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Volume 25, no. 1, January–February 1996, Copyright
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Evaluation of a Prototype Decision Support System for Selecting Trench Cap Designs

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ABSTRACT

A computer-based prototype decision support system (PDSS) to assist the risk manager in selecting an appropriate trench cap design for waste disposal sites is evaluated. The selection of the "best" design among feasible alternatives requires consideration of multiple and often conflicting objectives. The methodology used in the selection process consists of: selecting and parameterizing decision variables, using data, simulation models, or expert opinion; selecting feasible trench cap design alternatives; ordering the decision variables and ranking the design alternatives. The simulation models incorporated in the PDSS are the Hydrologic Evaluation of Landfill Performance (HELP) model which is used to simulate the trench cap water balance and the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) erosion component that is used to simulate trench cap erosion. The decision model is based on multi-objective decision theory and uses a unique approach to order the decision variables and rank the design alternatives. The PDSS is evaluated using the Hill Air Force Base landfill cover demonstration project. The water balance and surface erosion of four alternative landfill cover designs were monitored for a 4-yr period. Two of the cover designs were used to calibrate and test the simulation models. The results of the PDSS, using both data from all four designs and long-term simulations from two of the designs, illustrate the relative advantages of each of the cover designs and which cover is the "best" alternative for a given set of criteria and a particular importance order of those decision criteria.

The primary purpose of the U.S. Department of Energy (DOE) Environmental Restoration Program is to manage the health and ecological risks associated with intentional and accidental releases of radioactive and hazardous contaminants to the environment. The DOE sites from past and ongoing operations are being evaluated for possible clean up action. At sites where health and ecological risks are considered to be low based on preliminary baseline risk assessment studies, regulatory requirements for final closure can often be met using a well designed trench cap to isolate the buried waste (USDOE, 1990).

The essential functions of a trench cap are to isolate the buried waste from the surface environment and control the hydrologic processes that can lead to migration of contaminants from the site (USEPA, 1980, 1985). Water that infiltrates into the soil cap can lead to enhanced percolation of water and solutes out of the burial environment. Likewise, excessive erosion of cap soil can expose buried waste and lead to off-site transport of contaminants. The selection of an optimum cap design requires consideration of multiple and often conflicting objectives, as well as both quantitative and qualitative input (Hakonson et al., 1982, 1994; Nyhan et al., 1990). One of the objectives of the cap is to enhance runoff and therefore decrease the potential for infiltration into the waste. A conflicting objective is to minimize soil erosion, a process which is caused by runoff.

The U.S. Environmental Protection Agency (USEPA) guidance (USEPA, 1989) recommends that an analysis of the final cover design be presented in the closure plan. The technical guide for final covers describes a recommended cover design, often called EPA's RCRA cap, that will meet the final performance standards. Research in trench cap designs (Hakonson et al., 1982, 1994; Lane and Nyhan, 1984; Nyhan et al., 1990) have demonstrated that there may be alternatives to the EPA RCRA recommended design that offer certain technical and economic advantages. The basic problem is to evaluate and compare these alternative designs with the EPA RCRA design for specific waste sites while taking into account the technical, regulatory, and economic issues.

The ability to evaluate the environmental and economic effects of a particular trench cap design often requires the use of sophisticated computer models. The models are used to simulate the availability and movement of water, the potential for contaminant transport, and the long-term viability of the cap. Simulation results can then be used to estimate the immediate and long-term economic costs. To use these models as management rather than research tools, they must be embedded in a framework devised to aid the risk manager in evaluating alternatives and supporting decisions. A method to quickly determine realistic parameters of the model for a given location by linking it to a database is also needed. In addition, output of the simulation models should be structured to help the decision maker/risk manager decide on the proper course of action.

To meet these needs, we have developed a prototype decision support system (PDSS) to evaluate alternative trench cap designs for shallow landfill waste disposal sites. The objectives of developing the prototype are to: (i) design and build a computer-based decision support system, incorporating multi-objective decision theory, to evaluate the hydrologic performance of various capping alternatives within the context of applicable regulations and cost; (ii) validate the PDSS predictions of cap performance using field data from a study of four cover alterna-

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Published in J. Environ. Qual. 25:127-135 (1996).

Abbreviations: PDSS, prototype decision support system; HELP, hydrologic evaluation of landfill performance; CREAMS, chemicals, runoff, and erosion from agricultural management systems; FML, flexible membrane liner.

tives; and (iii) provide a framework for an operational decision support system. The major components of the PDSS are a simulation model, a decision model, default data bases, input file generators, output interpreters, and a system driver. The intended use of the PDSS is to aid the risk manager (user) in setting the parameters needed by the simulation model for several different capping alternatives and to use the output of the simulation model in the decision model to choose the most appropriate trench cap design for a given situation.

In this paper, the PDSS is illustrated and evaluated using both field data and computer simulations of trench cap designs from the Hill Air Force Base cover demonstration study in Layton, UT. First, the PDSS is described and illustrated using field data from four trench cap designs that were monitored for a 4-yr period. Second, two of the cover designs are evaluated using computer-simulated data. The simulation models embedded in the PDSS were calibrated using data from two of the cover designs. The calibrated models were run for 60-yr simulation periods, and the output from the simulation models were evaluated in the decision model. The results of the decision model analysis using both the Hill Air Force Base data and the 60-yr simulations are assessed.

MATERIALS AND METHODS

Simulation Models

In the absence of actual field observations and data, a computer simulation model is used to predict the values for the decision criteria for a given site. The simulation models incorporated in the PDSS are the hydrologic evaluation of landfill performance (HELP) (Schroeder et al., 1988) model version 2, and the erosion component of the chemicals, runoff, and erosion from agricultural management systems (CREAMS) (Knisel, 1980) model. The HELP model is used to simulate the trench cap water balance and the CREAMS model is used to simulate erosion of the cap.

The HELP model is being used in the PDSS because it is easy to parameterize and is recommended by the USEPA for solid waste landfill design (Schroeder et al., 1984, 1988; U.S. DOE, 1990). The model was developed by the U.S. Army Corps of Engineers Waterways Experiment Station for the EPA Hazardous Waste Engineering Research Laboratory. It is a quasi-two-dimensional model that uses climatologic, soil and design data, and calculates the infiltration, surface runoff, percolation, evapotranspiration, soil water storage, and lateral drainage in a shallow landfill system with up to 12 different layers. The model simulates water flow within three different soil layer types: vertical percolation, lateral drainage, and barrier soil liner (compacted clay layer) with or without a flexible membrane liner (FML). The HELP model can not simulate flow above or through capillary barriers. Both default (USDA soil classes) or user specified soil characteristics can be used in designing the trench cap system and include the following soil properties: total porosity, field capacity, permanent wilting point, saturated hydraulic conductivity, and initial soil water content. The program accepts both user specified and default climate data and includes WGEN, the synthetic weather generator developed by USDA-ARS (Richardson and Wright, 1984), which produces daily precipitation, temperature, and solar radiation values. These last two values are used in HELP to determine snow melt and evapotranspiration. HELP also includes the vegetative growth model from SWRRB (Arnold et al., 1989) to calculate daily leaf area indices. Runoff is estimated using a modified SCS curve number method. Version 2 of the HELP model is currently being used in the PDSS. Version 3 of the HELP model (Schroeder et al., 1994) was released in late 1994, after this study was completed.

The CREAMS overland flow erosion component has been added to the HELP model to simulate trench cap erosion. The erosion component of CREAMS can be used to predict sediment yield and particle composition of the sediment on a storm by storm basis for a given cap design. The erosion component requires the input of hydrologic parameters for each runoff event simulated by the HELP model and an erosion parameter file. The principal outputs from the overland flow component are sediment load and the concentration of each particle type for each storm. The model also calculates the soil loss per unit area and the particle sizes and organic matter content of the sediment leaving the site.

Decision Model

The decision model uses scoring functions as a means of scaling the decision criteria that have different units and magnitudes to a common scale between 0 and 1. The conventional and feasible alternatives are scored on the same set of decision criteria (i.e., percolation of leachate, runoff, evapotranspiration, sediment loss, and cost). The individual criterion scores are then aggregated for each alternative with a minimum amount of interaction with the decision maker. In particular, while an additive value function is assumed, the alternatives are not ranked on a single vector of weights associated with the criteria. The method considers all possible weight vectors consistent with an importance order of the decision criteria computed by the decision model from the simulation results and scoring functions. The trench cap design with the highest aggregated score, for a given importance order of the criteria, is considered to be the "best" design among the conventional and feasible alternatives.

The decision model, based on multi-objective decision theory, combines the dimensionless scoring functions of Wymore (1988) with the decision tools presented in Yakowitz et al. (1992, 1993). The scoring functions convert predicted or observed data to values on a 0 to 1 unitless scale and can be altered interactively by the user for each decision criterion. The scoring functions from Wymore (1988) were previously used to evaluate shallow land burial systems (Lane et al., 1991). Four generic shapes of scoring functions are shown in Fig. 1. These functions can be modified for each criterion by implicitly setting threshold values or allowing the model to set these values by default based on the data or simulation results. The baseline values can be determined by a standard or conventional practice, federal regulation, or expert opinion. The scoring functions are set up so that the conventional design or baseline scores 0.5 for each decision variable. All of the other alternative designs are scored relative to the conventional design for each criterion. A design that performs better than the conventional design with regard to a specific criterion will score >0.5 for that criterion and one that performs worse will score <0.5. A default importance order for the decision criteria is established based on the normalized slopes of the scoring functions. The decision variable with the steepest sloped scoring function (i.e., the scoring function that is the most sensitive to a change in the value of a decision variable) is the most important. Once all the alternatives have been scored, a score matrix is available to complete the analysis. Best and worst composite scores assuming an additive value function are determined by maximizing and minimizing a simple linear program

Fig. 1. Generic scoring function types.

for each alternative and these two composite scores are aggregated to determine the preference ranking of the alternatives.

Algorithm for Ranking Alternatives

Using the established importance order of the decision criteria, best and worst composite scores for each of the alternatives are determined by the PDSS by maximizing and minimizing Eq. [1], respectively (Yakowitz et al., 1992). These solutions to these linear programs are the most optimistic and most pessimistic composite scores (weighted averages) consistent with the importance order.

$$\sum_{i=1}^{m} w(i)\, Sc(i,j)$$

subject to

$$\sum_{i=1}^{m} w(i) = 1 \qquad w(1) \geq w(2) \geq \ldots \geq w(m) \geq 0 \qquad [1]$$

Suppose there are m criteria that are ordered in importance as determined above. Let $Sc\,(i,j)$ be the score of the alternative j evaluated with respect to criterion i in the importance order. If $w(i)$ indicates the unknown weight factor associated with criterion i, the highest or best additive composite score for alternative j consistent with the importance order is found by solving the following linear program for the weights $w(i)$, $i = 1, \ldots, m$. The lowest or worst additive composite score for alternative j consistent with the importance order is found by minimizing Eq. [1]. In both cases, the first constraint normalizes the sum of the weights to 1, the second requires that the solution be consistent with the importance order and restricts the weights to positive values. Thus, the decision maker is not asked to determine an exact weight factor for each criterion. Maximizing and minimizing Eq. [1] yields the full range of possible composite scores for the given importance order. Any weight vector that is consistent with the importance order will produce a composite score that falls between the best and the worst composite scores. The designs are then ranked in descending order by the average of the best and worst composite scores. Yakowitz et al. (1993) provide the theoretical justification for this method of ranking the alternatives.

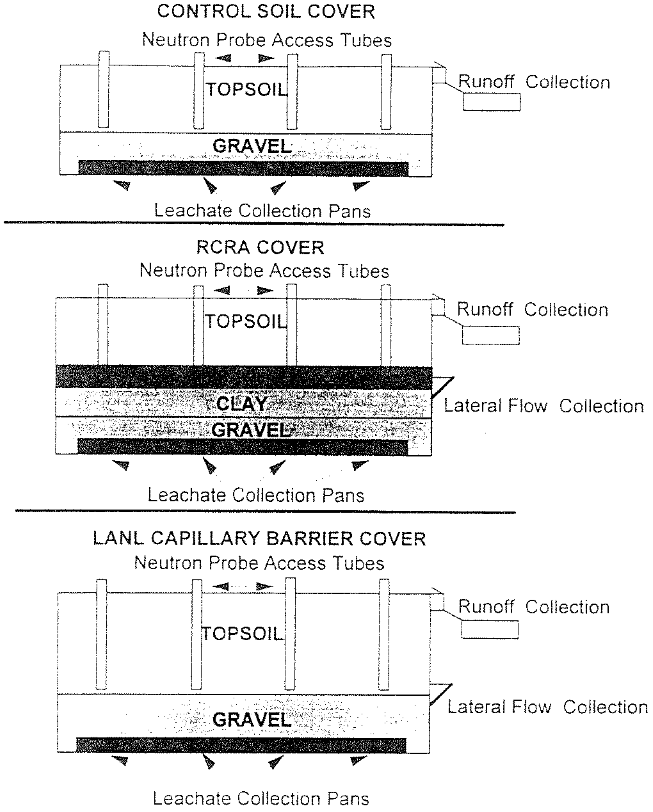

Fig. 2. Side view of the trench cap designs from Hill Air Force Base, Layton, UT (not to scale).

Hill Air Force Base Cover Demonstration

Four shallow landfill cover design test plots were installed at Hill Air Force Base in Layton, UT, and their performance monitored for a 4-yr period (Hakonson et al., 1994). There are three basic cover designs: a control soil cover; a modified EPA RCRA cover; and two versions of a Los Alamos design (Fig. 2). The Los Alamos designs contain erosion control measures, an improved vegetation cover to enhance evapotranspiration, and a capillary barrier to divert downward flow of water. The control soil cover consists of 90 cm of soil over 30 cm of a gravel drainage layer. The modified RCRA cover design consists of 120 cm of soil, 30 cm of sand (lateral drainage layer), 60 cm of compacted clay (defined as a barrier soil liner in the HELP model), and 30 cm of a gravel drainage layer. The Los Alamos designs consist of 150 cm of soil over 30 cm of gravel (capillary barrier), and 30 cm of a gravel drainage layer. The Los Alamos designs also have a thin layer of gravel on the surface to help control erosion (Simanton et al., 1986; Nyhan et al., 1990).

The soil used in the top layer of all four covers was a sandy loam compacted to a bulk density of 1.86 g/cm^3. The soil porosity, 30%, and the saturated hydraulic conductivity of 2.8×10^{-4} cm/s (SD of 3.2×10^{-5} cm/s) were determined from 15 soil core samples. The 60 cm clay barrier (clay loam amended with bentonite) was compacted to a bulk density of approximately 1.76 g/cm^3. The saturated hydraulic conductivity at installation was 3.4×10^{-6} cm/s. The EPA recommended conductivity is 10^{-7} cm/s. It is important to note that the clay barrier was not saturated when installed.

All four of the cover designs were seeded with native perennial grasses. In addition, one of the Los Alamos designs (Los Alamos 2) was planted with seedlings of two species of shrubs, Rubber Rabbitbrush (*Chrysothamnus nauseosus*) and

Four Winged Saltbush (*Atriplex canescens*), to enhance evapotranspiration. A porous geotextile (Mirafi 600X)[1] was used to separate the layers in all the cover designs. The surface and all of the underlying layers of the covers were installed at a 4% slope.

The plots were instrumented to measure the performance of the covers with respect to controlling the hydrology and erosion of the trench cap. Daily precipitation data were measured using tipping bucket rain gages linked to data loggers. Lateral flow, and percolation out of the gravel drainage layer were also measured daily using tipping buckets connected to a data acquisition system, and then into cumulative flow collectors that served as backup. Soil moisture, measured with a neutron probe moisture meter, surface runoff and sediment yield, were measured approximately bimonthly. Evapotranspiration was estimated by solving the water balance equation over an approximate 2-wk time interval:

$$\mathrm{ET} = P - L - I - R - dS \qquad [2]$$

where ET is evapotranspiration (m), P is precipitation (m), L is percolation (m), I is barrier lateral flow (m), R is surface runoff (m), and dS is the change in soil moisture (m).

RESULTS AND DISCUSSION

Observed Data

The decision criteria selected for evaluating these designs are: runoff (including lateral flow), evapotranspiration, percolation (leachate production), sediment yield, and cost. They are all based on federal regulations for site closure (USEPA, 1980, 1985; USNRC, 1982). Runoff, evapotranspiration, and percolation are important criteria for evaluating the ability of a cover design to control the hydrology of a trench cap. The main objective of the cover is to minimize the production of leachate. This may be accomplished in three ways: by maximizing runoff, evapotranspiration, or lateral flow. Sediment yield is an important criterion for evaluating the long-term integrity of the cover. The average annual values from 4 yr (1990–1993) of monitoring the plots are presented in Table 1.

Cost is an important criterion in selecting options for remediating contaminated sites. The economic objective is to reduce costs to a minimum while satisfying technical and regulatory constraints. For this example, the cost criterion for the covers was parameterized by construction cost. An economic component will be added to the PDSS in the future to include the monitoring and long-term costs of the different cover designs. The control soil cover costs approximately $0.12 million/ha, the modified RCRA cover costs approximately $4.9 million/ha, and the Los Alamos designs cost about $2.5 million/ha. The maximum threshold was set at $80 million/ha, which is the cost of removing the waste, and the minimum was set to $0.0, which is the cost of no action (Hakonson et al., 1994).

Scoring functions are selected and set up for each of the decision criteria using the conventional design threshold and baseline values. For this case, the modified RCRA cover is selected as the "conventional" design because it is in widespread use and is considered to be the state-of-the-art by regulators and practicing engineers. For sediment yield, a "more is worse" scoring function (see Fig. 1) was selected. The generic scoring function included a lower threshold of the sediment yield produced by the conventional design for the 4-yr period (Fig. 3a). The average annual sediment yield for the conventional cover by definition scores 0.5. The slope of the scoring function at the baseline value is a function of the threshold values determined by the maximum and minimum annual values of the conventional design. The score for each of the alternative designs is then determined by evaluating the average annual value from the alternative designs for each of the criteria.

Figure 3b illustrates the scoring for each of the alternative designs with respect to sediment yield. The "more is worse" scoring function was also used for cost and percolation. However, for ET and runoff the "more is

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[1] The USDA neither guarantees nor warrants the standard of the product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may also be suitable.

Table 1. Observed results: Average annual value for each decision criterion.

	Decision criteria				
Cap designs	Runoff	Percolation†	Lateral flow	ET	Sediment yield
	cm				Kg/ha
Control cover					
min:	0.04	2.60	N/A‡	17.53	0.00
avg:	1.40	14.74		27.37	118.70
max:	3.98	29.43		35.66	390.31
RCRA cover					
min:	0.06	0.00	0.06	23.34	0.00
avg:	1.30	0.13	10.74	28.80	76.70
max:	3.57	0.51	20.46	35.33	187.82
Los Alamos 1					
min:	0.00	0.34	1.66	18.00	0.00
avg:	0.35	6.83	4.83	24.25	4.50
max:	1.02	13.15	7.84	28.00	19.98
Los Alamos 2					
min:	0.00	1.25	1.27	22.92	0.00
avg:	0.56	7.28	2.95	33.99	4.80
max:	1.88	17.45	4.28	44.58	18.81

† Percolation out of trench cap and into waste storage layer.
‡ Not applicable.

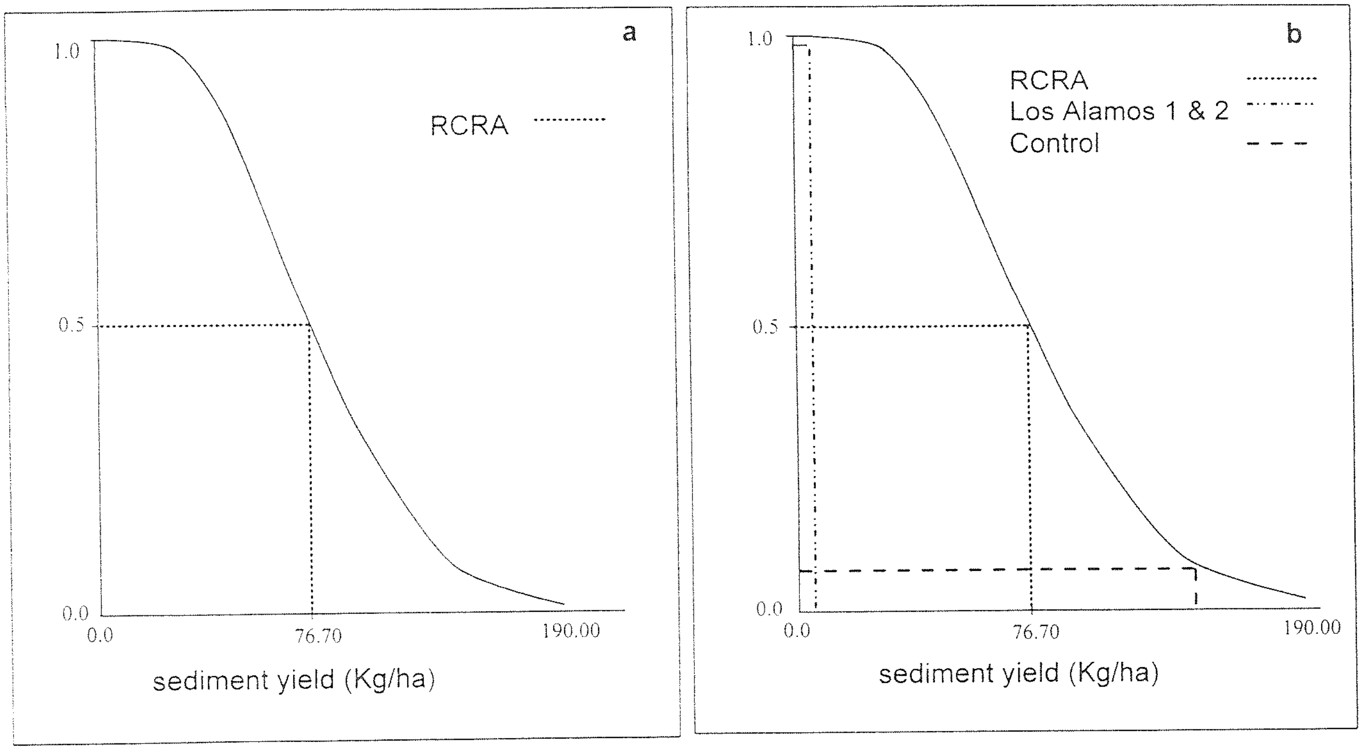

Fig. 3. (*a*) Parameterization of the sediment yield scoring function using the annual minimum, average, and maximum values of the conventional design. (*b*) Scoring of the alternative designs for sediment yield using the parameterized scoring function.

better" scoring function was selected. The resulting score matrix for the modified RCRA cover and three alternative designs is presented in Table 2. The modified RCRA cover design, as the "conventional," has a score of 0.5 for each of the decision criteria evaluated. As a result of the very low annual average percolation from the modified RCRA cover during the 4 yr of monitoring (Table 1), the Los Alamos and control soil cover designs all score 0 for this criterion even though there is a significant difference in the percolation from the Los Alamos covers and the control soil cover. It is also important to note that no one alternative scores better in all of the decision criteria than another alternative design.

The next step is to rank the decision criteria in order of importance and determine the composite score of each of the alternatives. The decision model determines a default importance order using the absolute values of the slopes of the scoring functions of each decision criterion at the baseline values that have been normalized to remove the units. The PDSS will also allow the decision maker to specify the importance or priority order. An importance order may be established based on environmental policy or regulations. The result of maximizing and minimizing Eq. [1] to determine the best and worst composite scores for each of the alternatives is presented in Fig. 4. These composite scores are based on the default importance order determined by the PDSS. The best and the worst composite scores for the modified RCRA cover design are both 0.5 since this design scores 0.5 for each criterion. The bar graph for each of the alternative designs represents the range of best and worst composite scores considering all possible weight vectors. A large spread in the range of possible composite scores indicates that it is highly sensitive to a particular weight vector. The best possible score for alternative 1, the control soil cover, is 0.999 when cost is ranked first in the importance order resulting from its very low construction cost. However, because the control soil

Table 2. Score matrix for Hill Air Force Base Data.

	Trench cap designs			
Design criteria	RCRA cover	Control cover	Los Alamos 1	Los Alamos 2
Runoff and lateral flow	0.5	0.008	0.080	0.038
Sediment yield	0.5	0.099	0.997	0.997
ET	0.5	0.450	0.345	0.675
Percolation	0.5	0.000	0.000	0.000
Cost	0.5	0.999	0.882	0.882

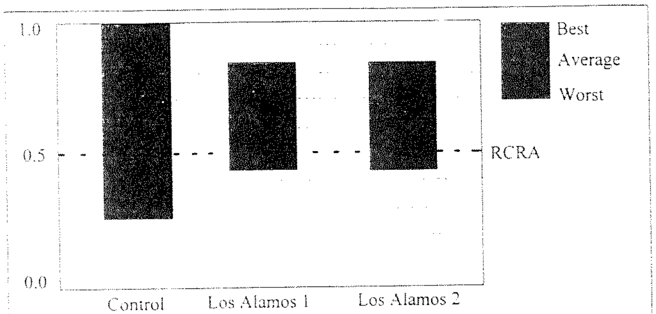

Fig. 4. Bar graph illustrating range of composite scores from best to worst for each alternative using the default importance order of the decision variables. The importance order is: cost, followed by percolation, sediment yield, runoff and lateral flow, and evapotranspiration.

cover does not score very well in the other decision criteria, it can score relatively low depending on the weight vector.

All three of the alternatives have average scores that are better than the conventional (modified RCRA) cover design. The composite scores for Los Alamos designs 1 and 2 are the same for this importance order, and show less sensitivity to a particular weight vector than the control soil cover. For this importance order, ranking the designs in descending order by the average of the best and worst composite scores yields: Los Alamos 1 and 2, the control soil cover, and the modified RCRA cover. It is important to note that the cost decision criterion only represents construction cost, and not long-term monitoring, maintenance, or potential remediation costs. Though the control soil cover costs much less to construct than the alternative designs, it has a much higher percolation rate and therefore the potential for clean up costs is much greater. These factors should be taken into account when evaluating particular design with cost as one of the decision criteria.

The risk manager/user is able to change the importance order of the decision variables in an interactive format and then compare the composite results of the alternatives for different importance orders side by side. The risk manager may consider minimizing erosion of the trench cap or percolation into the waste layer more important than minimizing cost for a given situation, and therefore give them a higher importance level. Changing the importance order of the decision variables so sediment yield is the most important improves the average scores of the Los Alamos designs while decreasing both the average score of the control soil cover and the sensitivity of the composite score to a particular weight vector. This importance order produces a slightly different order in the ranking of the alternatives with the modified RCRA cover scoring higher than the Control soil cover (Fig. 5a). The Los Alamos designs score much higher than the control and modified RCRA cover designs for minimizing sediment yield (Table 1). However, all of the designs have average annual sediment yields well below the federal regulation of 4400 Kg/ha per yr (USEPA, 1989), indicating that this may not be the most appropriate importance order to select for this specific site evaluation.

Changing the decision variable order a third time produces a third ranking of the alternatives (Fig. 5b). In this case, the composite score of the modified RCRA cover is better than the average scores of all three alternatives. Federal regulations for landfill capping require a cover design which will (i) minimize the migration (i.e., percolation) of liquids into the waste and (ii) promote runoff while minimizing erosion. This is probably the most appropriate importance order for the risk manager to select and thus the most likely ranking of the alternative designs for this set of data.

In each of the three rankings, there is not one alternative that clearly dominates the others (worst score greater than the best score of all the other alternatives). In this case, the decision maker may want to base the ranking of the alternatives on a specific weight vector consistent with a priority order.

Calibration and Long-Term Simulation

The HELP and CREAMS simulation models were calibrated and tested using data from the Hill Air Force Base cover demonstration study. Long-term simulations using the calibrated model parameters were run to evaluate the long-term stability of the models. The HELP and CREAMS simulation models were calibrated for two of the Hill Air Force Base cover designs, the control soil cover and the modified EPA RCRA design (Paige et al., 1996). The HELP model is unable to simulate capillary barrier designs, therefore, the PDSS could only be used to evaluate two of the four designs when using the embedded simulation models. The daily precipitation collected at the site, as well as the soil properties and cover characteristics, were used to parameterize and calibrate the simulation models.

The models were calibrated using annual water balance and erosion data for the last 3 yr of the 4-yr study. The results of the annual calibrations of the two models were

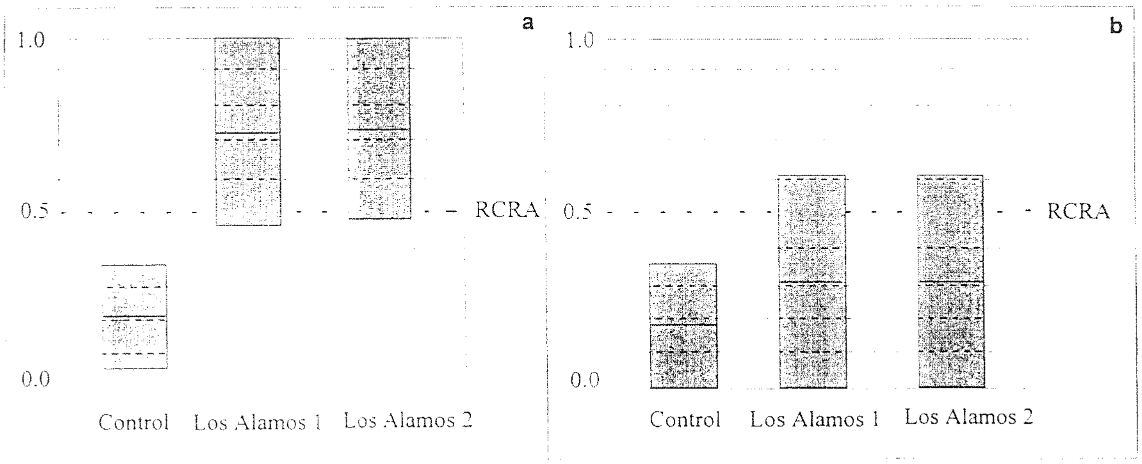

Fig. 5. Composite scores of the alternatives with user defined importance orders. For (*a*), the importance order is sediment yield, percolation, cost, runoff and lateral flow, and evapotranspiration. For (*b*), percolation is the most important followed by sediment yield, cost, runoff and lateral flow, and evapotranspiration.

Table 3. Score matrix for 60-yr simulation.

	Scores	
Design criteria	RCRA cover	Control cover
Runoff and lateral flow	0.5	0.000
Sediment yield	0.5	0.241
ET	0.5	0.541
Percolation	0.5	0.000
Cost	0.5	1.000

reasonable. The predicted values followed the annual trends in the field data and were often within 15% of the measured values relative to the annual precipitation. The largest bias when comparing observed and predicted values was an under estimation of the percolation out of the control cover in 1993. This was primarily a result of the HELP model's inability to effectively simulate spring snow melt. Details of the calibration and testing of the models is presented in Paige et al. (1996).

Risk managers are interested in assessing the long-term performance of a landfill cover design for a particular site. Landfill covers are designed and installed to last hundreds of years. The decision model in the PDSS uses the annual average value of the decision criteria for each of the alternatives. The annual average, maximum, and minimum of the conventional design were used to parameterize the scoring functions.

To evaluate the long-term performance of the Hill Air Force Base cover designs, the calibrated HELP and CREAMS models were run for longer periods. The weather generator CLIGEN (Nicks and Lane, 1989) was used to generate a 200-yr precipitation record for the Hill Air Force Base location. The 200-yr simulation was run in 20-yr periods, the maximum allowable in the HELP model, with an overlap of 5 yr to alleviate the effect of the initial soil conditions on the results of the model. The long-term stability and performance of the simulation models are important when predicting the long-term performance of landfill cover designs. The ability of the simulation models to predict long-term average values that are representative of a particular design and climate is especially important for the PDSS that uses the annual average, maximum and minimum values predicted by the simulation models to parameterize the decision model. For both designs, the progressive mean of each of the decision variables approached the long-term mean well within the 200-yr period, and was within the 95% confidence limits of the long-term mean by Year 60 (Paige et al., 1994). This is especially important for the PDSS that uses the average annual values of the decision criteria to parameterize the scoring functions and determine the scores for the alternative designs.

Simulated Data

The results from the long-term simulations for the 60-yr period were used to parameterize the decision variables for the two cover designs in the decision model. The output (max., min., and avg) from the 60-yr simulation period for the modified RCRA cover was used to parameterize the scoring functions. The resulting score matrix for the modified RCRA and control soil covers is presented in Table 3. Comparing the scores for the 60-yr simulation for the control soil cover with the scores from the Hill data (Table 2), it is evident that the shape of the scoring functions parameterized by the modified RCRA cover changed for some of the decision criterion. The most significant change in score was for the sediment yield criterion. The change in the shape of the sediment yield scoring function also changed the default importance order on the decision model. Cost, which is the initial cost of constructing the covers, was the only decision criterion that did not change.

The results from the decision model for the 60-yr simulation of two of the Hill Air Force Base designs are presented in Fig. 6. As illustrated using the original data (Fig. 4 and 5), changing the importance order of the decision criteria effected the composite scores of the designs. The results for the 60-yr simulation period are similar to the data results for the importance orders that they have in common. In both cases (observed and 60-yr simulations), the control soil cover is ranked higher than the modified RCRA cover, the average of the best and worst possible score for the control soil cover is >0.5,

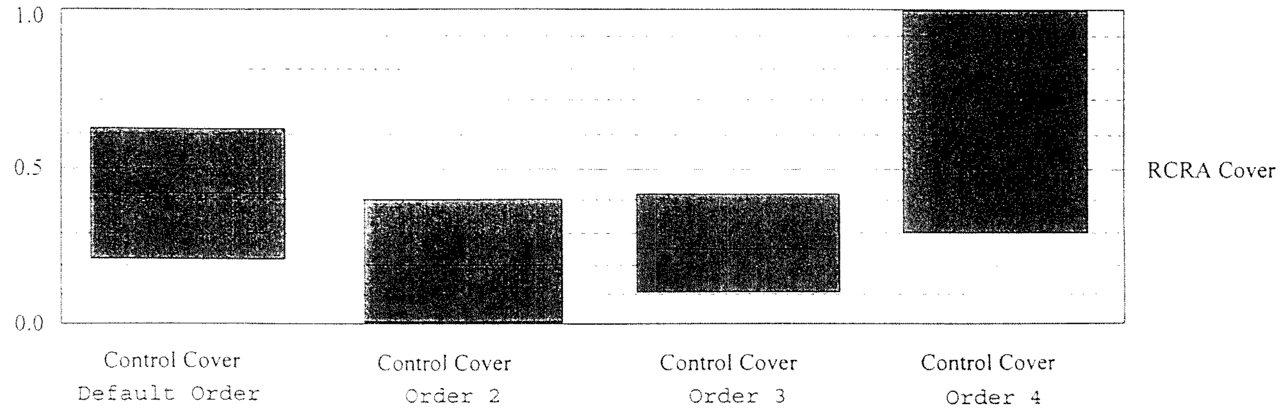

Fig. 6. Prototype decision support system (PDSS) composite scores for the RCRA and control soil covers for four different importance orders using the 60-yr simulation results. The default order is sediment yield, cost, runoff and lateral flow, evapotranspiration, percolation. Importance order 2 is: percolation, sediment yield, cost, runoff and lateral flow, and evapotranspiration. Importance order 3 is: sediment yield, percolation, cost, runoff and lateral flow, and evapotranspiration. Importance order 4 is: cost, percolation, sediment yield, runoff and lateral flow, and evapotranspiration.

only when cost is the most important decision criterion. Cost is the only decision criterion for which the control soil cover scores better than the modified RCRA design. For all other importance orders, the modified RCRA cover is ranked higher than the control soil cover. In all but one case, the modified RCRA cover dominates the control soil cover (i.e., the best possible score for the control soil cover is <0.5). These are the results that one would expect to obtain when comparing a control soil cover (only 90 cm of compacted top soil) with a modified RCRA design with a compacted clay barrier, lateral drainage layer, and 120 cm of top soil.

The annual values for the decision criteria runoff, percolation, and sediment yield were evaluated in the decision model to determine the relative frequency of each of the alternatives ranking number 1 for each possible importance order for each year of the 60-yr simulation period. The results are presented in Table 4. When percolation was the most important criteria the modified RCRA cover always ranked higher than the control soil cover. The frequency of the modified RCRA ranking first for every year decreased to 0.97 and 0.98 when sediment yield was the most important decision criteria. Only when runoff was the most important and percolation the least important criteria did the control soil cover have a 29% probability of ranking higher than the modified RCRA cover.

SUMMARY

The PDSS is a tool to assist risk managers in selecting the "best" landfill cover design for a waste disposal site. The example using the Hill Air Force Base designs demonstrated the ability of the PDSS to evaluate and rank alternative designs using the embedded simulation models and the multi-objective decision model. The simulation models were calibrated using annual data for a total of only 3-yr of data. The percent bias between the data and the simulation results for the calibration period were relatively small. The greatest differences for the model calibrations were for percolation in the control soil cover and lateral drainage in the modified EPA RCRA cover. As can be seen in the results of the decision model, these biases had little impact in the long-term results of the simulation models. The change in the minimum, maximum, and annual average values for the sediment yield component for the 60-yr simulation period altered the default importance order of the decision variables (i.e., changed the slope of the scoring function) and thus slightly decreased the probability of the modified RCRA cover ranking 1 when sediment yield is the most important criterion. The overall results of the decision model were not altered as a result of this change.

Table 4. Frequency of a cover ranking first in the decision model for all possible importance orders when the RCRA design is the conventional.

	Frequency of ranking first	
Importance order†	RCRA cover	Control cover
1) R, P, S	0.94	0.06
2) R, S, P	0.71	0.29
3) P, R, S	1.00	0.00
4) P, S, R	1.00	0.00
5) S, R, P	0.97	0.03
6) S, P, R	0.98	0.02

† R = runoff and lateral flow, P = percolation, S = sediment yield.

To evaluate a complete landfill site design, the risk manager would have to consider multiple external factors including a complete risk analysis. The most appropriate or "best" alternative trench cap design also depends on the specific needs and characteristics of the site in question, the type of waste and how it is stored, and the potential long-term risks and costs. The ultimate decision would have to be made by the risk manager taking many of these factors into consideration and local and federal regulations. The goal of the PDSS is to improve the quality of the technical information used by the risk manager to select capping designs that are cost effective and meet regulatory performance standards. The risk manager will be able to evaluate potential capping technologies with the PDSS to identify technical and regulatory problems inherent in the designs and evaluate long-term projected performance.

Current Status of the PDSS

Two of the three primary objectives for the development of the PDSS have been accomplished. The two embedded simulation models have been linked and alterations made in the code to provide the decision variables needed in the decision model. The individual components, the simulation models and the decision model, of the PDSS have been evaluated and tested using field data from a cover demonstration study. A major drawback of the HELP model is its inability to model flow in a capillary barrier cover design. Currently, capillary barrier designs can only be evaluated in the PDSS using data, however, a capillary barrier simulation component may be integrated into the PDSS depending on progress in capillary barrier research.

To provide a complete framework for an operational decision support system, the graphical user interface needs to be completed and a complete validation and sensitivity analysis of all the components needs to be conducted. Full validation and testing of the simulation models were not possible with the Hill AFB data, because of the short duration of the study and the limited number of covers that could be evaluated by the HELP model. To fully validate and test the PDSS and its embedded simulation models, other field data sets of landfill covers for waste disposal sites in a variety of climates are needed.

ACKNOWLEDGMENTS

We gratefully acknowledge the source of funding to USDA-ARS-SWRC and Los Alamos National Laboratory for the development of the PDSS from the Department of Energy through the Mixed Waste Landfill Integrated Demonstration (MWLID) at Sandia National Laboratories. The Hill AFB landfill capping demonstration was funded by the U.S. Air Force through the Engineering Services Center at Tyndall Air Force Base and the Department of Energy MWLID.

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