LA-10177-M

Manual

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

Surface Water Management: A User's Guide to Calculate a Water Balance Using the CREAMS Model

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This work was supported by the US Department of Energy, National Low-Level Waste Management Program.

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UC-70B
Issued: November 1984

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CONTENTS

EXECUTIVE SUMMARY

This report adds information to that given in the CREAMS manual (USDA Conservation Research Report No. 26, Knisel 1980) and emphasizes several aspects not discussed in previous publications. First, we emphasize arid and semiarid areas of the West, whereas the CREAMS model originally emphasized agricultural areas. Second, we emphasize application for shallow land burial (SLB) systems and thus deal with bare soil, grass cover, and shrubs rather than traditional agronomic species. Third, example parameter values and sources for parameter estimates are discussed in considerable detail. Using information herein and in the references, the user should be able to derive parameter input files for several ecosystems in the West. Fourth, the user is guided through examination of simulation results (output data) and methods of interpreting them as related to SLB systems. Finally, we show the user how to apply results of the CREAMS hydrologic model to develop performance criteria such as allowable runoff or percolation amounts at a SLB facility.

The introduction describes the recent developments that led to more formalized regulations and policies governing SLB of low-level radioactive wastes and details the subsequent need to develop hydrologic models to compute a water balance for surface and near-surface SLBs. A simple form of the water balance equation is presented and is explained using an illustration of a SLB system.

To select, operate, and maintain a SLB site, it is necessary to model the system and characterize it hydrologically. We show how the CREAMS model can be used and describe some previous applications in waste management.

Parameter estimates and estimation procedures for the CREAMS model are presented in detail. First, each card image in the input files is described (precipitation data input file and parameter file) and then the parameter names, functions, source of estimates, and methods of estimation are shown. Section 2.1 defines parameters that represent the soil and gives first-order or generalized estimates of all soils parameters as functions of soil texture classes. These generalized or first-order estimates for the soil parameters are given in Tables I-V, with Table VI as a "locator summary" for the user's convenience.

Section 2.2 defines the plant parameters, including leaf-area data (Table VII) and maximum rooting depth data for vegetation types (Table VIII). These rooting depth data represent the cumulative frequency of maximum reported rooting depths (Table VIII); an appropriate effective rooting depth might be the median (50 percentile) depth interpolated from data in Table VIII.

Section 2.3 describes the topographic data and explains how they are used to estimate runoff peak discharge while avoiding unreasonably large estimates for small-plot modeling.

Section 2.4 outlines the required climatic data. Precipitation data are contained in a separate file of 37 card images per year of precipitation data. Mean monthly temperature and solar radiation data are entered as part of the parameter input file.

Section 2.5 explains the control variables or switches used to control operation of the program and to activate various options. To terminate the simulation run, the last card in the parameter input file (card 14) should have a −1 in the first position.

Sections 2.6 and 2.7 discuss sensitivity analysis and cautions that help the user avoid some of the more common errors. In addition, Section 2.7 briefly describes representation of porosity, field capacity, wilting point, and percolation in the CREAMS model.

Section 3 describes in detail the example precipitation and parameter input files in the exact formats required by the computer program and follows three examples of the model in semiarid areas (Los Alamos, New Mexico) and in arid areas (Rock Valley, Nevada). The first example deals with range grass conditions at Los Alamos, the second shows how the parameters would be modified to represent bare soil conditions and the third illustrates an application at Rock Valley, Nevada, in the northern Mojave Desert.

Section 4 first describes special features of the computer output and emphasizes the variables, units, and conversions the user must recognize to use the output data or simulation results. Then, output from the examples given in Section 3 are interpreted and implications for SLB systems are discussed.

Section 4.3 suggests how the user might apply the simulation results to design a trench cap for SLB facilities at Los Alamos or similar locations. Finally, we discuss some practical limits the user should recognize when applying the CREAMS hydrologic model in design or evaluation of SLB systems.

The summary section a presents brief review and helps the user quickly locate specific information. The discussion section provides a perspective on using both the CREAMS model and this manual.

SURFACE WATER MANAGEMENT:

A USER'S GUIDE TO CALCULATE A WATER BALANCE USING THE CREAMS MODEL

by

Leonard J. Lane

ABSTRACT

The hydrologic component of the CREAMS model is described and discussed in terms of calculating a surface water balance for shallow land burial systems used for waste disposal. Parameter estimates and estimation procedures are presented in detail in the form of a user's guide. Use of the model is illustrated with three examples based on analysis of data from Los Alamos, New Mexico and Rock Valley, Nevada. Use of the model in design of trench caps for shallow land burial systems is illustrated with the example applications at Los Alamos.

1. INTRODUCTION

Although shallow land burial of wastes began with early civilizations, recently developed rules and regulations require the ability to model hydrologic processes on shallow land burial (SLB) systems used for the disposal of low-level radioactive wastes. An important part of hydrologic models for SLB systems is the surface water balance. This balance is an accounting or budgeting of water from the soil through its entire profile to the plant rooting depth, an accounting that includes input, output, and storage terms. Precipitation is the input to the system, whereas outputs are net surface runoff, evaporation and transpiration losses, and net subsurface flow. The subsurface flow can be either lateral or vertical; the vertical downward flow below the root zone is often called deep seepage or percolation. Changes in soil water content account for gains or losses of the water stored in the soil profile (see Fig. 1).

Trench covers that isolate wastes at SLB facilities are subject to the interactive factors of a dynamic system, which includes water dynamics. Failure of the trench cap can cause failure of engineered barriers, excessive soil erosion, plant and animal intrusion into the waste, and percolation of infiltrated water into the waste, ultimately allowing mobilization and transport of radionuclides. Such failures emphasize the importance of water management at SLB facilities, and have been documented by Jacobs et al. (1980), Clancy et al. (1981), Kahle and Rowlands (1981), and Hakoson et al. (1982).

It is unlikely (e.g., see Federal Register 10 CFR 61 1981) that many future sites will be located in the water table, therefore, infiltration and percolation through the soil to the plant rooting depth are both the upper boundary and initial conditions for subsurface water flow and radionuclide transport calculations. However, because water management can in fact vary the potential subsurface water flux by orders of magnitude, SLB designs should include analysis of surface and near-surface water dynamics to calculate a water balance and the upper boundary conditions for subsequent subsurface flow calculations. Therefore, there is an urgent need for user-oriented documentation of hydrologic models used to compute a water balance at SLB facilities.

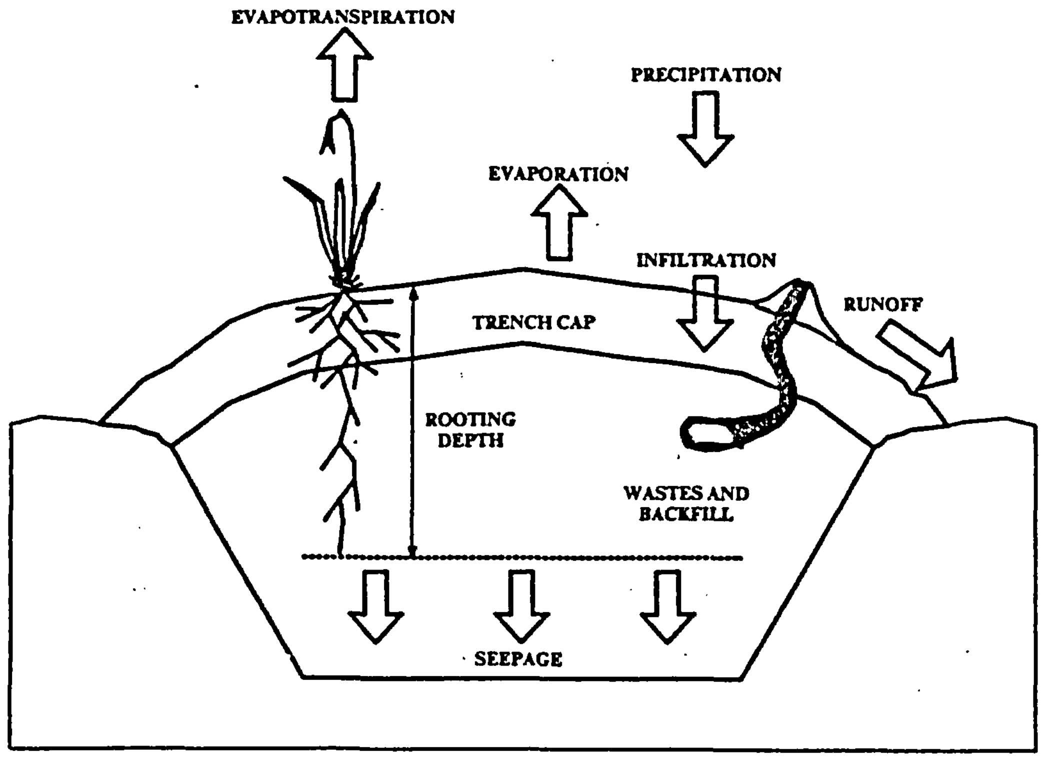

Fig. 1. Schematic illustration of a shallow land burial (SLB) facility showing important interactive factors and possible contaminant pathways.

1.1 Background

Water balance at a SLB facility, as conceptualized in Fig. 1, has been discussed in previous publications (e.g., see Hakonson et al. 1982) and is a paradigm for interactive factors, especially surface and near-surface water balance dynamics, that control the performance of SLB facilities. If we restrict our attention to net rates and amounts and consider one-dimensional movement of water in the soil profile, then we have the following simplified water balance equation:

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

where

$\frac{ds}{dt}$ = time ratio of change in soil moisture,

P = precipitation,
Q = runoff,
ET = evapotranspiration,
L = seepage or percolation, and
t = time.

Applying this equation to the plant rooting depth illustrates that the rate of change in soil moisture with time (ds/dt) is equal to the difference between input (P) and output (Q, ET, and L).

Units of the terms are expressed as volume per unit area per unit time, or equivalently, as units of depth per unit time (e.g., in. or mm per day, month, or year). Hakonson et al. (1982) point out that the performance of SLB facilities is controlled by interactive factors, including surface, near-surface, subsurface processes; this fact is demonstrated when Eq. (1) is used to explain Fig. 1. Hakonson et al. (1982) described terms in Eq. (1) and Fig. 1 as follows:

> *The amount of soil moisture (S) stored in the profile is a function of the water holding capacity of the soil, plant rooting depth, and the antecedent and current values for the variable on the right side of Eq. 1. Precipitation (P) is a function of the climate at a particular waste burial site and is highly variable in time and space. Runoff (Q) is a function of precipitation, soil type, vegetation, surface management practice, and soil moisture. Evapotranspiration (ET) is a function of climatic variables (e.g., precipitation, temperature, solar radiation), soil properties, vegetation type, and soil moisture. Percolation (L) is a function of soil properties and soil moisture.*
>
> *Because soil erosion and sediment transport are strongly related to precipitation and runoff, they are also related to the other terms in the water balance equation. Finally, because plant and animal intrusion through the trench cap affect the water balance they also affect infiltration rates and erosion.*
>
> *Based on the foregoing discussion, most of the components of the water balance equation illustrated in Figure 1 also illustrate contaminant transport pathways that can result in dose to man. Specific examples include:*
>
> - *erosion of the trench cover and exposure of the waste,*
> - *percolation of surface water into the trench with subsequent leaching and transport of the waste,*
> - *capillary forces by evapotranspiration, which transport waste to the ground surface, and*
> - *plant and animal transport of the waste to the ground surface.*
>
> *In order to control those pathways and to determine site characteristics that must be measured to ensure control, we must recognize that we are dealing with an interactive system. For example, suppose we adopt a conservation measure to control trench cover erosion by reducing surface runoff. We need to know how this conservation measure influences other terms in the water balance equation, and, by extension, the other contaminant transport pathways such as plant uptake and percolation. Likewise, if we install a biological intrusion barrier system (e.g., a rock layer within the cover profile) to prevent plant and animal access to the buried waste, we need to determine how this action might influence the water balance equation and, again by extension, contaminant transport pathways associated with runoff, erosion, and percolation.*

Models to compute surface water balance would help meet policy and regulatory requirements (e.g., Federal Register 10 CFR 61 1981), and they would also fill scientific, engineering, and practical needs. Several modeling needs are discussed in the following material.

1.2 Site Selection, Operation, and Monitoring

The water balance equation must be solved if SLB sites are to be hydrologically characterized. One way to solve the water balance equation is to measure each of its components [Eq. (1)] for a sufficiently long period, but how long an area must be gauged to establish an accurate representation depends upon the objectives (i.e., daily means, monthly means, annual means, or all these means and their associated variances. etc.). To establish mean annual precipitation values, hydrologists often speak of a "30 year normal." In contrast, design criteria for hydrologic analysis often require the 25-, 50-, or 100-year flood. We could cite many other examples (e.g., Brakensiek et al. 1979) of the extensive time and resources required to hydrologically gauge a site to specify terms in the water balance equation.

Clearly, we cannot wait decades before using the water balance equation in SLB site selection; an accurate, valid hydrologic model for predicting terms in the equation would shorten the long gauging process.

Moreover, because construction of SLB facilities disturbs the natural or existing hydrologic systems and changes terms in the water balance equation, we need a model to project these terms into the future. Also, SLB sites cannot be operated without considering the processes represented by the water balance equation. For example, enough water can accumulate in the trench and waste material during operations so that subsequent percolation causes transport of contaminants after closure—even if the integrity of the trench cap prevents percolation below the root zone. Moreover, SLB site operation obviously affects both the buried wastes (e.g., layering and degree of compaction) and the trench cap, which in turn affect the water balance equation.

Hakonson et al. (1982) described the need for a simulation model as follows:

> *Because climatic, hydrologic, and biologic processes are highly variable in time and space, it is impossible to measure or monitor them under conditions representative of all possible combinations of soils, climate, topography, vegetative cover, and land use. Consequently, there is a need for mathematical models to predict those processes under a wide range of environmental conditions. Procedures to estimate runoff, erosion, infiltration, percolation, evapotranspiration, and soil moisture in trench cover systems, such as are illustrated in Fig. 1, will be essential in designing and monitoring the performance of future SLB sites.*

The above does not adequately discuss the interaction of modeling and monitoring. Proper designs for sampling frequency cannot be prepared without first establishing rates, amounts, and the interactions between the processes being monitored and the environment in which they are occurring. For example, if percolation occurs within a few hours or days following rainfall, then monthly sampling might not detect significant percolation. Many other, and more sophisticated, examples could be presented. The point is that an accurate water balance model can be useful in design and operation of monitoring schemes.

1.3 The CREAMS Model

In 1978, the US Department of Agriculture assembled a team of scientists who were to prepare a state-of-the-art model for estimating non-point-source pollution. Knisel and Nicks (1980) described the development of a field-scale model (called CREAMS):

> *A question arose immediately: What size is a field? The physical size of farm fields varies from a few acres in ridge and valley provinces to a few tens of acres in the Corn Belt to a few hundreds of acres in the Wheat Belt and western rangelands. Such a size range required some arbitrarily imposed constraints. Thus, a field herein is defined as a management unit having (1) a single land use, (2) relatively homogeneous soils, (3) spatially uniform rainfall, and (4) single management practices, such as conservation tillage or terraces. The definition allows different physical sizes in different climatic regions and Land Resources Areas (LRAs).*
>
> *To achieve the goal of model assembly in a year, state-of-the-art models were assembled and/or modified. Criteria for the model were: (1) the model must be physically based and not require calibration for each specific application, (2) the model must be simple, easily understood with as few parameters as possible and still represent the physical system relatively accurately, (3) the model must estimate runoff, percolation, erosion, and dissolved and adsorbed plant nutrients and pesticides, and (4) the model must distinguish between management practices.*
>
> *Although hydrology is only one component of the total system, water is the principal element; it causes erosion, carries chemicals, and is an uncontrolled natural input. Each climatic region and physiographic area has its own characteristics that affect the response of the system. These varied conditions must be kept in mind when considering wide-scale applicability of a model.*

Therefore, the CREAMS model is intended for field-scale application, which limits its use to drainage areas on the order of an acre to perhaps a few hundred acres. Since this report is limited to the hydrologic components, the following comments by Smith and Williams (1980) are appropriate.

Central to the simulation of pollutant movement on and from a field site is the simulation of the amount and rate of water movement on the surface and through the soil. All major hydraulic processes which occur during a rainstorm – such as rainfall infiltration, soil water movement, and surface water flow can be simulated in detail with current knowledge of hydraulics and the capabilities of modern computers. The constraint in the construction of this model, however, is to approximate the complexity of these processes and their interrelations with a model whose sophistication is appropriate to the detail of data expected to be available in its intended use.

The field-scale hydrologic response simulation includes models for infiltration, soil water movement, and soil/plant evapotranspiration between storms. It is a continuous simulation model using a day as the time step for evapotranspiration and soil water movement between storms, and using shorter time increments dictated by available rainfall records during storms. The between-storm simulation provides prediction of amount of seepage below the root zone and gives an initial soil water content at the beginning of a storm, which is an important initial condition for storm runoff simulation. When storm rainfall records are not available, runoff is estimated by the SCS curve number procedure (7).

In other words, the CREAMS model has two options: We describe the daily option (daily rainfall-runoff model) for the reasons indicated above and because of its simplicity.

The CREAMS model is described in detail by Knisel (1980) in USDA Conservation Research Report No. 26, which users should review before running the computer simulation model.

1.4 Examples of Prior Use of the CREAMS Model in Arid SLB

In 1981, as part of the National Low-Level Waste Management Program (NLLWMP), the Environmental Science Group at Los Alamos began investigating the possible use of the CREAMS model in SLB technology development and corrective measures and found that the CREAMS model had enormous potential in many areas of waste management research (Lane and Nyhan, 1981). After we examined the model and assessed its applicability, we accelerated efforts to apply it to waste management problems and we established experimental runoff-erosion plots (e.g., Nyhan and Lane, 1982) to determine parameters for the water balance equation under semiarid conditions.

Hakonson et al. (1982) prepared a synthesis paper that discussed CREAMS model applications in waste management and related such applications directly to Fig. 1. The hydrologic component of the CREAMS model was applied to data from Rock Valley, Nevada, to estimate a water balance and predict net primary production of perennial desert shrubs (Lane et al. 1984). This extended its application to an arid site. Application of the erosion component at SLB systems has recently been described by Nyhan et al. (1984).

In addition to these publications, CREAMS model applications in waste management have been documented in monthly reports, annual reports, information reports, and presentations at workshops and symposia. This report describes the differences between SLB systems and the agricultural systems used in the original CREAMS documentation (Knisel 1980) and provides additional parameter value estimates for SLB systems.

1.5 Scope and Limitations

This report deals only with the hydrologic component of the CREAMS model. Although the erosion component is closely related (and is in fact driven by) the hydrologic component in CREAMS, it is described elsewhere. We limited our attention to the daily rainfall-runoff model

(Option 1) for the practical reasons described earlier.

This report should "stand alone" for individuals who have some experience with SLB techniques and with the CREAMS model. It is assumed that the user has access to the CREAMS model on a digital computer and will use the program to make calculations related to SLB technology development, operations, monitoring, corrective measures, or design.

The CREAMS model is a widely known and accepted model used in waste management. However, research scientists, users, and program administrators should not see the CREAMS model as an absolutely accurate and final representation of hydrologic processes in the surface and near-surface areas of SLB facilities. Instead, the CREAMS model is one step in continuing efforts to understand and improve models of the water balance and associated technology for surface water management.

2. PARAMETER ESTIMATES AND ESTIMATION PROCEDURES

For efficiency, precipitation and parameter data files are entered into the computer in a particular order, but for ease of description we discuss them as follows.

2.1 Parameters to Represent the Soil

There are six main parameters and two derived parameters to describe the soil profile in the CREAMS hydrologic model. The six main parameters are the runoff curve number (CN) the effective saturated hydraulic conductivity (RC), the soil evaporation parameter (C), the porosity (P), the field capacity (FC), and the wilting point (WP). The two derived parameters are pore-space fraction filled at field capacity (FUL) and the plant-available soil water storage capacity (UL). These eight parameters are described in detail in the following section and are summarized in Table VI. Chapter I (Hydrology) in Vol. II of the CREAMS documentation is a user manual for the hydrologic component (Williams et al. 1980, pp. 165-192). Table II-6 on pp. 174-177 lists card numbers and parameters for each input card image in the parameter data file. (Note: throughout this report the terms card and card image are synonymous.) The following notation will be used herein to describe input parameters and relate them to information presented by Williams et al. 1980, Table II-6: Parameter Name (FORTRAN Variable Name, card number, position on card).

Curve Number (CN2, Card 6, Variable 2)

This notation means that the infiltration parameter or runoff curve number (CN) is called CN2 in the CREAMS manual, that it is entered on parameter input file card image 6, and that it is the second value or number listed on card 6. This notation will be followed where possible.

The Soil Conservation Service runoff equation is

$$Q = \begin{cases} 0 & P \leq I_a = 0.2S \\ \dfrac{(P - 0.2S)^2}{P + 0.8S)} & P \geq I_a = 0.2S \end{cases} \tag{2}$$

where S = retention parameter (in.),
P = daily rainfall depth (in.),
Q = daily runoff volume (in.), and
I_a = initial abstractions.

The initial abstraction term is sometimes taken as a variable fraction of S but will be taken as 0.2S herein. The relation between S and CN is

$$CN = \frac{1000}{10 + s} \quad , \qquad (3)$$

or equivalently

$$S = \frac{1000}{CN} - 10 \qquad (4)$$

Values of CN vary from 0.0 (no runoff) to 100 (all precipitation becomes runoff). Smith and Williams (1980) detail how this runoff equation is used in a continuous simulation mode so we will examine only the estimation methods for CNs.

The Soil Conservation Service National Engineering Handbook (NEH-4 1972) is the basic source document for estimation of CNs and uses the concept of hydrologic soil groups. In general, infiltration decreases and runoff increases in hydrologic soil groups A (high infiltration), B (moderate infiltration), C (slow infiltration), and D (very slow infiltration). Characteristics of hydrologic soil groups are summarized in Table I.

On the basis of information published by Rawls et al. (1982), which represented analysis of over 1300 soils in 32 states, and on the basis of SCS (1982) and Lane and Stone (1983), we can generalize relationships between soil textural classes and hydrologic soil groups as shown in Table II. The data in Table II do not reflect any infiltration restricting or reducing layers and assume a deep soil profile (say 36 in. or more in depth).

Information from Table I could of course, change the preliminary hydrologic soil group classification from Table II. For example, if the soil were described as a sandy loam, we might classify it as A or B soil from Table II. However, if the profile description said there were restricting layers or hardpan at a depth of about 10 in., then Table I would suggest a D soil. In summary Table I identifies hydrologic soil groups based upon general depth, texture, infiltration rate, and profile description material, whereas Table II suggests hydrologic soil groups based upon texture alone. The tables should be used together, but Table I is more discriminatory.

Given that the soil is classified as A, B, C, or D, then to estimate a CN the user needs to consider land use, management, and cover complexes. Information from NEH-4 (1972), Zeller (1979), and Branson et al. (1981) was used to compile CNs for various hydrologic soil group/vegetation cover complexes as shown in Table III. The runoff curve numbers shown in Table III synthesize much information from various soil groups/vegetation cover complexes in the western United States. As a synthesis, the data in Table III represent a good deal of smoothing and generalization. Therefore, if specific SLB conditions do not match the "cover type and conditions" description found in Table III, the user has the option of either extrapolating from Table III or conducting on-site experiments to determine runoff curve numbers.

Rainfall-runoff data from watersheds can be used to derive data-based runoff curve numbers. The difficulty of collecting watershed data was discussed earlier, but techniques for small watersheds are described in detail by Brakensiek et al. (1979). An alternative is to use rainfall simulators on experimental plots. Proceedings of Rainfall Simulator Workshop, USDA (1979) discusses these techniques and the particular technique used in related research at Los Alamos and elsewhere in the West is described by Simanton and Renard (1982).

Effective Saturated Conductivity
(RC, Card 5, Variable 2), and
Soil Evaporation Parameter
(CONA, Card 5, Variable 5)

The effective saturated conductivity represents the profile-effective or profile-average saturated hydraulic conductivity, which determines percolation rates. There are many ways to estimate an average or effective saturated hydraulic conductivity of a soil profile. Considering the

TABLE I

SUMMARY OF HYDROLOGIC SOIL GROUPS AND THEIR CHARACTERISTICS USED TO DEFINE RUNOFF CURVE NUMBERS (CN).
[See NEH-4 (1974) for additional details]

Soil Group	Typical or Unusual Characteristics	Comments
A	High infiltration rates even when wetted. Well-drained to very well drained gravel, sand, loamy sands, and sandy loams. Soils with depths of 36 in. or more without infiltration reducing or restricting layers.	Low runoff potential and very low CNs. Final infiltration rates on the order of 0.30 to 0.45 in./h or higher.
B	Moderate infiltration rates. Moderately well-drained to well-drained soils with moderately fine to somewhat coarse texture. Usually soils with depths of 20 in. or more.	Low to moderate runoff potential and CNs. Final infiltration rates on the order of 0.15 to 0.30 in./h.
C	Slow infiltration rates. Moderately fine to fine texture or infiltration reduction caused by layering. Usually 20 in. or less of soil over an infiltration reducing layer.	Moderate to high runoff potential and CNs. Final infiltration rates on the order of 0.05 to 0.15 in./h.
D	Very slow infiltration rates. Clay soils with swelling potential. Shallow soils over nearly impervious material (i.e., rock). Usually less than 12 in. of soil over a layer restricting infiltration.	High runoff potential and CNs. Final infiltration rates on the order of 0.05 in./h or less.

TABLE II

APPROXIMATE COMPOSITION OF 12 SOIL TEXTURAL CLASSES AND THEIR RELATIONSHIPS WITH HYDROLOGIC SOIL GROUPS WITHOUT INFILTRATION RESTRICTING LAYERS
(Amounts of clay, silt, and sand are in percent)

Soil Texture Class	Clay	Silt	Sand	Hydrologic Soil Group Association
Sand	3	7	90	A
Loamy sand	5	15	80	A
Sandy loam	10	20	70	A to B
Loam	20	40	40	A to C
Silt loam	15	65	20	A to D
Silt	5	87	8	B to C
Sandy clay loam	30	10	60	A to D
Clay loam	35	35	30	C to D
Silty clay loam	35	55	10	D
Sandy clay	45	5	50	B to D
Silty clay	45	50	5	D
Clay	65	20	15	D

TABLE III

RUNOFF CURVE NUMBERS FOR VARIOUS HYDROLOGIC SOIL GROUP-COVER COMPLEXES, ANTECEDENT MOISTURE CONDITION II

(Percent cover designations are approximate.)

Cover Type and Conditions	Runoff Curve Numbers By Soil Groups A	B	C	D
Hard, compacted surfaces such as dirt roads, etc.	74	84	90	92
Unimproved bare soil	72	82	87	90
Desert brush				
<10% cover	a	84	88	93
20% cover	a	83	87	92
40% cover	a	82	86	90
Pasture or range				
poor	68	79	86	89
fair	49	69	79	84
good	39	61	74	80
Herbaceous plants, brush, and grass				
20% cover	a	79	86	92
40% cover	a	74	82	90
Piñon/juniper/grass				
40% cover	a	65	75	88
60% cover	a	57	70	86
80% cover	a	48	62	83
Ponderosa pine				
40% cover	a	61	75	80
60% cover	a	55	70	77
80% cover	a	49	65	73

[a] Data not available.

storage-routing methods used to calculate percolation in the CREAMS model, we recommend using the minimum saturated hydraulic conductivity anywhere in the profile as the value controlling percolation.

Lane and Stone (1983) estimated gross soil properties (see Tables II, IV, and V) based on the extensive data, including textural triangles, of Rawls et al. (1982) and SCS (1982). In the tables, data labeled "avg" represent a central, or representative, value of the mean properties. The columns labeled "low" and "high" refer to low and high estimates on the single estimate of the mean but do not refer to the maximum expected range for the given parameter or even the statistical range of the estimated mean. Rather, they refer to the type of variation one might find by interpolating between iso-lines plotted on a soil textural triangle if the iso-lines were derived from data as presented by Rawls et al. (1982).

TABLE IV

EFFECTIVE SATURATED HYDRAULIC CONDUCTIVITY ARE BARE-SOIL EVAPORATOR PARAMETER ESTIMATES BY SOIL TEXTURE CLASS

Soil Texture Class	Saturated Hydraulic Conductivity (in./hr)			Bare Soil Evaporation Parameter (mm/$d^{1/2}$)		
	avg	low	high	avg	low	high
Sand	9.1	4.6	17.0	3.3	3.05	3.32
Loamy sand	2.4	1.4	4.6	3.3	3.05	3.32
Sandy loam	0.87	0.67	1.4	3.5	3.10	4.06
Loam	0.51	0.36	0.67	4.5	3.20	4.57
Silt loam	0.27	0.18	0.36	4.5	3.20	4.57
Silt	0.20	0.12	0.24	4.0	3.15	4.40
Sandy clay loam	0.12	0.10	0.18	3.8	3.15	4.32
Clay loam	0.08	0.07	0.10	3.8	3.15	4.32
Silty clay loam	0.07	0.06	0.08	3.8	3.15	4.32
Sandy clay	0.05	0.04	0.06	3.4	3.10	3.56
Silty clay	0.04	0.03	0.05	3.5	3.10	3.81
Clay	0.03	0.02	0.04	3.4	3.10	3.56

TABLE V

POROSITY, FIELD CAPACITY (−⅓ bar), WILTING POINT (−15 bar), AND THE PARAMETER FUL BY SOIL TEXTURE CLASSES

(Porosity, field capacity, and wilting point are in terms of water content in % by volume. The parameter FUL is dimensionless.)

Soil Texture Class	Total Porosity			Field Capacity			Wilting Point			FUL
	avg	low	high	avg	low	high	avg	low	high	avg[a]
Sand	41	39	43	9	7	15	3	2	6	0.16
Loamy sand	43	39	45	12	10	20	6	4	8	0.16
Sandy loam	45	39	52	20	14	29	9	5	12	0.31
Loam	47	45	52	26	20	36	12	9	18	0.40
Silt loam	50	49	55	31	20	36	13	7	20	0.49
Silt	51	49	55	28	26	30	9	6	12	0.45
Sandy clay loam	42	38	45	27	17	34	17	11	21	0.40
Clay loam	47	40	51	34	29	38	20	16	24	0.52
Silty clay loam	47	46	51	36	33	40	21	18	24	0.58
Sandy clay	42	40	44	31	27	40	21	18	30	0.48
Silty clay	48	46	49	40	35	46	27	23	32	0.62
Clay	49	44	52	42	34	49	29	23	38	0.65

[a]Values of FUL calculated for average values only to indicate a typical range of values. The user should calculate the actual value of FUL using Eq. (5) once P, FC, and WP are selected.

Therefore, the user should interpret data from these tables as rough estimates designed to distinguish gross differences in soil properties between generalized textural classes. Subtle differences must be determined with laboratory analysis of soil samples and perhaps field studies including rainfall simulator studies. Finally, these data are derived predominantly from agricultural soils and probably do not represent desert soils with high gravel content. An exception is engineered soil profiles containing gravel mulch for erosion control at SLB sites.

In the evaporation equation, the soil evaporation parameter C or CONA in mm/day$^{1/2}$ is used to estimate evaporation from bare soil. Lane and Stone (1983) estimated values of C by synthesizing data from Ritchie (1972), Jackson et al. (1976), SCS (1982), and a derivation of the effective depth of evaporation as a function of soil water-holding capacity. The calculated bare-soil evaporation is proportional to the quantity (C −3) raised to a power. Therefore, C cannot be less than 3 and the evaporation calculations are sensitive to small changes in C as it approaches 3.

Representative values of effective saturated hydraulic conductivity and the effective soil evaporation parameter are summarized by soil texture class in Table IV. Very low hydraulic conductivity values are often given for pure or nearly pure clays. The terms clay, sand, etc., used herein refer to soil texture classes and not to the pure minerals. Representative proportions of sand, silt, and clay in each texture class are given in Table II.

Porosity (POROS, Card 5, Variable 6)

Minus 1/3 Bar Water Content
(not directly entered)

Minus 15 Bar Water Content
(BR15, Card 5, Variable 7)

Pore Space Fraction Filled
(FUL, Card 5, Variable 3)

These parameters describe the water-holding capacity of the soil profile, specified for each layer or horizon to the plant rooting depth. A depth-weighted average is computed for each of them to derive a representative value for the entire profile. The amount of smoothing resulting from this averaging depends upon the variability between layers in the soil profile.

Porosity, P, is a measure of the void space and is thus a measure of the soil's ability to store water. The −1/3 bar water content, often termed field capacity or FC, is the water content of the soil at a −1/3 bar potential correlating with that soil water content at which the rate of drainage or percolation is drastically reduced over its rate at saturation. Some CREAMS users estimate FC as the water content at −1/10 bar.

The −15 bar water content is often called the wilting point, WP, because it is the approximate water content at which some plants come under stress and begin to wilt. Obviously, plants adapted to arid conditions usually continue to extract water well below −15 bar to perhaps as much as −40 bars, so although the concept of wilting point remains valid it may not be well represented by the −15 bar water content; the user can lower the wilting-point soil water content to better represent soil water extracting abilities of plants in arid and semiarid environments. Under extreme desert conditions, we recommend using wilting-point water content near the air-dry values (e.g., perhaps near −50 bars).

The parameter FUL is the fraction of the pore space filled at field capacity. Therefore, although field capacity is not an input parameter for CREAMS, it is used to calculate FUL as follows (see Fig. 2 in Section 2.7):

$$FUL = (FC - WP)/(P - WP) \quad (5)$$

where FC = field capacity,
WP = wilting point, and
P = porosity.

Again, the variables in Eq.(5) are the depth-weighted averages for the soil profile to the plant rooting depth. Moreover, the definitions of FC and WP can vary as follows: Field capacity, FC, can be defined as the water content in the tension range −1/10 to −1/3 bar and wilting point, WP, can be defined as the water content in the tension range −15 to −50 bar. Therefore, P and WP are only approximations representing gross soil properties.

Table V shows values of porosity, field capacity, wilting point, and average values of FUL by soil texture class. Notice that for convenience the water content data (P, FC, and WP) are given in percent water content by volume, whereas the actual values read in by the CREAMS program are in absolute units (e.g., 0.50 rather than 50%). Therefore, the user would divide P and WP by 100 to enter as POROS and BR15 on card 5 in the parameter input file.

Plant-Available Soil Water Storage (UL(1-7), Card 7, Variables 1-7).

The CREAMS model represents the soil profile to the plant rooting depth, RD, by seven layers. If the soil profile is uniform, then the soil water storage per unit depth remains constant. If water storage characteristics vary with depth, then the CREAMS model approximates this depth variation by allowing UL(1) to UL(7) to vary. The general formula UL(I) is

$$UL(I) = D(I)\,[P(I) - WP(I)]\,RD, \tag{6}$$

where UL(I) = plant-available water storage in layer I (in.),
D(I) = weighting factor for layer I,
P(I) = porosity averaged over the depth interval D(I) RD,
WP(I) = wilting point averaged over the depth interval D(I) RD,
RD = plant rooting depth (in.), and I = index for the soil layer.

The weighting factors D(I), I = 1 to 7, are 1/36, 5/36, 1/6, 1/6, 1/6, 1/6, and 1/6, respectively.

Summary of Soils Parameters in CREAMS

The "soils" parameters required for the CREAMS parameter file are summarized in Table VI. Notice that the indexed notation [e.g., P(I)] refers to a "layer" property, whereas the unindexed notation (e.g., P) refers to a profile-average value.

The parameter values represent general trends and relationships based on gross soil properties as organized by soil texture class. As such, they reflect significant, rather than subtle, differences in soil properties. If these parameters are insufficient or inappropriate to estimate CREAMS parameters for an actual or planned SLB site, then the user has two options: (1) Change the parameter values to represent the actual SLB conditions if the amount and direction of change is known, and can be calculated. For example, compaction can change bulk density. If the change in bulk density is known the change in porosity can be calculated directly. (2) Measure soil properties to estimate appropriate parameter values, if the magnitude and direction of change in a given parameter is unknown and cannot be calculated or deduced. Some on-site measurements will probably be necessary anyway and will always be desirable when using CREAMS or any other model.

TABLE VI

SUMMARY OF "SOILS" PARAMETERS USED IN THE CREAMS PARAMETER INPUT FILES, THEIR LOCATION, AND SOURCE OF ESTIMATES

Parameter Name	Name and Location in CREAMS Parameter Input File	Source of Estimate In this Paper
Runoff curve number, CN	CN2, Card 6, Variable 2	Tables I, II, and III
Effective saturated hydraulic conductivity	RC, Card 5, Variable 2	Table IV
Soil evaporation parameter, C	CONA, Card 5, Variable 5	Table IV
Porosity, P	POROS, Card 5, Variable 6	Table V
Field Capacity, FC		Table V
Wilting point, WP	BR15, Card 5, Variable 7	Table V
Pore space fraction filled	FUL, Card 5, Variable 3	Eq. (5) using P, FC, and WP
Plant available soil water storage	UL(I), Card 7, Variables 1-7	Eq. (6) using D(I), P(I), WP(I), and RD

2.2 Descriptions of the Plant Component

In the CREAMS hydrologic model, the three main descriptors of the plant components are (1) the leaf-area index (ratio of projected leaf surface area to unit area of the soil used in estimating evapotranspiration), (2) plant rooting depth (describing the depth of the soil profile and water extraction from the soil), and (3) the winter cover factor (as a measure of cover material affecting soil evaporation).

Seasonal Leaf-Area Index
(LDATE, AREA, Card 13, Variables 1 and 2)

The FORTRAN variable LDATE is the Julian date for the given leaf-area index value AREA. Even though there are only 365 days in nonleap years, the final values of LDATE must be 366 to accommodate leap years. Smith and Williams (1980) describe the actual evapotranspiration (AET) computations used in the CREAMS model. The following equations show AET computations on daily time steps. The actual soil evaporation, ES_o is computed as

$$ES_o = E_o \exp(-0.4\ \mathrm{LAI})\ , \tag{7}$$

where E_o = potential evaporation (in.), and
LAI = leaf area index.

The actual plant transpiration, T_o, is computed as

$$T_o = \begin{cases} E_o(\mathrm{LAI}/3) & 0 \le \mathrm{LAI} \le 3 \\ E_o - E & \mathrm{LAI} \ge 3 \end{cases}\ , \tag{8}$$

where E is the actual soil evaporation and the other variables are as described above. If the soil water is limiting (at or below 0.25 field capacity, FC), then the plant transpiration is reduced as

$$T = T_o \, SM/(0.25FC) , \quad (9)$$

where SM = soil moisture ≤0.25 FC, and FC is field capacity of the soil. Of course, the sum of soil evaporation, E, and plant transpiration, T, cannot exceed the potential daily evaporation, E_o. This potential is computed with temperature and solar radiation following the procedure described by Ritchie (1972).

Seasonal leaf-area index data (LAI) for selected plant communities are summarized in Table VII. Notice that many of these data are estimated because it is difficult and time consuming to compute LAIs. Nonetheless, there is a real need for additional seasonal leaf-area index data measured over several years and in several ecosystems. At present, data shown in Table VII are probably representative of various locations in the West, but they are not definitive and precise;

TABLE VII

SUMMARY OF SELECTED LEAF AREA INDEX (LAI) DATA
FOR AREAS IN THE WESTERN UNITED STATES
ORIGINAL DATA INTERPOLATED AND EXTRAPOLATED TO A FULL CALENDAR YEAR

Calender Date	Julian Date	Texas Meadow Grass[a]	Texas Panhandle Native Grass[b]	Shortgrass Prairie[c]	Range Grass[d]	Cottonwood Midgrass Prairie[e]	Los Alamos 40% Cover Grass and Shrubs[f]	Rock Valley, Nevada, Desert Shrubs[g]
Jan 1	1	—	—	—	—	—	0.70	0.02
Feb 1	32	—	—	—	—	—	0.70	0.02
Mar 1	60	—	—	—	—	—	0.70	0.15
Apr 1	91	—	0.05	0.02	0.02	0.06	0.70	0.35
Apr 15	105	0.70	0.06	0.06	0.03	0.35	1.00	0.33
May 1	121	1.50	0.20	0.10	0.05	0.65	1.33	0.30
May 15	135	1.50	0.30	0.20	0.10	1.10	1.70	0.21
June 1	152	1.50	0.47	0.33	0.20	1.49	1.70	0.10
June 15	166	1.50	0.40	0.44	0.60	1.57	1.70	0.10
July 1	182	1.50	0.32	0.39	1.00	1.52	1.70	0.10
July 15	196	1.50	0.24	0.32	1.00	1.32	1.70	0.10
Aug 1	213	1.20	0.18	0.25	1.00	1.15	1.70	0.10
Aug 15	227	0.88	0.12	0.24	0.90	1.03	1.60	0.12
Sept 1	244	0.45	0.05	0.05	0.80	0.82	1.50	0.15
Sept 15	258	0.10	—	0.05	0.50	0.70	1.28	0.17
Oct 1	274	—	—	0.05	0.20	0.69	1.08	0.20
Nov 1	305	—	—	0.02	0.01	0.40	0.70	0.10
Dec 1	335	—	—	—	—	—	0.70	0.02
Dec 31	366	—	—	—	—	—	0.70	0.02

[a]Williams, et al. (1980), Fig. II-VIII, p. 183.
[b]Becker (1984), Fig. 6, Knight (1973) data adjusted for Texas climate.
[c]Knight (1973), Fig. 2, average values.
[d]Nyhan and Lane (1982), estimated values.
[e]Hanson (1973), plots with light grazing at Cottonwood, South Dakota, 1969-1971.
[f]LAI values estimated for mixed grass and shrubs at Los Alamos, New Mexico.
[g]Lane et al. (1984) estimated values from leaf biomass, percent cover, and phenology data.

the user will undoubtedly have to make LAI estimates or on-site measurements. In the absence of such hard data, the data shown in Table VII are proposed for first approximations.

Plant Rooting Depth

(RD, Card 6, Variable 5)

It is difficult to measure plant rooting depth and root mass distribution with depth to estimate effective rooting depth. Environmental, genetic, and physiological factors affect the effective rooting depth; site specific rooting depth data and soil survey data should be used when available.

Literature reviews provide approximate *maximum* expected rooting depths. For instance, Whittaker and Marks (1975) provide root data, especially tabular data, summarizing root/shoot ratios for various types of plants. Root/shoot ratios for annual herbs vary from about 0.1 to 0.2, prairie grass is given as 0.22, and a desert shrub (creosote bush) a root/shoot ratio of 0.39. These data are not quantitative, but they provide the following rule of thumb: For the plants discussed above, some 10 to 40% of the total plant mass is root material. Thus, one can view standing plant material and roughly visualize the approximate mass of root material. Again, these are only rough approximations that provide an "order-of-magnitude" range for investigating more quantitative estimates of effective plant rooting depth.

We need more leaf-area and plant rooting data for arid and semiarid SLB sites. Long-term studies would assess the influences of climate, seasonal variations, soil factors, and competition, while short-term studies would yield leaf-area indexes and plant rooting depths for immediate use in SLB designs. In the meantime, the user may use data given above, data in Table VIII from Foxx et al. (1984), and on-site measurements to estimate plant rooting depth. Data in Table VIII represent maximum reported rooting depths. Therefore, we recommend using the 50 percentile value as an approximate rooting depth.

TABLE VIII

MAXIMUM ROOTING DEPTH DATA FROM TABLE IV IN FOXX ET AL. (1984) TO USE AS UPPER LIMIT ESTIMATES FOR EFFECTIVE PLANT ROOTING DEPTH IN WATER BALANCE CALCULATIONS

(Data listed are percent of plants having rooting depths less than the indicated depths.)

Life Form	36 in.	72 in.	108 in.	144 in.	180 in.
Annual grasses	75	100	—	—	—
Biennial forbs	65	100	—	—	—
Annual forbs	65	88	97	100	—
Perennial forbs	42	71	85	93	97
Subshrubs	41	85	96	96	96
Perennial grasses	40	79	94	99	99
Evergreen	33	80	86	86	86
Deciduous trees	7	52	70	78	80
Shrubs	10	47	60	72	77

Winter Cover Factor
(GR, Card 12, Variable 1)

This parameter reflects the influence of ground cover during winter. The CREAMS user manual and subsequent documentation provide limited information, so we make the following recommendations: If the SLB facility has bare soil (no significant litter, plant residue, standing dead vegetation, or gravel mulch), use a value of GR = 1.0; otherwise, use GR = 0.50. In the past, users have interpolated between GR = 0.5 and GR = 1.0, depending upon the soil condition. However, these interpolations have not been supported by hard data.

2.3 Topographic Data

The topographic input data are: watershed area, watershed length-width ratio, and channel slope. Watershed area is the most hydrologically important of the geomorphic or topographic variables and is required to convert between units of depth per unit area (e.g., in. or mm) and volume units (e.g., cubic feet or cubic meters). Moreover, many other highly significant factors are strong functions of watershed or drainage area. Like channel slope, the watershed length-width ratio is a parameter used to estimate peak discharge given runoff volume.

Watershed Area
(DACRE, Card 5, Variable 1)

Because it is so important, it is fortunate that watershed area can be measured by standard surveying techniques in the field or by calculating drainage areas from aerial photographs or topographic maps. Therefore, determination of this input parameter is straightforward.

Watershed Length-Width Ratio
(WLW, Card 6, Variable 4)

This ratio is calculated as the square of the maximum hydrologic length (surface water flow path) divided by the watershed area. However, the units must be consistent. If the drainage area is in acres and the watershed length is in feet, then the user must multiply the drainage area by 43 560 (square feet per acre) before dividing.

Channel Slope
(CHS, Card 6, Variable 3)

This parameter is estimated by dividing the difference in elevation of the main channel's headwaters and outlet by the channel length. Because the most complex watershed appropriate for the CREAMS model is a single channel with contributing overland flow areas, selection of the main channel and its slope is straightforward.

Discussion of Practical Limits on
Topographic Factors

The upper watershed area limits for application of the CREAMS model, e.g., the definitions of a field and field-scale model, have been stated. Of interest in this section is the lower limit. This aspect is important when the hydrologic component is used to drive the erosion and chemistry components. For management purposes, the CREAMS water balance or hydrologic modeling

(SLB Technology Development—Arid) is separate from the erosion component (Corrective Measures—Arid), but most users will probably want to be able to use the erosion component. If this is the case, erosion component users should be aware of a possible error source in the hydrologic component.

Peak runoff (used in the erosion component of CREAMS through the hydrology pass file) is estimated using the following equation:

$$q_p = 200(DA)^{0.7}(CS)^{0.159}(Q)^{(0.917DA^{0.0166})}(LW)^{-0.187}, \quad (10)$$

where q_p = peak runoff rate (cfs),
DA = drainage area (sq mi),
CS = channel slope (ft/mi),
Q = daily runoff volume (in.), and
LW = length-width ratio of the watershed.

Equation (10) was derived using runoff volume-runoff peak rate data from a number of natural and cultivated watersheds. For SLB or experimental plot applications, Eq. (10) may produce unreasonable results. Some typical results are shown in Table IX. For these calculations, we assumed a 1% channel slope (52.8 ft/mi), a watershed length-width ratio of 2, and a runoff volume of 1 in. This left q_p as a function of drainage area only to examine its behavior as predicted with Eq. (10) under the above assumptions as drainage area changed.

Now, for plots or small areas on the order of 0.01 to 0.10 acre, the peak runoff rates are probably too high. The peak rate, q_p, should be approximately equal to the rainfall intensity rate minus the infiltration rate. If the user suspects a problem, then he should print out the pass file and examine the magnitude of the computed runoff volumes and peak rates. (Note: The peak rates in the pass file will be converted to in./h and are often called rainfall excess rates in the CREAMS documentation.) At this point the user has two options: (1) the pass file can be modified (by a text editor) to adjust the peak rates to known or more reasonable estimates, or (2) the topographic data to the CREAMS hydrologic component can be adjusted to "trick" the model. Suppose the user has a 0.01-acre plot 72.6-ft long with conditions such that a peak discharge rate of 3 to 4 in./h is appropriate for a runoff volume of 1.0 in. Then using the values of the parameters as shown in Table IX with a dummy drainage area of 1 acre will produce reasonable peak discharge estimates for the pass file. Because the watershed area input value is also read in by the erosion component of CREAMS, the original value of 0.01 acre can be restored in the erosion component input file. The channel slope value used in Eq (10) and shown in Table IX is in ft/mi. The channel slope value read in by the CREAMS program is dimensionless (i.e., 52.8 ft/mi = 0.01 being read in by the computer).

TABLE IX

VARIATION IN Q_P WITH DRAINAGE AREA USING EQ. (10) AND CS = 52.8 ft/mi, LW = 2.0 and Q = 1.0 IN.

Drainage Area		Peak Runoff Rate q_p	
sq. mi.	acres	cfs	in./h
0.000015625	0.01	0.143	14.14
0.00025626	0.10	0.715	7.09
0.0015625	1.0	3.58	3.55
0.01	6.4	13.14	2.05
0.10	64.0	65.80	1.02
1.0	640.	330.	0.51

Finally, Eq. (10) approximates the relationship for peak discharge as a function of runoff volume and watershed characteristics. It is a statistical relationship, and as such, shares the strengths and weaknesses of such procedures. Equation (10) is necessary because daily rainfall is the only model input and is a poor predictor for peak discharge rate on small watersheds. Option 2 (the breakpoint rainfall option) explicitly computes peak discharge but requires breakpoint (hourly or much finer) rainfall data, not just daily precipitation.

2.4 Climatic Data

The main climatic data required are daily rainfall, mean monthly temperature, and mean monthly solar radiation. As discussed earlier, precipitation is the input to the water balance equation and is used in the computation of all the other terms. Mean monthly temperature and mean monthly solar radiation are fitted with Fourier series and then interpolated to daily values for use in the evapotranspiration calculations.

Precipitation Data (Precipitation Data File, 37 cards per year, in Williams et al. 1980, Fig. II-2, p. 166)

This input file is separate from the parameter input file discussed above. Notice that there is room for 10 daily rainfalls per card image so that 37 cards are required to represent each year of data. Extensive precipitation data are available from the National Weather Service, National Weather Data Center, Asheville, North Carolina. Daily rainfall data are also available from climatological reports and state experiment station records, as well as other sources. A sample precipitation data file will be given later.

Mean Monthly Temperature (TEMP, Cards 8 and 9, All Variables)

These data are calculated as the mean (°F) over the month from National Weather Service measurements. Mean monthly temperature data are more readily available than daily data so the CREAMS model interpolates for the daily values. One source for a rough approximation of mean monthly temperatures is on pp. 102-103 of the National Atlas of the United States of America (USGS,1970). The National Weather Data Center is the primary source for climatic data.

Mean Monthly Solar Radiation (RADI, Cards 10 and 11, All Variables)

These data are the monthly means of daily solar radiation (langleys/day). The National Atlas (USGS, 1970, p. 93) contains maps of mean daily solar radiation on an annual average basis, and also means for January, April, July, and October. Unfortunately, the CREAMS model requires means for all 12 months. Therefore, to supplement these data and to provide data for the remaining months of the year, Table X reproduces selected solar radiation data taken from Table II-7, pp. 180-182 of Williams et al. (1980). The complete Table II-7 contains data from the entire United States, but Table XX herein was limited to the more arid and semiarid regions of the West. The user should select appropriate solar radiation data for the particular SLB site from (1) direct measurement, (2) Table X, (3) interpolations from Table X and the National Atlas, or (4) estimates from the National Atlas.

TABLE X

SELECTED SOLAR RADIATION DATA FOR ARID AND SEMIARID AREAS OF THE WEST

[Data from Table II-7 of Williams et al. (1980). Units are in langleys/day and representative mean values.]

State and Station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Arizona													
Page	300	382	526	618	695	707	680	596	516	402	310	243	498
Phoenix	301	409	526	638	724	739	658	613	566	449	344	281	520
Tucson	315	391	540	655	729	699	626	588	570	442	356	305	518
California													
Davis	174	257	390	528	625	694	682	612	493	347	222	148	431
Fresno	184	289	427	552	647	702	682	621	510	376	250	161	450
China Lake	306	412	562	583	772	819	772	729	635	467	363	300	568
La Jolla	244	302	397	457	506	487	497	464	389	320	277	221	380
Los Angeles	248	331	470	515	572	596	641	581	503	373	289	241	463
Riverside	275	367	478	541	623	680	673	618	535	407	319	270	483
Santa Maria	263	346	482	552	635	694	680	613	524	419	313	252	481
Soda Springs	223	316	374	551	615	691	760	681	515	357	248	182	459
Colorado													
Boulder	201	268	401	460	460	525	520	439	412	310	222	182	367
G. Junction	227	324	434	546	615	708	676	595	514	373	260	212	456
Granby	212	313	423	512	552	632	600	505	476	361	234	184	417
Amer. Univ.	158	231	322	398	467	510	496	440	364	278	192	141	333
Idaho													
Boise	138	236	342	485	585	636	670	576	460	301	182	124	395
Twin Falls	163	240	355	462	552	592	602	540	432	286	176	131	378
Montana													
Glasgow	154	258	385	466	568	606	645	531	410	267	154	116	288
Great Falls	140	232	366	434	528	583	639	532	407	264	154	112	366
Summit	122	162	268	414	462	493	560	510	354	216	102	076	312
Nevada													
Ely	236	339	468	563	625	712	647	618	518	394	289	218	469
Las Vegas	277	384	519	621	702	748	675	627	551	429	318	258	509
New Mexico													
Albuquerque	303	386	511	618	686	726	683	626	554	438	334	276	512
Oregon													
Medford	116	215	336	482	592	652	698	605	447	279	149	093	389
Texas													
Brownsville	297	341	402	456	564	610	627	568	475	411	296	263	442
El Paso	333	430	547	654	714	729	666	640	576	460	372	313	536
Ft. Worth	250	320	427	488	562	651	613	593	503	403	306	245	445
Midland	283	358	476	550	611	617	608	574	522	396	325	275	466
San Antonio	279	347	417	445	541	612	639	585	493	398	295	256	442
Utah													
Flaming Gorge	138	498	443	522	565	650	599	538	425	352	262	215	426
Salt Lake City	163	256	354	479	570	621	620	551	446	316	204	146	394
Washington													
Prosser	117	222	351	521	616	680	707	604	458	274	136	100	399
Pullman	121	205	304	462	558	653	699	562	410	245	146	096	372
Wyoming													
Lander	226	324	452	548	587	678	651	586	472	354	239	196	443
Laramie	216	295	424	508	554	643	606	536	438	324	229	186	408

2.5 Program Control Variables

The above information summarized most of the input data required to run the computer program to implement the daily rainfall option of the CREAMS hydrologic model. Remaining variables read in are title cards and program control variables, briefly summarized here.

Title or Header Cards
(TITLE, Cards 1-3, 80 Columns on each card)

These simply let the user identify the particular job or simulation run using three card images with up to 80 columns on each of the three cards.

Beginning Date for the Simulation Run
(BDATE, Card 4, Variable 1)

This beginning date must precede the first storm date and must be a Julian date. For example, Jan 1, 1955, would be entered as 55001.

Output Control Flag
(FLGOUT, Card 4, Variable 2)

This variable controls the type of output required by the user. FLGOUT = 0 gives an annual summary output only, whereas FLGOUT = 1 will give storm-by-storm and annual summary output. The value for this print control variable will depend upon how much detail the user requires.

Pass File Control Flag
(FLGPAS, Card 4, Variable 3)

This variable or "switch" controls the creation of a hydrology pass file for the erosion component of the CREAMS model. A value of 0 will not create a pass file and a value of 1 will.

Hydrologic Model Option
(FLGOPT, Card 4, Variable 4)

This variable is used to choose the daily rainfall (1) or breakpoint (2) rainfall hydrologic models. Discussions herein are limited to the daily rainfall option so the user should enter FLGOPT = 1.

Breakpoint of Hourly Precipitation
Control (FLGPRE, Card 4, Variable 5)

This variable is used only with the Option 2 hydrologic model so this space is left blank.

New Temperature and Stop Code

(NEWT, Card 14, Variable 1)

A card 14 is read after each year of simulation. A value of NEWT = 0 uses temperature data from the previous year's simulation run. If NEWT = 1, then a new set of 12 mean monthly temperatures must be supplied (cards 8 and 9). This variable is important because NEWT = −1 terminates program execution.

New Solar Radiation Code

(NEWR, Card 14, Variable 2)

With a value of NEWR = 0, the program uses the previous year's radiation data; with NEWR = 1, 12 mean monthly radiation data values must be supplied (cards 10 and 11).

New Leaf-Area Index Code

(NEWL, Card 14, Variable 3)

With a value of NEWL = 0, the program uses the previous year's leaf area index, whereas NEWL = 1 means that new leaf-area data (LDATE, AREA) must be read in (card 13). Notice that "card 13" is actually repeated for as many dates and index values as needed to describe the seasonal curve. The last LDATE value must be 366.

2.6 Sensitivity Analysis

The user needs sensitivity analyses to understand how the model works and to interpret the model output. The following material (Lane and Ferreira 1980, p. 113) describes the type of sensitivity analyses suggested:

> *Sensitivity analysis is a technique for assessing the relative change in a model response or output resulting from a change in inputs or in model parameters. For simple, explicit models, it is possible to take derivatives of the output with respect to input or parameters, and express the sensitivity as explicit functions. However, as the models become more complex, sensitivity is more easily expressed in the form of differentials, relative changes, graphs, and tables, rather than as functions. This is the approach used for the field-scale model.*
>
> *Based on derived parameters values and representative values of the input variables, base values are selected. For a given set of base parameter values, computations are performed, and then the input variables are varied over a range of values and the computations repeated. For given values of the input variables, the procedure is repeated with the parameters varying about their base values. The resulting computations show the model outputs vary with changes in the input and parameters. This shows how the model functions and how important each of the parameters is in determining the output. Such analyses also aid in parameter estimation.*
>
> *The main short comings of this procedure are (1) the parameters are varied individually so that complex interactions are difficult to determine, and (2) the number of simulation runs increases rapidly with the number of parameters and inputs and with the number of points selected to vary about the base values. For example, nm + 1 simulation runs are required for a model with n parameters and input variables, and with simulation runs for the base values and m points around the base value of each parameter and input variable. In some cases, it may be necessary to limit the sensitivity analysis to a subset of the model parameters. Finally, the sensitivity analyses given in this chapter are for a complex watershed including detachment, transport, and deposition processes in overland flow and in concentrated flow. Sensitivity for other conditions may be much different. Users should determine model sensitivity for the particular application.*

The user should consult previous sensitivity analyses for an overall impression of model performance and its parameters and input, remembering that the sensitivity analyses summarized by Lane and Ferreira (1980) were for a cultivated agricultural watershed in Georgia. Moreover, the results were for a single watershed and do not represent western conditions or disturbed systems such as SLB facilities.

Only by conducting sensitivity analyses under the particular SLB conditions can the user determine model sensitivity for a site-specific application. This is also the only way to judge if results from previous sensitivity analyses apply to the particular SLB conditions.

2.7 Miscellaneous Comments and Cautions

The present version of CREAMS, documented here and in Conservation Research report No. 26 (Knisel 1980) is limited to a 20-year simulation period. Longer simulations can be made by combining the results of successive 20-year simulations so that conditions (antecedent soil moisture) at the end of one period become initial conditions for the next period. Of course, shorter periods down to a single storm event can be simulated, but the user should be aware of the 20-year upper limit. This means that at most there can be 20 NEWT, NEWR, and NEWL cards (and appropriate input data sets if any of these values are 1) and that the 20th value of "card 14" must have a −1 in the NEWT position.

We emphasize here that two input files are required to run the hydrologic component of CREAMS: (1) the precipitation data file containing 37 cards or card images per year of precipitation data and (2) the parameter data file that must end with a −1 in the NEWT position on card 14.

The model will create one or two output files at the user's option. The program will always create an output file summarizing the hydrologic computations. If the user specifies FLGPAS = 1 on card 4, then the hydrologic model will also create a pass file as input to the erosion component.

As a general rule, the parameter input file is short compared with the output file containing the hydrologic computations. We recommend that the user print the parameter input file and store it with the output file for later reference. Although most input parameters are printed in the output files, the formats will have been changed. Often the previously used parameter file only requires minor modifications for the next simulation run. Finally, continual use of the CREAMS model generates a great deal of computer output and if each output set is stored with the input parameter file that created it, then it is much easier for the user (or other users) to duplicate a particular hydrologic analysis.

Because percolation or seepage below the root zone is often significant in hydrologic analysis of SLB systems, the user should be aware of methods used in soil water accounting and percolation calculation in the CREAMS model. Figure 2 is a schematic illustration of a control volume used to represent the soil in the CREAMS model. The ratio of void space to the total volume (void + solids) is porosity. To approximate rates of percolation, the model assumes significant soil water movement as percolation when soil water content is between saturation and field capacity. At field capacity, drainage rate is an insignificant or vanishingly small proportion of the rate at saturation. Of course, some soil water movement can occur at all levels of soil moisture, but the above approximate definition of field capacity is used in the CREAMS model.

The wilting point of the soil is defined as the lowest level of water content at which plant roots can make water move from the soil to the roots. Water in the soil below the wilting point is assumed to be unavailable to plants. A certain amount of water remains in the soil even after the plants are unable to extract it. Thus, the total water storage capacity includes the plant-available water (difference between saturation and wilting point) and the water content of the soil between the wilting point and a dry condition (oven dry). These relationships are illustrated in Fig. 2. Soil moisture levels labeled wilting point and field capacity are merely concepts and are only approximate under actual field conditions. Moreover, soil water movement and redistribution processes occur at all soil water content levels, but the CREAMS model simulates percolation only when soil moisture levels are between the user specified levels of field capacity and saturation.

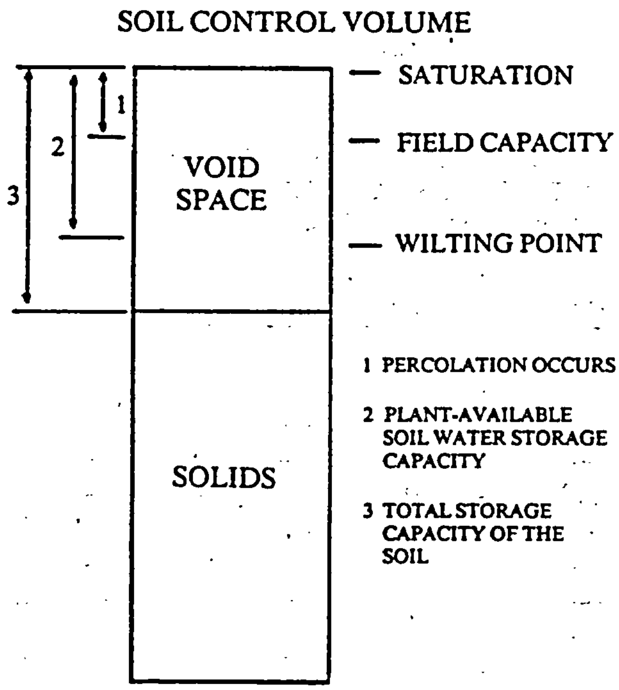

Fig. 2. Schematic of a control volume used to illustrate representation of the soil profile in the CREAMS hydrologic component.

3. EXAMPLE INPUT DATA AND PARAMETER FILES

3.1 Precipitation Data Files (Option 1, Daily Rainfall)

Again, the rainfall data are on a file separate from the parameter input data. The amount of daily rainfall P(I) (I = 1 to 365 or 366 in leap years) is P(I) in inches and I is the cumulative day of the year. For example, a value of P(20) = 1.50 would mean that 1.50 in. of rain fell on the 20th day of the year (January 20). Rainfall values are read in with the FORTRAN format (10X, 10F5.2), which means that (1) the first 10 spaces per card or card image are available for user identification (location, year, etc.); (2) 10 rainfall values per card are read in, each value occupying 5 spaces with 2 positions after the decimal point, (3) because 10 daily values are read in per card, 37 cards are required to represent a year of data, and (4) there are 20 blank spaces per card following the 10th data entry so that the user can use columns 61-80 for additional identification, sequence numbers, etc.

Daily precipitation data for Los Alamos, New Mexico during 1951 are shown in Table XI. Notice that this table lists the data in a standard month/day format. These data are shown in the CREAMS model input format in Table XII. The first column in Table XII is the 10-column user identification space. The numbers 51 1–10, 51 11–20,...refer to the year (51) followed by the day numbers 1–10 on the first card, 11–20 on the second card, and so on up to the last card 51 361–370. Here the spaces 366–370 are not used because 1951 was not a leap year and thus contained only 365 days. Again, these numbers are simply for convenience in coding, preparing, and reading the file. The only data read in by the CREAMS model are the numbers in Table XII labeled as positions 1–10. Of course, any identification code could be used in columns 1–10, but daily precipitation amounts in inches must be in positions 1–10 (the 10 F5.2 format), which are columns 11–60 on each card image. Columns 61–80 should also contain the numbers 1–37 to aid in keeping the cards in proper sequence. This is not required but is a suggestion.

A final example can help interpret the data in Tables XI and XII. Table XI shows a daily rainfall value of 2.26 in. on August 1, 1951. August 1 is the 213th day of the year, so a value of 2.26 is listed on the 213 position in Table II (i.e., the 22nd card, days 211–220, in the third column, which represents day 213).

TABLE XI

DAILY PRECIPITATION FOR 1951 AT LOS ALAMOS, NEW MEXICO IN MONTH/DAY OR STANDARD CALENDAR FORMAT

(Values are daily precipitation amounts in inches.)

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.06	—	0.02	—	—	—	—	2.26	—	—	—	—
2	0.15	—	—	—	—	—	—	—	—	—	—	—
3	—	—	—	—	—	—	—	—	—	—	—	—
4	—	—	—	0.13	—	0.42	—	0.10	—	—	—	0.06
5	—	—	—	0.03	—	—	—	0.20	—	—	—	0.04
6	—	—	—	0.35	—	—	—	—	—	0.05	—	—
7	—	—	—	0.55	—	—	—	—	—	—	—	0.04
8	—	—	—	0.05	—	—	—	—	—	—	—	—
9	—	—	—	—	—	—	—	—	0.52	—	—	0.01
10	—	—	—	0.02	—	—	—	—	—	—	—	—
11	—	—	—	—	—	—	—	—	—	—	—	—
12	—	—	—	—	—	—	0.03	—	—	—	—	—
13	0.08	0.06	0.19	—	—	0.50	—	—	—	—	—	—
14	0.06	0.18	0.06	—	—	—	1.42	—	—	—	—	—
15	—	—	—	—	—	—	—	—	—	—	—	—
16	—	—	—	—	—	—	—	—	—	—	—	—
17	—	—	—	—	0.60	—	—	—	—	—	—	—
18	—	0.03	—	—	0.35	—	—	—	—	—	—	—
19	—	0.04	0.07	—	—	—	0.51	—	—	—	—	0.05
20	—	—	—	0.06	—	—	0.02	—	—	0.05	—	0.08
21	—	—	—	0.27	—	—	—	0.10	—	—	—	0.04
22	—	—	—	—	—	—	—	0.26	—	—	—	—
23	—	—	—	—	0.08	—	1.08	0.10	—	—	—	—
24	—	0.27	—	—	—	—	—	0.03	—	—	0.12	—
25	—	0.18	—	—	—	—	—	0.50	—	0.02	—	—
26	—	—	—	—	—	—	0.10	0.20	—	0.67	—	—
27	—	—	—	—	—	—	—	0.26	—	0.69	—	—
28	—	—	—	—	—	—	—	0.04	—	—	—	—
29	—	—	0.02	—	—	—	—	0.42	—	—	—	0.35
30	0.35	—	0.03	—	—	—	0.05	0.04	—	0.08	—	0.15
31	0.20	—	—	—	—	—	—	—	—	—	—	—

TABLE XII

DAILY PRECIPITATION OF 1951 AT LOS ALAMOS, NEW MEXICO
IN THE CREAMS MODEL INPUT FORMAT;
10 VALUES PER CARD WITH 37 CARDS PER YEAR
(Data are precipitation amounts in inches.)

Comments		Position of F5.2 Field on Card										
		1	2	3	4	5	6	7	8	9	10	Card No.
51	1-10	0.06	0.15	—	—	—	—	—	—	—	—	1
51	11-20	—	—	0.08	0.06	—	—	—	—	—	—	2
51	21-30	—	—	—	—	—	—	—	—	—	0.35	3
51	31-40	0.20	—	—	—	—	—	—	—	—	—	4
51	41-50	—	—	—	0.06	0.18	—	—	—	0.03	0.04	5
51	51-60	—	—	—	—	0.27	0.18	—	—	—	0.02	6
51	61-70	—	—	—	—	—	—	—	—	—	—	7
51	71-80	—	0.19	0.06	—	—	—	—	0.07	—	—	8
51	81-90	—	—	—	—	—	—	—	0.02	0.03	—	9
51	91-100	—	—	—	0.13	0.03	0.35	0.55	0.05	—	0.02	10
51	101-110	—	—	—	—	—	—	—	—	—	0.06	11
51	111-120	0.27	—	—	—	—	—	—	—	—	—	12
51	121-130	—	—	—	—	—	—	—	—	—	—	13
51	131-140	—	—	—	—	—	—	0.06	0.35	—	—	14
51	141-150	—	—	0.08	—	—	—	—	—	—	—	15
51	151-160	—	—	—	—	0.42	—	—	—	—	—	16
51	161-170	—	—	—	0.50	—	—	—	—	—	—	17
51	171-180	—	—	—	—	—	—	—	—	—	—	18
51	181-190	—	—	—	—	—	—	—	—	—	—	19
51	191-200	—	—	0.03	—	1.42	—	—	—	—	0.51	20
51	201-210	0.02	—	—	1.08	—	—	0.10	—	—	—	21
51	211-220	0.05	—	2.26	—	—	0.10	0.20	—	—	—	22
51	221-230	—	—	—	—	—	—	—	—	—	—	23
51	231-240	—	—	0.10	0.26	0.10	0.03	0.50	0.20	0.26	0.04	24
51	241-250	0.42	0.04	—	—	—	—	—	—	—	—	25
51	251-260	—	0.52	—	—	—	—	—	—	—	—	26
51	261-270	—	—	—	—	—	—	—	—	—	—	27
51	271-280	—	—	—	—	—	—	—	—	0.05	—	28
51	281-290	—	—	—	—	—	—	—	—	—	—	29
51	291-300	—	—	0.05	—	—	—	—	0.02	0.67	0.69	30
51	301-310	—	—	0.08	—	—	—	—	—	—	—	31
51	311-320	—	—	—	—	—	—	—	—	—	—	32
51	321-330	—	—	—	—	—	—	—	0.12	—	—	33
51	331-340	—	—	—	—	—	—	—	0.06	0.04	—	34
51	341-350	0.04	—	0.01	—	—	—	—	—	—	—	35
51	351-360	—	—	0.05	0.08	0.04	—	—	—	—	—	36
51	361-370	—	—	0.35	0.15	—	not used					37

To construct a precipitation data file, 37 card images as in Table XII will be required for each year of data. The blank spaces in Tables XI and XII represent days with no precipitation, but the CREAMS program requires a space of five columns (blank or containing data) for each day of the year.

3.2 Parameter Input Files

Before, we discussed input parameters in the order of their relationships to soil, plants, climate, or control variables. In this section, we will follow the order required as input to the computer program. The construction of parameter input files will be illustrated with a series of examples including past applications and hypothetical applications at SLB sites.

3.3 Example 1: Mixed Range Grasses at Los Alamos

These input data generally follow simulation studies reported by Nyhan and Lane (1982) but will be described here in more detail. The parameter input file will be described card by card following the sequence required by the model. The headings will indicate card numbers and FORTRAN names used in the CREAMS model, followed by the actual input values used.

Cards 1-3 TITLE

(Format 20A4; 3 cards, columns 1-80)

Card 1: CREAMS hydrology, daily rainfall model, cover integrity study Oct. 1981
Card 2: Base values, S = 0.05, range, TS = 6, BB = 0.0, BF = 30
Card 3: Run "a"

Card 1 identifies that the run uses the daily rainfall model and that the work was done in October 1981 as part of a SLB trench cover integrity study. Card 2 identifies that the run uses base values in the study as follows: Slope S = 0.05; rangeland conditions are 6 in. of topsoil, no biobarriers, and 30 in. of backfill material. Card 3 identifies this as run "a" in the sequence of runs.

Card 4 BDATE, FLGOUT, FLGPAS, FLGOPT,

FLGPRE (Format 518)

BDATE	FLGOUT	FLGPAS	FLGOPT	FLGPRE
51001	1	1	1	0

Where BDATE = 51001, January 1, 1951, is the beginning date for the simulation, FLGOUT = 1 for storm and annual summary output, FLGPAS = 1 for creation of a pass file for the erosion component, FLGOPT = 1 for the daily rainfall model as option 1, and the unused value of FLGPRE is zero.

Card 5 DACRE, RC, FUL, BST, CONA,

POROS, BR15 (Format 7F8.0)

This card looks like the following (the headings are added for clarity):

DACRE	RC	FUL	BST	CONA	POROS	BR15
1.00	0.13	.310	.30	3.3	.460	.083

The six inches of topsoil in the 36-in. soil profile was assumed to have the following values: POROS = 0.46, FC = 0.25, and BR15 = 0.10. The backfill material (compacted crushed tuff) was assumed to have the following values: POROS = 0.46, FC = 0.19, and wilting point = 0.08. Therefore, the depth-weighted values were calculated as

$$POROS = \frac{6(0.46) + 30(0.46)}{36} = 0.46,$$

$$FC = \frac{6(0.25) + 30(0.08)}{36} = 0.20,$$

$$BR15 = \frac{6(0.10) + 30(0.08)}{36} = 0.083 .$$

These profile-average values were then used in the subsequent calculations. The actual input values selected were as follows:

DACRE = 1.0 acre was a unit area assumed for convenient computation.
RC = 0.13 in./h was an approximate saturated hydraulic conductivity assumed as the minimum value for the profile.

FUL = 0.310 was calculated, using the profile-average values derived above, as FUL = (FC−WP)/(P−WP) = (0.20−0.083)/(0.46−0.083) = 0.310.

BST = 0.30 was an assumed fraction of the plant-available water in storage at the beginning of the simulation. A value of BST = 0.30 means that we assumed 30% of the total plant-available soil water storage capacity was filled on January 1, 1951. This value can be converted to total amount of water in storage, S_o, as follows:

$$S_o = BST(POROS-WP)\ RD = 0.30\ (0.46-0.083)(36)$$
$$S_o = 4.07,$$

or

S_o = 4.07 in. of water as the initial stored water in the profile.

CONA = 3.3 mm/d$^{1/2}$ was a soil evaporation parameter value selected according to the CREAMS manual (e.g., Smith and Williams 1980).

POROS = 0.46 was the profile-average porosity assumed as described above.

BR15 = 0.083 was the profile-average wilting-point water content calculated earlier.

Card 6 SIA, CN2, CHS, WLW, RD (Format 5F8.0)

This card looks like the following:

SIA	CN2	CHS	WLW	RD
0.20	89.0	0.05	2.0	36.0

SIA = 0.20 is the user-recommended (or default) value of the initial abstraction coefficient for the SCS runoff curve-number method.

CN2 = 89 is the runoff curve number assumed in the original analysis. The topsoil was assumed to be a mixture of soil (sandy loam, clay, and gravelly clay) from the Hackroy sandy loam soil (Nyhan et al. 1978). From the data shown in Table III, a value of CN2 equal to 89 would suggest a C or D soil and poor rangeland conditions or mixed piñon/juniper/grasslands with about 40% cover.

CHS = 0.05 is an arbitrary channel slope selected to correspond with the 5% land slope assumed for the erosion calculations.

WLW = 2.0 is also an arbitrary value selected for the length/width ratio that is reasonable for most watersheds and, like CHS, affects the peak discharge estimates for the pass file to the erosion component.

RD = 36 in. was a typical SLB trench cover depth and was selected for that reason. Also, notice that 36 in. = 91 cm is a reasonable value for plant rooting depths of the type being considered in this example (e.g., Table VIII).

Card 7 UL(1-7) (Format 7F8.0)

This card contains the plant-available water storage for each of seven soil layers and looks like the following:

UL(1)	UL(2)	UL(3)	UL(4)	UL(5)	UL(6)	UL(7)
0.36	1.80	2.28	2.28	2.28	2.28	2.28

These values of UL(I) were computed using Eq. (6), a rooting depth of RD = 36 in., and the following data:

Index I	1	2	3	4	5	6	7
Weighting factor D(I)	1/36	5/36	1/6	1/6	1/6	1/6	1/6
Porosity P(I)	0.46	0.46	0.46	0.46	0.46	0.46	0.46
Wilting point WP(I)	0.10	0.10	0.08	0.08	0.08	0.08	0.08
Storage UL(I)	0.36	1.80	2.28	2.28	2.28	2.28	2.28

The sum of the UL(I) values is the total plant-available water storage capacity of the entire soil profile.

Cards 8 and 9 TEMP (1-12)
(Format 10F8.0, 2F8.0)

Card 8 contains 10 monthly mean temperature (°F) values (January-October) and card 9 contains the monthly means for November and December. For this example, the data are as shown below.

Card 8: 29. 33. 37. 46. 56. 65. 68. 66. 61. 51.

Card 9: 39. 31.

Cards 10 and 11 RADI(1-12)
(Format 10F8.0, 2F8.0)

Card 10 contains 10 monthly mean solar radiation values (langleys/day for January—October) and card 11 contains the monthly means for November and December. For this example, the data are as follows:

Card 10: 250. 357. 448. 612. 696. 597. 565. 491. 421.

Card 11: 317. 299.

Card 12 GR (Format F8.0)

This card contains the winter cover factor, which in this example was estimated as 0.8. However, as stated earlier, we recommend entering a value of 0.5 for all surface conditions except bare soil.

Card 13 LDATE, AREA (Format 2F8.0)

Actually, these leaf-area index data are entered on a series of cards and probably should be designated 13a, 13b,...because they represent two columns of numbers long enough to describe the seasonal leaf-area index. The user should remember that the input pattern is LDATE, AREA and that the LDATE variable is in Julian days. The first LDATE value must be 001 and the last one must be 366. The user may read in as many intermediate values as required. For this example, the LAI input data are listed below.

LDATE	AREA
1	0.0
91	0.02
121	0.05
152	0.20
182	1.00
213	1.00
244	0.80
274	0.20
305	0.01
366	0.0

These data describe the seasonal leaf-area index curve; the computer program interpolates between successive input values to estimate values for each day during the year. The user should be aware of some limitations in using the CREAMS model. First, even though a bare-soil condition requires all leaf-area data be zero, the program sums leaf area-days. Therefore, to avoid numerical errors, at least one of the AREA variables must be nonzero. A typical pattern for bare soil might be as follows:

LDATE	AREA
1	0.0
2	0.001
3	0.0
366	0.0

These values will allow the program to operate but will not simulate any plant water use except vanishingly small amounts beween January 1 and January 3. Again, the final value of LDATE must be 366.

Card 14 NEWT, NEWR, NEWL (Format 3I8)

These three FORTRAN variables or "switches" allow the user to change or update the temperature, solar radiation, and leaf-area data for each year of simulations. For example, if grass were mowed one year and not the next, the seasonal leaf-area curve should be changed to reflect the mowing. Zero values of NEWT, NEWR, and NEWL will not cause new data to be read in, whereas a value of 1 will. Temperature, solar radiation, and leaf-area index data can be updated or changed at the end of each year. If they are changed, then the new data will be read in, in the same sequence and formats as specified above (i.e., TEMP cards 8 and 9, RADI cards 10 and 11, and LDATE, AREA on card 13). Also, the winter cover factor, GR, will be read in each time new leaf-area data are entered.

Notice that a card 14 is required for each year to be simulated and that a value of NEWT = −1 is required to stop the program run. For the present example, the temperature, solar radiation, and leaf-area data were not updated so that no parameters were read in after the initial input. Under these conditions, the NEWT, NEWR, NEWL data were as follows:

NEWT	NEWR	NEWL	Line No.
0	0	0	1
0	0	0	2
.	.	.	.
.	.	.	.
.	.	.	.
0	0	0	19
−1	0	0	20

The 19 lines of zero are required to follow the initial year of simulation so that the number of years is 20 (initial + 19); the −1 value of NEWT on the 20th line is required to terminate the simulation run normally. Because the length of precipitation input files will vary (more or less than 20 years), it is a good idea for the user to scan the annual summary output to verify (1) that the beginning year is correct, (2) that the ending year is correct, and (3) that the total number of years is correct.

3.4 Example 2: Conditions as in Example 1 Except Bare Soil

For this example, we will briefly describe modifications required for the parameter input file to simulate bare soil. Unless stated otherwise, all parameter values will remain the same as in Example 1.

Card 1,—3 TITLE (Format 20A4)

These title cards should be changed to reflect "bare soil" in the user comments.

Card 6, SIA, CN2, CHS, WLW, RD
(Format 5F8.0)

The value of CN2 was increased from 89 in Example 1 (range grass) to 92 for hard, compacted bare soil (see Table III).

Card 12 GR (Format F8.0)

The value of GR was changed to 1.0 to reflect bare soil during winter months.

Card 13 LDATE, AREA (Format (2F8.0)

These cards were exactly as in Example 1 except the AREA values were changed as shown.

LDATE	AREA
1	0.0
91	0.001
121	0.0
152	0.0
182	0.0
213	0.0
244	0.0
274	0.0
305	0.0
366	0.0

Of course, in this example we could have entered as few as three leaf-area cards, but because this was only one in a number for simulation runs, the number of LDATE values was kept constant for subsequent restoration of the range grass leaf-area index values.

3.5 Example 3: Application in the Northern Mojave Desert

This example is based on a recent application of the CREAMS model to compute a water balance and the aboveground net primary production of perennial vegetation at Rock Valley on the Nevada Test Site (NTS) (Lane et al. 1984).

Except as noted below, all parameters were estimated with the CREAMS User Manual. Kleinkopf et al. (1980) presented photosynthesis-soil moisture data that showed desert shrubs in the Mojave Desert extracting soil water at potentials as low as −50 bars. The CREAMS User Manual suggests using the wilting-point estimate at −15 bars, whereas we estimated the wilting-point water content at near the air-dry soil water content. Although the Rock Valley site is over 100 km from Las Vegas, Nevada, we used monthly solar radiation data from Las Vegas, Nevada (Table X). The value of the soil evaporation parameter was reduced 15 percent from Manual recommendations to compensate for the mulching effect of desert pavement. Leaf-area index estimates for perennial desert vegetation were not available in the User Manual, so a seasonal leaf-area index curve was estimated (see Table VII) from leaf mass-leaf area and standing biomass data presented by Kleinkopf et al. (1980) and Romney et al. (1973). However, these data were taken at peak standing crop during the spring growing season, so our seasonal leaf-area index estimates are tentative. Additional data, over an entire season, will improve upon our preliminary estimates. However, our estimates do include observed dates of leaf emergence and dormancy from phenological data reported by Ackerman et al. (1980).

The input parameter file for the Rock Valley example is summarized in Table XIII. Notice that the starting date (card 4) is 68001 or January 1, 1968, and that there are nine card 14s so this parameters file will cause a 9-year simulation run (1968−1976). The Los Alamos and Rock Valley parameter files produced simulations that illustrate applications of the CREAMS hydrologic model at SLB systems and arid sites. These output results will be described in detail in the next section after a brief introduction.

4. INTERPRETATION OF SIMULATION RESULTS

It is difficult to properly interpret simulation model results (computer output) without first having the experience of running the model. As a general rule, first compare the parameter input file with the results or output file. This first check should include a comparison of the parameter input file (cards 1−14 as in Table XIII) with the corresponding information printed at the beginning of the output (the first 50 lines or so). This is to ensure that the input and output files

TABLE XIII

PARAMETER INPUT FILE, SUMMARY FORM, FOR APPLICATION OF THE CREAMS HYDROLOGIC MODEL AT ROCK VALLEY, NEVADA, 1968-1976

Card	Contents									
1	CREAMS Test Run for Mojave Desert, Nevada Test Site (Tucson Run)									
2	Unit Area Watershed									
3	Rock Valley Average Soil Conditions, Prelim Est LAI									
4	68001	1	0	1	0					
5	1.00	0.640	0.550	.240	3.01	0.340	0.050			
6	0.20	78.0	0.05	2.0	25.					
7	.201	1.007	1.208	1.208	1.208	1.208	1.208			
8	43.	49.	54.	59.	68.	77.	85.	85.	78.	64.
9	52.	41.								
10	277.	384.	519.	621.	702.	748.	675.	627.	551.	429.
11	318.	258.								
12	0.5									
13a	1	0.020								
13b	32	0.020								
13c	60	0.150								
13d	91	0.350								
13e	121	0.300								
13f	152	0.100								
13g	182	0.100								
13h	213	0.100								
13i	244	0.150								
13j	274	0.200								
13k	305	0.100								
13l	335	0.020								
13m	366	0.020								
14a										
14b										
14c										
14d										
14e										
14f										
14g										
14h										
14i	−1									

match, that the input file was in fact used to produce the output file (it is surprising, but errors of this type do occur). Next, the total number of years indicated in the input file (card 4, BDATE as the starting date and the number of card 14s, i.e., 68.001, and 9 lines of card 14, 14a—14i in Table XIII) should be reproduced in the output file. If not, then the precipitation data file may be shorter than specified for the simulation run, or there may have been an execution error that terminated the simulation run before the proper end.

4.1 Description of the Output for Example 3

The simulation data for Example 3, Rock Valley, NTS, Northern Mojave Desert, will be used to describe the simulation results because (1) the simulation period for Rock Valley is shorter than for Los Alamos, (2) the more arid climate illustrates extremes in a shorter recording period, and

(3) the user can directly compare the following output data with the input parameter file shown in Table XIII.

The initial material in the Example 3 output is shown in Fig. 3. Notice that the CREAMS version is 1.7 dated April 10, 1982, and that the title cards (cards 1–3) in Table XIII (input) and Fig. 3 (output) agree. Next, note that the input temperatures and solar radiation do not agree perfectly with the corresponding data shown in the output because the monthly data from the input file are fitted with Fourier series to interpolate for daily values and individual months. The temperature and solar radiation data in Table XIII and Fig. 3 should be examined to obtain a measure of the magnitude of differences to expect. Differences larger than those shown here might indicate an error in the input data file, causing a poor Fourier series fit.

Tabular values of leaf-area index data are shown next in the output, followed by the winter C factor (GR = 0.5) and by the integrated area under the seasonal leaf-area curve, which is a measure of the "annual average" leaf area (in this case an average of 48.99/366 = 0.13).

The following table in the output (Fig. 3) lists the field area (1.000 acres), the rooting depth (25 in.), and various input data down to the initial soil water storage (1.740 in. which is BST times the sum of UL(I) or 0.24 × 7.248 = 1.740 in.). Thus, the soil profile can store 7.248 in. of water and the beginning amount of stored water was 24% of this total. The following two data lines in the output are labeled "upper limit of storages" and "initial storage" and are a layer-by-layer representation of the total storage capacity and the amount actually in storage at the start of the simulation. Notice that the initial soil water content is assumed uniform throughout the soil profile to the plant rooting depth.

A complete year of simulation results is shown in Fig. 4. The column headings for the storm-by-storm simulations are self-explanatory except for the second column (rainfall) and the last three columns. Notice that dummy rainfall values of 0.001 in. were entered on January 31, February 29, March 31, etc., because it was necessary to have a "storm" on the last day of each month. These dummy rainfall values were entered so that the model was "tricked" into making monthly calculations in the last two columns of Fig. 4, labeled "actual ep inches" and "potent. ep inches." These are cumulative values of actual and potential plant transpiration.

The dummy rainfall values were also entered on the last day of each month so that the model would produce monthly totals of plant transpiration estimates. As an alternative, the user could enter the rainfall data and then interpolate between plant transpiration values on storm dates to estimate the monthly values. But by tricking the model with the 0.001 rainfall values, interpolation is done by the model rather than by the user; moreover, this is the only place (storm-by-storm summary) in the output where plant transpiration is separated from total evapotranspiration (ET). This separation allows the user to partition total ET into evaporation from the soil (E) and plant transpiration (T), whereas annual summaries list total ET only.

A very important point is also illustrated by the data in the last two columns of Fig. 4. Notice that the potential plant transpiration (4.0408 in. for 1968) is much less than the potential evapotranspiration (PET), which is traditionally calculated under agricultural conditions. The values of PET one normally encounters are for a complete cover (leaf-area index >3.0) and under conditions where water is not limiting. The values of potential plant transpiration shown in the last column of Fig. 4 are for the given leaf-area index (in this case much less than complete cover) as modified by the available soil moisture computed by the model.

The leaf-area index tries to follow the seasonal values read in from the parameter input file. However, when available soil moisture reaches the wilting point, the current value of LAI is kept constant until plant-available soil moisture is again present. This feature approximates a feedback loop among plant-available soil moisture, plant growth, and seasonal leaf-area index. However, note that year-to-year variations in the computed "potential plant transpiration," as controlled by "within-model" variations in LAI, are small compared with variations computed in actual plant transpiration.

CREAMS HYDROLOGY OPTION ONE

(DAILY PRECIPITATION VALUES)

VERSION 1.7 APR 10, 1982 TIFTON GA

CREAMS TEST RUN FOR MOJAVE DESERT, NEVADA TEST SITE (TUCSON RUN)
UNIT AREA WATERSHED
ROCK VALLEY AVERAGE SOIL CONDITIONS, PRELIM EST LAI

MONTHLY MEAN TEMPERATURES, DEGREES FAHRENHEIT

42.19	43.97	50.83	60.93	71.56	79.87
83.64	81.86	75.00	64.90	54.28	45.96

MONTHLY MEAN RADIATION, LANGLEYS PER DAY

302.28	381.68	495.22	612.47	702.02	739.87
715.88	636.48	522.94	405.69	316.15	278.29

LEAF AREA INDEX TABLE

1	.02
32	.02
60	.15
91	.35
121	.30
152	.10
182	.10
213	.10
244	.15
274	.20
305	.10
335	.02
366	.02

WINTER C FACTOR = .50
LAI-DAYS = 48.99

FIELD AREA	=	1.000 ACRES
ROOTING DEPTH	=	25.000 IN
SATURATED CONDUCTIVITY	=	.640 IN/HR
FUL	=	.550
INITIAL STORAGE FRACTION	=	.240
INITIAL ABSTRACTION	=	.200
EVAPORATION COEFFICIENT	=	3.010
POROSITY	=	.340 CC/CC
SCS CURVE NUMBER	=	78.000
CHANNEL SLOPE	=	.050
WATERSHED LEN/WIDTH RATIO	=	2.000
PEAK FLOW RATE COEFFICIENT	=	4.629
PEAK FLOW RATE EXPONENT	=	.824
UPPER LIMIT OF STORAGE	=	7.248 IN
IMMOBILE SOIL WATER CONTENT	=	0.50 IN/IN
INITIAL SOIL WATER STORAGE	=	1.740 IN

UPPER LIMIT OF STORAGES

.201	1.007	1.208	1.208	1.208	1.208	1.208

INITIAL STORAGE

.048	.242	.290	.290	.290	.290	.290

Fig. 3. Illustration of the initial output of the CREAMS model for Example 3.

DATE JULIAN	RAINFALL INCHES	RUNOFF INCHES	PERCOL. INCHES	AVERAGE TEMP. DEG. F.	AVERAGE SOIL W. IN./IN.	ACTUAL EP INCHES	POTENT FP INCHES
68002	.3100	0.0000	0.0000	43.2314	.1230	.0012	.0012
68031	.0010	0.0000	0.0000	42.3543	.1120	.0203	.0203
68032	.0900	0.0000	0.0000	42.4782	.1041	.0212	.0212
68044	1.2400	0.0000	0.0000	43.0824	.1047	.0470	.0470
68059	.0010	0.0000	0.0000	45.0571	.1323	.1273	.1273
68074	.3000	0.0000	0.0000	48.3431	.1178	.2924	.2924
68090	.0010	0.0000	0.0000	52.7490	.1082	.6102	.6102
68094	.2000	0.0000	0.0000	55.9691	.0956	.7119	.7119
68120	.0010	0.0000	0.0000	61.2095	.0783	1.2254	1.4290
68151	.0010	0.0000	0.0000	71.0522	.0566	1.3548	2.0780
68162	.2100	0.0000	0.0000	77.3445	.0503	1.3589	2.2098
68181	.0010	0.0000	0.0000	80.6285	.0503	1.3675	2.4451
68192	1.5400	0.0000	0.0000	82.8458	.0552	1.3799	2.5820
68212	.0010	0.0000	0.0000	83.6302	.0891	1.6041	2.8237
68214	.5200	0.0000	0.0000	83.4500	.0845	1.6246	2.8476
68225	.1700	0.0000	0.0000	82.7385	.0812	1.7715	3.0283
68243	.0010	0.0000	0.0000	80.5921	.0690	1.8758	3.2410
68273	.0010	0.0000	0.0000	75.0839	.0559	1.9469	3.6829
68298	.4100	0.0000	0.0000	66.2096	.0506	1.9506	3.9243
68304	.0010	0.0000	0.0000	60.7141	.0617	1.9601	3.9559
68326	.1000	0.0000	0.0000	55.8901	.0566	1.9720	4.0182
68334	.0010	0.0000	0.0000	51.1030	.0538	1.9728	4.0254
68366	.0010	0.0000	0.0000	46.2260	.0505	1.9797	4.0408

ANNUAL TOTALS FOR 1968

PRECIPITATION	=	5.102
PREDICTED RUNOFF	=	0.000
DEEP PERCOLATION	=	0.000
TOTAL ET	=	6.842
BEGIN SOIL WATER	=	1.740
FINAL SOIL WATER	=	0.000
WATER BUDGET BAL.	=	0.000

Fig. 4. Illustration of the storm-by-storm output for 1968 at Rock Valley, Example 3 simulation results.

Actual plant transpiration is limited by soil moisture; it proceeds at the potential rate from saturation down to a point between field capacity and wilting point, decreases linearly to the wilting point, and then is zero when the wilting point is reached. The annual estimates of actual plant transpiration (AT), potential plant transpiration (PT), and actual total evapotranspiration (AET) are shown in Table XIV.

Differences between AET and AT in Table XIV are evaporation losses, primarily evaporation from bare soil, but could include evaporation from interception losses if they were lumped in the evaporation term. Values of AT such as those shown in Table XIV were used by Lane et. al. (1984) to estimate net primary production of perennial vegetation and thus can potentially be applied for SLB technology. For example, net primary production estimates could be used to estimate potential plant uptake of contaminants.

The column labeled "average soil w. in./in." in Fig. 4 includes the soil water content at the wilting point (BR15 = WP = 0.05 in this case) and thus has a minimum value at the wilting point. The user should be aware of this distinction because the "avg SW" (average soil water data) printed in the annual summary output refers to plant-available soil moisture and can be zero.

TABLE XIV

ANNUAL ESTIMATES OF AT, PT, AND AET FOR ROCK VALLEY. EXAMPLE 3, 1968-1976

(Values are in inches and are estimated by the CREAMS model as described in the text.)

Variable	1968	1969	1970	1971	1972	1973	1974	1975	1976
AT (IN)	1.98	3.50	0.84	1.07	1.27	2.65	0.73	0.62	2.64
PT (IN)	4.04	4.06	1.96	3.79	3.84	3.81	3.97	3.55	3.41
AET (IN)	6.84	9.47	4.09	4.95	5.97	8.52	4.72	3.60	7.81

The data labeled "annual totals for 1968" in Fig. 4 are given for each year of the simulation run with the storm-by-storm summary output option. Notice that in this particular case there was no runoff or percolation, so the water balance equation only contains terms for P (5.102 in.), ET (6.842 in.), and change in soil moisture (0 − 1.740 = −1.740 in.). Thus, a water balance or budget is maintained as shown by the "water budget bal. = 0.000" data printed as the last line in Fig. 4.

Figure 5 shows the annual summary data for 1968, 1969, 1975, and the annual average values for 1968 to 1976 in Example 3 for Rock Valley. The years 1970-1974 and 1976 were deleted to save space, but their extremes and the 9-year averages are shown.

Notice that annual precipitation averaged 6.35 in. over the 9 years and ranged from a low of 2.64 in. in 1975 to a high of 11.62 in. in 1969. Also note that 1969 was an exceptional year: over 4 in. of rainfall in February was estimated to have resulted in significant runoff (0.887 in.) and a surprisingly large estimate of water movement (0.757 in.) below the rooting depth of 25 in. Although there is no direct confirmation of these estimates, floods were widespread over the region in 1969 and soil moisture estimates were in fairly good agreement with measured values over the period.

Therefore, the user should not dismiss the fact that significant percolation below a rather shallow root depth is suggested to have occurred even in an area as arid as Rock Valley, Nevada. The fact that a model suggests such an occurrence also suggests that additional on-site measurements are required and that there are possible implications for water management technology development even at the most arid SLB sites.

Again, notice that the column labeled "ET" corresponds to total ET, that all values shown in Fig. 5 are in inches, and that the column labeled "avg sw" refers to the monthly average plant-available soil water content (amount above the wilting point) in the entire soil profile to the effective plant rooting depth. Also notice that the "average annual" value of percolation of 0.109 in. is entirely due to the estimated value of 0.977 in. during 1969. This fact should alert the user to the potentially misleading results obtained (1968-1976 in this case), especially in arid areas with inherently high variability. Quite simply, 9 years of data is not sufficient to establish average annual percolation with any degree of confidence. Moreover, runoff was estimated to be zero in 5 out of the 9 years so that 9 years is also insufficient to establish average annual runoff estimates at Rock Valley. What the data shown in Fig. 5 do establish is that there is high variability in hydrologic variables at arid sites such as Rock Valley and the model suggests that significant runoff and percolation are possible. Finally, the data used in Example 3 (1968-1976) are insufficient to establish the probability of significant runoff and percolation with any degree of confidience. However, the user may place more confidence in saying, "it may occur" than in saying, "it cannot occur" when speaking of runoff or percolation at very arid sites such as Rock Valley.

CREAMS HYDROLOGY SUMMARY

VERSION 1.7 TIFTON GA APR 10, 1982

CREAMS TEST RUN FOR MOJAVE DESERT, NEVADA TEST SITE
(TUCSON RUN)
UNIT AREA WATERSHED
ROCK VALLEY AVERAGE SOIL CONDITIONS, PRELIM EST LAI

1968

MONTH	RAIN	RUNOFF	ET	PERC	AVG SW
JAN	.311	0.000	.734	0.000	1.565
FEB	1.331	0.000	.805	0.000	1.739
MAR	.301	0.000	.982	0.000	1.548
APR	.201	0.000	1.003	0.000	.736
MAY	.001	0.000	.347	0.000	.152
JUN	.211	0.000	.225	0.000	.005
JUL	1.541	0.000	.846	0.000	.697
AUG	.691	0.000	1.057	0.000	.624
SEP	.001	0.000	.329	0.000	.135
OCT	.411	0.000	.158	0.000	.075
NOV	.101	0.000	.293	0.000	.139
DEC	.001	0.000	.062	0.000	.008
TOT	5.102	0.000	6.842	0.000	.619

1969

MONTH	RAIN	RUNOFF	ET	PERC	AVG SW
JAN	2.851	.038	.714	0.000	.632
FEB	4.450	.887	.919	.757	2.103
MAR	.851	0.000	1.428	.220	3.584
APR	.016	0.000	1.159	0.000	2.595
MAY	.111	0.000	.969	0.000	1.560
JUN	.701	0.000	.790	0.000	1.130
JUL	.201	0.000	.718	0.000	803
AUG	1.401	0.000	1.015	0.000	1.034
SEP	.001	0.000	.595	0.000	.627
OCT	.280	0.000	.406	0.000	.275
NOV	.761	0.000	.426	0.000	.415
DEC	.001	0.000	.328	0.000	.401
TOT	11.625	.925	9.468	.977	1.263

1975

MONTH	RAIN	RUNOFF	ET	PERC	AVG SW
JAN	.051	0.000	.441	0.000	.720
FEB	.181	0.000	.406	0.000	.462
MAR	1.081	0.000	1.071	0.000	.598
APR	.431	0.000	.736	0.000	.215
MAY	.341	0.000	.346	0.000	.042
JUN	.001	0.000	.045	0.000	.003
JUL	.001	0.000	.001	0.000	0.000
AUG	.101	0.000	.101	0.000	.001
SEP	.241	0.000	.241	0.000	.014
OCT	.021	0.000	.021	0.000	.000
NOV	.191	0.000	.091	0.000	.010
DEC	.001	0.000	.101	0.000	.035
TOT	21526.642	0.000	3.601	0.000	.175

ANNUAL AVERAGES

MONTH	RAIN	RUNOFF	ET	PERC	AVG SW
JAN	.611	.004	.527	0.000	.871
FEB	1.361	.105	.614	.084	1.254
MAR	.883	.007	1.040	.024	1.554
APR	.232	0.000	.828	0.000	.973
MAY	.230	0.000	.552	0.000	.528
JUN	.205	0.000	.341	0.000	.319
JUL	.393	0.000	.404	0.000	.279
AUG	.404	0.000	.442	0.000	.286
SEP	.541	.005	.447	0.000	.331
OCT	.507	.003	.403	0.000	.395
NOV	.351	0.000	.318	0.000	.410
DEC	.631	.010	.301	0.000	.520
TOT	6.350	.130	6.219	.109	.643

Fig. 5. Illustration of annual summary output for 1968, 1965, 1975, and 1968–1976 averages for Rock Valley, Example 3 simulation results.

4.2. Implications for SLB Systems: Interpretation for Examples 1 and 2 at Los Alamos

Recall that Example 1 involved a 20-year simulation (1951—1970) for range conditions at Los Alamos and Example 2 involved the same conditions except that the surface was assumed to be bare, compacted topsoil. We shall now examine some methods used to interpret such simulation in management of surface and near-surface water in a SLB trench cap through the role of vegetation in the water balance. Example 1 might represent expected conditions if range grasses were established and maintained with a seasonal leaf area index as described in Example 1 and Table VII. Example 2 might be expected if no vegetation were allowed to establish on the trench cap. Although the examples are simulations, they should indicate relative differences between vegetated (range grass) and bare-soil conditions.

Average monthly values for the 20-year simulations are shown in Tables XV and XVI. Notice that the last column in these tables contains monthly average plant-available soil water and that the last row labeled "Total" is the sum of the monthly variables for all columns except in the "Ave. Soil Water" column, where "Total" represents an average annual value in inches of water in the entire 36-in. profile (6 in. of topsoil and 30 in. of crushed tuff as a silty sand backfill material). The average annual values (from Tables XV and XVI) are summarized in Table XVII.

Notice that in Table XVII the same precipitation input data were used (hence, the ratio of this variable under bare-soil conditions to its value under range conditions = 1.00). In going from vegetated (range) to bare-soil conditions, the model suggests the following: (1) about a two- to threefold increase in runoff, (2) about a 20% reduction in ET losses, (3) about an order-of-magnitude increase in percolation below the 36-in. rooting depth, and (4) about a fourfold increase in average soil moisture in the soil profile. The 20% reduction in ET amounts to about 3 in. of water and about 1 in. of this went to increased runoff while the remaining 2 in. went to increased percolation.

TABLE XV

AVERAGE MONTHLY VALUES (1951-1970) FOR HYDROLOGIC VARIABLES UNDER RANGE CONDITIONS AT LOS ALAMOS CREAMS MODEL SIMULATIONS RESULTS FROM EXAMPLE 1
(Values are in units of inches per unit area.)

Month	Precipitation	Runoff	ET	Percolation	Ave. Soil Water
Jan	0.74	0.004	0.72	0.000	1.48
Feb	0.73	0.001	0.72	0.000	1.46
Mar	0.94	0.005	0.93	0.000	1.49
Apr	0.80	0.015	0.85	0.033	1.45
May	1.11	0.018	1.22	0.000	1.34
Jun	1.30	0.015	2.04	0.000	0.92
Jul	3.35	0.150	3.26	0.000	0.35
Aug	4.58	0.291	3.78	0.045	0.67
Sep	1.46	0.021	1.80	0.002	0.64
Oct	1.62	0.108	1.00	0.030	0.71
Nov	0.76	0.014	0.73	0.079	0.98
Dec	1.04	0.026	0.73	0.000	1.12
Total	18.43	0.670	17.70	0.189	1.05

TABLE XVI

AVERAGE MONTHLY VALUES (1951-1970) FOR HYDROLOGIC VARIABLES UNDER RANGE CONDITIONS AT LOS ALAMOS CREAMS MODEL SIMULATIONS RESULTS FROM EXAMPLE 2

(Values are in units of inches per unit area.)

Month	Precipitation	Runoff	ET	Percolation	Ave. Soil Water
Jan	0.74	0.026	0.74	0.037	3.86
Feb	0.73	0.016	0.73	0.012	3.83
Mar	0.94	0.021	0.92	0.000	3.85
Apr	0.80	0.052	0.82	0.049	3.78
May	1.11	0.059	1.02	0.030	3.71
Jun	1.30	0.084	1.09	0.037	3.77
Jul	3.35	0.413	2.23	0.212	4.04
Aug	4.58	0.675	2.86	1.020	4.34
Sep	1.46	0.082	1.42	0.172	4.19
Oct	1.62	0.256	1.04	0.351	4.07
Nov	0.76	0.036	0.79	0.130	3.94
Dec	1.04	0.071	0.80	0.165	3.89
Total	18.43	1.792	14.44	2.215	3.94

TABLE XVII

AVERAGE ANNUAL VALUES (1951-1970) FOR HYDROLOGIC VARIABLES FROM CREAMS SIMULATIONS AS DESCRIBED IN EXAMPLES 1 AND 2

(Values are in units of inches per unit area.)

Condition	Precipitation	Runoff	ET	Percolation	Ave. Soil Water
Range	18.43	0.670	17.77	0.189	1.05
Bare	18.43	1.792	14.44	2.215	3.94
Ratio of Bare/Range	1.00	2.67	0.81	11.72	3.75

Small percentage changes in ET can reflect large percentage changes in runoff and percolation because ET is usually large compared with runoff and percolation; hence, the importance of managing ET in the control of runoff and percolation. This is important for SLB technology development. Reduced runoff can dramatically reduce erosion and the potential for off-site migration of radionuclides in runoff and with sediment. Reduced percolation and reduced soil moisture can dramatically reduce flow into buried waste, mobilization, and thus potential for subsequent radionuclide migration from SLB facilities to groundwater.

The point here is not whether the absolute values of the estimates shown in Tables XV—XVII are accurate, but whether models such as CREAMS can be used to examine relative magnitudes of terms in the water balance equation under various SLB management practices. The results clearly suggest that vegetation management can influence potential radionuclide migration from SLB facilities by runoff and subsurface flow and transport. Valuable data are being collected to quantify relationships such as those represented in Tables XV—XVII, for example, rainfall simulation techniques are being applied to quantify components of the water balance in several Southwest ecosystems. The user should consult Simanton and Renard (1982), Lane and Stone (1983), Lane et al. (1984), and Bostick et al. (1984) for additional details.

Hydrologic data from CREAMS simulations for Los Alamos, 1951—1970, Examples 1 and 2, were analyzed to determine rough estimates of probabilities of exceeding certain levels. A frequency analysis of the original (untransformed) data is summarized in Table XVIII. Various probability distributions (i.e. normal, log-normal, etc.) can be fitted to data such as shown in Table XVIII. The user is urged to consult with a qualified scientist to determine which probability distribution is most appropriate for a given variable. Some general conclusions can be made from the raw or untransformed data shown in Table XVIII. The coefficient of variation (CV) is the ratio of the standard deviation to the mean and is a normalized measure of the variability represented by the data in the particular sample. In terms of increasing variability (least to most), the annual variables in Table XVIII are ranked as follows: (1) ET, (2) precipitation, (3) runoff, and (4) percolation.

The variability in precipitation is comparable to the variability in ET, although ET may be slightly less variable. If true, difference in this variability would suggest that in wet years the soil could store water in excess of ET and that in dry years ET could draw on soil moisture stored in the soil profile during the previous year. However, the plant transpiration component (i.e., CV = 0.38 for range conditions) is more variable than the soil evaporation components (i.e., CV = 0.20 for range conditions). Because runoff and percolation are more strongly dependent upon storm size, frequency, and sequence of occurrence, they are in turn more variable than the other components of the water balance.

Some rough estimates of probabilities or frequency of occurrences can be made from the data in Table XVIII. The mean annual ET value for range grasses is 18 in. with some 10% of the annual values greater than 21 to 23 in. The mean bare-soil evaporation is about 14 in. with some 10% of the annual values greater than about 18 in. The mean annual precipitation is 18 in. with some 10% of the annual values greater than 26 to 28 in.

Mean annual runoff under range conditions is about 0.67 in. with some 10% of the annual values greater than 1 to 2 in. The corresponding values for bare-soil conditions are a mean annual value of about 1.8 in. with some 10% annual values greater than 3 to 4 in.

The mean annual percolation under range conditions was about 0.2 in., but percolation was estimated to have occurred in only 3 out of 20 years, so the mean annual value is not well determined. In contrast, the mean annual percolation under bare-soil conditions was about 2.2 in. and percolation was estimated to have occurred in 19 out of 20 years. Moreover, some 10% of the annual values were greater than 4 to 6 in.

Therefore, the simulation data suggest striking differences in percolation under vegetated and bare-soil conditions. These simulation results are supported by data from lysimeter studies at Los Alamos (Hakonson et al. 1982 and Lane et al. 1984).

Soil moisture data (mean monthly values from 1951-1970 and for the entire 36-in. profile) from Tables XV and XVI were converted to soil water content in percent by volume (Table XIX).

TABLE XVIII

FREQUENCY ANALYSIS OF ANNUAL HYDROLOGIC VARIABLES (UNTRANSFORMED) FROM 1951-1970 AS SIMULATED BY THE CREAMS MODEL

Rank m	Return Period T=N+1/m (years)	Probability P=1 −m/(N+1)	Annual values of hydrologic variables in inches. Range grasses and bare soil conditions from Examples 1 and 2. Precipitation	Runoff Range	Runoff Bare	Evapotranspiration Range	Evapotranspiration Bare	Percolation Range	Percolation Bare
1	21.0	0.952	29.31	2.272	4.521	23.70	18.80	2.188	6.573
2	10.5	0.905	28.03	2.086	4.457	23.21	18.05	0.937	6.132
3	7.00	0.857	25.67	1.095	2.884	21.27	17.95	0.651	3.750
4	5.25	0.810	23.70	1.058	2.685	20.47	16.91	0.000	3.635
5	4.20	0.762	21.55	0.970	2.340	20.27	15.82	0.000	3.389
6	3.50	0.714	20.80	0.844	2.204	29.80	15.80	0.000	3.074
7	3.00	0.667	20.22	0.791	2.184	18.87	15.50	0.000	2.682
8	2.63	0.619	19.56	0.791	2.062	18.86	15.25	0.000	2.552
9	2.33	0.571	18.44	0.539	1.750	18.76	14.99	0.000	2.046
10	2.10	0.524	17.82	0.473	1.499	81.67	14.69	0.000	1.756
11	1.91	0.476	17.48	0.449	1.397	18.64	14.56	0.000	1.732
12	1.75	0.429	16.73	0.361	1.335	18.31	14.37	0.000	1.566
13	1.62	0.381	16.70	0.356	1.285	18.19	13.94	0.000	1.163
14	1.50	0.333	16.20	0.346	1.187	17.93	13.80	0.000	0.964
15	1.40	0.286	15.48	0.324	1.142	16.41	13.58	0.000	0.875
16	1.31	0.238	15.40	0.284	1.015	16.12	13.15	0.000	0.869
17	1.24	0.190	14.93	0.205	0.807	16.10	13.11	0.000	0.746
18	1.17	0.143	12.45	0.115	0.623	12.16	10.68	0.000	0.680
19	1.11	0.095	11.26	0.025	0.304	10.81	10.68	0.000	0.112
20	1.05	0.048	6.80	0.013	0.157	6.88	7.20	0.000	0.000
		Mean	18.43	0.670	1.792	17.77	14.44	0.189	2.215
		Std. Dev.	5.50	0.611	1.182	4.01	2.73	0.532	1.809
		C.V.	0.30	0.91	0.66	0.23	0.19	2.81	0.82

TABLE XIX

SUMMARY OF MEAN MONTHLY SOIL MOISTURE AVERAGE OVER THE 36-IN. SOIL PROFILE IN EXAMPLES 1 AND 2 CREAMS MODEL SIMULATION RESULTS, LOS ALAMOS, 1951-1970

(Monthly values are means for 20-year period.)

Month	Plant Available Soil Water (in.)		Soil Water Content in Percent by Volume		Mean Unsaturated Flow Rate (in./mo) For The Mean Water Content[a]	
	Range	Bare	Range	Bare	Range	Bare
Jan	1.48	3.86	12.4	19.0	0.011	0.64
Feb	1.46	3.83	12.4	18.9	0.011	0.61
Mar	1.49	3.85	12.4	19.0	0.011	0.64
Apr	1.45	3.78	12.3	18.8	0.010	0.58
May	1.34	3.71	12.0	18.6	0.0081	0.52
Jun	0.92	3.77	10.9	18.8	0.0032	0.58
Jul	0.35	4.04	9.3	19.5	0.0007	0.82
Aug	0.67	4.34	10.2	20.4	0.0017	1.26
Sep	0.64	4.19	10.1	19.9	0.0016	1.00
Oct	0.71	4.07	10.3	19.6	0.0019	0.86
Nov	0.98	3.94	11.0	19.2	0.0035	0.71
Dec	1.12	3.89	11.4	19.1	0.0050	0.68
Annual	1.05	3.94	11.2	19.2	0.050[b]	8.52[b]

[a]Based on assumed relationship for unsaturated hydraulic conductivity soil water content and a unit hydraulic gradient assumption.
[b]Total value for the entire year.

An approximate unsaturated hydraulic conductivity/soil water content relationship, together with a unit hydraulic gradient,was assumed and applied to the monthly mean soil water content. The result was a rough estimate of the vertical water flux as unsaturated flow. Of course, a month is far too long a period to assume a constant moisture flux and, moreover, because the conductivity/soil water content relationship is highly nonlinear, the conductivity for the average water content is not equal to the average conductivity for each of the daily water contents throughout the month. Nonetheless, the annual percolation fluxes as unsaturated flow are shown as 0.05 in./yr for range conditions and 8.52 in./yr for bare-soil conditions. The corresponding CREAMS estimates from Tables XV and XVI are 0.189 in./yr and 2.215 in./yr. Thus, the annual percolation estimate for range conditions from Table XIX is about 26% of the value estimated by CREAMS (e.g., 0.05/0.189 = 0.26).

On the other hand, the annual percolation estimate for bare-soil conditions from Table XIX is about 4 times as large as the CREAMS estimate (e.g., 8.52/2.215 = 3.85). Thus, percolation estimates based upon mean monthly soil moisture and on an assumed unsaturated conductivity/soil water content relationship can differ significantly from estimates made by the CREAMS model that uses a daily, rather than monthly, time step. Therefore, the user should be aware that there are limits in the use of monthly data as described above.

The monthly data could have been used as a reasonable estimate if the difference between daily and monthly time step percolation estimates (Table XIX) had been consistent. Instead, one estimate was high and one was low. However, in this example the user would probably want to apply the unsaturated flow/soil water content relationship to daily soil water content estimates for the entire 20 years and then average for each month to more closely match the daily time step methods used in the CREAMS model.

The above examples should aid the user in preparing precipitation and parameter input files for the hydrologic component of the CREAMS model. They should also significantly help the user understand and interpret the simulation result. The examples have included two applications at a semiarid site (Los Alamos) and one application at a very arid site (Rock Valley). The examples have also included obvious and subtle methods of extending the CREAMS model to arid and semiarid sites and extending it from agricultural to SLB applications at arid and semiarid sites. The next section describes a design application and illustrates an appropriate use with a user-oriented example.

4.3 SLB Trench Cap Design: Hydrologic Aspects and Design Criteria

Basic data from Examples 1 and 2 at Los Alamos are extended to the problem of designing trench cap thickness (see Fig. 1) for a SLB facility at Los Alamos. The user can, in this example, choose a soil thickness from 6 in. to 7 ft and revegetate the cap with range grasses or leave it bare. All other factors remain as specified in Examples 1 and 2. We choose to manipulate trench cap thickness (because a thicker cap can store more water) and vegetative cover (because of potential for increased ET and subsequently reduced soil moisture and percolation into the buried wastes).

The question is what effective depth in the soil profile does bare-soil evaporation reach? By effective depth we mean the maximum depth of the soil that dries to the wilting point or below between subsequent rewetting by significant precipitation events. During the 20-year period there were 1807 storms or roughly (365×20)/1807 = 4 days between storms on the average, and there were 115 runoff-producing storms under the range conditions (Example 1) or 365×20)/(115) = 63 days between runoff-producing storms. Under bare soil conditions (Example 2) there were again 1807 total storms and 241 runoff-producing storms. This value suggests (365×20)(241) = 30 days between runoff-producing storms. Therefore, a reasonable estimate for the number of days between significant storms is between 4 and 63 days and probably somewhat fewer than 30 days. If this estimate is reasonable, then we can estimate total soil evaporation losses during a 30-day period following wetting. Once these losses are estimated, then we can approximate the depth affected during this period.

Using the work of Ritchie (1972), Lane and Stone (1983) estimated effective depths influenced by soil evaporation. For soil conditions similar to those assumed in Examples 1 and 2, they found depths of from 16 to 38 cm (6 to 15 in.) with a mean value of 20 to 30 cm or 8 to 12 in. From this analysis, one might expect that under bare-soil conditions, soil evaporation might not significantly affect soil moisture below 8 to 12 in., depending upon soil characteristics and storm sequencing. Therefore, under these bare-soil conditions, one might expect soil moisture below 8 to 12 in. to reach a steady-state condition controlled by the unsaturated hydraulic conductivity within and below the trench cap and by climatic history. Simulation results for range conditions and bare-soil conditions and for trench cap thicknesses of 6 in. to 84 in. are summarized in Table XX.

Bare Soil Conditions

As predicted earlier, annual components of the water balance did not change much for soil depths greater than 12 in. Runoff stabilized at about 2 in., ET at about 14 in., and percolation at about 2 in. Therefore, the user can conclude from the data in Table XX that increasing trench cover depth beyond about 12 in. does not improve SLB performance much with respect to average annual values of ET, runoff, and percolation as long as the soil surface remains bare. Of course, this analysis does not consider other benefits such as erosion protection of thicker covers.

Range Conditions

When range grasses are established and maintained on the trench cover, then the annual water balance is much different than under bare-soil conditions. Average annual values of ET continue to

TABLE XX

INFLUENCE OF TRENCH CAP THICKNESS AND VEGETATIVE COVER UPON ET, RUNOFF, AND PERCOLATION BELOW THE ROOT ZONE CREAMS MODEL SIMULATIONS FOR LOS ALAMOS

Trench Cap Thickness (in.)			Average Annual Values From 1951—1970					
			Evapotranspiration (in.)		Runoff (in.)		Percolation (in.)	
Topsoil	Backfill	Total	Range	Bare	Range	Bare	Range	Bare
6	0	6	15.41	14.21	0.829	1.672	2.220	2.575
6	6	12	16.69	14.48	0.722	1.737	1.083	2.250
6	18	24	17.45	14.46	0.678	1.746	0.434	2.270
6	30	36	17.77	14.44	0.670	1.792	0.189	2.215
6	42	48	17.96	14.43	0.663	1.852	0.078	2.146
6	78	84	18.25	14.43	0.645	1.822	0.005	1.822

Note: Examples 1 and 2 were the 6-in. topsoil, 30-in. backfill cases for range conditions and bare soil conditions.

increase with depth, and average annual values of runoff and percolation continue to decrease with increasing depth as shown in Table XX. However, judging from the data shown in Table VIII, most perennial grasses have maximum rooting depths greater than 16 in., but less than 72 in. Therefore, unless the user is sure that the effective rooting depths would be greater than the maximum of 72 in. indicated above, not much improvement (in annual values of ET, runoff, and percolation) would be expected for trench caps thicker than about 6 ft. or 2 m with perennial range grass cover.

Design Criteria

Design criteria for the assumed conditions at Los Alamos based on average annual values of terms in the water balance equation (see Table XX for examples) would suggest that (1) the trench cap must be at least 12 in. thick for bare-soil conditions but that additional thickness conditions would not further reduce runoff or percolation, (2) that soil depth and vegetative cover are interactive, and (3) that with range grasses an optimal depth might be about 72 in. and would probably be limited by the effective rooting depth (e.g., see Tables VIII and XX). Further, under bare-soil conditions, average annual runoff and percolation probably cannot be reduced much below 2 in. However, with vegetation management, average annual runoff might be reduced to as low as about 0.6 in. and average annual percolation might be reduced to below 0.1 in. Also, this average value of 0.1 in. reflects significant percolation in wet years and sequences of several years wherein no percolation would be expected.

Of course, design criteria might also be based on extreme values rather than an average annual values for terms in the water balance equation. If so, then much longer simulation periods (e.g., longer than 20 years) are needed to establish probability distributions for components in the water balance (especially percolation as shown in Table XVIII where only 3 nonzero values for percolation were produced in 20 years under range conditions).

Table XX suggests that as the SLB designs better control percolation, longer simulation periods would be required to obtain statistical confidence in percolation estimates because the number and size of percolation events would decrease. That is, the better the SLB design, the less frequent and smaller the percolation events become.

As the number of events decreases, the sample size for estimation of confidence limits, probability distribution, etc., must increase, therefore increasingly longer simulation periods are necessary.

To avoid having to simulate periods of infinite length (an impossibility) to reduce uncertainty in components of the water balance, the user must be willing to accept a reasonable level of uncertainty and consider other interactive factors (e.g., erosion, plant uptake, subsurface leaching and transport) in the design of SLB systems. In other words, this discussion has extended the CREAMS hydrologic model to near its limits of applicability in SLB designs.

5. SUMMARY AND DISCUSSION

The summary section is intended as a brief review of the paper as an aid to quickly finding the location herein of specific user information. Therefore, the following material constitutes a brief outline of the text.

5.1 Summary

The Introduction describes the relatively recent developments leading to more formalized regulations and policies governing shallow land burial (SLB) of low-level radioactive wastes. These developments in turn have required the subsequent development and application of hydrologic models to compute a water balance for the surface and near-surface areas of SLB facilities. A simple form of the water balance equation is presented and is explained with reference to the well-known illustration of a SLB system (Fig. 1).

A requirement for SLB site selection, operation, and monitoring is hydrologic characterization of the site. Also, it is necessary to be able to model a SLB system. The Creams model is described as a valuable tool in this site characterization and modeling and examples of prior applications in waste management are presented in support of this contention.

Parameter estimates and estimation procedures for the CREAMS model are described in detail. Each card image in the input files is described (precipitation data input file and parameter input file) and then the parameters are described as to their names, functions, source of estimates, and methods of estimation. Section 2.1 describes parameters used to represent the soil and first-order or generalized estimates of all soils parameters are given as functions of soil classes. These generalized or first-order estimates for the soils parameters are given in Tables I-V, with Table VI as a "locator summary" for the user's convenience.

Section 2.2 describes the plant parameters used in the CREAMS model and includes leaf-area data in Table VII and maximum rooting depth data for various vegetation types in Table VIII. The user is advised that these rooting depth data represent cumulative frequency of maximum reported rooting depths (Table VIII) and perhaps an appropriate effective rooting depth might be the median or 50 percentile depth interpolated form data in Table VIII.

Section 2.3 describes topographic data used in the model and explains how these data are used to generate runoff peak discharge estimates. Moreover, this section describes how to avoid unreasonably large peak discharge estimates when applying the CREAMS model to small plots.

Section 2.4 describes climatic data required. The user should recall that precipitation data are contained in a separate file consisting of 37 card images per year of precipitation data. Mean monthly temperature and solar radiation data are entered as part of the parameter input file.

Section 2.5 describes the control variables or switches used to control operation of the computer program and to activate various options. The user should recall that the last card in the parameter input file (card 14) should have a −1 in the first position to terminate the simulation run.

Sections 2.6 and 2.7 discuss sensitivity analysis and cautions to help the user avoid some of the more common errors. Section 2.7 also repeats a brief description of how the concepts of porosity, field capacity, wilting point, and percolation are represented in the CREAMS model. Figure 2 is used for these illustrations.

Section 3 presents a detailed description of example precipitation and parameter input files in the exact formats required by the computer program. Three examples follow these descriptions to illustrate uses of the model in semiarid areas (Los Alamos, New Mexico) and in arid areas (Rock Valley, Nevada). The first example deals with range grass conditions at Los Alamos and the second example shows how the parameters would be modified to represent bare soil conditions. The third example illustrates an application at Rock Valley, Nevada in the northern Mojave Desert.

Section 4 describes special features of the computer output and emphasizes various variables, units, and conversions the user must recognize to utilize the output data or simulation results. Next, output from the examples given in Section 3 are interpreted and then implications for SLB systems are discussed. Section 4.3 describes how the user might use the simulation results to design a trench cap for SLB facilities at Los Alamos or similar locations. Finally, these applications are followed by a brief discussion of some practical limits the user should recognize when applying the CREAMS hydrologic model in designing or evaluating SLB systems.

5.2 Discussion

This report contains information in addition to that given in the CREAMS manual (Conservation Research Report No. 26, Knisel 1980) and emphasizes several aspects beyond what was available in previous publications. First, the emphasis is on arid and semiarid areas of the West whereas the original emphasis for the CREAMS model was for agricultural areas. Second, this report emphasizes application for shallow land burial systems and thus deals with bare soil, grass cover, and shrub cover rather than traditional agronomic species. Third, much more emphasis is given to providing the user with parameter estimates. Example parameter values and sources for parameter estimates are discussed in considerable detail. Therefore, the user has representative values (at least for Los Alamos and Rock Valley) for each input parameter. Using information contained here and in the cited references, the user should be able to derive parameter input files for several ecosystems in the West. Fourth, significant efforts are made to guide the user through examination of simulation results or output data and methods of interpreting them related to SLB systems. Finally, the user is shown how to use results from application of the CREAMS hydrologic model to develop performance criteria such as allowable runoff or percolation amounts at a SLB facility.

The CREAMS model is merely a tool, and .'ke all tools can be misused. This report describes the model, its inputs, operation, and outputs, together with special features and common user errors. But, because it is not possible to anticipate all possible future users of the model, it is not possible to anticipate all possible errors, misinterpretations, or improper applications of the CREAMS model. The original authors of the CREAMS model attempted to prepare an error-free program and associated documentation; considerable efforts have been made herein to prevent user errors, misinterpretations, and misapplications as well. Similarly, the user should also be conscientious in applying the CREAMS model, because the ultimate responsibility for proper use and interpretation of this, or any other model, rests with the user.

ACKNOWLEDGMENTS

Several individuals at Los Alamos have provided incentive and opportunity for application of hydrologic principles and the CREAMS model in waste management studies. Special credit and thanks should be given to G. L. DePoorter, T. E. Hakonson, J. W. Nyhan, and J. G. Steger. In addition, T. E. Hakonson and J. W. Nyhan have contributed significantly to extending the CREAMS model to waste management applications. Their efforts have benefited the waste management programs at Los Alamos, have positively impacted the national programs, and have been in the public interest.

Several individuals in the Agricultural Research Service of the US Department of Agriculture have earned special recognition for their contributions in developing the CREAMS model. Dr. W. G. Knisel, more than anyone, is responsible for development of the CREAMS model; he too has served the public interest. J. R. Williams, R. E. Smith, and A. D. Nicks contributed significantly to development of the hydrologic component of the CREAMS model.

I also wish to thank Cindy Gamble, Consuelo Lujan, and Maxine Lewis for typesetting this manuscript and thank the various reviewers for their helpful suggestions. Particularly helpful review comments were provided by Tom Hakonson, Rosemary Lane, Maxine Lewis, and Jack Nyhan.

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☆ U.S. GOVERNMENT PRINTING OFFICE 1984—576-034/4230

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