United States
Environmental Protection
Agency

Risk Reduction
Engineering Laboratory
Cincinnati OH 45268

Research and Development

EPA/600/S2-88/048 Dec. 1988

EPA

Project Summary

Evaluation of Hydrologic Models in the Design of Stable Landfill Covers

Fairley J. Barnes and John C. Rodgers

Federal regulations stipulate that landfill cover technology ensure the long-term stability and integrity of a hazardous waste landfill system. Specific guidance for achieving compliance with these regulations requires cover designs that manage the water balance on the landfill site. Special attention must be given to the design of the soil profile and the establishment of a stable vegetative cover in order to minimize erosion of the surface soils and the percolation of water into the waste. Recommendations for a specific landfill must be based on a combination of field and laboratory data, and computer modeling of water balance to assess specific design scenarios. The purpose of this study was to investigate the utility of two hydrologic models (CREAMS and HELP) for assisting in the process of designing landfill cover systems that are stable and free of maintenance requirements.

The process of parameterizing and using simple hydrologic models is outlined. Examples of modeling potential and actual sites are presented. Results of the modeling study suggest that, overall, CREAMS performs more satisfactorily than HELP in accurately predicting the soil water storage in the soil profile although more detailed calibration of HELP will probably improve model performance. While relative estimates of runoff, deep percolation and evapotranspiration are very useful for comparing different cover designs, absolute quantitative estimates of these values are subject to considerable error. Choice of values for soil parameters requires more experience and more detailed data than is indicated by the documentation for either model. Data to support choice of vegetation parameter values are largely unobtainable, especially for the native plant species which will inevitably invade a landfill site. Successional processes that lead to such invasions are discussed, and it is concluded that establishment of a vegetative community consisting of a mix of native plant species would result in a vegetative cover that is the most stable and most efficient in removing water from the soil profile.

This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research projects that are fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Landfill systems for the long-term containment of hazardous or municipal waste will be an essential component of hazardous waste management for the foreseeable future. Even under regulatory requirements for incinerating or degrading waste material in order to reduce the toxicity of the waste, the remaining sludges or residues must be disposed of or stored in such a manner as to protect the environment from toxic interactions.

Certain hazardous wastes will probably continue to be buried in landfills. In addition, a large number of older waste sites are in urgent need of closure technology to prevent further damage to the surrounding environment.

Major factors contributing to the mobilization of toxic constituents in wastes and their subsequent release to the biosphere include the infiltration of surface water, percolation of ground water into the waste, and intrusion into the waste by plants or animals. A critical determinant of the long-term successful application of land disposal technology is the stability of the cap or cover of the disposal unit. If, through a variety of potential mechanisms such as erosion, plant and animal disturbances, settling and other mechanical disturbances, the critical functions of the cover are compromised, then the long-term performance is compromised as well.

Establishment of a suitable and long-lasting plant cover is the critical factor for minimizing erosion of the surface soils of the cover system and also for the management of the water balance of the entire cover system. The understanding of the water balance components at a site is essential for the design of a cover system as well as for other remedial measures. The soil which can act as reservoir for water, or as a conduit for subsurface transport of infiltrating water, also supports the vegetative layer as a mechanical base and is a reservoir for water and nutrients. The water use and rooting characteristics of the vegetation can determine the extent of percolation of water below the rooting zone as much or more than soil hydrologic properties. Thus, an estimate of the effects of different soil and vegetation combinations on the water balance of a cover system must be an integral part of land disposal design process.

The purpose of the project was to investigate the utility of the hydrologic models HELP (*Hydrologic Evaluation of Landfill Performance*) and CREAMS (*A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems*) for assisting the process of designing landfill cover systems that are stable over long periods of time and have no maintenance requirements in the period after 30 years post-closure. The report discusses concepts of low maintenance and stability for soil/vegetation systems. The utility of these models was explored through studies of the parameters for the design of land disposal units at several sites, assuming a variety of regionally possible plant covers, and in an assessment of the performance of the models in simulating experimental landfill cover systems under a variety of controlled field conditions of vegetative cover.

Vegetative Succession on Landfill Sites

Although it has been recognized that the vegetative cover is an important component in cover design, the questions of long-term stability of the vegetation community on the landfill (and hence its long-term performance) is rarely addressed. Recommendations have been made to use cultivated or domesticated species, particularly grasses, for reclamation purposes. This is largely because many grass species tend to rapidly form a sod which can effectively protect the soil surface from erosion, and also because they have shallow rooting patterns and so are less likely to invade the waste than deeper rooted species. Although a grass cover may be an attractive alternative for the short-term, successional processes will inevitably lead to invasion of the site by native species from the surrounding area.

A few current documents suggest the use of native species where appropriate but successional processes per se, and their effect on cover integrity and effectiveness, have not been addressed. Few data are available on important native species which might be candidates for vegetative cover treatments. The specific course of succession can only be predicted from studies of specific habitats. In particular, studies on drastically disturbed areas would be invaluable. Without management intervention, the soil environment of a landfill cover is not likely to resemble the soil profile of a natural or mildly disturbed community for many years. Not only are the physical characteristics of the soil layers (porosity, bulk density, hydraulic conductivity) changed by the construction process, but the organic content is low until the soil biota reaches levels comparable to those in natural communities.

The plant cover on a landfill site will inevitably undergo successional changes. In the short term, relatively rapid changes in species and population sizes will result in a relatively unstable vegetative community. In the long term, dominant species from surrounding natural vegetation will invade the site to the extent that the soil environment resembles that of a natural community in terms of depth, layering, texture, water holding capacity, nutrient status, and organisms. Multiple pathways of su cession are possible, indeed likely, any given site. Management interventi can result in a vegetative commun being established that is most advan geous for long-term, low-maintenan equilibrium. Such management de sions, however, must be based on realistic assessment of the life hist characteristics and physiological tol ances of the species under considerati Competitive interaction between speci should also be considered in choosi species mixes. Such data are oft unavailable for native species. A study the plant associations present in particular locale, along with a history land usage, can often supply reasonable estimate of the possi stages of succession, and perhaps ev of the time course of the process. M detailed assessment of the soil conditi and microclimatic environment of desired vegetative phase should undertaken. These data will provide starting point for designing establishm procedures necessary to accelerate decelerate successional processes so to maximize the time the vegetative cov has an optimum mix of species.

Simulation of Potential Landfill Sites

Understanding and controlling wat balance relationships in hazardous was landfill cover treatments is an essent component of the design and operati of hazardous waste management sites. many climatic zones evapotranspirati accounts for the largest output co ponent of the water balance equation,

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

where over a time interval Δt, ΔS change in soil moisture content, P precipitation, Q = runoff, ET = evap transpiration, and L = seepage. It particularly important to understand t interrelationships between meteorolog vegetation, and soils that determi evapotranspiration so that the seepa component be estimated with confiden The development of computer simulati models of the hydrologic cycle offers t potential for simulating the several critic processes involved in tracking hydrolog responses to daily (or smaller) time ste of water input. In the present study t USDA model CREAMS and the E model HELP were used to mod hydrologic processes over varying ti periods. These are physically base models and so should not require calibration for each application. Field scale hydrologic responses are based on models for infiltration, soil water movement, and soil/plant evapotranspiration between storms. Processes are continuously simulated on a daily time step for evapotranspiration and soil water movement between storms. The simulation of water redistribution between storms provides the basis for prediction of seepage below the root zone.

The CREAMS model was intended for modeling field-scale agricultural systems. The model has been used in several areas of waste management research in semi-arid climates, including erosion studies, water balance and primary production of desert shrubs and landfill cover design. In this study it was used to evaluate two potential landfill sites, one in Houston, Texas and the other in Fresno, California. Both are areas with a history of problems with hazardous waste management and are on the Hazardous Waste Site National Priority List. Together with the Los Alamos experimental site, a wide diversity of climatic regimes, soil types, and native vegetation are represented by the modeling studies.

CREAMS was used in the daily rainfall-runoff mode to obtain a complete water budget (estimates of runoff, evapotranspiration, percolation and soil-water storage, or water content in the soil column to the depth of the rooting zone) on each day that there was a precipitation event. Monthly and annual water budgets are also obtained. The model is one-dimensional, treating only the process of vertical transport of water in the soil column. Lateral inflow or drainage are not accounted for.

The alternative model, HELP, developed by EPA, is directly applicable to most landfill designs. In contrast to the purely one-dimensional character of CREAMS, the HELP model permits quasi-two-dimensional modeling of soil water routing by including lateral flow simulation in drainage layers. Precipitation inputs are modeled one-dimensionally down to the depth of lateral drainage and impermeable membrane liners. Lateral flow out of drainage layers is treated separately. The infiltration routine is similar to that used in CREAMS, and there are changes (claimed to be improvements) in the treatment of percolation and evapotranspiration. The model is interactive and user-friendly, with default climatic and soils data available for many regions in the United States Default estimated vegetation data are also available to the user. Alternatively, the user can specify exact parameter values specific to the site being modeled. Both models require soil characteristics, seasonal vegetation characteristics and data, and soil cover design data as input. Monthly mean temperatures, mean monthly solar radiation values, and daily precipitation inputs are required.

A general plan for the evaluation of a potential landfill site and for acquiring the data for a modeling exercise is as follows.

1. Background information, including history and setting, climate, vegetation and soils, should be collected. This step is particularly important to provide a basic set of resources for the following data requirements and also to supply perspective to the entire exercise.
2. Examine climatic data, including 20 to 30 year records of temperature, precipitation and solar radiation. Such records are available from local or regional weather bureau stations or the U.S. Department of Commerce.
3. Examine soil data from the relevant USDA Soil Survey. Local sources of top soils, barrier soils (clays), fill soils (subsoils), and "special-needs" soils (cobbles, gravels, sands) must be located and the textural classes of the soils determined. Extra effort should be expended to determine the actual hydrologic properties of the soils: hydraulic conductivities, field capacity, wilting point and curve number under different topographic and vegetative conditions.
4. Evaluate the vegetation of the region. The results of this study strongly suggest that vegetation of the landfill be accomplished with native species which are preadapted to the soils and climate of the region and are thus most likely to form a stable vegetative community for as long as possible. The species present in the different vegetative communities should be determined, along with the relative importance of the species Likely successional sequences should be evaluated, as well as the approximate timing of the various stages under natural conditions, and if at all possible, an estimate of how succession is modified by management practices Details on leaf area indices, above ground biomass, seasonal variabilities, rooting structures, and physiological characteristics (especially transpiration rates) should be compiled for the dominant members of each community type. Lists of species present in the various communities are relatively easy to obtain from floras of the state or region. However, all other attributes are generally very difficult to obtain, and are often unavailable. If the data is not forthcoming from these sources, limited field studies were indicated.
5. The selection of a particular model must depend on demonstrating the appropriateness of the model to addressing the objectives. In the cases discussed in this report, the objectives were to specifically evaluate the effects of varying soils and vegetation characteristics on water balance of the landfill cover system, and thus the model results had to supply estimates of percolation, evapotranspiration, runoff, and soil water storage. In addition, the model could not be so "data hungry" that input data was impossible to obtain These considerations resulted in choosing one-dimensional hydrologic models with a high degree of flexibility in changing input parameters as well as a "user-friendly" operating environment.
6. If at all possible the model should be calibrated using data from a comparable landfill site or natural area in the same region.
7. The time scale of the model simulations must be considered with reference to the desired objectives. In an exercise to determine possible worst case scenarios in the event of unusually severe climatic conditions, the meteorological data base should be sufficiently long so as to incorporate such severe conditions
8. The interpretation of the results must be relevant to both the objectives of the study and the capabilities of the model. It may be unrealistic to expect absolute quantitative accuracy from model predictions. However. the values of the results can indicate with quite good accuracy the relative utility of design scenarios.
9. A major issue in a modeling exercise is to take the modeling results, along with other information and then design an actual vegetative cover of specific ratios of plant species. This may be the most difficult step in the evaluation of potential landfill design. The

success of this step depends largely on the accuracy and depth of the information gathered during steps 3 and 4 above.

The results of the modeling studies on two potential landfill sites showed that generally increasing cover thickness alone is not an efficient way of reducing deep percolation. If a poor selection of vegetative treatment is made, large amounts of water may be available for percolation at certain times of the year, and the simple expedient of increasing cover thickness is not likely to be an efficient remedy, particularly by comparison with use of low permeability or impermeable barriers. However, increasing the biomass of vegetation on a site will significantly increase ET and decrease percolation on a yearly basis. Seasonally, the form and phenology (seasonal activity) of the vegetation has a very significant effect on the size and frequency of percolation events. These results suggest that it is most important to select a variety of species to revegetate a site, so that different forms (trees, shrubs, forbs and grasses) and different phenologies (evergreen, deciduous, warm-season, cool-season) are well-represented. The ratio of these factors would ideally reflect the seasonal distribution of precipitation events. Mitigation of erosion will depend on having a vigorous plant cover throughout the year. The size of runoff events as modeled by CREAMS was not greatly affected by the biomass of the vegetation.

The advantages of computer model simulation of cover system performance are many. Once site data are assembled a large number of "what if" questions can be explored systematically, and the outcomes can be compared quantitatively. However, data deficiencies can be a serious problem leading to predicting results of uncertain value. Also a number of critical biological and geochemical questions about cover design and performance may be raised but cannot be readily answered by these models.

Simulation of Experimental Landfill Covers

Field Experiment

A study was undertaken on a low-level radioactive waste landfill site ("Area B") in Los Alamos, New Mexico. About half of the site had in place a layered soil cover consisting of local topsoils and crushed tuff. This type of soil profile has been the standard cover system on landfill sites at Los Alamos, and therefore a significant amount of data were already available on its physical and ecological characteristics. This profile was in two areas at Area B, termed "east control" and "west control". About 25% of the area of Area B had a soil profile consisting of 15 cm top soil, 50 cm crushed tuff, and a gravel-cobble layer designed to act as a biobarrier to prevent animal and root intrusion into the waste fill. This type of profile (termed "central biobarrier") has been studied at Los Alamos, and a considerable amount of information about its performance has been gained through erosion and subsurface studies. Furthermore, exactly such a layer combination has been recommended to EPA as a means for providing a gas channel for controlled release under tight soil caps. The profiles had been in place for a year before the start of the EPA-sponsored study.

East and west control profiles differ in the amount of sandy clay loam in the profile. The west profile is more typical of landfill covers at Los Alamos, having about 15 cm of top soil over 85 cm of crushed tuff. The east profile has a much higher amount of top soil (sandy clay loam) mixed into the profile as a result of the reconstruction in 1982, and thus the east soil profiles have significantly higher water holding capacity than the west soil profile.

Study plots were established on each profile with bare, grass and shrub vegetative covers. The dense rabbitbrush planting had shrubs planted on 0.68 m (2.2 ft) centers (2.15 plant/m^2), and the sparse rabbitbrush planting at 1/5 density had shrubs planted on 1.5 m (5 ft) centers (0.43 plants/m^2).

In each plot, three or four neutron access tubes were installed and soil moisture distribution with depth measured with a neutron moisture probe throughout the year.

Determining absolute values and seasonal changes in biomass and leaf area index (LAI) on each study plot was an important subtask in this project. LAI is the total projected leaf area (one side only) per unit area of ground. The CREAMS and HELP models require an estimate of LAI as input for calculating utilization of soil moisture by the vegetative cover, and these values have large seasonal variations. Hence, it was necessary to develop nondestructive methods that allow frequent estimates during the year without disturbing the vegetative cover.

For the shrubs and grasses, d
structive sampling was used to determi
the dry leaf mass as a fraction of c
mass of current growth and the speci
leaf mass (Table 1). Regression mod
were developed relating crown bioma
to crown volume for the shrubs a
canopy biomass to percent ground cov
for the grasses (Table 2). Using t
relationships developed, total bioma
and leaf area indices were estimat
during the growing season usi
nondestructive measurements of shr
volume or estimates of grass cano
ground cover.

Field Results

Both soil profile composition a
vegetative cover had a strong influen
on soil water storage in the rooting zo
(0 to 70 cm). Of the three soil profile
the east control profile (high clay conte
retained more moisture than the we
control profile (low clay content) or t
central biobarrier profile (shallow soil ov
a gravel-cobble capillary barrier laye
(e.g., Figure 1). Soil moisture in t
central profile decreased to very lo
levels during each growing season. Th
is most likely the result of efficient mini
of soil water by the shrub roots in t
restricted soil profile as well as late
drainage of soil water in the soil abo
the gravel-cobble layer which served
a barrier to capillary moisture flow.

Volumetric soil water was lowest und
vegetative cover of shrubs (e.g., Figu
2). After 2 years growth, bare plots had
to 7 cm more water in the assume
rooting zone (70 cm) than the shru
plots. Grass plots were intermediate
soil moisture. The maximum rate
decline in soil moisture was usual
observed on the shrub plots, with gra
plots having an intermediate rate a
bare plots lowest. The shrubs are know
to be quite deeply rooted. The effect
this was apparent in that soil moisture
60 to 80 cm depth decreased under t
shrub cover during the summer month
In contrast, water withdrawal by the gra
cover was not apparent at these depths.

Simulation of Field Experiment

Simulations of the different scenari
were made using the CREAMS a
HELP models. Parameter values for s
hydrologic characteristics were optimize
using data for a shrub plot for whi
there was a four-year record of s
moisture (two years prior to the start
the experiment plus two years during th
study). Optimization was performed

Table 1. *Biomass and Leaf Characteristics for Shrubs and Mixed Grasses*

	Mean Value	Standard Error	Number of Samples
Rabbitbrush			
specific leaf mass (g/cm^2)	0.0169	0.0013	33
leaf mass/total biomass	0.499	0.021	33
Mixed grass			
specific leaf mass (g/cm^2)	0.0243	0.0021	122
leaf mass/total biomass	0.424	0.023	10

Table 2. *Regression Relationships for Shrub and Grass Cover at Area B*

Cover	Equation	Y	X	r^2
Shrubs	$y = 43.43 + 1.57x$	biomass (g)	shrub volume ($m^3 \times 10^3$)	0.98
Grass	$y = 1.28 + 0.55x$	biomass (g/m^2)	% cover	0.66

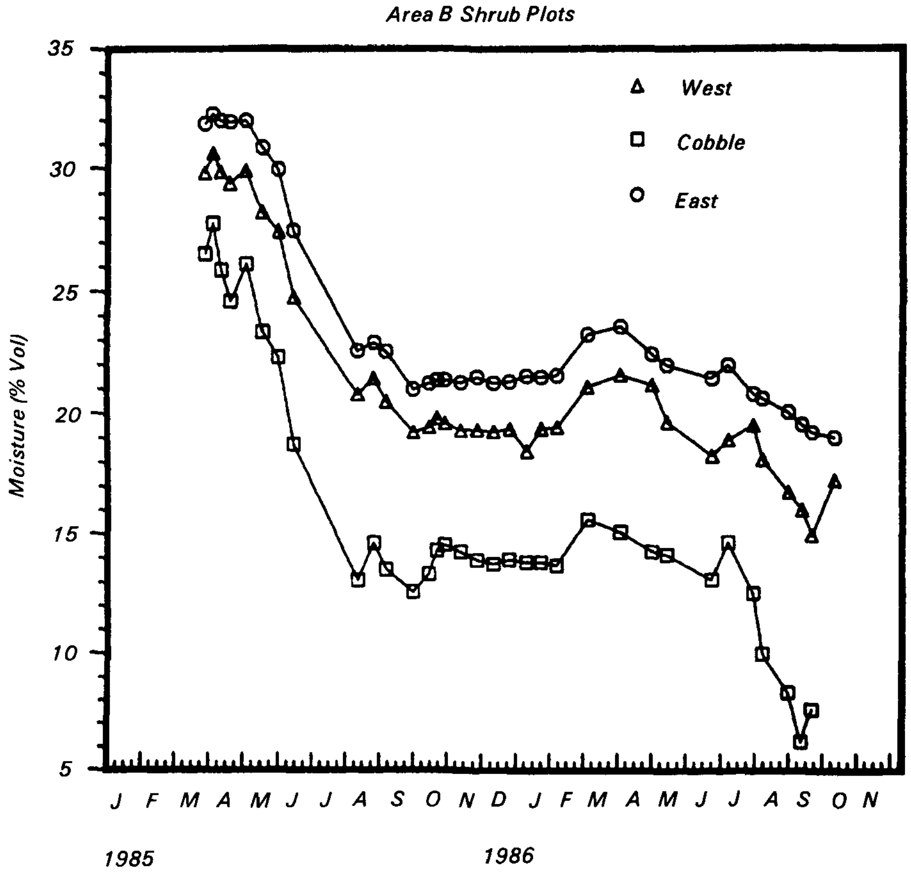

Figure 1. *Volumetric soil moisture (average of 20, 40 and 60 cm depths) on shrub plots at Area B over 2 years.*

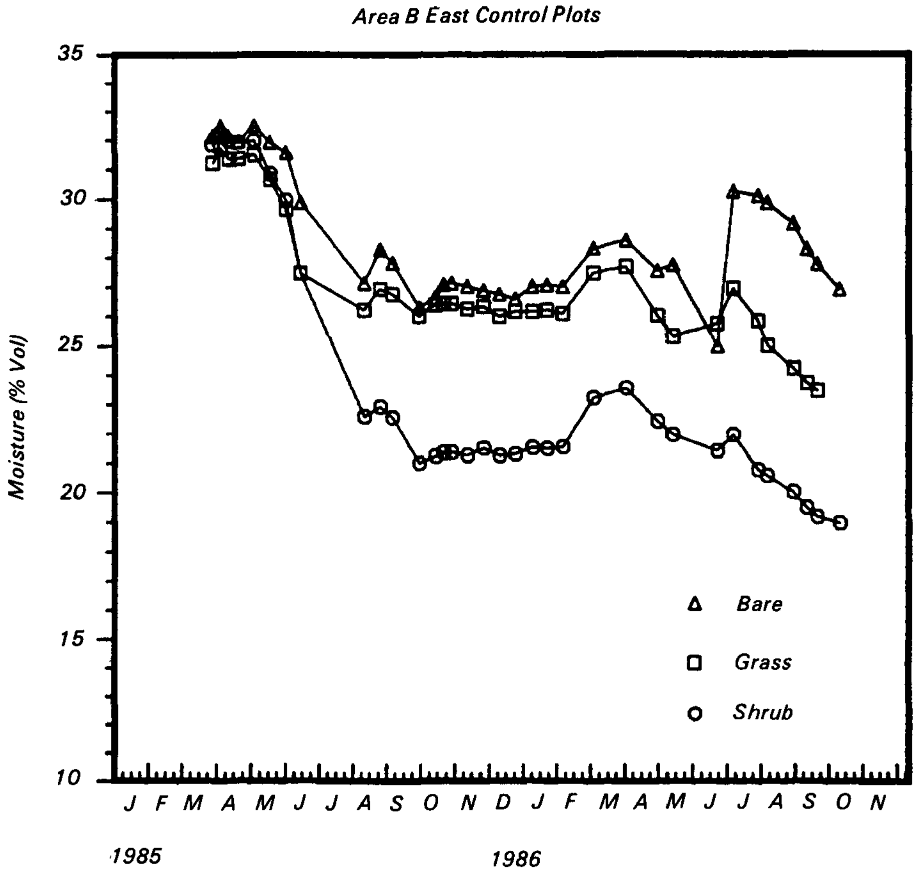

Figure 2. *Volumetric soil moisture (average of 20, 40 and 60 cm depths) on plots on the east soil profile at Area B.*

varying values within recommended ranges for hydraulic conductivity, field capacity, wilting point and curve number and then performing a linear regression analysis between observed and predicted soil moisture over a three-year period. The process was repeated until it was apparent which combination of parameter values resulted in the highest correlation coefficient (indicating the least amount of scatter in values), the slope of the regression line closest to 1.0 (indicating a dynamic range in predicted values that most closely approximates the variability observed in the field) and an intercept closest to 0.0 (indicating an absolute value of soil moisture values most closely resembling the observed values).

Simulation of all treatment scenarios were performed for a two-year period with CREAMS (using optimized soil parameters), and with HELP (using optimized soil parameter values and also again using the default parameter values as supplied by the HELP model). The overall predictive power of each model was assessed by a linear regression analysis of predicted versus observed soil moisture over all plots (summarized in Table 3).

Predications of soil moisture using the CREAMS model more closely resembled the measured soil moisture over a range of soil and vegetation treatments than predictions obtained using the HELP model using either set of soil parameter values. The HELP model produced more accurate predicted values for soil moisture using the default soil parameter values.

Simulations of the soil profile treatments which more closely resembled a natural profile were more accurate than those of the profiles which had a more artificial layered structure. Treatments with shrub or bare covers were more accurately modeled than treatments with grass covers.

The optimization process of CREAMS narrowed the range of choices of several parameters, and the final selection of parameter values departed from the average values in a meaningful way. The most successful HELP runs were cor ducted with the default options availabl in the program itself, resulting in relatively naive selection of paramete values and low correlation betwee predicted and observed soil moisture. is noteworthy that CREAMS runs cor ducted with average parameter value based on soil texture classes als resulted in poor correlation coefficient for the comparison between observe and predicted soil moisture values. It i quite likely that calibrating the HEL model with particular reference to later transport, seepage and runoff (obse vations which were not available from th field experiments in this study) woul substantially improve the performance c the model.

Although CREAMS more accuratel predicted field observations than th HELP model, CREAMS still should b used with several precautions. Actu values for soil hydrologic parameters wi undoubtedly produce better results tha values assumed on the basis of so texture class. However, actual values fc the soils to be used on the landfill will, in all probability, not be readily available. A reasonable effort to develop values for soil parameters through laboratory tests would greatly increase the accuracy of the model.

Modifying vegetation parameters and soil layer depths and then assessing the resultant model predictions for percolation events should indicate the minimum levels of plant LAI necessary to control percolation at different times of the year and the appropriate soil layer depths. Implementing the soil profile design is trivial compared to choosing species that would rapidly produce the desired LAI values within the seasonal constraints suggested by the modeling exercise. Site specific field studies on natural communities in the area of the proposed landfill site are needed to determine what species make up different communities, the possible successional communities, and the natural timing of succession. Some of this information could be obtained from literature or anecdotal research, while field studies might be necessary for the rest.

Conclusions

The results of this study have demonstrated unequivocally that the role of native vegetation in determining site stability and integrity must be evaluated and considered in designing a hazardous waste landfill cover system. It is apparent that native species are much hardier than cultivated species. Given a long enough period of time with no human interference (i.e. no maintenance) native species will invade and colonize a landfill site, and some sequence of succession will proceed thereafter. Unfortunately, these processes are not well documented, especially for severely disturbed sites or on constructed soil profiles.

The use of simple hydrologic models to simulate the water balance of landfill cover systems can assist the process of designing soil and vegetative systems for site closure. Two models (CREAMS and HELP) were used to simulate eight experimental cover designs on a landfill site at Los Alamos, New Mexico. Results of the modeling study suggest that, overall, CREAMS performs more satisfactorily than HELP in accurately predicting soil water storage in the soil profile, although more detailed calibration of HELP will probably improve model performance. Careful parameterization of the models was a key to successful simulation. Few data exist for leaf area indices and rooting depths of native plant species. Values of hydrologic parameters of soils may be quite different in the constructed soil profiles of landfill covers than under laboratory or natural conditions. These areas are in critical need of further research.

***Table 3**. Linear Regression Relationships ($y = a + bx$) Between Observed Average Soil Moisture from 0-70 cm (x) and Soil Moisture (y) as Predicted by CREAMS (Using Optimized Parameters) and HELP (Using Default Parameters)*

		CREAMS Model			HELP Model		
Plot	Treatment	a	b	r^2	a	b	r^2
2	Bare	13.04	0.59	0.61	5.93	0.58	0.42
3	Shrub[1]	-3.04	1.09	0.62	11.09	0.47	0.63
4	Grass	11.90	0.54	0.72	11.36	0.40	0.25
7	Shrub-Cobble[2]	5.18	0.68	0.50	13.77	0.17	0.33
10	Sparse Shrub[3]	13.87	0.46	0.72	17.87	0.14	0.13
11	Shrub	-0.89	0.87	0.60	15.66	0.23	0.26
12	Grass	20.49	0.27	0.68	15.86	0.22	0.26
13	Bare	22.07	0.10	0.14	10.75	0.24	0.26
All Plots		3.83	0.82	0.62	12.47	0.33	0.39
East Plots4		-1.73	1.06	0.71	13.36	0.34	0.36
West Plots[5]		9.34	0.58	0.29	16.85	0.14	0.05
Shrub Plots[6]		4.14	0.75	0.56	12.40	0.35	0.48
Grass Plots[7]		20.52	0.24	0.45	14.57	0.28	0.31
Bare Plots[8]		8.94	0.69	0.56	-1.39	0.79	0.58

[1] Shrub density 2.15 plants/m^2

[2] Shrub density 2.15 plants/m^2 over a soil profile with a cobble-gravel layer

[3] Shrub density 0.43 plants/m^2

[4] Plots 2,3,4

[5] Plots 10,11,12,13

[6] Plots 3,10, 11

[7] Plots 4,12

[8] Plots 2,13

Fairley J. Barnes and John C. Rodgers are with the Los Alamos National Laboratory, Los Alamos, NM 87545.
***Naomi P. Barkley** is the EPA Project Officer (see below).*

The complete report, entitled "Evaluation of Hydrologic Models in the Design of Stable Landfill Covers," (Order No. PB 88-243 811/AS; Cost: $21.95, subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650

The EPA Project Officer can be contacted at:

Risk Reduction Engineering Laboratory
U.S. Environmental Protection Agency
Cincinnati, OH 45268

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati OH 45268

BULK RATE
POSTAGE & FEES PAID
EPA
PERMIT No. G-35

Official Business
Penalty for Private Use $300

EPA/600/S2-88/048

PL