing in the winter. The water warmer contained an automatic internal thermostat, but power applied to it was controlled by the computer. It had a power rating of 450 watts at 120 v AC, which corresponds to 24.5 watts at 28 v AC. A temperature sensor in the bottom of the tank was monitored by the computer, which activated the water warmer when the temperature reached two degrees Celsius. The only space heated was the water in the 30-cm diameter tanks.

Lightning-induced transients on the incoming power line were snubbed and blocked by the varistors and a filter. Further suppression of power line voltage transients was accomplished with additional varistors. The purpose of the diode networks and adapters was to protect the electronics from lightning induced transients.

A few runoff samples were collected and processed to determine total sediment yield from each plot (Lopez et al., 1988; LANL, 1991; see Appendix F). Sediment yields from each plot for each runoff event were measured from April 1987 through February 1989. Personnel limitations precluded continuous measurement of soil loss on all plots from May through October 1989 soil erosion was measured on only the west soil profile (Plots 9-12, which includes one plot of each cover treatment type). Snowmelt runoff from all plots was measured in January and February of 1991. Subsequent erosion measurements were not obtained. The plots were instrumented to collect sediment in bags during the fall of 1993, after the automated runoff collection system had been installed, but no runoff occurred during the 1993 to 1994 winter, and hence no sediment was collected.

The water balance equation given below was solved for each time period in the study by using the precipitation and runoff data described previously.

$$\Delta S = P - Q - L - ET$$

(Equation 1)

where:

ΔS = change in soil water storage

P = precipitation

Q = runoff

L = seepage or percolation

ET = evapotranspiration

Evapotranspiration was determined by difference after estimating the change in soil water inventory and seepage. Soil water inventory was calculated for each plot by calculating the average volumetric water content for the 20-, 40-, and 60-cm depths (three locations per depth), dividing this number by 100, and multiplying this result by 60 cm (the thickness of the landfill cover).

When the original landfill cover restoration occurred at MDA B, we were not allowed to install a seepage collection system over portions of the old waste cover (Figure 2), even though this would have been the best technique for measuring the seepage term of the water balance equation. Thus, the water balance calculations for the study plots were performed on the 60-cm-thick landfill cover layer, with seepage estimated by increases in soil water inventory at the 80- and 100-cm depths for the east and west plots, and by increases in soil water inventory at the 160- and 180-cm depths (beneath the biobarrier) for the central plots.

Detailed graphs of the water balance calculations are presented for each sampling data in Appendix D.

C. Vegetation Measurements

Treatments for each soil profile included two vegetative covers: two plots with a shrub overstory of rubber rabbitbrush (*Chrysothamnus nauseosus*) and a sparse understory of mixed grasses and forbs, and two plots with a mixed grass and forb cover. One plot from each pair with the same plant cover was randomly assigned a gravel mulch treatment. The gravel had a diameter of less than 1.5 cm and was applied at 13 kg/m². Vegetation was periodically mowed to the north of the plots to maintain access along a dirt road and on the south side of the plots for maintenance around the collection gutters.

Plant canopy cover and ground cover (plant crowns, litter, and gravel) were estimated using a point frame. Detailed procedures for point frame measurements are provided in Appendix Q of the November 1991 Environmental Restoration Workplan for Los Alamos National Laboratory (LANL, 1991). Estimates were obtained once in 1987 (October), three times in 1988 (5/24–6/10, 7/19–7/22, and 8/23–9/02), once in 1989 (8/28–8/31), once in 1990 (7/17–7/19), and once in 1994 (10/1). These data are presented in Appendix G. Leaf area relationships reported in Barnes and Rodgers (1988) have been used previously to determine leaf area indices from the cover data from MDA B. Spherical volume of the cover and canopy of each shrub was estimated from shrub dimensions. The biomass of shrub cover has been estimated previously using relationships between shrub dimensions and biomass (Barnes and Rodgers, 1988).

III. RESULTS AND DISCUSSION

The hydrologic cycle at MDA B was characterized quantitatively by solving the water balance equation on a target biweekly time schedule. In this way we were able to keep an inventory of the water added to MDA B as rain and snow, and apportion these additions to changes in soil water inventory (calculated directly from the volumetric water content data collected at each sampling depth), evapotranspiration, runoff, and seepage. Water balance data is presented in a group of 120 figures in Appendix D for every set of measurements collected from March 1987 through June 1995.

A. Precipitation Probabilities for Study Site

The overall significance of each year's water balance data can perhaps best be understood by first understanding the spatial and temporal occurrence of precipitation around the Laboratory (Bowen, 1990). Proceeding from the Jemez Mountains on the western border of Los Alamos County to the Rio Grande to the east, Bowen shows that mean annual precipitation decreases from 45.3 cm at TA-59 to only 33.7 cm at White Rock. The overall pattern of annual mean precipitation across the county (presented in Figure 3.3 of Bowen, 1990) leads us to believe that the precipitation at MDA B can be estimated by an average of these two reporting stations, each of which has a much longer data base than the precipitation data base we have collected in our field study at MDA B. However, since two different probability distributions of annual precipitation are involved, we decided to compared our MDA B data with the Los Alamos precipitation data. Using the probability distributions of Los Alamos annual precipitation (Bowen, 1990), we used a regression model to predict the probability (Y) of having an annual precipitation event (X):

$$Y = -3.6133 + (1.0751)(\ln X)$$

(Equation 2)

This model successfully predicted probability from cm of annual precipitation with a coefficient of determination of 0.967 and a standard error of 7.41.

The information presented in Table 1 has been obtained from Bowen's report, which summarizes precipitation probabilities for Los Alamos (TA-59) and from predictions of precipitation probabilities from Equation 2 for our study site at MDA B. The data presented in the first column of Table 1 represent the percentage of time that precipitation is less than, or equal to, the specified amount of precipitation for a given year. The frequency of the mean annual precipitation event occurring within 100 years is presented in the second column (an event occurring 50% of the time is listed as occurring once every two years, or a two-year event, corresponding to a precipitation value of 39.1 cm).

TABLE 1.
ANNUAL PRECIPITATION PROBABILITIES FOR LOS ALAMOS AND MDA B STUDY SITE.

		Annual precipitation (cm)		
Percentage	Frequency of event	Los Alamos	MDA-B study site	Year of study
≤ 5.00 [a]	1.05-year	28.8		
≤ 10.0 [a]	1.11-year	33.4		
≤ 17.2 [b]	1.21-year		33.8	1992
≤ 19.4 [b]	1.24-year		34.5	1993
≤ 25.0 [a]	1.33-year	39.0		
≤ 37.9 [b]	1.61-year		41.0	1994
≤ 39.2 [b]	1.65-year		41.5	1990
≤ 40.3 [b]	1.67-year		41.9	1989
≤ 49.1 [b]	1.97-year		45.5	1991
≤ 50.0 [a]	2.00-year	45.3		
≤ 72.4 [b]	3.62-year		56.5	1988
≤ 90.0 [a]	10-year	64.5		
≤ 95.0 [a]	95-year	74.3		

[a]Estimates from Bowen (1990).
[b]Probability values estimated from regression analysis model.

From this analysis of the precipitation data, we can now see the overall significance of the precipitation data collected in this field study, which is listed in the fourth column of Table 1 by calendar year (last column). Of the seven full years of data in this study, we observed two dry years which were about once in 1.2 year events (1992 and 1993). There were three years (1989, 1990, and 1994) in which annual precipitation ranged from 41.0 to 41.9 cm, resulting in about 1.6-year events. The amount of precipitation received in 1991 is so close to Bowen's predicted 2.00-year event that we are referring to it as such in the remainder of this report. We observed a 3.62-year event in 1988 when the site received 56.5 cm of precipitation.

B. Water Balance Estimates

The water balance estimates for each of the 12 field plots will be presented in the next three subsections for a once in two-year event (1989), for a once in ten-year event (1988), and for the entire life of the field experiment.

1. A Once in Two-year Event Year: 1991

The water balance data collected in 1991 is summarized in Table 2. This year was chosen because it was the first year of the study that could be categorized as an approximate two-year event. The data presented in Table 2 shows that evapotranspiration made up the largest component of the loss of the 45.5 cm of precipitation from the plots, comprising 71% of the average across all plots. However, the grass plot without gravel mulch (number 4) exhibited only 25.82 cm of evapotranspiration during 1991, largely due to a loss of 16.14 cm of runoff during the year. Runoff was greatly reduced on plots that had a gravel mulch in 1991, with the highest runoff rates being found on the grass plots without gravel mulch. The shrub plots without gravel mulch exhibited from 4.41 to 14.00 cm of runoff.

The seepage term of the water balance equation (described in more detail in subsection 3 of Part III of this report) varied greatly from plot to plot. The average amount of seepage for all of the plots was equal to 0.92 cm, approximately 2% of the total annual precipitation for 1991. A little less seepage was observed on the plots containing the shrubs, suggesting that shrub covers appear to have depleted soil moisture deeper in the profile than plots with grass cover.

TABLE 2.
WATER BALANCE SUMMARY FOR 1991 FOR ALL PLOTS AT MDA B. TOTAL PRECIPITATION RECEIVED BY THE STUDY SITE WAS 45.5 CM, CORRESPONDING TO A ONCE IN TWO-YEAR EVENT.

			Water balance parameter (cm)			
Treatment	Plot Number	Location	Runoff	Seepage	Soil water inventory	Evapotranspiration
shrub/gravel	1	east	6.06	1.00	2.79	35.62
	8	center	4.72	1.68	10.26	28.82
	9	west	3.37	0.00	4.50	37.60
shrub/bare	2	east	14.00	0.66	2.55	28.26
	7	center	9.20	1.68	6.01	28.59
	10	west	4.41	0.00	7.15	33.91
grass/gravel	3	east	7.31	0.55	2.01	35.60
	5	center	3.20	1.68	6.07	34.52
	11	west	5.47	1.61	2.95	35.43
grass/bare	4	east	16.14	0.50	3.01	25.82
	6	center	3.99	1.68	1.86	32.15
	12	west	8.39	0.00	3.63	33.45
	Average of all plots:		7.19	0.92	4.40	32.48

2. A 3.62-year Event: 1988

The water balance data collected in 1988 is summarized in Table 3. This year was chosen because it was the wettest year of the study and could be categorized as an approximate 3.62-year event (Table 1).

The evapotranspiration term of the water balance equation was still the largest term, accounting for an average, across all of the plots, of 44.13 cm (78%) of the 56.54 cm of total precipitation received in 1988. The next largest term was the runoff term, which accounted for an average (across all plots) of 16% of the 56.54 cm of precipitation. Again, two of the plots without the gravel mulch demonstrated the largest amounts of runoff measured to date in this field study. Grass/bare plot number 4 and shrub/bare plot number 2 lost 29% and 28%, respectively, of the precipitation added to these plots in 1988.

Although the seepage term was a smaller proportion of the water balance equation than the runoff term, the amounts of seepage occurring on these plots represent to our knowledge the largest amounts of seepage measured on landfills in a semiarid environment. The average across all of the plots amounted to 3.5 cm of flow, or approximately 6% of the precipitation received by the site. Although most of the annual seepage ranged from 2 to 4 cm for most of the plots (Table 3), plot number 1 with the shrub/gravel treatment produced over 10 cm of seepage, representing 18% of the annual precipitation. Thus, unlike in the two-year event discussed previously, the water uptake rates of the shrub roots deeper in the soil profile were much smaller than the infiltration of water through the soil profile in this wet year.

3. Entire Field Study

The water balance data collected over the entire life of the field study to date is presented in Table 4 to give the site operator the idea of what changes to expect over an eight year time period at MDA B (from March 19, 1987, through June 30, 1995). Since most of the years of this field study were not like the 3.62-year event discussed in the previous section, we should expect to see smaller percentages of runoff and seepage and a larger percentage of evapotranspiration in the water balance equation. The data in Table 4 show that evapotranspiration accounts for an even larger proportion of the total precipitation received by the site than either the two-year or the 3.62-year events discussed previously. Evapotranspiration accounted for an average of about 90% of the water loss across all of the plots over the life of the field study. Runoff is the second largest component, comprising 31.36 cm (expressed as an average across all plots) of the total 332.69 cm of precipitation (Table 4). Seepage over the life of the field study amounted to about 3% of the precipitation, amounting to almost 10 cm of average flow across all of the plots (Table 4). The largest amounts of seepage for this time period were observed on two plots with the grass/gravel cover, and these plots exhibited about 16 cm of seepage, amounting to about 5% of the precipitation received by the site.

From the data presented in Table 4, it is obvious that the shrub/gravel surface treatment appears to be the best surface treatment for a landfill because of the fact that through June 30, 1995 total precipitation received by the study site was 332.69 cm.

C. Relationship of Landfill Slope to Runoff and Seepage

Many of the data interpretations are not quite as simple as presented in the Water Balance Estimates section of this report, since all of the field plots did not have the same steepness (Figure 2). The plots had slopes ranging from 1.9 to 6.9%, and previous studies have documented that both the length and steepness of the land slope can substantially affect runoff and soil loss and are included as the Topographic Factor in the USLE (Nyhan and Lane, 1986). Thus, the runoff data collected in the field from resulting in the overall expected trend of increased runoff for plots at larger slopes. For example, the runoff for the field plots with the shrub/bare surface treatment exhibited 24 and 60 cm of runoff as the steepness of the plots increased from 2.1 to 6.0%, respectively.

However, three of the field plots exhibited reduced runoff over the life of the field experiment as slope increased (Figure 3). For example, the grass/bare plot with a slope of 4.7% (Plot number 4) exhibited 64.7 cm of runoff, the largest amount of runoff observed in any of the plots (Table 4). Increasing the slope to 5% on field plots having a similar surface treatment should have increased the amount of runoff observed in the field, but only 13.4 cm was actually observed (Figure 3). Likewise, the plots with the shrub/gravel treatment had 12.03 cm runoff at a slope of 1.9% whereas only 28.21 cm of runoff was observed at a slope of 6.9%, in spite of the fact that a plot (shrub/bare plot) with a similar slope (6%) had 60.2 cm of runoff. Thus, the influence of slope is not the only factor influencing the runoff relationships portrayed in Figure 3. As we will elaborate in more detail in the next section of the report, the major reason for the reduced runoff in these plots with the larger slopes was attributed to larger amounts of plant cover.

TABLE 3.
WATER BALANCE SUMMARY FOR 1988 FOR ALL PLOTS AT MDA B. TOTAL PRECIPITATION RECEIVED BY THE STUDY SITE WAS 56.54 CM, APPROXIMATELY CORRESPONDING TO A 3.62-YEAR EVENT.

			Water balance parameter (cm)			
Treatment	Plot Number	Location	Runoff	Seepage	Soil water inventory	Evapotranspiration
Shrub/gravel	1	east	10.71	10.19	0.88	41.73
	8	center	3.42	2.28	1.65	49.19
	9	west	4.18	3.22	0.18	48.96
Shrub/bare	2	east	13.67	2.31	-0.18	40.74
	7	center	15.63	2.28	1.23	37.40
	10	west	9.40	3.96	-0.56	43.75
Grass/gravel	3	east	11.62	4.52	-1.26	41.67
	5	center	1.74	2.28	5.50	47.01
	11	west	5.81	3.82	-1.55	48.47
Grass/bare	4	east	16.36	2.63	-0.95	38.50
	6	center	1.60	2.28	-1.77	47.87
	12	west	12.25	2.21	-1.64	44.29
	Average of all plots:		8.86	3.50	0.13	44.13

TABLE 4.
WATER BALANCE SUMMARY FOR ALL PLOTS AT MDA B FROM MARCH 19, 1987 THROUGH JUNE 30, 1995. TOTAL PRECIPITATION RECEIVED BY THE STUDY SITE WAS 332.69 cm.

			Water balance parameter (cm)			
Treatment	Plot Number	Location	Runoff	Seepage	Soil water inventory	Evapotranspiration
Shrub/gravel	1	east	28.21	9.39	-2.58	297.67
	8	center	14.64	4.72	-7.49	320.82
	9	west	12.03	9.39	-9.28	320.54
Shrub/bare	2	east	60.20	11.84	-3.18	263.83
	7	center	49.82	4.72	-7.44	285.60
	10	west	24.38	9.64	-3.75	302.42
Grass/gravel	3	east	35.63	17.52	-3.23	282.78
	5	center	8.55	4.72	-5.29	324.71
	11	west	22.87	14.59	-9.18	304.41
Grass/bare	4	east	64.66	12.19	-2.80	258.64
	6	center	13.41	4.72	-7.41	321.97
	12	west	41.97	12.03	-4.62	283.31
	Average of all plots:		31.36	9.62	-5.52	297.22

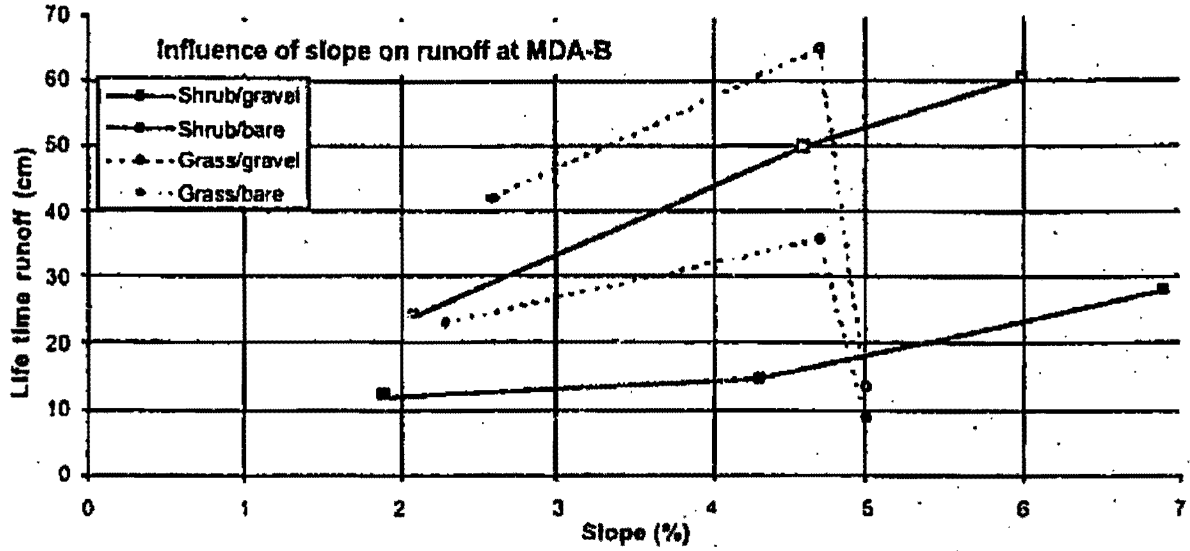


Figure 3. Influence of slope on amounts of runoff measured over the life of the field experiment at MDA B.

Omitting the slope and runoff data from the three previously mentioned plots, the data shown in Figure 3 was subjected to regression analysis using an exponential model. This model expressed lifetime runoff (Y), received from March 19, 1987, through June 30, 1995, as a function of percent slope (X) as:

$$Y = -2.040 + (15.98)(e^{-X/-4.1949})$$

(Equation 3)

Considering that plant cover and soil profile (Figure 2) differences had not been taken into account, this model successfully related runoff and slope. The coefficient of determination, r^2, for the regression model was only 0.48 and the standard error of the model was 15.98 cm of runoff. This model predicts that as the slope increases from 2 to 6%, a 2.7-fold increase in runoff should occur. This difference in runoff with increasing slope agrees quite well with the 3.1-fold change in soil loss predicted to occur for plots with these slopes and slopelengths using the USLE (Nyhan and Lane, 1986).

According to recent guidance on the design of landfill covers (US EPA, 1989), landfill covers should have a slope ranging between 3 to 5%, but not more than 5%. The reason given by EPA for this recommendation was that as slope increases, it is at this slope range that increases in runoff are optimized with decreases in seepage. We analyzed our field data to see if this relationship could be valid for our site. The results are presented in Figure 4, in which we have plotted lifetime runoff and seepage verses percent slope. Our field data does not support this conclusion: as slope increases, runoff increases, but seepage demonstrates no significant relationship with either slope or runoff.

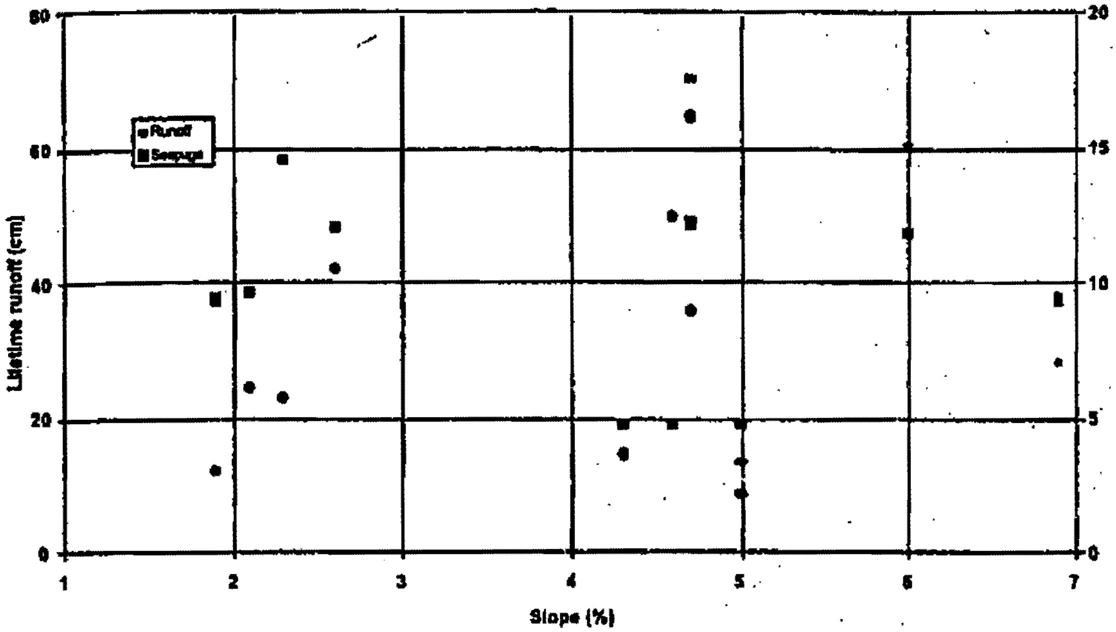


Figure 4. ***Lifetime runoff and seepage on all of the MDA B field plots as a function of slope.***

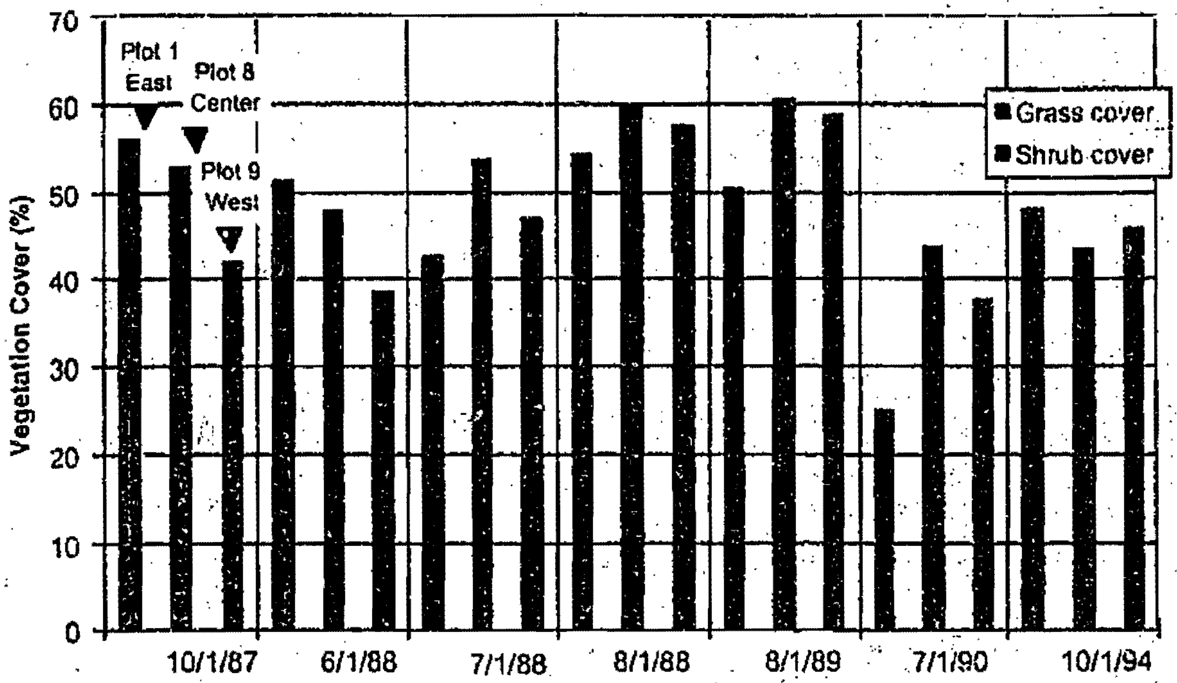
[illegible] Vegetation and Water Balance Dynamics

[illegible] species list for the MDA B plots is presented in [illegible] describing the forbs, grasses and shrubs found on [illegible] plots in 1994. Both the scientific and common [illegible] presented in this table, according to previous [illegible] Los Alamos (Foxx and Tierney, 1985) and [illegible] of western North America (Spellenberg, 1979). [illegible] NTS database provided by the Natural Resources [illegible] tion Service (NRCS) of the United States Depart- [illegible] griculture (USDA) was also consulted as a [illegible] (USDA, NRCS, 1995).

Plant cover data collected from 1987 through 1994 on the MDA B study plots are presented for the plots receiving the shrub/gravel and shrub/bare treatments (Figure 5) and for the plots receiving the grass/gravel and grass/bare treatments (Figure 6). More details are presented in Appendix G. The first interesting observation that can be made about this plant cover data is that once a vegetation treatment of either shrubs or grass is applied, this treatment seems to be dominant over this eight-year time span.

TABLE 5.
PLANT SPECIES FOUND ON THE MDA B FIELD PLOTS IN 1994.

Scientific name	Common name
Forbs:	
Artemisia carruthii	Carruth's sagewort, wormwood
Artemisia dracunculus	False tarragon
Artemisia frigida	Fringed sagebrush
Artemisia ludoviciana	Louisiana wormwood
Chenopodium fremontii	Fremont's goosefoot
Chrysopsis villosa	Hairy goldenaster
Cirsium undulatum	Wavyleaf thistle
Convolvulus arvensis	Field bindweed
Conyza canadensis	Horseweed, Canadian horseweed
Erigeron divergens	Spreading fleabane
Erigeron flagellaris	Trailing fleabane
Euphorbia serpyllifolia	Thymeleaf sandmat, thymeleaf spurge
Geranium caespitosum	Purple geranium
Grindelia aphanactis	Curlytop gumweed, gumweed
Gutierrezia sarothrae	Snakeweed
Lycurus phleoides	Common wolfstail, wolftail
Machaeranthera bigelovii	Bigelow aster, Bigelow's tansyaster
Medicago sativa	Alfalfa
Melilotus albus	White sweet clover
Melilotus officinalis	Yellow sweet clover
Mentzelia pumila	Golden balzing star, dwarf mentzelia
Muhlenbergia montana	Mountain muhly
Oenothara hookeri	Hooker's evening primrose
Salsola kali	Prickly Russian thistle
Sphaeralcae sp.	Globemallow
Sporobolus cryptandrus	Sand dropseed
Thelesperma trifidum	Stiff greenthread, greenthread
Tragopogon dubius	Yellow salsify, salsify, goatsbeard
Taraxacum officinale	Common dandelion
Trifolium repens	White clover
Verbascum thapsus	Flannel mullein, common mullein
Grasses:	
Agropyron desertorum	Russian wheatgrass
Agropyron smithii	Western wheat grass
Bahia dissecta	Yellow ragweed, bahia, ragleaf bahia
Bouteloua gracilis	Blue grama
Bromus inermis	Smooth brome, Hungarian brome
Festuca ovina	Sheep fescue
Shrubs:	
Chrysothamnus nauseosus	Rubber rabbitbrush



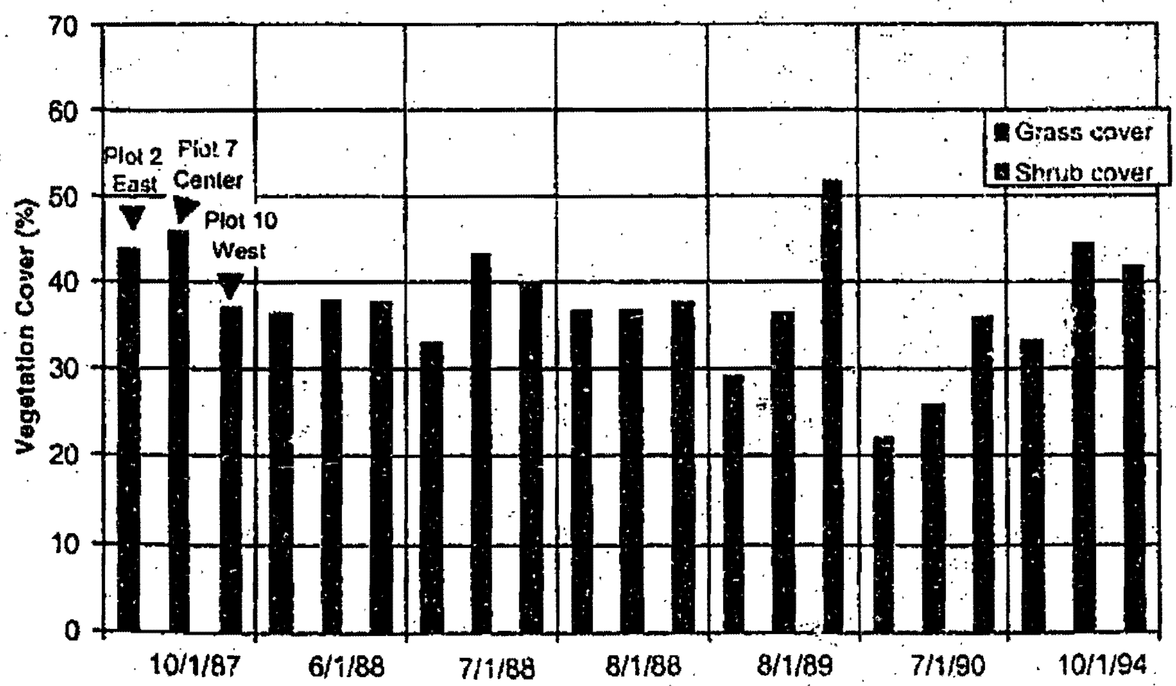
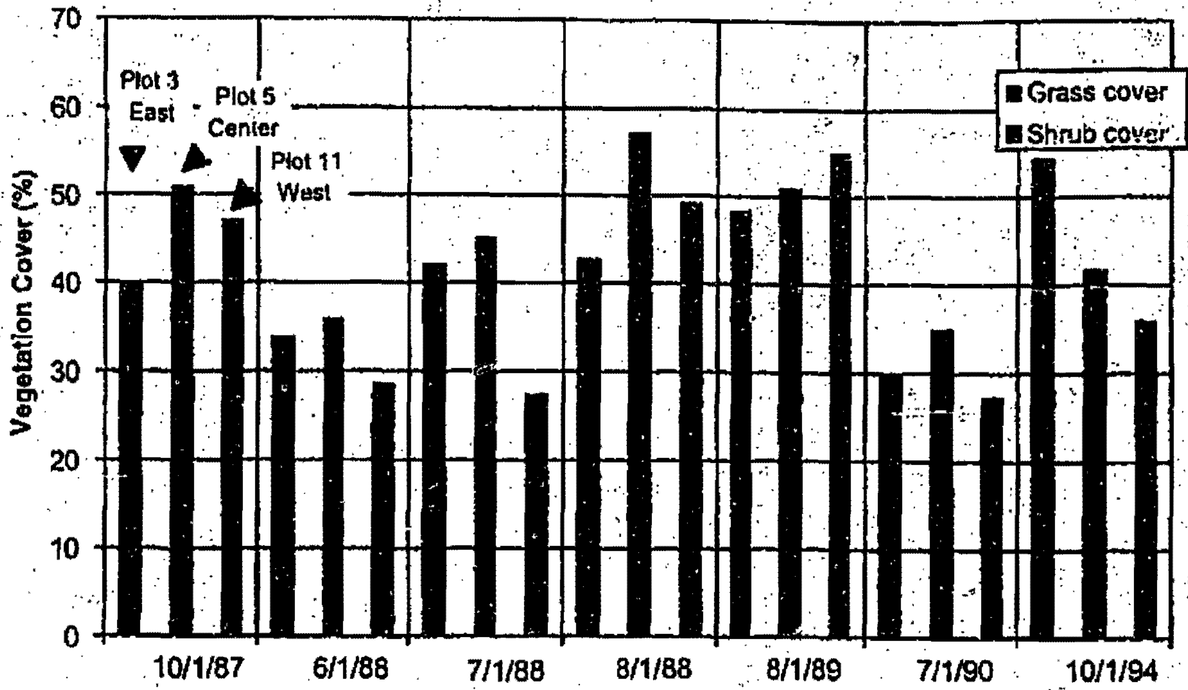


Figure 5. *Grass and shrub cover on MDA B study plots with the shrub/gravel and shrub/bare treatments from 1987 to 1994.*



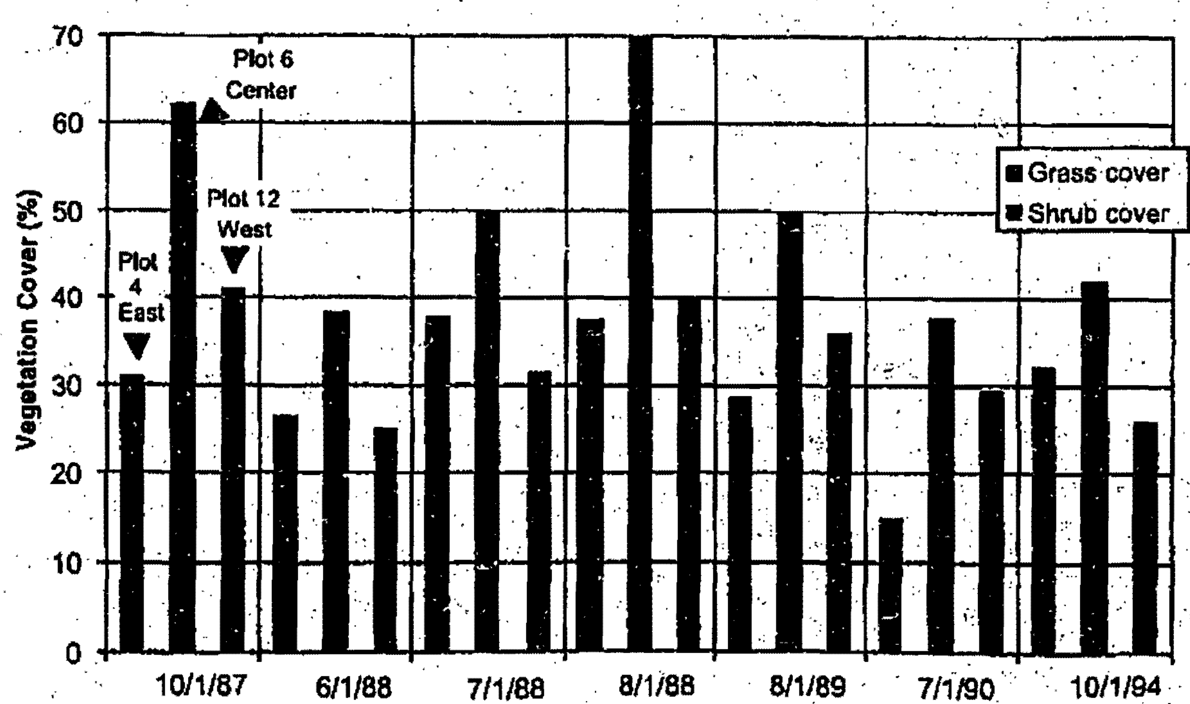


Figure 6. *Grass and shrub cover on MDA B study plots with the grass/gravel and grass/bare treatments from 1987 to 1994.*

Thus, the average shrub covers observed in the shrub/gravel and the shrub/bare treatments over this time period were 25.4 and 21.2%, respectively (Figure 5). Some of the shrubs in plots 1 and 2 did not survive after a couple of years after being planted, resulting in shrub cover estimates of less than 5% for these plots in 1994. The plots receiving the grass treatments were kept free of shrubs during 1987 and then natural succession of shrubs was allowed to occur. In spite of this natural succession, the average shrub covers observed on the plots with grass/gravel and grass/bare treatments were 1.6 and 1.4%, respectively (Figure 6). Thus, the plots receiving grass vegetation as a surface treatment persistently contained 40.2% (grass/gravel treatment) and 36.0% grass cover (grass/bare treatment).

1. Gravel Mulch

The second interesting observation has to do with the influence of the gravel treatment on the plots: gravel with a diameter of less than 1.5 cm and was applied at 13 kg/m^2. The gravel mulch increased the plant cover on our study plots (Figures 5 and 6).

The shrub and grass cover estimates were averaged over time and are presented for each of the field plots in Table 6 to further illustrate this point. On the plots where shrubs were added (shrub/gravel and shrub/bare treatments), plots receiving no gravel mulch averaged 21.2% shrub cover, while plots with gravel had a 20% larger percent cover of shrubs (Table 6). However, the influence of gravel mulch was even more pronounced on the grass cover on these plots, where the average grass cover on the plots with no gravel was 16.3%, compared with a 42% increase in percent grass cover due to gravel mulch. Similar results were observed with grass cover on the plots where only grass was added to the plots, except for the plots in the center location (Table 6).

2. Evapotranspiration

More evapotranspiration usually occurred during the warm summer months than during the other seasons on all of our study plots. Figure 7 presents the monthly estimates of evapotranspiration (summed from weekly estimates of evapotranspiration) plotted as a function of time for the entire life of the experiment for two plots in the western area of MDA B (Figure 2). Evapotranspiration estimates for some months usually exceeded 10 cm in the summer, and exceeded 15 cm in 1991 and 1992.

Negative evapotranspiration (Figure 7) usually occurred in the winter, and represents time periods when either snow is intercepted by the vegetative cover or the snow undergoes sublimation: in either case, the water is never added to the topsoil as liquid water, but is measured as precipitation at the rain gauge. Rabbitbrush covers commonly intercepted snow during the winter and this snow was commonly maintained aboveground in their voluminous canopies, potentially making the snow more available for sublimation processes. This relationship probably occurred in the winter of 1989 and the late fall of 1991, periods when negative evapotranspiration on the plot with the shrub cover exceeded that on the plot with the grass cover (Figure 7).

TABLE 6.
AVERAGE GRASS AND SHRUB COVER FOR SHRUB AND GRASS TREATMENT PLOTS WITH AND WITHOUT GRAVEL MULCH AT MDA B.

Plot Location	Average grass cover (%)		Average shrub cover (%)	
	With gravel mulch	No gravel mulch	With gravel mulch	No gravel mulch
Shrub treatment plots				
East	24.8	16.6	22.1	17.2
Center	21.9	18.2	29.9	20.6
West	22.7	14.5	24.1	25.8
Average:	23.1	16.3	25.4	21.2
Grass treatment plots				
East	41.0	29.7	0.7	0.1
Center	45.1	49.9	0.3	0.1
West	34.7	28.6	3.9	4.1
Average:	40.2	36.1	1.6	1.4

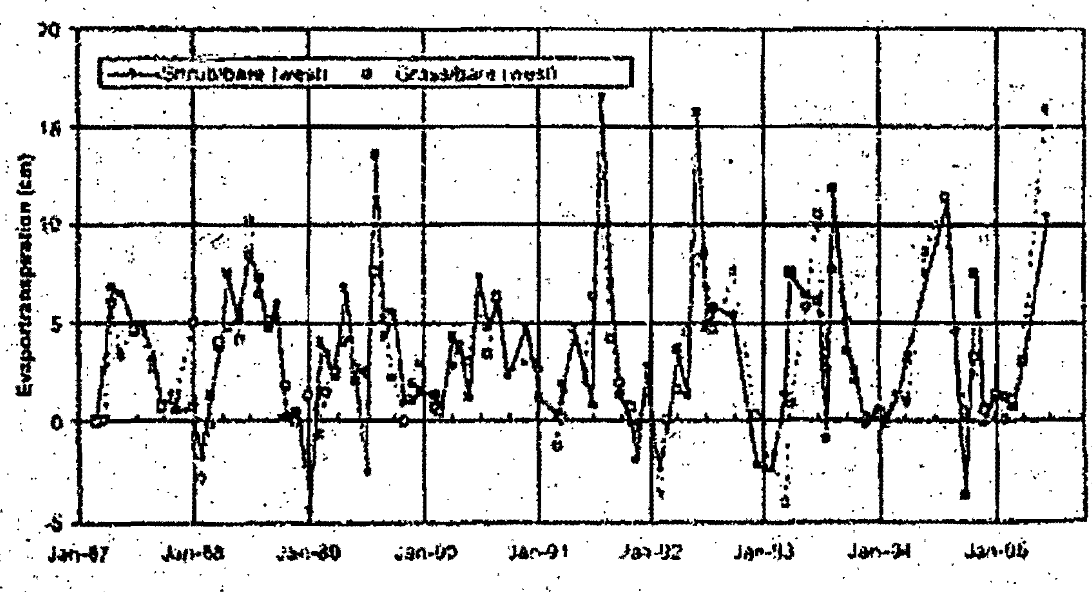


Figure 7. Monthly evapotranspiration for MDA B west plots with shrub/bare and grass/bare covers.

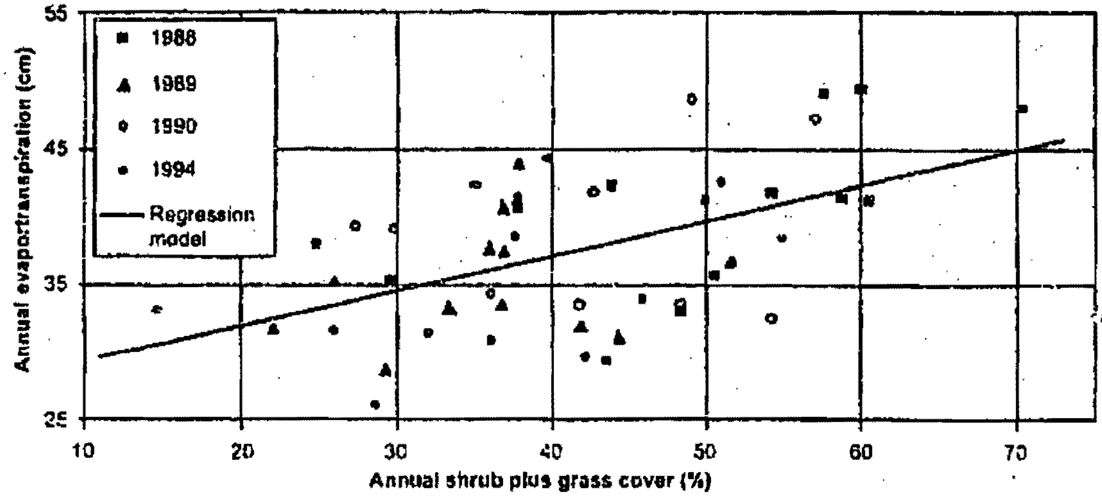
Plots with predominantly shrub cover usually exhibited larger evapotranspiration than plots with grass cover, in spite of the large negative evapotranspiration values occasionally observed on the plots with shrub cover (Figure 7). The evergreen shrubs (*Chrysothamnus nauseosus*) used in this field study typically grew year-round, whereas the grasses and forbs (Table 5) are usually dormant from October to April. Rabbitbrush is not an evergreen plant in the sense of a plant like a ponderosa pine, but even if rabbitbrush loses its leaves in the early winter, this plant can transpire because it still has green stems. Thus, we compared the amounts of lifetime evapotranspiration occurring on the field plots for two time periods: May through September (grasses, forbs and shrubs actively transpiring) and October through April (only shrubs transpiring, but at a reduced rate). This seasonal difference in evapotranspiration is presented for all of the plots in the western and eastern portions of MDA B in Table 7.

The data in Table 7 is presented to demonstrate that plots with shrub covers usually exhibited more evapotranspiration than plots containing grass covers over the life of the field experiment (from March 19, 1987, through June 30, 1995). This was accomplished by grouping the data by pairs of surface treatments whose only difference is predominantly shrub or grass cover, as well as by western and eastern plots, since the soil profiles in these two areas are dissimilar. Thus, comparing the shrub/bare and grass/bare treatments in the western plots (Figure 7), we discovered that there was 2.8 cm more evapotranspiration on the shrub/bare plot than on the grass/bare plot between May through September and that this difference amounted to 16.3 cm between October through April. The shrub/gravel western plot exhibited 10.6 cm more evapotranspiration than the corresponding grass/gravel plot between May through September, and 5.6 cm more evapotranspiration between October through April (Table 7); similar relationships for this treatment pair occurred on the eastern plots. This data supports the conclusion that landfill covers containing rabbitbrush can evapotranspire more water out of the soil profile than covers with only grass vegetation, and that this total yearly difference can be as much as 19.1 cm.

Plant cover on the MDA B field plots was related to evapotranspiration both on an annual basis and for the life of the field experiment (March 19, 1987, through June 30, 1995), representing the first field determination of this relationship at Los Alamos. Since we only collected plant cover data on four of the years of this field study, the annual evapotranspiration estimates for all of the plots for these years were compared by year (top part of Figure 8) and surface treatment (bottom part of Figure 8). Shrub plus grass cover annual values for all of the plots ranged from 14.7 to 70.4% as annual evapotranspiration estimates ranged from 26.3 to 49.2 cm (Figure 8). The estimates of plant cover and annual evapotranspiration were significantly smaller for all of the plots in 1989 than in 1990 (Figure 9). Annual shrub plus grass cover was significantly related to annual evapotranspiration using the data from all of the field plots (Figure 8), but exhibited considerable variation (the coefficient of determination, r^2, for the linear regression model was only 0.27 and the standard error of the model was 4.99 cm of water). In spite of the temporal and spatial variation in the field data, the regression model predicts that doubling percent annual shrub plus grass cover (30% verses 60% cover) results in a 22% increase in annual evapotranspiration.

TABLE 7.
SEASONAL DIFFERENCE IN LIFETIME EVAPOTRANSPIRATION (FROM MARCH 19, 1987, THROUGH JUNE 30, 1995) FOR THE WESTERN AND EASTERN MDA B PLOTS.

Treatment	Plot Number	Evapotranspiration (cm) for: May-September	October-April
Western plots			
Shrub/gravel	9	247.1	73.4
Grass/gravel	11	236.5	67.9
Shrub/bare	10	222.3	80.1
Grass/bare	12	219.5	63.8
Eastern plots			
Shrub/gravel	1	224.1	73.6
Grass/gravel	3	214.1	68.7
Shrub/bare	2	204.2	59.7
Grass/bare	4	193.3	65.4



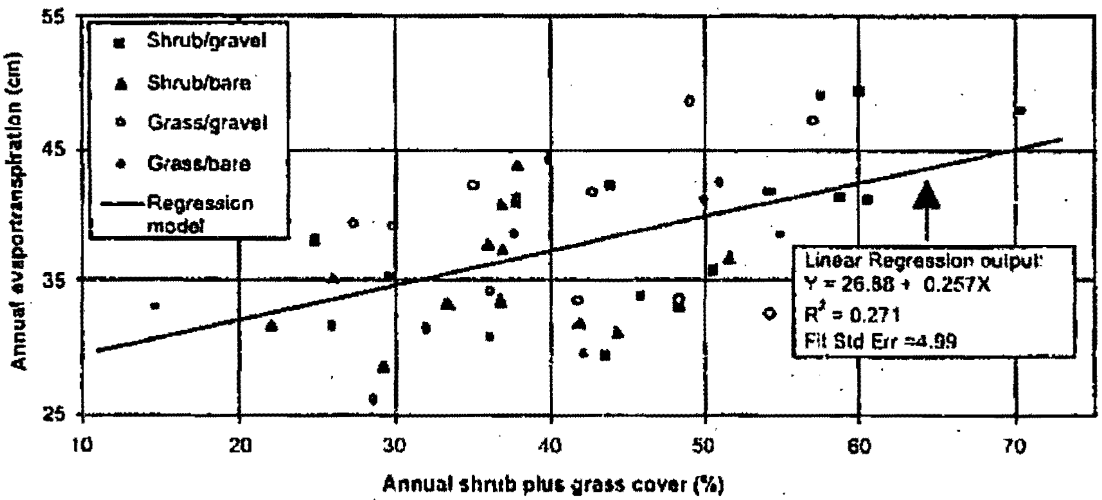


Figure 8. Annual evapotranspiration as a function of shrub plus grass cover for the MDA B field plots. The upper portion of the figure presents this data for the four years where plant cover data was collected, whereas the lower portion of the figure presents the same field data only as a function of surface treatment.

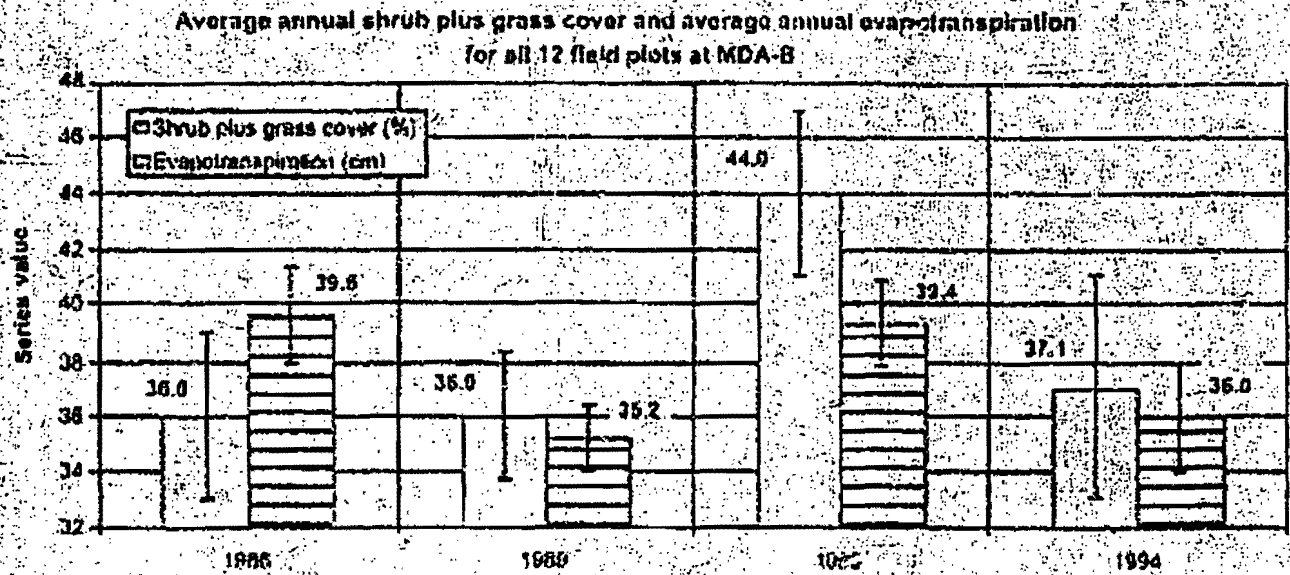


Figure 9.- Average annual shrub plus grass cover and evapotranspiration for MDA B field plots. Each number represents the average annual value, with error bars to indicate plus or minus the standard error of the value.

The annual field data presented in Figure 8 was then used to determine if there was a relationship between shrub plus grass cover and evapotranspiration over the entire field study (from March 19, 1987, through June 30, 1995), commensurate with long-term performance standards in landfill cover regulations. We first estimated the percent shrub plus grass cover for the years of the field experiment where we did not have data by performing a linear interpolation of these values for each field plot and determining the average annual shrub plus grass cover to reduce temporal variation.

This value was then averaged for of the three field plots containing each of the four surface treatments to reduce spatial variation. This final average annual shrub plus grass cover number was then plotted as a function of lifetime evapotranspiration for each of the four surface treatments at MDA B (Figure 10). The statistical analysis of this long-term plant cover-evapotranspiration data (Figure 10) showed much less variation than the annual data presented in Figure 8. The linear regression model of this data predicts that doubling the percent shrub plus grass cover (25% verses 50%) on the landfill cover increases lifetime evapotranspiration by 28%. There was a substantial reduction in spatial and temporal variation in this data, as evidenced by an r^2 value of 0.796, and a standard error of the regression model of only 10.2 cm over the life time of the field data collection efforts.

A quantitative evaluation of plant dry matter production requires a knowledge of the net photosynthesis of individual leaves, as well as that of the total leaf area (Chang, 1971). The leaf area index (LAI) is the leaf area subtended per unit area of each field plot. Several hydrologic models require an estimate of LAI as input for calculating utilization of soil water by plants (Nyhan and Barnes, 1989). Using the relationships developed previously (Barnes and Rogers, 1988), LAI estimates were derived for each of the field plots during October and November, 1994 (Appendix G). Shrub volumes were used to estimate total shrub biomass and shrub leaf biomass, which were subsequently used to estimate LAI. Shrub volumes on the shrub/gravel and shrub/bare plots ranged from 0.48 to 15.69 m^3, resulting in shrub biomass estimates ranging from 334 to 9673 g per field plot. This range of shrub biomass for these plots resulted in shrub leaf biomass estimates of 59 to 1712 g per field plot. Foliar LAI values were also made, and added to the resulting shrub LAI estimates, resulting in total foliar and shrub LAI estimates ranging from 0.34 to 0.70 cm^2/cm^2.

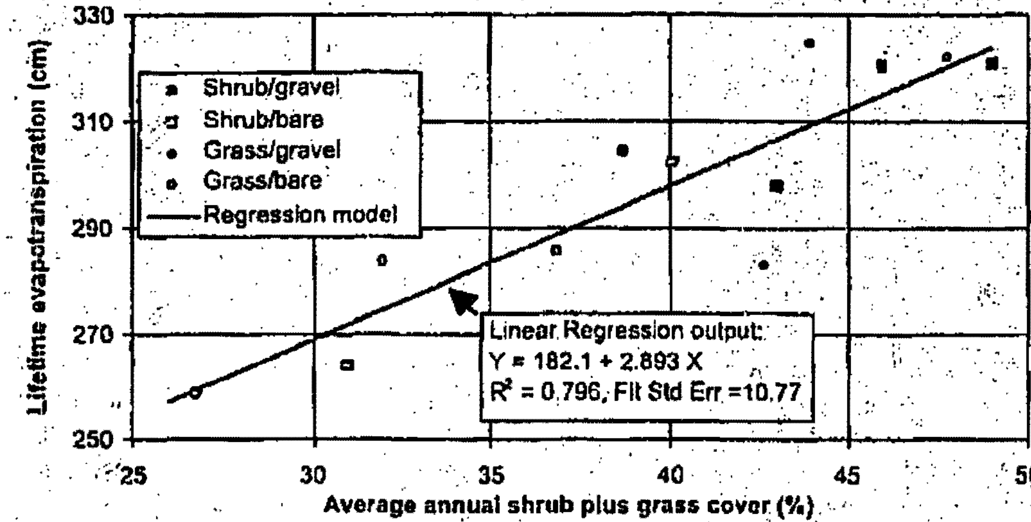


Figure 10. Lifetime evapotranspiration as a function of average annual shrub plus grass cover for the MDA B field plots.

A linear regression model was found to successfully express the relationship between total foliar and shrub LAI and lifetime evapotranspiration (Figure 11). These two variables were highly correlated with this model, which resulted in an r^2 value of 0.854, and the standard error of the regression model was only 8.69 cm over the life time of the field data collection efforts. This model predicts that increasing foliar and shrub LAI by only 0.15 (0.35 to 0.50 cm^2/cm^2) results in 17% increases in lifetime evapotranspiration in our field study.

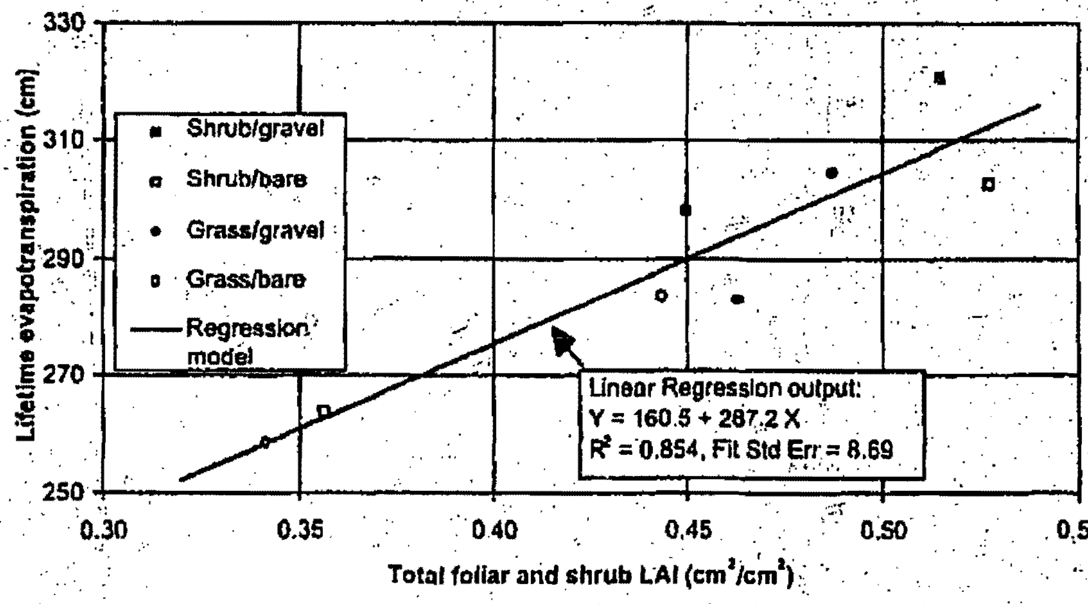


Figure 11. Total foliar and shrub leaf area index verses lifetime evapotranspiration for each of the four surface treatments at MDA B.

3. Seepage

The water balance calculations for the study plots were performed on the 60-cm thick landfill cover layer, with seepage estimated by increases in volumetric water content either at the 80 and 100 cm depths for the east and west plots or at the 160 and 180 cm depths (beneath the biobarrier) for the central plots (Figure 1). At the onset, we were not sure how well this would work out since seepage estimates are usually a small percentage of evapotranspiration (Tables 2–4), and since there is significant variation in the annual estimates of evapotranspiration (Figure 8).

The volumetric water content of the deep portions of the landfill covers at MDA B are presented in Figure 12 for the life of the field study: from March 19, 1987, through June 30, 1995. The data presented in Figure 12 represents changes in the average volumetric water content, averaged across either the 80 and 100 cm depths for the east and west plots, or the 160 and 180 cm depths (beneath the biobarrier) for the central plots. The volumetric water content estimates for the west field plots are generally lower than those for the east field plots, due to the coarser-textured characteristics (and thus, water holding capacities) of the backfill used in these plots (Figure 1). The average volumetric water content for all 156 sampling times for west plots 2, 3, and 4 was 12.4, 15.5, and 14.7%, respectively, whereas the corresponding values for the east plots 9, 10, 11, and 12 was 26.1, 27.2, 27.9 and 27.4%, respectively. The center plots exhibited an average volumetric water content of 15.6% for the 156 sampling times, similar to that of the west plots.

Even though some years of our field study were considerably wetter than others in terms of annual precipitation (Table 1), the volumetric water content of these deep soil depths (Figure 12) seemed to exhibit the largest increases in volumetric water content in the spring of average to below-average water years. For example, the amount of precipitation received in 1993 resulted in 1993 being a below-average water year for this study, yet all of the field plots demonstrated elevated soil moisture levels during April of this year (Figure 12). Maximum soil moisture levels (Figure 12) were attained in May 1987 (center plots, Plot 9, and Plot 10), May 1989 (Plot 2), and April 1993 (Plots 3, 4, and 12). These increases were a result of snowmelt occurring on the field plots, usually after prolonged cold periods during which the field plots maintained their snow cover. The only exception to this observation occurred in August 1988 when so much precipitation occurred on the plots that a portion of the precipitation did make it through the soil profile as seepage (Figure 12).

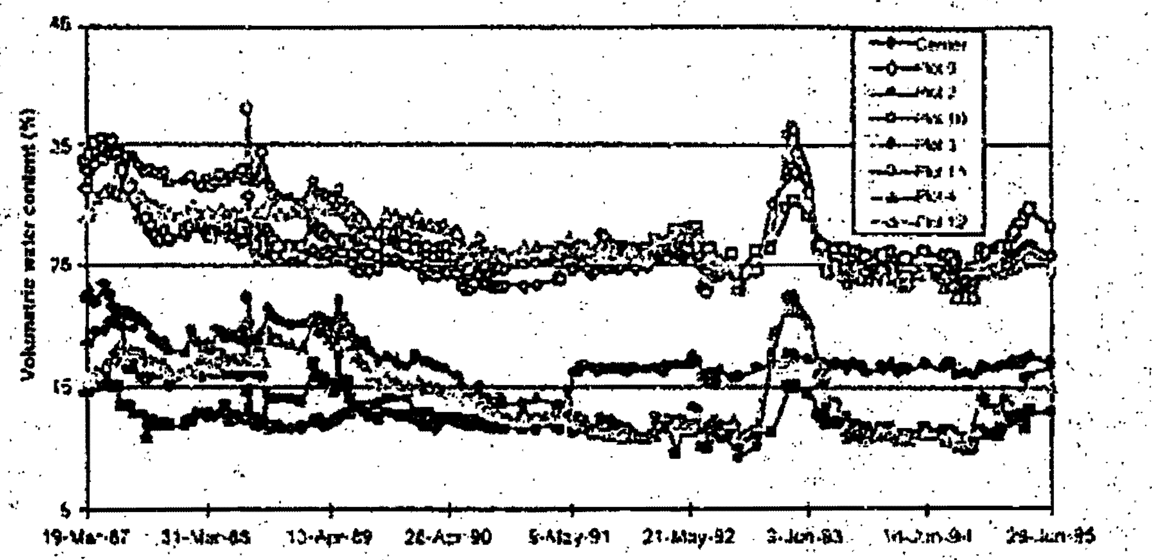


Figure 12. *Soil water content data at the 80–100 cm depth for MDA B Plots 2,3,4,9,10,11, and 12, and at the 160–180 cm depth (beneath the biobarrier) for the Center plots. The average volumetric water content at both sampling depths is presented verses time.*

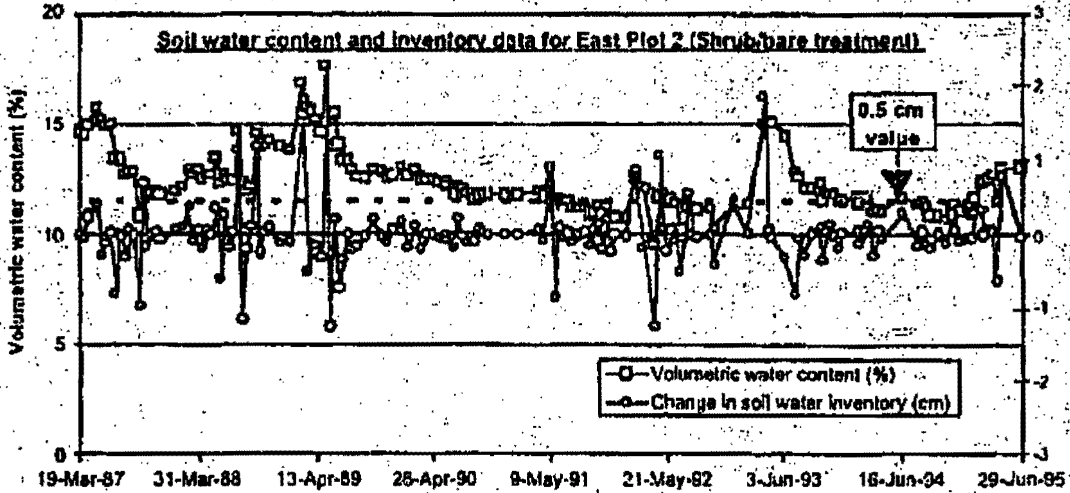
The volumetric water content and soil water inventory changes with time are presented in Figure 13 for two MDA B plots with the shrub/bare treatment to demonstrate how seepage was estimated for the study plots. Most of the time there was very little change in soil water content on these two plots, and during these time periods the soil water inventory changes ranged from -0.5 to 0.5 cm of water. However, on a few of the 156 sampling times, the changes in soil water inventory were greater than 0.5 cm. This happened ten times and nine times on Plots 2 and 10, respectively, and the seepage events usually occurred in the winter and spring (Figure 13). Plots with replicate treatments behaved similarly relative to the occurrence of seepage only when large soil water inventory changes were observed. For example, between March 31,1993 and April 16,1993, when the average volumetric water content at the 80–100 cm depth on Plot 2 increased from 11.3 to 15.0%, 1.86 cm of seepage occurred (Figure 13). During this time period, the volumetric water content of this soil layer on Plot 10 increased from 26.3 to 29.6%, resulting in a seepage estimate of 1.65 cm. Usually when seepage occurred in the east and west portions of MDA B, it occurred on one plot but not the replicate plot with the same treatment (Figure 13). This was most probably due to differences in soil properties (Figure 2) and plant cover (Figure 5).

Data similar to that presented for Plots 2 and 10 in Figure 13 is presented for the soil layers beneath the gravel cobble biointrusion barrier associated with the central plots in Figure 14. Seepage took place much less frequently on these plots than on the plots from the east and west portions of the study area. Seepage occurred at different time intervals on these plots (Figure 15), happening only between July 20, 1988 and August 3, 1988 (1.22 cm), April 10, 1991 and May 8, 1991 (0.97 cm), and May 8, 1991 and May 22, 1991 (0.71 cm). This phenomenon has been previously observed on the ITP plots at Los Alamos, which also contained a shallow soil layer overlying a gravel/cobble biointrusion barrier (Nyhan et al., 1990). The central plots at MDA B had this same shallow soil profile, which promoted more evapotranspiration to occur on these plots than the east and west plots (Table 4). Increasing the evapotranspiration on these plots generally greatly reduced seepage production on these plots. However, this shallow soil profile configuration also changed the seasonal distribution of seepage on the central plots (Figure 15), allowing no seepage to occur on these plots between October and April.

The type of vegetation growing in the plots also influenced when and how much seepage was produced on the MDA B plots (Table 8). The seepage data for the plots containing the shrubs were compared with similar data collected on the plots with dominantly grass cover for the same two time periods used for the evapotranspiration data in Table 7: May through September (grasses, forbs, and shrubs actively transpiring) and October through April (only shrubs transpiring, but at a reduced rate). This seasonal difference in seepage was compared with the lifetime average shrub cover measured on the east and west plots (Table 8); the central plots were not considered in this comparison because they were influenced by the hydrologic relationships related to a shallow soil profile, as discussed previously. As shrub cover increased from 0.13 to 23%, the seasonal difference in seepage decreased from 5.73 to 1.19 cm (Table 8), showing that shrubs could continue to transpire throughout the fall, winter, and early spring, thus reducing the amounts of seepage occurring on the plots.

Several analyses of the runoff data (Barnes et al., 1986; Barnes and Rodgers, 1987, 1988; Barnes and Warren, 1988; Lopez et al., 1988, 1989) and soil erosion data (LANL, 1991) have been performed, and these are presented in Appendices E and F, respectively.

A preliminary analysis of the runoff data from the MDA B plots was performed with the idea that the decreases in runoff with time were due to increases in vegetative cover. This analysis did not take into account the occurrence of cryptogams, which started to appear on the soil surfaces of many of the plots in 1987, about three years after the plots were emplaced at the site. Since this effect was not quantified, the percentage of ground cover (with or without cryptogams) for each of the 12 plots was plotted as a function of annual runoff for each of the years where both types of data were available (1988, 1989, 1990, and 1994). This analysis did not show a very good relationship between these two variables for our field study because the amounts of runoff generated during the 3.62-year event were so large that the influence of ground cover was not an important factor for 1988,



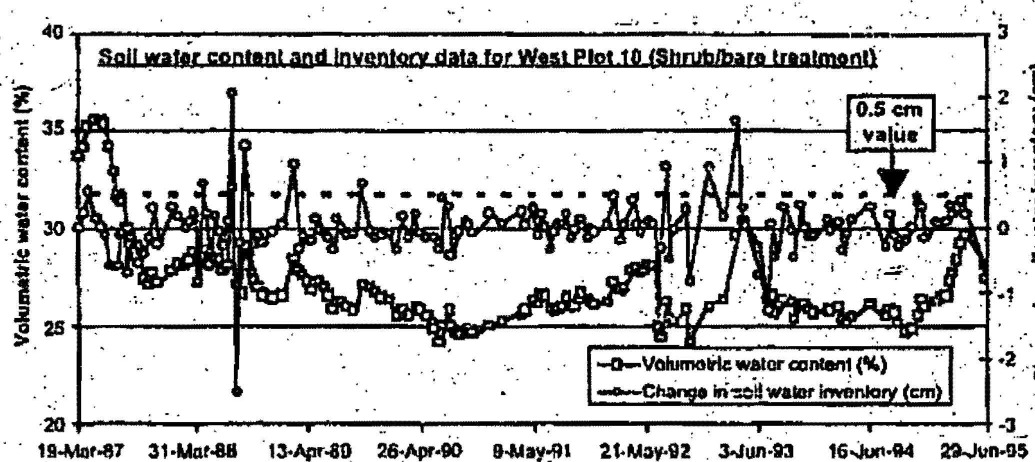


Figure 13. ***Soil water content and change in soil water inventory verses time for two MDA B plots with the shrub/bare surface treatment: the upper portion of this figure deals with data from east Plot 2 and the lower portion of this figure deals with data from west Plot 10. Seepage estimates were determined when inventory changes were greater than 0.5 cm (dashed line).***

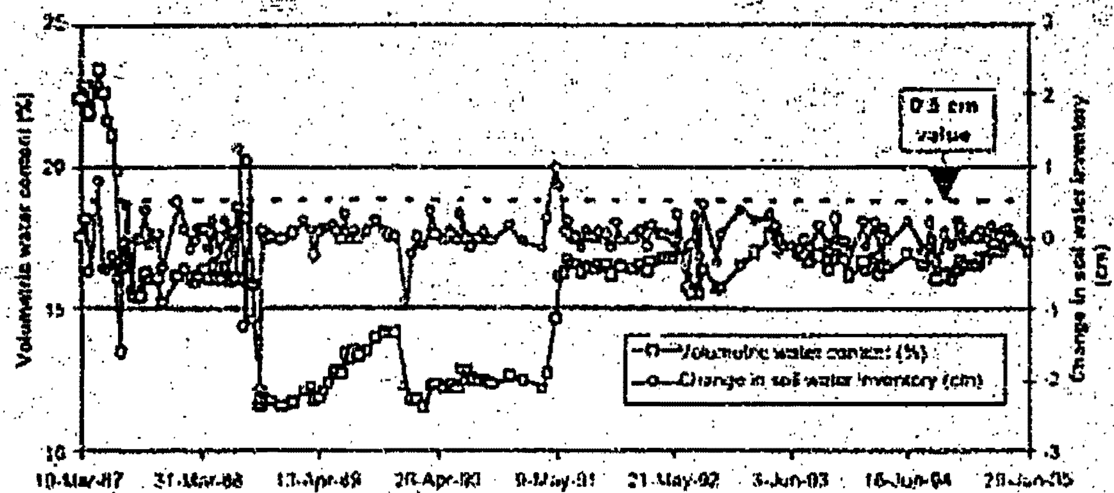


Figure 14. ***Soil water content and change in soil water inventory verses time for the central MDA B plots. Seepage estimates were determined when inventory changes were greater than 0.5 cm (dashed line).***

TABLE 8.
THE RELATIONSHIP BETWEEN LIFETIME AVERAGE SHRUB COVER ON THE EAST AND WEST MDA B PLOTS AND SEASONAL DIFFERENCE IN LIFETIME SEEPAGE.

Plot Number	Treatment	Lifetime average shrub cover (%)	Lifetime Seepage (cm) during: October–April	Lifetime Seepage (cm) during: May–September	Seasonal difference in seepage (cm)
4 east	Grass/bare	0.13	8.96	3.23	5.73
3 east	Grass/gravel	0.88	11.61	5.91	5.69
11 west	Grass/gravel	7.09	8.08	6.50	1.58
12 west	Grass/bare	7.96	8.77	3.26	5.51
2 east	Shrub/bare	11.52	8.01	3.83	4.18
1 east	Shrub/gravel	13.77	5.26	4.13	1.13
9 west	Shrub/gravel	22.21	5.26	4.13	1.13
10 west	Shrub/bare	23.00	5.41	4.23	1.19

4. Runoff

Taking the 1988 runoff and ground cover data out of the comparisons, the data was regraphed and presented in Figure 16. Ground cover was found to be significantly related to annual runoff, in spite of the fact that other factors influencing runoff, such as slope (Figure 3), were not taken into account (Figure 16). Almost 61% of the variance in runoff was described by a model describing a power relationship between cm of runoff and percent ground cover, with a standard error only 2.22 cm of runoff. This model predicts that as ground cover is increased from 30 to 90%, annual runoff is reduced from 8.8 to 0.98 cm, almost a 9-fold decrease.

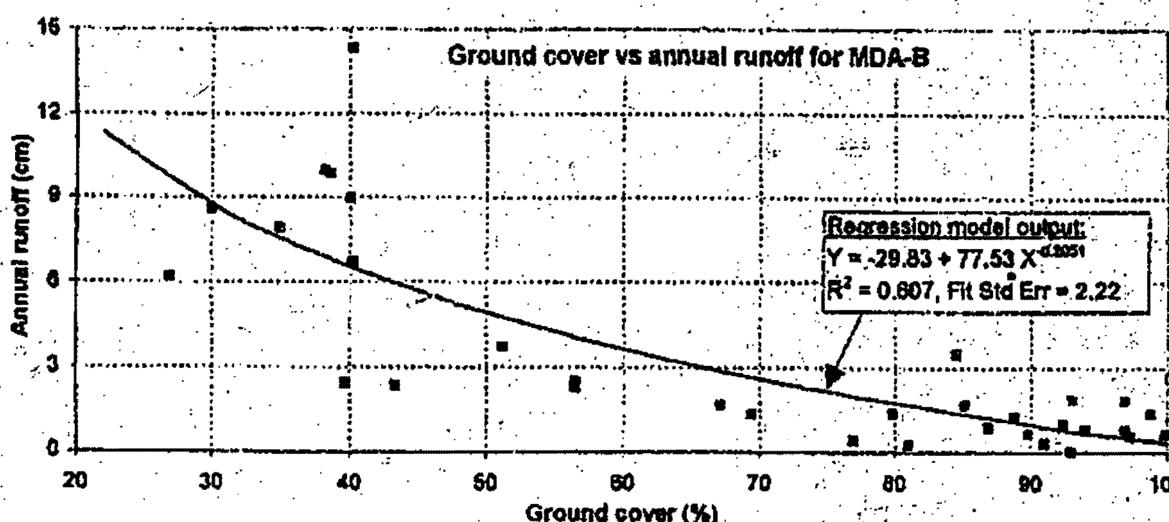


Figure 16. Ground cover and annual runoff for the MDA B plots for 1989, 1990, and 1994.

IV. USEFULNESS OF THE STUDY AND FUTURE RESEARCH

The information gathered in this field study at MDA B provides us with an insight into the interactive relationships between plant and gravel cover, site characteristics such as slope, and water balance parameters. This insight is necessary for the waste site operator to be able to put a landfill cover on this site that can be used to satisfactorily close the site and minimize risk to man in the future.

Since the landfill cover design must perform satisfactorily for hundreds of years, it must withstand annual precipitation that has ranged from 17.3 cm in 1956 to 77.1 cm in 1941 (Bowen, 1990). In our seven-year study, we experienced five years that were drier than average, one year that had about average annual precipitation, and a 3.62-year event. Comparing water balance relationships across all of the field plots between the average year and the 3.62-year events, seepage increased dramatically as amounts of precipitation increased. Seepage consisted of 2.0% and 6.2% of the precipitation in the average and 3.62-year events, respectively. These increases in seepage were accompanied by corresponding decreases in evapotranspiration, which accounted for 86% (average year) and only 78% (3.62-year event) of the precipitation. If this trend continues, it will be critical to evaluate how the landfill covers respond to events occurring less frequently than a 3.62-year event.

However, over the seven years of the field study only 2.9% of the total precipitation received at the field site ended up as seepage, and 9.4% as runoff. Comparing these values with the average and 3.62-year events, this is undoubtedly a reflection of the fact that the study period encompassed five years that were drier than average, decreasing the average seepage and runoff values for the entire seven years.

Slope is a very important variable in the design of a landfill. Our study shows that as slope increases from 2 to 6%, a 2.7-fold increase in runoff should occur. However, as slope increases no significant relationship was found between increasing runoff and decreasing seepage, because seepage was not related to either slope or runoff over the life of the experiment. This latter relationship is obviously more strongly influenced by the soil properties of the entire profile, by vegetative cover differences, and by site factors such as aspect, which has been previously shown to impact the amounts of solar radiation and antecedent moisture condition of the landfill cover (Nyhan et al., 1994).

Two interesting observations were made concerning the surface cover treatments on the field plots. During the seven years of our field study, once a vegetative cover of either shrubs or grass is applied to the landfill cover, this treatment seems to dominate with time. In addition, gravel mulches increased the plant cover on our study plots, having a larger influence on grass cover than on shrub cover. Plots receiving no gravel mulch averaged 21.2% shrub cover, while plots with gravel had a 20% larger percent cover of shrubs; however, the average grass cover on the plots with no gravel was 16.3%, compared with a 42% increase in percent grass cover due to gravel mulch. These relationships are extremely important in the semi-arid and arid portions of the southwestern portions of the United States, where plant cover can be very hard to establish on landfills, unlike the wetter portions of the United States.

Cover relationships on the landfill were found to be very important in influencing runoff. Ground cover was found to be significantly related to annual runoff, in spite of the fact that other factors influencing runoff, such as slope, were not taken into account. Almost 61% of the variance in runoff was described by a model describing a power relationship between runoff and ground cover. This model predicts that as ground cover is increased from 30 to 90%, annual runoff is reduced from 8.8 to 0.98 cm, almost a 9-fold decrease.

Several interesting relationships were quantified between evapotranspiration estimates from the field plots and vegetation parameters. A regression model of our field data predicts that increasing foliar and shrub LAI by only 0.15 (0.35 to 0.50 cm^2/cm^2) results in 17% increases in lifetime evapotranspiration. Expressed in terms of plant cover estimates from point frames, we found that doubling the percent shrub plus grass cover (25% verses 50%) on the landfill cover increases lifetime evapotranspiration by 28%. Both of these observations prove that evapotranspiration is a water balance parameter that the site operator can use to manage water relationships on the landfill.

Different amounts of seepage occurred across the study area as a function of landfill cover soil properties, which also influenced the time when seepage occurred. Large amounts of seepage occurred on the east and west plots in the winter and the spring. Seepage occurred much less frequently and during the spring and summer in the portions of MDA B containing a more shallow soil cover with an underlying biobarrier.

Part of the explanation for these soil profile differences is related to the observation, which could only be made for the east and west portions of the study area, that seasonal differences were found in seepage production on the plots as a function of the type of plant cover present. These seasonal differences were due to the fact that our evergreen shrubs were transpiring all year, whereas the grasses and forbs were not. Thus, as shrub cover increased from 0.13 to 23%, the seasonal difference in seepage decreased from 5.73 to 1.19 cm, showing that shrubs could continue to transpire throughout the fall, winter, and early spring, thus reducing the amounts of seepage occurring on the plots in the eastern and western study areas. This relationship could not be verified for the central portions of the study area, because these areas had shallow soil profiles that enhanced evapotranspiration and promoted interflow with the underlying biobarrier.

The goal of disposing of low-level radioactive and hazardous waste in shallow landfills is to reduce risk to human health and to the environment by isolating contaminants until they no longer pose an unacceptable hazard. The interrelationships between surface gravel and vegetation treatments, water balance parameters, and site physical parameters (such as slope) which were discovered in this field study can now be applied to improve landfill cover technology currently needed so badly at Los Alamos and throughout the United States.

THIS PAGE LEFT BLANK INTENTIONALLY.

ACKNOWLEDGMENTS

Over the entire life of this program, this work was supported by DOE National Low Level Waste Management Program, DOE Waste Interim Operations, the Los Alamos National Environmental Research Park, the US Environmental Protection Agency, and the Los Alamos National Laboratory Environmental Restoration Project.

Many technicians and students contributed to this report. Tim Ellis, Ernest Antonio, Wilfred Herrera, Susan Johnson, Martina Kincaid, Clif Meyer, Mark Ritchie, Sharon Tarbox, Johnny Salazar, Wayne R. Wilson, and Tracy Schofield collected field data. Leo Martinez, Ken Bostick, and Elton Karlen also helped with installation. Chuck Martin and Tracy Schofield helped design and install the automated runoff collection system. Gary Langhorst, Johnny Salazar, Laura Campbell, Wayne Wilson and Clif Meyer helped with data compilation.

In addition, several staff members in the Environmental Science Group contributed. John Rodgers, Fairley Barnes, and Tom Hakonson helped initiate the project and install the cover treatments. David Breshears and Everett Springer helped with data analysis and overall project supervision and management.

The senior author would be gravely remiss without acknowledging the heartfelt support of his soulmate, Sondra Cantrell, who listened to his complaints about work, spent thousands of hours alone while he worked on this report, yet gave him family-based strength to do the job. Thanks, Sondra!

LITERATURE CITED

Anderson, J. E., R.S. Nowak, T. D. Ratzlaff, and O. D. Markham. 1993. "Managing soil moisture on waste burial sites in arid regions." J. of Environ. Quality 22: 62–69.

Barnes, F. J., E. J. Kelly, and E. A. Lopez. 1990. "Pilot study of surface stabilization techniques for shallow-land burial sites in the south-western USA." Pages 1201–1202 in F. Arendt, M. Hinsenveld, and W. J. van den Brink, editors. Contaminated Soil '90. Kluwer Academic Publishers.

Barnes, F. J. and J. R. Rodgers. 1987. "Hydrologic modeling of soil water storage in landfill cover systems. Proceedings of International Conference on Measurement of Soil and Plant Water Status." Utah State University, Logan UT, pp. 173–182.

Barnes, F. J. and J. R. Rodgers. 1988. "Evaluation of hydrologic models in the design of stable landfill covers." Final report IAG No. DW89930235-0101. US EPA Office of Research and Development, Cincinnati, OH (Los Alamos National Laboratory Report LA-UR-88-2018).

Barnes, F. J., J. R. Rodgers, and G. Trujillo. 1986. "The role of water balance in the long-term stability of hazardous waste site cover treatments." Proceedings of the Twelfth Annual Research Symposium, EPA report number EPA/600/9-86/022, US EPA, Cincinnati, OH, pp. 50–58.

Barnes, F. J. and J. L. Warren. 1988. "Cover technology demonstration for low-level radioactive sites." Proceedings of Tenth Annual DOE Low-Level Waste Management Conference, Aug. 30–Sept. 1, 1988, Denver, CO. Idaho National Engineering Laboratory report INEL CONF-88-839-SES.VI: 33-44.

Bowen, B. M. 1990. "Los Alamos climatology." Los Alamos National Laboratory Report LA-11735-MS, Los Alamos, NM.

Chang, J. 1971. "Climate and agriculture." Aldine Publishing Company, Chicago, IL.

Dadkhah, M. and G. F. Gifford. 1980. "Influence of vegetation, rock cover, and trampling on infiltration rates and sediment production." Water Resources Bulletin 16:979-986.

Foxx, T. S. and G. D. Tierney. 1985. "Status of the flora of the Los Alamos National Environmental Research Park." Los Alamos National Laboratory Report LA-8050-NERP, Vol. III, Los Alamos, NM.

Jacobs, D. G., J. S. Epler, and R. R. Rose. 1980. "Identification of technical problems encountered in the shallow land burial of low-level radioactive wastes." Technical Report ORNL/SUB-80/13619/1, Oak Ridge National Laboratory, Oak Ridge, TN.

Kennedy, W. R., and W. D. Purtymun. 1971. "Plutonium and strontium in soil near Technical Area 21, Los Alamos Scientific Laboratory, Los Alamos, New Mexico." Los Alamos Scientific Laboratory Report LA-4563, Los Alamos, NM.

Los Alamos National Laboratory, 1991. "Los Alamos National Laboratory Installation Work Plan for Environmental Restoration, Revision 1, Appendix Q." November 1991.

Lopez, E. A., F. J. Barnes, and E. J. Antonio. 1988. "Effects of vegetation and soil-surface cover treatments on the hydrologic behavior of low-level waste trench caps." Pp. 579–586 in M.E. Wacks and R. G. Post (eds.) Waste Management '88, Department of Nuclear and Energy Engineering, University of Arizona, Tucson, AZ.

Lopez, E. A., F. J. Barnes, M. L. Kincaid, and E. J. Antonio. 1989. "Variation in runoff and erosion rates from different trench cap cover systems." Pp. 765–769 in M. E. Wacks and R. G. Post (eds.) Waste Management '89, Department of Nuclear and Energy Engineering, University of Arizona, Tucson, AZ.

Luxmoore, R. J., and M. L. Tharp. 1993. "Simulation of barrier heterogeneity and preferential flow effects on the performance of shallow land burial facilities." Oak Ridge National Laboratory report number ORNL/TM-12058, Oak Ridge, TN

Meyer, D. D. 1971. "Volume of transuranium wastes buried at Los Alamos," Los Alamos Scientific Laboratory memorandum from D. D. Meyer (H-1) to C. W. Christenson (H-7), Los Alamos, NM.

Mielke, J. 1993. "Native plants for southwestern landscapes." University of Texas Press, Austin, TX.

Nyhan, J. W. 1989. "Development of technology for the long-term stabilization and closure of shallow land burial sites in semiarid environments." Los Alamos National Laboratory report LA-11283-MS, Los Alamos, NM.

Nyhan, J. W. and F. J. Barnes. 1989. "Development of a prototype plan for the effective closure of a waste disposal site in Los Alamos, New Mexico." Los Alamos National Laboratory report LA-11282-MS, Los Alamos, NM.

Nyhan, J. W., G. L. DePoorter, B. J. Drennon, J. R. Simanton, and G. R. Foster. 1984. "Erosion of earth covers used in shallow land burial at Los Alamos, New Mexico." J. of Environ. Quality 13: 361–366.

Nyhan, J. W., T. E. Hakonson, and E. A. Lopez. 1986. "Corrective measures technology for shallow land burial at arid sites: field studies of biointrusion barriers and erosion control." Los Alamos National Laboratory report LA-10573-MS, Los Alamos, NM.

Nyhan, J. W., T. E. Hakonson and B. J. Drennon. 1990. "A water balance study of two landfill cover designs for semiarid regions." J. of Environ. Quality 19: 281–288.

Nyhan, J. W. and L. J. Lane. 1986. "Erosion control technology: a user's guide to the use of the universal soil loss equation at waste burial facilities." Los Alamos National Laboratory report LA-10262M, Los Alamos, NM.

Nyhan, J. W., J. L. Martinez, and G. J. Langhorst. 1994. "Calibration of neutron moisture gauges and their ability to spatially determine soil water content in environmental studies." Los Alamos National Laboratory report LA-12831-MS, Los Alamos, NM.

Nyhan, J. W., T. G. Schofield, and C. E. Martin. 1994. "Use of time domain reflectometry in hydrologic studies of multilayered landfill covers for closure of waste landfills at Los Alamos, New Mexico." Symposium on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications, Northwestern University, September 7–9, 1994; U. S. Department of Interior, Bureau of Mines Special Publication Sp 19-94:193–206.

Purtymun, W. D., and W. R. Kennedy. 1966. "Distribution of moisture and radioactivity in the soil and tuff at the contaminated waste pit near Technical Area 21, Los Alamos, New Mexico." US Geological Survey open file report.

Rogers, M. A. 1977. "History and environmental settings of LASL near surface land disposal facilities for radioactive wastes (Areas A, B, D, C, E, F, G, and T): a source document." Los Alamos National Laboratory Informal Report LA-6848-MS, Vol. I., p. B-1–B-9, Los Alamos, NM.

Spellenberg, R. 1979. "The Audubon Society field guide to North American wildflowers, Western region." A. A. Knopf Publishers, New York, NY.

Suter, G. W., R. J. Luxmoore, and E.D. Smith. 1993. "Compacted soil barriers at abandoned landfill sites are likely to fail in the long-term." J. of Environ. Quality 22: 217–226.

Tierney, G. D., and T. S. Foxx 1982. "Floristic composition and plant succession on near-surface radioactive waste disposal facilities in the Los Alamos National Laboratory," Los Alamos National Laboratory Report LA-9219-MS, Los Alamos, NM.

Tierney, G. D, and T. S. Foxx. 1987. "Root lengths of plants on Los Alamos National Laboratory lands," Los Alamos National Laboratory Informal Report LA-10865-MS, Los Alamos, NM.

Trocki, L., 1977. "Results of a surface contamination survey at closed Radioactive Waste Burial Area B," Los Alamos National Laboratory (unpublished report), Los Alamos, NM.

United States Department of Agriculture, NRCS. 1995. The PLANTS database. National Plant Data Center, Baton Rouge, LA.

United States Department of Energy. 1988. "Radioactive Waste Management," US DOE Order 5820.2A, September 26, 1988, Washington, D.C.

United States Environmental Protection Agency. 1989. "Technical guidance document: final covers on hazardous waste landfill and surface impoundments," EPA/530-FW-89-047, July 1989.

United States Nuclear Regulatory Commission. 1982. "10CFR Part 61 licensing requirements for land disposal of radioactive waste." *Federal Register*, Vol. 47, No. 248, pp. 57446–57482.

Wenzel, W. J., T. S. Foxx, A. F. Gallegos, G. Tierney, and J. C. Rodgers. 1987. "Cesium-137, plutonium-239/240, total uranium, and scandium in trees and shrubs growing in transuranic waste at Area B." Los Alamos National Laboratory Report LA-11126-MS, Los Alamos, NM.