A PROTOTYPE DECISION SUPPORT SYSTEM FOR THE EVALUATION OF SHALLOW LAND WASTE DISPOSAL TRENCH CAP DESIGNS

G.B. Paige, T.E. Hakonson, D.S. Yakowitz, L.J. Lane, and J.J. Stone*
US Department of Agriculture

ABSTRACT

A computer based prototype decision support system (PDSS) is being developed to assist the risk manager in selecting an appropriate trench cap design for shallow land waste disposal sites. 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 or criteria, selecting feasible trench cap design alternatives, ordering the decision variables and ranking the design alternatives. Decision variables can be parameterized using data, expert opinion, or simulation models. The simulation models incorporated in the PDSS are the HELP (Hydrologic Evaluation of Landfill Performance) model which is used to simulate the trench cap water balance and the CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) erosion component which 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 decision variables, which are of different magnitudes and dimensions, are normalized to a common 0-1 scale through the use of scoring functions. The scoring functions are parameterized based on a conventional design or existing conditions at the disposal site. Each decision variable for each alternative is compared to the conventional design or existing condition using the scoring functions. The decision variables are ordered and a simple linear program is used to compute the best and worst aggregate scores of each alternative for all possible weights of the decision variables. This approach significantly reduces user subjectivity and bias inherent in most decision making methodologies. The application of the PDSS is illustrated using data from the Hill Air Force Base landfill cover demonstration to evaluate four alternative landfill cover designs; a plain soil cover, a modified EPA RCRA cover, and two versions of a Los Alamos design that contain erosion control measures, an improved vegetation cover to enhance evapotranspiration, and a capillary barrier to divert the downward flow of water.

INTRODUCTION

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. 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 of old landfills can often be met using a well designed trench cap to isolate the buried waste.

The selection of an optimum cap design requires consideration of multiple and often conflicting objectives, as well as both quantitative and qualitative input. The primary functions of a trench cap (see Fig. 1) are to isolate the buried waste from the surface environment and to control the hydrologic processes that can lead to off-site transport of contaminants. 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 surface erosion, a process which is caused by surface runoff.
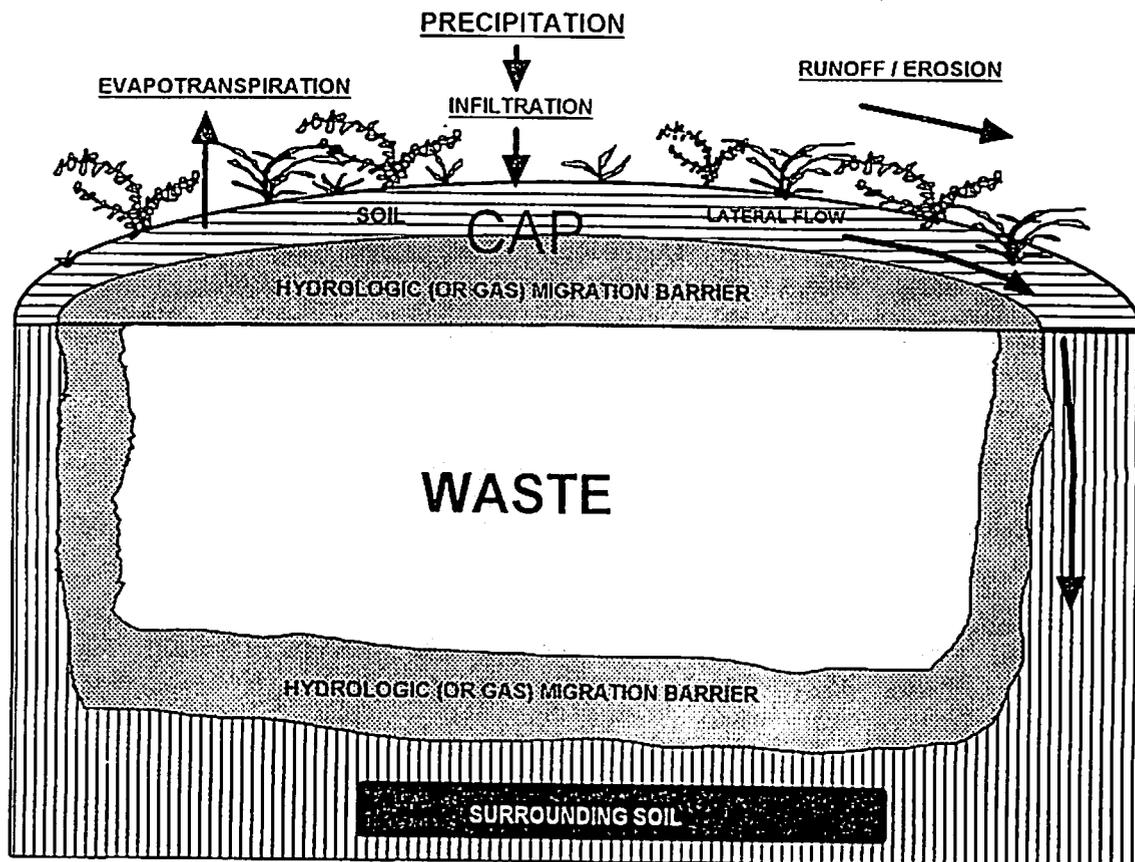
The ability to evaluate the environmental and economic effects of a particular trench cap design often requires the use of sophisticated models which simulate the availability and movement of water and potential for contaminant transport and the long-term viability of the cap, as well as the immediate and long term economic costs. To use these models as management rather than research tools, a framework around the simulation model is needed to aid the risk manager in evaluating alternatives and supporting decisions. 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 do this, a prototype decision support system (PDSS) to evaluate alternative trench cap designs for shallow landfill waste disposal sites is being developed. The objectives of developing the prototype are to: 1) 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; 2) compare the PDSS predictions of cap performance against actual field data from an ongoing study on the hydrologic performance of four capping alternatives; 3) use the PDSS to evaluate candidate capping design alternatives for the DOE Mixed Waste Landfill Integrated Demonstration in Albuquerque, New Mexico; and 4) 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

INTEGRATED MIGRATION BARRIER SYSTEM FOR CONTAINMENT OF RADIOACTIVE AND HAZARDOUS WASTE

PRECIPITATION

EVAPOTRANSPIRATION

INFILTRATION

RUNOFF / EROSION

SOIL   CAP   LATERAL FLOW

HYDROLOGIC (OR GAS) MIGRATION BARRIER

WASTE

HYDROLOGIC (OR GAS) MIGRATION BARRIER

SURROUNDING SOIL

BARRIER TYPES

IMPERMEABLE	PERMEABLE
CLAYS	GEOCHEMICAL
CAPILLARY	BIOLOGICAL
MEMBRANES	
GROUTS	

Fig. 1. Trench cap design.

simulation model in the decision model to choose the most appropriate trench cap design for a given situation.

SIMULATION MODEL

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 HELP (Hydrologic Evaluation of Landfill Performance (Schroeder et al., 1988)) model, which is used to simulate the trench cap water balance, and the CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems (Knisel, 1980)) model, which is used to simulate erosion of the cap.

HELP was developed by the U.S. Army Corps of Engineers Waterways Experiment Station (WES) for the U.S. Environmental Protection Agency (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 moisture storage, and lateral drainage in a shallow landfill system with up to twelve different layers. The model simulates water flow within three different soil layer types: vertical percolation, lateral drainage, and barrier soil

layers with or without a geomembrane. Both default (15 USDA soil classes) or user specified soil characteristics can be used in designing the landfill system and include the following soil properties: porosity, field capacity, wilting point, saturated hydraulic conductivity and initial soil water content. The program accepts both manual 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., 1986) to calculate daily leaf area indices. The surface runoff is estimated using a modified SCS curve number method.

The CREAMS overland 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 landfill 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 principle output 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 as well as the particle and organic matter distribution and the index of the specific surface.

DECISION MODEL

The decision model uses value or scoring functions as a means of scaling the decision criteria which have different units and magnitudes to a common scale between 0 and 1. The conventional and viable alternatives are scored on the same set of decision criteria (i.e., percolation of leachate, runoff, evapotranspiration, sediment loss, 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 discerned 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; Ascough 1992). Four generic shapes of scoring functions are

shown in Fig. 2. These functions can be modified for each criterion by implicitly setting threshold values or allowing the model to set these values by default based upon the data or simulation results. The scoring functions are set up so that the conventional design scores 0.5 as a baseline for each decision variable. All of the other alternative designs are scored relative to the conventional design for each criterion. A design which 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. Once all of 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 the solutions of two simple linear programs for each alternative and these two composite scores are aggregated to determine the preference ranking of the alternatives.

Algorithm for Ranking Alternatives

Based on the established importance order of the decision criteria, best and worst composite scores for each of the alternatives are determined by the PDSS by solving the linear programs presented below (Yakowitz et al., 1992). The solutions to these linear programs are the most optimistic and most pessimistic composite scores (weighted averages) consistent with the importance order.

Suppose there are m criteria which 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
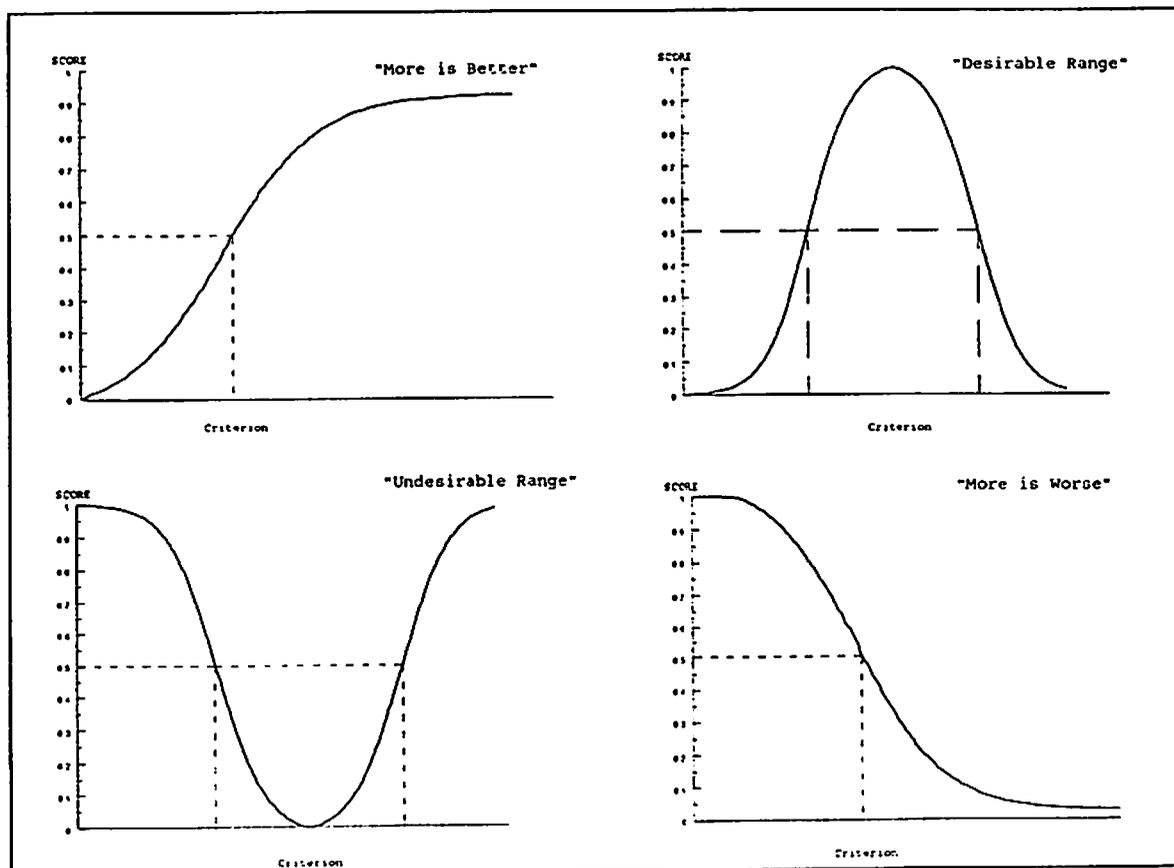

Fig. 2. Generic scoring function types.

asociated 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,......m* (note s.t. indicates "subject to" in the formulations).

Best Composite Score: (1)

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

$$s.t. \sum_{i=1}^{m} w(i)=1$$

$$w(1) \geq w(2) \geq ... \geq w(m) \geq 0$$

The lowest or worst additive composite score for alternative *j* consistent with the importance order is found by minimizing rather than maximizing the above function.

Worst Composite Score: (2)

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

$$s.t. \sum_{i=1}^{m} w(i)=1$$

$$w(1) \geq w(2) \geq ... \geq w(m) \geq 0$$

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 criteria. The solution to the two programs given above yields the full range of possible composite scores given the 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. Details of this methodology are presented in the next section using observed data from the Hill Air Force Base Cover Demonstration as an example.

EXAMPLE: Hill Air Force Base Cover Demonstration

Four shallow landfill cover design test plots were installed at Hill Air Force Base in Layton, Utah and their performance monitored for a four year period (Hakonson et al., 1993). There are three basic cover designs: a control soil cover; a modified EPA RCRA cover; and two versions of a Los Alamos Design that contain erosion control measures, an improved vegetation cover to enhance evapotranspiration, and a capillary barrier to divert downward flow of water. The control soil cap consists of 90 cm of soil over 30 cm of a gravel drainage layer. The EPA RCRA design consists of 120 cm of soil, 30 cm of sand (lateral drainage layer), 60 cm of compacted clay (hydraulic barrier), and 30 cm of a gravel drainage layer. The Los Alamos designs consist of a thin gravel mulch over 150 cm of soil, 30 cm. of gravel (capillary break), and 30 cm of a gravel drainage layer. One of the Los Alamos designs was seeded with native perennial grasses and the other (Los Alamos 2) with both native perennial grasses and two species of shrubs to enhance evapotranspiration. The surface and all

of the underlying layers of the covers were built with a four percent slope.

The plots were instrumented to measure the performance of the covers with respect to controlling the hydrology and erosion of the trench cap. Precipitation, surface runoff and sediment yield, lateral flow, and percolation out of the gravel drainage layer were measured on a daily basis. Soil moisture was monitored approximately bi-weekly using a neutron probe moisture meter. Evapotranspiration was estimated by solving the water balance equation over an approximate two week time step:

TABLE I
Observed Results: Average Annual Value for Each Decision Criterion

Design Criteria	Trench Cap Designs			
	Soil cap	EPA RCRA	Los Alamos 1	Los Alamos 2
Runoff (cm) [+]	1.40	12.05	5.18	3.50
Sed. Yield (Kg/ha)	118.7	76.7	4.5	4.8
ET (cm)	27.37	28.80	24.25	33.99
Percolation (cm) [*]	14.74	0.13	6.82	7.28
Cost ($M/ha) [**]	0.12	4.9	2.5	2.5

[+] includes lateral flow where applicable.

[*] percolation out of trench cap and into waste storage layer.

[**] Thomas Hakonson, personal communication.

$$ET = P - L - I - R - dS \qquad (3)$$

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

The decision criteria considered for evaluating these designs are: runoff (including lateral flow), evapotranspiration, percolation (leachate production), sediment yield, and cost. 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 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 a the long term integrity of the cover. Cost will always be 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. The average annual values from four years (1990-1993) of monitoring the plots are presented in Table I.

Scoring functions are selected and set up for each of the decision criteria using the conventional design threshold and baseline values. The EPA RCRA cap 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. 2) was selected. The generic scoring function included a lower threshold of the sediment yield produced by the conventional design for the three year period (Fig. 3). 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
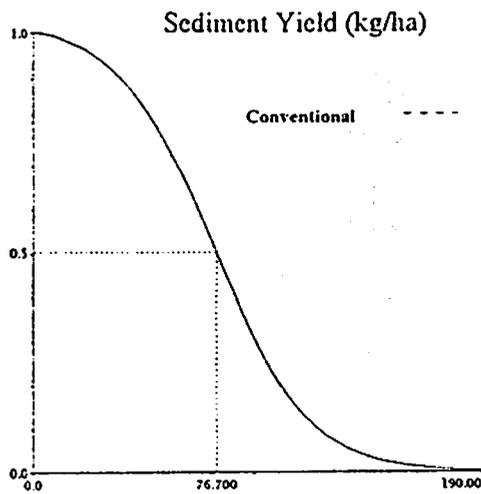
Fig. 3. Scoring function for the conventional.

Fig. 4. Alternative design scores.

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 decision criteria. Figure 4 illustrates the scores for each of the alternative designs with respect to sediment yield. The alternative designs, A1, A2, and A3, represent the Soil cap, and Los Alamos designs 1 and 2 respectively. The"more is worse" scoring function was also used for cost and percolation. However, for ET and runoff the "more is better" scoring funtion was selected. The resulting score matrix for the EPA RCRA and three alternative designs is presented in Table II. The EPA RCRA design, as the "conventional" has a score of 0.5 for each of the decision criteria evaluated. Due to the very low annual average percolation from the EPA RCRA cap during the four years of monitoring (Table I), the Los Alamos and Soil cap designs all score 0 for this criterion even though there is a significant difference in the percolation from the Los Alamos Caps and the Soil cap. 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. The decision model determines a default importance order using the absolute values of the slopes of the scoring functions of each decision criteria at the baseline values which 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 due to environmental policy or regulations. However, in the absence of a preferred importance order, the importance order is determined by default in the decision module of the PDSS.

The result of solving the two linear programs to determine the best and worst composite scores for each of the alternatives is presented in Fig. 5. These composite scores are based on the default importance order determined by the PDSS (see Table III). The best and the worst composite scores for the EPA RCRA design, represented by C, 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 Soil cap, is 0.999
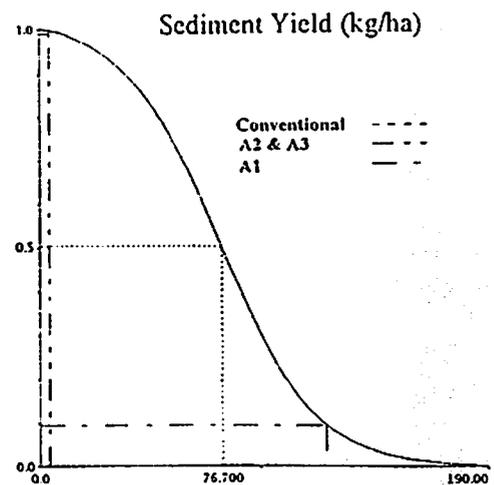
TABLE II
Score Matrix for Hill Air Force Base Data

Design Criteria	Trench Cap Designs			
	Soil cap	EPA RCRA	Los Alamos 1	Los Alamos 2
Runoff	0.008	0.5	0.080	0.038
Sed Yield	0.099	0.5	0.997	0.997
ET	0.450	0.5	0.345	0.675
Percolation	0.000	0.5	0.000	0.000
Cost	0.999	0.5	0.882	0.882

when cost is ranked first in the importance order due to its very low construction cost. However, because it does not score very well in the other decision criteria it can score relatively low depending upon the weight vector.

All three of the alternatives have average scores which are better than the conventional, EPA RCRA cap, 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 Soil cap. 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 Soil Cap, and EPA RCRA. 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 Soil cap 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 (Table
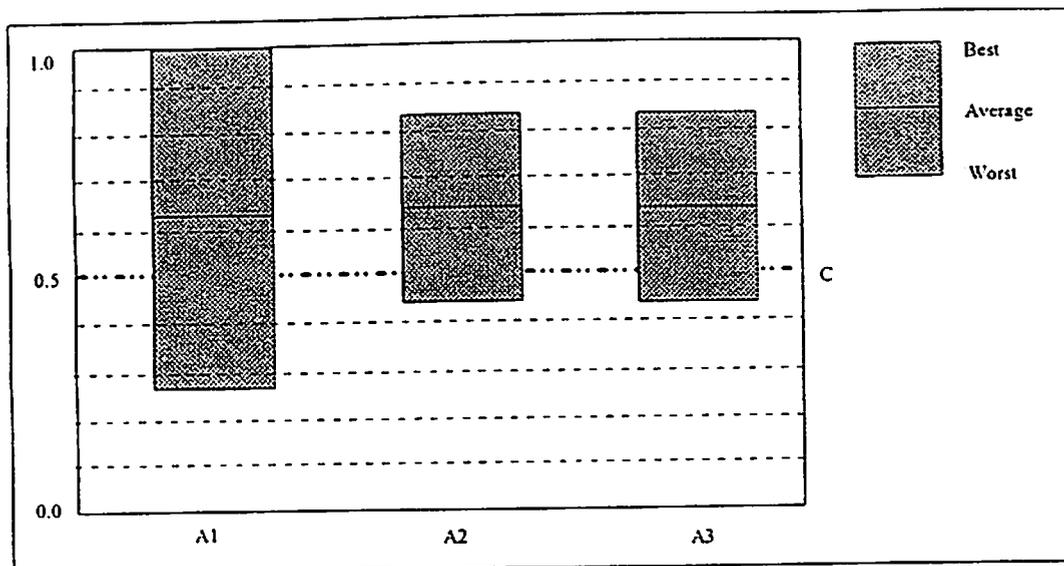
Fig. 5. Bar graph illustrating range of composite scores from best to worst for each alternative.

III), improves the average scores of the Los Alamos designs while decreasing both the average score of the Soil cap 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 EPA RCRA cap scoring higher than the Soil cap (Fig. 6). The Los Alamos designs score much higher than the Soil cap and EPA RCRA designs for minimizing sediment yield (Table I). However, all of the designs have average annual sediment yields well below the federal regulation of 4400 Kg/ha/year (see Table I), 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 (User Order 2, Table III) produces a third ranking of the alternatives (Fig. 7). In this case, the composite score of the EPA RCRA cap is better than the average scores of the alternatives. Federal regulations for landfill capping require a cover design which will 1) minimize the migration (i.e. percolation) of liquids into the waste and 2) promote runoff while minimizing erosion. Therefore, 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 which 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.

DISCUSSION & CONCLUSION

The Hill Air Force Base example demonstrates the potential of the PDSS for evaluating shallow land waste disposal trench cap designs. The PDSS is designed to aid the risk manager assess the multiple and often conflicting objectives associated with shallow landfill trench cap designs. Changing the importance order of the decision variables had a significant affect on the composite scores of the alternative designs and thus their relative ranking. This example illustrates the specific benefits and drawbacks of each of the alternative designs considered. It is important to note that these results are based on only four years of data collected from a specific climate. Once the simulation models are implemented in the PDSS and able to simulate 20 years of data, the risk manager may obtain different results.

The simulation models are currently undergoing revisions before being integrated into the PDSS. The HELP model is being modified to simulate capillary barrier designs and both the HELP and CREAMS models will be calibrated and tested using data from Hill Air Force Base and Los Alamos National Laboratory demonstration plots. Uncertainty and sensitivity analyses of the simulation and decision models will also be conducted and the results incorporated into the PDSS.

The PDSS is being developed for the evaluation of trench cap designs. In order 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 upon the specific needs and characteristics of the site

TABLE III
Decision Criteria Importance Orders

Importance Orders		
Default	User Order 1	User Order 2
Cost	Sediment yield	Percolation
Percolation	Percolation	Sediment yield
Sediment yield	Cost	Cost
Runoff & lateral flow	Runoff & lateral flow	Runoff & lateral flow
Evapotranspiration	Evapotranspiration	Evapotranspiration

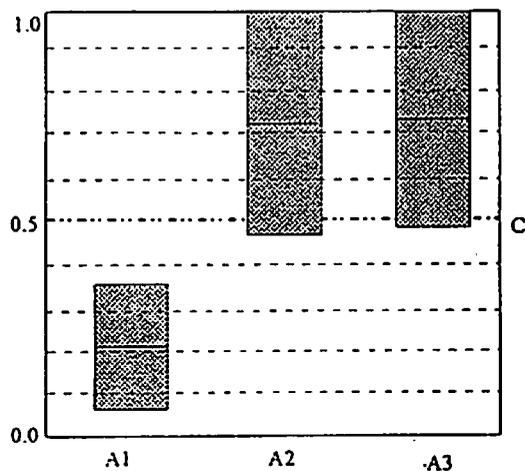Fig. 6. Composite scores of the alternatives with sediment yield as most important.

Fig. 7. Composite scores of the alternatives with percolation as most important.

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 as well as local and federal regulations into consideration. 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 in order to identify technical and regulatory problems inherent in the designs and evaluate long term projected performance.

ACKNOWLEDGEMENTS

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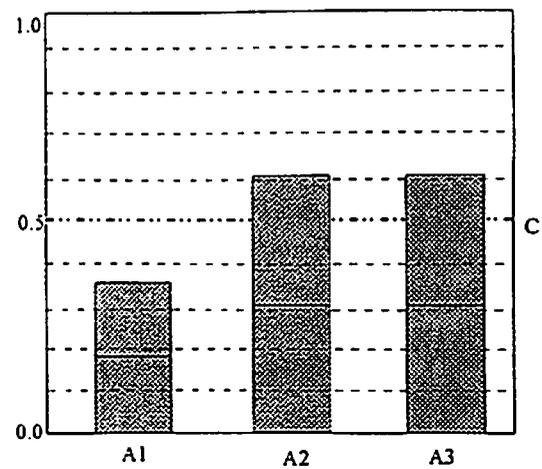
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