Title: DESIGN DOCUMENT FOR LANDFILL CAPPING PROTOTYPE
DECISION SUPPORT SYSTEM

Author(s): Jeffrey J. Stone
Ginger Paige
Thomas E. Hakonson
Leonard J. Lane

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**DESIGN DOCUMENT FOR LANDFILL CAPPING
Prototype Decision Support System
(Draft 1.0)
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J.J. Stone, G. Paige, T. Hakonson, and L.J. Lane¹

¹ Hydrologist and Soil Scientist, SWRC-USDA-ARS, 2000 E. Allen Rd., Tucson, AZ 85719, Professor, CSU, Fort Collins, CO, Research Leader, SWRC.

1. Introduction

The overall objective of the Prototype Decision Support System for shallow land burial project is to

"Develop a Decision Support System tool which incorporates simulation modeling and multi-objective decision theory for the purpose of designing and evaluating alternative trench cap designs for mixed waste landfill covers. The goal is to improve the quality of technical information used by the risk manager to select landfill cover designs while taking into account technological, economical, and regulatory factors."

The primary purpose of DOE's Environmental Restoration Program is to manage the health and ecological risks associated with intentional and/or accidental releases of radioactive and hazardous contaminants to the environment. Those releases are a consequence of past and ongoing DOE research, development, and operational activities over the last 52 years and involve thousands of sites that are currently being evaluated for possible cleanup actions. In selecting a cleanup action that adequately protects human health and the environment, the risk manager must synthesize and evaluate a large amount of technical, regulatory, and socio-economic information to arrive at an optimum, or best, decision for remediating a site (Figure 1). Depending on the level of risk from contaminants to both humans and ecosystems, the alternatives for remediating a site can range from no action to removal of the source via excavation and/or waste treatment processes.

The complexity of the technical and non-technical information, and how the information varies in importance across sites, points to the need for decision analysis tools that provide a common basis for integrating, synthesizing, and valuing the decision input. Because the cost of remediating thousands of contaminated DOE sites is projected to be in the 10's - 100's of billions of dollars, methods will be needed to establish cleanup priorities and to help in the selection and evaluation of cost effective remediation alternatives.

Even at this early stage in DOE's cleanup program, it is certain that capping technologies will be heavily relied upon to remediate the 3000+ landfills on DOE

property. Capping is favored in remediating most DOE landfills because, based on preliminary baseline risk assessments, human and ecological risks are considered to be low at most of these sites and the regulatory requirements for final closure of old landfills can be met using a well designed cap to isolate the buried waste.

This report describes a program plan to design, develop, and test a decision support system (DSS) for assisting the DOE risk manager in evaluating capping alternatives for radioactive and hazardous waste landfills. The DOE DSS will incorporate methods for calculating, integrating and valuing technical, regulatory, and economic criteria.

This report is organized into 9 sections:

1. Introduction
2. Problem Statement - A discussion of the technical, economic, and regulatory issues of trench cap design and evaluation.
3. Specific Objectives of the Project
4. Methodology - An overview of the multi-objective decision methodology to be used in the DOE DSS.
5. Applications - A discussion of how the DOE DSS will be used.
6. Requirements - General performance requirements of the DOE DSS.
7. DOE DSS Components - Detailed description of the design of the DOE DSS.
8. Operational Requirements - Hardware, software, and run time requirements of the DOE DSS.
9. Testing and Validation of the DOE DSS - Description of the data and methodology to be used in testing and validating the DOE DSS.

2. Problem Statement

The process of selecting containment cover technologies for radioactive and hazardous waste landfills requires consideration of many complex and interrelated technical, regulatory, and economic issues. The fundamental problem is to design and evaluate alternative cover technologies in a repeatable, objective, and scientifically defensible manner while taking into account all the necessary technical, regulatory, and economic factors.

2.1. Historical background

Increasing concern about the health and environmental effects of radioactive and hazardous wastes led to Federal and State regulations mandating improved methods for waste disposal in landfills in the early 1970s. Today there are a plethora of Federal and State regulations controlling all aspects of landfill disposal of municipal, radioactive, and hazardous waste. The problem, however, is that several thousand landfills in the U.S. were operated and then decommissioned prior to current regulations. For example, in the 52 year history of DOE's (AEC, ERDA, etc.) nuclear weapons program, an estimated 3000+ landfills, covering thousands of hectares, were used for radioactive and hazardous waste disposal and then decommissioned. Most of those old landfills are currently being evaluated under DOE's Environmental Restoration Program to determine whether they pose unacceptable health and environmental risks and, if so, to remediate the landfills to reduce risks to acceptable levels.

2.2. Technical Issues

Depending on the calculated health and environmental risks, the options for remediating a landfill range from doing essentially nothing to physically removing the buried waste. Most of the current research and development effort in DOE (Office of Technology Development) is to develop technologies that remove the contaminant source from the burial environment, either through physical removal or conversion of the source to a less toxic state. Relatively few of the contaminated DOE sites will

require these types of cleanup actions to reduce what will be obvious health and environmental concerns.

Containment technology involves leaving the contaminant source in place and controlling the processes that cause the waste to migrate. Containment is viewed as a viable cleanup solution for most DOE sites that have low to intermediate levels of residual contaminants and pose low risks to humans or ecosystems. Control of contaminant migration is usually achieved with natural or synthetic barriers that control the movement of water and/or gases (Figure 2) and can be placed completely or partially around the burial environment. Migration barriers can be permeable or impermeable depending on the type of contaminant and its mode of transport. The cover or trench cap placed over the waste is a central feature of most containment strategies and can range from a very simple soil cover to a very complex engineered design that mitigates both the vertical and lateral flow of water and gases.

Under ideal conditions, the primary functions of the trench cap are to isolate the buried waste from the surface environment and to control hydrologic processes, including erosion, that can cause contaminant migration from the site (Hakonson et al., 1992). Water that infiltrates into the soil cap can lead to enhanced percolation of water and solutes out of the burial environment. Likewise, excessive erosional loss of cap soil can expose buried waste and lead to off site transport of contaminants. Biological processes, including plant root and burrowing animal intrusion into the waste can also contribute to migration of contaminants from the waste zone (Hakonson et al., 1992). However, the relative importance of biological processes, in either positively or negatively affecting the migration of the waste, is strongly related to the hydrologic characteristics of the site (Hakonson et al., 1992).

The fate of meteoric water falling on the surface of a landfill is often referred to as the water balance of the site. A simplified equation of a water balance can be expressed on a per unit area basis as

$$\frac{\Delta S}{\Delta T} = P - Q - ET - L \quad (1)$$

where ΔS = change in soil moisture, ΔT = time step, P = precipitation, Q = runoff, ET = evapotranspiration, and L = percolation below the root zone. Application of the concept of water balance to design of landfill caps takes advantage of the fact that there are strong interactions among the various components of the water balance. For example, a reduction or elimination of the runoff term increases infiltration of water into the soil, resulting in increased soil moisture storage and increased evapotranspiration and/or percolation. Likewise, reducing percolation necessitates that more of the precipitation be partitioned between soil moisture storage, evapotranspiration, and/or runoff. The coupled nature of the processes comprising the water balance can be used to advantage in designing landfill caps that minimize or eliminate processes in Equation 1 that contribute to contaminant migration (i.e. percolation) while enhancing other terms (i.e. evapotranspiration) that do not.

The concept of water balance and methods to manipulate its various components has served as the basis for research in the design and evaluation of a variety of capping alternatives for radioactive and hazardous waste landfills (Nyhan et al., 1990a; Hakonson et al., 1992; Hakonson et al., 1993; Lane, 1984; Lane and Nyhan, 1984). The water balance concept serves as the basis for the simulation model HELP (Hydrologic Evaluation of Landfill Performance, Schroeder et al., 1984) that will be embedded in the DOE DSS to conduct the hydrologic analysis of alternative landfill cap designs.

2.3. Economic Issues

Cost will always be an important criteria for selecting options for remediating contaminated sites. In general, the objective is to reduce costs to a minimum while satisfying technical, regulatory, and political/social constraints. Often, however, minimizing costs are in direct conflict with the best technological solution derived from the health and environmental risk assessments. Estimated unit costs for construction

(i.e. O&M costs not included) of several capping alternatives at Los Alamos are compared to the cost of excavating the waste in Table 1. Note that the most costly capping alternative (i.e. the RCRA cap at \$4.9M/ha) is still a factor of 15 less expensive than removal of the waste. Additionally, the cost of different capping designs can vary by at least a factor of 10 (i.e. from \$0.12M - \$4.9M), depending on the complexity of the design and, again, the need for reducing risks. Although capping costs are relatively inexpensive compared to other remediation options, they still represent substantial outlays of capital when considering that thousands of hectares of landfill area exist in the U.S.

2.4. Regulatory Issues

The regulatory requirements for closure of hazardous and mixed waste landfills are found in 40CFR Parts 264 and 265, Subpart N. Under these regulations, owners/operators of landfills are required to perform landfill closures. The primary closure requirement of 264.310 and 265.310 require the owner/operator to design and construct a low-permeability cover over the landfill to minimize migration of liquids into the waste and to provide 30 years of post-closure monitoring and maintenance in order to prevent waste or constituent migration into the environment.

EPA guidance to permit applicants (EPA-530-SW-84-004) recommends that an analysis of the final cover design be presented in the closure plan. The analysis of the final cover design should describe how the design meets the following performance standards:

- minimizes liquid migration
- promotes drainage while controlling erosion
- minimizes maintenance
- has a permeability equal to or less than the permeability of natural subsoil
- accounts for freeze/thaw effects
- accommodates settling and subsidence so that the cover's integrity is maintained

EPA's technical guidance for final covers describes a recommended cover design, often called EPA's RCRA cap, that will meet the final cover performance standard. It is important to note that EPA offers the RCRA cap design as guidance and does not require its use if another design can be shown to meet the technical performance standards.

In order to demonstrate that a proposed final cover design complies with the regulatory performance standard, DOE (DOE/EGD-RCRA-002/0690, June 1990) indicates that it will be necessary to model the hydrologic performance and erosion potential of the proposed cover. It also recommends that data or model predictions demonstrate that the proposed design will not result in erosion in excess of 2 tons/acre/year. EPA suggests that the HELP model be used for the evaluation of the water balance (User's Guide for the Hydrologic Evaluation of Landfill Performance (HELP) Model, EPA/530-SW-84-009) and that the Universal Soil Loss Equation (Wischmeyer and Smith, 1978) be used to estimate erosion.

3. Objectives

Specific objectives of the DOE DSS program for landfill caps are to (1) develop a computer based decision support system that incorporates simulation modeling with multi-objective decision theory to design and evaluate the hydrologic performance of various capping alternatives with respect to applicable regulations and cost, (2) compare the DOE DSS predictions of cap performance against field data from an ongoing study on the hydrologic performance of four capping alternatives, (3) use the DOE DSS to evaluate candidate capping design alternatives for the DOE's Mixed Waste Landfill Integrated Demonstration Advanced Landfill Cover Demonstration (ALCD) in Albuquerque, New Mexico, and (4) use the monitoring data for the ALCD to further evaluate the DOE DSS as an operational tool.

The goal in developing the DOE DSS is to improve the quality of technical information used by the risk manager to select landfill capping designs that are cost effective in meeting regulatory performance standards. The use of a DSS to design and evaluate barrier cover remediation technology will reduce the likelihood of selecting a barrier cover technology that doesn't meet performance objectives and the attendant costs of fixing mistakes. Candidate remediation technologies can be evaluated with the DSS, before-hand, to identify technical and regulatory problems inherent in the technologies, evaluate projected long term performance, and assess the practicality of the designs from a construction and economic viewpoint.

4. Methodology

Lane et al. (1991) presented an approach for the evaluation of alternative trench cap designs using multi-objective decision making theory. The multi-objective approach was chosen because of the factors (see section 2.4. above) that should be considered in the evaluation of a final cover design (i.e. minimize liquid migration, promote drainage while controlling erosion, minimize maintenance, etc). In addition, the multi-objective approach allows the evaluation of designs when the objectives of the design factors are in conflict. For example, minimizing percolation into the waste containment area has a potential of increasing the amount of surface runoff and thus increasing erosion of the trench cap surface.

The DOE DSS will follow the approach by Lane et al. (1991) using the methodology outlined below:

1. Problem definition
2. Selecting and parameterizing evaluation criteria or decision variables
3. Using the evaluation criteria to evaluate design alternatives
4. Recommending a decision

The key to the approach is selecting and parameterizing the relevant decision variables or evaluation criteria and using these criteria in an objective and repeatable manner to recommend the best trench cap design alternative or alternatives.

4.1. Problem definition

The EPA recommended cover design is the RCRA cap. However, research in trench cap designs (Hakonson et al., 1982, Hakonson et al., 1993, Lane and Nyhan, 1984, Nyhan et al., 1984, Nyhan et al., 1990a, Nyhan et al., 1990b) have demonstrated that there may be alternatives to the EPA recommended design which offer certain technical and economic advantages. The basic problem is to evaluate and compare these alternative designs with the RCRA design for specific waste sites while taking into account the technical, regulatory, and economic issues. Because the RCRA design is the EPA recommended design, it will be termed the baseline or

"conventional" design.

4.1.1. Designing trench cap systems

The most widely used methods of designing trench caps are experimentation, simulation modeling, and a combination of both. Experiments have the advantage of being direct analogs of the system being evaluated but have disadvantages in that they are relatively expensive to set up and monitor, need a long time period to evaluate the performance, and are site specific. Simulation modeling has the advantages of being inexpensive and obtaining long term evaluations of many design alternatives quickly. The disadvantages are those associated with most simulation models; uncertainty and errors in model structure, parameter estimation, and model output. However, simulation models used in combination with experience offer the only feasible method of designing trench cap systems on a regular basis.

The EPA recommends using the HELP model (Schroeder et al., 1984) to design landfill covers and evaluate their performance in terms of the water balance. An alternative to the EPA recommended USLE (Universal Soil Loss Equation, Wischmeier and Smith, 1978) estimates of water induced erosion of the cover is using a continuous simulation model to account more directly for the temporal variation of the erosion process and to represent design features (i.e. areas of sediment deposition) where the USLE does not apply.

4.2. Evaluation criteria

The evaluation of design alternatives depends on the evaluation criteria or decision variables. Examples of decision variables are runoff, erosion, percolation, and cost.

4.2.1. Selection

The general category of decision variables for the evaluation of trench cap designs is specified by the EPA guidelines (see section 2.4 above). These include such factors as the elements of the water balance, erosion, and subsidence. The

specific decision variables will depend on the current state of the science (i.e. unsaturated flow dynamics, contaminant pathway analysis, erosion mechanics), regulations (minimize percolation and erosion), and socio-economics (cost, site location).

4.2.2. Parameterization

To parameterize decision variables, a value must be computed or assigned to each decision variable for each design alternative. For example, for the decision variable "cost", the average value for the RCRA cap is \$4.9 M/ha, for the soil capillary barrier is \$3.7 M/ha, and for the bio-engineered soil/vegetative cover is \$0.24 M/ha (Table 1). Ideally, the value of each decision variable should reflect or be representative of the performance of that decision variable for the design life of a given design alternative.

Lane et al. (1991) recommended using simulation models to parameterize the decision variables as a means of incorporating the "best science" in the decision making process. In terms of trench cap processes, the two models which simulate the minimum necessary decision variables are the HELP model and the erosion component of the CREAMS model (Chemicals, Runoff, and Erosion from Agricultural Management Systems, Knisel, 1980).

4.3. Evaluation of design alternatives

After the alternative designs are completed, the decision variables parameterized by simulation models or data need to be used in the evaluation of the design alternatives. When only a single objective is considered, it is easy to determine which alternative is the best. For example if the only objective were to minimize cost, the surface management with erosion control in Table 1 would be the best alternative. However, because of the need to evaluate designs under many, often conflicting, objectives, a structured evaluation process is required.

4.3.1. Decision model

The major purpose of using a decision model is to make the decision making process as repeatable, objective, and scientifically defensible as possible. The decision model which will be used for the DOE DSS uses the scoring function methodology presented by Wymore (1988) as modified by Lane et al. (1991) for trench cap evaluation and by Yakowitz et al. (1993) for agricultural management system evaluation.

4.3.1.2. Scoring functions

Scoring functions are a means of normalizing on a 0-1 scale decision variables which have different magnitudes and dimensions. Examples of such variables are runoff amount in millimeters, sediment yield in tons/hectare, and cost in dollars/hectare. The four generic scoring function types are 1. more is better, 2. more is worse, 3. desirable range, and 4. undesirable range (Figure 3). Each decision variable can be associated with one of the four scoring function types depending on specific objectives of maximizing a decision variable, minimizing it, or maintaining it within a specific range.

An individual scoring function is parameterized by

1. Choosing a scoring function from the four categories in Figure 3.
2. Defining the annual average value of a given decision variable for the conventional design to score 0.5 (Figure 4a).
3. Computing the shape of the scoring function using the annual maximum, minimum, and average value of a given decision variable for the conventional design (Figure 4a).

The scores for a given decision variable for the alternative designs are obtained by using the annual average value for an alternative and using the scoring function parameterized from the conventional design to obtain the score (Figure 4b).

4.3.1.3. Best and worst score

At this point in most decision making methodologies, it becomes necessary to order the decision variables in importance and assign a weight to each variable.

Yakowitz et al. (1993a) developed a methodology which avoids assigning individual weights but instead considers all possible weighting vectors for a given importance order of the decision variables. This is done by solving two simple linear programs for the "best and worst scores". Within the range of the best and worst score are all possible weighting vectors for a given importance order of the decision variables. This methodology of presenting the scores has an important implication in determining the "best" design alternative and several important benefits in the evaluation of alternatives. The implication of the best-worst score is that if one alternative's worst score is better than another alternatives best score, then the first alternative completely dominates the second (Yakowitz et al., 1993a). This means that given the importance order of the decision variables, no weighting vector exists which will make the second alternative score higher than the first. One benefit follows directly from this in that if an alternative dominates, then there is no reason to assign individual weights to the decision variables thus eliminating a source of subjectivity in the decision making process. Another important benefit is that when these results are presented graphically, it allows the user to see at a glance the sensitivity of each design alternative to the importance order and the relationship among the alternatives and the conventional designs.

4.3.1.4. Ranking alternatives

Ranking the design alternatives and recommending the "best" design(s) is the ultimate purpose of the decision model. Yakowitz et al. (1993a) recommend using a combination of dominance of one alternative over others and using the average of the best and worst score to rank the alternatives.

5. Applications

The primary user of the DOE DSS will be the U.S. Department of Energy National Labs for the design and evaluation of trench cap designs for closure of landfills at DOE National Labs and U.S. Department of Defense sites. Other potential users are other federal agencies (i.e. EPA), state and local agencies, and consulting firms who are responsible for the design and evaluation of landfill covers for waste disposal.

5.1. D.O.E.

The DOE DSS will be used to design and evaluate trench caps at DOE and DOD sites where preliminary baseline risk assessment has determined that the waste material possesses minimal human and ecological hazard. Example of locations where the DOE DSS will be used are the Experimental Engineered Test Facility at Los Alamos National Laboratories, the Landfill Cover Demonstration site at Hill Air Force Base, Layton, UT., the Advanced Landfill Cover Demonstration at Sandia National Laboratories, Albuquerque, NM., and Kaneohe Marine Corps Air Station on Oahu, HI.

5.2. Other

The HELP model is the only model currently sanctioned by the EPA for design and evaluation of landfill covers. With the addition of the CREAMS erosion component and the decision model, the DOE DSS will be a powerful tool for other agencies who are concerned with the design and evaluation of landfills.

6. Requirements

This section details the minimum performance requirements of the DOE DSS in terms of which designs it will be able to simulate and evaluate, which design factors will be used in the evaluation, and the flexibility and ease of use of the system.

It should be noted that the system will NOT optimize for a given design.

6.1. Design Requirements

The main requirement is that the user will be able to use site specific information such as climate, vegetation, and existing soil characteristics to design RCRA and alternative trench caps. The minimum designs which will be considered are those which can be specified using the HELP and CREAMS models. Other designs such as the LANL capillary barrier may be designed by the HELP and CREAMS models depending on progress in capillary barrier research.

6.1.1. Design Factors

The design factors are those input parameters to the HELP and CREAMS models over which the designer has control. Examples of design factors are the thickness of the various types of layers, the number and type of layers, the hydraulic characteristics of the engineered layers, the surface characteristics including vegetation, mulch, slope gradient, and length, and materials and construction costs.

6.2. Evaluation Requirements

The evaluation of alternative designs requires the consideration of environmental, economic, and regulatory factors termed herein decision variables. The key to evaluating alternative designs is choosing which decision variables to use and to parameterize or assign values to each decision variable for each alternative.

The major concept of evaluation is that there exist feasible design alternatives to a conventional design. In the context of trench cap design, the conventional is the EPA RCRA cap. Examples of feasible alternatives are a simple soil cap and the LANL capillary barrier designs.

6.2.2. Decision variables

The minimum decision variables to be considered are the components of the water balance as computed by the HELP model, erosion as computed by the CREAMS model, and the costs of materials and construction. Examples of additional decision variables which may be specified are cost of maintenance, cost of remediation due to failure, risk, and lateral flow and break through in a LANL or SNL capillary barrier systems. There will be no restrictions to the number or type of decision variables. However, those decision variables not computed by the HELP and CREAMS models will have to be supplied by the user in a manner which can be repeated, documented, and shown to be scientifically defensible.

6.2.3. Conventional design

The default conventional design will be the EPA RCRA cap. If the situation dictates, the conventional design can be changed.

6.2.4. Alternative designs

The types of designs to be evaluated are not restricted by the decision model but by the choice and parameterization of the decision variables. The minimum designs to be evaluated are those which can be parameterized by the HELP and CREAMS models. If values can be assigned to other alternative design decision variables, these designs can also be evaluated. However, in this case the values of these decision variables will have to come from a simulation model or models other than the HELP and CREAMS models.

6.3. Ease of use

On the design side of the DOE DSS, the system will be flexible enough to enable the user to quickly build a trench cap design based on climatic, soil, vegetation, and economic characteristics of the location of the burial site. Existing designs should be easily modified so that the user can play "what if" games to determine the effects of altering sensitive parameters on the relevant decision variables.

On the evaluation side of the DOE DSS, the system will allow the user to quickly change the type and shape of the scoring functions and change the importance order of the decision variables.

All output will be graphically presented so that the user can readily see the effects of the design, the evaluation, and any changes made to default parameters on the ultimate decision.

7. DOE DSS Components

The DOE DSS will be composed of the following components:

- 1. simulation model**
- 2. decision model**
- 3. data bases**
- 4. user interface**
- 5. report generator**

7.1. Simulation model

The simulation model which will be used in the DOE DSS is a combination of the Version 2 HELP landfill water balance model (Schroeder et al., 1984) and the overland flow erosion component of the CREAMS model (Knisel, 1980). When Version 3 of the HELP model is released, it will replace Version 2 in the DOE DSS. The HELP model will compute the water balance, soil water movement within the trench cap system, and the necessary input variables for use by the erosion component of the CREAMS model. The CREAMS model will compute erosion of the trench cap surface. The major modifications to the HELP and CREAMS models will be in the manner in which they accept input parameter values and display simulation results. The combined Help and CREAMS models will be referred to as the HC model in this document.

7.1.1. HELP

The HELP model (Schroeder et al. 1988) is a "quasi-two-dimensional" hydrologic model used to evaluate the effectiveness of shallow landfill burial designs. The model was developed by the US Army Corps of Engineers Waterways Experiment Station (WES) for the EPA Hazardous Waste Engineering Research Laboratory.

HELP uses climatologic, vegetation, soil, and site design characteristics to simulate infiltration, surface runoff, percolation, evapotranspiration, soil moisture storage, and lateral drainage in a shallow landfill. Both observed climate data and climate data computed by the WGEN climate generator (Richardson and Wright, 1984)

can be used in the simulation. HELP also includes the vegetative growth model from the SWRRB model (Arnold et al. 1986) to compute the daily leaf area index for the evapotranspiration routine. Surface runoff is computed using a modified Soil Conservation Service Curve Number method (SCS, 1971).

HELP can consider landfill designs containing up to 12 different types of drainage layers, four of which can be barrier layers. Both default (15 USDA soil classes) or user specified soil characteristics can be used in designing the land fill system. The soil layers are classified into three types; vertical drainage, lateral drainage, and barrier with or without a geotextile. Infiltration into the landfill is computed as the sum of daily rainfall and snowmelt minus surface runoff and evaporation. Subsurface flow is modeled from the top of the landfill to the bottom and is dependent on the type of soil layer. Flow in the vertical drainage layer is either downward due to gravitational forces or upward due to evapotranspiration in the top most layer. Saturated flow is computed using Darcy's law and assumes a gravity induced gradient. Vertical flow in a lateral drainage layer is computed in the same manner as for a vertical drainage layer. Lateral drainage is computed using the Campbell equation (1974) as parameterized by the Brooks-Corey (Brooks and Corey, 1964) model.

7.1.2. CREAMS

CREAMS (Knisel, 1980) is a field scale model developed to simulate the effects of agricultural management systems on non-point source pollution. The erosion component computes erosion, sediment yield, and enrichment ratios of the eroded soil taking into account the temporal and spatial variability of the erosion process. A modified USLE method is used to compute erosion by raindrop impact while an overland flow model developed by Foster et al. (1981) is used to compute concentrated flow detachment. Output of the model includes net detachment, net deposition, sediment yield, and the particle size distribution of the eroded soil.

7.1.3. HC input data

Input to the HELP model include climate, physical dimensions of the trench cap system (area, slope length and gradient, number and thickness of the different soil layers), initial conditions, vegetation and soil surface characteristics, and soil hydraulic parameters.

Input to the CREAMS erosion component include runoff volume and peak, USLE parameters, the Manning's n of the flow surface, slope characteristics, erodibility, and critical shear stress of the soil. Certain of the input parameters can be varied stepwise during the year to account for the effects of changes in soil surface or vegetative cover on the erosion parameters. The input variable of runoff volume will be computed by the water balance routine of the HELP model. Overland flow peak discharge, the other necessary input variable will be computed as in the CREAMS model.

All input parameters except those dealing with the physical dimensions of the waste site will have default values within the DOE DSS (Tables 2 and 3).

7.1.3.1. Climate

The minimum climatic input needed to run the HC model include daily rainfall amount, monthly average temperature, and monthly average solar radiation. These values can be from observed data, simulated data, or a combination of both depending on the availability of observed data or applicability of simulated data. Two climate generators will be included within the system; the WGEN model (Richardson and Wright, 1984) used by the HELP model and the CLIGEN model (Nicks and Lane, 1989).

7.1.3.2. Vegetation

The vegetation type is the design component which affects both the water balance within and the amount of erosion from the trench cap. The major impact on the water balance is through transpiration from the root zone which in turn affects the amount of infiltration into the soil and the amount of percolation through the bottom

of the root zone. The major impact on erosion is through the protection it gives the soil surface from detachment by raindrop impact and concentrated flow.

Default vegetation types or complexes will be based on those which are compatible with the climatic zone.

7.1.3.3. Layer types

Version 1 of the HELP model specifies the following three layer types; vertical drainage, lateral drainage, and barrier. The three layers are defined as follows:

Vertical drainage layer - The vertical drainage layer is defined as any layer not above a barrier layer. The processes which is active within this layer is vertical drainage, either by saturated or unsaturated flow. The top soil layer is also defined as a vertical drainage layer and is in contact with the atmosphere. Processes which are active for this layer include surface runoff and erosion, evapotranspiration, and percolation below the root zone into the next layer.

Lateral drainage layer - The lateral drainage layer is defined as being above a barrier layer. Processes which are active within this layer are vertical and lateral drainage. As with the vertical drainage layer, vertical flow can be saturated or unsaturated. Lateral drainage is always saturated flow.

Barrier layer - The barrier layer is a layer within which the soil or geotextile has a conductivity significantly less than the layer above it. In general, it is composed of a clay material with a conductivity of less than or equal to 10^{-7} cm/hr. Other barrier layer systems may be composed of a geotextile or combination of geotextile and clay.

7.1.3.4. Soil

The top layer has erosion parameters to be estimated and all the layers have soil hydraulic parameters to be estimated. The DOE DSS will provide default values from the HELP model (Schroeder et al., 1984) for the soil hydraulic parameters and from the CREAMS User Guide (Knisel, 1980) for the erosion parameters. User defined parameter values will be able to be used in place of the default values.

7.2. Decision model

The decision model will be the same as developed for the USDA Water Quality Initiative (Yakowitz et al. 1993b) and described in Section 4 of this document. The methodology involves four major steps: selecting baseline and alternative designs, selecting and parameterizing decision variables for the designs, scoring or normalizing the decision variables and assigning weights to them, and using the total scores to rank the alternatives.

7.2.1. Decision model input data

Input to the decision model include the values of the decision variables, the types of scoring functions, and the importance order of the decision variables. All of these will have default values or methods computed within the DOE DSS. After the default results have been displayed, the user will be able to modify the input values.

7.2.1.1. Decision variables

The default decision variables which will be considered are listed in Table 4. Values for the decision variables will come from the output of the HC model or be supplied by the user as applicable. The values of the decision variables used will be the maximum, minimum, and average annual amounts. If observed data are used to compute these values, then a length of record needs to be used which gives a representative sample. The default simulation period will be 20 years.

There are cases in which the user will have observed data for decision variables provided by the HC model or may want to include decision variables not computed by the HC model. Examples of additional decision variables not computed by the HC model are listed in Table 5. In these cases, the user will be able to input the lower and upper threshold and the average value for the decision variable.

7.2.1.2. Scoring functions

7.2.1.2.1. Type

The default generic scoring functions are illustrated in Figure 3. The default scoring function for most of the decision variables will be scored with the more is worse function type. However, the default scoring function type will be able to be changed according to the specific objectives of the user.

7.2.1.2.2. Parameterization

The default parameterization of the scoring function will be based on the conventional or baseline design's (RCRA cap) annual average, maximum, and minimum value for a given decision variable. The user will be able to modify the scoring function parameters of lower and upper thresholds and the slope.

7.2.1.3. Importance order of decision variables

The default importance order of the decision variables will be computed as a function of the normalized slope of the scoring function for each decision variable (Yakowitz et al., 1993a). The user will be able to change the importance order of the decision variables after the default results are shown.

7.2.1.4. Ranking of design alternatives

The default ranking of the design alternatives will be based on the average of the best and worst composite score for each alternative (Yakowitz et al., 1993a).

7.3. Data bases

The data bases will include HC parameter values, decision model parameter values, and input/output of the DOE DSS. The three classes of data bases will be static, edit dynamic, and non-edit dynamic.

7.3.1. Static data bases

The static data bases will contain all the default parameter values for the DOE DSS. These data bases will only be able to be edited by the system manager. The default parameters stored in these data bases will include those for the HC model and

for the decision model.

7.3.2. Edit Dynamic data bases

The edit dynamic data bases will contain all user defined input parameter values for the DOE DSS. The data within the data bases will be able to be retrieved and modified by the user during the run time of the DOE DSS. Examples of types of data stored are user defined soils, trench cap designs, and climate.

7.3.3. Non-edit dynamic data bases

The non-edit dynamic data bases will contain the output from the HC file builder, HC simulation output, decision model output, and the DOE DSS output. Data will be written to the data base at various stages of a decision run. The data will be able to be retrieved at run time by the user for viewing, but not for modification.

7.4. Output

Output from the HC model will include both decision variables to be used by the decision model and other variables needed to evaluate the performance of the HC model. These results will be presented in text and graphical formats. The text format will include all of the input parameters used and output simulated for a given simulation run. The graphical format will include time series of output variables and the capability to import observed data for comparison with model results.

The output from the decision model will be the same as for the USDA Water Quality Decision Support System (Yakowitz et al., 1993b) and include graphical output of the best and worst scores and a text view of the results.

7.5. User interface

The user interface will follow the Soil Conservation Service (SCS, 1990) user interface convention which consists of a menu bar, work space, and action bar.

7.5.1. HC interface

The HC interface will be designed to require a minimum amount of user interaction in order to build an input file to run the simulation and will include help on design requirements, and graphical output of results.

7.5.1.1. Climate

The climate interface will consist of a map of the United States on which the user will choose the state of interest by moving the cursor to the state and clicking the mouse button. The next screen will be a county map of the chosen state on which the user will choose the county of interest. At this time the user will have the options of using an existing climate file (either observed or simulated) or generating a new file.

7.5.1.2. Vegetation complex

The vegetation interface will consist of a map of the United States on which the user will choose the state of interest by moving the cursor to the state and clicking the mouse button. The next screen will be a county map of the chosen state on which the user will choose the county of interest. At this time the user will have the options of using an existing vegetation complex or choosing another.

If a climate has already been chosen, a default vegetation complex based on the climate selection will be presented to the user to be accepted or modified.

7.5.1.3. Trench cap layers

The trench cap layer interface will consist of a single screen with a graphic of the waste layer and top soil at the beginning of the design session. As layers are added to the design, these will appear within the graphic of the trench cap. Selecting layer types will be done by clicking on a selection of buttons representing the layer types and dragging to the trench cap graphic. The parameter values of the current design layer will be displayed and be able to be changed by the user.

7.5.2. Decision model

The user interface of the decision model will be the same as that for the Decision Support System for the USDA Water Quality Initiative (Yakowitz et al., 1993).

7.6. Report generator

Because this system has the potential of recommending design alternatives which may replace the EPA sanctioned RCRA design, all the steps in the design and evaluation process must be documented. An automatic input/output documentation procedure will be implemented along with inclusion of user supplied notes.

All input and output of the DOE DSS will be listed in an easily read format. Any changes to the default values will be noted.

8. Operational Requirements

8.1. Hardware and Software

The prototype is intended to be a framework for the future development of an operational system, we have assumed reasonable advancements in the availability of hardware and software. The hardware requirement is any platform which supports the software requirements with at least 5 MB of memory for the DOE DSS. The software requirements are SunOS 4.1.3., an ANSI compliant C compiler, an X-Windows server, libraries, and fonts for X11R5, and Motif 1.2.1.¹

8.2. Robustness

Robustness means that the system will tolerate out of range values in the simulation and decision models and will not "bomb" unexpectedly or without explanation. Both the simulation models, HELP and CREAMS, have been used extensively and the algorithms satisfy for the most part the criteria of robustness. If out of range values are given, the user will be notified.

9. Validation of the DOE DSS

Both the decision model and the embedded simulation models will be validated and tested to ensure that reasonable results will be obtained by the user. The simulation models will be tested and validated using observed data from the Los Alamos National Laboratory field demonstration plots at Hill Air Force Base Layton, Utah (Hakonson et al., 1994?). Graphical and statistical methods will be used to evaluate and compare the predicted and observed results. The decision model results will be compared with the observed field data to ensure that the recommendations made by the decision model are valid.

¹ Mention of trade names is for the reader's convenience and does not imply endorsement or recommendation by the authors or their organizations.

9.1 Method

Split-sample testing will be used to evaluate the HC model. The trench cap designs from the Hill Air Force Base demonstration will be created using the HELP model interface and the known design parameters. The model will be calibrated using the first year of observed data for each of the four design plots. The simulation models will then be run for each of the four designs using the measured daily precipitation data from the remaining three years of observation. Graphical and statistical methods will be used to compare the predicted with the observed values for the components of the water balance and the soil surface erosion.

9.2 Validation data

Water balance and surface erosion data from the Hill Air Force Base demonstration project (Hakonson et al., 1993a) will be used to calibrate and validate the HC model. 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 from 1990-1993. There are three basic cover designs including 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 (Figure 5). The designs were constructed in large 15 by 30 ft contained lysimeters. The control soil cap consists of 3 ft. of soil over 2 ft. of a gravel drainage layer. The EPA RCRA design consists of 4 ft. of soil, 1 ft. of sand (lateral drainage layer), 2 ft. of compacted clay (hydraulic barrier), and 1 ft. of a gravel drainage layer. The Los Alamos designs consist of a thin gravel mulch over 5 ft. of soil, 1 ft. of gravel (capillary break), and 1 ft. of a gravel drainage layer. One of the Los Alamos designs was seeded with native perennial grasses and the other 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 (Figure 6).

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. The decision criteria considered for evaluating these four designs are: runoff (including lateral flow), evapotranspiration, percolation (leachate production), and sediment yield. The annual average and range for each decision variable from four years of data collection are presented in Table 6.

Available water balance and surface erosion data on landfill cover systems is very limited, especially for periods longer than the initial equilibration of the system. Other data sets will be used to validate the DSS if they become available.

9.3 Statistical measures of success

The performance of the simulation models in predicting the observed values will be evaluated using both quantitative and graphical methods. The graphical methods will primarily consist of time series plots of the observed and predicted values. The quantitative methods will include: comparison of mean observed and simulated values; standard error; coefficient of model efficiency; and linear regression analysis. Other standard statistical methods will be employed as warranted.

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Table 1. Estimated 1992 costs of remediation alternatives for landfills at Los Alamos, NM.

Alternative ¹	Cost (Million \$/ha)
Excavate	80
RCRA cap	4.9
Soil/capillary barrier cover	3.7
Bio-engineered soil/veg cover	.24
Surface management w/erosion control	.12

¹ Technical basis for selection of alternative should be based on human and ecological risk assessment.

Table 2. User defined input parameters for the HC model

Parameter
Landfill surface area
Number of layers
Thickness of layer
Compaction
Soil surface cover
Slope length
Slope gradient
Daily potential runoff fraction ¹

¹ - only applies to uncovered landfills

Table 3. Default input parameters for the HC model

Parameter	Source
Curve Number	Soil texture, vegetation
Vegetation type	Vegetation zone
Initial soil water content	Climate
Leakage fractions for liners	Liner type
Porosity	Soil Texture
Saturated hydraulic conductivity	Soil Texture
1/3 bar soil water	Soil Texture
15 bar soil water	Soil Texture
Bare soil evaporative depth	Soil Texture
Cover erosion factor	Soil, Vegetation
Conservation erosion factor	Soil surface characteristic
Manning's n	Soil, Vegetation
Rooting depth	Vegetation

Table 4. Default decision variables considered by the DOE DSS.

Decision Variable	Source
Surface Runoff	HELP
Lateral Drainage	HELP
Evapotranspiration	HELP
Deep Percolation	HELP
Erosion	CREAMS
Materials cost	User supplied
Construction cost	User supplied

Table 5. Examples of addition decision variables which could be considered by the DOE DSS.

Decision Variable
Remediation cost
Maintenance cost
Risk
LANL lateral drainage ¹
SNL lateral drainage ²
¹ Los Alamos capillary barrier
² Sandia dry barrier

Table 6. Observed Results from Hill AFB: Average annual values and range for each decision variable.

Cap Designs		Design Criteria			
		Runoff (cm) ¹	Sed. Yield (Kg/ha)	ET (cm)	Percolation (cm) ²
Control Cap	min:	0.04	0.00	17.53	2.60
	ave:	1.40	118.70	27.37	14.74
	max:	3.98	390.31	35.66	29.43
EPA RCRA	min:	3.63	0.00	23.34	0.00
	ave:	12.05	76.70	28.80	0.13
	max:	20.90	187.82	35.33	0.51
Los Alamos 1	min:	0.34	0.00	18.00	0.34
	ave:	5.18	4.50	24.25	6.82
	max:	8.21	19.98	28.00	13.15
Los Alamos 2	min:	1.39	0.00	22.92	1.25
	ave:	3.50	4.80	33.99	7.28
	max:	4.28	18.81	44.58	17.45

¹ percolation out of trench cap and into waste storage layer.

² includes lateral flow where applicable.

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Figure 3. The four generic types of scoring functions.

Figure 4. Example of using a scoring function. a) Parameterizing the scoring function based on the annual average, maximum, and minimum value of the decision variable for the conventional design and b) using the annual average value of the decision variables of the alternative designs to obtain the scores.

Figure 5. Schematic of the Hill Air Force Base Cover Demonstration cover plots and data collection system, Layton UT (not drawn to scale).

Figure 6. Side view of cover designs at Hill Air Force Base, Layton UT (not drawn to scale).

Figure 1. Decision process in managing risks to humans and ecosystems.

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VALUE		SCORE	
C	- conventional	sc	- conventional = 0.5
A ₁	- alternative 1	s1	- alternative 1
A ₂	- alternative 2	s2	- alternative 2

Figure 4. Example of using a scoring function. a) Parameterizing the scoring function based on the annual average, maximum, and minimum value of the decision variable for the conventional design and b) using the annual average value of the decision variables of the alternative designs to obtain the scores.

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