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*Development of a Prototype Plan
for the Effective Closure
of a Waste Disposal Site
in Los Alamos, New Mexico*

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DEVELOPMENT OF A PROTOTYPE PLAN FOR THE EFFECTIVE CLOSURE OF A WASTE DISPOSAL SITE IN LOS ALAMOS, NEW MEXICO

by

John Nyhan and Fairley Barnes

ABSTRACT

The purpose of this study was to develop a prototype plan for the effective closure and stabilization of a semiarid low-level waste disposal site. This prototype plan will provide demonstrated closure techniques for a trench in a disposal site at Los Alamos based on previous shallow land burial (SLB) field research both at the Los Alamos Experimental Engineered Test Facility (EETF), and at a waste disposal area at Los Alamos.

The accuracy of modeling soil water storage by two hydrologic models was tested by comparing simulation results with field measurements of soil moisture in eight experimental landfill cover systems at Waste Disposal Area B having a range of well-defined soil profiles and vegetative covers. Regression analysis showed that one of the two models tested represented soil moisture more accurately than the second model.

The accuracy of modeling all of the parameters of the water balance equation was then evaluated using field data from the Integrated Systems Demonstration plots at the EETF. Optimized parameters were developed for one model to describe observed values of deep percolation, evapotranspiration, and runoff from the field plots containing an SLB trench cap configuration.

Precautions for determining parameter values for model input and for interpreting simulation results are discussed. Several examples are presented showing how the field-validated hydrologic models developed in this endeavor can be used to develop a final prototype closure plan. Future directions of field research efforts and subsequent hydrologic modeling activities are recommended in terms of their usefulness for waste management decisions to be made at Los Alamos.

I. INTRODUCTION

A. Background

Since the beginning of the Manhattan Project during World War II, major federally funded research involving the use of radioactive materials has been conducted at government-owned and -operated laboratories. Weapons production,

nuclear power research, and marine power production are the main government-sponsored activities generating radioactive waste. In the weapons program, radioactive materials used for nuclear explosive devices are produced, processed chemically, assembled, and maintained. The Department of Energy (DOE) reprocesses spent fuel from marine power plants and DOE-owned test reactors and reuses the recovered uranium and performs nuclear power research activities. Each of these activities generates significant quantities of radioactive waste, much of which is disposed of in near-surface disposal facilities at DOE sites.

Regulations and DOE Orders exist which mandate stabilization and final closure of low-level radioactive waste disposal sites. Present requirements are based on radioactive half-lives and other characteristics of radionuclides contained in low-level waste (LLW). However, uranium and transuranic wastes were also buried prior to 1970 at most existing DOE LLW disposal sites. The half-lives of these radioisotopes greatly exceed the required performance period for LLW stabilization activities. In addition, many sites contain uncharacterized volumes of liquid, mixed, and hazardous wastes. Requirements for management of LLW, specifically for stabilization and closure of disposal sites, are sometimes inadequate for site stabilization or are contradictory to regulations pertaining to other materials buried in existing DOE disposal sites. Inadequate disposal records and lack of cost-effective in situ characterization techniques complicate determining which regulations apply to a site, or to areas within a waste disposal site.

B. Burial Site Closure Performance Requirements

Site closure performance requirements are criteria set prior to closure of the facility by which the acceptability of the site for closure is to be judged. Performance requirements may be written in the form of prescriptive

requirements or performance objectives. The prescriptive requirement demands specific technical design features. Use of prescriptive requirements permits more straightforward regulation of a greater number of sites. Performance objectives mandate a level of performance without stipulating how that performance should be attained. Use of performance objectives, such as maximum exposure to radioactivity at levels that are below measurable limits, requires significant technical substantiation by site operators to show that closure designs will meet intended performance objectives. Performance objectives allow actions to be tailored to site-specific conditions, but do not preclude adoption of prescriptive requirements.

Because DOE Order 5820.2 contains only general requirements for site closure, other regulations, which are pertinent but perhaps not legally applicable, should be reviewed in the development of site-specific performance requirements, such as those published by the Nuclear Regulatory Commission (NRC) and the Environmental Protection Agency (EPA). Specific performance requirements found in present regulations 10 CFR 61 (US NRC 1982), 40 CFR 265 (US EPA 1980), and 40 CFR 191 (US EPA 1985) for closure of disposal sites containing LLW, transuranic (TRU) wastes, or hazardous wastes are shown in Table 1. Regulations for disposal of LLW and TRU are based both on site selection and design requirements stipulated under these requirements, and on a site containing only one waste type.

C. Development of a Closure Plan for a Los Alamos Waste Repository

Obviously, it is the intent of the post-closure requirements (Table 1) to limit the exposure of the general public to radioactive and hazardous wastes for time periods ranging from 100 to 10,000 years. If we examine the ecosystem processes that influence site closure and long-term site performance with potential impact on dose to man (Figure 1), we note that water and soil

Table 1. Post-Closure Requirements for Disposal of LLW, TRU, and Hazardous Waste

Statute	Sites Governed	Post-Closure Performance Objectives
DOE Order 5820.2 Chapter III ^a	DOE low-level waste disposal sites	- Annual dose limit of 500 mrem to any member of the general public; doses must be maintained at levels as low as reasonably achievable. (Operational limit only. No DOE-wide limits exist for closure.)
10 CFR 61 ^b	Commercial sites for shallow-land disposal of low-level waste	- Annual dose to any member of the general public not to exceed 25 mrem to whole body, 75 mrem to thyroid, 25 mrem to any other organ - Protection of individuals from inadvertent intrusion - Long-term stability of site (500 years) - 100-year maximum institutional control period - Buffer zone
40 CFR 191 ^c	Sites developed for management and disposal of spent nuclear fuel, high-level and transuranic radioactive wastes	- Long-term stability of site (10,000 years) - Meet release limits for specific radionuclides (191.13) - Annual dose to any member of the general public not to exceed 25 mrem to whole body, 75 mrem to thyroid, 25 mrem to any other organ, for 1000 years after (undisturbed) disposal - Meet specific ground water protection requirements for 1000 years disposal (undisturbed)
40 CFR 265 ^d	Hazardous waste facilities	- Minimize need for further maintenance of hazardous waste constituents, leachate, contaminated rainfall, or waste composition products to the ground or surface waters or the atmosphere

^aRadioactive waste management, management of low-level waste.

^bLicensing requirements for land disposal of radioactive waste.

^cEnvironmental standards for the management and disposal of spent nuclear fuel, high-level and transuranic radioactive wastes.

^dInterim status standards for owners and operators of hazardous waste treatment, storage, and disposal facilities.

Figure 1. Hydrologic processes affecting shallow land burial sites.

dynamics, as influenced by physical and biological factors, account for most of the performance-related problems. For example, erosion associated with the runoff from a trench cap can breach the cap and expose waste to the biosphere. Consequently, erosion rates on the cap must be within tolerances that leave the cap intact over the entire life of the LLW disposal facility. Likewise, water that infiltrates through the trench cap can accumulate in the trench (bathtub effect) and/or percolate in association with solutes into groundwater. Percolation also enhances subsidence of the trench cap as a result of decomposition of bulky waste in the trench. Finally, both plants and animals, in addition to playing an important role in water balance, can penetrate into the waste and transport radionuclides to the ground surface as a result of root uptake and/or burrowing activities.

Although trench cap configurations are usually arbitrarily chosen relative to SLB hydrology considerations, the major point that this report is making is that SLB design characteristics such as trench cap thickness do not have to be arbitrarily chosen. Hydrologic models are frequently used to estimate or predict water balance components in agricultural and rangeland watersheds (Lane and Stone 1983, Lane et al. 1984, Lane and Barnes 1987), or to aid in designing reclamation projects for surface mining or landfill operations (Hakonson et al. 1982, Nyhan et al. 1984). The choice of a model depends on the specific need, the data available, and the perceived accuracy of the simulation results. Comparisons between models for a wide range of site conditions and tests of the accuracy of the simulated results are necessary for an informed choice. Few such studies on commonly used models have been presented.

Since water is such an uncontrolled natural input to the total SLB system, varied meteorological conditions must also be kept in mind when considering the wide-scale applicability of a long-term SLB site closure design. With this idea in mind, a concurrently-written report presents an analysis of precipitation patterns at Los Alamos, New Mexico, with the ultimate target goals of predicting both long-term precipitation occurrences and SLB site behavior (Nyhan et al. 1988a).

In this study, the U.S. Department of Agriculture model CREAMS (a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems, see Knisel 1980) and the EPA model HELP (Hydrologic Evaluation of Landfill Performance, see Schroeder et al. 1984) were used to simulate soil water storage in eight experimental landfill cover systems over a two-year period. These models are widely used in the management of agricultural lands and hazardous waste landfill systems. The methods of parameterizing the

models are discussed. Field data on soil moisture and vegetation leaf area indices are presented for the various cover treatments. Soil moisture values predicted by each model are compared with field data at Waste Disposal Area B as well as the Integrated Systems Demonstration Plots, and the accuracy of each model assessed. Examples of how the CREAMS model can be used to optimize trench cap configurations at Los Alamos, NM, are then presented.

II. BACKGROUND

The CREAMS model was developed and intended for modeling field-scale agricultural systems (Knisel 1980). The model has been used in several areas of waste management research in semiarid climates, including erosion studies (Nyhan and Lane 1982), water balance and primary production of desert shrubs (Lane et al. 1984), and landfill cover design (Hakonson et al. 1982, Nyhan et al. 1984). Both CREAMS and HELP have been tested in a limited way with respect to percolation of water below a surface rooting zone, but not in any detail with respect to the effects of native plant cover on soil water storage.

CREAMS was used in the daily rainfall-runoff mode to obtain a complete water budget (estimates of runoff, evapotranspiration, percolation and soil-water storage, or water content in the soil column to the depth of the rooting zone) on each day that there was a precipitation event; using the simplified water balance equation:

$$\frac{ds}{dt} = P - Q - ET - L \quad (1)$$

where ds/dt = time rate of change in soil moisture, P = precipitation, Q = runoff, ET = evapotranspiration, and L = seepage or percolation. Monthly and

annual water budgets are also obtained. The model is one-dimensional, calculating the process of vertical transport of water in the soil column using a seven layer representation of the profile from the surface extending through the rooting zone of the vegetative cover. Initial responses to precipitation are calculated on a daily time-step using a modification of the Soil Conservation Service (SCS) curve number model (Knisel 1980).

An alternative model, HELP, is presented as being directly applicable to most landfill designs (Schroeder et al. 1984). In contrast to the purely one-dimensional character of CREAMS, the HELP model permits quasi-two-dimensional modeling of soil water movement by including lateral flow simulation in drainage layers. Precipitation inputs are modeled one-dimensionally down to the depth of lateral drainage layers or impermeable membrane liners. Lateral flow out of drainage layers is treated separately. The infiltration routine is similar to that used in CREAMS, and there are changes (claimed to be improvements) in the treatment of percolation and evapotranspiration. The model is interactive and user-friendly, with default climatic and soils data available for many regions in the U.S. Default estimated vegetation data are also available to the user. Alternatively, the user can specify parameter values specific to the site being modeled.

Both models require data on soil characteristics, seasonal vegetation characteristics, and soil cover design as input. Monthly mean temperatures, mean monthly solar radiation values, and daily precipitation inputs are also required.

III. MATERIALS AND METHODS

A. Description of Field Study Areas

1. Closed Waste Disposal Area B.

The study area was a closed low-level radioactive waste disposal site

("Area B") located at Los Alamos National Laboratory in north-central New Mexico. Area B (Fig. 2) has a generally uniform 5% slope and southeast aspect. Remediation treatment in 1982 resulted in three distinct soil profiles being installed across the site (east, west, and cobble-gravel). Eight experimental plots were established on the site, distributed on the three soil profiles as shown in Figure 2. The topsoil used in the construction of the Area B landfill cover remedial treatment is a local Hackroy sandy clay loam (Nyhan et al. 1978). The crushed Bandelier tuff used as an overburden to the waste material can be classified as a sandy loam. East and west control profiles differ in the amount of sandy clay loam in the profile. The west profile is more typical of landfill covers at Los Alamos, having about 15 cm of topsoil over 85 cm of crushed tuff. The east profile has a much higher amount of topsoil (sandy clay loam) mixed into the profile as a result of reconstruction in 1982, and thus the east soil profiles have significantly higher water

Figure 2. Plan view and cross-section of study site, Area B. Vegetation covers are bare (plots 12, 13), grass (plots 4, 12), shrubs (plots 3, 7, 11), and 1/5 density shrub (plot 10).

holding capacity than the west soil profile. The "biobarrier" profile has a layer of cobble and gravel (as a barrier to capillary moisture flow and biointrusion) overlain by 45 cm of crushed tuff and 15 cm of topsoil.

Each plot was 8 by 24 m (25 by 80 ft), oriented parallel to the slope. The vegetative cover treatments included bare, grass, and shrub covers (Table 2). The "bare" treatment was weeded frequently to remove all standing live

Table 2. Plot Numbers for Each Cover and Soil Profile Treatment at Los Alamos Area B Site

Cover Treatment	Soil Profile		
	East Control	West Control	Biobarrier
Bare	2	13	
grass/forbs	4	12	
rabbitbrush, dense	3	11	7
rabbitbrush, sparse		10	

vegetation, resulting in a variable vegetative cover during the summer months. The grass covers were weeded to remove forbs and seedling shrubs. Shrub plantings of rabbitbrush (Chrysothamnus nauseosus subsp. latisquameus [Gray] H. & C.) were established in 1984 at two densities: dense at 2.15 plants/m², and sparse at 0.43 plants/m². These covers were weeded to remove grasses and forbs.

2. Integrated Test Plots.

The purpose of the Integrated Test Plot (ITP) cover demonstration was to monitor and compare water balance on the conventional trench cap design (referred to in this report as Control Plots 1 and 2), similar to that used in Los Alamos for low-level radioactive waste disposal (Fig. 3), with that on an

Integrated Experiment: Control Plots

Figure 3. Conventional trench cap design on the Integrated Test Plots.

improved design (referred to in this report as Improved Plots 1 and 2; see Fig. 4). The demonstration plots (2 plots/cover design) were instrumented and designed so that a complete water balance of precipitation falling on the plots at the Los Alamos Experimental Engineered Test Facility (EETF; see DePoorter 1981) could be made (Nyhan et al. 1988b). The plots, which were about 3 by 10 m, were constructed and instrumented (Figs. 3 and 4) to provide measures of runoff, soil water storage, and seepage, as measured by leachate production from the trench drains emplaced in the plots. Except for a small amount of water sprinkled on the plots in mid-1984 to aid in establishing vegetation (average of 2.7, 4.4, 7.9, and 0.5 cm of total precipitation added in May, June, July, and August, respectively), only natural precipitation was added to the plots during the course of the study.

The technology for soil erosion control on both cover designs consisted of applying a 60 to 70% cover of gravel (about 2-cm diameter) and a plant cover of blue grama grass (Bouteloua gracilis) and western wheatgrass (Agropyron smithii). A dominant downhill slope of only 0.5% was used in the improved design, which successfully insured that no runoff was generated over the course of the experiment (in an attempt to simplify the estimation of the other parameters in the water balance equation).

The conventional and improved cover designs vary significantly beneath the soil surface. The conventional trench cap design consisted of 15 cm of topsoil emplaced on top of 76 cm of crushed tuff backfill. Cesium iodide tracer was applied to the tuff backfill at the interface between the bottom of the cover and the underly tuff backfill. Notice that this tracer layer conceptually separated the layers designated in this report as the trench cap (above the cesium iodide tracer layer) and beneath the trench cap (below the tracer layer). The crushed tuff backfill beneath the cesium iodide layer

Integrated Experiment: Improved Plots

Figure 4. Improved trench cap design on the Integrated Test Plots.

would normally contain low-level radioactive wastes in an actual waste disposal site at Los Alamos.

The improved cover plot design contains provisions for potential sub-surface water management and for controlling biological intrusion by plant roots and animals (Fig. 4). Approximately 71 cm of topsoil was emplaced on top of 46 cm of pea gravel and gravel (5-10 mm diameter) to provide for soil water storage and to form a capillary barrier to divert the vertical flow of water resulting from precipitation infiltrating the trench cap. The integrity of the soil-gravel interface was maintained with a very high conductivity geotextile (600x brand, manufactured by MIRAFI, Inc., El Toro, CA 92630). A 5% lateral slope (across the width of the plot) on this interface and a large difference in the saturated hydraulic conductivities of these two layers should theoretically cause the downward flow of water to have a strong lateral flow component and divert soil water into the overhang (upper) drain system in this plot. The underlying cobble layer made up the biointrusion barrier and consisted of a 91-cm-deep layer of cobble with diameters ranging from about 10 to 30 cm (Fig. 4). This layer should minimize plant root intrusion because the spaces between the cobble are relatively free of soil and water. The cobble layer also should prevent most burrowing animals from penetrating the biointrusion barrier, simply because the stones are too heavy to move. Cesium iodide tracer was applied to the surface of the crushed tuff immediately beneath the capillary-biointrusion barrier in the improved cover design. This layer, as with the conventional cover design, demarks the bottom of the trench cap.

B. Soil Water Determinations

Volumetric soil water content was measured at each field site with a neutron moisture probe (Campbell Pacific Nuclear Corp. Model 503, Pacheco,

CA), which had been previously calibrated for the crushed tuff used in these experiments (Nyhan et al. 1983). At Area B, neutron moisture probe data were collected at 20, 40, and 60 cm sampling depths within access tubes at three or four locations per plot. In the ITP experiment, similar data were collected at six locations per plot on the conventional trench cap design (20, 40, 80, 110 cm) and at nine locations per plot on the Improved Plots (20, 40, 60, and 220 cm).

C. Plant Parameter Measurements

These hydrologic models require estimates of leaf area index (LAI) and rooting depth as input for calculating utilization of soil moisture by the vegetative cover. LAI data are commonly available only for crop species or grass covers. In order to extend CREAMS and HELP modeling strategies to native plant covers, it was necessary to develop nondestructive methods that allowed frequent estimates of LAI during the year without disturbing the vegetative cover on the plots.

1. Shrubs.

A regression relationship was developed relating shrub crown dimensions and crown volume to total shrub biomass and total crown leaf area. Rabbit-brush shrubs of various sizes were harvested, both on the experiment site from areas planted specifically for harvest purposes and from naturally occurring stands in other areas on Los Alamos National Laboratory lands. Prior to harvest, crown dimensions (crown height, greatest diameter D_1 , and diameter D_2 perpendicular to D_1) were measured to the nearest cm. Three subsamples of actively growing twigs were taken from the crown, and the rest of the crown was separated into actively growing leaves and twigs (current season), and secondary (older) twigs and branches. The subsamples were separated into leaves and twigs and projected area of each portion determined using a leaf

area meter (LI-COR, Inc., Model 3050, Lincoln, NE). The subsamples and the rest of the shrub's crown portions were then dried at 75°C for 48 h and weighed. Specific leaf mass, SLM (gm cm^{-2}), was calculated for each subsample, the mean computed for each shrub harvested, and an overall mean computed for all shrubs sampled (Table 3). The dry leaf mass as a fraction of

Table 3. Mean Values, Standard Error (S.E.), and Sample Size (n) of Specific Leaf Mass (SLM, g/cm) and Leaf Mass as Percent of Total Aboveground Biomass (LM, %) for Rabbitbrush and Mixed Grasses

	Mean Value	S.E.	n
Rabbitbrush			
SLM	0.0169	0.0013	33
LM	0.499	0.021	33
Mixed grass			
SLM	0.0243	0.0021	122
LM	0.424	0.023	104

dry mass of current growth was determined and total crown leaf area estimated for each shrub. Several regression models relating crown biomass and leaf area to crown volume and crown dimensions were used. Tests showed that the highest correlation coefficients were obtained using spherical crown volume as the independent variable of crown architecture in the regression models (Fig. 5).

Using the relationships developed, total biomass and leaf area indices were periodically estimated for the plots with rabbitbrush cover. Shrub individuals were randomly selected on each plot, and the canopy dimensions recorded. A mean spherical crown volume for the plot was computed, and

Figure 5. Relationship between crown volume and total aboveground biomass of rabbitbrush.

biomass and leaf area index estimated using the regression relationships and planting densities.

2. Grass.

Regression relationships were developed between visually estimated percent cover and total aboveground dry biomass on the bare and mixed grass plots as follows. On each sampling date, quadrats (25 x 50 cm) were laid out randomly on each plot. The locations were selected so as to sample over the range of grass canopy cover on the site. For each quadrat, the percentage of ground covered by the grass canopy was estimated (percent cover). All standing biomass in the quadrat was clipped and bagged, and taken to the laboratory for sorting. Each sample was separated into green leaf, green stem, and standing dead fractions. Projected area was measured on the green

fractions. All fractions were dried at 75°C for 48 h, and then weighed. Biomass per unit ground area, leaf biomass as a fraction of total biomass (LB), and specific leaf mass (SLM, or mass of dry leaf per unit leaf area) were determined for each quadrat sample.

Several regression relationships between biomass and percent cover were developed and tested for the effect of time of harvest, plot location, or vegetative cover. Statistical analysis showed that effects of vegetative cover (bare versus grass) and plot locations were not significant. Neither time of harvest, vegetative cover, nor plot location had a significant effect on the overall SLM or LB. Time of harvest data were analyzed by month to give four linear regression equations. In the final analysis, it was found that use of the monthly regression equations had an insignificant effect on actual LAI estimates for each plot, and in the following discussion, the overall linear regression equation was used (Fig. 6). To estimate the changes in LAI

Figure 6. Relationship between canopy cover and total aboveground biomass of mixed grasses at Area B.

during the growing season, percent cover was estimated on each of a series of either 50 or 100 randomly placed quadrats on each plot. The overall regression equation was used to estimate average total biomass, and LB and SLM used to calculate LAI.

D. Modeling Studies

The modeling studies were conducted in two phases. Initially, a series of CREAMS simulations were conducted to optimize values of hydrologic soil parameters. Secondly, CREAMS and HELP simulations were conducted on all experimental scenarios at Waste Disposal Area B using the optimized parameters and, for HELP only, using the model's default values.

Lane (1984) gives a range of possible values for each soil parameter required for CREAMS (saturated hydraulic conductivity, bare soil evaporation, porosity, field capacity, and wilting point). The optimum values were chosen by initially conducting a series of simulations to explore the capability of the models to reproduce observed profile averaged soil moisture trends from 1983 to 1985 on the west control plot 11, which had a dense rabbitbrush cover, a standard landfill cover soil profile, and a two-year record of soil moisture measurements prior to the start of the study (Nyhan et al. 1986).

The basic structure and initialization of the model was established using known site specific data, actual daily precipitation totals for 1983-1985, and 20 year averages of air temperature and solar radiation for Los Alamos. LAI in 1983 and 1984 was estimated so as to agree with observed seasonality in growth patterns and LAI levels attained by herbaceous weeds in 1985. For 1985, estimates of LAI were based on field measurements on shrubs and herbaceous weeds. Instead of using recommended values for soil hydrologic parameters of the appropriate soil texture classes represented at Area B (Knisel 1980, Lane 1984, Schroeder et al. 1984), several simulations tested the

effects of varying the parameters over the reported ranges on predicted average soil moisture content.

First, average values of certain soil parameters (saturated hydraulic conductivity, field capacity, and wilting point) were used as recommended by Lane (1984) and Schroeder et al. (1984) for the soil texture classes represented in the plot 11 soil profile. Second, the ranges suggested for the soil texture classes (Lane 1984) were tested. Third, the effect of using the measured saturated hydraulic conductivities of the specific soils on the site (Abeele 1984) was tested. Finally, after determining which parameter values maximized the fit between observed and predicted retention and drainage of soil water, the curve number was adjusted to obtain the best possible representation of infiltration of precipitation from summer storm events.

The performance of CREAMS in predicting soil moisture on plot 11 at Area B and in the ITP experiment was assessed at each step (Fig. 7). The observed field values were averaged over three measurement depths (20, 40, and 60 cm) and over four locations on the plot to give one mean soil moisture value for each measurement time. Best fit of the predicted to the observed soil moisture patterns was assessed by the standard technique of regression analysis with the aim of maximizing the coefficient of determination (r^2) and optimizing the slope and intercept of the regression line to approach the equal value line (Pathak et al. 1984). The parameters that produced the optimum CREAMS simulation were the minimum saturated hydraulic conductivity of any layer ($RC = 2.5 \times 10^{-8}$ m/s for Hackroy sandy clay loam); and the average field capacity (19%) and average wilting point (8%) for sandy loam. The curve number used for the SCS representation of infiltration and runoff was 95, which results in most of the precipitation becoming runoff, and a very small amount infiltrating into the soil profile. These same parameters were used to

Model Performance Evaluation Technique

Figure 7. Flow chart of model optimization technique.

initialize a 3 year simulation of plot 11 data using the HELP model (version 1).

IV. RESULTS OF MODELING STUDIES AT AREA B AND IN THE ITP EXPERIMENT

A. Field Data Collected to Validate Models at Area B

1. Leaf Area Indices.

The estimated Leaf Area Indices (LAI) value for 1985 and 1986 are summarized in Figures 8-10. The high spring rains of 1985 resulted in a dense growth of cool season grasses and forbs on all plots. After weeding in June 1985, LAI dropped, and from that time, the plots were kept weeded as much as possible. In those cases where cover was not measured directly after weeding, an LAI value of 0.01 on the bare plots was assigned to the postweeding data.

Shrub LAI was not very different between the three densely planted plots by the end of 1986 (0.68 to 0.78). Plot 10, with 1/5 the density of shrubs, had about 1/3 the LAI of the densely planted plots, and a larger average size per individual.

2. Soil Water Content.

Differences in soil moisture retention by the three profiles can be seen by comparing average soil moisture (20-60 cm depths) on plots with similar vegetative covers (Figs. 11-13). Under all three vegetative covers (bare, grass, and dense shrub) it is readily apparent that the east profile (high percent sandy clay loam) retained more soil moisture throughout the year than the west profile which is predominantly crushed tuff overlain with a thin layer of sandy clay loam topsoil. The cobble-gravel profile was consistently drier than either the east or west profile. This was most likely due to lateral drainage of soil moisture above the gravel layer as well as to more complete water extraction by the plant roots in the shallower soil profile above the cobble-gravel layer.

Figure 8. Leaf area indices estimated on Area B bare soil cover plots in 1985 and 1986.

Figure 9. Leaf area indices estimated on Area B grass cover plots in 1985 and 1986.

Figure 10. Leaf area indices estimated on Area B shrub cover plots in 1985 and 1986.

Figure 11. Soil moisture (average 20, 40, and 60 cm depths) in bare soil plots at Area B with different soil profiles.

The effect of vegetative cover can be assessed by comparing plots with similar soil profiles. In both of the comparisons, soil moisture was lowest beneath a shrub vegetative cover. On the east plots, it is also apparent that in the profile under the shrub cover soil moisture started to decrease in May 1985 when the temperature had risen and the plants started to grow actively and thus transpired water actively.

This decrease in soil moisture continued through September 1985, with the result that average soil moisture was about 2/3 the values measured on the grass and bare plots. Although soil moisture increased on all plots with spring snow melt and again with summer rains in 1986, the soil moisture on the shrub plots never recharged to the levels observed on grass and bare plots. Spring precipitation levels were higher than usual in 1985, resulting in a

Figure 12. Soil moisture (average 20, 40, and 60 cm depths) in dense grass plots at Area B with different soil profiles.

Figure 13. Soil moisture (average 20, 40, and 60 cm depths) in shrub plots at Area B with different soil profiles.

very high soil water content on all plots in early spring 1985. Winter 1985-86 was also drier than usual and the general downward trend in soil water storage continued until the summer monsoon rains began in 1986. June had exceptionally high rainfall, September through November had higher than normal rainfall, and soil water recharge was apparent in most plots.

At the end of the 1986 growing season, soil moisture on shrub plots was several percent (by volume) below grass and bare treatments. The soil moisture averages are for the 20, 40, and 60 cm measurement depths. Since the neutron moisture probe has a measurement sphere-of-influence of up to 20 cm radius in soil, a conservative estimate is that the average of the three measurements represents 0 to 70 cm of soil depth. Using this soil depth, the total soil water storage was calculated at the approximate start and end of the growing seasons for 1985 and 1986. The differences between the treatments on the east control profile suggest that after 2 years, ET from the shrub cover resulted in 6.9 cm less water stored in the shrub soil profile than in the bare profile, and 3.6 cm less water than in the grass profile. Similar trends were noted on the west plots.

B. Field Data Collected to Validate Models in the ITP Experiment

1. Plant Biomass and Species Composition.

Biomass and species composition was determined in August 1987 for all four plots (Tables 4 and 5). The biomass for a 100% cover of blue grama and for a 100% cover of western wheatgrass was determined (Table 5), and the overall plot averages were calculated to be 429.3 g/m^2 and 1598 g/m^2 , respectively. The plant cover data (Table 4) were then used in conjunction with these data to calculate estimates of total biomass for each plot (Table 6).

Table 4. Plant Cover (%) Estimates in the ITP Experiment (August 1986)

Improved Plots					Control Plots			
		Plot 1		Plot 2		Plot 1		Plot 2
1	AGSM*	100	AGSM	20	BOGR	93	BOGR	95
2	AGSM	75	BOGR	90	AGSM	5	BOGR	95
	BOGR	25	AGSM	60	BOGR	94	AGSM	2
3	AGSM	80	BOGR	40	BOGR	96	BOGR	98
	BOGR	25	AGSM	5	BOGR	85	AGSM	1
4	AGSM	75	BOGR	100	BOGR	90	BOGR	100
	BOGR	25	AGSM	10	BOGR	100	BOGR	100
5	AGSM	25	BOGR	75	BOGR	90	BOGR	97
	BOGR	80	BOGR	95	BOGR	92	BOGR	96
6	AGSM	25	BOGT	5	BOGR	88	BOGR	95
	BOGR	80	AGSM	100	BOGR	93	BOGR	100
7	AGSM	10	BOGR	5	BOGR	92	BOGR	98
	BOGR	100	BOGR	100	AGSM	5	AGSM	3
8	AGSM	5	BOGR	50	BOGR	85	BOGR	50
	BOGR	75	AGSM	40	AGSM	5	LOWR	10
9	AGSM	50	BOGR	20	BOGR	98	BOGR	10
	BOGR	50	AGSM	80	AGSM	7	BOGR	20
10	AGSM	50	BOGR	100	BOGR	95	AGSM	70
	BOGR	45	AGSM	60	AGSM	1	BOGR	95
11	AGSM	95	BOGR	5	BOGR	82	AGSM	5
	BOGR	10	AGSM	90	BOGR	95	BOGR	98
12	AGSM	100	BOGR	20	AGSM	5	AGSM	1
13	AGSM	100	AGSM	55	BOGR	95	BOGR	100
	BOGR	5	BOGR	50	BOGR	96	AGSM	1
14	AGSM	90	AGSM	5	BOGR	75	BOGR	98
	BOGR	5	BOGR	100	BOGR	93	AGSM	1
15	AGSM	100	BOGR	100	BOGR	93	BOGR	97
16	AGSM	15	AGSM	60	BOGR	75	AGSM	1
	BOGR	90	BOGR	40	AGSM	40	BOGR	92
17	AGSM	100	AGSM	100			BOGR	100
	BOGR	5	AGSM	50			BOGR	92
18	AGSM	95	AGSM	60			BOGR	100
	BOGR	5	BOGR	50			BOGR	90
19	AGSM	95	BOGR	60				
	BOGR	10	BOGR	70				
20	AGSM	100	AGSM	100				
	BOGR	5						
21	AGSM	100						
22	AGSM	100						

* AGSM represents Agropyron smithii (western wheatgrass) and BOGR represents Bouteloua gracilis (blue grama).

Table 5. Plant Biomass Estimates in the ITP Experiment (August 1986)

	100 cm Quadrant	Species	% Cover	Dry Biomass (g)
Improved Plot 1	1	AGSM*	100	21.1
	2		100	13.3
	3		100	16.8
	4		100	14.9
	5		100	14.0
Improved Plot 2	1	AGSM	100	27.6
	2		100	12.5
	3		100	18.4
	4		100	9.7
	5		100	11.5
Control Plot 1	1	BOGR	100	3.643
	2	BOGR	100	4.497
	3	BOGR	100	2.712
	4	BOGR	100	4.104
	5	BOGP	100	6.095
Control Plot 2	1	BOGR	100	4.564
	2	BOGR	100	4.418
	3	BOGR	100	4.180
	4	BOGR	100	3.908
	5	BOGR	100	4.808

*AGSM represents Agropyron smithii (western wheatgrass) and BOGR represents Bouteloua gracilis (blue grama).

Table 6. Summary of Plant Species Cover and Biomass Data in ITP Experiment (August 1986)

Plot Description	Percent Cover		Total Estimated Biomass (g/m ²)
	BOGR	AGSM*	
Improved Plot 1	22.0	72.0	1245
Improved Plot 2	44.5	47.3	847.0
Control Plot 1	90.7	3.1	438.9
Control Plot 2	91.1	4.3	459.7

*AGSM represents Agropyron smithii (western wheatgrass) and BOGR represents Bouteloua gracilis (blue grama)

The results of this analysis revealed a quantitative estimate of what we had visually observed on these plots since the middle of the summer of 1985. All four plots had practically 100% plant cover, exhibiting the influence of the partial gravel cover on each plot. However, the two Improved Plots with the capillary barrier in the profile had more than twice the biomass that the Control Plots contained; the capillary barrier had evidently retarded the downward movement of water in these plots, allowing more water to be available for plant growth for longer time periods. The second difference observed since 1985 was that the Control Plots contained almost exclusively blue grama whereas most of the Improved Plots contained almost exclusively western wheatgrass (Table 6). Although the reasons for this observed difference are not fully understood at this time, one possible explanation is that the capillary barriers in the Improved Plots resulted in soil water inventories that were closer to maximum in the trench cap than they were in the Control Plots at the start of 1985. The western wheatgrass, being a cool-season grass (unlike the blue grama), exhibited much faster growth early in the spring of 1985 than the still inactive blue grama, and simply out-competed the blue grama for plant available water and biomass production from that time on. Differences in active plant root distributions could also supplement this explanation and/or offer a second explanation for the phenomenon.

2. Neutron Moisture Probe Data and Soil Water Inventories.

Since the soil water inventory data were calculated directly from the neutron moisture probe data, both types of information are presented for the Control Plots (Figs. 14-17) and for the Improved Plots (Figs. 18-21). The figures showing the soil water inventory estimates (Figs. 15, 17, 19, 21) contain the total precipitation received by the plots for each week of the study, as well as an indication of the maximum estimated soil water inventory

Integrated Test Plots Control Plot 1

Figure 14. Volumetric water content as a function of time for ITP Control Plot 1.

Figure 15. Total weekly precipitation and soil water inventory estimates as a function of time for ITP Control Plot 1.

Integrated Test Plots Control Plot 2

Figure 16. Volumetric water content as a function of time for ITP Control Plot 2.

Figure 17. Total weekly precipitation and soil water inventory estimates as a function of time for ITP Control Plot 2.

Integrated Test Plots Improved Plot 1

Figure 18. Volumetric water content as a function of time for ITP Improved Plot 1.

Figure 19. Total weekly precipitation and soil water inventory estimates as a function of time for ITP Improved Plot 1.

Integrated Test Plots Improved Plot 2

Figure 20. Volumetric water content as a function of time for ITP Improved Plot 2.

possible for each portion of the soil profile (the soil would be saturated at this value).

The soil moisture data collected on the Control Plots and the Improved Plots all show a pronounced increase in water content with additions of precipitation during the first winter of the field experiment in 1985. Although the vegetation on all of the plots was not fully established in 1984, the substantial decreases in soil water content during the spring and summer of 1985 were a direct result of evapotranspiration. Notice that plant roots had withdrawn water out of the trench caps in both designs, as well as beneath the trench cap in the conventional cap design (Figs. 14 and 16). This latter phenomenon occurred for every growing season, but did not occur on the Improved Plots (Figs. 18 and 20), pointing up the effectiveness of the cobble layer in keeping plant roots confined to the trench cap and not beneath it. The soil water inventory calculations show that the crushed backfill beneath the conventional trench cap design very quickly approached values close to saturation by early spring of 1985, as well as throughout the life of the field experiment. Thus, the corresponding soil water content values normally increased with depth for most sampling periods, whereas a variable relationship of soil water content to depth was observed on the improved plots.

3. Water Balance Estimates in the ITP Experiment.

Now that changes in precipitation and soil water inventories as have been described as they varied with time in the ITP experiment, the estimation of water balance for the field experiment can finally be presented. The elements of the water balance equation were previously described in Equation (1). Quantitatively, changes in soil water content (soil water inventories) with time ($\frac{\Delta SM}{\Delta t}$) are set equal to water added in precipitation (P) minus water lost by evapotranspiration (ET), leachate production (L), and runoff (R).

Using the plot data, we have direct field measurements of $\frac{\Delta SM}{\Delta t}$ (using the neutron probe data), P and L in this equation. Since no runoff occurred in the ITP experiment at any time, we could estimate ET by difference in this equation and quantitatively estimate all of the parameters of the water balance equation for every time interval for which we had field data.

The results of these water balance calculations are presented in Figure 22 for both of the Control Plots and in Figure 23 for the Improved Plots. The precipitation and neutron moisture data were collected more frequently in the early stages of the experiment than after 1985, resulting in smaller (but more frequent) changes in precipitation and soil water inventories with time from 1984-1985. Evapotranspiration rates were calculated from the data presented in Figures 22-23, and show the expected seasonality pattern of evapotranspiration rates: low evapotranspiration rates (less than 0.1 cm/day) in late fall-winter and peak evapotranspiration rates (greater than 0.2 cm/day) during the summers (Fig. 24). When the data were collected on a more frequent basis, Figure 24 reveals a great deal of variation in evapotranspiration rates from all of the plots depending on the frequency of precipitation and the amounts of plant-available water in the soil profiles.

We observed evapotranspiration differences with time between the Control and Improved Plots. Although we did not collect biomass data for every year of this experiment, the peak evapotranspiration rates in all plots were observed in 1985 during the first summer of peak plant growth in the plots. Although the total biomass estimates at this time were probably similar to those observed in August 1986 (Table 6), almost all of the biomass observed in 1985 was green biomass, unlike in the later stages of plant development on these plots within the duration of the field experiment. Another seasonal difference was that evapotranspiration started earlier in the spring on the

Integrated Test Plot Experiment: Control Plots

Figure 22. Precipitation, change in soil water inventory, and evapotranspiration estimates as a function of time for ITP Control Plots.

Figure 23. Precipitation, change in soil water inventory, and evapotranspiration estimates as a function of time for ITP Improved Plots.

Integrated Test Plots: Evapotranspiration rates

Figure 24. Evapotranspiration rate estimates as a function of time for ITP Control and Improved Plots.

Improved Plots than on the Control Plots (Fig. 24). This observation is due to the fact that the predominant plant species on the Improved Plots was the cool-seasoned western wheatgrass, in contrast to the warm-seasoned blue grama grass predominating the Control Plots (Table 6).

However, the most practical comparisons between the two types of SLB cap designs, in terms of their usefulness to the burial site operator, should be the performance comparison of the hydrologic parameters of the water balance estimates over the 3-year duration of the experiment (Table 7). These data

Table 7. Mass Balance Calculations for Water Associated with Two Trench Cap Designs in the ITP Experiment

	Control Plots		Improved Plots	
	1	2	1	2
Precipitation (cm)	173.72	173.72	173.72	173.72
Increase in Soil Water Inventory (cm)	12.09	9.09	4.15	4.43
Evapotranspiration (cm)	151.67	154.87	169.57	164.88
Leachate Production (cm)	9.96	9.76	0	4.41
Evapotranspiration/Precipitation	0.873	0.892	0.976	0.949
Leachate Produced/Precipitation	0.057	0.056	---	0.025

show that there was enhanced evapotranspiration on the Improved Plots over those observed on the Control Plots, due to both capillary barrier dynamics in retarding vertical water movement in the profile and to enhanced biomass on the Improved Plots. About 88% of the precipitation received was evapotranspired on the Control Plots, whereas about 96% of the precipitation received by the Improved Plots was removed from the trench cap via evapotranspiration.

The dynamics of soil water storage in the two trench cap designs also demonstrated an important waste management consideration in terms of leachate production. A little over 5% (about 10 cm) of the precipitation received by the Control Plots ended up as leachate that made it through the trench cap from 1985 to 1987. In contrast, Improved Plot 2 produced only about 4 cm of leachate, corresponding to only about 2% of the precipitation received by the plot, and this during the record wet winter of 1986-1987 (Table 7). In addition, the Control Plots accumulated almost 2.5-fold more soil water than the Improved Plots over the three years of this field experiment (Table 7). This is a significant difference between these two designs and definitely implies that more leachate production will eventually continue to occur in the Control Plots than in the Improved Plots, since the deeper portions of the Control Plot profiles will continue to remain close to field capacity soil water contents (which will in turn result in leachate production if conditions wetter than field capacity occur).

Because of the fact that all of the parameters of the water balance equation (Eq. 1) were directly measured, except for evapotranspiration, these data (Table 7) are unique for an SLB hydrologic cycle scenario, where ET, L, and R are usually estimated and not measured directly. These are the type of data which (1) can be used directly for waste management operations at Los Alamos, and (2) can be used to field validate hydrologic models, which can in turn be used to design better waste repositories.

4. Hydraulic Conductivity Determinations.

Soil cores were collected in October 1988 on two of the plots and assayed for saturated hydraulic conductivity (Black et al. 1965). The data, presented in Table 8, indicate a large difference in saturated conductivities between the topsoil and the crushed tuff used in the plots. The average conductivity

Table 8. Laboratory Determinations of Saturated Hydraulic Conductivity (K) Performed on Soil Cores Collected in the ITP Experiment

Plot and Sample Description	Sampling Depth (cm)	Saturated Average Hydraulic Conductivity (in./h)
<u>Improved Plot 1</u>		
Topsoil	0-12	6.73 (2) ^a
Topsoil	20-32	17.7 (2)
<u>Control Plot 2</u>		
Topsoil	0-12	6.56 (1)
Crushed tuff backfill	20-32	331 (2)

^aNumber in parentheses represents number of core samples collected and assayed.

values for the silty clay loam topsoil samples ranged from 6.56 to 17.7 in./h whereas the loamy sand tuff backfill samples exhibited average saturated conductivities of 331 in./h.

C. Hydrologic Model Predictions and Comparisons at Area B

The optimum CREAMS simulation and the corresponding HELP simulation as well as observed field data for Area B are shown in Figure 25. When the predicted and observed soil moisture were compared point for point by regression analysis, large differences (underpredictions or overpredictions) were observed. Using the coefficient of determination as a measure of overall goodness of fit, only a portion of the variation in soil moisture is explainable by the algorithms in the models (23% for CREAMS, 34% for HELP). This implies that a large portion of the variability in soil moisture results from processes which were either poorly represented or absent in the models. In both models, water transport from the surface zone (2 to 5 cm) to the

Figure 25. Observed average soil moisture (20, 40, and 60 cm depths) and average soil moisture predicted by CREAMS and HELP simulation of Plot 11 scenario at Area B (1983-1985).

layers below is a simple power function of soil water storage in the surface zone. Percolation below the rooting depth does not occur unless storage plus inflow exceeds field capacity. These simplifications of the soil hydrologic system, which undoubtedly contribute to the reduced accuracy of predictions on a daily time-step basis, may be less important if monthly or quarterly totals of water balance components are used to assess model performance. It is very clear that HELP grossly underestimates average soil moisture to the depth of the rooting zone throughout the 3 year simulations. This is due in part to the apparently excessive ET estimates predicted by the uncalibrated HELP model, which result in soil moisture depletion to a very low level.

The overall predictive power of each model for Area B was tested by assessing what percentage of the variability in the observed data was ex-

plained by model predictions in 2 year simulations on all soil/vegetation combinations. For CREAMS runs, the optimized parameter values for soil hydrologic properties were used (Table 9). For HELP runs, simulations were first performed using the CREAMS optimized values, and then repeated using the default values supplied by the HELP model. Each plot had soil profiles with varying percentages of sandy clay loam and sandy loam soils. For each plot, profile values for hydrologic parameters were calculated as weighted averages of the optimum field capacities and wilting points already determined. The driving variable was 1985 and 1986 daily precipitation totals. The first field measurement of 1985 was used to initialize profile soil moisture in CREAMS simulations. LAI data specific for each plot were used (Figs. 8-10).

The overall predictive power of each model was assessed by a linear regression analysis of predicted versus observed average soil moisture over all plots (Fig. 26). For the CREAMS model, the values are well clustered about the equal values line. The variability is high, and only 62% of the variability in the observed soil moisture values is explained by the algorithms of the model. Nonetheless, over a wide diversity of soil profiles and plant covers, the model predicts soil moisture with acceptable accuracy.

In contrast, the overall regressions of the HELP-predicted soil moisture values show that neither the CREAMS optimized soil parameters nor the default soil parameters gave acceptable estimates of soil moisture. The CREAMS-optimized parameters resulted in excessively low estimates of soil moisture regardless of precipitation events. The use of default values for parameters raised the average level of predicted soil moisture, but there was still a serious lack of correspondence between observed and predicted soil moisture, as suggested by the small slope of the regression line (0.33). The range of soil moisture was severely restricted compared to observed values, with HELP

Table 9. Optimized Parameters for CREAMS Simulation of Soil Water Storage on Plot 11 at Area B

Soils: 0 to 15 cm, sandy clay loam (SCL)
 15 to 75 cm, sandy loam (SL)

Slope: 5%

Plant Parameters:

Rooting Depth: 76 cm (30 in.)

Winter cover factor: 0.50

Leaf Area Index (LAI) Distribution:

Time (days)	1983	1984	1985
1	0.001	0.001	0.03
61	0.001	0.001	0.03
91	0.01	0.001	0.107
121	0.08	0.01	0.187
153	0.10	0.01	0.265
167	0.10	0.10	0.288
183	0.15	0.15	0.108
197	0.15	0.15	0.145
214	0.15	0.01	0.145
259	0.10	0.10	0.196
275	0.05	0.10	0.205
306	0.005	0.10	0.214
336	0.001	0.03	0.051
366	0.001	0.03	0.050

Soil Parameters:

Saturated hydraulic conductivity: 0.0035 in./h

Bare soil evaporation parameter: 3.30 mm/d^{1/2}

SCS Curve Number: 95

Porosity: SCL 0.46
 SL 0.46

Field Capacity: SCL 0.34
 SL 0.19

Wilting Point: SCL 0.15
 SL 0.08

Figure 26. Regression relationships between observed average soil moisture and soil moisture predicted by CREAMS, HELP using default parameters, and HELP using optimized parameters at Area B.

underestimating soil moisture when field soil moisture was high, and overestimating moisture when field soil moisture was actually low. It is noteworthy that HELP did not allow soil moisture to decrease below about 14%, regardless of the profile composition or the time since precipitation. In addition, soil water recharge was significantly below what was actually observed in the field. The necessity for considering the correlation coefficient (r^2), the slope and the intercept of the regression line, and the proximity of the line to the equal values line in evaluating the model predictions can be seen by comparing the two HELP regressions. The optimized values produced a regression with a higher overall correlation coefficient ($r^2 = 0.51$) and a lower intercept value (both indicative of good fit), but had lower slope than the regression of default parameter runs. In addition, inspection of the regression plot shows that the predicted values are far from the equal values line, and that the higher correlation coefficient is the result of some model-produced extreme restriction of the range of values produced.

These results suggest several areas of research that would be fruitful to pursue. The west plots have a more clearly stratified soil profile, consisting of crushed tuff and a thin layer of topsoil. This combination in no way represents a natural soil. The crushed tuff is a finely ground, sterile, compacted layer, which does not support vigorous plant growth. Presumably, plant roots do not penetrate this layer well. The topsoil layer is easily erodible, and there is a sharp boundary between the layers. Abrupt discontinuities in the soil profile will possibly result in lateral flow of subsurface water. Such processes are not considered by either model. In contrast, the east plots generally had much more topsoil in the profile, and more closely resembled agricultural soils. It would be advantageous to examine the

hydrologic properties of constructed, artificial soil profiles in greater detail. Neither CREAMS nor HELP is likely to be able to represent the movement of water in constructed profiles without more accurate assessment of soil properties and better representation in the models of water extraction processes by plants.

With respect to the vegetative cover, the LAI estimates on shrub and bare covers were more accurate than on the grass covers. Field measurements on grass covers were found to have high errors associated with them, even after doubling the number of samples from 50 to 100. Methods of estimating LAI are tedious, time-consuming, and relatively inaccurate, and there are few data published in the literature. Development of relationships between LAI and easily measured parameters (e.g., canopy cover) for individual species are needed. For grasses, the need is obvious.

Previous tests of CREAMS modeling of soil water storage (Devaurs 1985) showed that the accuracy of predictions of soil water storage decreased with the field scale of the study and with increasing artificiality of the soil profile. Similar conclusions were reached by Pathak et al. (1984) who found that agreement between observed and simulated runoff decreased as watershed size and soil heterogeneity increased. Both of these studies reported correlation coefficients of the regression relationship between observed and predicted parameter values of 0.21 to 0.76, similar to the range in this study. In addition, the slopes of the regression lines were from 0.91 to 0.49 (Pathak et al. 1984) and 0.16 to 0.22 (Devaurs 1985), indicating that the tendency of CREAMS to underestimate the dynamic range in seasonal soil water storage is also reflected in an underestimate of the range of runoff volumes. The wide range in r^2 values and regression line slopes reported in these studies and the present study shows that the absolute values of predicted

water balance components may be accurate only under certain conditions, such as relative uniformity of soils and slopes.

D. CREAMS Predictions in the ITP Experiment

The performance of CREAMS in predicting soil water content, evapotranspiration and percolation on Control Plot 1 in the ITP experiment was assessed at each step in model optimization using the same techniques used for the Area B modeling activities (Fig. 7). The observed field values of water content were averaged across all four measurement depths for Control Plot 1 (Fig. 14: 20, 40, 80, and 110 cm), and over six locations on the plot to give one mean volumetric moisture value for each measurement time. However, unlike the Area B modeling efforts (where evapotranspiration and seepage were not measured), the ITP modeling efforts focused on optimizing all of the components of the water balance equation (Table 7), and not just comparing observed and predicted volumetric water content, as was performed for the Area B data base.

In the process of finding the parameters that produced the optimum CREAMS simulation (summarized in Table 10), we quickly made several important observations early in the series of about 100 CREAMS simulations which were performed (Table 7). The first observation was that the laboratory-derived values for the saturated hydraulic conductivity (K) did not match up with the K-values suggested to be used in CREAMS for the texture of our topsoil (Table IV in Lane 1984). Recall that the laboratory-derived K estimates for the topsoil ranged from 6.56 to 17.7 in./h (Table 8), whereas Lane suggests using a K value of 0.07 in./h for a silty clay loam, with a range in K values of 0.06 to 0.08 in./h. Research performed at the University of Texas at Austin (Day and Daniel 1985) pointed out 1000-fold differences in K values produced in the laboratory versus those determined in the field for fine-textured

Table 10. Optimized Parameters for CREAMS Simulation of Soil Water Storage on ITP Control Plot 1 at EETF.

Soils: 0-20 cm, topsoil (silty clay loam)
 20-129 cm, crushed tuff (loamy sand)

Slope: 0.5%

Plant Parameters:

Rooting Depth: 128 cm (51 in.)

Winter Cover Factor: 0.50

Leaf Area Index (LAI) Distribution:

Time (days)	1985	1986	1987
1	0.00	0.00	0.00
91	0.00	0.00	0.00
121	0.05	0.05	0.05
152	0.80	0.50	0.36
180	1.00	0.90	0.30
210	0.90	0.60	0.40
240	0.60	0.25	0.20
280	0.25	0.01	0.10
310	0.00	0.00	0.00
366	0.00	0.00	0.00

Soil Parameters:

Saturated hydraulic conductivity: 0.020 in./h

Bare soil evaporation parameter: 3.05 mm/d^{1/2}

SCS Curve Number: 65

Porosity: topsoil: 0.42
 tuff: 0.35

Field Capacity: topsoil: 0.27
 tuff: 0.18

Wilting Point: topsoil: 0.17
 tuff: 0.09

soils, where K was equal to 0.01 in./h. Obviously, using the laboratory-derived K values for the CREAMS model was a bad idea.

We ultimately had to make a compromise to derive an optimum parameter value for K for use in CREAMS. The only field data that we could use for this purpose were from an erosion plot study (Nyhan and Lane 1986a) involving a trench cap design similar to the configuration on the ITP Control Plots (a plot with a partial gravel cover with wheatgrass growing on the same topsoil used in the ITP experiment). An estimate of K was derived from the very wet soil surface rain simulator run (average of two plots) by subtracting the peak runoff discharge rate of 2.30 in./h from the applied rainfall rate of 2.36 in./h, resulting in a K estimate of 0.06 in./h. Now we were more confident that our laboratory-derived estimates of K were at least two orders of magnitude too high (Table 8)! However, CREAMS simulations with values of K in excess of 0.02 in./h resulted in far more leachate production than we actually observed. Since CREAMS simulations where K was set equal to 0.01 in./h resulted in too little leachate production (i.e., only 0.793 in. for 1985) relative to what we observed for K equal to 0.02 in./h (i.e., 1.13 in. for 1985), we compromised on a K value of 0.02 in./h.

The second major observation we made concerned the value of the bare soil evaporation parameter (C) used in CREAMS. Actual soil evaporation in CREAMS is computed in two stages. First stage evaporation as occurs immediately after a rain is limited only by the energy available at the soil surface and is equal to potential soil evaporation. Second stage evaporation occurs after the soil has visibly dried and is generally described as the soil-limiting phase. This second phase is usually modeled by plotting evaporation rate versus the square root of time and determining the constant C (change in cumulative soil evaporation with a change in square root of time). Thus, C is

dependent on soil water transmission characteristics and varies directly with the hydraulic conductivity of the soil at -0.1 bar soil matric potential (Ritchie 1972) and also with soil temperature (Jackson et al. 1976). Thus, Lane has summarized the literature values of C for different soil texture classes, with suggested average C values ranging from about $4.5 \text{ mm/d}^{1/2}$ for silt loams to about $3.3 \text{ mm/d}^{1/2}$ for sands (Lane 1984); i.e., silt loams have higher soil water transmission characteristics than sands.

The suggested average value (Lane 1984) of C for our silty clay loam topsoil in the ITP experiment was $3.8 \text{ mm/d}^{1/2}$, with a suggested range in values of from 3.15 to $4.32 \text{ mm/d}^{1/2}$. CREAMS simulations using values of C as large as these resulted in gross overestimates of evapotranspiration throughout each simulation year. Since we had directly measured evapotranspiration in the ITP experiment, we decided to use a value of $3.05 \text{ mm/d}^{1/2}$ to describe the bare soil evaporation parameter. A C value this small would normally be used as a minimal C value for a sand or loamy sand (Lane 1984). However, it makes good sense that the 60% gravel cover used on the surface of the Control Plots probably greatly reduced bare soil evaporation in the field, resulting in a 20% lower optimized C value being used to accurately describe the data than that suggested by Lane.

The distribution of Leaf Area Index (LAI) with time was also a CREAMS parameter which was estimated and not directly measured. The only field data we had involved biomass estimates in the ITP experiment for one point in time (Table 5). Using the temporal distributions of LAI at Area B, the data from Table 5, and color photographs taken on the ITP plots with time, we came up with an initial set of LAI values. A final set of LAI values was derived (Table 10) by further optimizing the initial set of LAI values using observed versus measured field estimates of evapotranspiration and leachate production.

The results of the optimum CREAMS simulation as well as observed field data for the ITP Control Plot 1 are presented in Figure 27. Here, the average volumetric water content of the entire soil profile of Control Plot 1 is described as a function of time for the entire period modeled with CREAMS, from January 1985 through late 1987. A comparison of the CREAMS-predicted values with the observed values of volumetric water content generally shows that CREAMS underpredicts soil water storage in the ITP Control Plot profile (Fig. 27). When the predicted and observed soil water data were compared point for point by linear regression analysis (Fig. 28), several underpredictions and overpredictions were observed. However, using the coefficient of determination as a measure of the goodness of fit, CREAMS predicts soil moisture with acceptable accuracy ($R^2 = 0.70$). The value of the intercept in the regression equation (-0.0036) is not significantly different from zero, and the slope of the regression equation has a value close to unity (0.8289) with a standard error of only 0.080 . However, as with the Area B data, the variability is still high, with only 70% of the variability in observed soil water content being explained by the algorithms of the model.

However, we also had the unique ability to compare observed and predicted evapotranspiration and seepage to evaluate CREAMS predictive capabilities. For the two full years of field data where we could make comparisons, the observed total annual evapotranspiration for 1985 and 1986 was 24.73 and 20.24 inches, respectively. CREAMS predicted that 23.64 and 21.77 inches of evapotranspiration would occur in 1985 and 1986, respectively, which agreed very well with the observed values. The two periods of time when leachate was produced in the Control Plots were in May 1985, as well as December 1986 through the record-breaking January to May period of 1987. The CREAMS predictions of leachate production were 1.11 inches in May-June 1985 (0.22 in.

CREAMS-Predicted and Observed Soil Water Content for ITP Control Plot 1

Figure 27. Observed and CREAMS-predicted soil moisture on ITP Control Plot 1 as a function of time (1985-1987).

Figure 28. Regression relationships between observed versus CREAMS-predicted soil moisture on ITP Control Plot 1 (1985-1986).

observed in May), 0.46 in. in November–December 1986 (0.48 in. observed in December), and 1.18 inches in January through March 1987 (3.22 inches observed from January through May). In summary, the model predicted that a total of 2.75 inches of seepage would occur over the period of the field study and a total of 3.92 inches was observed to occur in the Control Plots in the field. Thus, 70% of the leachate production that actually occurred in the field was predicted by CREAMS, analogous to the 70% value we came up with between observed versus predicted soil water content (Fig. 28).

V. USE OF CREAMS TO DESIGN A PROTOTYPE CLOSURE PLAN AT A LOS ALAMOS WASTE REPOSITORY

As was pointed out earlier in this report, SLB design characteristics such as trench cap thickness do not have to be arbitrarily chosen. Now that we had a field-calibrated hydrologic model that described water balance relationships for the conventional SLB design configuration at Los Alamos, CREAMS was used as a tool to improve the design of SLB.

Using daily precipitation data from 1951 to 1970, a series of CREAMS simulations were performed by varying the thickness of the trench cap and determining the predicted amount of seepage occurring for both the average and the wettest year for each thickness. The parameters used in this effort were the same as those listed in Table 10 for the Control Plots, with the exception that the 1985 LAI distributions were used for the entire simulation period. One CREAMS simulation was performed for each of nine trench cap thicknesses (0.31, 0.46, 0.61, 0.91, 1.30, 1.52, 1.83, 2.13, and 2.52 m), one of which was similar to the total thickness of the ITP Control Plots (1.30 m).

One of the first major discoveries made in the use of CREAMS for SLB trench cap designs at Los Alamos was the influence of vegetative cover on

decreasing seepage through the SLB trench cap (Nyhan and Lane 1982). Since these early efforts were performed without field-calibrated CREAMS models, we decided to repeat this exercise with our field-calibrated model. The results of these CREAMS simulations are presented in Figure 29, where the performance of a trench cap with a bare soil surface with a 70% cover of gravel (zero LAI values, curve number equal to 82, winter cover factor equal to 1.0) is compared with one similar to that found on the ITP Control Plot (one with a 70% cover of gravel plus a good cover of range grass).

The results of this comparison (Fig. 29) show that the bare soil-gravel cover consistently produces about 10 cm of predicted annual seepage in the average year and about 23 cm of predicted annual seepage in the worst case (wettest year), regardless of the thickness of the trench cap. In contrast, the good range grass-gravel cover produces average annual seepage which ranges from predicted values of 8.3 cm to 0.36 cm as the trench cap thickness increases from 0.31 to 2.5 m. In the wettest year, the good range grass-gravel cover produced from 27 cm to 5.7 cm of predicted annual seepage as the trench cap thickness increased from 0.31 to 2.5 m. The major factor causing this observed difference between these two cover designs revolves around the vegetation enhancing evapotranspiration, and thus decreasing annual seepage, during the plant growing season. Thus, as the trench cap with the good range grass cover becomes thicker, the effective plant rooting depth increases, allowing more and more plant uptake of infiltrating precipitation.

If the results from the good range grass-gravel cover CREAMS simulation were used to design a trench cap for long-term repository closure, we can see (Fig. 29) that about 12 cm of annual seepage is predicted to occur in the wettest year (1957) with the thickness of the standard Los Alamos SLB trench cap configuration (1.30 m). This agrees with the amount of seepage which was

CREAMS 20 YEAR SIMULATION

Figure 29. Total annual seepage as a function of trench cap thickness in the average and wettest year for a bare soil-gravel and good range grass-gravel covers.

observed to occur on the ITP Control Plot in 1987 (8 cm). This is a good comparison of whether the CREAMS seepage predictions are on target or not, because the amounts of precipitation occurring in the winter months of 1957 and 1987 were similar (8.8 cm and 9.8 cm of precipitation received in the winter months of 1957 and 1987, respectively).

However, regardless of whether the CREAMS seepage predictions for the good range grass-gravel cover (Fig. 29) are for the 1.30 cm thickness (12 cm) or the 2.5-m-thick trench cap (5.7 cm), the amounts of annual seepage predicted for the wettest years between 1951 and 1970 are usually about 10-fold larger than the annual seepage occurring on the average year. The reason for this, of course, is that the wettest years (i.e., 1957 and 1987) are years where snowmelt dominates the seepage production temporal pattern, and seasonally when plant transpiration does not occur to help reduce potential seepage. This is a very important observation because neither the winters of 1957 nor 1987 were even 10-year events, in which 15 cm of precipitation would be received by the trench cap (Nyhan et al. 1988a), let alone a 100-year winter, in which even more precipitation would have occurred (Nyhan et al. 1988a). Since we mentioned in the last subsection that our CREAMS simulations generally underestimated seepage occurring in the field, the implications for the waste management site operator are that large amounts of percolation could occur in 10-year and 100-year winters, especially when antecedent fall soil moisture levels are large.

The second set of CREAMS simulations which we performed was designed to investigate whether doubling the leaf area index values could substantially increase evapotranspiration and thus decrease percolation. The results of these simulations are presented in Figure 30 for the small plant LAI distribution (the distribution used in the ITP Control Plot simulation in 1985: see

CREAMS 20 Year Simulation for
Range Grass-Gravel Cover (CN=65)

Average annual seepage: 1951-1970

Annual seepage in wettest year

Figure 30. Total annual seepage as a function of trench cap thickness in the average and wettest years for small and large plant LAI distributions.

Table 10) and for the large plant LAI distribution (twice the LAI values used in the ITP calibrated model: see Fig. 29). The reasoning behind using doubled LAI values was to approximate the LAI values which might occur if shrubs (Fig. 10) and grasses (Fig. 9) were in the plant cover at some stage in plant growth on the burial site approaching plant climax succession.

The results of doubling the plant LAI distributions generally reduced seepage production, but not significantly (Fig. 30). The annual seepage for the large and small LAI distribution simulations was essentially identical for trench cap thickness ranging from 0.31 to 1.52 m. However, doubling the LAI values in the wettest year did significantly decrease annual seepage by 2.1 to 2.6 cm for trench cap thicknesses greater than 1.52 m (Fig. 30). The overall effect on doubling the LAI values at the 2.5 m trench cap thickness for the wettest year was to decrease the annual seepage from 5.7 cm to 3.6 cm.

Most of the soil backfill materials used at Los Alamos would probably belong in Hydrologic Groups B and C (Lane 1984). In terms of the impact of soil type on annual seepage, Group B soils usually have infiltration rates on the order of 0.15 to 0.30 in./h, whereas Group C soil infiltration rates are usually 0.05 to 0.15 in./h. Thus, the final set of CREAMS simulations which we performed was designed to find out whether or not changing the type of soil used in the trench cap would influence the amount of annual seepage predicted to occur according to CREAMS.

The results of the CREAMS simulations on the two hydrologic soil groups are presented in Figure 31. Varying the Hydrologic Soil Group only had a small effect on the average amount of annual seepage predicted by CREAMS, using the same input parameters for good range grass-gravel cover as used for the ITP Control Plot (Fig. 29). In the wettest year, switching soils from

CREAMS 20 Year Simulation for
Good Range Grass-Gravel Cover

Average annual seepage: 1951-1970

Annual seepage in wettest year

Figure 31. Total annual seepage as a function of trench cap thickness in the average and wettest years for Hydrologic Groups B and C soils.

Hydrologic Group B to C usually decreased the amount of annual seepage by about 1 cm across all trench cap thicknesses tested. The overall effect of changing soil types used in the trench cap between these two hydrologic soil types appears to be insignificant, but needs to be field-tested because switching soil types may change other interdependent factors (such as LAI distributions) not considered by CREAMS.

VI. FUTURE DIRECTIONS OF FIELD RESEARCH AND MODELING ACTIVITIES

An ongoing field study at Waste Disposal Area B is studying runoff/infiltration characteristics of trench cap cover treatments consisting of shrubs, grasses, and shrub and grass covers with partial gravel cover. One future area of highly recommended modeling activities would be to investigate the influence of reducing the bare soil evaporation parameter (C) in CREAMS simulation results at Area B. The ITP modeling activities performed in this study indicated that C values should be decreased dramatically over those suggested to be used (Lane 1984) when a gravel cover was involved. Further field validation of this effect would greatly enhance the accuracy of the CREAMS predictions of seasonal seepage in SLB designs, since a partial gravel cover will certainly be used in these designs to reduce erosion of the trench cap. The near-surface field studies performed at Waste Disposal Area B will also greatly enhance our ability to predict soil loss rates for different cover treatments using the erosion component of CREAMS.

Another recommendation can be made as a result of the overall modeling efforts in this study. Since appreciable annual seepage is predicted to occur in the wettest years, capillary barriers should be used in the long-term closure designs of all SLB facilities. Since the Improved Plots contained capillary barriers which dramatically reduced annual seepage, this data base

should immediately be modeled with CREAMS and other hydrologic models. The field data and the modeling expertise are unique to Los Alamos and do not exist anywhere else in the US.

A possible alternative to capillary barriers might be to dramatically reduce winter seepage using conifers. Using an evergreen cover on the trench cap, in addition to a good cover of range grass, could greatly enhance evapotranspiration in the winter and early spring, thus reducing seepage in the wettest years (worst case) described in this study. This would probably make a good waste management decision, but would necessitate further studies of capillary/biointrusion barriers in prohibiting conifer roots from penetrating waste materials beneath the trench cap.

Finally, we would recommend additional future field research and concurrent hydrologic modeling in three other areas involved in the water balance equation. First, transpiration studies of various grass, shrub, and tree species need to be performed in the field at scales at least as large as our 3 by 10 m plots. The ultimate precision of a model like CREAMS to predict evapotranspiration will depend on our ability to accurately describe both seasonal transpiration and evaporation processes involved. The second area which needs further research involves further field investigations into seepage production in SLB configurations. Without seepage field data, both evapotranspiration and runoff parameter estimates need to be directly measured, which may not be possible with the technology at hand. Finally, a reliable technique needs to be developed and evaluated for determining the saturated hydraulic conductivity (K) for the field soils which agrees with the model estimates of K in a generic sense. A good field estimate of K representing a large field area would take a lot of guesswork out of CREAMS

parameter estimation, resulting in greatly enhanced accuracy in model predictions.

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