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A Water Balance Study of Two Landfill Cover Designs for Semiarid Regions

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ABSTRACT

The results from several field experiments on methods to control soil erosion, biointrusion, and water infiltration were used to design and test an enhanced landfill cover that improves the ability of the disposal site to isolate buried wastes. The performance of the improved cover design in managing water and biota at the disposal site was compared for 3 yr with that obtained from a more conventional design that has been widely used in the industry. The conventional cover design consisted of 20 cm of sandy loam topsoil over 108 cm of a sandy silt backfill, whereas the improved design consists of 71 cm of topsoil over a minimum of 46 cm of gravel, 91 cm of river cobble, and 38 cm of sandy silt backfill. Each plot was lined with an impermeable liner to allow for mass balance calculation of water dynamics. Results over a 3-yr period, including 2 wet yr, demonstrated that the improved design reduced percolation of water through the landfill cover by a factor of >4 over the conventional design. This decrease in percolation was attributed to a combination of increased evapotranspiration from the plant cover and the effect of a capillary barrier embedded in the enhanced cover profile in diverting water laterally in the cover. The field data are finally discussed in terms of its usefulness for waste management decisions to be made in the future for both new and existing landfills at Los Alamos, NM, and at other semiarid waste disposal sites.

THE PRIMARY objective of postclosure requirements for waste repositories is to limit the exposure of the general public to radioactive and hazardous wastes for time periods ranging from 100 to 10 000 yr (USNRC, 1982; USEPA, 1980, 1985). Hydrologic processes historically account for most of the performance-related problems (Jacobs et al., 1980; Hakonson et al., 1982b; USDOE, 1980). For example, erosion of the landfill cover can breach the cap and expose waste to the biosphere. Water that infiltrates into the cover can accumulate within the landfill, leach wastes into groundwater, and enhance subsidence with the landfill.

As Fig. 1 implies, the successful performance of the entire landfill is very much a function of interactive processes operating to control water balance within the landfill covers. If we restrict our attention to net rates and amounts, and consider one-dimensional movements of water in the soil profile, then the following equation can be used to represent a simplified water balance:

$$\Delta S = P - Q - ET - L \quad [1]$$

where

ΔS = change in soil water storage
P = precipitation
Q = runoff
ET = evapotranspiration, and
L = seepage or percolation.

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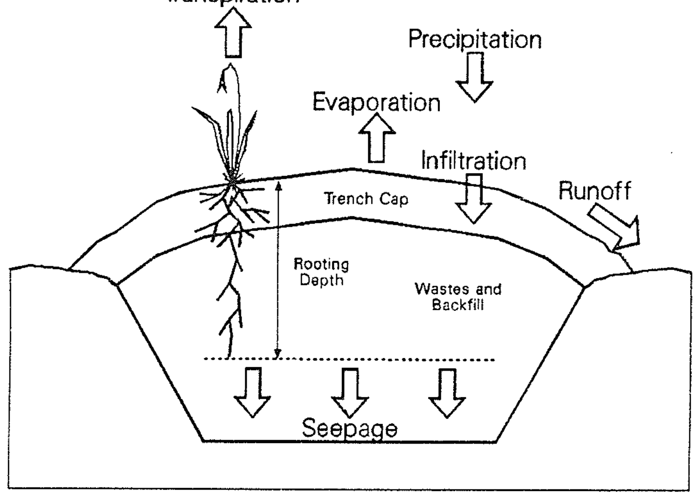

Fig. 1. Hydrology of shallow land burial of waste materials.

Traditional remedial engineering solutions, which do not include analyses of these interactive factors have already led to numerous landfill failures (Hakonson et al., 1982b). Future designs that ignore these interactive factors will certainly reproduce many of the failures of the past (Hakonson et al., 1982b, 1987; Nyhan and Lane, 1986a), and at a very high cost: landfill cover installation costs range from $400 000 to $4 000 000 per ha of landfill (Brandt, 1988; Cook, 1988).

Currently, adequate field data does not exist from carefully instrumented large-scale experiments on the movement of water and contaminants under unsaturated conditions to enable a site operator to define and engineer suitable barriers to prevent the migration of waste materials out of a landfill. Our approach to developing an effective landfill cover technology combined the results from individual studies at Los Alamos, NM, on soil erosion (Hakonson et al., 1982a; Nyhan et al., 1983a, 1984a,b; Nyhan and Lane, 1986a,b), on subsidence (Abeele, 1984a,b,c, 1985, 1986; Abeele et al., 1986; Nyhan et al., 1984a), on biointrusion barriers (Pertusa, 1980; Felthauser and McInroy, 1983; Hakonson et al., 1982a,c, 1983; Hakonson, 1986; Nyhan et al., 1984a, 1986), and on capillary barriers (Abeele and DePoorter, 1984; Nyhan et al., 1986) to design and emplace a landfill cover demonstration called the Integrated Test Plot (ITP) experiment. The purpose of the field demonstration was to monitor and compare water balance and biologic intrusion on a conventional landfill cover design with that on an improved design, which was based on the results of the previous studies.

MATERIALS AND METHODS

Plot Construction, Design, and Rationale

The purpose of the cover demonstration was to monitor and compare water balance on the conventional landfill

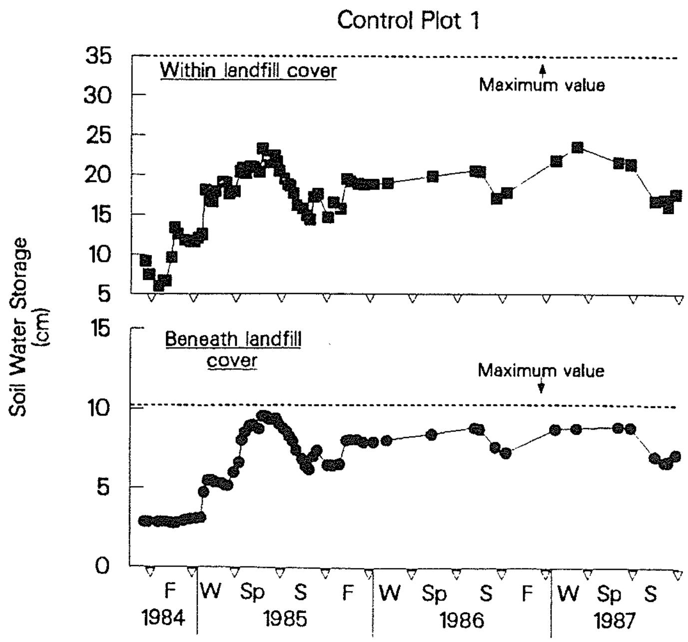

Fig. 5. Total weekly precipitation and soil water inventory estimates as a function of time for ITP Control Plot 1.

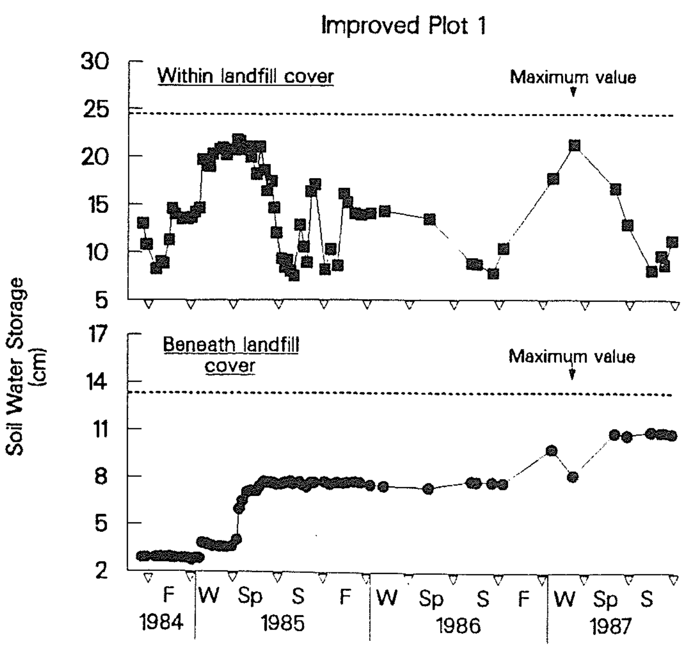

Fig. 6. Total weekly precipitation and soil water inventory estimates as a function of time for ITP Improved Plot 1.

The soil water storage calculations show that the crushed tuff backfill beneath the conventional trench cap design very quickly approached the values close to saturation by early spring of 1985, as well as throughout the life of the field experiment. Thus, the corresponding soil water content values normally increased with depth for most sampling periods, whereas a variable relationship of soil water content to depth was observed with the improved cover design.

Biomass and Plant Species Composition

Biomass and species composition were determined in August 1986 for all four field plots (Table 1), and

Table 1. Summary of plant species cover and biomass data in ITP experiment (August 1986).

Plot description	Percent cover		Total estimated biomass, g/m²
	BOGR†	AGSM†	
Improved Plot 1	22.0	72.0	1245
Improved Plot 2	44.5	47.3	847.0
Control Plot 1	90.7	3.1	438.9
Control Plot 2	91.1	4.3	459.7

‡ AGSM represents *Agropyron smithii* (western wheatgrass) and BOGR represents *Bouteloua gracilis* (blue grama).

these estimates revealed a quantitative estimate of what we had visually observed on these plots since the middle of the summer of 1985. All four plots had practically 100% plant cover, exhibiting the influence of the partial gravel cover on each plot (typical range grass cover in adjacent undisturbed areas is usually only about 20%). However, the two improved plots with the capillary barrier in the profile had more than twice the biomass that the control plots contained; the capillary barrier had evidently retarded the downward movement of water in these plots, allowing more water to be available for plant growth for longer time periods. The second difference observed since 1985 was that the control plots contained almost exclusively western wheatgrass (Table 1). Although the reasons for this observed difference are not fully understood at this time, one possible explanation is that the capillary barriers in the improved plots resulted in soil water inventories that were closer to maximum in the landfill cover than they were in the control plots at the start of 1985. The western wheatgrass, being a cool-season grass (unlike the blue grama), exhibited much faster growth early in the spring of 1985 than the still inactive blue grama, and simply outcompeted the blue grama for plant available water and biomass production from that time on. Differences in active plant root distributions could also supplement this explanation and/or offer a second explanation for the phenomenon.

Leachate Production

Very little field data are available where the leachate term of the water balance equation has been directly measured for a landfill profile (Fig. 1). The approach generally taken is to measure evapotranspiration, precipitation, runoff, and the changes in soil water storage, and to estimate leachate production by difference. However, small errors in the estimation of evapotranspiration in the field can result in a dramatic error in estimating leachate production using this procedure.

Generally, leachate was produced from all of the plots (Fig. 7) only following snowmelt (Fig. 4) during the winters of 1984–1985 and 1986–1987. Thus, leachate production occurred in late winter–early spring of 1985, and throughout the winter and spring of 1986–1987, with no leachate production occurring in the intervening winter-spring of 1985–1986. Maximum daily leachate production rates approached 0.2 cm/d in 1985, but were almost four times greater than this following the record snows occurring in 1987.

The two replicate control plots were amazingly similar in terms of the amounts and seasonability of their leachate production. At the initiation of leachate production in 1985, Plots 1 and 2 produced 183 and 140

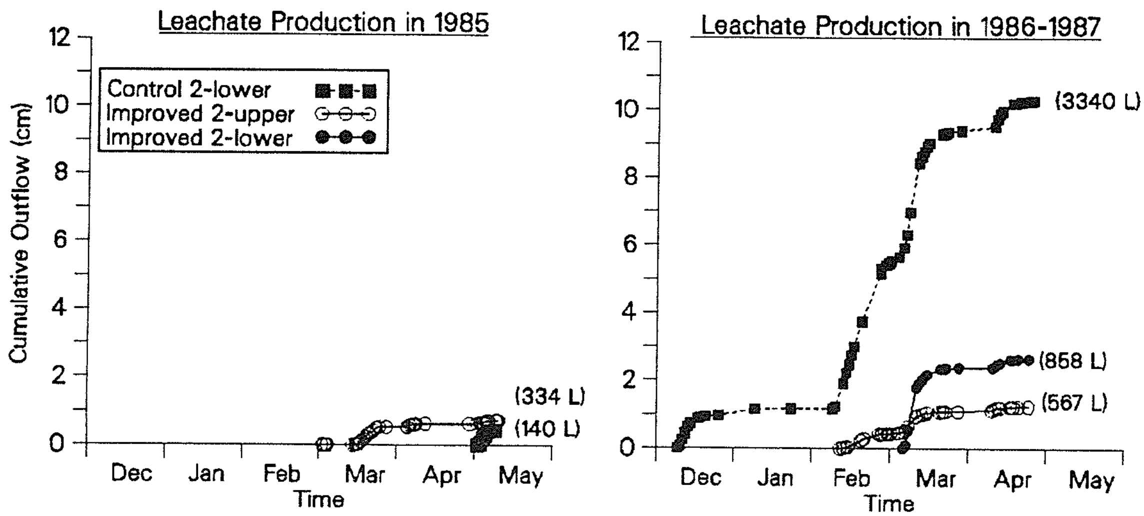

Fig. 7. Cumulative leachate production in the ITP experiment. No leachate production occurred at all other time periods during the year other than those indicated in the figure. The upper drain leachate data, originally on a 3.7- by 10-7-m basis, was multiplied by 0.83 so that it could be expressed on a 3.0- by 10.7-m basis with the rest of the data presented in this figure.

L of leachate, respectively. By the end of the experiment in 1987 the total leachate produced by Plots 1 and 2 was 3239 and 3176 L, respectively. Similar data are not available from the improved plots because Improved Plot 1 did not produce detectable leachate from either drain during the course of the study. This was probably the result of enhanced evapotranspiration on this plot with its larger plant biomass than Improved Plot 2 (see Table 1).

Both the amounts of leachate produced and the seasonability of leachate production varied with the landfill cover design. During the snowmelt events in the spring of 1985, leachate was produced from lateral water flow in the upper drain of Improved Plot 2 from March through early May, and totaled to 0.72 cm (Fig 7). During the first week in May the control plots began producing leachate from their cover profiles that totaled to 0.56 and 0.43 cm, from Plots 1 and 2, respectively. Therefore, by the end of the 1985 events, it appeared that the capillary barrier in the improved plots was satisfactorily diverting soil water laterally in the soil overlying the gravel, because no leachate was produced from the lower drain in these plots, unlike within the control plots (Fig. 7).

In December 1986, leachate production in the control plots began again—almost 600 d after the initial outflow in early May 1985. Control Plots 1 and 2 produced about 0.90 cm of leachate during December and about 1.30 cm in January and March, but the largest amount of leachate was produced in February–April 1987 (7.7 and 8.0 cm in Plots 1 and 2, respectively). In contrast, outflow in the improved plots did not begin until mid-February from the upper drain and in early March from the lower drain. Thus, the capillary barrier conducting water toward the upper drain did perform satisfactorily for about 3 wk (mid-February–early March), but finally failed (the soil above the gravel finally attained saturation with this extremely heavy snowmelt, allowing water to pass into the lower drain in the plot). The end result for the 1986–1987 period was that the control plots produced an average of 10.1 cm of leachate, compared with only 2.6 cm of leachate produced from the lower drain in the improved plot design. Even during this very wet period, the capillary barrier diverted about 1.2 cm of leachate to the upper drain.

Leachate production estimates presented in Fig. 7 should not be used as an absolutely accurate and final representation of the seepage process in the near-surface areas of Los Alamos shallow land burial (SLB) facilities. The reliance on plastic liners on the floors of the plots and French drains (which drains at near-saturated conditions) tends to temporarily minimize leachate production. As time proceeded in our field experiment, the soil water inventories near the plot floors in both landfill cover designs probably increased to amounts that would have been lower in a natural system without a plastic liner and drain. However, the scope of the experiment only included a comparison of the water balance between the two landfill designs in the field plots, and not a comparison between the plots and natural conditions (an area for future studies).

Evapotranspiration Estimates

Since no runoff occurred in the ITP experiment at any time, we could estimate ET by difference in Eq. [1] and quantitatively estimate all of the parameters of the water balance equation for every time interval for which we had field data. Evapotranspiration rates (Fig. 8) were calculated from these estimates and did show the expected seasonality pattern: low evapotranspiration rates (<0.1 cm/d) in the late fall–winter and peak evapotranspiration rates (>0.2 cm/d) during the spring and summer. Peak evapotranspiration rates occurred during seasons with peak precipitation rates in both cover designs. When these estimates were performed for shorter time periods i.e., biweekly instead of for an entire season, larger variation in evapotranspiration rates was observed with time from all of the plots, since the frequency of precipitation and the amounts of plant-available water were also more variable with time (Fig. 8).

Evapotranspiration differences were observed with

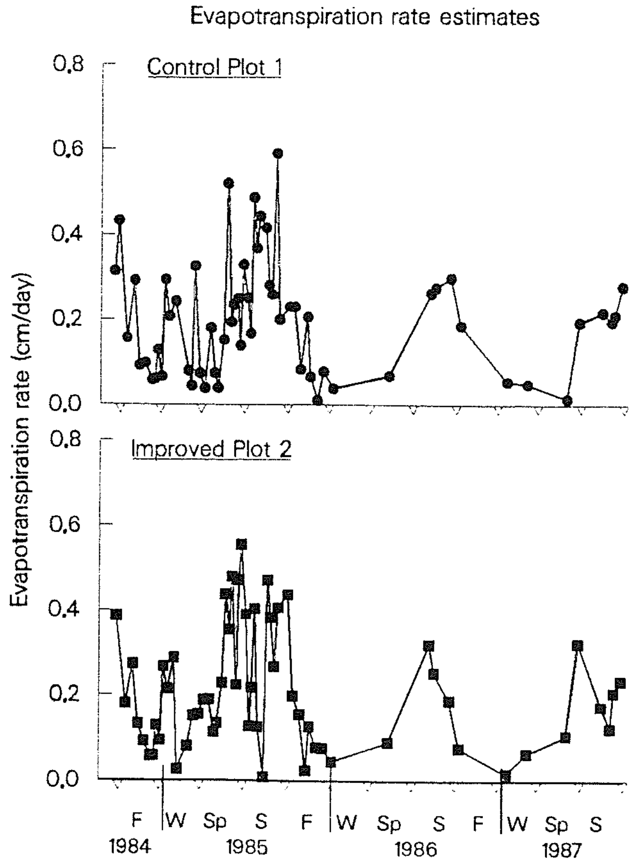

Fig. 8. Rate of change of evapotranspiration as a function of time for two ITP field plots.

time between the control and improved plots. Although biomass data was not collected for every year of this experiment, the peak daily evapotranspiration rates in all plots were observed in 1985 during the first summer of peak plant growth in the plots. Although the total biomass estimates at this time were probably similar to those observed in August 1986 (Table 1), almost all of the biomass observed in 1985 was green biomass, unlike in the later stages of plant development on these plots (when peak evapotranspiration rates were smaller than in 1985). Another seasonal difference we observed was that evapotranspiration started earlier in the spring in the improved plots than on the control plots (Fig. 8). This observation is due to the fact that the predominant plant species on the improved plots was the cool-seasoned western wheatgrass, in contrast to the warm-seasoned blue grama predominating the control plots (Table 1).

CONCLUSIONS AND USEFULNESS OF STUDY

The most practical comparisons between the two types of SLB cap designs for a semiarid region, in terms of their usefulness to the burial site operator, should be the overall performance comparison of the hydrologic parameters of the water balance estimates over the 3-yr-duration of the experiment (Table 2). The summary in Table 2 shows that there was enhanced evapotranspiration on the improved plots over

Table 2. Mass balance calculations for water associated with two landfill cover designs on the four field plots from 13 Aug. 1984 through 4 Sept. 1987.

	Control Plots		Improved Plots	
	1	2	1	2
Precipitation, cm	173.72	173.72	173.72	173.72
Increase in soil water inventory, cm	12.09	9.09	4.15	4.43
Evapotranspiration, cm	151.67	154.87	169.57	164.72
Leachate production, cm				
Lower drain	10.62	10.63	0.00	2.64
Upper drain†	0.00	0.00	0.00	1.93
Evapotranspiration/precipitation	0.873	0.892	0.976	0.948
Leachate produced (from lower drain)/precipitation	0.061	0.061	–	0.015

† The upper drain leachate data, originally on a 3.7- by 10.7-m basis, was multiplied by 0.83 so that it could be expressed on a 3.0- by 10.7-m basis with the rest of the data presented in this table.

that observed on the control plots, due to both capillary barrier dynamics in retarding vertical water movement in the profile, and to enhanced biomass on the improved plots. About 88% of the precipitation received was lost to evapotranspiration on the control plots, whereas about 96% of the precipitation received by the improved plots was removed from the landfill cover via evapotranspiration.

One measure of the overall efficiency of the two landfill cover designs is simply differences in the amount of leachate that penetrates the cover. The data presented in Table 2 show that the conventional SLB design used at Los Alamos produced fourfold more leachate than the improved SLB design. Since most of this difference in leachate production occurred in a record snowmelt season, it is our opinion that an even greater difference in leachate production would have occurred between the two designs given a more average annual precipitation input (as occurred in 1985). Nevertheless, the nature of the inputs of water infiltrating the conventional landfill cover design seems to occur for a couple of weeks in early May (if we take the 1985 data as typical), but may occur from December through April in an extremely wet year (as in winter-spring period of 1986–1987). The capillary barrier in the improved design can potentially greatly reduce leachate production in the typical year, and can reduce the time period during which leachate is produced in the extremely wet year by over half (as in the March–April period of 1987). This would especially be true if the surface of the improved design had a surface slope of 5 to 10% (compared with the 0.5% slope at the surface of the improved plot design), which would therefore result in increased runoff and decreased infiltration of precipitation into the landfill cover (see Eq. [1]).

The landfill cover design with the gravel cobble layer between two relatively fine-grained layers has four different advantages over the conventional SLB design. First, the layering sequence in the improved plots results in the development of a capillary barrier so that soil water is retained in the upper fine-grained layer, making it more available for evapotranspiration. This is helpful because a larger portion of the precipitation received by the landfill cover can then be removed via evapotranspiration during the plant growing season. The second advantage is that the gravel-cobble layer keeps plant roots from growing through the landfill cover and potentially translocating waste materials to the surface of the SLB facility (Hakonson, 1986). Thirdly, the enhanced levels of plant-available water that occur in the upper fine-grained layer result in enhanced plant biomass at the soil surface, which in turn translates to greatly improved soil erosion protection of the landfill cover. The fourth advantage is that snowmelt results in soil water penetrating into the coarse-grained layer and this water can be removed from the landfill cover by drains placed at the base of this layer. This is helpful because a vertical diversion of infiltrating snowmelt (at a time when potential evapotranspiration is low) means less soil water coming into contact with waste materials located beneath the landfill cover.

The data collected in this field experiment was used to field calibrate a simplistic, one-dimensional model (CREAMS) without extensive input parameters (Nyhan, 1990). For the first time, direct measures of all of the water balance components existed from this study to compare with model-simulated values, instead of just comparing observed and predicted soil water content values to evaluate the success of the hydrologic simulation. Ultimately, a multidimensional finite element model will be validated that takes into account soil, plant, and climatic variability. Models like these can be used to optimize configurations of specific landfill cover materials, such as the thickness of the cover. Using this approach, landfill closure designs can be further evaluated for 20 to 50 yr of meteorological conditions to encompass the average and record wet years, so that the effectiveness of the landfill covers can be assessed. The cost effectiveness and practicality of various designs will be evaluated with the help of our site operator, who will have a major input into the selection of a final closure design for low level radioactive and hazardous waste sites.

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