THE APPLICATION OF AN AGRICULTURAL WATER BALANCE AND EROSION MODEL IN ENVIRONMENTAL SCIENCE

A USER PERSPECTIVE

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INTRODUCTION

The science of ecology made major advances in the development of theory, models, and supporting data in the late 1940's. That progress, in large part, can be attributed to atmospheric testing of nuclear weapons and the generous sponsorship of the United States Atomic Energy Commission. Concern about the fate of fallout radionuclides in the environment led to a plethora of studies on the distribution and food chain transport of radionuclides such as ^{137}Cs, ^{90}Sr, and ^{131}I. Based upon that early radioecological work, and on the work of the International Biological Program, it became clear that ecological processes, which have evolved over millions of years to incorporate and distributed materials in the environment, dictated the eventual fate of fallout radionuclides. Because many radionuclides are chemical analogs of naturally occurring elements (i.e., Cs is an analog of K, Sr is an analog of Ca), knowledge of ecosystem processes was perceived as necessary for understanding the behavior of many, if not all, anthropogenic chemicals introduced into the environment.

As the science of ecology progressed, it became clear that the basic principles and interrelationships on material flow in ecosystems could be applied to understanding the consequence of (i.e., predicting) and potentially resolving environmental issues arising from many man-caused environmental stresses. Reclamation of disturbed lands, development of better practices for fertilizer and herbicide application to agricultural areas, and disposal of hazardous and radioactive waste have all benefited from application of ecosystem concepts to the problem.

In the early 1970's, the US Department of Energy (DOE, the Atomic Energy Commission's successor), began a major research program to understand the behavior and consequences of long-lived actinide elements in the environment. The environmental concern over actinides arose because these materials are associated with the nuclear fuel cycle, they are generally very long lived (i.e., ^{239}Pu has a 24,000 year physical half-life), and they are associated with waste streams generated by the nuclear industry.

Radioecological studies at Los Alamos (1, 2, 3, 4), as well as at many other locations (3, 4), resulted in two rather significant findings. First, greater than 99% of the actinide elements released to the environment deposit in soil and sediment. Secondly, the actinides are tightly bound to soil and sediment. Thus, processes that transport soil and sediment also transport these radionuclides. Studies at Los Alamos have shown that the hydrologic erosion of the soil is a major factor in the translational movement of plutonium deposited on the ground surface (5, 6) and, as a consequence of rain splash of soil, also greatly influences transport of plutonium to plants (7, 8) including vegetable crops (9).

This paper discusses the use of CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (10), in developing environmental research programs at Los Alamos and in designing and monitoring the performance of shallow land burial (SLB) sites for low-level radioactive waste (LLW). Discussion is also presented on research needs and ongoing studies involving Los Alamos to supply some of those needs.

ENVIRONMENTAL ISSUES CONCERNING LOW-LEVEL RAIOACTIVE WASTE DISPOSAL

Shallow land burial has been used as a waste disposal technique since the beginning of man. From recorded history, we know that as early as 6000 BC, Neolithic and pre-Elamite civilizations, in what is now Iran, used SLB for disposal of waste (11). In more recent times, as a consequence of expanding populations, industry, and development of energy for resources, concern has arisen about the adequacy of SLB for containing the potentially hazardous waste by-products generated by these activities.

In the United States low-level radioactive waste, such as generated by the nuclear power industry, hospitals, universities, and nuclear research and development facilities, is typically buried in shallow earth excavations of variable size but generally averaging 15-m wide by 15-m deep by about 200-m long (Figure 1). Trenches are filled with waste consisting of a heterogeneous mixture of materials, including laboratory trash, reactor parts, and dismantled buildings. A trench cap, of about 1-2 m thickness, is applied as a final covering to complete isolation of the buried waste from the biosphere.

Over the past 40 years, operating experience at SLB sites for LLW, demonstrates that current practices work fairly well in isolating buried radionuclides although virtually every one of the six commercial and five DOE sites has not proved 100% effective in confining the wastes to the trench environs (12, 13, 14). Of the six commerical LLW sites, three are currently operational; the closure of the three commercial sites is at least partly attributable to unanticipated problems with subsurface water and solute movement. Contamination of groundwater is of particular concern because it is so vital to man and his activities and is not readily subject to corrective measures for removal of pollutants. At the moment, no new low-level sites are being licensed by the US Nuclear Regulatory Commission partly because pending regulations (15) controlling siting, design, monitoring, and closeout of SLB sites have not been finalized.

Two important aspects of the pending regulation that affect SLB for LLW are that the waste must be buried in the unsaturated zone and that the performance of the site must be modeled. The first requirement is relatively easy to satisfy by not selecting sites located in or near groundwater aquifers. The

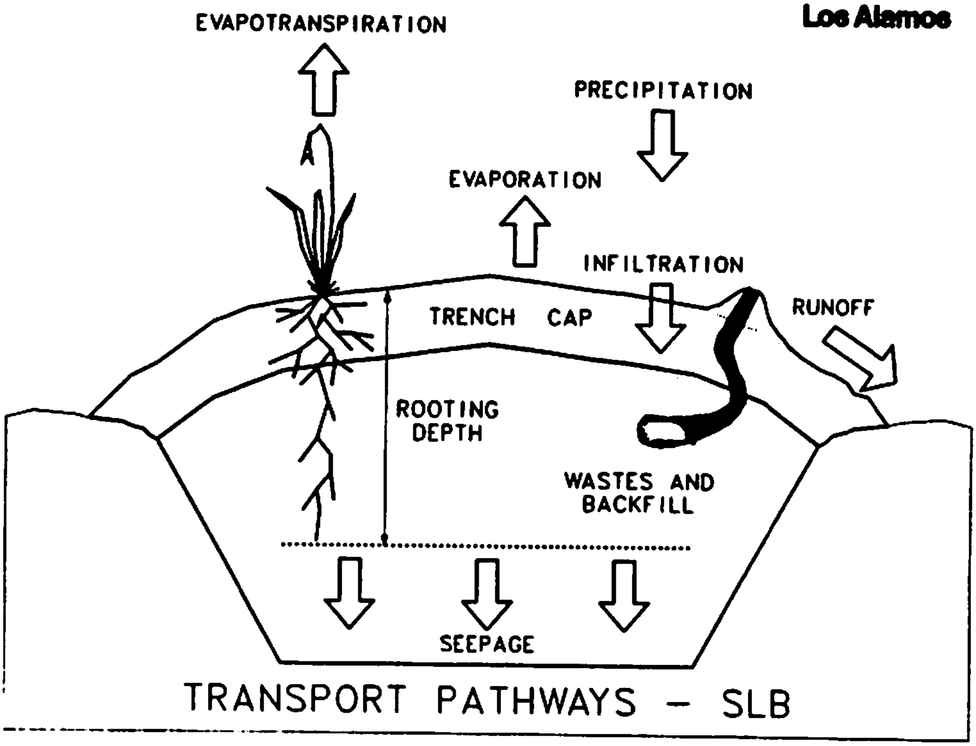

FIGURE 1. Hydrologic processes effecting shallow land burial sites.

second requirement is very difficult to satisfy because the models and data are, as yet, inadequate for predicting site performance, particularly as influenced by water and solute transport in the unsaturated zone.

If we examine the ecosystem processes that influence site performance with potential impact on dose to man (Figure 1), we note that water and soil dynamics, as influenced by physical and biological factors, account for most of the performance-related problems (12, 13). 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 100-200 year life of the LLW disposal facility. Likewise, water that infiltrates into 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.

A WATER BALANCE APPROACH FOR SLB

The conceptualization of water, soil, and biological processes that affect SLB integrity (Figure 1), reveals the interdependence of the physical and biological components of the trench cap (14). Precipitation incident on the site is subject to losses from runoff, infiltration into the soil, and interception by the plant canopy. Water that infiltrates into the soil can be lost back to the atmosphere by evaporation (E), transpiration (T) by the plant cover, or as the combined process of evapotranspiration (ET). Water remaining in the soil can be stored or, when it moves below the root zone, percolate or seep (L) into or through the waste trench. The following formulation describes some of the relationships that exist between the various components of the water balance:

$$\frac{dS}{dt} = P-Q-ET-L \tag{1}$$

where

S = soil moisture
P = precipitation
Q = runoff
ET = evapotranspiration
L = percolation or seepage
t = time

The experession relates the rate of change in soil moisture in the trench cap to input (P) and output (Q, ET, L) in units of volume per unit area per unit time, or equivalently, depth per time (e.g., mm per day).

Soil moisture stored in the trench cap is a function of water holding capacity of the soil, plant rooting depth and antecedent and current values for the terms on the right hand side of Eq. 1. Precipitation (P) is a function of the waste site locale and is highly variable in time and space. Runoff (Q) is a function of precipitation, soil characteristics, vegetation cover, soil moisture, and surface management practice, including slope and slope length. Evapotranspiration (ET) is a function of climatic variables, including precipitation, temperature, solar radiation, soil properties, vegetation type, and soil moisture. Percolation is a function of soil moisture and soil properties. Soil erosion and sediment transport are strongly related to precipitation and runoff, and, indirectly, to other terms in Eq. 1. Because plant and animal intrusion into and through a trench cap influences water balance, they also influence infiltration rates and erosion. Although the effects of burrowing animals are not directly represented in Eq. 1, they could be accounted for by the terms influencing soil moisture and erosion.

A water balance approach to resolving SLB issues offers the following advantages:

- it accounts for most of the hydrologic and biological factors that influence site integrity,
- water balance models can be used to screen various modifications in cap design for effect on erosion, percolation, and etc., and
- it can be used to estimate upper boundary conditions for subsurface water flow.

SIMULATING WATER BALANCE

Hydrologic and erosion processes are highly variable in time and space. As such it is not practical to measure them under all possible combinations of soils, climate, topography, biological conditions, and land use.

Consequently, mathematical models are needed to predict those processes under a wide range of conditions.

In response to similar needs in agriculture, the US Department of Agriculture (USDA) developed a reasonably simple computer simulation model called CREAMS (10, 17, 18, 19), which included water balance, erosion/sediment transport, and chemistry components. The model was intended to be useful in agricultural scenarios, without calibration or collecting of extensive site specific data to estimate parameter values, by taking advantage of extensive data sets (10) collected over several decades by USDA and others.

The CREAMS model has been widely used for agricultural applications (20) and recently has been used as a tool in waste management studies (21, 22). Although the model has been applied to SLB sites, it was developed for cropland situations and does not account for some of the physical and biological processes that are specific to non-agricultural ecosystems.

The CREAMS model predicts both water balance and erosion. The water balance components include two options, a daily rainfall model based on the US Soil Conservation Service runoff equation and an infiltration model using rainfall intensity data (23). The soil profile, to the plant rooting depth, is represented by up to seven layers (which could be a multilayered trench cap) each with a given thickness and water storage capacity. The evapotranspiration calculations, which are based on Ritchie's method (24), include soil evaporation and plant transpiration based on mean monthly air temperature, mean monthly solar radiation, and seasonal leaf area index. Flow through the rooting zone is computed using a soil water storage-routing routine and percolation is estimated when soil moisture exceeds field capacity. These calculations maintain a water balance as described in Eq. 1.

Using storm inputs from the hydrology component, the erosion/sediment yield component computes soil detachment, sediment transport and deposition by routing sediment through overland flow and in concentrated flow (19). Gross erosion and sediment yield are computed by sediment size classes, including soil aggregates. A more detailed description of the CREAMS model is presented in Conservation Research Report No. 26 (10), including results of model testing and evaluation, sensitivity analysis and a users manual for preparing model input.

APPLICATION OF CREAMS TO SLB

Evaluating Trench Cap Designs - The following two examples demonstrate the use of CREAMS in SLB to illustrate that water and soil dynamics in and on a trench cap can be modeled and that the ability to predict water balance and erosion in a highly disturbed trench cap can be used to optimize design in order to minimize or prevent unacceptable levels of erosion and/or percolation.

A paper entitled "Use of a State-of-the-Art Model in Generic Designs of Shallow Land Repositories for Low-Level Wastes" (22), describes the use of CREAMS to evaluate the effectiveness of various trench cap configurations in limiting erosion and percolation by varying trench cap soil type, soil depth, vegetative cover, slope steepness, and slope length. Selected results from that paper are presented below.

Model parameters for the simulation study were selected from conditions representative of Los Alamos, New Mexico, a semi-arid location in north-central New Mexico. Los Alamos receives an annual average precipitation input of 46 cm. Mean monthly temperature, solar radiation, and daily rainfall were selected for the 20 year period spanning 1951 to 1970. Trench cap soil parameters were selected from measurements on Hackroy soil (25) and a sandy backfill composed of crushed tuff configured with a uniform slope of 22 m and a slope steepness of 5%. Cover conditions included a non-vegetated soil, a sparse (20%) range grass cover, and a dense (40%) alfalfa cover.

Some significant results of the model simulation were that vegetation plays a key role in controlling both runoff, erosion, and percolation compared with a non-vegetated surface (Figure 2). Although the plant cover increased infiltration into the trench cap by reducing runoff (a 6-fold decrease for the alfalfa cover over that from the bare trench cap), the transpirational losses were sufficiently high to reduce percolation by a factor of at least five over that estimated for the bare cap surface. The great significance of the plant cover in controlling water balance and erosion on the trench cap will be examined in greater detail later in this paper.

Adding a clay layer within the trench cap effectively eliminated percolation compared with the soil/backfill cap design (Figure 3). However, the clay barrier reduced percolation at the expense of increasing runoff by almost 65% because of the higher antecedent moisture in the 15 cm of topsoil.

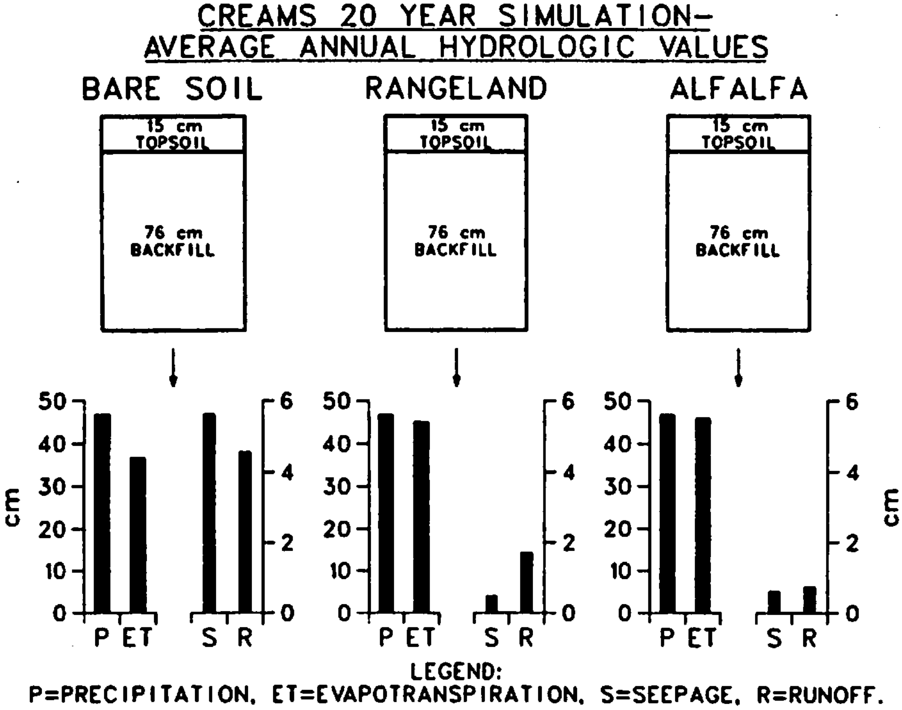

FIGURE 2. Predicted Average annual hydrologic values for a soil over sandy backfill trench cap at Los Alamos, N.M., 1951-1970. (from ref. 22).

Table I. Simulated 20 year average annual water balance for Maxey Flats, Kentucky during 1959-1978 as a function of trench cap management practice.

Practice	Rooting Depth (cm)	Runoff[a] (cm)	ET (cm)	Percolation (cm)	Erosion[b] T/ha
Bare soil	30[c]	49	65	3.8	457[d]
Grass, unmowed	60	23	93	2.1	12
Grass, mowed (3 times/yr)	60	24	93	2.0	15
Grass, mowed (every 3 weeks)	60	34	82	1.3	27
White Pine	90	11	105	0.61	0.0
White Pine	180	9.7	108	0.0	0.0

[a] 20 year average precipitation = 117 cm

[b] Sheet and rill erosion only

[c] Depth to which evaporation occurs

[d] Erosion rates greater than about 10T/ha are considered to be excessive in cultivated cropland for maintaining crop productivity.

Table II. Average annual precipitation and percolation (cm water) as a function of cover management practice on SLB trench designs at Maxey Flats, Kentucky.

Year	Annual Precipitation	White Pine	Mowed[a] Grass	Unmowed Grass
1959	112	5.6	5.9	6.9
1960	106	0.0	3.6	1.0
1961	121	0.0	0.0	0.8
1962	125	1.5	3.6	4.2
1963	89	0.0	0.0	0.5
1964	100	0.0	0.0	0.0
1965	117	0.0	0.5	2.8
1966	112	0.0	0.0	0.0
1967	114	0.0	0.0	0.0
1968	111	0.0	0.0	0.0
1969	85	0.0	0.0	0.0
1970	122	0.0	0.0	0.0
1971	114	0.0	0.0	1.4
1972	145	0.03	1.0	2.1
1973	112	0.0	1.1	2.9
1974	144	4.1	5.9	7.9
1975	150	0.8	4.0	5.8
1976	97	0.0	0.9	2.8
1977	111	0.0	0.0	0.0
1978	155	0.0	0.03	2.4
TOTAL	2312	12.0	16.5	41.5

[a] grass cover mowed every 3 weeks

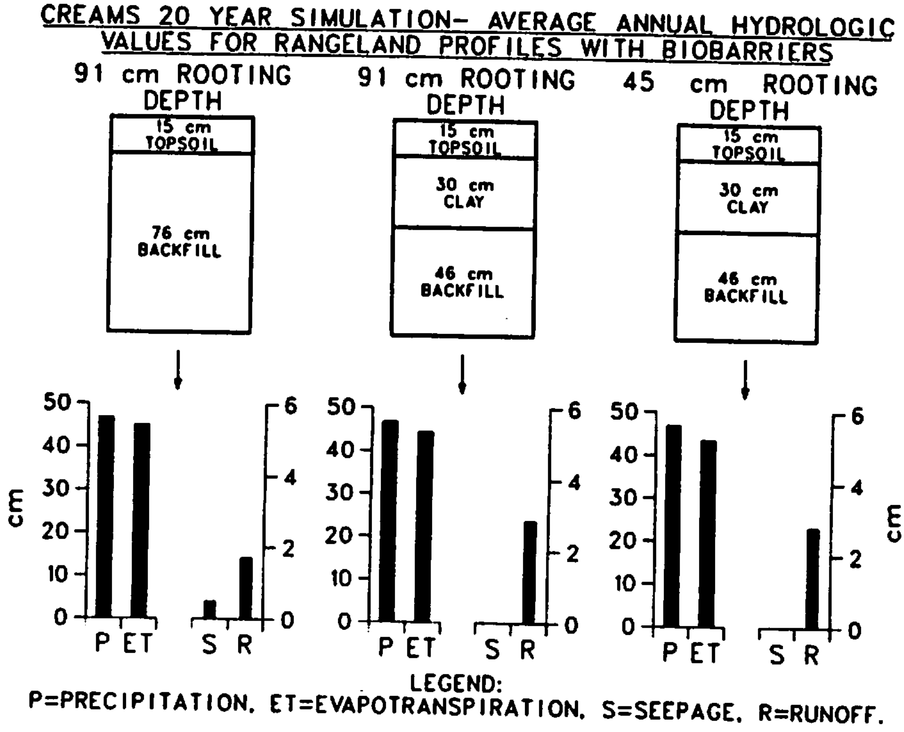

FIGURE 3. Predicted average annual hydrologic values for a topsoil over clay over backfill trench cap at Los Alamos, New Mexico, 1951-1970 (from ref. 22).

These results demonstrate the highly interactive nature of the ecosystem processes operating on an SLB site. To further emphasize that fact, studies at Los Alamos (16) have shown that while a clay moisture barrier may prevent percolation, the integrity of a saturated bentonite clay barrier (subject to swelling and shrinking) can be rapidly destroyed by invading plant roots, which abstract the moisture from the clay, causing it to shrink and crack.

In addition to evaluating the hydrologic response from multi-layered trench caps, CREAMS is useful in optimizing configurations of specific cap materials. For example, an important variable in the design of an SLB trench cap is the thickness of the cap material. Optimizing water storage capacity of the cap where it can be pumped back to the atmosphere by evapotranspiration, provides a potentially effective means of preventing percolation.

The effect of increased trench cap thickness on various components of the water balance for both vegetated and the bare soil conditions is illustrated in Figure 4. If we focus on seepage or percolation as a function of increasing cap thickness, we see that increasing thickness had little effect under bare soil conditions, but as thickness increased to about 1 m, seepage below the vegetated surface reached a minimum dictated by a plant rooting depth of 1 meter. Further increases in cap thickness had little effect on seepage because the plant roots could not exploit the deeper regions. Increasing

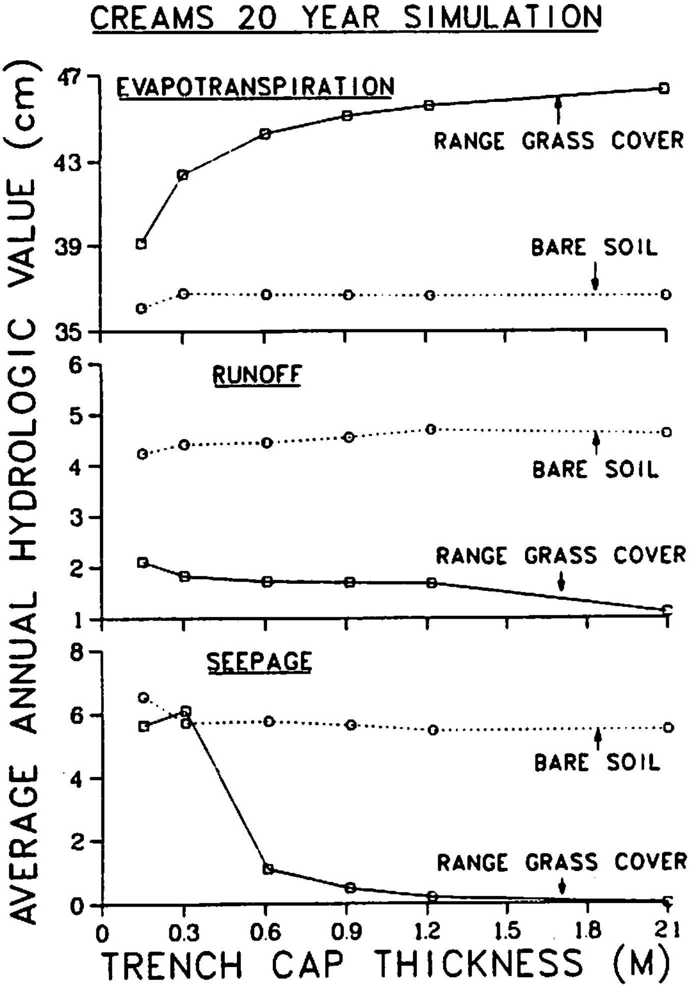

FIGURE 4. Predicted average annual hydrologic values as a function of sandy-loam trench cap thickness at Los Alamos, N.M., 1951-1970.

the cap thickness had little effect on runoff regardless of cover treatment although the very strong influence of vegetation in reducing runoff (compared to the non-vegetated surface) is apparent in Figure 4.

Evaluating Plant Cover Effects - The strong influence of the plant cover in controlling percolation and erosion led to the use of CREAMS to further explore the influence on vegetation type on water balance. Since plants use water at different rates, as controlled by species specific factors including phenology, species or species mixes could be chosen that maintain soil water as low as possible in order to store and eventually transpire precipitation arriving when ET is low (i.e., winter).

An increase of 5% in transpiration, over the year might reduce or eliminate percolation. Because vegetation species use water at different rates through the year (26), careful selection of the plant cover, to optimize transpirational losses through the year, may provide an inexpensive, long-term control of subsurface water and solute transport. However, as will be discussed later, relatively small changes in ET can result in large and significant changes in percolation and runoff, which leads to a dilemma. If we need to effect a 5% change in total ET but our methods of measuring and computing ET can result in errors on the order of 5%, then a great deal of uncertainty remains in our calculations for percolation and runoff. Clearly, carefully controlled and long term studies are required to validate ET models in general and the ET component of CREAMS in particular. Even so, the possibility of percolation control through vegetation and ET management as predicted by the CREAMS model has such enormous economic significance that continuing model improvements and applications appears warranted.

Maxey Flats in Kentucky, a commercial LLW site that was operated from 1963 to 1972, was chosen to illustrate the use of CREAMS for selecting optimum plant covers for trench caps. The site was chosen for the analysis because water accumulated in the trenches due to the bathtub effect described earlier. The accumulated water is pumped from the trenches and routed to a gas-fired evaporator to prevent subsurface water and solute transport to offsite areas. About 2.3 x 10^6 ℓ of water accumulated in the trenches each year until 1982 when most of the site was covered with an impermeable synthetic covering to prevent percolation into the trenches.

Annual precipitation at Maxey Flats averages 121 cm, of which about 3 cm percolated into trenches as measured by water levels and pumping volumes at the site. Estimates based on CREAMS simulations verify that the amount of percolation accounted for only 2-3% of the annual precipitation while runoff and ET distributed the remainder. The relatively small amount of percolation into the trenches at Maxey Flats led to the hypothesis that the problem of water accumulation in the waste trenches could be minimized by increasing runoff, evapotranspiration, and/or soil moisture storage capacity in the trench cover.

The CREAMS model was used to simulate water balance and erosion at Maxey Flats under a variety of plant cover conditions. Soil and climatological data for the CREAMS model were taken from existing site data and from Morehead, Kentucky, a nearby community. The native soil at Maxey Flats is a silt clay-loam that has very poor hydrologic characteristics because of the mechanical mixing of the soil on reapplication as a trench cap. Estimates of evapotranspiration as a function of plant species were made from the literature (27, 28, 29). Slope length was established as 70 m with a convex slope of 2-12% (2% on the peak of the trench cap, 12% on the flanks).

Average annual hydrologic values based on the CREAMS simulation for the 20 year climatologic record (1959-1978) are summarized in Tables I and II. Erosion rates from the vegetated trench cap averaged at least 30 times less than on the bare soil surface regardless of vegetation species used to cover the cap. While the plant cover reduced the amount of runoff over bare soil conditions, it did so at the expense of increased infiltration. However, by adding transpiration as a component of the water balance, the overall effect of the plant cover was to decrease percolation. The size of the decrease in percolation over bare soil conditions appeared to be a strong function of the plant species and cover management practices. For example, frequent mowing of the pasture resulted in less percolation than infrequent mowing or no mowing at all because more precipitation was lost to other sources including runoff. While ET was larger for the grass under the unmowed and infrequently mowed practice, it was not large enough to use the additional water that infiltrated into the cap. Moreover, the evergreen trees appeared to provide greater protection against percolation than the grass cover because of the higher transpiration rates throughout the year and, particularly, during the winter.

Seasonal averages of percolation over the 20 year period (Figure 5) identified late winter as the most critical period for the occurrence of percolation at Maxey Flats. All plant species and management practices prevented percolation during the summer months when evapotranspiration was occurring (Figure 6). However, the only species contributing to transpiration losses of water during the late winter, when the grass species were senescent, was the pine.

The ability to examine the consequences of various design and management practices in SLB sites on long-term hydrologic averages is useful. However, the large year to year variability in precipitation must be considered to design SLB systems that perform under climatic extremes. The data in Table II, on annual average percolation through the trench cap over the 20 year period, shows that the problem of percolation is not an annual occurrence for any of the cover or management practices examined, but is tied closely to fluctuations in annual precipitation. Measurable percolation was predicted in 13 years of the 20 year period for the unmowed grass cover while it was predicted

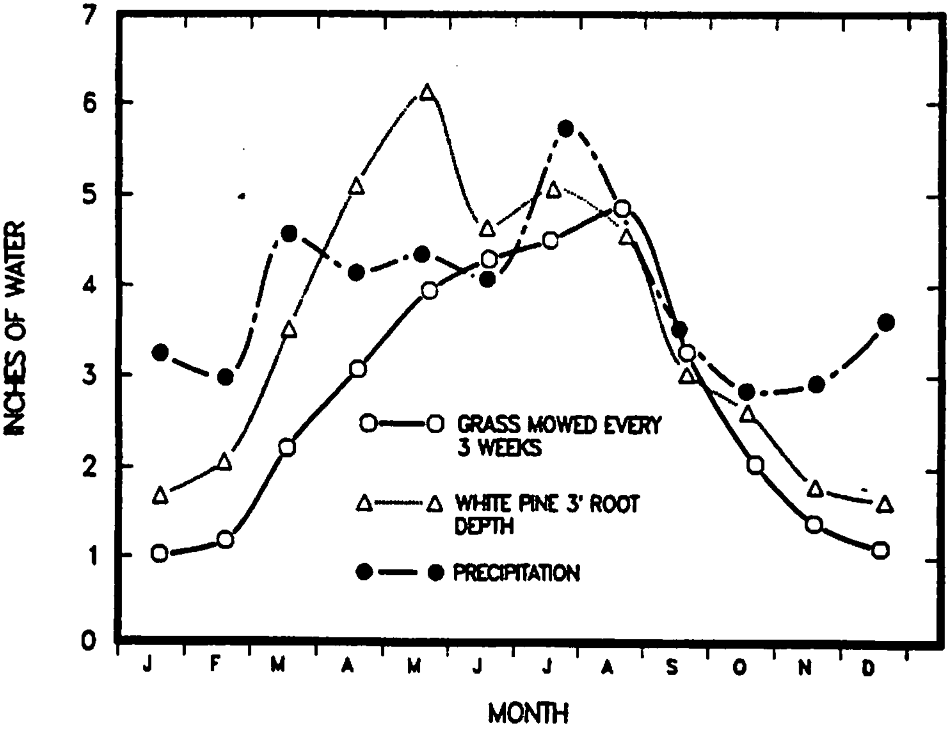

FIGURE 5. Predicted percolation through a 90 cm thick soil trench cap at Maxey Flats, Kentucky, 1959-1978, as a function of plant cover and management practice.

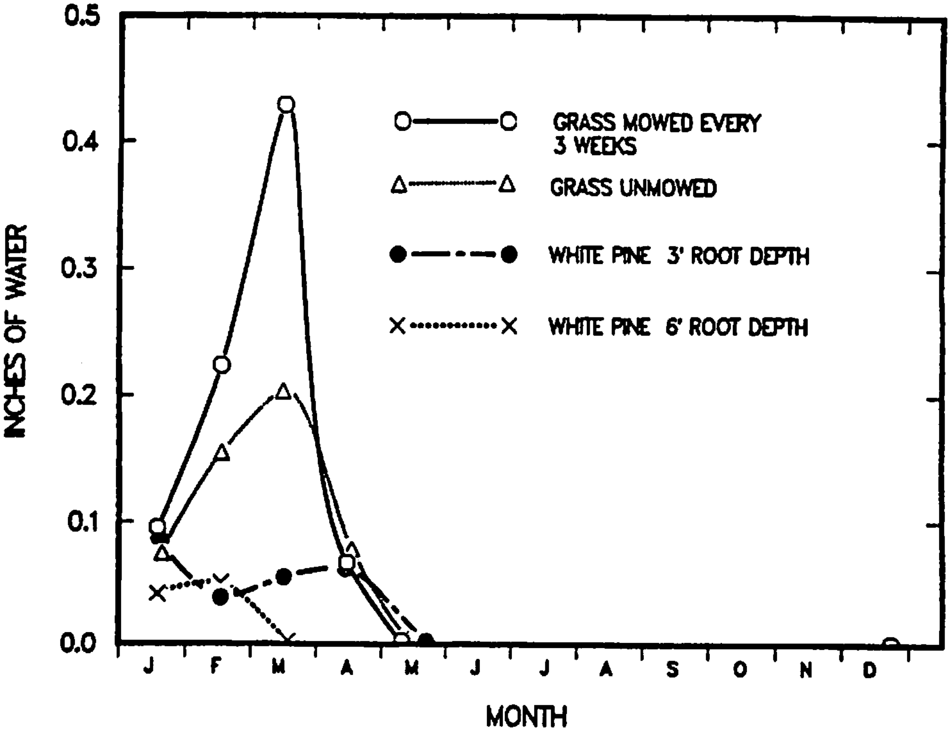

FIGURE 6. Predicted precipitation and evapotranspiration through a soil trench cap at Maxey Flats, Kentucky, 1959-1978, as a function of plant cover and management practice.

to occur in only 5 years with the White Pine cover. Although the pine cover did not eliminate the occurrence of percolation, it did reduce the total amount of percolation over the 20 year period by a factor of about 3 (12 cm vs 42 cm) over that estimated for the unmowed pasture cover.

ADVANTAGES/DISADVANTAGES OF CREAMS

The use of CREAMS for environmental science applications provides a powerful tool for examining ecological relationships involving soil, water, and biota. CREAMS is well-documented and accepted and used by several agencies and groups. Additionally, CREAMS is based upon extensive data sets from agricultural research in croplands and has been tested and validated for these conditions. There are ongoing efforts to improve various components of CREAMS including the hydrology and plant components (30, 31).

However, the application of CREAMS to arid/semiarid rangelands and, specifically, to waste management extends the model beyond its capabilities primarily because data describing those unique conditions are not readily available. For example, in rangelands, but particularly in disturbed systems such as SLB sites, plant succession becomes an important consideration in long-term water balance of a site. At Los Alamos, waste disposal site vegetation changes from initial invader species, such as Russian thistle (Gutierrezia sarothrae) and yellow sweet clover (Melilotus officinalis), to a shrub (Quercus spp, Rhus spp) and evergreen tree (Pinus ponderosa) community within 35 years of site closure. A similar situation exists in terms of changes in soil characteristics as climate and biota contribute to soil weathering. Trench cap soils on Los Alamos waste sites closed in the 1940's have changed from a relatively unproductive sandy material to a silt-loam with improved water retention characteristics and productivity.

Animal interactions, which are not directly represented in the model, are important in altering water balance, erosion and nutrient cycling (32, 33, 34). Studies at Los Alamos (35) suggested that pocket gophers *(Thomomys bottae)*, a fossorial rodent that commonly invades disturbed areas, may create significant disturbance of SLB trench caps with potential impact on erosion, percolation, and evapotranspiration (by altering plant density and plant succession) over the 100-200 year life of the site.

More immediate disadvantages of CREAMS for arid/semiarid site use is the lack of parameter estimates for the climatic, edaphic, and biological conditions that exist in these regions. Rainstorms, for example, often occur as intense thundershowers that are highly variable in space and time leading to problems in developing representative precipitation data for the model. A climate generator, reflecting that variability, would greatly facilitate adaption of CREAMS to arid-semiarid rangelands. Additionally, estimates of ET in native species as a function of season are not readily available, primarily because of the difficulty in making such measurements.

RESEARCH TO EXTEND CREAMS TO ARID SITES

Los Alamos is taking an active role in extending CREAMS to arid site SLB by fostering and participating in cooperative research with several groups and agencies. At Los Alamos and Nevada Test Site, USDA-ARS, University of California at Los Angeles, Nevada Applied Ecology Group, DOE, and Los Alamos National Laboratory are conducting joint studies using the USLE erosion plot configuration and the rainfall simulator (36, 37) to develop data and CREAMS model parameters under a variety of conditions ranging from undisturbed desert to semi-arid rangelands to highly disturbed SLB trench cap configurations. Significant results of those studies include:

- emerging data on the importance of soil fauna in mediating erosion and percolation,
- the importance of plant cover in limiting erosion and percolation in SLB,
- the effect of time on the hydrologic and erosional stability of disturbed sites, and
- the dominance of desert pavement (a natural gravel mulch) over vegetation in controlling erosion and percolation in a desert ecosystem.

The first three results are illustrated by the data in Figure 7 showing erosion (normalized to bare soil) from simulated SLB trench caps as a function of biological variables. The purpose of the experiment represented by the data in Figure 7 was to evaluate water balance and erosion as influenced by a 15-20% barley cover, burrowing animals *(Thomomys bottae* - Botts Pocket Gopher), and the interaction of plants and burrowing animals. Three rainfall simulator runs were made during a three month period in 1983 to examine time dependent relationships in the hydrologic response of the various treatments.

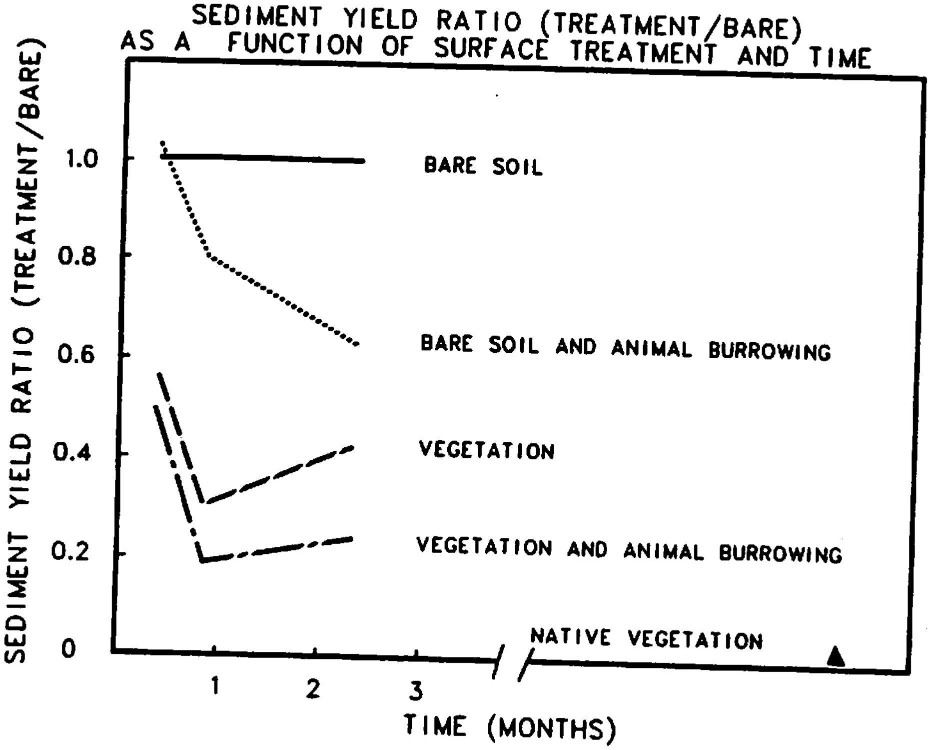

FIGURE 7. Sediment yield ratio (treatment/bare soil) as a function of biological factors and time.

The preliminary data indicated that soil cast to the trench cap surface by pocket gophers steadily decreased erosion to about 60% of bare soil erosion as a consequence of increased infiltration and decreased runoff velocities resulting from the surface soil casts. Erosion from the vegetated plots was 40% of bare soil conditions, after three months, while erosion from the vegetated plots with animals was the lowest at 20% of the bare plot treatment. While plants and animals provide effective control of erosion, they do so at the expense of increasing the infiltration of water into the trench cap.

The data for native vegetation in Figure 7 (solid triangle) is the normalized erosion rate from an undisturbed soil covered by a 15-20% blue gramma (*Bouteloua gracilis*) grass cover. Erosion rates from the natural plots averaged 2% that of the Barley plots despite the fact that both plots had about the same relative cover. These data suggest that both edaphic and biological successional processes are important in returning disturbed sites to erosional stability. The rates and pathways of disturbed land succession are important research questions that must be answered to improve designs and performance predictions for SLB sites.

Finally, results from ongoing rainfall simulator studies at Nevada Test Site (36) demonstrate the overwhelming importance of desert (or erosion) pavement in controlling runoff and erosion (Table III). In contrast, the sparse vegetation cover plays little direct role in controlling erosion. However, plants do greatly influence antecedent soil moisture, a variable that influences the amount of runoff and erosion.

Table III. Summary of sediment yield data from 12 experimental runoff-erosion plots on the Nevada Test Site. Average sediment yields in g/m^2, two plots per treatment, Spring 1983 (from reference 36).

Location	Treatment	Dry	Wet	Very Wet
Area 11	control, natural	1.3	6.0	12.3
	vegetation removed	1.2	8.2	16.2
	vegetation and erosion pavement removed	82.6	104.0	179.0
Mercury	control, natural	49.5	25.9	29.0
	vegetation removed	61.9	46.2	52.6
	vegetation and erosion pavement removed	555.0	404.0	302.0

SUMMARY AND CONCLUSIONS

The use of CREAMS in arid and semiarid rangelands and for applications to shallow land burial provides a powerful tool for developing management alternatives for land use and waste disposal. Because CREAMS was developed primarily for cultivated agriculture and parameterized in more humid conditions in the eastern half of the United States, it is not directly applicable to arid and semiarid systems without further development and calibration. Model parameters for CREAMS under the agricultural and environmental science applications discussed in this paper for the most part do not exist. Ongoing research by several groups and agencies is intended to rectify these deficiencies.

Perhaps the greatest weakness of CREAMS, or any similar model, is the lack of structure and feedback to account for time dependent changes in physical and biological attributes of a site. Plant and animal succession, and their influence on soils, becomes important over the time scales being considered for SLB performance. Until significant advances are made in our understanding and ability to mathematically describe ecosystem processes, models such as CREAMS will be somewhat limited in scope and utility. However, the need for tools to wisely manage natural resources will continue and represent challenges to the agricultural and environmental scientist to meet those needs.

REFERENCES

1. Hakonson, T. E., Nyhan, J. W. "Ecological Relationships of Plutonium in Southwest Ecosystems," Transuranic Elements in the Environment, W. C. Hanson (ed.), DOE/TIC 22800, US Department of Energy, NTIS, Springfield, Virginia, 1980, pp 403-419.

2. Hakonson, T. E., Nyhan, J. W., Purtymun, W. D. "Accumulation and Transport of Soil Plutonium in Liquid Waste Discharge Areas at Los Alamos," Transuranium Nuclides in the Environment, IAEA-SM-199/99, S. T. I./PUB/410. International Atomic Energy Agency, Vienna, 1976, pp. 175-189.

3. Watters, R. L., Edgington, D. N., Hakonson, T. E., Hanson, W. C., Smith, M. H., Whicker, F. W., Wildung, R. E., "Synthesis of Research Literature." Transuranic Elements in the Environment, W. C. Hanson (ed.), DOE/TIC 22800, US Department of Energy, NTIS, Springfield, Virginia, 1980, pp. 1-44.

4. Watters, R. L., Hakonson, T. E., Lane, L. J., "The Behavior of Actinides in the Environment," Radiochimica Acta, Akademsche Verlagsgesellschaft, Wiesbaden, Vol. 32, 1983, pp. 89-103.

5. Hakonson, T. E., Watters, R. L., Hanson, W. C., "The Transport of Plutonium in Terrestrial Ecosystems," Health Physics, Pergamon Press Ltd., Vol. 40, (January), 1981, pp. 63-69.

6. Lane, L. J., Hakonson, T. E., "Influence of Particle Sorting in Transport of Sediment Associated Contaminants" Waste Management 1982, R. G. Post (ed.), University of Arizona Press, Tucson, Arizona, 1982, pp. 543-557.

7. Dreicer, M., Hakonson, T. E., White, G. C., Whicker, F. W., "Rainsplash as a Mechanism for Soil Contamination of Plant Surfaces," Health Physics, Pergamon Press Ltd., Vo. 46(10), 1984, pp. 177-188.

8. Foster, G. R., White, G. C., Hakonson, T. E., Dreicer, M., "A Model for Splash Retention of Sediment and Soil-Borne Contaminants on Plants," J. Environmental Quality, Madison, Wisconsin, 1984 (in press).

9. White, G. C., Hakonson, T. E., Ahlquist, A. J., "Factors Affecting Radionuclide Availability to Vegetables Grown at Los Alamos." J. Environmental Quality, Madison, Wisconsin, Vol. 10, 1981, pp. 294-299.

10. Knisel, W. G., Jr. (ed.), CREAMS: A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems, USDA-Conservation Research Report No. 26, US Department of Agriculture, Science and Education Administration, May 1980, 640 pp.

11. Langer, W., An Encyclopedia of World History, Houghton Mifflin Co., Boston, Massachusetts, 1968, 1504 pp.

12. Duguid, J. O., "Assessment of DOE Low-Level Radioactive Solid Waste Disposal Storage Activities," Battelle Memorial Institute - 1984, Columbus, Ohio, (November 1977).

13. Jacobs, D. G., Epler, J. S., Rose, R. R., "Identification of Technical Problems Encountered in the Shallow Land Burial of Low-Level Radioactive Wastes," Oak Ridge National Laboratory/SUB-80/136/1, Oak Ridge, Tennessee, (March 1980).

14. Hakonson, T. E., Lane, L. J., Steger, J. G., DePoorter, G. L., "Some Interactive Factors Affecting Trench Cover Integrity On Low-Level Waste Sites," Low-Level Waste Disposal-Site Characterization and Monitoring,

M. G. Yalcintas (ed.), NUREG/CP-0028, CONF-820674, Vol. 2, NTIS, Springfield, Virginia, 1982, pp. 377-400.

15. 10CRF61, Licensing Requirements for Land Disposal of Radioactive Waste, (Proposed Rule) Federal Register 46(142), July 1981.

16. Hakonson, T. E., Cline, J. F., Richard, W. H., "Biological Intrusion Barriers for Large Volume Waste Disposal Sites," Low-Level Waste Disposal Facility Design, Construction and Operating Practices, M. G. Yalcintas (ed.), NUREG/CP-0028, CONF-820911, Vol. 3, NTIS, Springfield, Virginia, 1983, pp. 289-308.

17. Knisel, W. G., Jr., "Erosion and Sediment Yield Models-An Overview," ASCE Watershed Management Symposium, American Society of Civil Engineering, July 1980, pp. 141-150.

18. Knisel, W. G., Jr., Foster, G. R., "CREAMS: A System for Evaluating Best Management Practices," Economics, Ethics, Ecology: Roots of Production Conservation, W. E. Jeske (ed.), Soil Conservation Society of America, Ankevy, Iowa, 1981, pp. 174-179.

19. Foster, G. R., Lane, L. J., Nowlin, J. D., Laflen, J. M., Young, R. A., "Estimating Erosion and Sediment Yield on Field-Sized Areas," ASAE Vol. 24(5), 1981, pp. 1253-1262.

20. Warner, R. C., Dysant, B. C., "Erosion Modeling Approaches for Construction Sites," Proc. American Society of Agricultural Engineering Watershed Management Symposium, Boise, Idaho, July, 1980.

21. Lane, L. J., Romney, E. M., Hakonson, T. E., "Water Balance Calculations and Net Production of Perennial Vegetation in the Northern Mojave Desert," J. Range Management, Vol. 137(1), January 1984 pp. 12-18.

22. Nyhan, J. W., Lane, L. J., "Use of a State of the Art Model in Generic Designs of Shallow Land Repositories for Low-Level Wastes," Waste Management 1982, R. G. Post (ed.), University of Arizona Press, Tucson, Arizona, 1982, pp. 235-244.

23. Smith R. E., Williams, J. R., "Simulation of the Surface Water Hydrology," CREAMS: A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems, W. G. Knisel (ed.), USDA-Conservation Research Report No. 26, May 1980, pp. 13-35.

24. Ritchie, J. T., "A Model for Predicting Evapotranspiration From a Row Crop with Incomplete Cover," Water Resources Research, Vol. 8(5), 1972, pp. 1204-1213.

25. Nyhan, J. W., Hacker, L. W., Calhoun, T. E., Young, D. L., "Soil Survey of Los Alamos County, New Mexico," Los Alamos Scientific Laboratory Report LA-6779-MS, June 1978, 102 pp.

26. Saxton, K. E., "Evapotranspiration," Hydrologic Modeling of Small Watersheds, (C. T. Haan, H. P. Johnson, and D. L. Brackensiek, eds.), The American Society of Agricultural Engineers, 2950 Wiles Road, St. Joseph, Michigan, 1982, pp. 229-273.

27. Federer, C. A., "Evapotranspiration (Literature Review, 1971-1974)," Reviews of Geophysics and Space Physics, Vol. 13(3), 1985, pp. 442-445.

28. Ritchie, J. T., Rhoades, E. D., Richardson, C. W., "Calculating Evaporation from Native Grassland Watersheds," Transactions of ASAE, Vol. 19(6), 1976, pp. 1098-1103.

29. Hibbert, A. R., "Forest Treatment Effects on Water Yield," International Symposium on Forest Hydrology, (W. E. Sopper and H. W. Lull, eds.), Pergamon Press, Oxford, pp. 527-543.

30. Wright, J. R. (ed.), Spur- Simulation of Production and Utilization of Rangelend: A Rangelend Model for Management and Research, USDA-ARS Miscellaneous Publication No. 1431, 1983, 120 pp.

31. Renard, K. G., Foster, G. R., "Soil Conservation: Principles of Erosion by Water," Dryland Agriculture, (H. E. Dregne and W. O. Willis, eds.), ASA, CSSA, SSSA Monograph No. 23, 1982, pp. 155-176.

32. Abaturov, B. D., "The Role of Burrowing Animals in the Transport of Mineral Substances in the Soil," Pedobiologia, Vol. 12, 1972, pp. 261-266.

33. Chew, R. W., "The Impact of Small Mammals on Ecosystem Structure and Function," Populations of Small Mammals Under Natural Conditions, Pymatuning Laboratory of Ecology, Special Publication No. 5, May 1976.

34. Ellison, L., "The Pocket Gopher in Relation to Soil Erosion in Mountain Ranges," Ecology, Vol. 27, 1946, pp. 101-114.

35. Hakonson, T. E., Martinez, J. L., "Disturbance of a Low-Level Waste Site Trench Cover by Pocket Gophers," Health Physics, Vol. 42(6), June 1982, pp. 868-871.

36. Bostick, K. V., Simanton, J. R., Lane, L. J., Hakonson, T. E., "Results of Erosion and Contaminant Transport Research on the Nevada Test Site," Nevada Applied Ecology Program Symposium, Las Vegas, Nevada, June 28-30, 1983, (in press).

37. Nyhan, J. W., DePoorter, G. L., Drennon, B. J., Simanton, J. R., Foster, G. R., "Erosion of Earth Covers Used in Shallow Land Burial at Los Alamos," J. Environmental Quality, May-June Issue, 1984, (in press).

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