Analysis of Landfill Cover Options and Issues for the Allen Harbor Landfill

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May 1996

Customer:

Department of the Navy
Northern Division
Naval Facilities Engineering Command
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Contract No.:
N62472-96-M-1557

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INTRODUCTION

Mitretek Systems performed an expedited analysis of possible cover options and issues affecting the cover for the landfill at Site 09, Allen Harbor Landfill, Naval Construction Battalion Center, Davisville, Rhode Island. This report contains details that support conclusions and statements made in Mitretek's letter report number H050-L-BX508, dated 3 May 1996.

The Allen Harbor Landfill is located adjacent to the shore of Allen Harbor. A vegetative cover is one of the cover options suggested in the 1996 Feasibility Study and was included in possible actions to remediate the landfill. The purpose of this report is to present the results of the analyses and discuss pertinent issues relating to soil/vegetative covers.

CURRENT SITUATION

During our review of references [A to C][1] and the applicable regulations, we identified the following key issues relevant to the remediation efforts at this site:

- The landfill has been inactive for 24 years.
- The landfill contents were periodically burned before being covered.
- The contaminants of concern are (1) lead and other metals in surface soil, (2) volatile organic chemicals (VOCs) in soil and groundwater, (3) petroleum-based VOCs, in soil and groundwater and (4) chlorinated VOCs in soil and groundwater.
- The water table is above the base of the landfill which rests directly on the uppermost aquifer unit.

Considering the operational history of the landfill and its coastal marine environment, it is unlikely that free product remains in containers in the waste. Periodic burning of the waste prior to burial and the elevated salt content of the environment are not conducive to the integrity of chemical containers. Additionally, burning may have consumed large amounts of flammable materials. Remaining soluble and mobile metals should have since been removed by natural leaching.

The elevated chlorinated VOCs are found only in limited areas, and the data do not support the presence of a plume in the groundwater. In addition, modeling—as stated in the reports—indicates that the contaminants should not adversely impact the environment of the harbor. The groundwater associated with the site is not used as a potable water source.

[1] Numbers or letters in brackets refer to references in the reference list.

GEOLOGY AND SOILS

The regional surface geology of New England and including the areas surrounding the Naval Construction Battalion Center is predominately reworked, glacially derived sediments [21]. These sediments can be generally characterized by discontinuous layers of unconsolidated clastic material made up of sorted silts, sands, gravels, and cobbles. Clays of suitable thickness for barrier layers in a landfill cover are rare. Within this setting, ideal soils for use in a vegetative landfill cover are somewhat difficult to locate, although we identified six soils that are found in Rhode Island, Massachusetts, Vermont, Connecticut, and New York. The following soils series contain suitable soil material: Bridgehampton silt loam, Rainbow silt, Mansfield silt, Broadbrook silt loam, Narraganset silt loam, and Newport silt [1, 2 and 3]. The identified soils contain some rocks, but they can be used for soil/vegetative covers. These soils are not suitable for use as compacted landfill cover layers

LANDFILL COVER GOALS

The main purpose of the landfill cover at the Allen Harbor Landfill is to protect human health and the environment. This will be accomplished by limiting infiltration of surface waters into the fill material, by enhancing runoff, and by controlling water percolating into the cover. The cover is a barrier between contamination sources and receptors on the surface. It must be capable of withstanding extreme erosive forces induced by hurricane–force rain and wind so that it can prevent movement of landfill contents into the wetlands and harbor. One additional attribute specific to this site is the ease of repair following possible storm damage. The site is exposed to a marine environment and lies within the 100-year flood zone. The surface of the cover could experience some degree of erosion during extreme weather events. Therefore, the cover should provide maximum resistance to damage by erosion and be easily repaired at low cost. The ease with which the effectiveness of the repair may be verified is also important. In order to meet the requirements for erosion control, the cover soil must be sufficiently deep and fertile to permit the grass cover to remain healthy, thus effective, even after extended drought. These goals can be met by a soil/vegetative cover.

LANDFILL COVERS

The RCRA Cover

Numerous publications describe requirements for landfill covers under the Resource Conservation and Recovery Act (RCRA) rules and guidance. One of the covers that is widely accepted employs barriers or "impermeable" layers; we refer to it here as the RCRA cover. The RCRA cover contains the following, in order from the top: native soil, a lateral drainage layer, one or two *impermeable* layers, and a gas collector, [4 and 5]. The *impermeable* layer may be compacted clay, a flexible membrane used alone, a flexible membrane over a compacted clay layer, or other materials. In practice, these covers may provide good or poor control of infiltrating water depending upon how well the barrier layers approximate the goal of an *impermeable* material or actually meet construction specifications. If well-constructed and maintained, the RCRA covers leak only small amounts of precipitation. However, they tend to become less effective with time because they are designed to oppose natural forces and they naturally tend to deteriorate. Nonetheless, these covers are widely used and sanctioned as landfill covers, but they are expensive to build and to maintain.

Evapotranspiration (ET) Cover

The ET Cover is an inexpensive and practical cover that stores precipitation in the soil until it is removed by evaporation and plant transpiration (*evapotranspiration* or *ET)*. It provides adequate soil water-holding capacity to store infiltrating precipitation until ET can remove the water from storage but contains no *impermeable* materials. The ET Cover uses native grass communities to control soil erosion and remove water from the soil cover. The ET Cover is more completely described in documentation accompanying this report [6 to 9].

The ET Cover should have a sloping surface. The soil cover may be a mixture of several soil profiles from a borrow site, or it may be placed in layers to improve performance. The requirements for a layered ET Cover are that (1) the top soil layer should have high water-holding capacity and high runoff-producing potential, (2) the next layer should have high water-holding capacity, and (3) the bottom layer may be soil with low permeability to separate the cover from the waste. A mixture of native grasses and forbs growing on the cover removes water from the soil and prevents erosion of the surface. If the wastes produce dangerous gases, they must be collected and managed safely.

The ET Cover should be constructed from soil found near the site to reduce cost, and it should be loose and friable. The ET Cover limits the percolation of precipitation through the cover and requires less maintenance than covers currently in use. Little damage results from settling because the soil will naturally fill voids, and plant roots grow profusely in loose, disturbed soil such as that found near shear zones. It is natural, self-renewing, and not subject to long-term damage by wetting and drying of compacted clay layers nor the possible deterioration of synthetic materials over time. Damage caused by burrowing animals or depressions in the surface caused by settlement can be repaired easily and economically by filling holes with soil, regrading the surface, and replanting grass where needed.

The ET Cover requires soil with a high plant-available, water-holding capacity and an adequate supply of nutrients to support vigorous plant growth. Subsoil, if amended, usually satisfies this requirement. The plant cover should contain many different native grass species and associated forbs to ensure continuous water use under adverse growing conditions. Plants, soil, and variations in climate over long time periods interact with performance of the ET Cover.

EVALUATION OF LANDFILL COVER HYDROLOGY AT ALLEN HARBOR LANDFILL

The variability of soils, vegetation, and climate requires estimates of landfill hydrology for each site where a cover is required. These estimates permit selection of a cover that is adequate to protect the public health and the environment at the site in question. Although measurements of the performance of various cover systems are not available for each specific site, computer models are used to effectively estimate landfill cover performance. These models employ measured data for climate, soils, and vegetation that are representative of the site. Estimates were made using two different computer models: (1) the Hydrologic Evaluation of Landfill Performance (HELP) model, version 3.0, [12 and 13] and (2) the Erosion/Productivity Impact Calculator (EPIC) model [14 to 18].

Both models employ statistics from measured weather data to synthetically generate weather data on a daily basis; thus, they avoid the problem of assembling very large weather data sets for each site to be modeled. They both use the runoff and infiltration method described in the Hydrology Section of the National Engineering Handbook of the U.S. Department of Agriculture Soil Conservation Service [15]. The vegetative growth simulation is somewhat similar, but the EPIC model permits entry of much more complete data describing the plants and their growth than the HELP model permits.

The models have different goals and scopes for their estimates. The HELP model was developed to simulate all aspects of landfill design and operation. Therefore, it focuses on bottom-liner performance, leachate production, and cover performance. Its estimates of cover performance are somewhat limited to currently used landfill covers. The EPIC model does not estimate overall landfill performance. EPIC does effectively model the interaction between plants and soils as it was designed to do. As a result, EPIC is very useful for evaluating the ET Cover. Therefore, the HELP model was used to estimate performance of conventional covers, and the EPIC model was used to estimate the performance of the ET Cover.

HELP Model

The HELP model was developed by the U.S. Army Engineer Waterways Experiment Station for the U.S. Environmental Protection Agency (EPA). It is a quasi-two-dimensional hydrologic model of water movement, and it predicts landfill cover performance, including leakage through *impermeable* layers. The HELP model was extensively tested and is widely used by consulting engineers. Its estimates are accepted by most regulatory bodies in the United States.

The EPIC Model

The EPIC model was developed by the U.S. Department of Agriculture to assess the effectiveness of soil erosion control practices nationwide. As a result, the EPIC model incorporates all major aspects of hydrology, climate, soils, plant nutrients, plant growth, soil temperature, and plant environment. It also estimates a complete water balance. EPIC performs all calculations on a daily time step, but it is computationally efficient and can simulate hundreds of years in a few minutes on a desktop computer. It generates climatic data for the continental United States from internal coefficients and contains soils data for the major soils found within the United States, but the user may also enter measured data for a particular site. The EPIC model permits numerous sequential runs using the same climate file and allows preliminary runs to equilibrate the soil variables of nitrate and soil water. Approximately two dozen scientists and engineers contributed to the model development and documentation [14]; they tested and validated it against measured field data at more than 200 sites worldwide. Hauser and Shaw [6] and Hauser, et al. [7] more fully described the use of the EPIC model to evaluate landfill covers.

Estimates of deep percolation below the plant root depth are critical to the use of EPIC in estimates of performance of ET Covers. The difference between EPIC estimates and lysimeter measurements of deep percolation at Coshocton, Ohio during a three year period was 7 percent [19]. The EPIC model produced satisfactory estimates of deep percolation in a climate that is similar to that of Rhode Island.

Comparison of HELP and EPIC Estimates

The EPIC model best describes the interaction of factors controlling soil physics and hydrology, plant growth, and transpiration. The HELP model effectively describes a modern lined landfill and the process elements that control production of leachate. The two models were evaluated using parallel input data, and the models were found to be comparable. Because of their different objectives and input data requirements, these models cannot be expected to produce exactly the same results. The EPIC model is a more detailed evaluation of the active processes in the landfill cover, therefore, it can be used to validate the HELP results for our application.

We compared estimates of deep percolation (precipitation moving into the waste) on the existing landfill cover that were made by HELP and EPIC. The HELP model used internally stored coefficients for Providence, RI, and the EPIC model used coefficients derived from 68 years of measured weather data at Kingston, RI. The results in the table below show the difference between the two estimates, each derived from a 100-year simulation.

	Precipitation (inches)	Deep Percolation, %	Surface Runoff, %	ET, %
HELP	46.1	27	15	58
EPIC	48.5	34	13	53

RESULTS OF HYDROLOGIC COMPARISONS

We used the HELP model to estimate the performance of RCRA covers and the EPIC model to estimate the performance of ET Covers for the Allen Harbor Landfill. All of the estimates shown resulted from 100-year simulations to ensure sampling of climate variability. In the results that follow, the term "deep percolation" means precipitation that moved through the cover and into the waste stored in the landfill. We assumed that water defined as deep percolation moved through the landfill.

We used weather coefficients derived from the 68-year record at Kingston, RI in all of the EPIC simulations [20]. These data provide accurate estimates for weather at the Allen Harbor Landfill.

Table 1 shows the deep percolation through standard RCRA covers for Allen Harbor Landfill. The compacted clay layers were assumed to be 24 inches thick and have hydraulic conductivity of $1x10^{-7}$ cm/second. The high-density polyethylene (HDPE) was the standard 40-mil-thick material used in landfills. The HELP model revealed that the best construction quality produced some deep percolation of precipitation into the waste. The two-barrier systems are very expensive and are not justified for the Allen Harbor Landfill. The single-barrier RCRA covers produced substantial amounts of deep percolation into the waste.

Table 2 shows the performance of ET Covers as estimated by the EPIC model. All of the soils except the silty clay loam soil are found in Rhode Island and adjoining states. The Rainbow soil, a typical indigenous soil, sometimes contains no rock, but may contain as much as 10 percent rock in the layers of use in ET Covers. We made estimates for several soil configurations and soil depths.

We evaluated both native warm-season grasses and cool-season grasses and found little difference in cover performance (see Table 2). Even though cool-season grasses grow actively during a much longer growing season than the warm-season grasses, they did not evaporate more water. There are at least two reasons for this: (1) heat is required to evaporate water and there is little heat available during the cold months and (2) the cool-season grasses tend to be semi-dormant during the warmest months. Therefore, we used native warm-season grasses for our primary comparisons.

The evaluations for the existing cover at Allen Harbor Landfill assumed that the existing cover is similar to the Rainbow soil series because we found no data in the available reports that defined the existing cover soil. However, the existing cover could be composed of sandy soil, thus producing much greater deep percolation than shown in Table 2.

Single-layer covers produced by a mixture of the soils produced poor results. However, when we simulated a layer of clay soil either 6 or 12 inches thick either on the top or near the top of the soil profile, the ET Cover produced less than half as much deep percolation as for a single layer. The clay was uncompacted and had a bulk density of only 1.3, a typical density for productive clay soils. The three-layer profiles produced much better results than the single-layer profile (see Table 2). In addition, for layered profiles containing clay, increasing the thickness of the cover soil from 3.0 feet to 6.6 feet reduced the deep percolation by less than one inch per year. Discussion of the reasons is beyond the scope of this expedited evaluation; however, the information is available.

ET Cover soil layers only 3 feet thick will cost half as much to build as layers 6.6 feet thick and can produce adequate results. The ET Cover can reduce deep percolation to less than half that estimated for the existing cover. It will achieve the goals set for a landfill cover and at greatly reduced cost when compared to RCRA covers.

Figure 1 shows the probability for annual rainfall derived from the stochastically generated daily rainfall values used in the EPIC simulations. The model works on a daily time step; however, we show only annual total rainfall in this graph. EPIC produces rainfall distributions that are similar to measured rainfall at the site.

Figure 2 compares annual deep percolation through the existing cover and a layered ET Cover 6.6 feet thick. The average annual deep percolation (probability = 0.5) was 16.6 inches and 5.7 inches for the existing and layered ET Covers respectively. The existing cover produced 2.9 times as much deep percolation as the ET Cover.

DISCUSSION

These analyses demonstrate that a soil/vegetative cover meets the requirements for a landfill cover at the Allen Harbor Landfill.

The ET Cover concept is preferred because the technology associated with it evaluates the climate, soils, and vegetation found at the site. It is important to note that the comparisons shown in Table 2 are all for good soils; however, some of these good soils perform much better than others. Some soils not evaluated here would produce no better results than produced by the assumed, existing cover soils.

The proposed soil depth for the soil/vegetative cover proposed in reference A is 18 inches. During normal rainfall years, that depth of soil can produce an adequate cover of grass for erosion control. However, following one or two years of drier than normal years, the grass cover is likely to decline sufficiently to leave the cover vulnerable to soil erosion during a severe storm. Severe storms may occur at the end of a drought. Therefore, Mitretek recommends a minimum thickness of soil cover of 3 feet to provide an ample reservoir for water and plant nutrients needed by a healthy grass cover.

EFFECT OF THE 100-YEAR FLOOD

The 100-year flood plain is shown approximately at the 10 ft. mean sea level (msl) contour on Figure 1-1 of reference 3. The Allen Harbor Landfill is exposed to a marine harbor environment as a convex shoreline along more than half of its boundary. There are two potential problems associated with these site factors. The first is the effects of groundwater percolation into the fill material during a 100-year flood event. The second is the long-term competency of any artificial barriers that may be constructed to prevent movement of contaminants from the landfill.

A significant volume of the fill material is below the 100-year flood elevation. During extreme weather events, the amount of exposure of the fill material to groundwater will be determined by the landfill internal fluid pressure head differential caused by the high water, the conductivity of the surrounding barrier material, the conductivity of the fill material itself, and the duration of the event. The Environmental Assessment Phase III Investigation Report characterizes the distance of groundwater movement during a 12.4-hour median tide event as 13.8 to 12.1 feet. This provides an indication of water movement into the fill. The duration of an extreme weather event is unpredictable, as is the actual rate of groundwater flow during a storm. These considerations should be taken into account when determining the efficacy of a landfill cap or other barrier to fluid flow.

Over decades, the competency of any constructed vertical barrier or landfill cover will be questionable because of natural erosion forces. The wind force, wind direction in relation to the harbor mouth, wave length, direction of the tide, and harbor depth will be important factors in determining the actual vulnerability to erosion as a result of storm surge and wave action. The survival of any constructed landfill protective barriers—including vertical barriers such as pilings or riprap revetment—will be at maximum risk during a storm that results in a flood. Heavy precipitation may be enhanced by wind-driven, wave-generated, spray causing erosion of the cover. The site will be most at risk during high-velocity wind conditions blowing from the east.

The repair required for erosion damage to a RCRA cap after an extreme weather event would require expensive repairs of the artificial barriers and the competency of the barrier seams would remain questionable. On the other hand, the maintenance of an ET Cover requires only replacement of any eroded soil and re-establishment of the grass cover. In the long term, the ET Cover will provide sufficient protection to the environment because of its ability to protect that portion of the landfill not exposed to the normal water table or extreme events and its ease and predictability of maintenance. The unpredictable amount of groundwater flow through the landfill material, that is normally above the groundwater, during a 100-year flood event raises additional questions concerning the effectiveness and reasonableness of an expensive RCRA-type cap.

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Table 1. Annual Water Balance for Standard RCRA Covers
(100 year, HELP Model estimates for Allen Harbor Landfill).
The range for Deep Percolation is for construction quality from the best possible to the expected actual performance.

Cover Description	PRK (inches)	Lateral Drainage (inches)	Q (inches)	ET (inches)
Single–Barrier Systems				
Compacted Clay	**1.4 to >1.9**	11	7	27
HDPE Barrier Only	**1.0 to 9.0**	11	7	27
Two–Barrier Systems				
HDPE and Compacted Clay	**0.1 to >0.6**	13	7	27
HDPE and Bentonite Mat Barrier	**<0.1**	13	7	27

ET = Evapotranspiration
HDPE = High–Density Polyethylene
PRK = Deep Percolation (precipitation that moves into waste)
Q = Surface Runoff

Table 2. Allen Harbor Landfill—Summary of Water Balance for Selected Covers.

Soil	Description	Cover Depth (feet)	PRK (inches)	Q (inches)	ET (inches)
Existing Cover Using Warm–Season Grass					
Rainbow, RI Indigenous Soil	Silt Loam Soil, 0% Rock	2	**16**	6	25
Rainbow, RI Indigenous Soil	Silt Loam Soil, 10% Rock	2	**17**	6	25
Single Layer ET Cover Using Warm–Season Grass					
Rainbow	Silt Loam Soil, 10% Rock	6.6	**15**	5	25
Bridgehampton	Silt Loam Soil, 0% Rock	6.6	**12**	7	29
Multiple Layered ET Covers Using Warm–Season Grass					
Bridgehampton and Clay, RI Indigenous Soil	3 Soil Layers: 0.5 ft. Silt/**1.0 ft. Clay**/ 5.1 ft. Silt	6.6	**6**	14	28
Bridgehampton and Clay, RI Indigenous Soil	3 Soil Layers: 0.5 ft. Silt/**1.0 ft. Clay**/ 2.5 ft. Silt	4.0	**6**	14	28
Bridgehampton and Clay, RI Indigenous Soil	3 Soil Layers: 0.5 ft. Silt/**1.0 ft. Clay**/ 1.5 ft. Silt	3.0	**6**	14	28
Bridgehampton and Clay, RI Indigenous Soil	2 Soil Layers: **0.5 ft. Clay**/2.5 ft. Silt	3.0	**7**	14	26
Bridgehampton and Clay, RI Indigenous Soil	3 Soil Layers: 0.5 Silt / **0.5 ft. Clay**/2.0 ft. Silt	3.0	**7**	14	27
ET Cover, Comparison Between Cool and Warm Season Grass					
Warm Season Grass	Single Soil Layer, Silty Clay Loam	6.6	**10**	10	28
Cool Season Grass	Single Soil Layer, Silty Clay Loam	6.6	**10**	10	28

ET = Evapotranspiration
PRK = Deep Percolation (precipitation that moves into waste)
Q = Surface Runoff

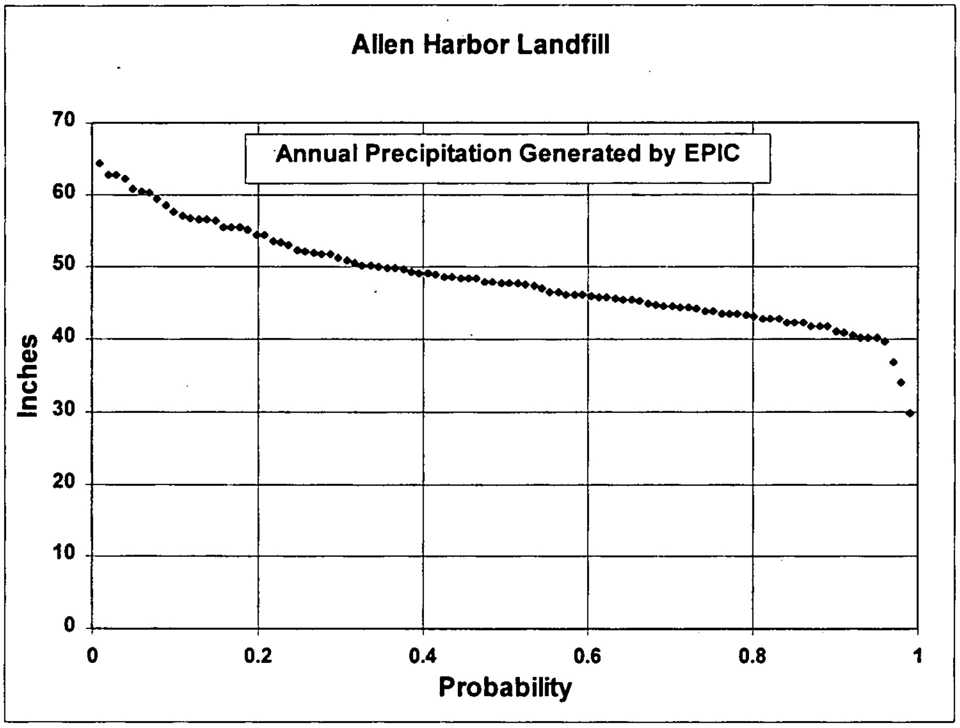


Figure 1. Probability for Annual Rainfall for Allen Harbor Landfill Estimated by the EPIC Model (100-year Estimate).

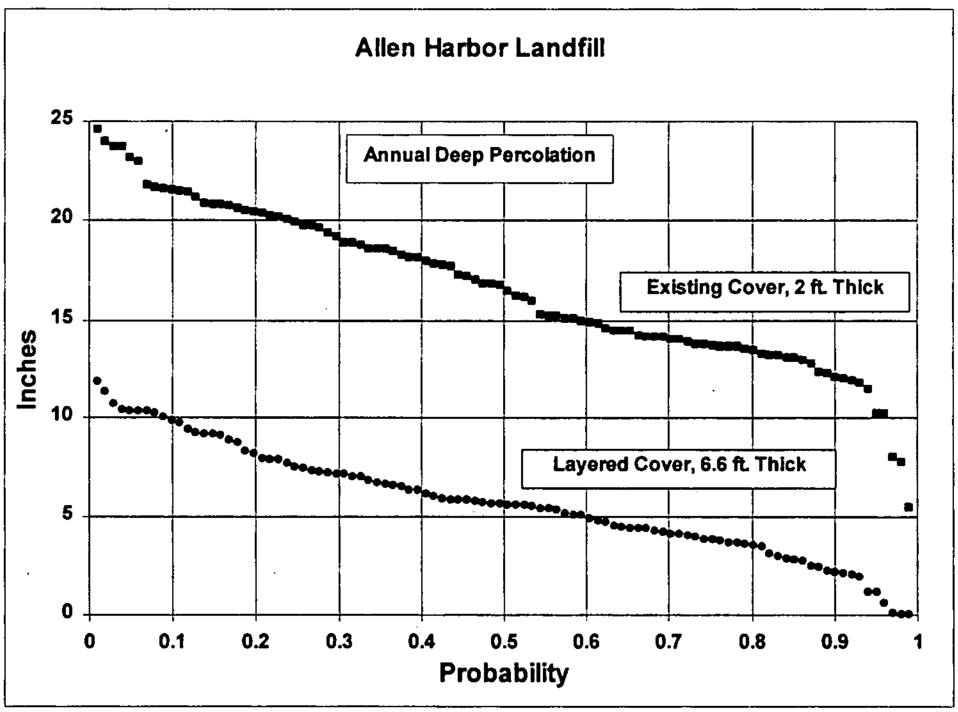
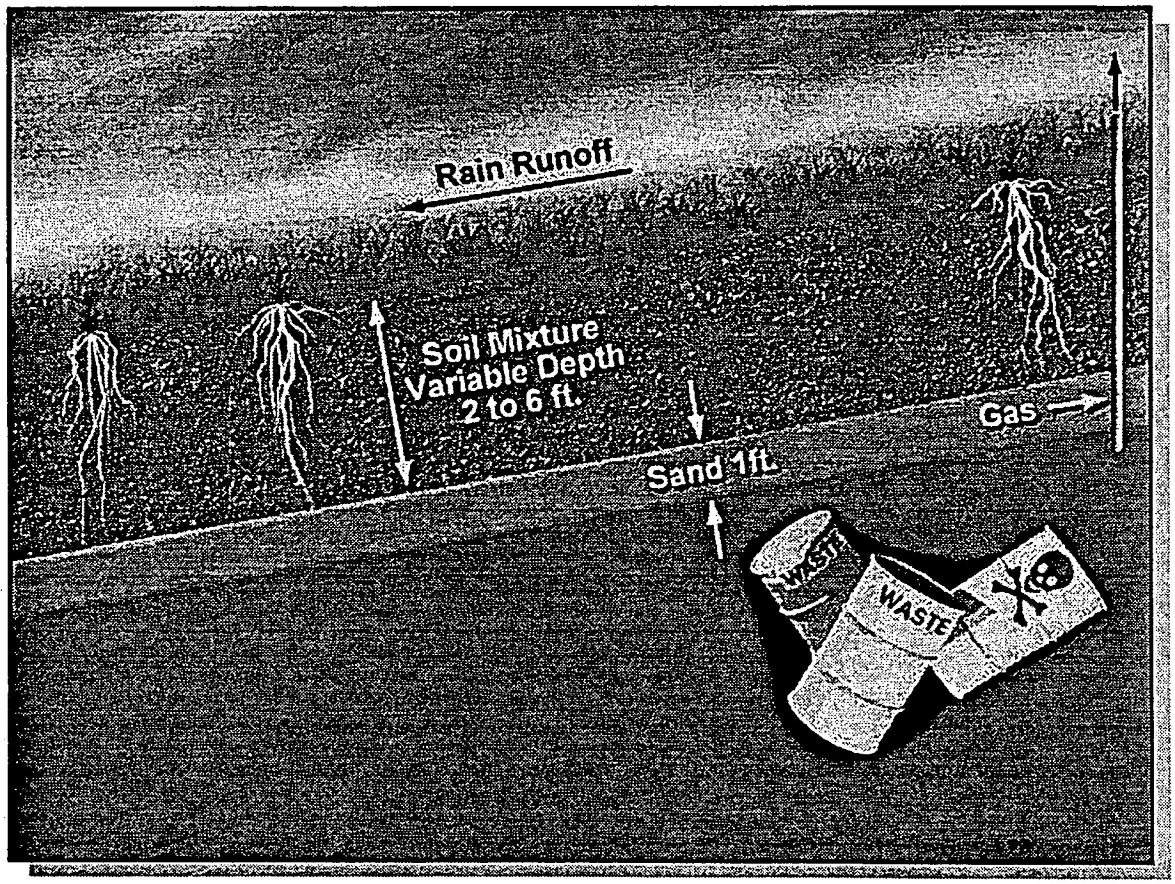


Figure 2. Comparison of the Probability for Annual Deep Percolation for the existing cover and an ET Cover for the Allen Harbor Landfill (Estimated by the EPIC Model).

The evapotranspiration (ET) Cover

The evapotranspiration (ET) Cover is an inexpensive and practical cover, for landfills, minelands or fire training areas. It stores infiltrating precipitation in the soil water reservoir until ET can remove the water from storage, therefore, it does not need artificial barriers to water flow. The ET Cover uses indigenous soils and native grass communities in the cover. It does not use the artificial barriers and impermeable membranes that are used in conventional covers and that may lose their effectiveness with time. The ET Cover is unique because it is a natural, self-renewing system that performs in a stable and predictable manner for centuries. The figure below illustrates the ET Cover concept.



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MITRETEK
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Natural Covers for Landfills -- A Closer Look

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An effective landfill cover will isolate the waste from receptors and minimize the leaching of soluble contaminants during the decomposition period, which may last for many decades or longer. Conventional landfill covers employ impermeable barriers (compacted clay and/or a geomembrane) to control water movement into the waste and are sufficiently thick to prevent contact between receptors and the waste. In contrast, the ET Cover, a natural landfill cover which has been described in detail elsewhere [Hauser and Shaw (1994), Hauser, et al. (1994, 1995)], contains no barrier or impermeable layers. In addition, the ET Cover is relatively inexpensive to construct and is easily maintained.

The ET Cover, consisting of a layer of soil covered by native grasses, allows natural processes to control infiltration. First, the uncompacted soil provides a water reservoir; and second, evapotranspiration (ET) -- a natural mechanism that includes the loss of water by evaporation from the soil plus transpiration by plants -- removes water from the soil water reservoir. Thus the soil cover stores rainfall that infiltrates through the surface until the evapotranspiration process removes it, thereby maintaining the cycle. The ET Cover concept has been shown to be potentially useful over much of the conterminous United States, particularly west of the Mississippi River.

Data collected during soil water balance studies support the ET Cover concept. Aronovici (1971) and Lotspeich et al. (1971) measured the depth of water penetration below native grass cover near Amarillo, Texas, where the average annual precipitation is 18.5 inches. Their data demonstrate that no precipitation has moved below the root zone under native grass during the past several hundred years. Hauser and Chichester (1989) measured the soil water balance under perennial grass cover in east-central Texas where the average annual precipitation is 35.5 inches. No water penetrated below the rooting depth of the perennial grass on five different soil profiles, despite one unusually wet winter during the 6-year experiment.

Evaluation of ET Cover Potential

This presentation focuses on the process by which a specific site was evaluated for the potential application of an ET Cover. Located at a defense facility in eastern Colorado, the site is an old landfill scheduled to be covered in conjunction with overall remediation efforts at the Base. This 74-acre landfill has been inactive for about 16 years, and may have been leached by infiltrating precipitation during its use as well as the following years of inactivity. To evaluate the potential applicability of an ET Cover at this site we followed a 4-step process to:

- ascertain the characteristics and availability of local soils amenable for use in an ET Cover;
- determine ET Cover requirements using hydrologic computer models;
- select vegetative species appropriate for the ET Cover at this site; and
- compare the relative effectiveness and cost of the ET Cover and conventional landfill covers.

Evaluation of Local Soils

Soils most suitable for an ET Cover should have high available water-holding capacity (AWC). Although several soils in the vicinity of the site meet this requirement, the Fondis and Weld soils are the most prevalent within a 12-mile radius. These soils are also desirable because they can be mixed and mined to a depth of 60 to 70 inches, thus minimizing cost for land purchase to acquire landfill cover materials. If the soil source can be mined 60 inches deep and the required ET Cover thickness is 18 inches, then about 0.3 acres are required for each acre of landfill covered. The soil properties which would result from mixing a vertical column of the soils located near the site are listed in table 1; these values were computed from data in the SCS Soils 5 data base and a local soil survey by Larsen and Brown (1971).

Table 1. Properties of mixtures of nearby soils.

	High AWC[1]		Low AWC	
Soil	**Fondis**	**Weld**	**Bresser**	**Truckton**
Soil depth[2] (in)	60	60	36	60
Clay, %	35	28	13	11
Silt, %	33	48	12	19
Sand, %	32	24	75	70
AWC, m/m	0.18	0.17	0.11	0.10
Organic Matter, %	0.5	0.7	0.5	1.0
pH	7.0	7.0	7.0	7.0

1. AWC = Plant-available soil water holding capacity.
2. Soil depth = Depth to the parent materials under the natural soil profile.

The other soils listed in table 1 could also be used in an ET Cover, but have a lower AWC and would require a thicker cover, thereby increasing the amount of soil to be hauled and the land area needed to acquire cover materials. However, if these soils could be found close enough to the landfill to minimize hauling costs, thereby reducing overall construction costs, then they may be suitable for an ET Cover.

Soils used in an ET Cover must also be able to support long-term and vigorous plant growth. This requires adequate cation exchange capacity to hold plant nutrients, low soil salinity and good soil structure. Soil organic matter content above 2 or 3 percent is desirable, although soils with otherwise good properties may be adequate even with less than 0.5 percent organic matter.

Application of Hydrologic Models

The variability of soils, vegetation and climate requires that landfill hydrology be evaluated specifically for each site where a cover is required. Computer models can effectively estimate landfill cover performance using data for climate, soils and vegetation which are representative of the site. We made estimates with two different computer models: (1) the Hydrologic Evaluation of Landfill Performance (HELP) model, version 3.01, Schroeder et al. (1994a), and Schroeder et al. (1994b); and (2) the Erosion/Productivity Impact Calculator (EPIC) model described by Williams et al. (1984, 1989, 1990), and Sharpley and Williams (1990).

The HELP model was developed by the US Army Engineer Waterways Experiment Station for the US Environmental Protection Agency (EPA). It is a quasi-two-dimensional hydrologic model of water movement and predicts landfill cover performance, including leakage through impermeable layers. The

HELP model has been extensively tested and is widely used by consulting engineers. Its estimates are accepted by most regulatory bodies in the United States.

The EPIC model was developed by the US Department of Agriculture to assess the effectiveness of soil erosion control practices nationwide. As a result the EPIC model incorporates all major aspects of hydrology, climate, soils, plant nutrients, plant growth, soil temperature and plant environment, and also estimates a complete water balance. More than 22 scientists and engineers contributed to the model development and documentation; they tested and validated it against measured field data at more than 200 sites world-wide. The EPIC model is particularly useful in evaluating the ET Cover, as described more fully by Hauser and Shaw (1994).

We used the EPIC model to estimate the performance of the ET Cover at the site. The input parameters for average monthly precipitation, and average, monthly maximum and minimum air temperatures were derived from the 45-year record at Stapleton airport, Denver, Colorado. Table 2 contains EPIC estimates of the hydrologic performance of several ET Covers which could potentially be used. The values shown are average annual results based upon a 100-year simulation. The soil parameters used were based on weighted averages and assume a uniform mixture of each soil to the top of the parent material. Both soils examined are common in the area, but the Fondis soil has relatively high available plant water holding capacity (AWC) while the Bresser soil has relatively low AWC. We also estimated the performance of a cover consisting of a one-foot layer of Fondis soil placed over the one-foot of sandy soil currently covering the landfill. No data were available on the properties of the existing sandy soil so we assumed that its AWC is less than that of the Bresser soil.

Table 2. Hydrologic performance estimates for potential ET Covers.

Description	Cover depth	Deep Percolation	Surface Runoff	Evapo-transpiration
	(ft)	(in)	(in)	(in)
Fondis soil mix	1.5	0.00	0.65	14.75
Bresser soil mix	4.0	0.01	0.06	15.31
Fondes/existing	2.0	<0.01	0.45	14.97

The plant parameters used in the simulations were for the perennial, cool season wheatgrass plant association that is native to the area. In practice, annuals establish themselves, whether planted or not. As a result, plants could grow during more weeks of the year than we simulated in the model and soil water could be removed more quickly than estimated by EPIC. Thus, decisions based on the data shown in table 2 are conservative.

Selection of Vegetation

The primary purposes of establishing vegetation on an ET Cover are to control wind and water erosion of the uppermost soil layer and to remove water from the soil. In a natural grassland ecosystem in eastern Colorado, most of the plant species will be grasses, even though the forbs form an important part of the plant community. Grasses are more widely planted than are the associated forbs because grass seeds are easier to harvest than are forbs, thus they are more readily available. However, over time, forbs appear naturally in a planting of multiple grass species. If seed supplies of locally adapted, desirable forb species are available, they should be included in the mixture.

Because they are adapted to the climate, cool-season grasses may eventually dominate the landfill site, whether planted or not. Desirable native cool-season grasses that may be used in the plant mix include: slender wheatgrass [*Agropyron (A.) trachycaulum* (Link) Malte], thickspike wheatgrass [*A. dasystachyum* (Hook.) Scribn.], western wheatgrass (*A. smithii* Rydb.), and green needlegrass (*Stipa viridula* Trin.). Slender wheatgrass becomes established quickly, but it may come and go in the mixture over time. Western wheatgrass becomes established slowly, however, it is a permanent, sod-forming species, therefore, it is important that it become established. The others may increase or decrease in density in response to climate variability.

Warm-season grasses are also an important part of the native plant community. Desirable, native warm-season grasses that may be used in the plant mix include blue grama (*Bouteloua gracilis* (H.B.K.) Lag. *ex* Steud.), and buffalograss (*Buchloe dactyloides* (Nutt.) Engelm.).

Comparison of Effectiveness and Cost

The primary factor in selecting the appropriate landfill cover at this site is the need to control percolation of precipitation into the waste. We define an adequate cover as one that allows one inch or less of water to enter the waste by deep percolation during a 100-year period. Modeling simulations using HELP and EPIC indicated that two variations of the ET Cover would provide protection equal to the two conventional landfill covers. We found that any of the following landfill covers could provide adequate control of deep percolation:

Table 3. Estimated effectiveness of conventional and ET covers.

Cover Description	Infiltration per century (in)
1. RCRA cover with a double barrier layer consisting of compacted clay, K= $1x10^{-7}$ cm/s and a flexible membrane.	<1.0
2. Compacted Clay cover with K= $1x10^{-7}$ cm/s.	0.0
3. ET Cover with 1.5 feet or more of Fondis soil mixture.	0.0
4. ET Cover with one foot of Fondis soil over one foot of existing cover soil.	<1.0

The lowest cost cover from the above group of adequate landfill covers would be the most desirable. Although site specific cost data are unavailable for all the cover options listed, observations regarding relative costs can be made that will be useful in choosing a recommended cover.

The RCRA cover clearly is most costly to build because it requires three expensive components, a drainage layer, a barrier layer and a gas control layer. All three of these layers must be installed in a RCRA cover because the drainage layer is required to quickly remove water stopped by the barrier layer and even small amounts of gas production could be concentrated under the barrier and become hazardous. Maintenance costs are high for RCRA covers because the barrier layer must be exposed during repair.

The compacted clay cover is less expensive to build and maintain than the RCRA cover because it contains no drainage layer and requires less expensive soil compaction. By definition, however, the compacted clay cover contains an impermeable barrier and needs a gas control layer. Gas control layers are high-cost components of landfill covers.

Either an ET Cover composed of a Fondis soil cover 1.5 feet thick or the alternative of one foot of Fondis soil over one foot of existing soil would provide adequate protection. The ET Cover incorporating existing soil requires only half as much soil to be moved onto the landfill from off site as would be required for a clay cover. Moreover, there is no soil compaction cost for an ET Cover. The RCRA cover requires up to five times as much volume of high cost material to be hauled onto the site and also requires expensive soil compaction and testing. Because the ET Cover is a natural, self renewing cover it is also easy and inexpensive to repair should landfill settlement damage the cover. Any depressions could simply be filled with soil to restore surface drainage and then seeded with new grass; these are relatively low cost procedures. Because of these lower construction and maintenance costs the ET Cover appears to be the most cost effective alternative.

Recommendations

Based upon the above analyses, as well as more detailed studies, we recommended that an ET Cover be used at this site by placing one foot of the Fondis or Weld soils over one foot of existing landfill cover soil. The ET Cover prevents leaching of soluble contaminants to groundwater, controls contact between receptors and the waste, and has low construction and maintenance costs.

Nationwide the number of landfill sites that require a cover to provide environmental safeguards far outstrip the funds available for the task. Use of the ET Cover at suitable sites can conserve limited environmental dollars while still achieving technical and regulatory goals. The ET Cover offers an effective, natural, and low cost solution to the long-term problem of landfill remediation.

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CLIMATE EFFECTS ON WATER MOVEMENT THROUGH SOIL VEGETATIVE LANDFILL COVERS[1]

Victor L. Hauser and Maurice A. Shaw[2]

Abstract

We propose an inexpensive and practical landfill cover that stores precipitation in the soil until it is removed by evapotranspiration (ET). We call it the *ET Cover*. The ET Cover contains no impermeable materials, but it requires adequate soil water-holding capacity to store precipitation until ET can remove the water from storage. We evaluated the ET Cover concept with the Erosion/Productivity Impact Calculator (EPIC) computer model across a 1,600-km strip of the southern United States. The ET Cover can reliably control infiltration into landfills, reclaimed mine land, oil shale residues, fire training areas, and similar sites where infiltration should be limited. It will be successful in most parts of the country. Previous experimental work demonstrates that the ET Cover will be effective in much of the intermountain and arid western part of the United States. Our work demonstrates that it will work in the semiarid and subhumid Southern Great Plains. The evaluation of whether the ET Cover is appropriate for a site is best achieved with a comprehensive computer model that is capable of simulating the variability of climate over periods in excess of 100 years.

Introduction

There are thousands of landfills, both old and new, scattered across most of the developed world. In the United States and many other countries, strict landfill closure laws are in effect. If rainfall percolates through the landfill, it may carry contaminants into the regional groundwater. Therefore, final landfill covers are required to control the movement of precipitation into the landfill contents. This is currently achieved by

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Presented at the Seventeenth International Madison Waste Conference, September 21–22, 1994, Department of Engineering Professional Development, University of Wisconsin-Madison.

including impermeable materials, such as compacted clay barriers or flexible membranes, in the landfill cover.

Landfill contents decompose and settle unevenly, which results in large differential movement of the cover. Thus, compacted clay or flexible membranes in currently used covers may rupture and leak. Wetting and drying and freezing and thawing cycles are known to reduce the effectiveness of compacted clay layers, and the durability of flexible membranes beyond a few decades is unknown. The currently used landfill covers are expensive to build and maintain. Covers should provide long-term (centuries) reliability and be inexpensive to build and maintain.

Previous Work

Nyhan, et al. (1990), discussed alternative landfill covers that utilized native grasses to control percolation through covers at a cool, dry site in New Mexico. The average annual precipitation during the 3-year experiment was 580 mm. One of their alternative covers produced no leachate, and the other produced average leachate of 15 mm per year.

Anderson, et al. (1992), evaluated soil covers with either native range grasses or sagebrush growing on them in the arid climate of southeastern Idaho. During their 3-year experiment, they found that no water percolated below the root zone of the plant cover. The authors reported no dead sagebrush plants during their experimental observations. In long-term use on landfills, some of the cover plants will die. When large roots (such as those from sagebrush) decay, they may leave preferential flow pathways for water movement through the soil cover. The authors did not evaluate the possible effect of preferential flow through large root channels.

Hakonson, et al. (1992), discussed biotic and abiotic processes that are pertinent to landfill design in deserts. They showed (by computer modeling) that range grass cover can reduce percolation to negligible amounts in desert regions.

Licht (1993) proposed the use of poplar (*Populus* spp.) trees for water management on landfill covers at Beaverton, Oregon. He reported extensive soil drying during the growing season, but showed no data for the dormant season. The amount of water percolating below the root zone was not reported. His proposal included the harvest of poplar trees for wood, which would result in the death of some tree roots. There was no evaluation of possible rapid percolation of precipitation through preferential flow paths created by decaying tree roots. He did not estimate long-term performance of the system.

Alternative Cover

We propose an alternative landfill cover concept that may be used at any place where climate and soil resources are appropriate. The proposed cover may also be used over reclaimed mine land, oil shale residues, fire training areas, and similar sites where infiltration should be controlled. The cover design was based on the following concept and field-measured data.

Concept

Native grasses and associated forbs have extensive, fibrous root systems and consume all of the water stored in the soil within the root zone of the grasses in many climates. Where the soils have adequate soil water-holding capacity, this results in no percolation of water below the root zone of these plants. The root zone depth below native grass varies according to soil wetness from a few cm to 2 m or more. Native grass communities are well adapted to the climate, insects, diseases, and other factors that affect plant growth and survival in the region where they developed. They reliably grow and consume water, even in years when one or more species have been weakened by insect, disease, or other attack, because not all species are adversely affected in any particular year. Therefore, where soils with adequate plant-available, soil water-holding capacity (AWC) are found, native grass communities can prevent deep percolation below the root zone.

Field Data

Aronovici (1971) measured the depth and amount of water penetration below native grass near Amarillo, Texas, where the average annual precipitation is 475 mm. He found that the soil water content was below the permanent wilting point to the maximum sampling depth at 15 m under native grass cover. Lotspeich, et al. (1971), measured water content under native grass with good surface drainage near Amarillo, and they found that the soil water content was at or below the permanent wilting point to the maximum sampling depth at 28 m. These data demonstrate that, with good surface drainage, no precipitation moved downward below the root zone under native grass in a semiarid climate with 475 mm of average annual precipitation.

Hauser and Chichester (1989) measured the soil water balance under perennial grass in a subhumid climate in east-central Texas during a 6-year experiment. The average annual precipitation was 960 mm at the site. At this subhumid site with twice as much rainfall as the site near Amarillo, no water penetrated below the rooting depth of the perennial grass on five different soil profiles.

The ET Cover

We propose an inexpensive and practical landfill cover that stores precipitation in the soil until it is removed by evapotranspiration (ET). We call it the *ET Cover*. It provides adequate soil water-holding capacity to store infiltrating precipitation until ET can remove the water from storage, but contains no impermeable materials. It uses native grass communities to control soil erosion and remove water from the soil cover. Native shrubs may be considered for the ET Cover if careful evaluation demonstrates that preferential flow will be sufficiently small through root channels. One possible design of the ET Cover is shown in figure 1.

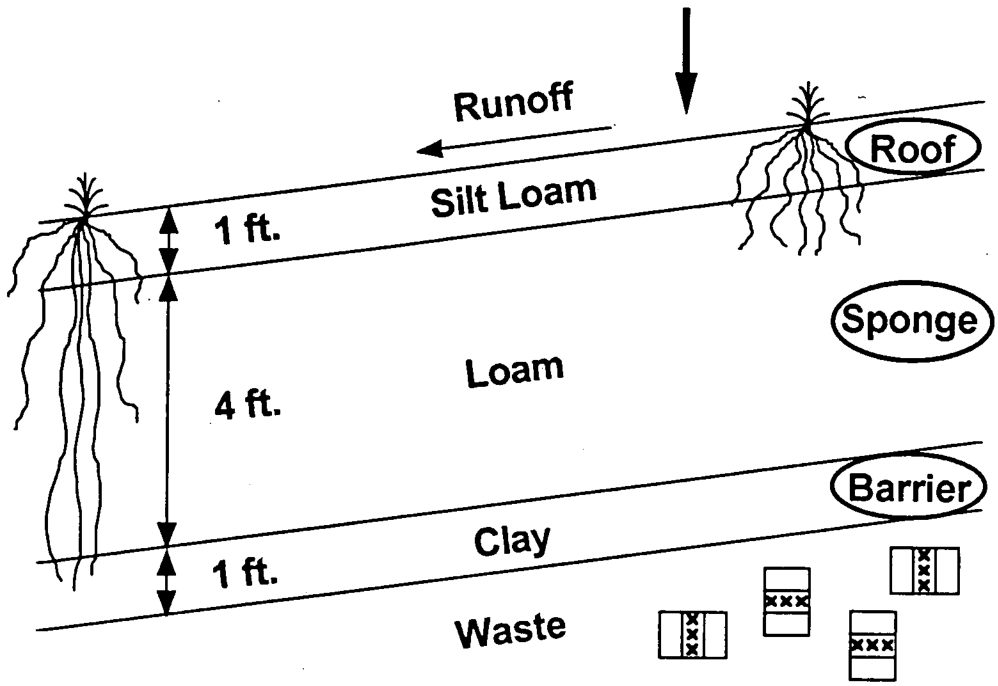

Figure 1. The proposed ET Cover incorporating a surface soil layer of high water-holding capacity and high runoff-producing potential, a soil water-storage layer, and a layer of slowly permeable soil to separate the cover from the waste. A mixture of native grasses and forbs should be grown on the cover to remove water from the soil and prevent erosion of the soil surface.

The ET Cover is constructed from soil material found near the site and requires no compaction. The successful ET Cover limits the percolation of precipitation into the landfill contents and requires less maintenance than currently used covers. The ET Cover suffers little damage due to settlement because the soil will naturally fill voids, and plant roots grow profusely in loose, disturbed soil. It is natural, self-renewing, and not subject to long-term damage by wetting and drying of compacted clay layers or possible deterioration of manmade materials over time. Damage, such as by burrowing animals, or depressions in the surface caused by settlement can be easily and economically repaired by filling holes with soil, regrading the surface, and replanting grass where needed.

Hauser and Shaw (1994) evaluated the ET Cover in east-central Texas with measured field data and the Erosion/Productivity Impact Calculator (EPIC) computer model. Where the AWC of the soil cover exceeded 225 mm, no water moved through the simulated cover in a 100-year simulation. They found that where soil resources near the site are limited, the soil with the highest water-holding capacity should be placed on top of the profile. The ET Cover can prevent deep percolation into landfills, mine spoil, or other materials in east-central Texas where the average annual precipitation is 830 mm.

Evaluation of the ET Cover

We evaluated the effect of soils and climatic variability on the ET Cover's performance at 7 sites across a 1,600-km (1,000-mile) strip of the southern United States (figure 2). The mean annual rainfall varied from 330 to 1,400 mm at the simulated sites.

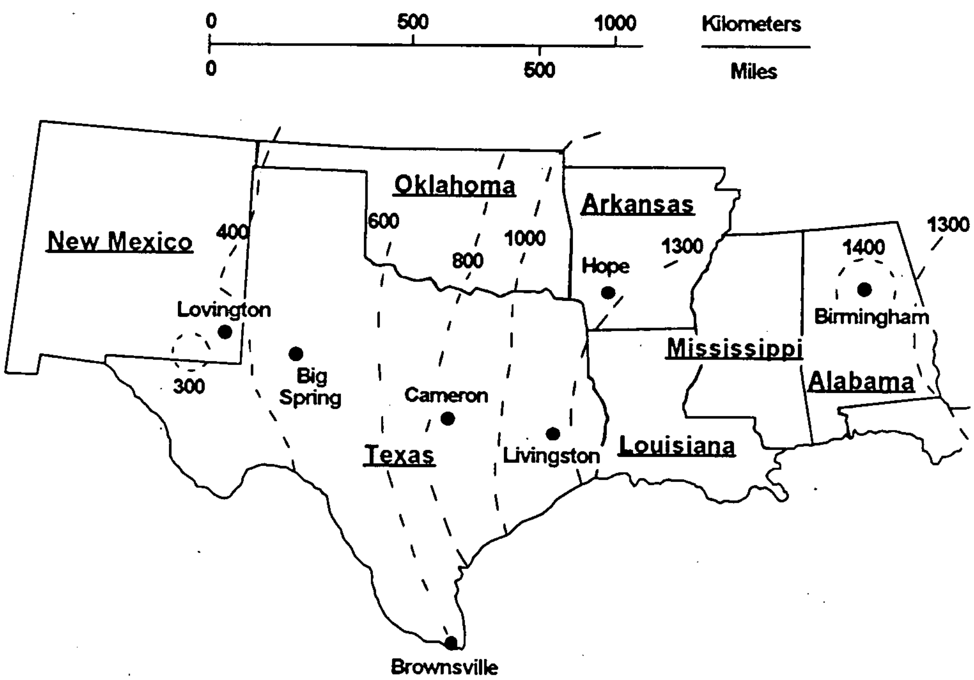

Figure 2. Test locations for the ET Cover and mean annual rainfall isohyets

We evaluated the ET Cover concept with the EPIC computer model (Williams, et al., 1984; Williams, et al., 1989; Sharpley and Williams, 1990; and Williams, et al., 1990). The EPIC model simulates the physical processes involved in water movement (simultaneously and realistically), and it uses readily available inputs. The model addresses all major aspects of hydrology, climate, soils, plant nutrients, plant growth, soil temperature, and plant environment. It also estimates a complete water balance. The EPIC model performs all calculations on a daily time step. It is computationally efficient and can simulate hundreds of years in a few minutes on a modern desktop computer. It generates climatic data for any spot in the continental United States from internal coefficients, and it contains soils data for the major soils found within the United States. The EPIC model permits numerous sequential runs using the same climate file and allows preliminary runs to equilibrate the beginning values of soil nitrate and soil water in response to climate at the site. More than 22 scientists and engineers contributed to the model's development and documentation (Sharpley and Williams, 1990); they tested and validated it against measured field data at more than 200 sites worldwide.

All simulations utilized kleingrass (*Panicum coloratum* L.) as the vegetative cover; it is a hardy perennial grass that is adapted to the southern United States. The simulation assumed that the maximum rooting depth was 2 m and that any water moving below 2 m would be lost to deep percolation. All other parameters were set to be consistent with perennial grass growth and production values common to the southern United States.

The simulations utilized two soils at each of 7 locations. The soils are described in table 1; the locations are shown in figure 2 and are listed in table 2. The soils are found in east-central Texas. The Axtell soil used for modeling in this investigation was located in an eroded, retired farm field and is typical of upland soils near Cameron, Texas (Chichester and Hauser, 1991, and Hauser and Chichester, 1989). Both soils were included in a field experiment that investigated simulated mine land covers, which are similar to landfill covers. The Axtell mix was a mixture of the Axtell soil from the surface to the 1.8 m depth that was used to simulate a mine spoil cover at the site (Hauser and Chichester, 1989). As a result of the field mixing, the Axtell mix soil had uniform properties throughout the profile. Other soils with similar water-holding properties and runoff potential are found in the southern United States from southeastern New Mexico to Alabama.

Additional details about the model and approach used in this evaluation can be found in Hauser and Shaw (1994).

Table 1. Particle size distribution and plant-available, soil water-holding capacity (AWC) for two soil profiles evaluated at each of 7 sites. The Axtell soil and Axtell mix are described as "site soil" and "site mix," respectively, in Hauser and Shaw (1994).

Soil Material	Depth (m)	Sand[1]	Silt[2] (percent by weight)	Clay[3]	AWC (m/m)
Axtell Soil, A	0.00–0.20	70.8	28.9	0.3	0.140
Axtell Soil, B–C	0.20–0.60	25.9	23.0	51.1	0.103
Axtell Soil, D	0.60–1.20	31.0	34.2	34.8	0.100
Axtell Soil, E	1.20–1.40	42.8	32.2	25.0	0.111
Axtell Soil, F	1.40–2.00	45.2	30.6	24.2	0.111
Axtell Mix	0.00–2.00	38.5	30.0	31.5	0.170

[1] 0.05 to 2 mm
[2] 0.002 to 0.05 mm
[3] Less than 0.002 mm

Table 2. Estimates by the Erosion/Productivity Impact Calculator (EPIC) computer model of 100-year average of total annual rainfall, deep percolation below the root zone, and surface runoff for Axtell mix and Axtell soil, and heat units at each of 7 locations in the southern United States.

Location	Rainfall	Deep Percolation Mix (mm)	Deep Percolation Soil (mm)	Runoff Mix (mm)	Runoff Soil (mm)	Heat Units (°C)
Lovington, New Mexico	330	0	0	12	10	5,800
Big Spring, Texas	440	0	0	11	11	6,500
Brownsville, Texas	600	0	0	52	49	8,500
Cameron, Texas	830	0	4	83	82	7,300
Livingston, Texas	1,260	5	61	204	194	7,000
Hope, Arkansas	1,290	9	104	213	200	6,300
Birmingham, Alabama	1,410	31	154	231	214	6,300

Prediction of Performance

Average annual deep percolation below the plant root zone from the 100-year simulation was zero for all sites with less than 830 mm of average annual rainfall (table 2). Where annual rainfall was greater than 830 mm, there was some deep percolation.

The AWC of the root zone was 340 mm for the Axtell mix and 192 mm for the Axtell soil profile (table 1). Accordingly, the Axtell soil profile produced greater deep percolation because the profile held less water in storage (table 2). Hauser and Shaw (1994) found that, at Cameron, Texas, soils with AWC greater than 225 mm produced no deep percolation. Where the rainfall was greater than that at Cameron (830 mm), there was some deep percolation even with the high AWC value for the Axtell mix profile (table 2).

EPIC computes annual heat units in degrees Celsius (°C) (table 2) as degree days of temperature above a plant-specific threshold for no growth. Hope, Arkansas, is located 400 km (250 miles) north of Livingston, Texas; these two locations receive nearly equal annual rainfall. However, there is a large difference in deep percolation between the two sites. The annual heat units for kleingrass are 7,000 °C for Livingston and 6,300 °C for Hope. Because of the greater number of heat units, kleingrass uses water during more days of the year at Livingston and dries the soil more completely than at Hope.

Discussion

In the region of our study, the climate varies from the edge of desert to a hot, humid climate influenced by hurricane rainfall. The discussion centers on the effects on deep percolation of the following variables: annual rainfall, heat units, AWC, and surface runoff.

Deep percolation was influenced most by annual rainfall. The number of days per year when ET consumes substantial water is also important, as shown by the correlation between deep percolation and annual heat units at Livingston, Texas, and Hope, Arkansas. If water use is high when rainfall is likely, deep percolation will be low or zero. However, if water use is low during long, rainy periods in winter, then there may be significant deep percolation.

Hauser and Shaw (1994) demonstrated that the AWC of the soil controls the amount of deep percolation in a subhumid climate. The EPIC model also estimated substantial differences in deep percolation between the two soils in humid climates.

Surface runoff was also influenced most by rainfall, but there are other important factors. The properties of the surface soil layer control the runoff amount and thus the amount of deep percolation. Surface runoff and deep percolation are closely related because more than 80 percent of incoming rainfall is lost by ET. Thus the sum of surface runoff and percolation are relatively small components of the hydrologic cycle. Even small increases in surface runoff may significantly reduce deep percolation. Increased surface runoff at Birmingham, Alabama, might reduce deep percolation to zero.

The EPIC computer model estimates water extraction by plants from all soil layers; however, it permits soil water evaporation from the top 0.2 m of the soil profile only. Therefore, water in soil layers below 0.2 m can be removed by plant extraction or by percolation to the next lower layer only. The EPIC model does not account for the small, upward movement of water through the soil in response to water pressure gradients produced by drying of the upper layers of soil. Therefore, the EPIC computer model estimates more deep percolation than may actually occur in the field. Thus the deep percolation estimates are conservative.

We used kleingrass as a monoculture in the model. Therefore, there were no plant species available to remove water from the soil profile during periods of cool weather when kleingrass uses little water. The ET Cover should support a mixture of cool and warm season plants to dry the soil during a greater part of the year. A mixture of plant species would reduce deep percolation and extend the range of usefulness for the ET Cover.

In dry climates, deep percolation will be easier to control because lower AWC is required. Suitable control may be achieved by selection of soil material with lower AWC or by reducing the thickness of the soil cover.

The work of Nyhan, et al. (1990); Anderson, et al. (1992); and Hakonson, et al. (1992), indicates that the ET Cover will be effective in much of the intermountain and arid western part of the United States. Our work indicates that it will work in the semiarid and subhumid regions of the Southern Great Plains. The ET Cover should also be tested in colder climates with native plant species.

Conclusions

The ET Cover can reliably control infiltration into landfills, reclaimed mine land, oil shale residues, fire training areas, and similar sites where infiltration should be limited. It will be successful in many parts of the country. Its usefulness must be judged by the climate and soils found at the site.

In the Southern Great Plains, the ET Cover will permit no deep percolation below the 2 m root depth between the foothills of the Rocky Mountains and the 830 mm average, annual rainfall isohyet.

The ET Cover may be used in more humid climates if soils with higher AWC are available, surface runoff is increased, and/or more diverse plant species are used on the cover.

The integration and evaluation of the many complex factors that influence the effectiveness of the ET Cover are best achieved with a comprehensive model, such as EPIC, that is capable of simulating the variability of climate over periods in excess of 100 years.

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EFFECTIVENESS OF SOIL-VEGETATIVE COVERS FOR WASTE SITES

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ABSTRACT

We propose an inexpensive and practical cover for landfills, reclaimed mine land, oil shale residues, fire training areas, and similar sites. This cover stores precipitation in the soil until it is removed by evapotranspiration (ET). We call it the *ET Cover*. The ET Cover contains no impermeable materials, but it requires adequate soil water-holding capacity to store precipitation until ET can remove the water from storage. This evaluation of the ET Cover concept demonstrated that it is appropriate for use in much of the United States west of the 95th meridian (western Missouri). It is not appropriate for use in wet, cool climates such as the northern California coast. The ET Cover controls infiltration effectively under high-precipitation conditions where potential evapotranspiration and surface runoff are high and the growing season is long. We evaluated the appropriateness of the ET Cover for each site with a comprehensive computer model that is capable of simulating the variability of climate over periods in excess of 100 years.

INTRODUCTION

The owners of landfills, reclaimed mine land, oil shale residues, fire training areas, and similar sites are required to cover the site and to control the amount of water percolating through the cover into the hazardous material below. This is currently achieved by including materials such as compacted clay layers or flexible membranes in the cover. The currently used covers are subject to damage by uneven settlement, freezing and thawing of clay layers, or chemical changes in manmade materials. Covers should provide long-term (centuries) reliability and be inexpensive to build and maintain. Currently used covers may not provide long-term reliability and low construction and maintenance cost.

We propose an improved cover design and examine the concept with a tested computer model and comparison with measured field data.

THE ET COVER

We propose an improved cover that can be used where climate and soil resources are appropriate. It can be used over landfills, reclaimed mine land, oil shale residues, fire training areas, and similar sites where infiltration should be controlled. The cover design was based on the following concept and field-measured data.

Concept

Native grasses and associated forbs have extensive, fibrous root systems and, in many climates, may consume all of the water stored in the soil within the root zone of the grasses. Where the soils have adequate water-holding capacity this precludes percolation of water below the root zone of these plants. The root zone depth below native grass extends to 2 m or more below the soil surface. Native grass communities are well adapted to the region where they developed and they reliably grow and consume water. Therefore, for soils with adequate plant-available, soil water-holding capacity (AWC), native grass communities may prevent percolation below the root zone.

Field Data

Aronovici (1) and Lotspeich et al. (2) measured the depth and amount of water penetration below native grass near Amarillo, Texas where the average annual precipitation is 475 mm. Their data demonstrated that

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Presented at the Superfund XV, Nov. 29 - Dec. 1, 1994, Washington, D.C. Superfund XV, One Church Street, Rockville, MD 20850 [(301) 251-1900]

with good surface drainage, no precipitation moved downward below the root zone under native grass.

Hauser and Chichester (3) measured the soil water balance under perennial grass in a subhumid climate in east-central Texas. During a 6-year experiment, the average annual precipitation was 960 mm at the site. At this subhumid site with twice as much precipitation as the site near Amarillo, no water penetrated below the rooting depth of the perennial grass on five different soil profiles.

Description of the ET Cover

We propose an inexpensive and practical cover that stores precipitation in the soil until it is removed by evapotranspiration (ET). We call it the *ET Cover*. It provides adequate soil water-holding capacity to store infiltrating precipitation until ET can remove the water from storage, but contains no impermeable materials. It uses native grass communities to control soil erosion and remove water from the soil cover. One possible design of the ET Cover is shown in Figure 1.

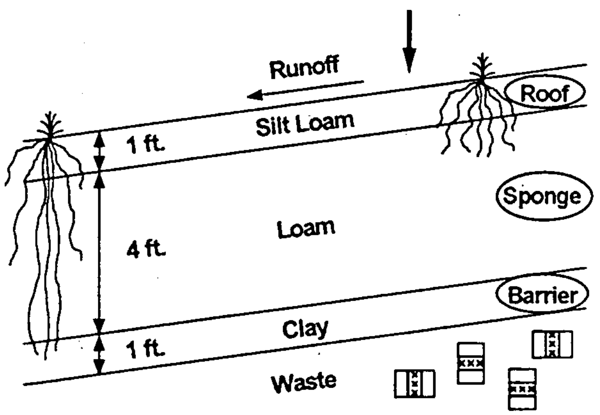

Figure 1. The proposed ET Cover over a landfill.

The ET Cover includes a sloped surface soil layer of high water-holding capacity and high runoff-producing potential (roof), a soil water-storage layer (sponge), and may incorporate a soil layer with low permeability (barrier) to separate the cover from the waste. A mixture of native grasses and forbs should be grown on the cover to remove water from the soil and prevent erosion of the soil surface.

The ET Cover is constructed from soil found near the site and requires no compaction. The successful ET Cover limits the percolation of precipitation through the cover and requires less maintenance than covers currently in use. Little damage is suffered due to settlement because the soil will naturally fill voids, and plant roots grow profusely in loose, disturbed soil such as that found near shear zones. It is natural, self-renewing, and not subject to long-term damage by wetting and drying of compacted clay layers nor the possible deterioration of manmade materials over time. Damage caused by burrowing animals or depressions in the surface caused by settlement can be easily and economically repaired by filling holes with soil, regrading the surface, and replanting grass where needed.

Hauser and Shaw (4) evaluated the ET Cover in east-central Texas with measured field data and a computer model. The 100-year, average annual precipitation is 830 mm at the site. Where the AWC of the soil cover exceeded 225 mm, Hauser and Shaw (4) found that no water moved through the simulated cover during a 100-year simulation. They found that the soil with the highest water-holding capacity should be placed on top of the profile and concluded that the ET Cover can prevent percolation through covers in east-central Texas.

EVALUATION PROCEDURE

We evaluated the effect of soil and climatic variability on the ET Cover's performance at 27 sites in the United States. To evaluate the ET Cover, we used the Erosion/Productivity Impact Calculator (EPIC) computer model described by Williams, et al., (5, 6, 7) and by Sharpley and Williams (8). Plant, soil and climate parameters were important to the evaluation and were part of the model database.

The EPIC Computer Model

The EPIC model simulates the physical processes involved in water movement, and it uses readily available data. The model addresses all major aspects of hydrology, climate, soils, plant nutrients, plant growth, soil temperature, and plant environment. It also estimates a complete water balance. The EPIC model performs all calculations on a daily time step. It is computationally efficient and can simulate hundreds of years in a few minutes on a modern desktop computer. It generates climatic data for any part of the continental United States from internal coefficients, and it contains chemical and physical data for the major soils found within the United States. The EPIC model permits numerous sequential runs using the same climate file and allows preliminary runs to equilibrate the beginning values of soil nitrate, soil water, and other variables in response to climate at the site.

More than 22 scientists and engineers contributed to the EPIC model's development and documentation (8). They tested and validated it against measured field data at more than 200 sites worldwide. In addition, Hauser and Shaw (4) compared EPIC's estimates of deep percolation through soil-vegetative covers with measured field data. They found that EPIC may estimate more deep percolation than would actually occur, suggesting that EPIC's estimates are conservative.

Plant Parameters

The EPIC model contains 52 plant-specific parameters. We used plant-specific parameters developed by the model developers.

Where average annual precipitation was greater than 700 mm, we used the "Range" parameters. Range plants have maximum plant height of 1 m, and rooting depth of 2 m. Estimates near the 450 mm isohyet used short grass range with maximum plant height of 0.3 m and rooting depth of 2 m. The optimum and minimum temperatures for plant growth were 25°C and 8°C respectively for all range grasses. These parameters are appropriate because similar native plants grow throughout this region. However, at the northern sites, other native range grasses could be used that have lower minimum temperature for plant growth; they would use more water during cool spring and fall weather than the range grasses used in EPIC.

The native range grasses of the California coastal regions are predominantly winter annuals. We simulated these grasses with winter pasture coefficients. The native grasses of eastern Washington include cool-season perennials and annual grasses. We simulated these grasses with winter wheat because there are no parameters in the current EPIC database that are specific to native grasses in eastern Washington. The optimum and minimum temperatures for plant growth were 15°C and 0°C respectively for the plants modeled at the California and Washington sites.

Soils

We estimated deep percolation below the plant rooting depth at each location for both the Pullman clay loam and the Amarillo fine sandy loam soils. These soils cover most of the High Plains and South Plains of Texas, and parts of eastern New Mexico. We used the soil properties as described for the native soils in place. Some of the soil properties are included in Table 1.

We used these two soils at all locations across the country to produce consistency and permit comparison between climatic regions. In use, the ET Cover would be built with soils found near the site. Acceptable soils may be found near most sites in the United States.

Because of the slowly permeable layer from 0.15 to 0.74 m, the Pullman soil produces large surface runoff. The Amarillo soil, however, produces little surface runoff (and more deep percolation) because of the high sand content of the near-surface soil profile.

Hauser and Shaw (4) demonstrated that soil-vegetative covers should have high water-holding capacity in the surface layers. The Pullman soil profile closely simulates that requirement, whereas the Amarillo soil has relatively low water-holding capacity in all layers, including the surface layers.

The Pullman soil profile fulfills the requirements for a good soil-vegetative cover, but the Amarillo profile in its natural state does not.

Climate

Climate has a major impact on the performance of the ET Cover. We evaluated the ET Cover at several sites chosen to represent widely differing climates, including subhumid/humid, semiarid, west coast, and intermontane. The mean annual precipitation varied from 265 to 1378 mm and included wet winter/dry summer as well as dry winter/wet summer combinations. Temperature regimes ranged from subtropical with year-long plant growth to long, cold winters with short growing seasons.

Table 1. Particle size distribution and plant-available soil water-holding capacity (AWC) for Pullman clay loam and Amarillo fine sandy loam soils.

Depth	**Sand**	**Silt**	**Clay**	**AWC**
m	**--------% by wt. ------**			**m/m**
		Pullman		
0.00 - 0.15	17.2	48.1	34.7	0.25
0.15 - 0.41	13.5	42.2	44.3	0.20
0.41 - 0.74	13.3	44.7	42.0	0.15
0.74 - 1.12	15.2	46.4	38.4	0.12
1.12 - 1.47	18.6	43.8	37.6	0.11
1.47 - 2.00	12.5	45.6	41.9	0.08
		Amarillo		
0.00 - 0.23	83.1	8.0	8.9	0.113
0.23 - 0.58	66.2	16.6	17.2	0.118
0.58 - 0.84	58.2	17.9	23.9	0.132
0.84 - 1.12	61.4	17.6	21.0	0.096
1.12 - 1.40	66.1	15.9	18.0	0.102
1.40 - 1.73	54.9	25.9	19.2	0.099
1.73 - 2.00	57.0	24.6	18.4	0.100

We chose sites for evaluation that show the effect of annual precipitation on ET Cover performance. For example, we evaluated locations near the 450, 800, and 900 mm annual precipitation isohyets and four sites with about 1350 mm annual precipitation.

Locations near the 450, 800, and 900 mm isohyets show the effect of progressively colder climate on similar annual precipitation amount and distribution during the year. Figure 2 shows the location of the sites where we evaluated the ET Cover with the EPIC computer model.

In the Great Plains, winters are dry and most of the annual precipitation occurs during the growing season in the summer. Precipitation is much larger and more evenly distributed during the year in the Deep South, although cool winters result in low potential evaporation rates. Central Florida has a year-long growing season with a major part of annual precipitation occurring in summer and early fall when plants consume large amounts of water.

Most precipitation occurs during winter on the west coast; potential evaporation rate is small at that time. A similar pattern exists for eastern Washington, although, the precipitation is more evenly distributed throughout the year than for the West Coast. The climate of eastern Washington is typical of many sites in the intermontane areas of the west.

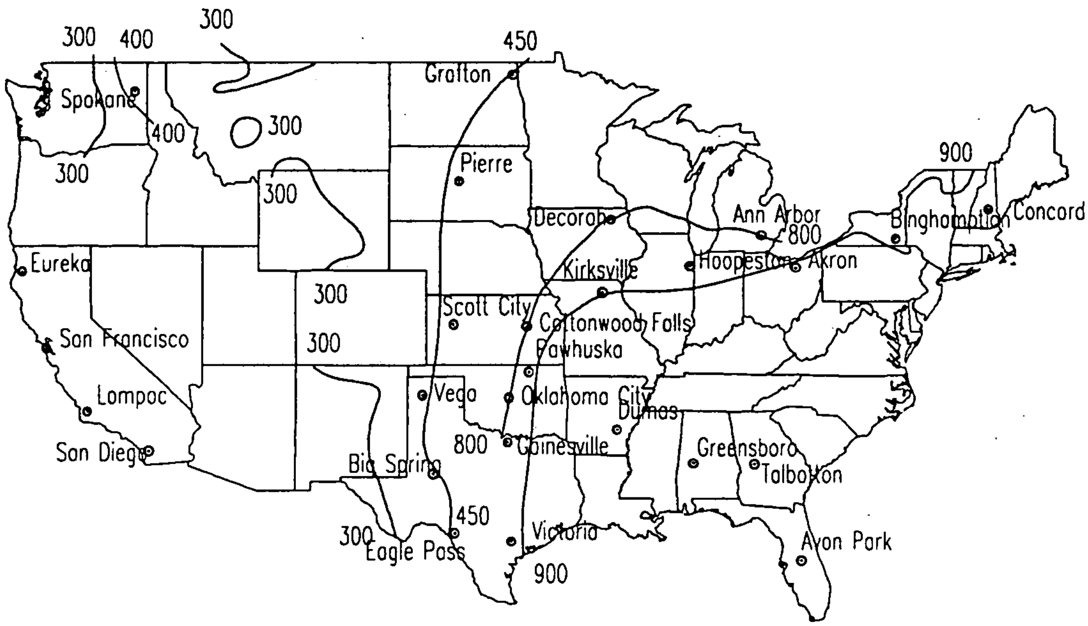

Figure 2. Locations used to estimate effectiveness of the ET Cover and selected annual precipitation isohyets.

PERFORMANCE ESTIMATES

The EPIC model first simulated ET Cover performance for 5 years to initialize soil water content, soil nitrate, and other variables to realistic starting values at each site. Then, beginning with these values, EPIC simulated ET Cover performance for a 100-year period for each site. Table 2 summarizes the results of the 100-year simulation for 27 sites.

The incoming precipitation is partitioned between ET, deep percolation (PRK), and surface runoff (Q). The EPIC model estimates snowfall where appropriate; however, all precipitation is summed as liquid water for the year and reported as "rain." The sum of ET, PRK, and Q should equal rain. The simulations by EPIC produced a balance with less than 1 percent error (Table 2). In most cases, ET accounts for the largest part of incoming precipitation. Relatively small changes in surface runoff are usually reflected directly in deep percolation amount.

The potential evapotranspiration (PET) shown in Table 2 was estimated by the Hargreaves equation. The PET is an estimate of the maximum possible amount of ET. Numerous factors, including plant parameters, precipitation, and radiation at the earth's surface control the amount of actual ET (Table 2).

Effect of Soil

The Amarillo soil produced more percolation below the root zone than the Pullman soil at all sites except in four arid or semiarid locations where there was no deep percolation from either soil. The Pullman soil produced the most surface runoff at all sites as expected.

Locations Showing Zero Deep Percolation

There was no deep percolation with Pullman soil at any of the semiarid sites. Only one semiarid site (Grafton, ND), had significant deep percolation on the Amarillo soil. We speculate that the deep percolation on Amarillo soil at Grafton was the result of using warm-season grass parameters in EPIC at this cold site.

Sites located near the 900 mm isohyet from the Gulf of Mexico to northern Missouri also produced no deep percolation. Other sites producing zero deep percolation include two southern California stations; Spokane, WA; and Avon, FL where average annual precipitation was 1334 mm.

Figure 3 shows areas of the United States in which EPIC estimated that the ET Cover would produce no deep percolation with a Pullman soil.

Table 2. Estimates by the Erosion/Productivity Impact Calculator (EPIC) computer model of 100-year average of total annual precipitation (Rain), deep percolation below the root zone (PRK), surface runoff (Q), evapotranspiration (ET), and potential evapotranspiration (PET) in four major climatic zones of the United States.

		------ Pullman Soil ----			----- Amarillo Soil -----			
Location	**Rain mm**	**PRK mm**	**Q mm**	**ET mm**	**PRK mm**	**Q mm**	**ET mm**	**PET mm**
Subhumid and Humid								
Victoria, TX	873	0	115	753	4	52	809	2010
Gainesville, TX	880	0	90	786	15	32	824	2070
Pawhuska, OK	916	0	100	811	24	35	847	1900
Kirksville, MO	915	3	103	805	97	29	778	1550
Hoopeston, IL	955	12	102	834	136	24	780	1510
Akron, OH	917	44	88	779	166	19	719	1370
Binghamton, NY	924	116	111	687	257	24	626	1180
Concord, NH	951	89	124	728	233	33	667	1390
Oklahoma City, OK	810	0	71	735	14	24	765	1810
Cottonwood Falls, KS	836	0	64	766	21	19	787	1770
Decorah, IA	820	8	86	723	110	23	676	1340
Ann Arbor, MI	795	10	60	721	99	12	675	1330
Avon Park, FL	1334	0	163	1164	53	58	1209	2300
Talbotton, GA	1356	31	200	1114	244	40	1048	2040
Greensboro, AL	1378	31	238	1097	251	64	1039	2000
Dumas, AR	1350	42	237	1060	262	65	1000	2000
Semiarid								
Eagle Pass, TX	504	0	45	467	0	17	492	2420
Big Spring, TX	439	0	12	425	0	3	433	2160
Vega, TX	475	0	13	460	0	4	468	1980
Scott City, KS	512	0	22	488	1	8	500	1940
Pierre, SD	480	0	18	461	1	6	470	1490
Grafton, ND	451	0	14	436	25	5	418	1280
West Coast								
San Diego, CA	265	0	10	255	0	3	261	1360
Lompoc, CA	368	0	35	330	16	9	339	1640
San Francisco, CA	524	11	77	432	63	19	434	1350
Eureka, CA	1003	326	232	426	521	44	408	880
Intermontane								
Spokane, WA	419	0	12	404	26	3	385	1330

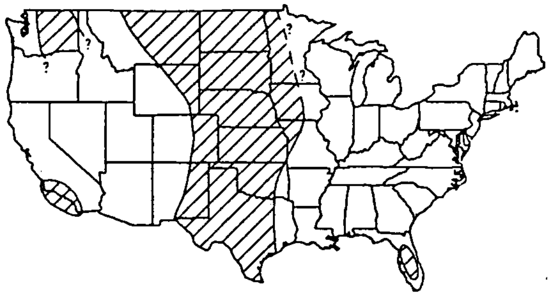

Figure 3. Areas of the United States where the ET Cover produced no deep percolation with the Pullman soil and the plants included in this simulation.

DISCUSSION

The estimates by EPIC of the performance of the ET Cover agree with field measurements made in the southwestern Great Plains by Aronovici (1) and Lotspeich et al. (2). Hauser and Shaw (4) evaluated the ET Cover with the EPIC computer model and verified results with field data. They found good agreement between the model and field measurements and determined that the ET Cover concept is appropriate in east-central Texas.

Field measurements published by Nyhan et al. (9) and Anderson et al. (10), and computer models by Hakonson et al. (11) demonstrated that covers that use soil and vegetation to manage precipitation performed well in New Mexico and Idaho. Both locations are within the intermontane region of the West.

Low precipitation in the intermontane parts of the western states is generally associated with low elevation where waste sites are more likely to be located. Therefore, one may extrapolate the field results and the results of this modeling effort and conclude that the ET Cover should produce acceptable results for much of the intermontane region of the western states. As a result, it appears that the ET Cover will work in much of the United States west of the 95th meridian (western Missouri).

Soils

As used in these estimates, the natural Pullman soil profile performed well. However, the layer of Pullman soil between 0.15 and 0.74 m depth could be placed on top of a soil-vegetative cover. Such a modified cover would have both high water-holding capacity in the surface and ability to produce substantially more surface runoff than the native soil profile. This rearrangement of the soil could be easily and inexpensively accomplished during construction and could produce zero deep percolation in much wetter and/or colder climates than was the case with the natural profile.

At some sites, the best available local soil may be similar to the Amarillo soil. The Amarillo soil layers between 0.58 and 1.12 m depth contain enough clay to produce substantially more surface runoff and hold more water than the top layer of the natural Amarillo soil. The 0.58 to 1.12 m layer of Amarillo soil should be used as the top layer (roof) of the ET Cover. An ET Cover with the Amarillo soil layers rearranged should perform much better than the natural profile evaluated in this study.

Climate

The climate must be considered to ensure success of the ET Cover. The average annual precipitation at Eureka, CA is only 1003 mm, yet the ET Cover concept is clearly not appropriate there. In contrast, at Avon Park, FL, the average annual precipitation is 1334 mm, and there was no deep percolation with Pullman soil and only 53 mm/yr with the Amarillo soil. The difference between these sites may be explained by differences in air temperature, solar energy reaching the ground, and other variables that control the potential evapotranspiration (PET). The PET at Avon Park is 2300 mm/yr or 2.5 times the amount at Eureka. The low PET at Eureka causes very large amounts of precipitation to be partitioned to surface runoff and/or to deep percolation.

Annual precipitation and monthly distribution are similar between Oklahoma City, OK and Decorah, IA. However, because of the longer, colder winter at Decorah, the ET Cover concept produced some deep percolation there. Although the average annual precipitation was similar in Avon Park, FL and Talbotton, GA, the cooler climate at Talbotton produced substantially more deep percolation than at Avon Park.

Plants

The warm-season range grasses that we simulated in EPIC for the eastern United States, grow over all of the area where we modeled them. However, there are hardy cool-season perennial grasses that grow and use substantial water during cool weather in the northern part of the United States. The use of these grasses in mixtures with warm-season grasses should produce much better results in cold climates than we estimated in this study.

ET Cover Design

A large number of parameters affect the performance of the ET Cover, and there are numerous interactions between variables. Some of the interacting parameters are site-specific, and require evaluation over small areas. Therefore, a tested, comprehensive model, such as EPIC, should be used to evaluate the potential for the ET Cover at a site and to guide the design of the ET Cover.

CONCLUSIONS

Based on the simulations using EPIC and the field measurements presented in references 1 through 4, and 9 and 10, we arrive at the following conclusions.

1. The ET Cover can reliably control infiltration into landfills, reclaimed mine land, oil shale residues, fire training areas, and similar sites. It is appropriate for use in much of the United States west of the 95th meridian (western Missouri).

2. The ET Cover is not appropriate for use in wet, cool climates such as the northern California coast.

3. The ET Cover controls infiltration effectively under high-precipitation conditions where potential ET and surface runoff are high and the growing season is long.

4. The integration and evaluation of the many complex factors that influence the effectiveness of the ET Cover at a particular site are best achieved with a comprehensive model, such as EPIC, that is capable of simulating the variability of climate over periods in excess of 100 years.

Acknowledgment

The authors gratefully acknowledge the assistance with the EPIC computer model given to them by the following individuals: Mr. Dan Taylor, Texas Agricultural Experiment Station; Drs. J. R. Williams, J. R. Kiniry, and C. W. Richardson, U.S. Dept. of Agriculture, Agricultural Research Service; and Dr. V. W. Benson, U.S. Dept. of Agriculture, Soil Conservation Service. They are all associated with the Grasslands Soil and Water Research Laboratory, Temple, Texas 76502.

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A NATURAL COVER FOR BURIED WASTE

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INTRODUCTION

Reclaimed mine land, oil shale residues, fire training areas, landfills, and similar sites are covered to control the amount of rainfall that may percolate through hazardous material. The currently used covers employ materials that have low permeability, such as compacted clay layers or flexible membranes placed as layers within the cover. These materials are usually described as "impermeable" even though they permit some water percolation. Currently used covers may be damaged by uneven settlement, freezing or drying of clay layers, and chemical changes in synthetic materials. Ideally, covers should be reliable for centuries and inexpensive to build and maintain. Currently used covers may not provide long-term reliability, and they are expensive. We propose an improved cover design and estimate its geographical area of application.

CONCEPT

Native grass mixtures and associated forbs have extensive, fibrous root systems and are capable of consuming all of the water stored in the soil within the plant root zone. The combination of soils having adequate water-holding capacity, with water removal by plants and evaporation from the soil, may preclude percolation of water below the root zone of native grasses. The root zone depth of native grasses may extend to 2 or more meters (m) below the soil surface, thus creating a large soil reservoir in which to store water. Native grass communities are well adapted to the regions where they developed, and they reliably grow and consume water.

Field data support the concept. Aronovici (1971) and Lotspeich et al. (1971) measured the depth of water penetration below native grass near Amarillo, Texas, where the average annual precipitation is 475 mm. Their data demonstrate that no precipitation moved below the root zone under native grass during the past several hundred years. Hauser and Chichester (1989) measured the soil water balance under perennial grass in east-central Texas where the average annual precipitation is 960 mm. No water penetrated below the rooting depth of the perennial grass on five different soil profiles, in spite of one unusually wet winter during the 6-year experiment.

American Defense Preparedness Association
21st Environmental Symposium and Exhibition
San Diego, CA, 18-23 April 1995

Short-term field measurements published by Nyhan et al. (1990) (New Mexico); Anderson et al. (1993) (Idaho); and Waugh et al. (1994) (Washington) and computer models by Hakonson et al. (1992) demonstrated that covers using soil and vegetation to manage infiltrating water could keep wastes dry in the intermontane region of the West. These short-term field experiments also support the concept.

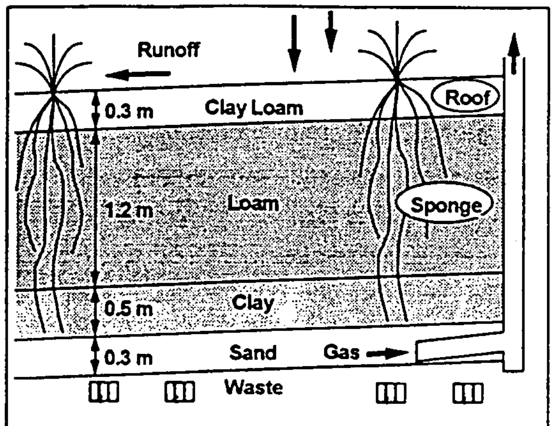

Figure 1. The ET Cover over a landfill.

THE ET COVER

We propose an inexpensive and practical cover that stores precipitation in the soil until it is removed by evaporation and plant transpiration (*evapotranspiration* or *ET*); we call it the *ET Cover*. It provides adequate soil water-holding capacity to store infiltrating precipitation until ET can remove the water from storage but contains no "impermeable" materials. The ET Cover uses native grass communities to control soil erosion and remove water from the soil cover. Figure 1 shows one possible design of the ET Cover.

The ET Cover should have a sloping surface. The top soil layer (the roof in Figure 1) should have high water-holding capacity and high runoff-producing potential. The next layer (the sponge) serves as a soil water-storage layer, and the bottom layer may be soil with low permeability to separate the cover from the waste. A mixture of native grasses and forbs growing on the cover removes water from the soil and prevents erosion of the surface. If the wastes produce dangerous gases, they must be collected and managed safely.

The ET Cover should be constructed from soil found near the site, and it should be loose and friable. The ET Cover limits the percolation of precipitation through the cover and requires less maintenance than covers currently in use. Little damage results from settling because the soil will naturally fill voids, and plant roots grow profusely in loose, disturbed soil such as that found near shear zones. It is natural, self-renewing, and not subject to long-term damage by wetting and drying of compacted clay layers nor the possible deterioration of synthetic materials over time. Damage caused by burrowing animals or depressions in the surface caused by settlement can be repaired easily and economically by filling holes with soil, regrading the surface, and replanting grass where needed.

EVALUATION METHODOLOGY

The ET Cover requires soil with a high plant-available, water-holding capacity and an adequate supply of nutrients to support vigorous plant growth. Subsoil, if amended, usually satisfies this requirement. The plant cover should contain many different native grass species and associated forbs to ensure continuous water use under adverse growing conditions. Plants, soil, and variations in climate over long time periods interact with performance of the ET Cover.

We evaluated the effect of climatic variability with the Erosion/Productivity Impact Calculator (EPIC) computer model described by Sharpley and Williams (1990). EPIC contains plant, soil, and climate parameters as part of the model database. The EPIC model (1) simulates the physical processes involved in water movement; (2) uses readily available data; and (3) addresses all major aspects of hydrology, climate, soils, plant nutrients, plant growth, soil temperature, and plant environment. Hauser and Shaw (1994) and Hauser et al. (1994) more fully described the use of the EPIC model.

Deep percolation is water that moves below the root zone of grasses in the ET Cover or through a conventional cover; it moves into the waste. We evaluated deep percolation through the ET Cover at several sites using warm-season or cool-season tall grasses, or warm-season short grasses as appropriate. Hauser and Shaw (1994) and Hauser et al. (1994) explored the effect of soil properties on ET Cover performance. The estimates reported here are for Pullman clay loam soil, which covers much of the Southern Great Plains. Each estimate is for a 100-year period to assess the effect of climate variability. We present the effect of grass species and climate on performance, and estimate the required thickness of soil for an ET Cover at two sites.

AREA OF APPLICATION

The ET Cover with a 2-m thick layer of Pullman soil allowed no water to percolate into the covered waste within the geographical area shown in Figure 2. Areas at high elevation with high precipitation and low potential ET within the region are exceptions. Note, however, that most waste sites are located at lower elevations where rainfall is relatively low and potential evaporation is high. The ET Cover would permit some deep percolation in the cool, wet climate of the northwestern coast and under the high rainfall conditions of the eastern states. Figure 2 shows the location of the field measurements in Washington (Waugh et al., 1994), Idaho (Anderson et al., 1993), New Mexico (Nyhan et al., 1990), and two sites in Texas (Aronovici, 1971; Lotspeich et al., 1971; and Hauser and Chichester, 1989).

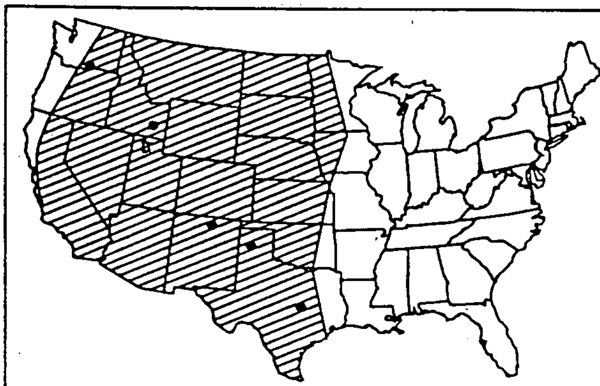

Figure 2. Area in which the ET Cover prevented deep percolation with Pullman soil, and the location of the field measurements.

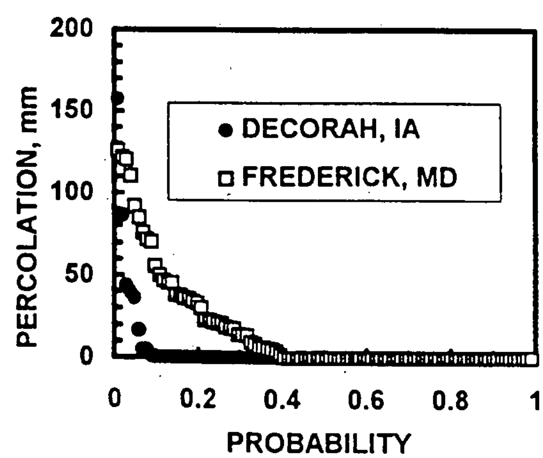

Figure 3. Annual, deep percolation at Decorah, IA, and Frederick, MD. (100-year estimate; 2-m deep, ET Cover).

Currently accepted covers cannot prevent deep percolation. Thus, the requirement for no deep percolation assumed in the preparation of Figure 2 is conservative. There may even be situations in which some deep percolation is desirable. Therefore, the potential area of usefulness for the ET Cover is actually larger than that shown in Figure 2. Figure 3 shows the probability for deep percolation at two sites. At Decorah, in northeastern Iowa, deep percolation below a 2-m thick Pullman soil cover would be zero in 91 of 100 years, and less than 50 mm in 98 of 100 years. At Frederick, Maryland, deep percolation would be zero in 60 of 100 years and less than 50 mm in 89 of 100 years.

On currently used covers, grass grows in about 0.6 m of soil over the "impermeable" or barrier layer. The soil water reservoir is small. As a result, large volumes of water frequently percolate through the cover soil and present the opportunity for leakage through the barrier for extended periods of time. The application of the ET Cover concept on top of the cover could substantially reduce the frequency and duration of saturation above the barrier. A thicker soil cover would reduce the potential annual leakage volume substantially. Figure 4 shows the probability for deep percolation through ET Covers of two different thicknesses (Hauser and Shaw, 1994). The 0.5-m thickness is similar to the soil layer over a conventional cover with a barrier layer. Rainfall would percolate through the surface soil and accumulate above the barrier layer in 90 percent of the years. However, with 1.9 m of soil on top, rainwater would percolate through the surface soil and accumulate above the barrier layer in only 20 percent of the years.

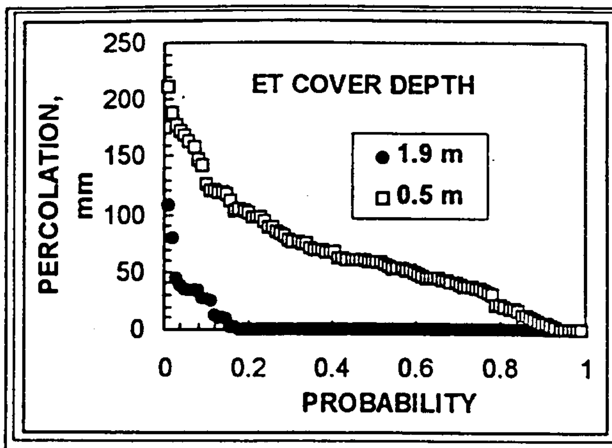

Figure 4. Annual, deep percolation through ET Covers in East Central Texas with a soil of only moderate water-holding capacity.

SOIL THICKNESS REQUIREMENTS

Where annual rainfall is low, the ET Cover will prevent deep percolation with thin soil covers. For example, near Denver, Colorado (annual rainfall 330 mm), a Pullman soil cover would prevent deep percolation with a cover soil thickness of only 0.4 m. At San Antonio, Texas (annual rainfall 730 mm), the minimum cover thickness is 1.0 m.

EFFECTS OF GRASS SPECIES

Warm-season native grasses stop growing at about 8°C, and cool-season native grasses stop growing at about 0°C. In cold climates, cool-season grasses grow during more months of the year than do warm-season grasses. However, heat energy is required to evaporate water, and there is less heat energy available during cool months. Therefore, in cold climates, EPIC simulations show that warm-season grasses can extract more water from the soil than cool-season grasses, thus allowing less deep percolation below the root zone (Table 1).

Table 1. Comparison of deep percolation below the root zone of cool-season or warm-season tall, perennial grasses growing on a 2-m depth of Pullman soil. The data are simulations of the 100-year, average annual values. Rain is total annual precipitation.

	Rain	Percolation	
		Cool season	Warm season
Location	mm	mm	mm
Decorah, IA	820	50	4
Frederick, MD	970	93	16
Clayton, NC	1150	110	27
Williamstown, KY	1120	110	32

SUMMARY

We propose a practical and reliable cover to control rainwater infiltration into waste. The ET Cover consists of a layer of soil covered by native grasses. It uses two natural processes to control infiltration. First, the uncompacted soil layer is a water reservoir. Second, evaporation and plant transpiration (*evapotranspiration* or *ET*) are natural mechanisms that remove water from the soil water reservoir. The soil cover stores rainfall that infiltrates through the surface until the ET process removes it. This process empties the soil reservoir for another cycle. The ET Cover is relatively inexpensive, practical, and easily maintained; it is a self-renewing, reliable, biological system. It will remain effective over extended periods of time—perhaps centuries—at low cost. Previous short-term field tests in the intermontane and arid western states confirm the concept. Field measurements of soil water under native rangeland in the Southern Great Plains demonstrated that the ET Cover concept prevented deep percolation for centuries. We evaluated the ET Cover for other regions using long-term climatic data containing extreme hydrologic events. The results show that the ET Cover is appropriate for use in much of the United States. The Department of Defense should use the ET Cover to obtain the benefits of this practical, cost-effective, low maintenance, and natural cover system.

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Paper No. 942176
An ASAE Meeting Presentation

WATER MOVEMENT THROUGH SOIL-VEGETATIVE LANDFILL COVERS

by

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Written for Presentation at the
1994 International Summer Meeting
Sponsored by
ASAE

Kansas City, Missouri
June 19-22, 1994

Summary:

Landfills should be operated, maintained and closed in a manner that is protective of public health and the environment. We propose an inexpensive and practical landfill cover that stores precipitation in the soil until removed by evapotranspiration (ET). We call it the ET Cover. The ET Cover contains no impermeable materials, but it requires adequate soil water holding capacity to store storm rainfall until ET can remove the water from storage. We evaluated the concept in east-central Texas with the model, EPIC, and verified the estimates by published data derived from field measurements at the site. No water moved through the cover where the plant-available soil water-holding capacity exceeded 225 mm. The ET Cover controls soil erosion, prevents direct contact between receptors and landfill contents and controls the movement of precipitation into the landfill.

Keywords:

Cap, Contamination, Evapotranspiration, Grass, Percolation

Water Movement Through Soil-Vegetative Landfill Covers[1]

Victor L. Hauser and Maurice A. Shaw[2]

Abstract

There are thousands of landfills, both old and new, scattered across most of the developed world. All of them should be operated, maintained, and closed in a manner that is protective of human health and the environment. Landfill closure requires a cover that controls soil erosion, prevents direct contact between receptors and landfill contents, and controls the movement of precipitation through the cover into the landfill contents. The evapotranspiration (ET) Cover performs these functions without the aid of man-made, impermeable covers or compacted clay layers. The ET Cover controls water movement into the landfill by holding the infiltrated precipitation in the plant root zone and then removing the water through evaporation and transpiration by perennial grass. We evaluated the concept in East-Central Texas with the Erosion/productivity impact calculator (EPIC) model and verified the estimates by published data derived from field measurements at the site. Where the plant-available soil water-holding capacity of the 1.9 m deep soil cover exceeded 225 mm, no water moved through the simulated cover in a 100-year simulation. EPIC simulations revealed that where soil resources near the site are limited, the soil with highest water-holding capacity should be placed on top of the profile. The integration of the many complex factors that influence the effectiveness of the ET Cover is best achieved with a comprehensive model such as EPIC. The ET Cover can prevent deep percolation into landfills, minespoil, or other similar materials in East-Central Texas.

Introduction

Landfills are extensively used as a repository for waste, and they contain a wide variety of chemicals. Landfills act as biological reactors that change some materials to harmless, basic chemicals (CO_2, H_2O, NaCl, etc.). Some materials found in landfills are inherently dangerous, and the decomposition process may produce potentially harmful materials. Landfill owners are required to control the movement of contaminants from landfills to protect human health and the environment.

Chemical contaminants may be carried out of landfills by water; the primary source for water entering the landfill is the precipitation falling on top of the landfill. Currently, the owners are required to cover their landfills with impermeable materials to limit the amount of infiltration through the top, thus reducing the potential leachate volume to a low level.

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The EPA regulations (U.S. EPA, 1991) for covers on municipal solid waste landfills require an owner to minimize infiltration and erosion. Many of these final landfill covers incorporate either a compacted clay layer or a flexible, impermeable membrane to meet the requirements; sometimes, both are combined for added safety. These layers or membranes must be covered by at least 18 inches of soil and a vegetative cover to control erosion. Covers on hazardous waste landfills are required to be more watertight than covers on municipal solid waste landfills (U.S. EPA, 1992).

Landfill contents settle or compress over time as a result of compaction and digestion of organic matter by biological systems. The resulting differential compaction of the material in the landfill may cause large vertical movement of part of the cover, thus causing either compacted clay or flexible membranes to rupture and leak. Wetting and drying, and freezing and thawing are also known to reduce the effectiveness of compacted clay layers. It is difficult and expensive to protect the landfill cover against these forces. Therefore, the covers used currently are difficult and expensive to maintain and are likely to allow some precipitation to enter the landfill. In addition, the landfill covers used currently are expensive.

Perennial grasses and associated forbs have extensive, fibrous root systems and can consume all of the precipitation that infiltrates the soil in many climates. Aronovici (1971) measured the depth and amount of water penetration below native grass near Amarillo, Texas, where the average annual precipitation is 475 mm. He found that the soil was at or below the permanent wilting point to the maximum sampling depth at 15 m under native grass cover. Lotspeich et al. (1971) measured water content under native grass with good surface drainage near Amarillo and found that the soil water content was at or below the wilting point to the 28 m depth. These data demonstrate that, with good surface drainage, no precipitation moved downward through the soil profile under native grass in a semi-arid climate with 475 mm of average annual precipitation.

Hauser and Chichester (1989) measured the effects of climate on forage production of perennial grass in a sub-humid climate in East-Central Texas. The average annual precipitation was 900 mm at the site, and they measured soil water content one or more times in each month over a five-year period. At this wet site, with almost twice as much rainfall as at the site near Amarillo, no water penetrated below the rooting depth of the perennial grass.

Proposed Concept

We propose a less expensive and more practical landfill cover that stores precipitation in the soil until removed by evapotranspiration (ET). We call it the ET Cover. The ET Cover contains no impermeable materials, but it requires adequate soil water-holding capacity to store storm rainfall until ET can remove the water from storage. The ET Cover can normally be constructed from natural material found near the site and does not require compaction; therefore it is low in cost. The successful ET Cover will prevent or limit to an acceptable level the percolation of precipitation into the landfill contents and will require less maintenance than covers used currently. The ET Cover will suffer little damage as a result of settlement because the soil will naturally fill voids and plant roots grow profusely in loose, disturbed soil. It is natural, self-renewing, and not subject to long-term damage by wetting and drying of compacted clay layers or possible deterioration of man-made materials over time. Damage, such as by burrowing animals, or depressions in the surface caused by settlement could be easily and economically repaired.

The purpose of the ET Cover is to control the movement of water into the landfill, to prevent direct contact between receptors and the landfill contents, and to prevent movement of the contents by wind or water erosion. The objectives of this work were to (1) Test the concept at one site with a suitable model, (2) evaluate the performance of the model with measured data, and (3) identify important climate, soil, and plant variables. Extensions of this work will include assessment of the concept over a wide range of climate, soil, and vegetation types found in the United States.

Procedure

We evaluated the ET Cover concept with the EPIC computer model (Williams et al., 1984; Williams et al., 1989; Sharpley and Williams, 1990, and Williams et al., 1990) for a location near Rockdale, in East-Central Texas. We chose the EPIC model because it simulates the physical processes involved in water movement, simultaneously and realistically, and it uses readily available inputs. The model addresses all major aspects of hydrology, climate, soils, plant nutrients, plant growth, soil temperature, and plant environment. It also estimates a complete water balance. EPIC performs all calculations on a daily time step. However, it is computationally efficient and can simulate hundreds of years in a few minutes on a modern desktop computer. It generates climatic data for any spot in the continental United States from internal coefficients and contains soils data for the major soils found within the United States. The EPIC model permits numerous sequential runs using the same climate file and allows preliminary runs to equilibrate the soil variables nitrate and soil water. More than 22 scientists and engineers contributed to the model development and documentation (Sharpley and Williams, 1990); they tested and validated it against measured field data at more than 200 sites worldwide.

We chose the East-Central Texas site for this evaluation because it is in a sub-humid climate, the growing season is long, and a set of measured and applicable data are available to test model output (Chichester and Hauser, 1984; Hauser and Chichester, 1987; Hauser and Chichester, 1989; and Chichester and Hauser, 1991). They measured climatic parameters hourly, soil water content monthly or semi-monthly, forage production two to four times per year, soil nutrient and chemical status annually, and hydraulic, chemical, and physical properties of each soil material as appropriate. The experiment included one native soil and four constructed soils similar to covers for minespoils or landfills. Kleingrass (*Panicum coloratum* L.), a perennial grass, grew on each soil profile.

We evaluated the ET Cover concept on four major soil groups: Axtell, site soil, site mix, and spoil (table 1). Axtell soil was found in abundance near the site, and its properties were stored in the EPIC database. The site soil (Hauser and Chichester, 1987) was an eroded Axtell soil that existed at the site; the properties of its surface layers were changed by water erosion and tillage, and it differed from the typical Axtell profile at depth. The site mix was a mixture of the site soil from the surface to the 1.8 m depth; the simulated profile was 1.93 m thick. The soil profile created from spoil was a mixture of overburden stripped from the upper 15 m of soil cover over a nearby coal mine; it was selected for low pyrite content. The plant-available, soil water-holding capacity (AWC) for each of four soil profiles is shown in figure 1. Soil materials 2, 3, and 4 (table 1) were included in the field study and were discussed in more detail in Hauser and Chichester (1989), and in Chichester and Hauser (1991).

Our analysis included nine soil profiles derived from the four soils; they are illustrated in figure 2 and described in table 1. The Axtell and site soil profiles were undisturbed natural profiles (fig. 2). The Axtell-sand profile was the same as Axtell to 0.8m, but the sandy Axtell A layer was placed from 0.8 to 1.93 m. Both the spoil and site mix were uniform mixtures of soil from the surface to the 1.93 m depth.

Two profiles (landfill-mix and landfill-spoil) simulate a conventional landfill cover with maximum rooting depth of 0.9 m (table 1 and fig. 2). Both of them contained drainage sand from the 0.61 m to 1.93 m depth to simulate the 0.3 m freely drained layer in a landfill cover. The landfill-mix profile contained a mixture of selected layers from the site soil profile from the surface to the 0.61 m depth. The landfill-spoil profile contained spoil from the surface to the 0.61 m depth.

The layered profiles compared the effect of a 0.2-m-thick layer having low AWC when placed on the soil surface or when placed between 0.2 and 0.4 m depth. Both layered soil profiles had the same total profile AWC (table 1 and fig. 2), and both had maximum rooting depth of 0.5 m.

Saturated soil layers, thin soil covers, gases moving upward from a landfill into the ET Cover, compacted soil layers, adverse soil chemistry, or other factors could limit the maximum rooting depth of plants growing on the cover. Therefore, three maximum rooting depths were entered into the model for Axtell, Axtell-sand, site soil, spoil, and site mix to determine the effect of maximum rooting depth on percolation through the cover (fig. 2). While some root depth limitations would be transient, we assumed constant, limited root depths that are more severe than one would expect in many real cases.

All simulations utilized Kleingrass as the vegetative cover; it is a hardy perennial grass that is well adapted to the site. The model applied enough nitrogen fertilizer to supply 80 percent of the N requirement for maximum plant growth. This strategy limits potential nitrate leaching to a small value, yet provides enough nitrogen for good plant growth and near maximum ET rates. The simulations used the climate generated by EPIC for Cameron, Texas, about 12 miles from the study site of Hauser and Chichester (1989). The climate simulation was identical for all simulations. All other parameters were set to be consistent with perennial grass growth and production values common to the Southern Great Plains.

Results

Evaluation of EPIC

We compared estimates of forage yield by EPIC to measured yields published by Hauser and Chichester (1989). Forage yield is a good integrator of the many climatic and soil factors affecting this ecosystem, and the estimate by EPIC agreed well with the measured data. The average forage yield measured over a five-year period was 7.8 T/ha and the 100-year average estimated by EPIC was 8.5 T/ha for the site soil. The yields for spoil were 6.7 and 7.6 T/ha respectively for measured and simulated yields.

The soil water estimates by EPIC generally agree with published field measurements, but they suggest that EPIC's estimates of deep percolation are higher than actual values, thus, conservative. Hauser and Chichester (1989) measured water movement through five different soil profiles. During a five-year period, the measured water content of the 1.2 to 1.5 m soil layer became progressively more dry for the site mix soil and remained below field capacity for all others in spite of three years with above average-precipitation. They measured soil water during a five-month winter period when precipitation was 675 mm, well above average for the region. At maximum wetting, four of the profiles were at or below the field-measured, permanent wilting point or the lowest water content of the previous season at all depths below 1 m. The site soil was also dry below 1.5 m. During the five-year period, there was no evidence that water penetrated below the rooting depth of the perennial grass (Hauser and Chichester, 1989). The average 100-year annual deep percolation estimated by EPIC for maximum root depth of 1.9 m was 0 mm for site mix and spoil treatments and only 2 mm for the site soil (table 2). These simulations are similar to treatments measured in the field study. In the field study, the site soil wetted to a greater depth than any other treatment, but not below the maximum rooting depth of Kleingrass (Hauser and Chichester, 1989).

Water Balance

The EPIC model partitions precipitation between ET, surface runoff, and deep percolation. Figure 3 shows the water balance for four ET Cover simulations that produced a large range of deep percolation values. The sums of 100-year average annual deep percolation, surface runoff, and ET were within 1 percent or less of the rainfall amount, thus producing a satisfactory water balance. Most of the rainfall returned to the atmosphere via the ET term for all four treatments.

The 100-year average annual surface runoff estimate was not significantly different between most treatments (table 2). Soil profiles with high AWC in the surface layer or with limited rooting depth produced larger amounts of surface runoff than other treatments.

ET Cover Evaluation

The ET Cover is presumed to be effective if little or no water moves below the plant root zone as deep percolation. The 100-year average annual amount of water moving below the root zone as deep percolation was small or zero for all of the profiles with 1.9 m rooting depth, table 2. Soils with moderate to large total soil profile AWC produced no deep percolation. With restricted rooting depth of 1.0 and 0.5 m, the spoil and site mix, and the spoil, respectively, produced no deep percolation (table 2). These data show that the concept of the ET Cover is valid for this climate with appropriately chosen soils.

Rooting Depth

Axtell soil with rooting depth of 1.9 m, produced average annual deep percolation of 5 mm (table 2); however, the probability is greater than 0.8 that it will be 0 mm in a particular year (fig. 4). In 4 of each 100 years, deep percolation exceeded 38 mm for Axtell soil with 1.9 m rooting depth. Reduced rooting depth increased deep percolation.

Rooting depth affected the amount of deep percolation for all other treatments examined. However, there are important interactions with AWC that affect the amount of water moving below the root zone (table 2).

Soil Water-Holding Capacity

The amount of water that the soil could hold within the plant root zone while remaining available for plant use strongly affected the amount of deep percolation below the root zone, (table 2 and fig. 5). EPIC estimated that in East-Central Texas climate, soil profiles that held more than 225 mm of plant-available water produced no deep percolation (fig. 5). However, spoil had an available water-holding capacity of 0.29 m/m, the highest of all materials examined (fig. 1), and produced no deep percolation with root zone water-holding capacity of only 145 mm for the maximum rooting depth of 0.5 m (table 2).

Evaporation directly from the soil surface is a significant part of total ET. The EPIC simulations for these soil profiles revealed a range of evaporation from the soil from 33 to 48 percent of total ET. Evaporation from the soil surface was greater for higher available soil water-holding capacity of the top 0.2 m of the soil profile (fig. 6). These data suggest that soil with the highest water-holding capacity should be placed at the top of the cover.

All ET Covers should be constructed with locally available—thus, sometimes limited—soil resources to meet requirements. They need not resemble natural soil profiles; thus, it is important to understand the effect of placement of valuable or scarce material. The two landfill cover simulations had similar maximum rooting depth, 0.9 m, and both contained drainage sand layers beginning at the 0.61 m depth (table 1 and fig. 2). Both had shallow (0.61 m deep) soil layers available to store water for plant growth. The available water-holding capacity of the landfill-mix was one-third that of the spoil (table 1). However, the landfill-mix treatment produced 35 times the amount of deep percolation that was produced by landfill-spoil (table 2). These data show that available water-holding capacity is important, and that there are large interactions with the climate, plant growth, and other factors.

The frequency of zero or large amounts of deep percolation is also important when considering ET Cover performance. Figure 7 shows the probability of occurrence for the annual deep percolation amounts estimated by EPIC for the two landfill designs. The probability that deep percolation will be 0 mm is about 0.93 for landfill-spoil, but only 0.09 for landfill-mix. Deep percolation exceeded 50 mm once for landfill—spoil and in 63 years for landfill—mix during a 100-year simulation.

Layer Effects

The two landfill simulations produced large differences in deep percolation; these differences appear to be related to the root zone AWC (fig. 8). The two layered treatments, however, had equal AWC within the root zone, yet they produced vastly differing deep percolation (fig. 8). Where the top 0.2 m of the profile had high AWC, the deep percolation was dramatically reduced.

Figure 9 shows the probability of occurrence for the annual deep percolation amounts estimated by EPIC for the two layered profiles. The layered profiles had equal root zone AWC; however, the probability that deep percolation will be 0 mm is about 0.6 for high AWC on top and about 0.16 for low AWC on top. Deep percolation exceeded 50 mm during 7 and 52 years of a 100-year period estimated for layered profiles with high AWC on top and low AWC on top, respectively.

Discussion

Climate

The climate at any site will determine whether an ET Cover can control water movement through the landfill. The climate in East-Central Texas provides a long growing season for perennial grasses: a wet spring followed by a hot, dry summer, with another relatively wet period in fall. Perennial grasses grow during most of the wet spring and fall periods. They suffer significant drought stress during summer in all years, and occasionally during other seasons. EPIC estimated that during more than one-third of the days in each year, grass production was most limited by insufficient water. This was true even though the average annual precipitation is relatively high (833 mm). These estimates by EPIC agree with field measurements and observations at the site.

Soil

Because of the large volume required for a landfill cover and the large unit weight of soil, the cost for transporting soil is high; thus one should use soil found close to the landfill. Even where soil surfaces are sandy in texture, there are often clay or silt layers at depth that can provide soil mixtures with high water-holding capacity and also produce large surface runoff volumes. Contrary to the common belief, the work of Chichester and Hauser (1991) and Hauser and Chichester (1989) demonstrated that soils from deep in the profile can produce good plant growth and large ET.

Surface soils are the primary determining factor for surface runoff. Evaporation from the soil is greatest from the surface layers. The density of plant roots is greatest in the surface layers; thus, plants remove water quickly and most completely from surface layers. As a result, soils that have high AWC capacity should be placed on top of the ET Cover.

Plants

The ET Cover requires hardy, perennial grasses that will survive drought or other adversity and be ready to consume water when precipitation occurs. The plant cover should include several different species, and some of them should grow in different seasons of the year. All plants should be well adapted or native to the area.

ET Cover Evaluation

The performance of the ET Cover is influenced by climate, soil, insects, disease, plant nutrients, plant type, and other factors. The processes that govern the water balance in the soil frequently cause large and rapid changes in parameters. Therefore, evaluation of the ET Cover for any site requires a computer model such as EPIC that operates on a daily or shorter time step and integrates all of the complex factors affecting the water balance. It should be capable of simulating system performance for 100 years or more in a few minutes of computer operating time.

The EPIC model permits both transpiration and evaporation loss of water from the soil layer between the surface and the 0.2 m depth. Water may be removed from deeper layers only by transpiration by the plant or by percolation downward into the next lower layer. In the field, some water may move upward from deep soil layers in response to water pressure gradients. Upward movement from deep soil layers is generally believed to be small. As a result of EPIC's, handling of water movement from deep soil layers, the estimates of deep percolation are likely to be slightly larger than one would expect in the real world. Therefore, EPIC produces a relatively conservative evaluation of deep percolation through the ET Cover.

Conclusions

The ET Cover can control infiltration of precipitation through the cover and can prevent deep percolation into landfills, minespoil, or other materials at the site modeled in East-Central Texas. The soil with the highest AWC in the plant root zone produced the least deep percolation. In East-Central Texas, a root zone AWC greater than 225 mm produced no deep percolation. Where soil resources near the site are limited, the soil with highest AWC and low infiltration rate should be placed on top of the profile. Integration of the many complex factors that influence the effectiveness of the ET Cover is best achieved with a comprehensive model such as EPIC.

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Table 1. Particle size distribution and plant-available, soil water-holding capacity (AWC) for four natural or field-tested soil profiles (no. 1 through 4) and five derived soil profiles.

Soil Material	Depth (m)	Sand*	Silt†	Clay‡	AWC (mm)
		(Percent by Weight)			
(1) Axtell, A	0.00 - 0.15	55.8	38.1	6.1	0.131
Axtell, B	0.15 - 0.36	30.0	29.2	40.8	0.100
Axtell, C	0.36 - 0.63	33.8	33.2	33.0	0.086
Axtell, D	0.63 - 0.99	34.9	32.2	32.9	0.075
Axtell, E	0.99 - 1.55	56.9	21.2	21.9	0.100
Axtell, F	1.55 - 1.93	71.0	13.8	15.2	0.100
(2) Site Soil, A	0.00 - 0.20	70.8	28.9	0.3	0.140
Site Soil, B-C	0.20 - 0.60	25.9	23.0	51.1	0.103
Site Soil, D	0.60 - 1.20	31.0	34.2	34.8	0.100
Site Soil, E	1.20 - 1.40	42.8	32.2	25.0	0.111
Site Soil, F	1.40 - 1.93	45.2	30.6	24.2	0.111
(3) Site Mix	0.00 - 1.93	38.5	30.0	31.5	0.170
(4) Spoil	0.00 - 1.93	10.9	71.1	18.0	0.290
Axtell-Sand, A	0.00 - 0.15	55.8	38.1	6.1	0.131
B	0.15 - 0.36	30.0	29.2	40.8	0.100
C	0.36 - 0.63	33.8	33.2	33.0	0.086
D	0.63 - 0.80	34.9	32.2	32.9	0.075
(A)	0.80 - 1.93	55.8	38.1	6.1	0.131
Landfill- Mix	0.00 - 0.61	34.8	30.2	35.0	0.098
Sand§	0.61 - 1.93	97.0	2.0	1.0	0.066
Landfill- Spoil	0.00 - 0.61	10.9	71.1	18.0	0.290
Sand§	0.61 - 1.93	97.0	2.0	1.0	0.066
Layered					
Low AWC	0.00 - 0.20	34.9	32.2	32.9	0.075
High AWC	0.20 - 1.93	10.9	71.1	18.0	0.290
Layered					
High AWC	0.00 - 0.20	10.9	71.1	18.0	0.290
Low AWC	0.20 - 0.40	34.9	32.2	32.9	0.075
High AWC	0.40 - 1.93	10.9	71.1	18.0	0.290

* 0.05 to 2 mm
† 0.002 to 0.05 mm
‡ less than 0.002 mm
§ Drainage sand with high permeability

Table 2. The estimated, 100-year average annual deep percolation below the root zone (PRK), surface runoff (Q) and evapotranspiration (ET); and the plant-available, soil water-holding capacity (AWC) of the root zone and maximum rooting depth for each profile. The average annual precipitation for each 100-year simulation was 833 mm.

Soil Description	Root Depth (m)	PRK	Q	ET	AWC
		(mm)			
Axtell, (EPIC file)	1.9	5	82	740	185
Axtell-Sand (EPIC file)	1.9	1	81	744	225
Site Soil	1.9	2	81	744	210
Spoil	1.9	0	86	743	560
Site Mix	1.9	0	83	745	328
Axtell, (EPIC file)	1.0	16	82	729	92
Axtell-Sand (EPIC file)	1.0	23	82	722	103
Site Soil	1.0	21	82	724	109
Spoil	1.0	0	86	743	290
Site Mix	1.0	0	83	745	170
Axtell, (EPIC file)	0.5	65	90	671	53
Axtell-Sand (EPIC file)	0.5	65	90	671	53
Site Soil	0.5	54	91	681	59
Spoil	0.5	0	94	735	145
Site Mix	0.5	19	90	720	85
Landfill-Mix	0.9	70	71	683	79
Landfill-Spoil	0.9	2	95	732	196
Layered, Low AWC Top[1]	0.5	56	78	691	102
Layered, High AWC Top[2]	0.5	12	99	717	102

[1] Layer with Low AWC on the top of the soil profile.
[2] Layer with High AWC on the top of the soil profile.

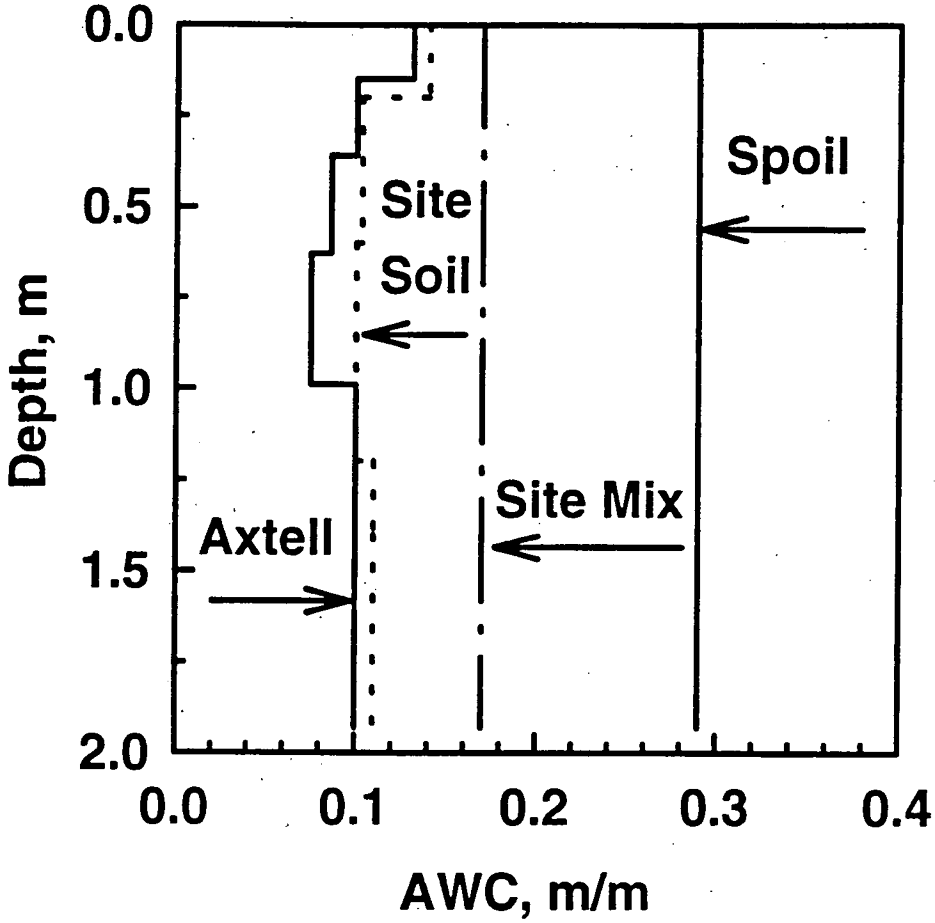

Figure 1. Estimates of plant-available, soil water-holding capacity (AWC) as a function of depth below soil surface for Axtell soil, site soil, site mix, and spoil.

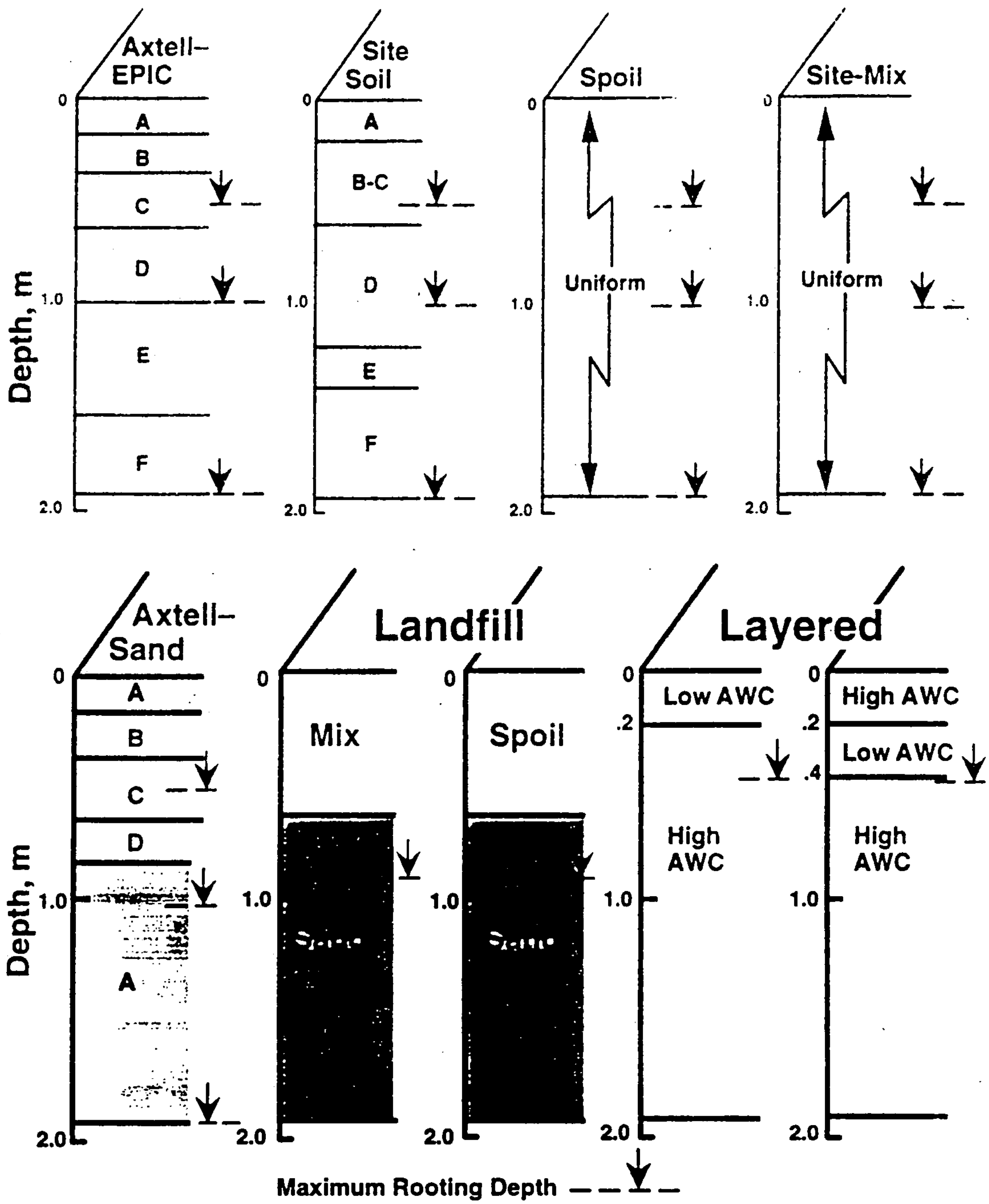

Figure 2. The nine undisturbed or created soil profiles examined and the variable rooting depths evaluated by the EPIC model.

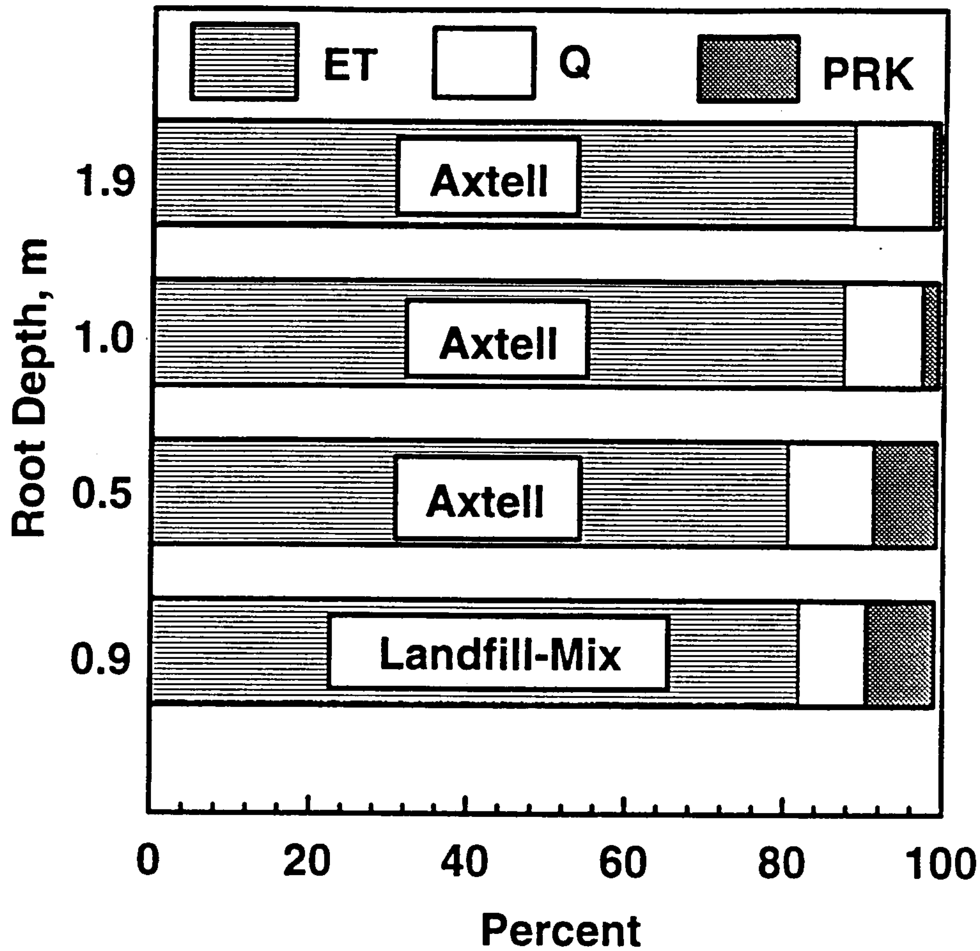

Figure 3. The average annual water balance for four ET Covers showing the division of precipitation between ET, surface runoff (Q), and deep percolation below the root zone (PRK).

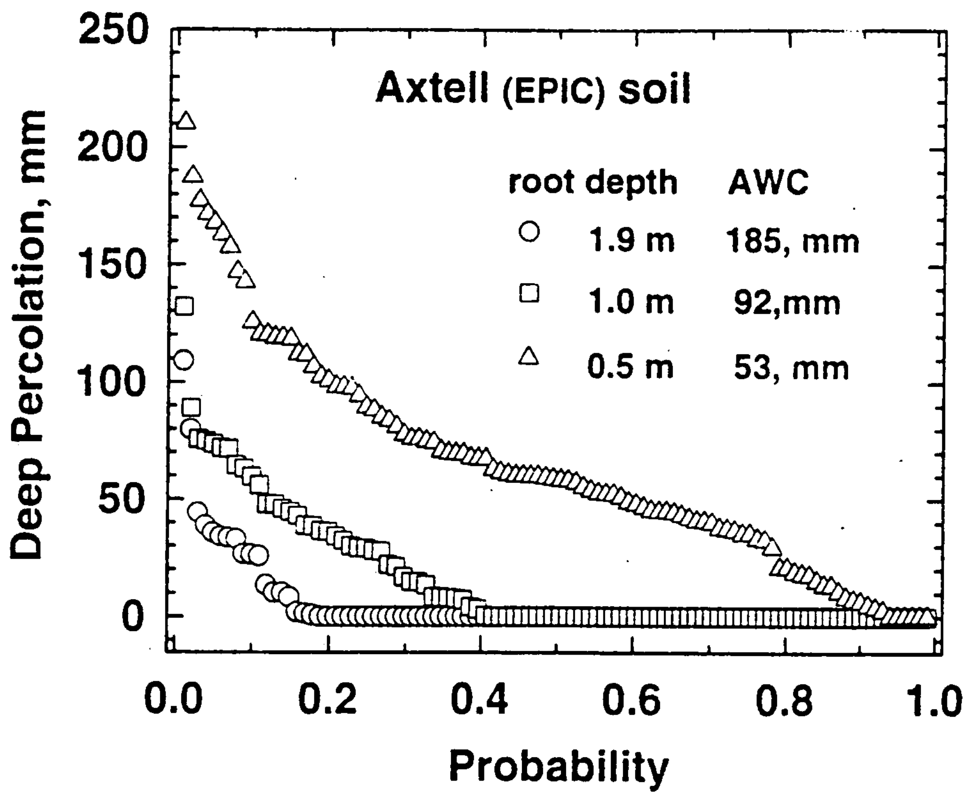

Figure 4. Probability that total annual deep percolation will equal or exceed the amount shown for Axtell soil profiles with 0.5, 1.0, and 1.9 m maximum rooting depth.

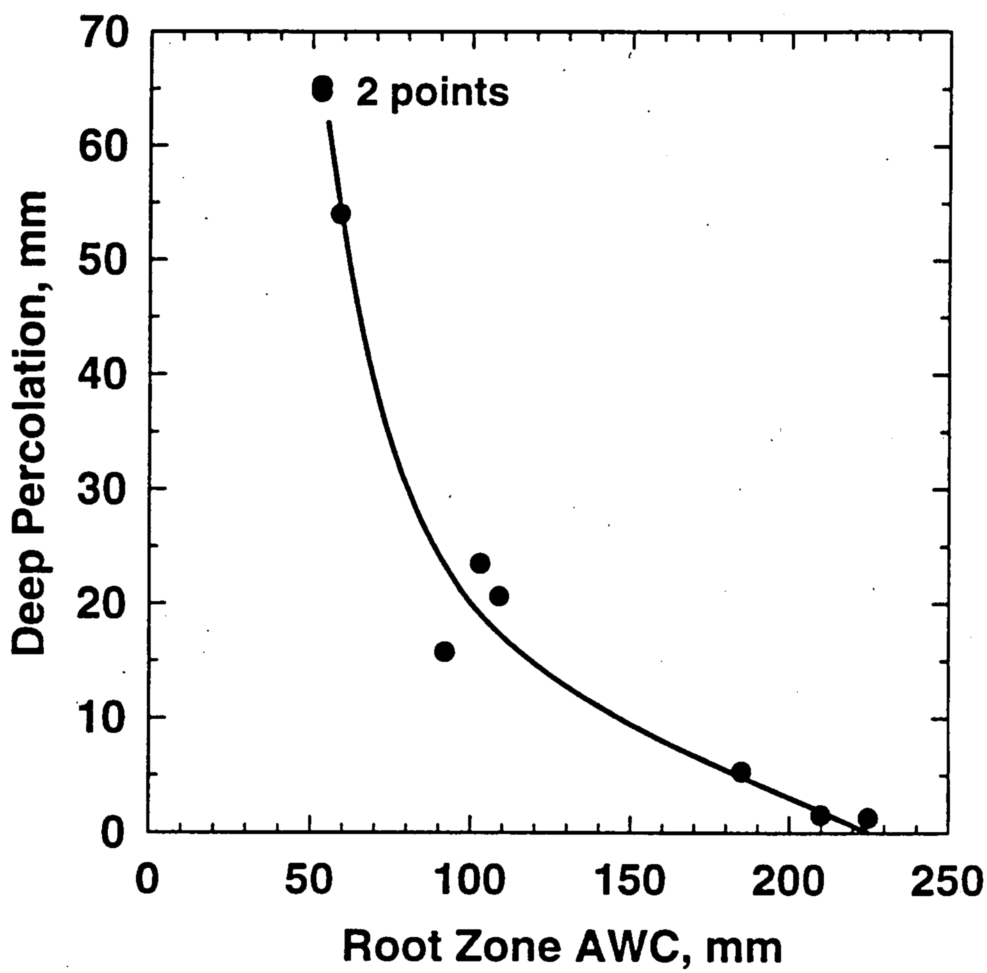

Figure 5. The relationship between 100-year average annual deep percolation and plant-available soil water-holding capacity (AWC) within the root zone for Axtell, Axtell-sand, and site soil profiles with maximum rooting depths of 0.5, 1.0, and 1.9 m.

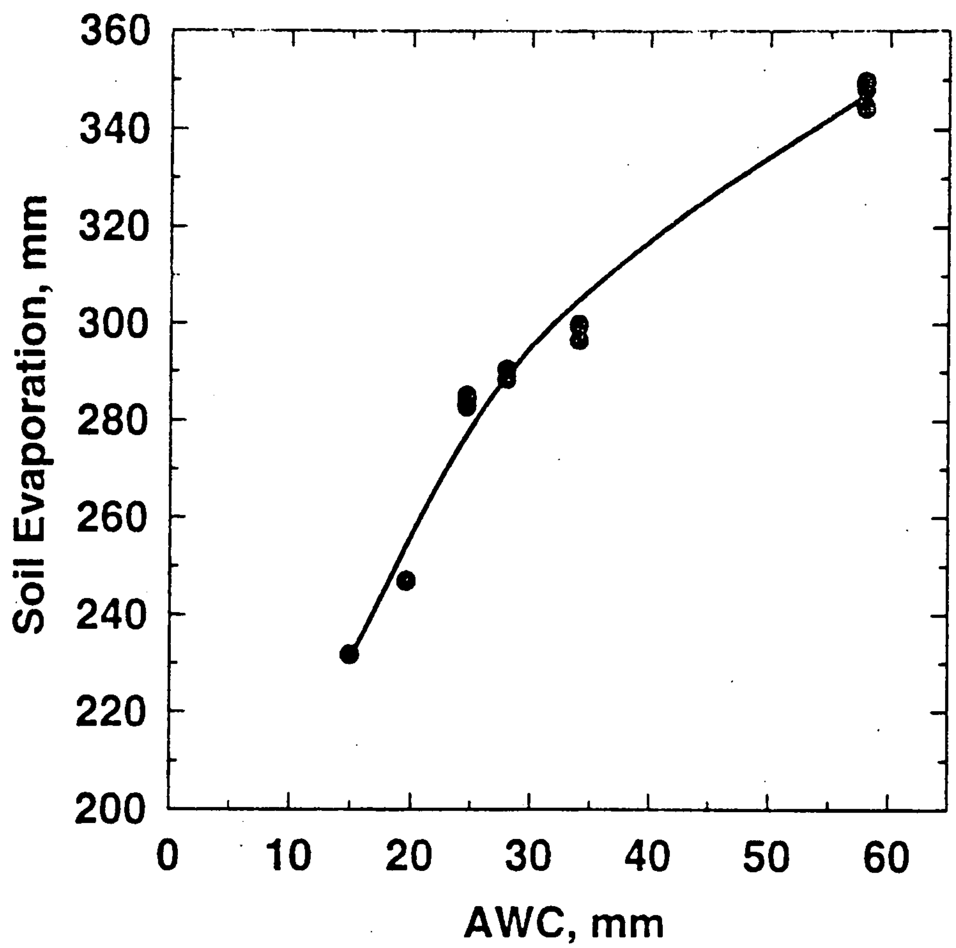

Figure 6. Average annual evaporation from the soil as a function of plant-available soil water-holding capacity (AWC) in the top 0.2 m of the soil profile.

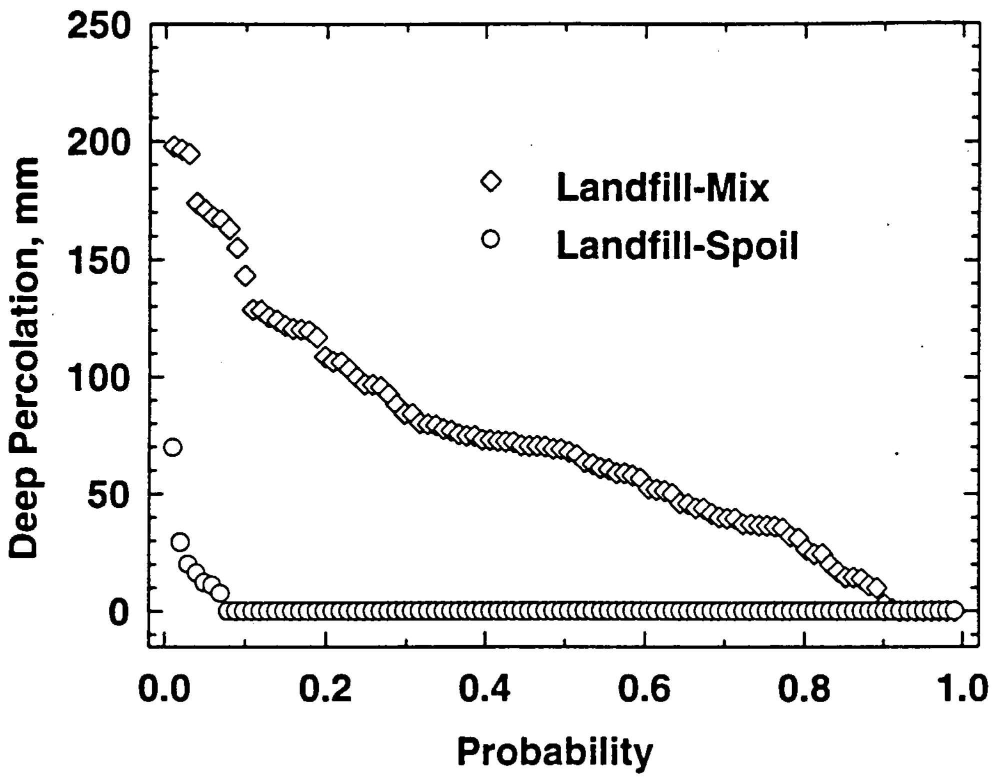

Figure 7. Probability that estimated annual deep percolation will equal or exceed the amount shown for landfill-mix or landfill-spoil treatments.

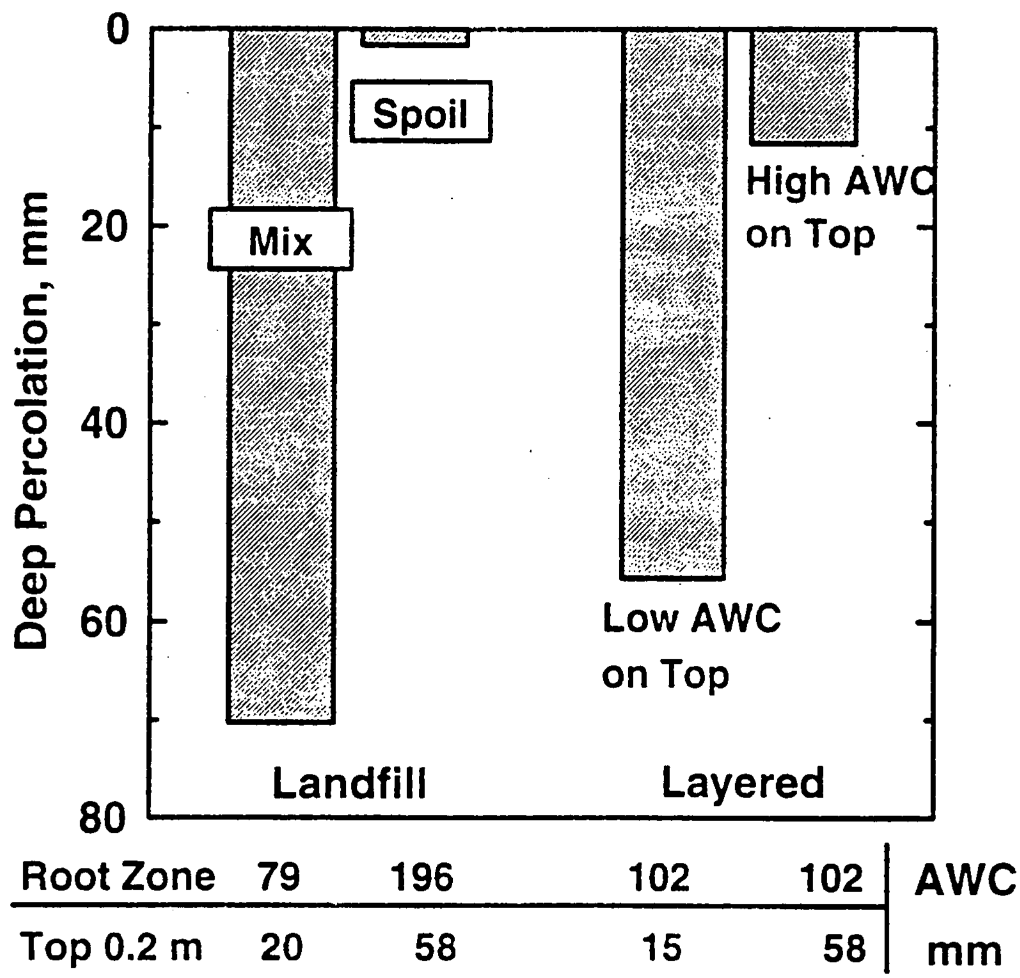

Figure 8. Average annual deep percolation resulting from differing root zone plant-available soil water-holding capacity (AWC) between landfill covers and the effect of the placement of a single 0.2 m thick layer of high AWC on top or not on top of the layered soil profile.

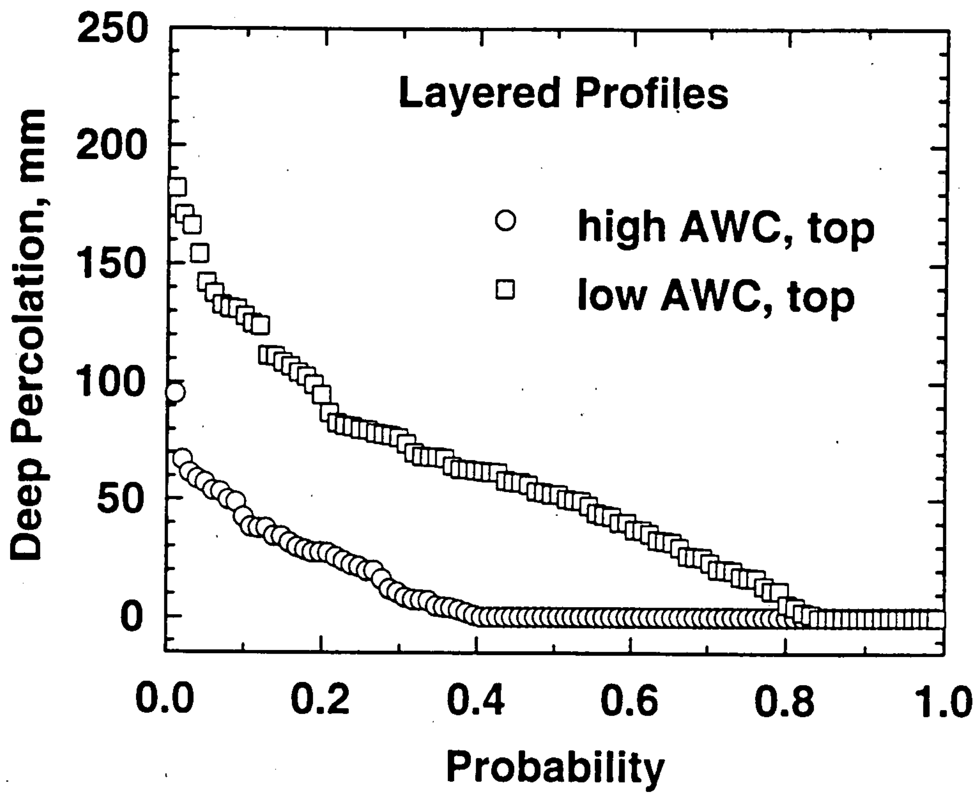

Figure 9. Probability that annual deep percolation will equal or exceed the amount shown for layered profiles with a single 0.2 m thick layer of high or low plant-available soil water-holding capacity (AWC) on top and with equal root zone AWC.