ASSESSMENT AND MODIFICATION OF THE CREAMS HYDROLOGIC MODEL FOR SMALL GRASSLAND WATERSHEDS

By

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PREFACE

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CHAPTER I

INTRODUCTION

Statement of Problem

Increasing dependable water supplies and water quality are of major concern in this complex world. This in turn requires a knowledge of the watersheds under various climatological conditions that are expected to occur. Consequently, scientists and engineers have expended much effort in developing mathematical models in the past two decades. These models vary in simplicity, purpose, adequacy, and the range of conditions they cover. As a result, the use of existing models for simulating runoff is limited by the overall range of conditions considered during their formulation. Therefore, any hydrologic model should be tested and evaluated in a similar range of conditions for which it was designed.

In hydrologic models, input parameter estimation has been a difficult task, particularly for soil-plant characteristics, surface conditions, and management practices. Therefore, when the models are employed for simulating runoff, input parameters have to be selected which come mostly from parameter evaluation, or from relevant references under similar watershed conditions. Thus, before the models can be used on grassland watersheds in the region concerned, there exists a potential need to evaluate the input parameters for the watersheds.

The performance of models on the basis of data acquisition, computer cost, and the accuracy with which they can predict the storm runoff, is an important consideration. The evaluation of these performances will assist engineers to determine potential storm runoff and various possible land uses on the watershed more economically. Also, agricultural planners may use these models to determine potential non-point source pollution as part of the large models. From such models, CREAMS model (Chemical Runoff and Erosion From Agricultural Managements Systems) was selected for this study.

The principal objective of the study was to determine the capability and problem sources of the CREAMS hydrologic model to simulate runoff from small native grassland watersheds in central Oklahoma. The model was also modified to improve the accuracy of runoff simulation. The study utilized available meteorological and hydrologic data on four watersheds.

The CREAMS model was specifically designed for field size watersheds which have single land use, single management practice, relatively homogeneous soils and uniform rainfall. It has four components: (1) hydrologic model, (2) erosion model, (3) nutrient model and (4) pesticide model. This study was concerned only with the hydrologic model.

The CREAMS hydrologic model has not been adequately and independently tested and evaluated on grassland watersheds in central Oklahoma. Therefore, this study offers an independent test and evaluation of the model. Also, it provides a set of values for various other input parameters for the region.

Objectives

The objectives of the study were as follows:

1. To assess the capability of the CREAMS hydrologic model to

simulate the runoff from small native grassland watersheds in central Oklahoma.

2. To identify the problem sources and propose modifications of the components of CREAMS hydrologic model for the improvement of runoff simulation.

3. To modify the CREAMS hydrologic model and test the revised model on small native grassland watersheds.

Scope of Investigation

The research study was conducted on four grassland watersheds in central Oklahoma. The watersheds vary in size, soil types and cover conditions. The rainfall-runoff data-base varied from 8 to 20 years.

The model parameters were selected for variation based on sensitivity and difficulty in their estimation. The parameters were varied until the cumulative simulated runoff was within ±1% error of cumulative observed runoff. Also, the best possible fit of the monthly runoff regression line and the equal value line was achieved. The model was assessed with respect to simulated and observed monthly and annual runoff. The deficiencies of the model components were identified and problem sources were discussed. Some possible modifications were utilized and analyzed for the improvement of the accuracy of runoff simulation.

CHAPTER II

REVIEW OF LITERATURE

Mathematical models play important roles in solving engineering problems in water resources systems, where the model is a tool to be utilized in the optimum operation of the system. Hydrologic models are mathematical models which represent the hydrologic processes with varying degrees of sophistication. The hydrologic processes such as infiltration, evapotranspiration, flow routing, subsurface, and surface runoff are the major components in hydrologic modeling.

Mathematical Modeling in Hydrology

Mathematical models have been used in the field of hydrology for quite some time. Overton and Meadows (1976) defined a mathematical model as a quantitative expression of a process or phenomenon one is observing, analyzing or predicting. Fleming (1975) defined the mathematical model in hydrology as a methodology which represents the hydrologic concepts and processes quantitatively.

It is difficult to observe any hydrologic process completely because of the spatial and temporal variability. Therefore, any mathematical expression for a given process involves some error and uncertainty. However, with the development of mathematical models, the hydrology of a particular area can be studied. With certain probability levels, short term as well as long term predictions can also be made. Models are also used for evaluating land use changes, effects of urbanization, transport mechanisms of pollutants, design of reservoirs, extension of flow records, and effects of channel improvement.

Models are divided into three categories: (1) deterministic, (2) parametric, and (3) stochastic. The first two are based on a conceptual approach whereas the last one uses a statistical approach.

A deterministic model is an equivalent mathematical representation of the physical system. It can be expressed as a series of equations which show the internal physical laws of the system and measure of initial and boundary conditions. By adequate evaluation of the deterministic models, a high degree of accuracy can be obtained.

Parametric models lie between deterministic and stochastic models in their approach and level of certainty. These models are evaluated for a given region through the optimization of a set of parameters. Such a process is known as a regionalization of the model parameters.

Stochastic models use a statistical approach for describing the response of the system. The statistical parameters, e.g. mean, standard deviation, and auto-correlation coefficient, are used to generate hydrologic data sets which are statistically not different from the measured data. However, in the stochastic models, there are difficulties in selecting the proper probability distribution function of the input and in choosing the proper model for the system.

Rainfall-Runoff Modeling

The efforts to model the rainfall and runoff processes have provided a significant contribution to engineering hydrology. Rainfall-runoff modeling pertains to formulation of mathematical expressions of the direct and/or indirect relationship of rainfall with runoff through hydrologic components of the hydrologic cycle, and physical characteristics of a watershed. To model the rainfall-runoff relationship, the laws of conservation of mass, energy, and momentum are used in a set of theoretical principles. One or more of these principles along with several empirical relationships form the basis for most models. [It appears that the fundamental processes in hydrology are the same in all watersheds. However, rate of infiltration, amount of evapotranspiration and other processes do vary with the vegetation and soil characteristics of the watershed.]

Linsley (1982) has listed the principal purposes for which models can be applied. They are research, forecasting, engineering application, record extension, operational simulation, data fill-in, and data revision. In addition, the models can serve as a basis for algorithms, for simulation of water quality, or sediment transport, and finally, they may be incorporated into the environmental models.

Three approaches are used in model building. They are conceptual, blackbox and statistical approaches. In the conceptual approach, cause and effect relationships among the hydrologic components of the hydrologic cycle and physical characteristics of the watershed are used. The blackbox approach to rainfall-runoff modeling is known as a constrained linear system. Todini and Wallis (1974) state that the approach operates on the basis of dividing lumped precipitation input into multiple time streams on the basis of accumulated antecedent precipitation. Hence, the nonlinear system is simulated by a set of concurrent linear systems. The stochastic models use a statistical approach to generate rainfall and runoff with certain levels of probabilities assigned to the inputs and outputs. Also, the simple and multiple regression models are used to generate runoff from the pertinent independent variables.

Woolhiser (1982) points out that four levels of models have been recognized. They are individual process models, component models, integrated models, and global models. An individual process model is a mathematical expression of one of the physical processes involved in the hydrologic cycle, for example, models of flow in unsaturated porous media, and evaporation from water surface. The component model is a linked model of individual processes with a component operator that divides the flow of water into the individual processes in the sequence, for example, surface runoff model, and evapotranspiration model. An integral model contains a set of linked component models along with an operator, which separates the flow of water into the individual components with varying degrees of simplification. Unlike linkage of individual components in the integral model, a global model assumes a functional relationship between a set of input and output variables. Global models are an alternative to integral models.

Components of the Hydrologic Model

The hydrologic processes, which are components of the hydrologic cycle, are used in the modeling at various levels of abstractions. Several of the most important individual processes, namely, infiltration, evapotranspiration, soil water distribution,and deep percolation, are described in the next sections. Although many theoretical and empirical expressions have been developed only some developments are cited.

Infiltration

Infiltration is defined as the entry of water from the surface into the soil. For a given storm, infiltration determines the amount and time distribution of rainfall excess, soil water storage, and deep percolation. Because of the importance of the infiltration processes, accurate infiltration estimates are indispensable in describing the hydrology of a watershed for rainfall-runoff modeling. The infiltration process is affected by type and density of vegetation cover, surface crust, rainfall intensity, hydraulic properties of soil, and antecedent soil moisture content. Many scientists have developed empirical and theoretical infiltration formulae. Morel-Seytoux (1973), Hillel (1981), and Skaggs and Khaleel (1982) have presented literature reviews of the infiltration process.

Green-Ampt Infiltration Equation

A conceptual model using Darcy's law was proposed by Green and Ampt (1911) with the following assumptions:

(1) There exists a distinct and precisely definable wetting front where suction at this wetting front remains essentially constant regardless of time and position; (2) Behind the front, the soil is uniformly wet and of constant conductivity; therefore, the wetting front is viewed as a plane separating a uniform wetted infiltrated zone from a totally uninfiltrated zone; (3) In effect, this supposes the relation between hydraulic conductivity and soil moisture to be discontinuous at the value of suction prevailing at the wetting front.

The equation is expressed as

$$f = K_s(H_o + H_c + L_f)/L_f \tag{1}$$

where:

f = infiltration rate

K_s = hydraulic conductivity of transmission zone

H_o = depth of water ponded on the surface

H_c = effective suction at the wetting front

L_f = distance from the surface to the wetting front

If it is assumed that at all times the ponded surface is such that the infiltration rate is equal to the infiltration capacity and the ponding depth is shallow, Equation (1) can be rewritten as:

$$f = K_s + \frac{K_s D H_c}{F} \tag{2}$$

where:

$F = DL_f = (\theta_s - \theta_i)L_f$

F = cumulative infiltration volume

D = fillable porosity

θ_s = final soil water volume content

θ_i = initial soil water volume content

H_c = effective suction at the wetting front

K_s = effective hydraulic conductivity

By integrating Equation (2), and substituting $f = \frac{dF}{dt}$ with condition $F = 0$ at $t = 0$ the following equation is obtained:

$$K_s t = F - H_c D \ln(1 + \frac{F}{H_c D}) \tag{3}$$

Green-Ampt Parameter Estimation

Many researchers have estimated the Green-Ampt equation parameters. The parameters are hydraulic conductivity, suction head at wetting front and fillable porosity.

Hydraulic Conductivity. Bouwer (1966, 1969) showed that the hydraulic conductivity parameter in the Green-Ampt equation should be less than the saturated value, K_o, because of entrapped air. He described K_o as hydraulic conductivity at residual air saturation. Chu and Engman (1982) used the Green-Ampt equation based on a two-phase infiltration process on two small watersheds. They found that effective hydraulic conductivity is directly proportional to fillable porosity.

Suction Head at Wetting Front. Bouwer (1966) used the water entry suction head, h_{ce}, for H_c in Equation (3). Mein and Larson (1973) used the average suction head at wetting front, S_{av}, for H_c in Equation (3), and used unsaturated hydraulic conductivity as a weighting factor. The average suction head at the wetting front is defined by Equation (4).

$$S_{av} = \int_o^1 \psi \, dK_r \qquad (4)$$

where:

S_{av} = average suction head at wetting front

ψ = soil water suction

$K_r = \frac{K(\psi)}{K_s}$ = relative hydraulic conductivity

Morel-Seytoux and Khanji (1974) suggested the concept of effective matrix drive, H_c, which is similar to the suction head at the wetting front. They found that for most cases the value of S_{av} given by Equation (4) is a reasonable approximation of H_c and dependent on the relative conductivities of water and air. Brakensiek (1977) determined the value of S_{av} for five soils, which were originally used by Mein and Larson (1973). He showed that Equation (4) may be integrated to obtain Equation (5)

$$S_{av} = h_{ce} \frac{\eta}{(\eta-1)} \qquad (5)$$

where:

h_{ce} = water entry (or air exist) suction

= one-half of air entry value (bubbling pressure)

η = graphical parameter

He also found from regression analysis that Equation (6) is a good approximation for the soils considered:

$$S_{av} = 0.76 \; P_b \qquad (6)$$

where:

P_b = desorption (bubbling) pressure of a soil

<u>Soil Hydraulic and Textural Relationships</u>. In recent years, many researchers have conducted experiments and collected a wide range of

soil samples to compute the Green-Ampt equation parameters. Clapp and Hornberger (1978) developed empirical equations for some soil hydraulic properties of 11 different soil textural classes. They developed a formula for suction head at wetting front, H_c, by using a power function relating soil moisture and hydraulic conductivity. Rawls et al. (1982) presented various soil water characteristics of different soil textures. McCuen et al. (1981) presented a statistical analysis of Green-Ampt equation parameters across soil texture classes. They presented means and standard errors of the parameters for the soil texture classes. Zirbel et al. (1982) presented field and laboratory methods for estimating the Green-Ampt equation parameters over a range of soil textures on Minnesota soils.

Green-Ampt Parameter Evaluation

Brakensiek and Onstad (1977) determined the Green-Ampt equation parameters by fitting infiltrometer data. They considered spatial variation of the estimated parameters and showed the methods for averaging the values to give lumped parameter values. A sensitivity analysis for the parameters showed that computed infiltration and runoff were most sensitive to the errors in fillable porosity and effective hydraulic conductivity and less sensitive to the errors in effective suction at the wetting front.

Green-Ampt Equation Evaluation

Bouwer (1969) showed that the Green-Ampt equation may be used for nonuniform initial soil moisture content.

Morel-Seytoux and Khanji (1974) reported an equation similar to Equation (2), in which the air and water movements were considered simultaneously. They accounted for resistance due to air movement by introducing a viscous resistance factor, β, which was defined as a function of the soil and fluid properties. The value of β for five soils ranged from 1.1 to 1.7 compared to an assumed value of β=1 when the air phase was neglected. Infiltration rates were overpredicted by 10 to 40 percent when the air movement was not considered.

Bouwer (1976) showed the use of the Green-Ampt equation on the soil profiles where hydraulic conductivity increases with depth.

Li et al. (1976) gave the solution of the Green-Ampt equation. They found that, based on theoretical considerations, the approximation of the infiltration Equation (3) should be performed on the cumulative infiltration, not on the infiltration rate. They employed a power series expansion of the logarithmic term in Equation (3) and obtained Equation (7):

$$\Delta F = \left[2K_s \Delta t(H_c D + F) + \left(F - \frac{K_s \Delta t}{2}\right)^2\right]^{\frac{1}{2}} - \left[F - \frac{K_s \Delta t}{2}\right] \qquad (7)$$

where:

ΔF = difference in infiltration volume in Δt time interval

K_s = effective hydraulic conductivity

H_c = effective suction at the wetting front

D = fillable porosity

F = cumulative infiltration volume

This simple explicit solution resulted in a maximum error of 8 percent.

Green-Ampt-Mein-Larson Infiltration Equation

Mein and Larson (1973) applied the Green-Ampt equation for rainfall conditions by calculating cumulative infiltration at the time of surface ponding from Equation (2).

When $t = t_p$; $F = F_p$ and $H_c = H_{av}$, then,

$$F_p = \frac{H_{av} D}{R/(K_s - 1)} \tag{8}$$

$$f_p = R = K_s + \frac{K_s D H_{av}}{F} \tag{9}$$

$$t_p = \frac{F_p}{R} \tag{10}$$

where:

F_p = cumulative infiltration volume at time of surface ponding

f_p = infiltration rate at time of ponding

t_p = time of surface ponding

R = rainfall intensity

D = moisture deficit (fillable porosity)

H_{av} = average suction at the wetting front

K_s = effective hydraulic conductivity

Thus, for steady rainfall, infiltration rate is expressed as:

$$f=R \quad \text{for} \quad t<t_p \tag{11}$$

and

$$f = K_s + \frac{K_s D H_{av}}{F_p} \quad \text{for} \quad t>t_p \tag{12}$$

Mein and Larson (1971) used Equation (12) and time required to infiltrate volume F_p under initially surface ponded conditions to obtain Equation (13) for rainfall infiltration, similar to Equation (3).

$$K_s(t-t_p+t'_p) = F - D\, H_{av} \ln(1 + \frac{F}{DH_{av}}) \quad (13)$$

where:

t'_p = equivalent time to infiltrate volume F_p under initially ponded surface conditions.

The Green-Ampt equation has also been used for unsteady rainfall. Reeves and Miller (1975) favored the use of the Green-Ampt equation and found that the infiltration capacity, f_p, for unsteady rainfall could be approximated as a function of cumulative infiltration, F.

James and Larson (1976) found that the Green-Ampt equation along with the soil water redistribution equation consistently over-predicted the infiltration capacities for intermittent rainfall conditions.

Chu (1978) found good agreement between observed and simulated run-off events on a 113 acre watershed using the Green-Ampt-Mein-Larson equation for unsteady rainfall.

Knisel et al. (1980) used the equations developed by Mein and Larson (1973) in the CREAMS hydrologic model-option 2. They utilized Equation (7), which is a simple explicit solution developed by Li et al. (1976) for rainfall infiltration after surface ponding.

Modified Green-Ampt-Mein-Larson Infiltration Equation

Moore (1981) showed the modified Green-Ampt Mein-Larson equation to include surface sealing effects. He presented the infiltration equations for a constant rainfall intensity greater than the saturated hydraulic conductivity for a soil of uniform moisture content.

Moore and Eigel (1981) developed equations for infiltration into a two-layered soil profile by modifying the Green-Ampt-Mein-Larson equation. They presented Equations (14) and (15) for a surface layer of soil profile of depth L_1 and a subsurface soil of depth L_2, respectively.

$$F - G_1 D_1 \ln(1 + \frac{F}{G_1 D_1}) = K_1 t; \text{ for } L \leq L_1 \quad (14)$$

$$F + (E-H) \ln(1 + \frac{F}{H-F_1}) = K_2 t; \text{ for } L > L_1 \quad (15)$$

where:

$E = L_1 D_2 (\frac{K_2}{K_1})$

$H = D_2 (L_1 + G_2)$

$F_1 = L_1 D_1$

K_1 = hydraulic conductivity of wetting zone behind the wetting front in the surface layer

G_1 = effective suction at the wetting front in the surface layer

D_1 = initial soil moisture deficit in the surface layer

L_1 = depth of surface layer

K_2 = hydraulic conductivity of wetting zone behind the wetting front in the subsurface layer

G_2 = effective suction at the wetting front in the subsurface layer

D_2 = initial soil moisture deficit in the subsurface layer

L_2 = depth of subsurface layer

F = cumulative infiltration volume

t = time elapsed

Evapotranspiration

Evapotranspiration is one of the principal processes in the hydrologic cycle. It influences the depth and time distribution of soil water and antecedent hydrologic conditions. A large amount of the rainfall (about 70 percent) that reaches the ground is lost to the atmosphere by evapotranspiration. Accurate spatial and temporal estimations of evapotranspiration are needed for hydrologic modeling.

Many models of evapotranspiration with varying degrees of complexity have been developed. Jensen et al. (1973), Jensen (1980), and Saxton and McGuiness (1982) have presented excellent reviews of literature on evapotranspiration.

Ritchie (1972) presented a series of equations beginning with the Penman equation to represent actual evapotranspiration and define potential evaporation by Equation (16); he then separately calculated soil and plant evaporation.

$$E_o = \left[\frac{1.28\Delta}{\Delta + \gamma}\right] H_o \qquad (16)$$

where:

E_o = potential evaporation

Δ = slope of saturation vapor pressure curve at mean air temperature

γ = psychrometric constant

H_o = net solar radiation, $H_o = \frac{(1-\lambda)R}{583}$, R = daily solar radiation, λ = albedo of surface

The slope of the saturation vapor pressure curve at the mean air temperature, Δ, was given by Equation (17).

$$\Delta = \frac{5304}{T^2}\left[e^{(21.255-5304/T)}\right] \tag{17}$$

where:

Δ = slope of the saturated vapor pressure curve at mean air temperature T in degrees kelvin.

The potential soil evaporation, first stage drying, was given by Equation (18):

$$E_{So} = E_o\left[\text{Exp}(-0.398\ \text{LAI})\right] \tag{18}$$

where:

E_{So} = potential soil evaporation

E_o = potential evaporation

LAI = leaf area index

When the cumulative soil evaporation exceeds stage one, the upper limit which was defined by Equation (19), then the second stage of soil evaporation begins, which was computed by Equation (20):

$$U = 9(\alpha_s - 3)^{0.42} \tag{19}$$

$$E_{S2} = \alpha_s\left[t^{1/2} - (t-1)^{1/2}\right] \tag{20}$$

where:

E_{S2} = soil evaporation for t days

t = number of days since the second stage began

α_s = soil evaporation parameter

Plant transpiration was represented by the empirical Equation (21):

$$E_p = E_o\left[-0.21 + 0.70(\text{LAI})^{1/2}\right] \tag{21}$$

where:

E_p = transpiration by plants

E_o = potential evaporation

LAI = leaf area index

Equation (21) is valid only for conditions when water is not limiting and LAI varies from 0.1 to 2.7 and for LAI > 2.7, $E_p = E_o$. Equation (21) was tested on cotton and grain sorghum.

In the development of the CREAMS model, Knisel et al. (1980) used Equation (22), instead of Equation (21), to compute the plant transpiration under no soil water limitation.

$$E_p = E_o \cdot \frac{LAI}{3} \tag{22}$$

Equation (23) was used under limiting soil moisture conditions:

$$E_{pl} = E_p \cdot \frac{SM}{0.25\ FC} \tag{23}$$

where:

E_{pl} = plant transpiration reduced by limited soil moisture SM

E_p = plant transpiration under no soil moisture limitation

FC = field capacity of soil

Ritchie et al. (1976) calculated daily evaporation for three small native grassland watersheds. They modified the evapotranspiration model developed by Ritchie (1972). Seasonal changes in soil water content were computed, which were within ±5 cm of measured soil water during a one-year period. They found differences in evapotranspiration from two adjacent watersheds at Chickasha, Oklahoma. These differences were principally due to differences in transpiration between these two areas since soil evaporation in both areas were about equal. This pointed out the important effects of management systems utilization for the two grassland watersheds.

Knisel et al. (1980) used Ritchie's (1972) evapotranspiration equation in the CREAMS hydrologic model.

Soil Moisture Distribution

Soil moisture distribution in the soil profile is an important phase in determining the movement of the wetting front during the infiltration process and the rate of soil water removal by plant roots.

The soil water distribution during infiltration from a ponded surface into a uniform soil profile is divided into four zones. At the top there is a saturated zone approximately 0.5 inches thick. The transition zone is a region of rapid decrease of soil water content, extending from the zone of saturation to the transmission zone. The transmission zone is a zone of nearly constant water content which lengthens as infiltration proceeds. The wetting zone maintains a nearly constant shape during infiltration and ends in the wetting front, which is the limit of water penetration into the soil. There has been considerable disagreement in the literature on the existence of saturation and transition zones.

Often the movement of soil water in the root zone of the plants occurs while the soil is in an unsaturated condition. When the soil is wet, most of the crop's moisture is withdrawn from the soil near the surface. As the moisture content of the soil near the surface decreases, more moisture is extracted from lower depths until the moisture content of the soil near the surface approaches the permanent wilting point.

Williams and Hann (1978) developed a simple model to determine the distribution of water in the soil profile.

The total water use was divided into six equal storages given by Equation (24):

$$UW = \sum_{i=1}^{6} UW_i \qquad (24)$$

where:

UW = total water use

UW_i = water use by crop in soil storage i

The water use within any storage was given by Equation (25):

$$UW_i = \frac{V_o}{\kappa} (e^{-\kappa RD_{i-1}} - e^{-\kappa RD_i}) \qquad (25)$$

where:

V_o = water use rate by the crop at the surface

κ = water use rate constant

RD_{i-1} = root depth at storage i-1

RD_i = root depth at storage i

It was assumed that the top storage was twice as large as the second storage, which was given by the following equation:

$$UW_1 = 2UW_2 \qquad (26)$$

By substituting Equation (25) into Equation (26), the nonlinear equations were obtained and solved. The value of κ was determined to be 4.16. The value of V_o was computed by Equation (27), which was obtained by integrating Equation (25) and substituting the total water use equal to evapotranspiration:

$$ET = \frac{V_o}{4.16}(1 - e^{-4.16}) \qquad (27)$$

The above described water use model (William and Hann, 1978) was used as a sub-model in the CREAMS hydrologic model-option 1 (Knisel et al., 1980).

Deep Percolation

The process of water flow beyond the root zone is defined as deep percolation. This flow continues down to join a body of ground water. Although many research workers have developed ground water flow models, very few are used in hydrologic modeling. The amount of detail about how subsurface water flow is used depends on the objective of the model and physical set up of the system.

A simplified Equation (28) is used by the CREAMS hydrologic model-option 1 (Knisel et al., 1980) to estimate percolation rate per day:

$$D = \sigma(F + \frac{SM}{\Delta t}), \qquad (28)$$

where:

D = percolation rate per day

σ = storage coefficient

F = infiltration or inflow rate

SM = soil water storage

Δt = routing interval (1 day)

Storage coefficient, σ, is estimated from the following equation:

$$\sigma = \frac{2\Delta t}{2t + \Delta t} \qquad (29)$$

where:

σ = storage coefficient

t = travel time through a storage

Δt = routing interval

Travel time (t) through a storage is given by this equation:

$$t = \frac{SM-FC}{K_s} \qquad (30)$$

where:

t = travel time through a storage

SM = soil water storage

FC = field capacity

K_s = saturated hydraulic conductivity of the soil

Equation (31) is used by CREAMS hydrologic model-option 2 (Knisel et al., 1980) to determine daily water movement from the upper soil zone, which is very shallow in depth (about 2 inches), to the root zone. The movement of water is a function of the difference in saturation between the two zones.

$$q_s = C_s S_s^3 (S_s - S_p)\phi \cdot D_s; \; S_s > S_p \qquad (31)$$

where:

q_s = daily water movement from surface to root zone

C_s = coefficient (normally 0.1)

S_s = saturation by volume in surface zone

S_p = saturation by volume in root zone

ϕ = porosity of soil

D_s = depth of surface zone (2-5 cm)

The percolation from the root zone is computed when soil water in the root zone exceeds field capacity of the soil. Percolation is estimated as the daily excess of soil water in the surface zone over the field capacity.

Hydrologic Model

Renard et al. (1982) have listed as many as 75 currently available hydrologic models. Users are faced with the problem of selecting the appropriate model. Many are site or physiographic specific. Therefore, the users must select the model which would effeciently provide the information required under the time and economic constraints.

In this study the CREAMS hydrologic model, which is described in detail in the next section, was applied to the grassland watersheds of central Oklahoma.

The CREAMS Model

The CREAMS model (Chemical, Runoff, and Erosion from Agricultural Systems) was developed by a team of USDA-SEA-AR scientists (Knisel et al., 1980). It was assembled from state-of-the-art mathematical models to evaluate non-point source pollution for field scale areas. The model consists of four components, namely, hydrologic, erosion, plant nutrient, and pesticide components.

The hydrologic component includes models for infiltration, soil water movement, and soil and plant evaporation. It uses one day as the time step for evaporation and soil moisture movement. The component consists of two options for rainfall data input: (1) daily rainfall and (2) hourly or breakpoint rainfall (at the breakpoints in the slope of the rainfall vs. time curve). The daily rainfall option uses the SCS curve number model, while the breakpoint rainfall option uses the Green-Ampt infiltration model to estimate the surface runoff. Both methods estimate evapotranspiration and percolation through the root zone of the soil.

In this research study, only the breakpoint rainfall option was utilized. Therefore, more detail of the hydrologic model will be provided in the subsequent sections. Readers are referred to the CREAMS manual (Knisel et al., 1980) for additional details.

Model Inputs

The model inputs can be grouped into two classes: (1) input data and (2) input parameters. Input data consists of observed and/or measured values of climatological and watershed characteristics. Input parameters include the estimated values, either by literature search or by experiments, of soil profile and plant cover condition parameters.

Climatological Input Data. The continuous record of rainfall data, in the breakpoint form, is entered as the cumulative rainfall, BP(I)*, at its corresponding time, T(I), format. The average monthly temperature, TEMP(I), and solar radiation, RAD(I), are utilized and can be

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*The abbreviations used for inputs are those used in the CREAMS manual (Knisel et al., 1980).

updated at the end of each year of simulation. If they cannot be updated, then the averages of number of years values may be used.

Watershed Characteristics Data. The watershed characteristic data includes the watershed area, DACRE; effective hydraulic slope, SLOPE; effective slope length, XLP; and Manning's roughness coefficient for the field surface, RMN. These watershed characteristics can be measured directly or estimated from a topographic map of the watershed.

Soil Profile Parameters. The soil profile input parameters include effective saturated hydraulic conductivity of soil, RC; effective capillary tension of soil, GA; soil evaporation parameter; CONA, soil porosity, POROS; the portion of available water storage filled at field capacity, FUL; and soil water content at 15 bar tension, BR15. All soil parameters used herein are related to soil texture. They could be estimated by referring to published soil sample analyses on similar soil textures or by performing experiments in situ and laboratory. The latter procedure would produce comparatively accurate estimates; however, it is a time consuming and expensive process. The accuracy requirements of the soil parameters vary, depending upon the sensitivity of the model.

Plant Cover Parameter. Plant cover parameter is given by leaf area index, X(I), for the crop grown. For each year, the leaf area index data are used along with the corresponding Julian calendar date. The model has an option to input a different leaf area index for each year of simulation. Typical leaf area index distribution for various crops are shown in the CREAMS manual (Knisel et al., 1980).

Model Structure and Operation

A brief description of the hydrologic processes used in the model is presented in the following paragraphs.

Infiltration during rainfall is composed of two phases. At the beginning of the rainfall, the initial soil water content in the small upper depth, DS, affects the infiltration. In the early stages of rainfall, the soil water increases from initial soil water to maximum fillable porosity (i.e., equal to porosity minus air residual value). If the rainfall lasts long enough, then the soil controls water entry and the time when it starts is called ponding time, t_p. Subsequent to the ponding time, infiltration is given by the Green-Ampt equation. An explicit solution of the Green-Ampt equation, Equation (7), is used to compute the amount of infiltrated water in the soil profile.

The model uses a set of equations developed by Ritchie (1972) to compute evapotranspiration. It utilizes Equation (16) to compute potential evaporation. Soil evaporation and plant transpiration are computed by Equations (18) and (22), respectively. Both equations are functions of leaf area index, potential evaporation, and soil water content. The actual evapotranspiration is computed by adding the soil evaporation and plant transpiration, which cannot exceed potential evaporation.

A root growth model uses the relative root depth proportional to relative leaf area index. Soil water extraction from roots occurs from both surface and root zones in proportion to the relative root depth. Water movement from the surface layer, DS, to the root zone, DP, is given by Equation (30). Deep percolation is computed as the daily excess of saturation of surface layer over field capacity when saturation of root zone exceeds field capacity.

After water enters the soil by the infiltration process, it becomes either evapotranspiration, soil water storage, or percolation below the root zone. A water balance Equation (32) uses a one day time interval to update the soil water storage in the root zone:

$$SM_i = SM_{i-1} + F_i - ET_i - O_i + M_i \tag{32}$$

where:

SM = soil water storage in the root zone

F_i = infiltration on day i

ET_i = evapotranspiration on day i

O_i = percolation from the root zone on day i

M_i = snowmelt amount on day i

Model Output

The model output for the simulation period includes daily, monthly, and annual values of rainfall, runoff, evapotranspiration, percolation, and average soil water in the root zone. It also contains monthly and annual totals and means for each component.

Previous Research on the CREAMS Hydrologic Model

Knisel et al. (1980) applied the CREAMS hydrologic model-option 2 to 9 watersheds, ranging in area from 0.6 to 23.7 acres. The watersheds were located in Arizona, Georgia, Nebraska, Ohio and Oklahoma. For comparing the observed and simulated runoff, peak discharge, and percolation, data sets of 2 to 26 years were utilized. The correlation coefficients between observed and simulated daily runoff varied from 0.80 to 0.90. However, some years of simulation produced correlation coefficients as low as 0.10 to 0.20.

Lane and Ferreira (1980) performed sensitivity analyses on the CREAMS hydrologic model on a 3.2 acre watershed at Watkinsville, Georgia. They analyzed 138 rainfall events over a two year period. They found that the model generally overpredicted runoff volume and runoff peak. The model explained only 76 percent of variance in runoff volume and 75 percent of variance in runoff peak for 58 runoff-producing events.

It was found that sensitivity of the parameters varies with the objectives for which the model is to be utilized. For simulating runoff volume, effective saturated hydraulic conductivity, RC, is a significantly sensitive parameter. Four parameters, i.e., soil evaporation parameter, CONA; effective capillary tension, GA; soil porosity, POROS; and solar radiation, RAD(I); are moderately sensitive. The other eight parameters affect the runoff volume slightly. However, simulated runoff peak is not significantly affected by any single parameter.

CHAPTER III

APPLICATION OF THE CREAMS HYDROLOGIC MODEL TO TEST WATERSHEDS

Introduction

This chapter describes the watersheds, the CREAMS hydrologic model inputs and simulation procedure.

The model was applied to four grassland watersheds in central Oklahoma. Two of the watersheds, Guthrie W-V and Chickasha R-7, are relatively small in size and have relatively homogeneous soils. The other two watersheds, Stillwater W-4 and Stillwater W-3, are relatively large and have heterogenous soils. The input values of the soil profile parameters, plant cover parameter, watershed characteristics data, and climatological data were obtained for each watershed. Thereafter, the simulation runs were made with initial and varied parameters values.

Watershed Descriptions

Guthrie W-V Watershed

The Guthrie W-V watershed is about 4 miles southeast of Guthrie in Logan County, Oklahoma. It has an area of 15.5 acres and an average slope of 3.9 percent with rolling topography. A topographic map is shown in Figure 1. The vegetative cover was moderately grazed native grass which was mowed every spring and kept in excellent condition

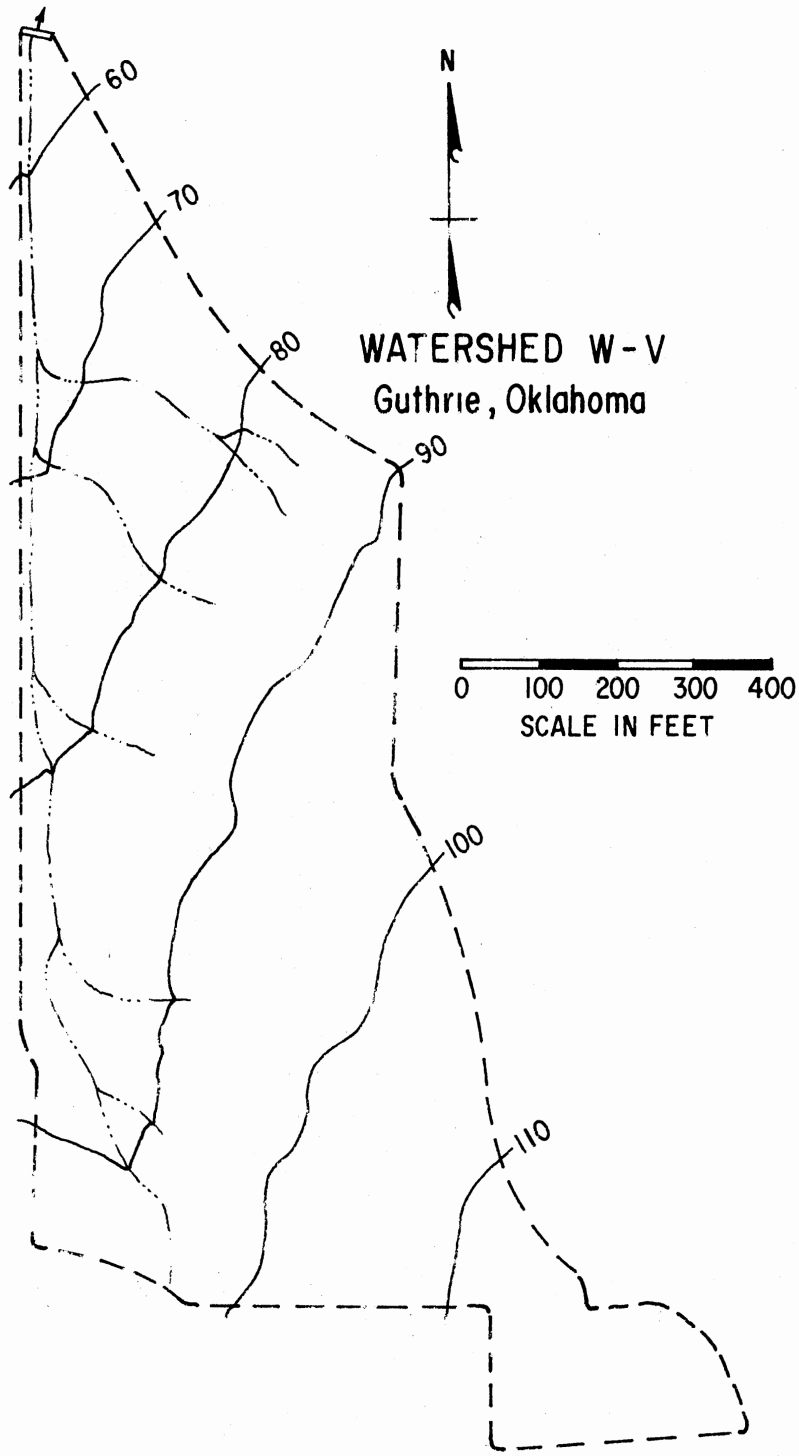

Figure 1. Topographic Map for Guthrie W-V Watershed

during the simulation period.

The soils were described in Soil Survey of Noble County by USDA-SCS (1960). They were classified as Zanies Loam and hydrologic soil group C. The topsoil and subsoil textures are loam and clay loam. The depths of topsoil and subsoil are 10 inches and 21 inches, respectively (Table I).

Chickasha R-7 Watershed

The Chickasha R-7 watershed is located about 9 miles northeast of Chickasha in Grady County, Oklahoma. It has an area of 19.5 acres and slope that ranges from 2.0 to 4.5 percent. Figure 2 is a topographic map of the watershed.

The watershed was cultivated from 1907 to 1935. Severe erosion occurred during the latter years of cultivation. The area was changed to pasture and a 69 percent cover of little bluestem grass established by natural reseeding. The rest of the area was covered by the annual threeawn grass.

USDA-SCS (1978) describes the soils in Soil Survey of Grady County. They are 38 percent Kingfisher silt loam, 39 percent Renfrow silt loam and 23 percent Kingfisher-Lucien complex. Table II shows the topsoil and subsoil textures and depths, and hydrologic soil groups of the soils.

Stillwater W-4 Watershed

The Stillwater W-4 watershed is located about 15 miles north of Stillwater in Noble County, Oklahoma. It has an area of 206 acres. Three ponds with total drainage area of 41 acres and 5.8 acre-ft storage are located on the watershed. The slope varies from 4.7 to 6.3 percent.

TABLE I

SOIL CLASSIFICATIONS FOR GUTHRIE W-V WATERSHED

Soil Series	Area Covered (Percent)	Top Soil Texture	Sub Soil Texture	Top Soil Depth (Inches)	Sub Soil Depth (Inches)	Hydrologic Soil Group
Zanies	100	Loam	Clay loam	10.0	21.0	C

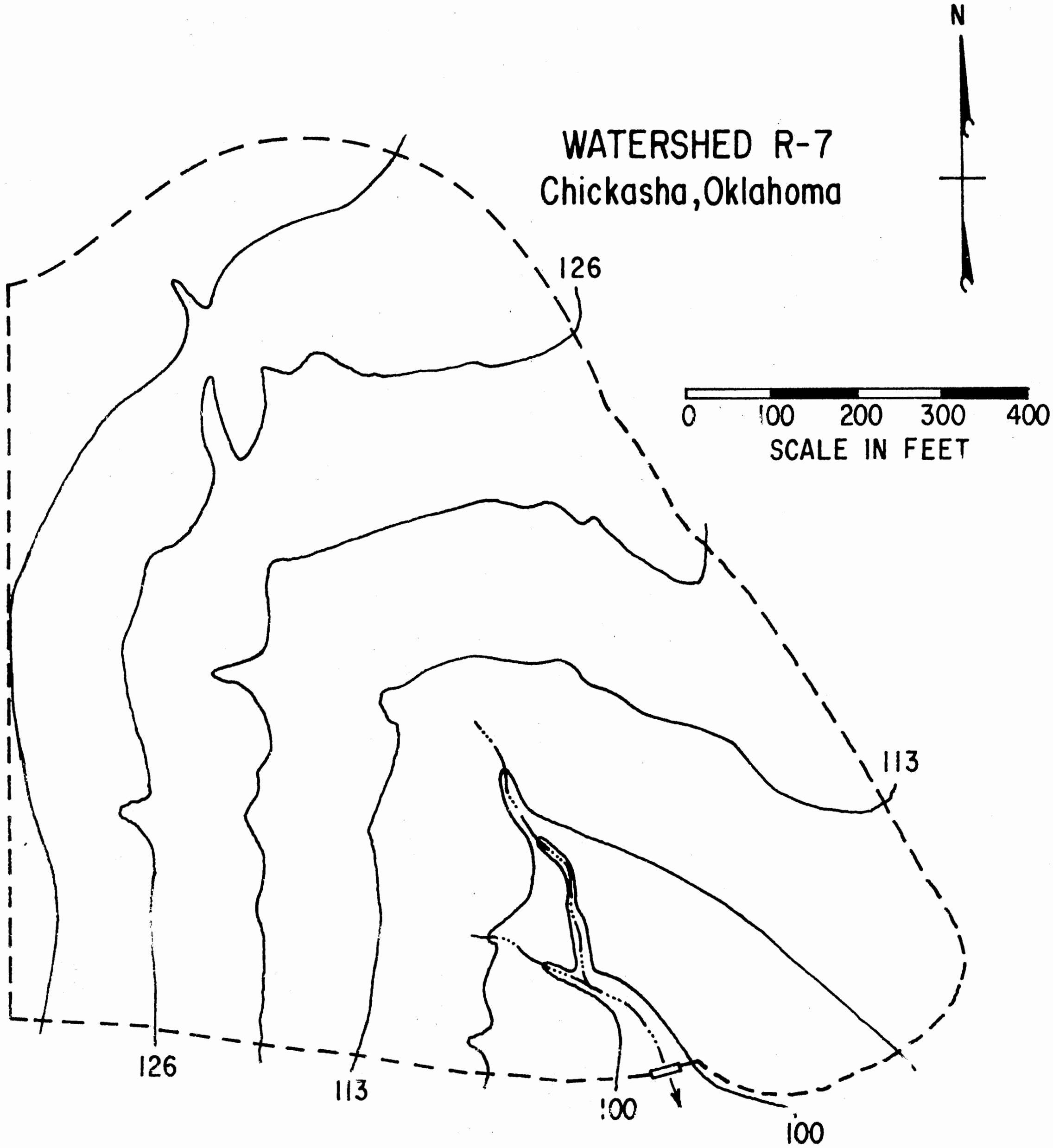

Figure 2. Topographic Map for Chickasha R-7 Watershed

TABLE II

SOIL CLASSIFICATIONS FOR CHICKASHA R-7 WATERSHED

Soil Series	Area Covered (Percent)	Top Soil Texture	Sub Soil Texture	Top Soil Depth (Inches)	Sub Soil Depth (Inches)	Hydrologic Soil Group
Kingfisher	38	Silt loam	Silty clay	14.0	24.0	C
Renfrow	28	Silt loam	Silty clay	9.0	54.0	D
Kingfisher-Lucien	34	Complex	Silty clay	9.0	7.0	C

A topographic map is shown in Figure 3.

The vegetative cover on the watershed is native grass consisting of 30 percent short perennial grass, 50 percent tall perennial grass and 20 percent annual grass.

Soil Survey of Noble County by USDA-SCS (1956) shows the soils on the watershed. Unlike Guthrie W-V and Chickasha R-7 watersheds, various soil series are present on the watershed. The dominant soil is Vernon, which constitutes 40 percent of the watershed, with topsoil and subsoil textures of clay loam and clay, respectively. The other soils are: Renfrow (16 percent), Lucien (14 percent) and Albion (13 percent) soil series. Table III shows the soils with their respective areal coverage, topsoil and subsoil textures and depths, and hydrologic soil groups.

Stillwater W-3 Watershed

The Stillwater W-3 watershed is adjacent to the Stillwater W-4 watershed. It has an area of 92 acres including a pond. The pond drainage area is 20 acres. Figure 4 shows a topographic map of the watershed. It has a rolling topography with slopes that range from 3.7 to 5.1 percent. The vegetative cover was native grass similar to the Stillwater W-4 watershed.

USDA-SCS (1956) describes the soils in Soil Survey for Noble County. Like the Stillwater W-4 watershed, its soils vary in the soil series. One-half of the watershed area is covered with the Vernon soil series which has clay loam and clay soil textures of topsoil and subsoil respectively. It also has Renfrow silt loam, Renfrow silt clay loam and Miller soil series, which cover 18.5, 14.5 and 12.5 percent of the watershed area. Table IV shows the topsoil and subsoil textures and

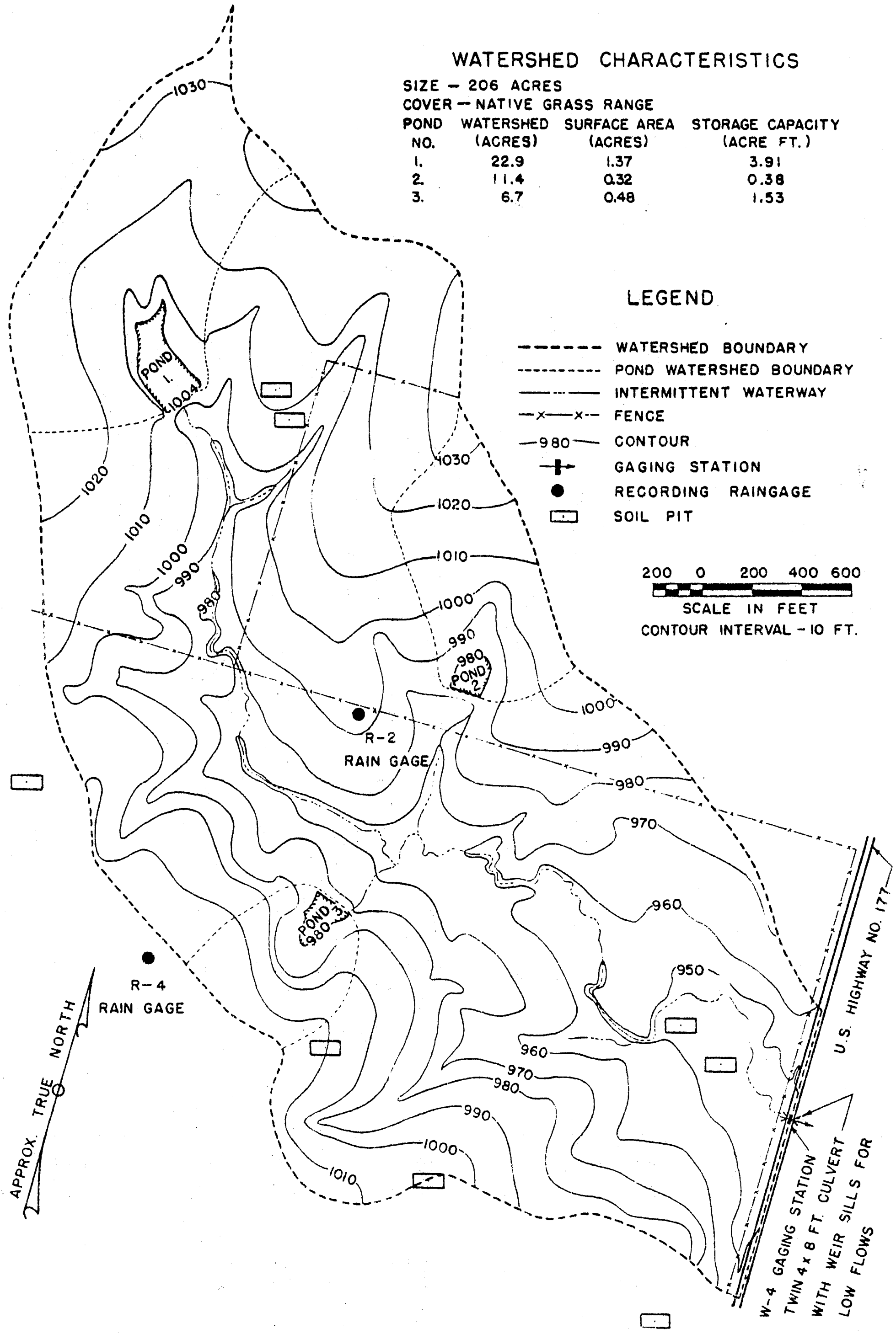

Figure 3. Topographic Map for Stillwater W-4 Watershed

TABLE III

SOIL CLASSIFICATIONS FOR STILLWATER W-4 WATERSHED

Soil Series	Area Covered (Percent)	Top Soil Texture	Sub Soil Texture	Top Soil Depth (Inches)	Sub Soil Depth (Inches)	Hydrologic Soil Group
Albion	13.2	Loam	Sandy loam Sandy clay loam Coarse sand	10	35	B
Gowen	9.6	Silt loam	Loam Silt loam Clay loam	20	40	C
Kirkland	3.4	Silt loam	Clay	10	35	D
Lucien	14.1	Fine sandy loam	Very fine sand loam	7	38	C
Norge	3.5	Silt loam	Loam Clay loam Sandy clay loam	12	48	C
Renfrow	16.2	Silt loam	Clay	10	35	D
Vernon	40.0	Clay loam	Clay	6	39	D

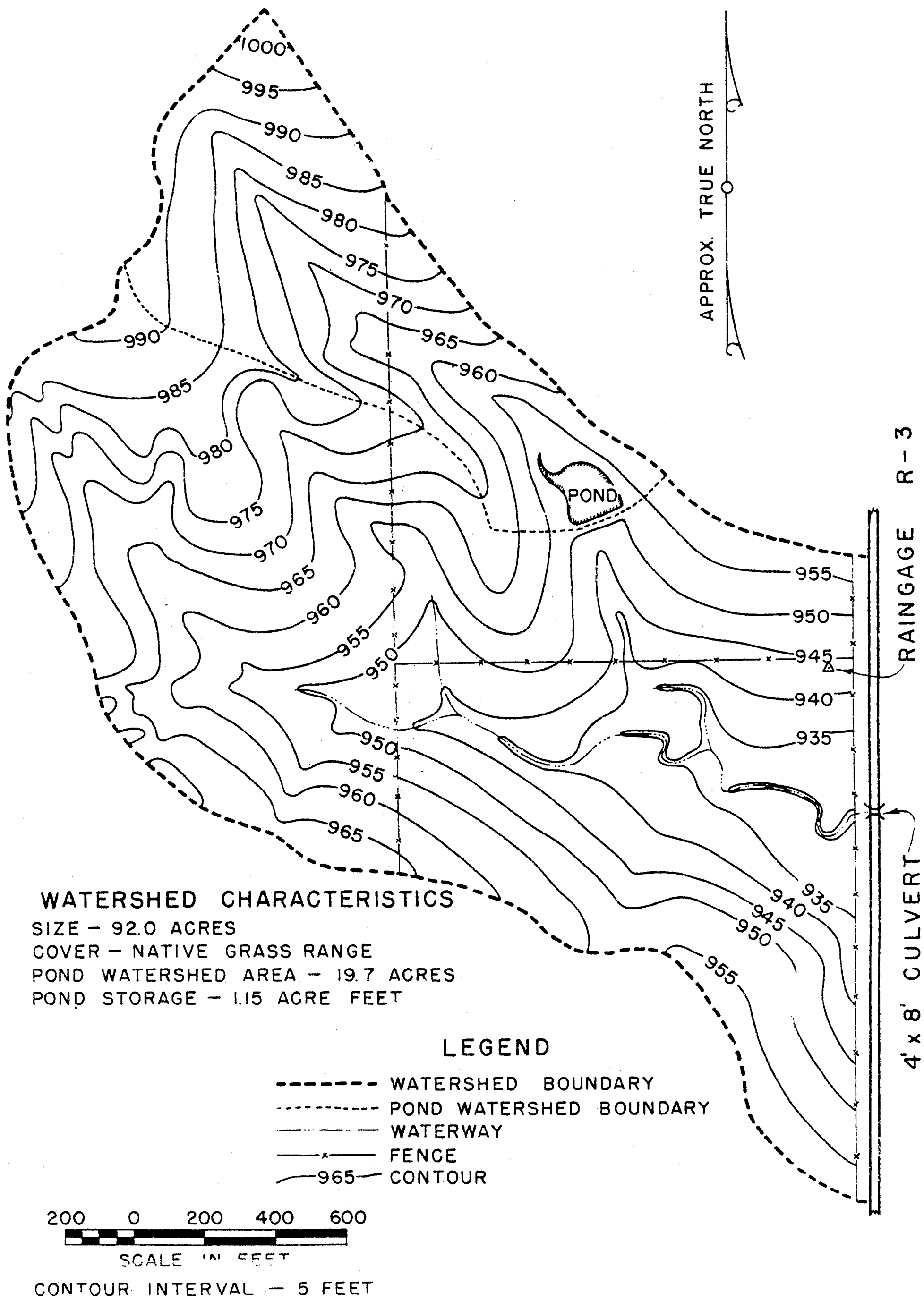

Figure 4. Topographic Map for Stillwater W-3 Watershed

TABLE IV

SOIL CLASSIFICATIONS FOR STILLWATER W-3 WATERSHED

Soil Series	Area Covered (Percent)	Top Soil Texture	Sub Soil Texture	Top Soil Depth (Inches)	Sub Soil Depth (Inches)	Hydrologic Soil Group
Renfrow	14.5	Silt clay loam	Clay	10	35	D
Renfrow	18.5	Silt loam	Clay	10	35	D
Kirkland	3.5	Silt loam	Clay	10	35	D
Vernon	51.0	Clay loam	Clay	6	39	D
Miller	12.5	Clay	Clay	15	45	D

depths, and hydrologic soil groups.

Determination of CREAMS Hydrologic Model Inputs

Soil Profile Parameters

The values of the soil profile parameters were selected such that they allowed the objective assessment of the input. The value of each parameter was selected according to predetermined criteria for the soil profiles of the watersheds. The selection criteria were based on (1) the understanding of the process of soil water movement into and within the soil profile as described by the model, and (2) by establishing relationships between the optimized values of the soil profile parameters and the soil physical properties of the test watershed.

Laboratory measurements of the soil physical properties of the watersheds were not available. Therefore, the best estimate of the soil properties were obtained from published references on similar soils as described by the soil survey of the watersheds. Each soil profile parameter value was selected from a value for the topsoil, a value for the subsoil, or a weighted average value (with respect to depths) for the soil profile. On the spatially varied soils, the values of the soil profile parameters were estimated from the weighted average with respect to their areal coverage.

Effective Saturated Hydraulic Conductivity. The effective saturated hydraulic conductivity, RC, was estimated from soil texture using average values of saturated hydraulic conductivity published by Rawls et al. (1982) and shown in Table V.

Effective Capillary Tension. The effective capillary tension, GA,

TABLE V

HYDROLOGIC SOIL PROPERTIES CLASSIFIED BY SOIL TEXTURE (FROM RAWLS ET AL.)[1]

Soil Texture	Saturated Hydraulic Conductivity (in/hr)	Bubbling Pressure (Inches)	Capillary Tension (Inches)	Soil Water at 15 Bar Tension (in^3/in^3)	Soil Porosity (in^3/in^3)
Sand	8.26	6.30	4.80	0.033 (0.007-0.059)[2]	0.437 (.374-0.50)
Loamy sand	2.40	8.10	6.10	0.055 (0.019-0.091)	0.437 (0.368-0.506)
Sandy loam	1.02	11.90	9.00	0.095 (0.031-0.159)	0.453 (0.351-0.555)
Loam	0.27	15.80	12.00	0.117 (.069-0.165)	0.463 (0.375-0.551)
Silt loam	0.52	20.00	15.20	0.133 (0.078-0.188)	0.50 (0.420-0.582)
Sandy clay loam	0.17	23.40	17.80	0.148 (0.085-0.211)	0.398 (0.332-0.464)
Clay loam	0.09	22.20	16.90	0.197 (0.115-0.279)	0.464 (0.409-0.519)
Silty clay loam	0.06	27.70	21.00	0.208 (0.138-0.278)	0.471 (0.418-0.524)
Sandy clay	0.05	31.30	23.80	0.239 (0.162-0.316)	0.430 (0.370-0.490)

TABLE V (Continued)

Soil Texture	Saturated Hydraulic Conductivity (in/hr)	Bubbling Pressure (Inches)	Capillary Tension (Inches)	Soil Water at 15 Bar Tension (in^3/in^3)	Soil Porosity (in^3/in^3)
Silty clay	0.03	30.10	22.90	0.250 (0.193-0.307)	0.479 (0.425-0.533)
Clay	0.02	33.70	25.60	0.272 (0.208-0.336)	0.475 (0.427-0.523)

[1]From Rawls, et al. (1982): Estimation of Soil Water Properties, Transaction of the ASAE, Vol. 25, No. 5.

[2]First line is the mean value. Second line is ± one standard deviation about the mean.

is also known as suction head at the wetting front. Brakenseik (1977) estimated the parameter by multiplying a value of 0.76 by the bubbling pressure of the soil. The bubbling pressures for various soil textures are given by Rawls et al. (1982). Table V shows the bubbling pressure and the capillary tension values for ten different soil textures.

Soil Porosity. Soil porosity, POROS, is an important property that varies with soil texture and structure. Rawls et al. (1982) collected large amounts of data and presented soil porosity for various soil textures, which are shown in Table V.

Immobile Soil Water Content. The immobile soil water content, BR15, is the volumetric water content of soil at 15 bar suction. Table V shows the values of immobile soil water content for various soil textures as presented by Rawls et al. (1982).

Soil Evaporation Parameter. The soil evaporation parameter, CONA, values are shown in Table VI. The values were adopted from Mean Physical Properties of Soils given by Franzmier (USDA-SCS, 1982).

Portion of Available Water Storage Filled at Field Capacity. The value for portion of available water storage at field capacity, FUL, was calculated for each soil texture using the following equation from Franzmier (USDA-SCS, 1982).

$$FUL = \left[\frac{\text{Field Capacity} - BR15}{\text{Porosity} - BR15}\right] \qquad (33)$$

Table VI shows the FUL values, which were presented in Mean Physical Properties of Soils given by Franzmier (USDA-SCS, 1982).

TABLE VI

SOIL PROFILE INPUT PARAMETERS OF CREAMS MODEL CLASSIFIED BY SOIL TEXTURE (FROM FRANZMIER)[1]

Texture	Portion of Available Water Storage Filled at Field Capacity (FUL)	Soil Evaporation Parameter (CONA)
Coarse sand	0.28	3.3
Sand	0.40	3.3
Fine sand	0.42	3.3
V. fine sand	0.63	3.3
L. coarse sand	0.40	3.3
Loamy sand	0.48	3.3
Loamy f. sand	0.55	3.3
L. V. f. sand	0.92	3.3
Coarse s. loam	0.48	3.3
Sandy loam	0.55	3.5
F. sandy loam	0.75	3.5
V. f. sandy loam	0.92	3.5
Loam	0.65	4.5
Silty loam	0.74	4.5
Silt	0.57	4.0
Sandy clay loam	0.75	4.0
Clay loam	0.80	4.0
Silty clay loam	0.77	4.0
Sandy clay	0.70	3.5
Silty clay	0.92	3.5
Clay	0.83	3.5

[1]From Franzmier (USDA-SCS, 1982), Mean Physical Properties of Soil.

Portion of Available Water Storage Filled When Simulation Begins. The portion of available water storage filled when simulation begins, BST, is a fraction of the available soil water at the beginning of the simulation. In this study, simulation began in the first week of January when soil profiles in central Oklahoma are usually fairly wet. Therefore, BST value was estimated to be about 0.50.

Depth of Surface Soil Layer. A surface soil layer depth, DS, of 2 inches was used for all the watersheds in accordance with the recommended values given in the CREAMS manual. Little information was available on the parameter estimation.

Depth of Soil Root Zone. The depth of soil root zone, DP, is the total root zone minus the depth of the surface soil layer. Total root depth is the maximum soil depth from which plants can extract water. Bengtson (1980) used total root depth as the sum of the depths of soil horizons A and B on grassland watersheds in central Oklahoma.

Soil Profile Parameters for Specific Watersheds

The Guthrie W-V and Chickasha R-7 watersheds have relatively homogenous soils. Tables VII and VIII show the values of the soil profile parameters for the Guthrie W-V and Chickasha R-7 watersheds.

Unlike the other two watersheds, the Stillwater W-4 and W-3 watersheds have a wide variety of soil textures. The values for the soil profile parameters are shown in Tables IX and X for the Stillwater W-4 and W-3 watersheds.

TABLE VII

ESTIMATED SOIL PROFILE PARAMETERS USED WITH CREAMS MODEL ON GUTHRIE W-V WATERSHED

Soil Texture	Saturated Hydraulic Conductivity (in/hr)	Effective Capillary Tension (Inches)	Soil Porosity (in/in)	Soil Water at 15 Bar Tension (in/in)	Soil Evaporation Parameter	FUL
Top soil Loam Sub soil	0.27	12.0	0.46	0.12	4.5	0.65
Clay loam	0.09	16.9	0.46	0.20	4.0	0.80
Depth Weighted Average		15.3	0.46	0.18		0.80

TABLE VIII

ESTIMATED SOIL PROFILE PARAMETERS USED WITH CREAMS MODEL ON CHICKASHA R-7 WATERSHED

Soil Texture	Saturated Hydraulic Conductivity (in/hr)	Effective Capillary Tension (Inches)	Soil Porosity (Inches)	Soil Water at 15 Bar Tension (in/in)	Soil Evaporation Parameter	FUL
Top soil Silt loam Sub soil	0.52	15.2	0.50	0.13	4.5	0.74
Silty clay	0.03	22.9	0.48	0.25		0.92
Depth Weighted Average		20.7	0.48	0.22		0.85

TABLE IX

ESTIMATED SOIL PROFILE PARAMETERS USED WITH CREAMS MODEL ON STILLWATER W-4 WATERSHED

Soil Texture	Area Covered (Percent)	Saturated Hydraulic Conductivity (in/hr)	Effective Capillary Tension (Inches)	Soil Porosity (in/in)	Soil Water at 15 Bar Tension (Inches)	Soil Evaporation Parameter	FUL
Top Soil							
Clay loam	40.0	0.09	16.9	0.46	0.20	4.0	0.80
Silt loam	32.7	0.52	15.2	0.50	0.13	4.5	0.74
Loam	13.2	0.27	12.0	0.46	0.12	4.5	0.65
Fine sandy loam	14.1	1.02	9.0	0.45	0.09	3.5	0.55
Area Weighted Average			14.6	0.47	0.15	4.2	0.68
Sub Soil							
Clay	60.0	0.02	25.6	0.47	0.27	---	0.83
Loam Very fine sand	14.1	0.27	12.0	0.46	0.12	---	0.65
Sandy loam Sandy clay loam Coarse sand	13.2	0.17	17.80	0.40	0.15	---	0.75
Loam Silty clay Clay loam	9.6	0.03	12.0	0.46	0.12	---	0.65

TABLE IX (Continued)

Soil Texture	Area Covered (Percent)	Saturated Hydraulic Conductivity (in/hr)	Effective Capillary Tension (Inches)	Soil Porosity (in/in)	Soil Water at 15 Bar Tension (Inches)	Soil Evaporation Parameter	FUL
Loam Clay loam Sandy clay loam	3.5	0.09	12.0	0.46	0.12	---	0.65
Area Weighted Average	---	----	20.9	0.46	0.21	---	0.77
Depth Weighted Average	---	----	19.7	0.47	0.19	---	0.72

TABLE X

ESTIMATED SOIL PROFILE PARAMETERS USED WITH CREAMS MODEL ON STILLWATER W-3 WATERSHED

Soil Texture	Area Covered (Percent)	Saturated Hydraulic Conductivity (in/hr)	Effective Capillary Tension (Inches)	Soil Porosity (in/in)	Soil Water at 15 Bar Tension (Inches)	Soil Evaporation Parameter	FUL
Top Soil							
Clay loam	57.0	0.09	16.9	0.46	0.20	4.0	0.80
Silt loam	22.0	0.52	15.2	0.50	0.13	4.5	0.74
Silt clay loam	14.5	0.06	21.0	0.47	0.20	4.0	0.77
Clay	12.5	0.02	25.6	0.47	0.27	3.5	0.83
Area Weighted Average			18.2	0.47	0.19	4.0	0.79
Sub Soil							
Clay	100	0.02	25.6	0.47	0.27	---	0.83
Depth Weighted Average	---	----	24.2	0.47	0.26	---	0.83

Plant Cover Parameter

The leaf area index (LAI) versus time pattern for a year was selected to simulate grass cover conditions. The values for pasture in excellent condition are given in the CREAMS manual. The values were made half for the good grass cover conditions and shown in Table XI. A winter cover factor of 0.5 for grass cover was used as suggested.

Watershed Characteristics Data

The watershed area, DACRE, hydraulic slope, SLOPE, and slope length, XLP, were determined for each watershed. A value of 0.03 was used for Manning's roughness coefficient, RMN, for flow over the native grass surface.

Climatological Data

Rainfall data (in the breakpoint format) and average monthly temperatures were used for each year of simulation period. The data for the Guthrie and Chickasha watersheds were obtained from the USDA-ARS (1956) and the USDA-SEA (1972). For the Stillwater W-4 and W-3 watersheds the data were collected from USDA-SEA (1972).

Average monthly solar radiation data were obtained from the CREAMS manual (Knisel et al., 1980). The data from Oklahoma City, Oklahoma were used for Guthrie and Chickasha watersheds, whereas Stillwater, Oklahoma, data were used for the Stillwater W-4 and W-3 watersheds.

The climatological data are shown in Appendix A, B and C.

Simulation Period

Different simulation periods were utilized for all four watersheds

TABLE XI

LEAF AREA INDEX FOR NATIVE GRASS
(FROM KNISEL ET AL.)[1]

Julian Day	Leaf Area Index[2]
001	0.00
091	0.00
114	0.92
137	1.50
160	1.50
188	1.50
206	1.50
220	1.50
252	1.35
275	1.07
298	0.98
321	0.25
366	0.00

[1]From CREAMS manual (Knisel et al. 1980).

[2]Values were 50 percent of the excellent pasture conditions.

due to availability of rainfall, temperature and runoff data. The Guthrie watershed runoff was simulated from January 1941 to December 1953. The simulation period for the Chickasha watershed was from January 1967 to December 1974. Stillwater W-4 and W-3 watersheds used the same climatological input data, starting in January 1952 and ending in December 1972.

Simulation Procedure

Simulation runs were made on each of the four watersheds. For each simulation run the following analyses were performed: (a) Cumulative runoff error (in percent) was given by the following equation:

$$CRE = \left(\frac{Q_{cs} - Q_{co}}{Q_{co}}\right) 100 \tag{34}$$

where:

Q_{cs} = cumulative simulated runoff volume

Q_{co} = cumulative observed runoff volume

CRE = cumulative runoff error (percent)

(b) Linear regression analysis between simulated and observed monthly runoff were performed. The regression line slope, correlation coefficient, and standard deviation were emphasized.

(c) A similar type pf analysis as in (b) was used but on an annual basis.

Table XII shows the initial model input values for the Guthrie W-V, Chickasha R-7, Stillwater W-4 and Stillwater W-3 wastesheds.

The input soil profile parameters varied were: effective saturated hydraulic conductivity, effective capillary tension, soil porosity, soil

TABLE XII

INITIAL VALUES OF CREAMS MODEL INPUT PARAMETERS FOR TEST WATERSHEDS

Parameters	Guthrie W-V	Chickasha R-7	Stillwater W-4	Stillwater W-3
Field Area (acres)	15.5	19.5	206	92
Effective Saturated Hydraulic Conductivity (in/hr)[1]	0.27	0.03	0.06	0.02
Fraction of Pore Space Filled at Field Capacity	0.80	0.87	0.72	0.83
Fraction of Available Water Storage Filled When Simulation Begins	0.50	0.50	0.50	0.50
Soil Evaporation Parameter	4.5	4.5	4.2	4.0
Soil Porosity (in/in)[1]	0.46	0.48	0.47	0.47
Immobile Soil Water Content (in/in)	0.18	0.22	0.20	0.25
Depth of Surface Soil Layer (in)	2	2	2	2
Depth of Maximum Root Growth Layer (in)	31	36	45	45
Effective Capillary Tension (in)[1]	15.3	20.7	19.7	24.2
Manning's n for Overland Flow	0.03	0.03	0.03	0.03
Effective Hydraulic Slope	0.039	0.038	0.055	0.044
Effective Hydraulic Slope Length (ft)	266	290	562	411

[1]These parameters were varied to determine the best estimates.

evaporation parameter, and soil root zone depth. The plant cover parameter, leaf area index was also varied. The parameters were varied one at a time to produce the best fit. The best fit was determined from the cumulative runoff error of ±1 percent, the slope of the regression line for simulated and observed monthly runoff volumes, the standard deviation from the regression, and correlation coefficient.

After the value of the parameter that produced the best fit was determined, it was left fixed at this value while determining values that produce the best fit for the other parameters. The process of parameter variation was repeated until the best estimates of all parameters were observed.

CHAPTER IV

RESULTS AND DISCUSSION OF SIMULATED RUNOFF FROM THE MODEL

Results and Analyses of Simulated Runoff

The results of the simulations and analyses for each watershed are presented and discussed in the following sections.

Guthrie W-V Watershed

Hydrologic records for 1941 to 1953 were used for the simulation. The year 1941 was not included in the analysis because an incorrect estimate of the initial soil moisture content at the beginning of the simulation year may affect the simulated runoff for that year.

The input parameters varied were effective saturated hydraulic conductivity, RC, effective capillary tension, GA, soil porosity, POROS, soil evaporation parameter, CONA, soil root depth, DP, and leaf area index, X.

The initial value of the RC parameter was not known explicitly. The CREAMS manual suggests a tentative value of 0.20 inches per hour for the parameter for good pasture cover and hydrologic soil group C which prevailed on the watershed. Also, Rawls et al. (1982) suggested the values of saturated hydraulic conductivity of 0.27 and 0.08 inches per hour for loam topsoil and clay loam subsoil of the watershed, respectively.

A computer run was made with each of the three values for the RC parameter. The other parameters were kept constant at their initial values. The simulated runoff obtained by using the saturated hydraulic conductivity value of 0.08 inches per hour of the least permeable layer in the soil profile (i.e. subsoil) showed the best cumulative runoff error of -5 percent, regression line slope of the monthly runoff volume and correlation coefficient. Hillel (1980) also proposed that under prolonged wetting conditions, the least permeable soil layer in the soil profile controls the infiltration process. Thus, a value of saturated hydraulic conductivity of the least permeable soil layer may be used for the RC parameter.

An initial value of 15.3 inches was estimated for the GA parameter from the weighted average value of the bubbling pressure of the topsoil and subsoil. Also, the CREAMS manual suggests a tentative range of 12 to 17 inches and mean of 15 inches for the parameter under the hydrologic soil group C. Three computer runs were made and a value of 14.5 inches was obtained which produced the best fit.

The weighted average value of 0.47 for topsoil and subsoil was used as the initial POROS value. Four trial runs were made in which the parameter was varied and a value of 0.52 was obtained that gave the best fit for the simulated runoff.

An initial value of 4.5 was used for the CONA parameter for the loam topsoil. Another value of 4.0 was used for clay loam subsoil and a computer run was made. A value of 4.5 produced the best fit. Thus, it was observed that the CONA parameter should be estimated on the basis of topsoil texture.

Initially, the soil root zone depth, DP, of 31 inches was utilized.

It is the sum of the depths of soil horizons A and B minus the depth of the soil control layer (2 inches). Reduction in the DP parameter value by 50 percent did not affect the simulated runoff. However, the amount of percolation was increased in some months of simulation which was balanced by the decrease in the amount of evapotranspiration.

Table XI shows annual leaf area index (LAI) values initially for "good" pasture conditions. These values were 50 percent of the LAI values suggested by the CREAMS manual for excellent pasture conditions. The cumulative simulated runoff was increased 6 percent by using 100 percent of annual leaf area index values for excellent pasture conditions. Thus, the initial values of annual leaf area index were used for the best fit.

The final values of the parameters after obtaining the best fit were: RC = 0.08 inches per hour, GA = 14.5 inches, POROS = 0.52, CONA = 4.5 and DP = 31 inches.

The monthly simulated and observed runoff values are shown in Table XIII. The following equation was obtained from linear regression analysis:

$$Q_{sm} = 0.08 + 0.76\, Q_{om} \tag{35}$$

where:

Q_{sm} = simulated monthly runoff (inches)

Q_{om} = observed monthly runoff (inches)

with a correlation coefficient (r) of 0.87 and a standard deviation (s.d.) of 0.33 inches.

Figure 5 shows the plot of the simulated and observed monthly runoff

TABLE XIII

SIMULATED AND OBSERVED MONTHLY RUNOFF FROM GUTHRIE W-V WATERSHED

Year	Runoff* Type	Runoff Values for the Specified Month of the Year (in)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1942	Q_s	0	0.14	0	0.71	0.25	0.48	0	0.36	0.67	0.01	0	0.01	2.65
	Q_o	0	0.02	0	2.74	0.13	0.13	0	0.07	0.42	0.02	0	0.01	3.44
1943	Q_s	0	0	0.02	0.01	1.03	0.16	0	0	0.01	0.56	0	0.01	1.81
	Q_o	0	0	0	0	2.95	0.08	0	0	0	0.22	0	0	3.25
1944	Q_s	0.03	0	0.36	0.69	1.00	0.15	0.03	0	0.37	0.66	0.02	0.02	3.32
	Q_o	0	0	0.25	0.70	0.74	0.12	0	0	0.04	0.65	0.01	0.27	2.78
1945	Q_s	0.01	0.08	0.15	0.31	0.01	3.35	0.37	0	0.69	0	0	0	4.97
	Q_o	0	0.01	0.04	0.62	0	2.17	0.09	0	1.46	0	0	0	4.38
1946	Q_s	0.01	0.09	0.04	0.06	0.82	0.33	0	0.86	0	0.68	0.62	0.03	3.55
	Q_o	0.02	0.04	0.01	0	0.46	0.11	0	0.22	0	0.21	0.45	0	1.52
1947	Q_s	0.06	0	0	1.61	1.04	0.05	0.18	0	0	0	0	0.02	2.96
	Q_o	0	0	0	3.81	1.65	0	0.06	0	0	0	0	0	5.52
1948	Q_s	0	0.03	0.37	0.54	0.01	2.17	0.16	0	0	0	0.02	0	3.30
	Q_o	0	0	0.17	0.71	0.01	2.21	0	0	0	0	0	0	3.10

TABLE XIII (Continued)

Year	Runoff* Type	Runoff Values for the Specified Month of the Year (in)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1949	Q_s	0.04	0.01	0.03	0	5.45	2.37	0.99	0	0.86	0.01	0	0.01	9.79
	Q_o	0.25	0.02	0	0	5.37	2.60	0.79	0	0.38	0.01	0	0	9.42
1950	Q_s	0.02	0.06	0	0	0.17	1.52	0.97	0.03	0	0	0	0	2.79
	Q_o	0	0	0	0	0.13	1.37	1.89	0	0	0	0	0	3.39
1951	Q_s	0	0.08	0	0.12	0.61	1.72	0.22	1.24	0.73	0.13	0.11	0	4.98
	Q_o	0	0.14	0	0.44	1.18	1.27	0.28	0.79	0.37	0	0.12	0	4.59
1952	Q_s	0	0	0	0	0.12	0.07	0.49	0.52	0	0	0.02	0.06	1.28
	Q_o	0	0.01	0.44	0.01	0.32	0	0.01	0.08	0	0	0	0	0.87
1953	Q_s	0.01	0.13	0.13	0.04	0.18	0.03	0.45	1.07	0.37	0.70	0	0.16	3.28
	Q_o	0	0	0.28	0.05	0.07	0	0.12	0.74	0.14	0.29	0.19	0.15	2.03
Mean	Q_s	0.01	0.05	0.09	0.34	0.89	1.03	0.32	0.34	0.31	0.23	0.07	0.03	3.71
	Q_o	0.02	0.02	0.10	0.76	1.08	0.83	0.27	0.16	0.23	0.12	0.06	0.03	3.74

*Q_s - Stands for simulated runoff.

Q_o - Stands for observed runoff.

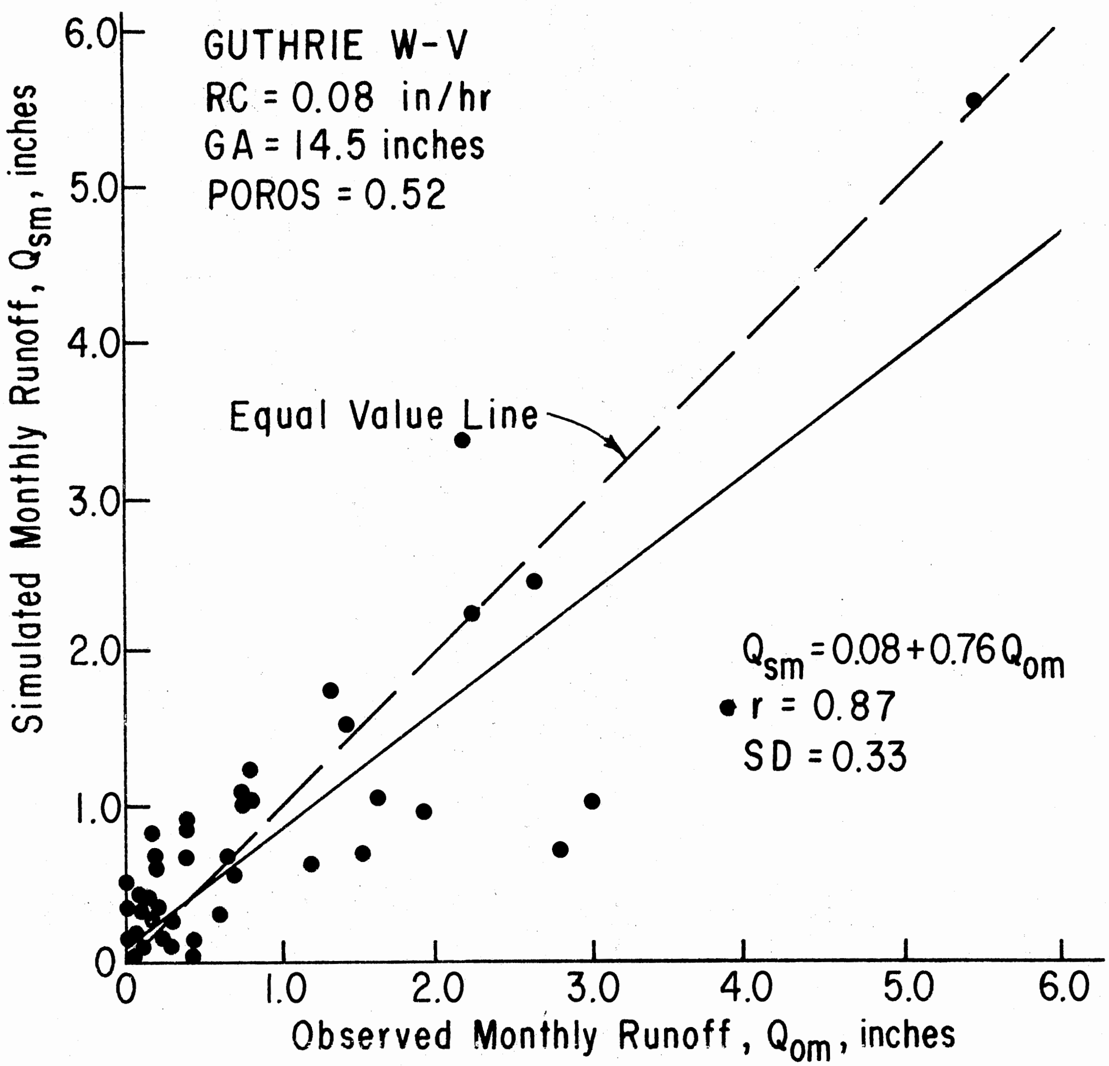

Figure 5. Simulated and Observed Monthly Runoff for Guthrie W-V Watershed From 1942 to 1953

values. The regression line intercept of 0.08 inches was close to the zero value. However, the regression line slope of 0.76 showed that the simulated monthly runoff amounts were underestimated. The dry months, which are small runoff producing months, were overestimated while wet months which produce large amounts of runoff were considerably underestimated.

The extreme overestimation occurred in June 1945. Simulated runoff was 1.18 inches (54 percent) higher than the observed runoff. Rainfall during that month was 10.37 inches which was higher than normal.

The runoff amounts were highly underestimated in April 1942 and May 1943. Simulated runoff amounts were 2.03 and 1.91 inches (74 and 65 percent) less than the observed runoff. The rainfall amounts during these months were 8.05 and 9.02 inches which were also higher than normal.

Means and standard deviations of monthly simulated and observed runoff are shown in Table XIV and the corresponding plot is shown in Figure 6. The mean monthly runoff for the first three months (i.e. January through March) and last two months (i.e. November and December) were simulated considerably well when the rainfall and runoff amounts were low during a normal rainfall year. Mean monthly runoff was underestimated in April and May, particularly, in April when it was underestimated by a factor of about two. Mean monthly runoff was overestimated from June through October. The runoff for August and October was also overestimated by a factor of two.

The annual simulated and observed runoff are shown in Table XV and plotted in Figure 7. The linear regression equation was:

TABLE XIV

MEANS AND STANDARD DEVIATIONS OF SIMULATED AND OBSERVED MONTHLY RUNOFF FOR GUTHRIE W-V WATERSHED FOR 1942-1953

	Simulated Runoff		Observed Runoff		
Month	Mean (in)	S.D. (in)	Mean (in)	S.D. (in)	Error (pct)
Jan	0.01	0.02	0.02	0.07	- 35
Feb	0.05	0.05	0.02	0.04	+165
Mar	0.09	0.14	0.10	0.15	- 7
Apr	0.34	0.48	0.76	1.23	- 55
May	0.89	1.49	1.08	1.61	- 18
Jun	1.03	1.14	0.83	1.03	+ 25
Jul	0.32	0.35	0.27	0.56	+ 19
Aug	0.34	0.47	0.16	0.29	+116
Sep	0.31	0.35	0.23	0.42	+ 32
Oct	0.23	0.31	0.12	0.20	+196
Nov	0.07	0.18	0.06	0.13	+ 5
Dec	0.03	0.05	0.03	0.08	- 25

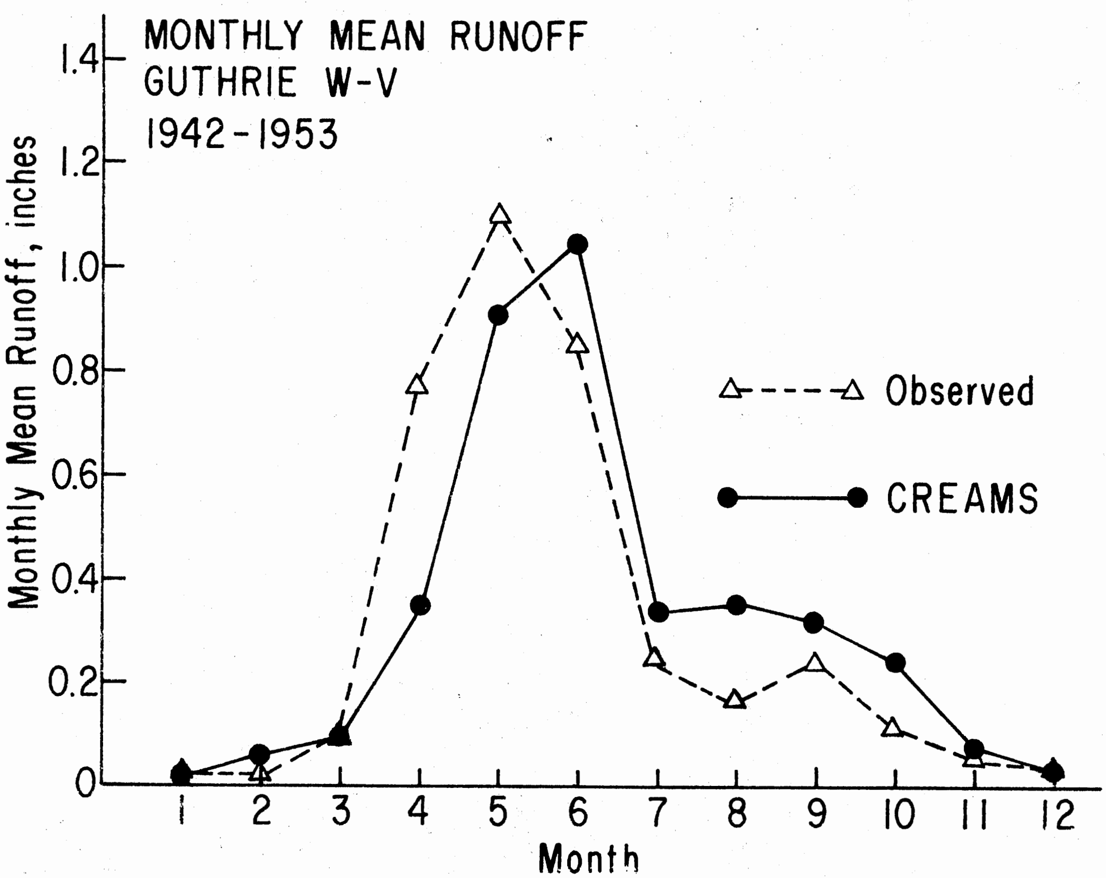

Figure 6. Monthly Mean Simulated and Observed Runoff for Guthrie W-V Watershed From 1942 to 1953

TABLE XV

ANNUAL SUMMARY OF WATER BALANCE FOR GUTHRIE W-V WATERSHED

Year	Rain (in)	Observed Runoff (in)	Simulated Runoff (in)	Error (pct)	ET (in)	Percolation (in)
1942	31.09	3.44	2.65	- 23	30.81	1.40
1943	22.32	3.25	1.81	- 44	19.31	0.0
1944	30.87	2.78	3.32	+ 19	27.06	0.0
1945	31.92	4.38	4.97	÷ 13	27.13	0.0
1946	26.71	1.52	3.55	+113	23.82	0.0
1947	25.60	5.52	2.96	- 46	22.76	0.66
1948	22.88	3.10	3.30	+ 6	19.98	0.0
1949	41.43	9.42	9.79	+ 4	31.44	0.0
1950	26.65	3.39	2.79	- 18	25.07	0.0
1951	32.27	4.59	4.97	+ 8	26.61	0.0
1952	19.03	0.87	1.28	+ 47	17.45	0.0
1953	31.86	2.03	3.28	+ 62	26.75	0.0
Mean	28.46	3.74	3.71	-0.8	24.84	0.17

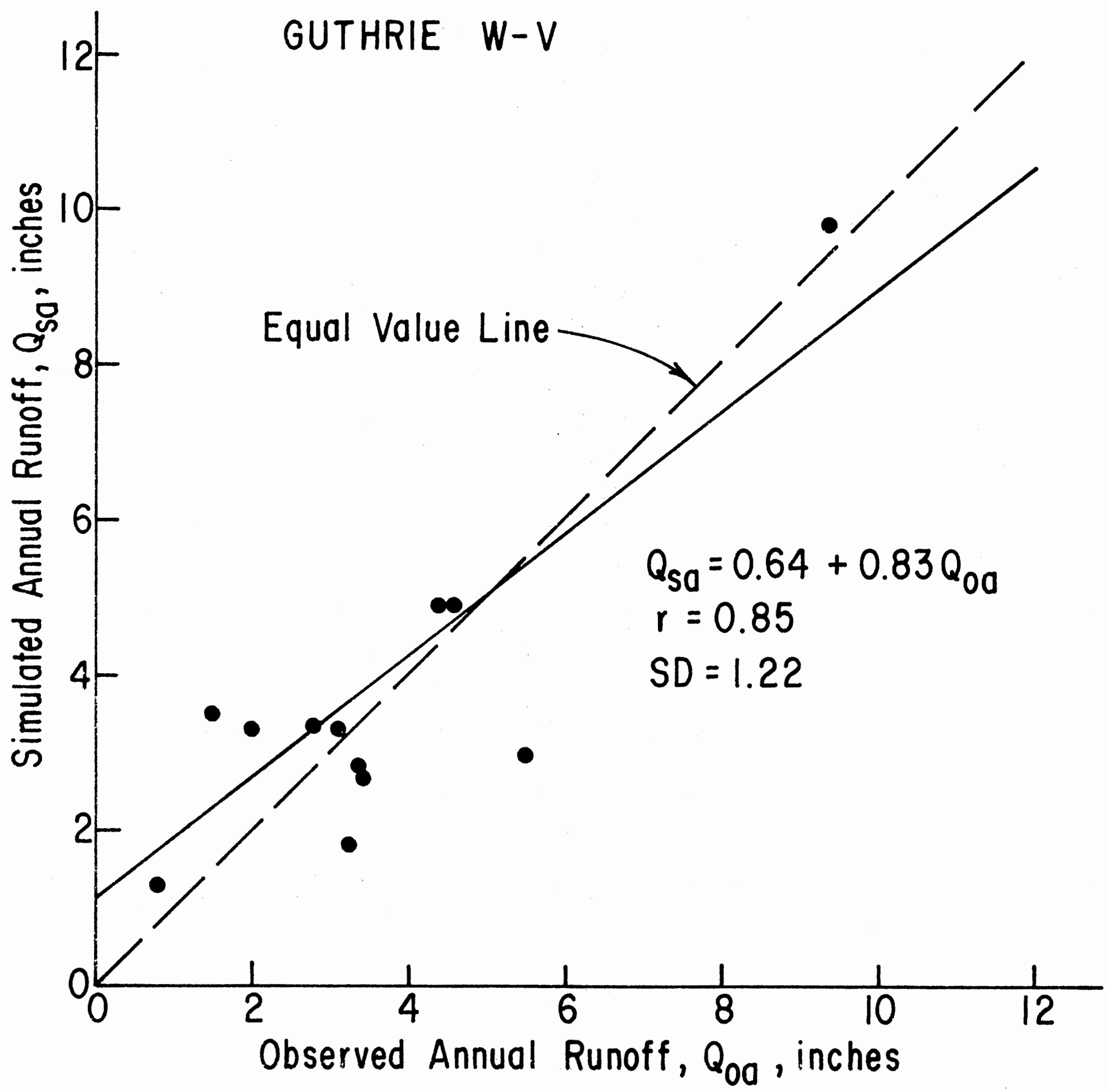

Figure 7. Simulated and Observed Annual Runoff for Guthrie W-V Watershed From 1942 to 1953

$$Q_{sa} = 0.64 + 0.83\, Q_{oa} \tag{36}$$

where:

Q_{sa} = simulated annual runoff (inches)

Q_{oa} = observed annual runoff (inches)

with r = 0.85 and s.d. = 1.22 inches.

By comparing the regression equations for monthly runoff and for annual runoff, it was found that the slope of the regression line and the correlation coefficient of the annual runoff were better. However, the annual runoff regression intercept and standard deviation were large. It is to be noted that the annual regression equation was developed from a smaller sample size than those used for the monthly runoff regression equation.

The extreme overestimations and underestimations of annual runoff occurred in 1946 and 1947. The simulated runoff amounts were higher and lower than the annual observed runoff by 2.02 and 2.56 inches (+133 and -46 percent) respectively. The annual rainfall amounts for these years (26.7 and 25.6 inches, respectively) were close to the average for the 12 year simulation period.

Chickasha R-7 Watershed

The simulation for the watershed was performed for the period of 8 years (i.e. from 1967 to 1974). The best fit was obtained by varying three parameters, namely, effective saturated hydraulic conductivity, RC, effective capillary tension, GA, and soil porosity, POROS. Other parameters (i.e. soil root depth, DP, and leaf area index, X) were held constant because simulation at the Guthrie W-V watershed showed that they produced very little change in the simulated runoff. The soil evaporation parameter, CONA, also was not varied. This parameter was estimated on the basis of the topsoil texture (silt loam).

Initial estimates for the input parameters are shown in Table XII. The initial estimates for the varied parameters were: (1) RC = 0.03 inches per hour, (2) GA = 20.7 inches, and (3) POROS = 0.48.

The following set of values was obtained after varying the parameters to achieve the best fit: (1) RC = 0.04 inches per hour, (2) GA = 16.4 inches and (3) POROS = 0.48.

The simulated and observed monthly runoff amounts are shown in Table XVI and plotted in Figure 8. The linear regression equation was:

$$Q_{sm} = 0.05 + 0.91\, Q_{om} \tag{37}$$

with r = 0.88 and s.d. = 0.38 inches.

The intercept of the equation is close to zero. The regression line slope of 0.91 indicates that the monthly runoff amounts were underestimated. The correlation coefficient of 0.88 shows fairly good correlation between the simulated and observed monthly runoff.

The monthly runoff amounts were highly underestimated in October 1972, March 1973, and October 1974. The simulated runoff amounts and percent errors were 1.14, 1.32, and 1.20 inches, and 36, 157, and 76 percent lower than the observed runoff for the respective months. The simulated runoff amounts for June and July, 1969, and August 1974 were overestimated by 0.84, 1.25, and 0.93 inches, which were 69,138 and 87 percent higher than the observed runoff respectively. The monthly rainfall amounts were higher than the average rainfall for the months in

TABLE XVI

SIMULATED AND OBSERVED MONTHLY RUNOFF FROM CHICKASHA R-7 WATERSHED

Year	Runoff Type	Runoff Values for the Specified Month of the Year (in)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1967	Q_s	0	0	0.11	2.43	0.87	0	0	0.03	1.07	0	0	0	4.53
	Q_o	0	0	0	2.31	0.66	0.03	0	0	0.71	0.05	0	0	3.77
1968	Q_s	0.08	0	0.24	0.18	0.25	0.66	0.58	0.05	0.82	0.42	0.09	0.10	3.51
	Q_o	0.29	0.01	0.63	0.11	0.45	0.62	0.90	0	0.47	0.43	0.73	0	4.66
1969	Q_s	0	0.04	0.04	0.03	1.00	2.05	2.15	0.19	0.37	0	0	0.02	5.89
	Q_o	0	0.31	0.18	0	1.40	1.20	0.90	0.02	0.20	0	0	0	4.23
1970	Q_s	0	0	0.02	0.21	1.11	0.03	0.01	0.52	2.30	0.78	0	0	4.98
	Q_o	0.01	0	0	0.21	0.42	0	0	0.06	1.79	0.41	0	0	2.92
1971	Q_s	0	0.24	0	0	0.95	1.57	0.10	0.78	1.99	2.07	0	0.27	7.97
	Q_o	0	0.18	0	0	0.28	1.33	0	0.47	1.81	2.03	0	0.63	6.73
1972	Q_s	0	0	0.27	1.35	0.31	0	0.01	0.92	0.81	0.45	1.30	0	4.56
	Q_o	0	0	0	1.27	0.63	0	0	0.48	1.14	0.73	1.68	0	5.48
1973	Q_s	0.12	0	0.84	0.22	4.59	1.81	0.82	0.92	0.81	0.45	1.30	0	11.89
	Q_o	0.83	0	2.16	0.46	3.93	2.36	0.43	0.48	1.14	0.73	1.68	0	14.21

TABLE XVI (Continued)

Year	Runoff Type	Runoff Values for the Specified Month of the Year (in)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1974	Q_s	0	0.23	0.40	1.29	0.30	0.19	0	2.00	0.12	0.37	0.02	0.01	4.95
	Q_o	0	0.36	0.34	1.36	0.55	0.06	0	1.07	0.25	1.57	0.40	0.08	6.05
Mean	Q_s	0.02	0.06	0.24	0.71	1.17	0.79	0.46	0.57	1.00	0.76	0.18	0.05	6.03
	Q_o	0.14	0.11	0.41	0.71	1.04	0.70	0.28	0.26	0.80	1.04	0.41	0.09	6.00

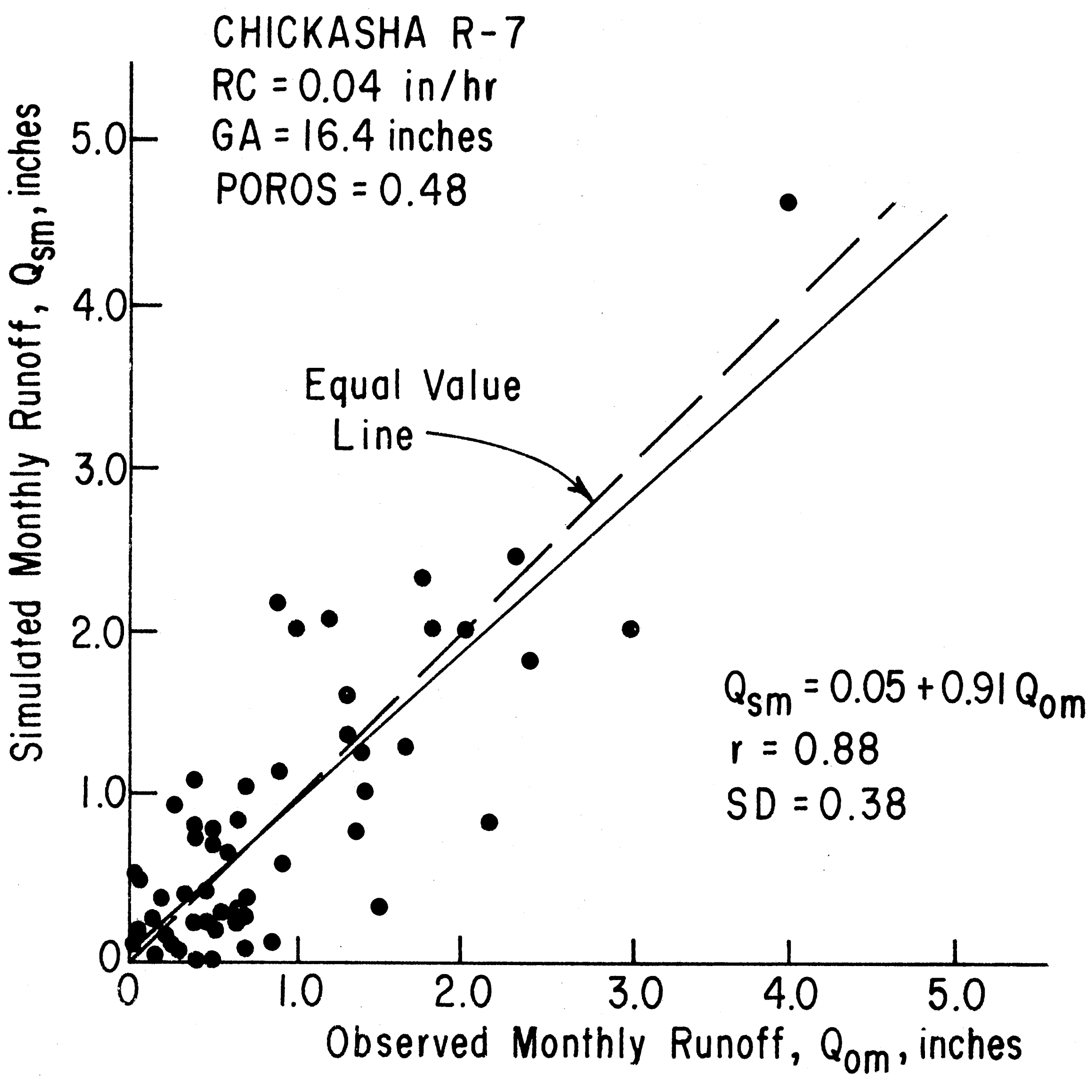

Figure 8. Simulated and Observed Monthly Runoff for Chickasha R-7 Watershed From 1967 to 1974

which the runoff amounts were underestimated and overestimated.

The means and standard deviations of the simulated and observed monthly runoff by months are shown in Table XVII and plotted in Figure 7. Mean runoff was underestimated in January, February, March, October, November and December. Mean runoff was overestimated during the summer months, May through September. Simulated runoff during March and October was particularly lower than mean monthly observed runoff, whereas during July and August the simulated runoff was higher than the observed runoff.

The annual simulated and observed runoff and water balance are shown in Table XVIII. Figure 10 shows the plot of simulated versus observed annual runoff. The linear regression equation was:

$$Q_{sa} = 1.89 + 0.69\ Q_{oa} \tag{38}$$

with r = 0.90 and s.d. = 1.25 inches.

The regression line slope of 0.69 showed an underestimation of simulated annual runoff. Also, the intercept of the equation was high. Runoff was underestimated by 2.06 inches in 1970 and overestimated by 2.32 inches in 1973. It was noted that 1970 had the lowest annual rainfall and 1973 had the greatest rainfall over the 8 year simulation period.

Stillwater W-4 Watershed

The climatological data from 1952 to 1972 were used for the simulation and the analysis were performed for the period from 1953 to 1972.

The three varied parameters were RC, GA and POROS. The following set of initial values was used: RC = 0.06 inches per hour, GA = 19.7

TABLE XVII

MEANS AND STANDARD DEVIATIONS OF SIMULATED AND OBSERVED MONTHLY RUNOFF FOR CHICKASHA R-7 WATERSHED FOR 1967-1974

Month	Simulated Runoff Mean (in)	Simulated Runoff S.D. (in)	Observed Runoff Mean (in)	Observed Runoff S.D. (in)	Error (pct)
Jan	0.02	0.05	0.14	0.29	- 82
Feb	0.06	0.11	0.11	0.15	- 40
Mar	0.24	0.28	0.41	0.74	- 71
Apr	0.71	0.88	0.71	0.84	0
May	1.17	1.42	1.04	1.21	+ 13
Jun	0.79	0.88	0.70	0.87	+ 12
Jul	0.46	0.75	0.28	0.41	+ 63
Aug	0.57	0.67	0.26	0.39	+117
Sep	1.00	0.77	0.80	0.71	+ 32
Oct	0.76	0.88	1.04	1.10	- 27
Nov	0.18	0.45	0.41	0.58	- 56
Dec	0.05	0.09	0.90	0.22	- 42

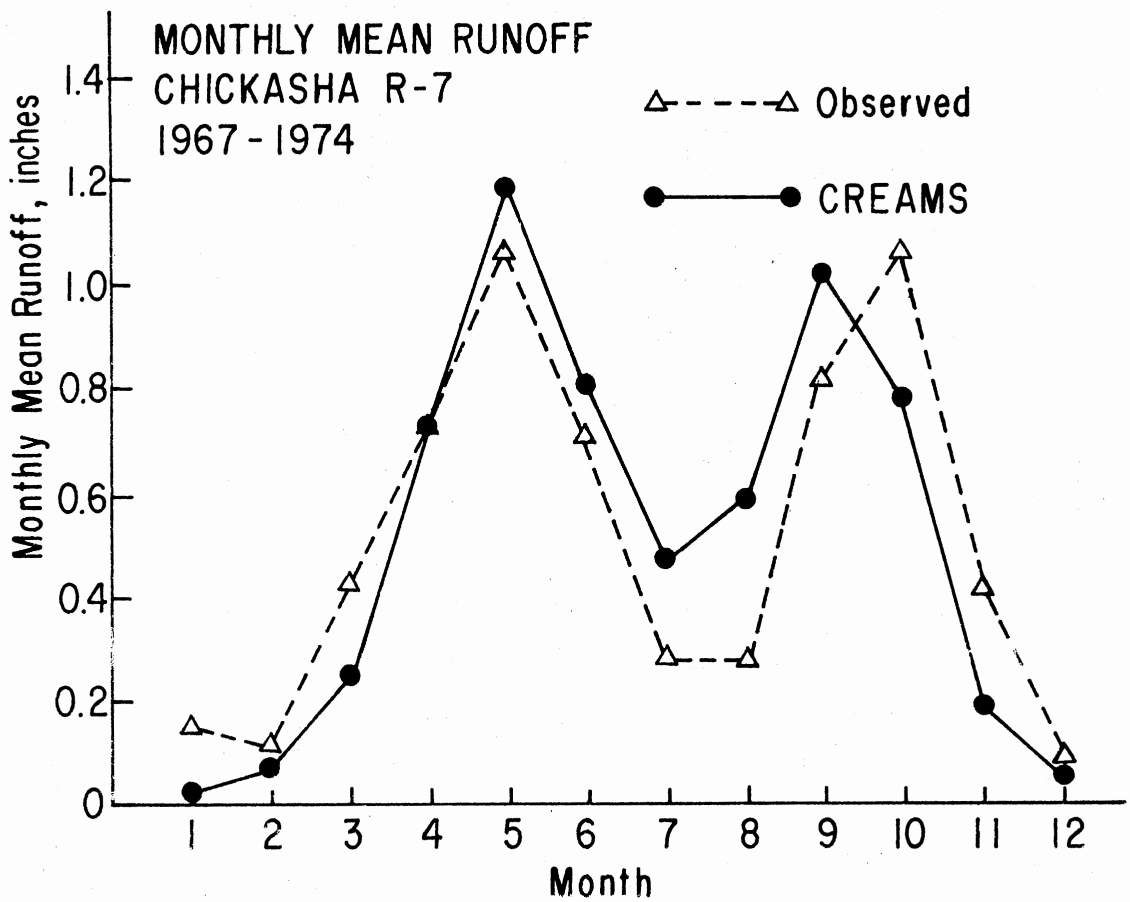

Figure 9. Monthly Mean Simulated and Observed Runoff for Chickasha R-7 Watershed From 1967 to 1974

TABLE XVIII

ANNUAL SUMMARY OF WATER BALANCE FOR CHICKASHA R-7 WATERSHED

Year	Rain (in)	Observed Runoff (in)	Simulated Runoff (in)	Error (pct)	ET (in)	Percolation (in)
1967	26.7	3.77	4.53	+ 20	25.41	0.0
1968	30.23	4.66	3.51	- 25	24.31	0.0
1969	27.92	4.23	5.89	+ 39	24.11	0.0
1970	24.06	2.92	4.98	+ 70	18.82	0.0
1971	32.72	6.73	7.97	+ 18	23.09	0.0
1972	25.88	5.48	4.56	- 17	18.70	0.0
1973	45.42	14.21	11.89	- 16	34.42	2.60
1974	28.31	6.05	4.95	- 18	21.33	0.0
Mean	29.98	6.00	6.03	+0.45	23.68	0.32

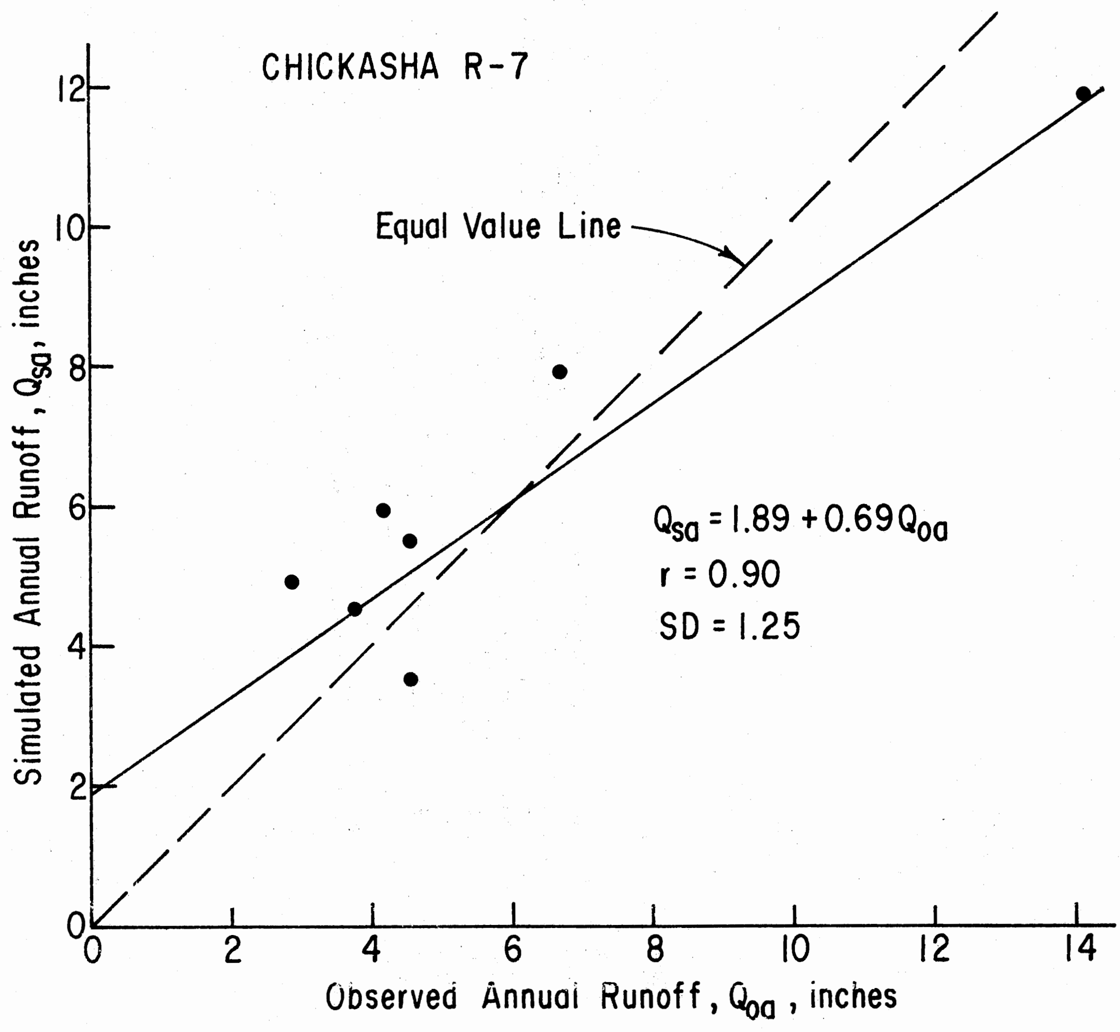

Figure 10. Simulated and Observed Annual Runoff for Chickasha R-7 Watershed From 1967 to 1974

and POROS = 0.47. The best estimates of parameter values, obtained by the best fit, were as follows: RC = 0.09 inches per hour, GA = 17.2 inches and POROS = 0.47.

The simulated and observed monthly runoff amounts are shown in Table XIX and plotted in Figure 11. The linear regression equation was:

$$Q_{sm} = 0.16 + 0.55\, Q_{om} \tag{39}$$

with r = 0.78 and s.d. = 0.39 inches.

The intercept of the regression equation was close to zero. However, the runoff was overestimated for the small runoff producing months. The regression line slope of 0.55 shows that the monthly runoff amounts were underestimated, particularly, the large runoff producing months were greatly underestimated.

The months which considerably underestimated runoff were: May 1955, May and June 1957, and October 1959. The simulated amounts were less than the observed runoff by 2.64, 2.19, 3.34 and 3.75 inches (41, 53, 55 and 55 percent), respectively. The overestimations of runoff occurred in July 1953, August 1955, July 1956, June 1972. The amounts (and percent) of the overestimates for the respective months were 0.77, 2.69, 1.06, 1.36 and 1.77 inches (137, 384, 279, 216 and 224 percent). Similar to the other two watersheds, the rainfall amounts were higher than the average monthly rainfall for the months in which the runoff amounts were significantly underestimated and overestimated.

The means and standard deviations of the simulated and observed monthly runoff from January to December are shown in Table XX and plotted in Figure 12. Mean monthly runoff was underestimated in March,

TABLE XIX

SIMULATED AND OBSERVED MONTHLY RUNOFF FROM STILLWATER W-4 WATERSHED

Year	Runoff Type	Runoff Values for the Specified Month of the Year (in)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1953	Q_s	0	0.10	0.04	0.04	0.68	0.50	1.33	0	0.60	0.07	0.99	0	4.35
	Q_o	0	0	0.12	0.05	1.04	0.04	0.56	0	0.04	0	0.37	0.17	2.39
1954	Q_s	0	0	0	0.52	0.63	0.02	0	0.37	0	0	0	0.20	1.74
	Q_o	0	0	0	0.06	0.54	0	0	0	0	0	0	0	0.60
1955	Q_s	0.17	0.07	0.33	0	3.76	0.91	0	3.39	0	0.56	0	0	9.20
	Q_o	0.01	0.04	0.19	0	6.40	0.09	0	0.70	0	0.91	0	0	8.34
1956	Q_s	0	0.03	0	0.02	0.09	0.24	1.44	0	0	0.08	0	0.04	1.96
	Q_o	0	0	0	0	0	0	0.38	0	0	0	0.01	0	0.39
1957	Q_s	0	0	0.12	2.50	1.91	2.77	0.31	0.08	0.45	0	0.04	0	8.19
	Q_o	0	0.02	0.05	3.48	4.10	6.11	0.71	0	0.22	0	0	0	14.69
1958	Q_s	0	0.59	0.62	0.29	0	0.16	0.96	0.09	0.21	0	0	0.24	3.16
	Q_o	0.06	0.05	1.95	0.22	0.02	0.16	0.23	0.01	0.07	0	0	0	2.77
1959	Q_s	0	0	0.01	0.20	0.11	0.21	3.48	0.81	1.31	3.03	0	0	9.17
	Q_o	0	0	0.02	0.14	0.38	0.02	3.33	0.02	1.50	6.78	0	0.37	12.56

TABLE XIX (Continued)

Year	Runoff Type	Runoff Values for the Specified Month of the Year (in)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1960	Q_s	0	0.04	0.02	0	1.84	0.16	0.76	0.03	0	0.01	0	0.01	2.87
	Q_o	0.25	0.66	0.66	0.07	1.63	0.10	0.37	0	0	0.06	0	0.02	3.82
1961	Q_s	0	0.02	0.02	0	2.25	0.70	0.49	0.77	1.07	0.04	0.17	0	5.54
	Q_o	0	0	0.13	0	2.89	1.33	0.25	0.06	1.85	0.74	1.14	0.46	8.85
1962	Q_s	0	0	0	0.01	0.15	1.34	0.69	0	0.12	0	0	0.05	2.36
	Q_o	0.31	0.15	0.22	0.08	0	2.02	0	0	0	0	0	0.12	2.90
1963	Q_s	0	0	0.28	0.02	1.12	0	0.67	1.04	0.77	0.28	0	0.04	4.24
	Q_o	0	0	0.29	0	0.38	0	0.24	0.19	1.02	0.26	0.04	0	2.42
1964	Q_s	0.05	0	0.05	0.18	0.20	0	0	1.13	0.44	0	0.14	0.10	2.30
	Q_o	0	0.18	0.02	0.47	0.64	0	0	0.24	0.03	0	0.48	0.08	2.14
1965	Q_s	0.01	0.04	0.06	0	0.39	0	0.76	0.01	1.11	0	0	0.26	2.64
	Q_o	0.11	0.07	0.07	0.06	0.07	0	0.03	0	0.07	0	0	0	0.48
1966	Q_s	0	0.14	0.05	0.05	0.02	0.02	2.00	0.82	0.37	0	0	0	3.47
	Q_o	0	0.03	0	0	0	0	0.63	0.15	0	0	0	0	0.81
1967	Q_s	0.06	0	0	0	0.17	0.89	0.64	0.36	0.74	0.25	0.03	0	3.15
	Q_o	0.05	0	0	0.08	0.21	1.33	0.29	0	0.82	0.34	0	0	3.12

TABLE XIX (Continued)

Year	Runoff Type	Runoff Values for the Specified Month of the Year (in)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1968	Q_s	0	0.04	0.32	0.62	0.82	0.14	0.03	0.13	0.31	0	0.24	0.01	2.67
	Q_o	0.04	0	0.42	1.19	2.15	0	0	0	0	0	0.18	0.03	4.01
1969	Q_s	0	0.35	0.08	0.58	0.79	1.07	0	0.67	0.88	0	0	0.16	4.59
	Q_o	0	0.35	0.78	0.69	1.22	0.54	0	0.02	0.19	0.05	0	0.09	3.93
1970	Q_s	0	0	0.07	0.70	0.05	0.06	0	0	1.00	0.03	0	0	1.91
	Q_o	0	0	0.40	1.22	0.02	0	0	0	0.04	0.03	0	0	1.71
1971	Q_s	0.06	0.17	0	0.39	0.09	1.15	0.46	0	1.50	0.55	0	0.01	4.37
	Q_o	0.07	0.25	0	0.03	0.03	1.10	0.06	0	1.10	0.09	0	0.51	3.24
1972	Q_s	0	0.07	0.01	0.34	0.27	2.56	0.11	0.10	0.23	0.06	0.09	0.16	4.00
	Q_o	0.02	0.01	0	0.08	0.10	0.79	0.12	0	0.01	0.36	0.53	0.40	2.42
Main	Q_s	0.02	0.08	0.10	0.32	0.77	0.64	0.71	0.49	0.55	0.25	0.08	0.06	4.09
	Q_o	0.04	0.09	0.26	0.39	1.09	0.68	0.36	0.07	0.35	0.48	0.14	0.11	4.08

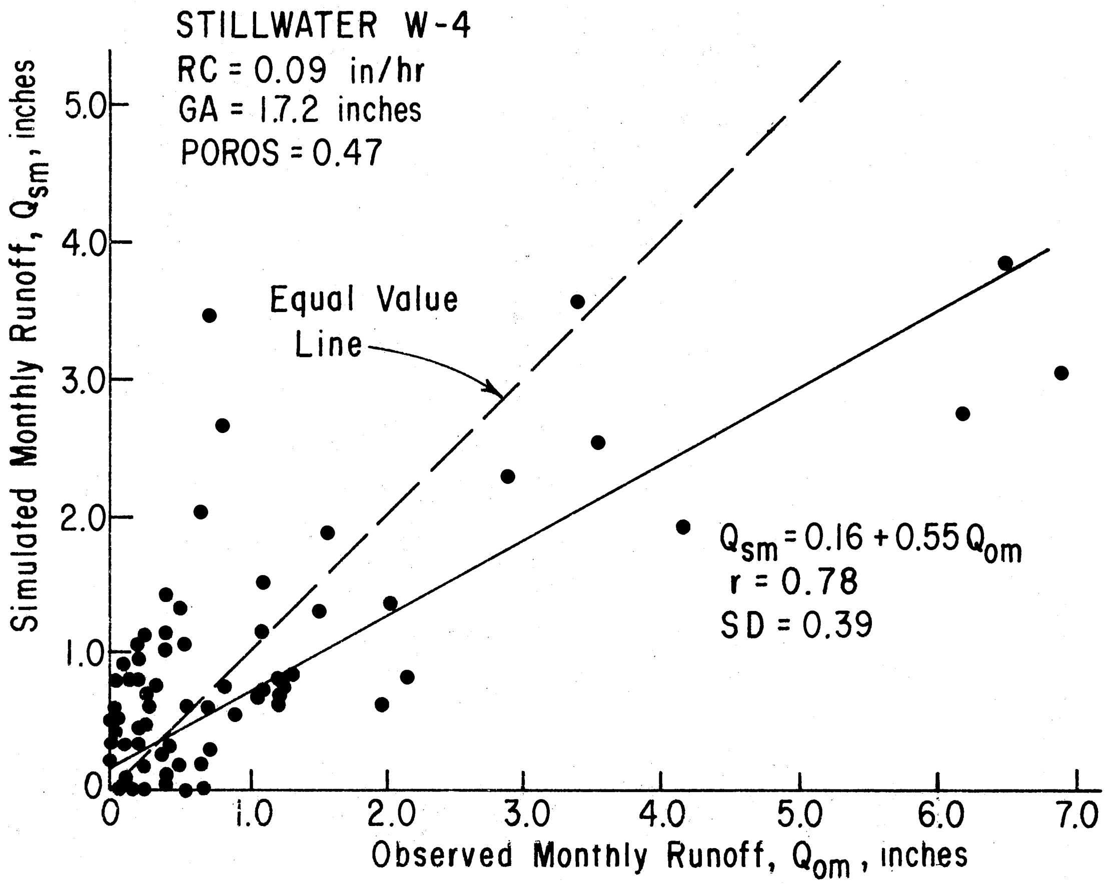

Figure 11. Simulated and Observed Monthly Runoff for Stillwater W-4 Watershed From 1953 to 1972

TABLE XX

MEANS AND STANDARD DEVIATIONS OF SIMULATED AND OBSERVED MONTHLY RUNOFF FOR STILLWATER W-4 WATERSHED FOR 1953-1972

	Simulated Runoff		Observed Runoff		
Month	Mean (in)	S.D. (in)	Mean (in)	S.D. (in)	Error (pct)
Jan	0.02	0.04	0.04	0.08	- 63
Feb	0.08	0.14	0.09	0.16	- 9
Mar	0.10	0.16	0.26	0.46	- 61
Apr	0.32	0.56	0.39	0.82	- 18
May	0.77	0.98	1.09	1.67	- 29
Jun	0.64	0.82	0.68	1.41	- 5
Jul	0.71	0.86	0.36	0.73	+ 97
Aug	0.49	0.78	0.07	0.16	+603
Sep	0.55	0.47	0.35	0.57	+ 60
Oct	0.25	0.68	0.48	1.50	- 48
Nov	0.08	0.22	0.14	0.29	- 38
Dec	0.06	0.09	0.11	0.17	- 43

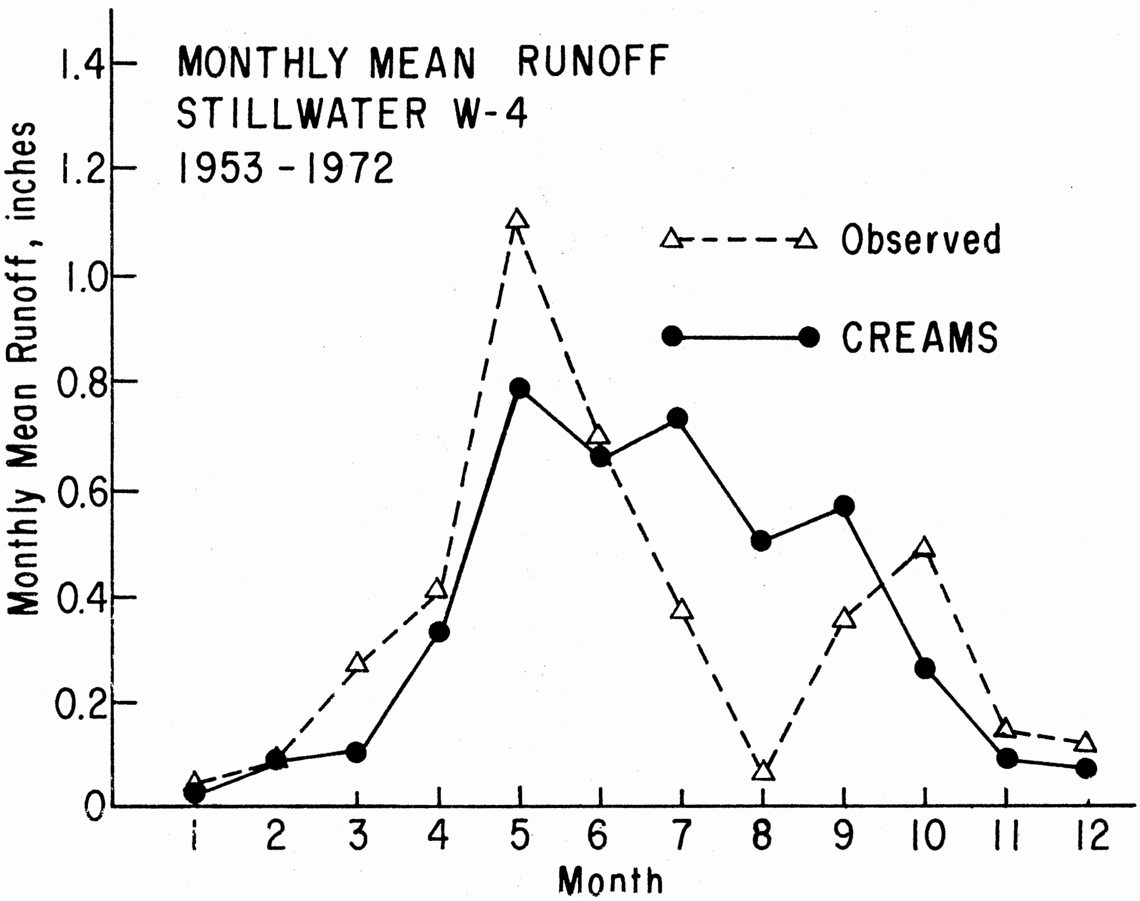

Figure 12. Monthly Mean Simulated and Observed Runoff for Stillwater W-4 Watershed From 1953 to 1972

April, May, October, November and December. The mean runoff amounts were underestimated by 0.10 and 0.24 inches (61 and 48 percent) in March and October, respectively. During July, August, and September the runoff was overestimated by 0.34, 0.42 and 0.20 inches (97, 603 and 60 percent), respectively.

The annual and observed runoff and water balance are shown in Table XXI. Figure 13 shows the plot of simulated versus observed annual runoff. The linear regression equation was:

$$Q_{sa} = 2.02 + 0.51\, Q_{oa} \tag{40}$$

with r = 0.87 and s.d. = 1.14 inches.

Like the monthly regression equation, the annual regression equation overestimated the small amounts of runoff and underestimated the large amounts of runoff.

Annual runoff amounts were underestimated in 1957 and 1959 by 6.49 and 3.39 inches (44 and 27 percent), respectively. The model overestimated runoff for 1956, 1965, and 1966 by 1.57, 2.16 and 2.66 inches (402, 450 and 328 percent) respectively. Underestimation occurred in the years that had higher than average annual rainfall and overestimation occurred in years which had less than average annual rainfall.

<u>Stillwater W-3 Watershed</u>

Similar to the Stillwater W-4 watershed, the climatological data from 1952 to 1972 were used for the simulation, and the analysis was performed excluding the year of 1952.

The initial values for the varied parameters were: RC = 0.02 inches per hour, GA = 24.2 inches and POROS = 0.47. The following set

TABLE XXI

ANNUAL SUMMARY OF WATER BALANCE FOR STILLWATER W-4 WATERSHED

Year	Rain (in)	Observed Runoff (in)	Simulated Runoff (in)	Error (pct)	ET (in)	Percolation (in)
1953	30.62	2.39	4.35	+ 82	24.47	0.0
1954	16.17	0.60	1.74	+190	16.05	0.0
1955	35.78	8.34	9.20	+ 10	26.40	0.0
1956	16.28	0.39	1.96	+402	13.76	0.0
1957	45.84	14.69	8.20	- 44	37.84	0.0
1958	28.31	2.77	3.16	+ 14	26.43	0.0
1959	48.20	12.56	9.17	- 27	31.13	0.07
1960	30.45	3.82	2.87	- 25	33.59	0.11
1961	39.28	8.85	5.54	- 37	32.68	0.0
1962	27.48	2.90	2.36	- 18	27.03	0.0
1963	31.18	2.42	4.24	+ 75	26.44	0.0
1964	30.45	2.14	2.30	+ 7	26.38	0.0
1965	20.91	0.48	2.64	+450	20.11	0.0
1966	20.43	0.81	3.47	+328	18.06	0.0
1967	32.44	3.12	3.15	+ 1	28.81	0.0
1968	32.22	4.01	2.67	- 33	27.38	0.0
1969	32.28	3.93	4.59	+ 16	29.43	0.0
1970	21.35	1.71	1.91	+ 12	19.70	0.0
1971	35.62	3.24	4.37	+ 35	29.34	0.0
1972	27.33	2.42	4.00	+ 65	22.21	0.0
Mean	29.33	4.08	4.09	+0.41	25.86	0.009

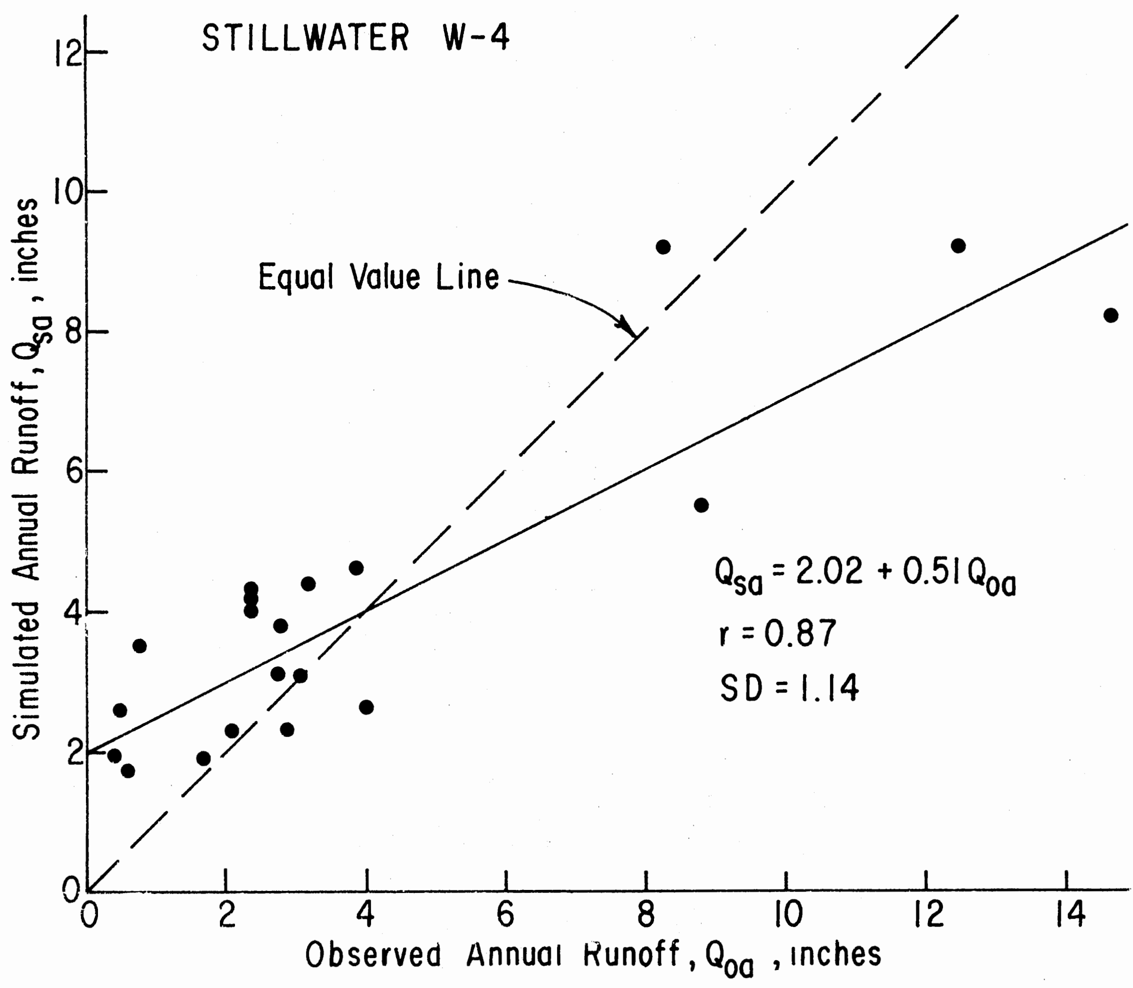

Figure 13. Simulated and Observed Annual Runoff for Stillwater W-4 Watershed From 1953 to 1972

of the best estimates of the parameters was obtained: RC = 0.05 inches per hour, GA = 19.0 inches and POROS = 0.54.

The simulated and observed monthly runoff are shown in Table XXII and plotted in Figure 14. The linear regression equation was:

$$Q_{sm} = 0.22 + 0.49\ Q_{om} \tag{41}$$

with r = 0.72 and s.d. = 0.52 inches.

The high intercept of regression equation shows that monthly runoff was overestimated during the low runoff producing months. However, runoff was underestimated during the high runoff producing months, which can be seen from the low regression line slope of 0.49. The high standard deviation (0.52 inches) and low correlation coefficient (0.72) indicates a rather high dispersion in the simulated monthly runoff.

Runoff was underestimated for May 1955, April, May and June 1957, March 1958, October 1959 and May 1968. The simulated runoff for these months were less than the observed runoff by 3.89, 2.11, 2.54, 2.91, 1.97, 4.60, and 1.15 inches (47, 42, 53, 54, 74, 57, and 55 percent), respectively. Runoff was overestimated for July 1953, August 1955, July 1966, and June 1972. The respective amounts (and percent) of overestimates were 1.14, 3.24, 1.10 and 2.83 inches (181, 469, 1105, and 2021 percent), respectively.

The means and standard deviations of the monthly simulated and observed runoff from January to December are shown in Table XXIII and plotted in Figure 15. The mean runoff amounts were underestimated in three spring months (March, April and May) and three fall and winter months (October, November, and December). The underestimations were significant in March, May and October by 0.35, 0.44 and 0.22 inches (74,

TABLE XXII

SIMULATED AND OBSERVED MONTHLY RUNOFF FROM STILLWATER W-3 WATERSHED

Year	Runoff Type	Runoff Values for the Specified Month of the Year (in)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1953	Q_s	0	0.10	0.06	0.04	0.93	0.80	1.77	0	0.76	0.07	1.22	0.07	5.83
	Q_o	0	0	0.02	0.03	1.02	0	0.63	0	0	0	0.23	0.16	2.09
1954	Q_s	0	0.03	0	0.60	0.76	0.07	0	0.48	0.01	0.20	0	0.24	2.40
	Q_o	0	0	0	0	0.49	0	0	0	0	0	0	0	0.49
1955	Q_s	0.17	0.07	0.46	0	4.46	0.85	0	3.92	0.01	0.79	0	0	10.74
	Q_o	0	0.03	0.34	0	8.35	0.10	0	0.69	0.68	0	0	0	10.19
1956	Q_s	0	0.03	0	0.04	0.15	0.27	1.58	0	0	0.14	0	0.04	2.26
	Q_o	0	0	0	0	0	0	0	0	0	0	0	0	0
1957	Q_s	0	0.02	0.12	2.87	2.23	3.41	0.41	0.17	0.65	0	0.04	0	9.94
	Q_o	0	0	0.07	4.99	4.77	6.32	0.68	0	0.04	0	0.03	0	16.90
1958	Q_s	0	0.59	0.68	0.29	0	0.23	1.35	0.15	0.21	0	0	0.24	3.75
	Q_o	0.09	0.07	2.65	0.29	0	0	0.06	0.01	0.02	0	0	0	3.19
1959	Q_s	0	0	0.02	0.21	0.13	0.40	4.06	1.04	1.87	3.42	0	0	11.17
	Q_o	0	0	0.04	0.38	0.91	0	3.93	0.09	1.96	8.02	0	0.65	15.98

TABLE XXII (Continued)

Year	Runoff Type	Runoff Values for the Specified Month of the Year (in)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1960	Q_s	0.02	0.04	0.02	0	2.24	0.23	1.14	0.03	0	0.05	0	0.01	3.79
	Q_o	0.07	0.85	0.94	0.08	2.54	0.03	0.21	0	0	0	0	0.08	4.80
1961	Q_s	0	0.03	0.02	0	2.74	0.97	0.70	0.93	1.56	0.14	0.24	0	7.34
	Q_o	0	0	0.16	0	3.27	1.34	0.05	0	1.55	0.77	1.30	0.44	8.88
1962	Q_s	0	0	0	0.01	0.21	1.83	0.98	0	0.15	0	0	0.11	3.30
	Q_o	0.21	0.12	0.35	0.03	0	2.30	0.01	0.01	0	0	0.01	0.03	3.07
1963	Q_s	0	0	0.45	0.02	1.33	0	1.05	1.29	1.08	0.41	0	0.04	5.68
	Q_o	0.02	0	0.61	0.05	0.17	0	0.02	0.06	0.82	0.14	0.13	0.03	2.05
1964	Q_s	0.05	0	0.05	0.37	0.27	0	0.02	1.51	0.63	0	0.16	0.10	3.18
	Q_o	0	0.51	0.14	1.16	0.93	0	0	0.28	0.01	0	1.39	0.14	4.51
1965	Q_s	0.01	0.04	0.06	0	0.48	0	0.91	0.06	1.18	0	0	0.26	3.01
	Q_o	0.15	0.01	0.09	0.07	0.09	0	0	0	0	0	0	0	0.41
1966	Q_s	0	0.14	0.05	0.05	0.07	0.03	2.29	1.00	0.37	0	0	0	4.01
	Q_o	0	0	0	0.01	0	0	0.19	0.02	0	0	0	0	0.22

TABLE XXII (Continued)

Year	Runoff Type	Runoff Values for the Specified Month of the Year (in)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1967	Q_s	0.11	0	0	0	0.27	1.16	0.88	0.46	1.01	0.32	0.03	0	4.25
	Q_o	0	0	0	0.12	0.31	1.61	0.25	0	1.25	0.61	0.01	0.01	4.17
1968	Q_s	0	0.04	0.35	0.95	1.21	0.22	0.03	0.26	0.42	0	0.35	0.03	3.87
	Q_o	0.16	0	1.15	2.10	3.26	0.07	0	0	0	0	0.42	0.20	7.36
1969	Q_s	0	0.35	0.09	0.74	1.06	1.32	0	0.88	1.14	0	0	0.20	5.79
	Q_o	0	1.14	1.77	1.20	1.39	1.02	0	0	0.04	0.02	0	0.11	6.69
1970	Q_s	0	0	0.02	0.91	0.05	0.13	0	0	1.13	0.04	0	0	2.28
	Q_o	0	0	1.19	2.94	0.06	0	0	0	0.01	0.30	0	0	4.50
1971	Q_s	0.09	0.19	0	0.61	0.22	1.49	0.75	0	1.88	0.69	0	0.06	5.99
	Q_o	0.14	0.53	0.02	0.23	0	1.01	0.02	0	1.36	0.52	0.02	1.21	5.06
1972	Q_s	0	0.07	0.03	0.53	0.35	2.97	0.11	0.18	0.43	0.06	0.12	0.21	5.09
	Q_o	0.24	0.04	0	0.22	0.42	0.14	0.21	0	0	0.40	1.04	0.76	3.47
Mean	Q_s	0.02	0.09	0.12	0.41	0.96	0.82	0.90	0.62	0.72	0.32	0.11	0.08	5.18
	Q_o	0.05	0.16	0.48	0.69	1.40	0.70	0.31	0.05	0.39	0.54	0.23	0.19	5.20

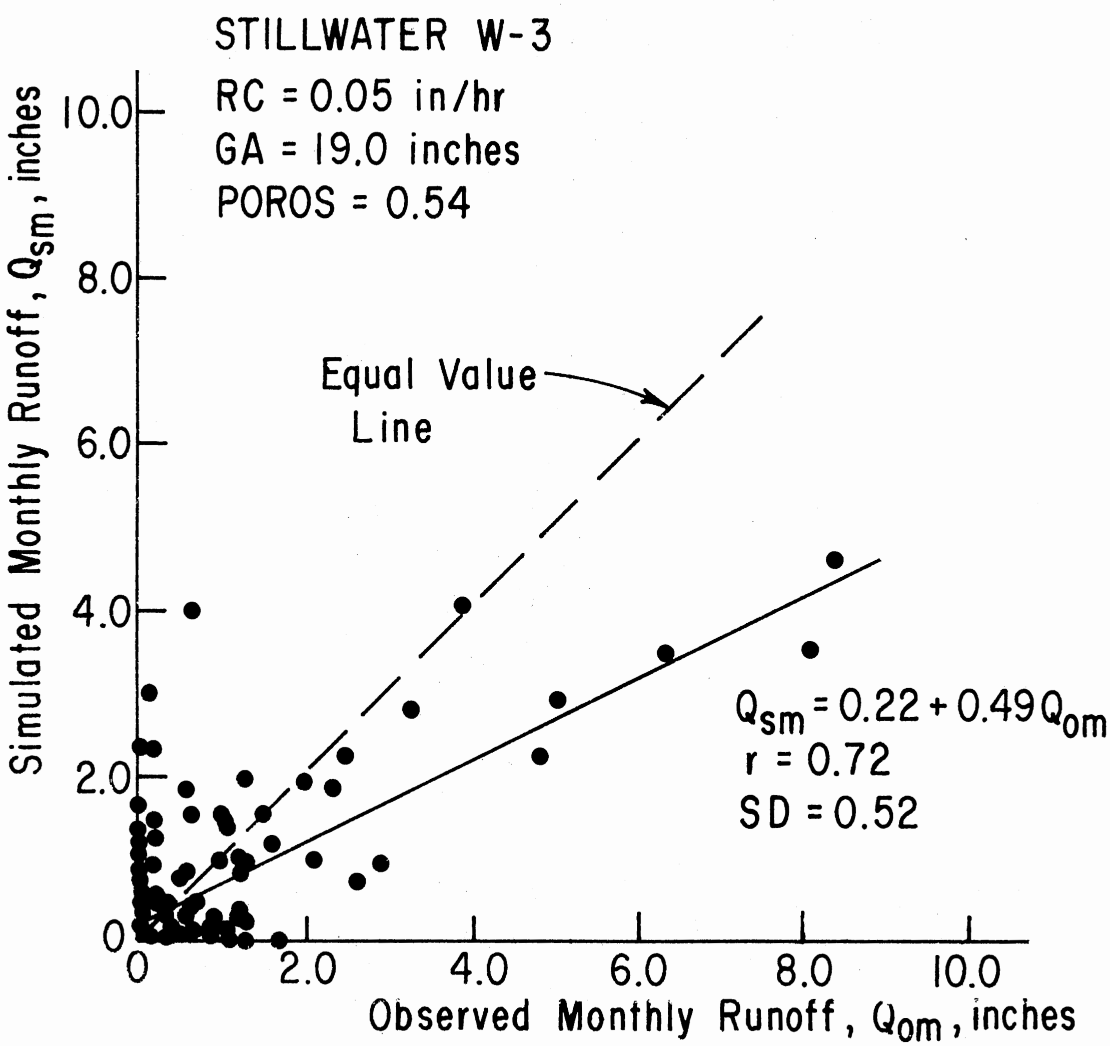

Figure 14. Simulated and Observed Monthly Runoff for Stillwater W-3 Watershed From 1953 to 1972

TABLE XXIII

MEANS AND STANDARD DEVIATIONS OF SIMULATED AND OBSERVED MONTHLY RUNOFF FOR STILLWATER W-3 WATERSHED FOR 1953-1972

Month	Simulated Runoff Mean (in)	Simulated Runoff S.D. (in)	Observed Runoff Mean (in)	Observed Runoff S.D. (in)	Error (pct)
Jan	0.02	0.05	0.05	0.08	- 57
Feb	0.09	0.14	0.16	0.33	- 47
Mar	0.12	0.19	0.48	0.72	- 74
Apr	0.41	0.66	0.69	1.28	- 41
May	0.96	1.16	1.40	2.13	- 31
Jun	0.82	0.98	0.70	1.49	+ 18
Jul	0.90	1.00	0.31	0.87	+ 188
Aug	0.62	0.92	0.05	0.16	+1005
Sep	0.72	0.61	0.39	0.64	+ 87
Oct	0.32	0.77	0.54	1.78	- 41
Nov	0.11	0.28	0.23	0.45	- 52
Dec	0.08	0.09	0.19	0.33	- 58

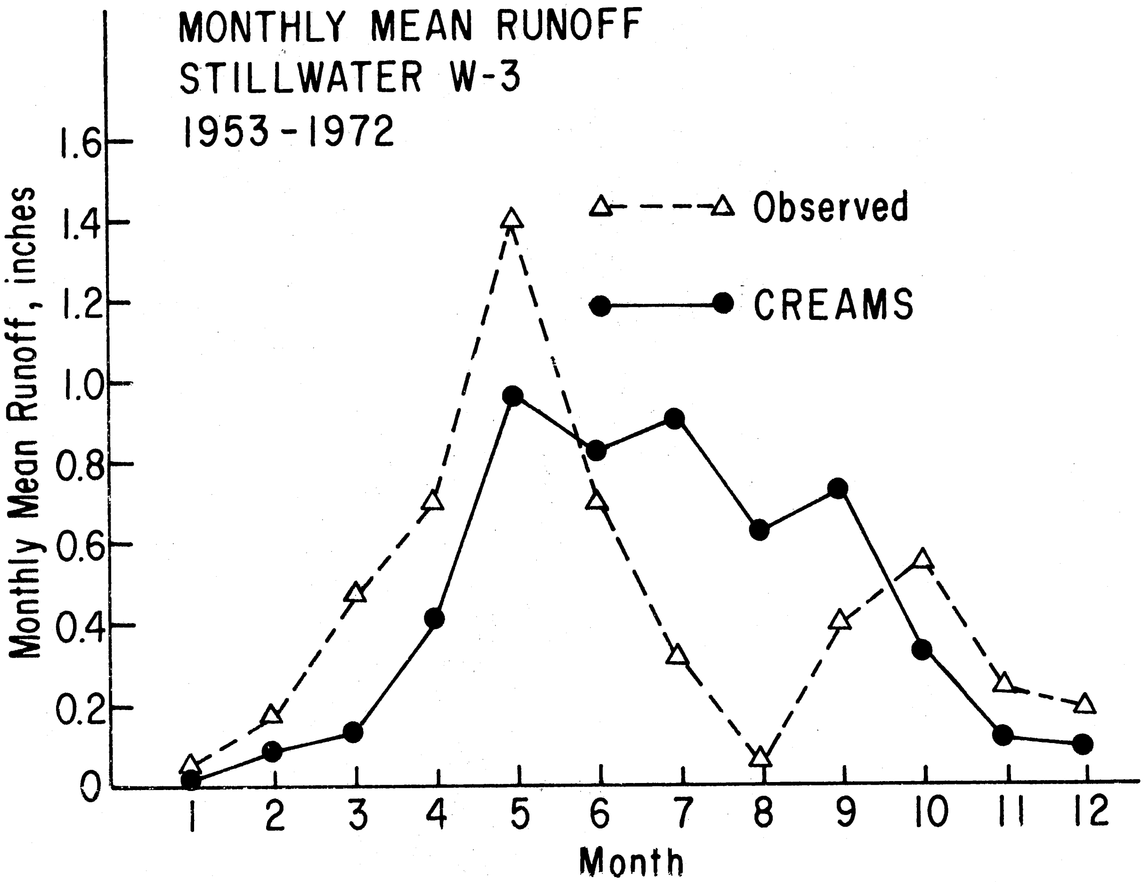

Figure 15. Monthly Mean Simulated and Observed Runoff for Stillwater W-3 Watershed From 1953 to 1972

31 and 41 percent) respectively. Mean monthly runoff was overestimated in July, August and September by 0.59, 0.56, and 0.34 inches (188, 1005 and 87 percent) respectively.

The annual simulated and observed runoff and water balance are shown in Table XXIV. The plot of simulated versus observed annual runoff is shown in Figure 16. The linear regression equation was:

$$Q_{sa} = 2.67 + 0.48\ Q_{oa} \tag{42}$$

with r = 0.84 and s.d. = 1.51 inches.

The intercept and slope of the regression equation show that the small runoff amounts were overestimated and the large runoff amounts were underestimated. The runoff for 1957 and 1959 were underestimated by 6.97 and 4.8 inches (41 and 30 percent). For the years of 1954, 1965, and 1966 the simulated runoff amounts were greater than the observed runoff by 1.91, 2.59, and 3.79 inches (390, 632 and 1723 percent) respectively. The rainfall for the years of underestimated runoff had higher than the average annual rainfall while the years of overestimated runoff had lower than average annual rainfall.

TABLE XXIV

ANNUAL SUMMARY OF WATER BALANCE FOR STILLWATER W-3 WATERSHED

Year	Rain (in)	Observed Runoff (in)	Simulated Runoff (in)	Error (pct)	ET (in)	Percolation (in)
1953	30.62	2.09	5.83	+ 179	23.21	0.0
1954	16.17	0.49	2.403	+ 390	15.31	0.0
1955	35.78	10.19	10.74	+ 5	24.77	0.0
1956	16.28	0.0	2.26	**	13.35	0.0
1957	45.84	16.90	9.94	- 41	36.06	0.0
1958	28.31	3.20	3.75	+ 17	25.82	0.0
1959	48.20	15.98	11.18	- 30	30.06	0.0
1960	30.45	4.80	3.79	- 21	31.96	0.0
1961	39.28	8.88	7.34	- 17	31.29	0.0
1962	27.48	3.07	3.30	+ 7	25.75	0.0
1963	31.18	2.05	5.68	+ 177	24.99	0.0
1964	30.45	4.51	3.18	- 29	25.47	0.0
1965	20.91	0.41	3.00	+ 632	19.73	0.0
1966	20.43	0.22	4.01	+1723	17.53	0.0
1967	32.44	4.17	4.25	+ 2	27.65	0.0
1968	32.22	7.36	3.87	- 47	26.33	0.0
1969	32.28	6.69	5.79	- 13	28.12	0.0
1970	21.35	4.50	2.28	- 49	19.26	0.0
1971	35.62	5.06	5.99	+ 18	28.11	0.0
1972	27.33	3.47	5.09	+ 47	20.91	0.0
Mean	29.33	5.20	5.18	- 0.3	24.76	0.0

**indeterminate

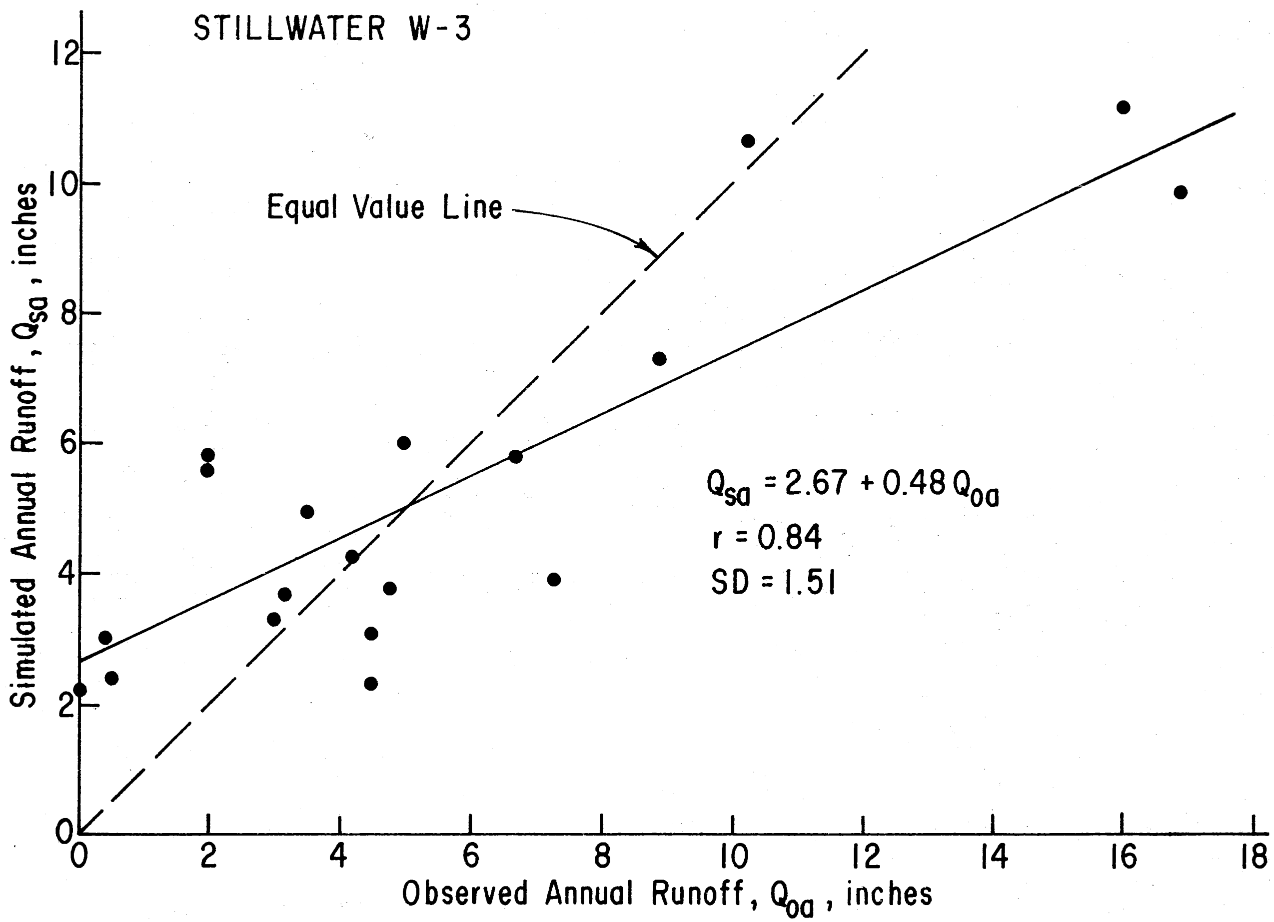

Figure 16. Simulated and Observed Annual Runoff for Stillwater W-3 Watershed From 1953 to 1972

CHAPTER V

MODIFICATIONS OF MODEL AND RESULTS AND DISCUSSION FROM MODIFIED MODEL

Based on the results presented in the previous chapter, the problem sources in the components of the model are identified and discussed in this chapter. The modifications of the model components and their respective performances are also presented and discussed.

Identification of Problem Sources for Simulated Runoff

One of the objectives of the study was to identify the problem sources in the components of the model. The differences between simulated and observed runoff can possibly be explained by the inter-related hydrological processes which are described by the empirical and semi-empirical equations in the model.

The analyses of the simulated and observed runoff showed that the overestimation of runoff occurred in dryer months, while the underestimations occurred in wet months. This in turn indicates that the runoff from small rainfall events is overestimated and the runoff from large rainfall events is underestimated.

The simulated runoff is computed in the model from the difference between rainfall and infiltrated water in a given time interval. Thus, overestimations and underestimations of runoff are directly dependent upon the infiltration sub-model.

The Green-Ampt infiltration equation uses three parameters: effective hydraulic conductivity, effective capillary tension and fillable porosity. Brakensiek and Onstad (1977) reported that infiltration was most sensitive to errors in fillable porosity and effective hydraulic conductivity, and less sensitive to errors in effective capillary tension of the soil. The effective hydraulic conductivity and effective capillary tension parameters are direct inputs in the model. Thus, the fillable porosity parameter should be investigated in detail.

The fillable porosity is a built-in parameter and is computed by subtracting the antecedent soil moisture from effective porosity of the soil. The antecedent soil moisture is computed from the soil water balance equation on one-day interval basis. Therefore, overestimation of runoff is associated with high simulated antecedent soil moisture and underestimation is associated with low simulated antecedent soil moisture.

The deviations in simulated antecedent soil moisture are caused by incorrect estimation of: (1) soil moisture distribution in soil profile and (2) evapotranspiration.

Soil moisture distribution is affected by extraction by the plant roots and by evaporation. Since evapotranspiration is the sum of soil moisture evaporation and plant transpiration, it appears that simulated plant transpiration may have been inadequate in the summer months, leading to high antecedent soil moisture and overestimation of runoff.

From the regression analyses of simulated versus observed runoff, it was found that the effective hydraulic conductivity parameter was approximately equal to the saturated hydraulic conductivity of the least permeable soil layer in the soil profile. Since the root zone often consists of two distinct soil layers, the hydraulic conductivity of the other soil layer was not taken into account, in this situation, because the Green-Ampt infiltration equation does not account for a two-layered soil profile.

Further, the Green-Ampt infiltration equation does not include the two-phase flow process, which involves simultaneous water flow into the soil and air flow out of the soil. The air phase along with the water phase represents a physically realistic treatment of the infiltration process. Such a flow process can be accounted for by varying the hydraulic conductivity along with the soil moisture content.

Modifications of Model and Their Results and Discussion

Three components of the CREAMS hydrologic model were modified. They are: (1) soil moisture distribution, (2) evapotranspiration and (3) infiltration components. Each one is presented in the following section. The modification in each component was incorporated and its performance was seen separately. Guthrie W-V watershed was utilized for the tests. The results and discussion of the simulated runoff from modified model are also presented in the following section.

Soil Moisture Distribution

Presently, the model divides the soil profile into two layers: (1) surface layer and (2) root zone layer. The surface soil layer is subjected to soil moisture evaporation and to a portion of plant transpiration as moisture extraction by the plant roots. The lower root zone layer is subjected to the moisture extraction, which is a remaining portion of the plant transpiration. Soil moisture extraction by roots occurs from both surface and root zone layers in proportion to the relative root depth. A root growth model is used to simulate relative root depth proportional to relative leaf area index.

For better accounting of moisture balance and distribution in the soil profile, the Williams and Hann (1978) model, described in the review of literature chapter, was used. Equations (25) and (27) were utilized to compute the portions of soil moisture extraction by plant roots from both surface and root zone layers. Equations (43) and (44) show the fractions of plant transpiration which was extracted from surface and root zone layers respectively.

$$UW_1 = \frac{[1 - \exp(4.16*DS/Root]E_p}{[1 - \exp(4.16)]} \tag{43}$$

$$UW_2 = E_p - UW_1 \tag{44}$$

where

$$Root = \frac{LAI}{LAI_{max}} (DS + DP)$$

UW_1 = moisture extracted by plant root from surface soil layer

DS = depth of the surface soil layer

DP = depth of the root zone layer

LAI = leaf area index on any day

LAI_{max} = maximum leaf area index during the growing season

E_p = actual plant transpiration

UW_2 = moisture extraction by plant roots from root zone depth

It is to be noted that the soil moisture evaporation from the surface soil layer was also considered in addition to the soil moisture extraction by the plant roots.

Equations (43) and (44) were incorporated in the soil moisture distribution submodel. A computer run was made to simulate the runoff for Guthrie W-V watershed. The values for the input parameters were those which were obtained by the best fit as described in the previous chapter.

The results obtained from this simulation showed a very minor change (about in the magnitude of one-hundredth of an inch of runoff) in the simulated runoff. Further, the simulation of other components of the model output (e.g. evapotranspiration and deep percolation) were unchanged.

Thus, the incorporation of a different soil moisture distribution model did not improve the simulated runoff.

Evapotranspiration

Presently, the model uses a set of equations developed by Ritchie (1972) to compute evapotranspiration. The equations have been divided into two parts: (1) soil moisture evaporation and (2) plant transpiration. The details are presented in review of literature chapter.

It was found that the model uses Equation (45) for computing the plant transpiration.

$$E_p = E_o \cdot \frac{LAI}{3} \qquad (45)$$

where:

E_p = plant transpiration

E_o = potential evaporation

LAI = leaf area index

However, the original evapotranspiration model developed by Ritchie (1972) to compute plant transpiration used Equation (46), which was developed as an empirical equation and was used on the native grassland watersheds by Ritchie et al. (1976).

$$E_p = [-0.21 + 0.70\ (LAI)^{\frac{1}{2}}]E_o \qquad (46)$$

where:

E_p = plant transpiration

E_o = potential evaporation

LAI = leaf area index

To determine the effect of using Ritchie's original equation in the CREAMS hydrologic model, Equation (46) was incorporated instead of Equation (45) in the evapotranspiration submodel. A computer run was made for Guthrie W-V watershed, with the same input parameters as obtained after best fit in previous chapter.

The results from the simulation showed similar runoff values, which were obtained after achieving the best fit described in the previous chapter. However, the average monthly evapotranspiration was increased in the months of July, August and September by 0.3 , 0.1 and 0.05 inches respectively compared to original model. The average annual evapotranspiration was also increased by 0.5 inches compared to original model.

Therefore, it was seen that the use of Ritchie's original empirical equation of plant transpiration did not cause any significant change in simulated evapotranspiration that in turn improved the simulated runoff.

Infiltration

Two-Layered Soil Profile Infiltration. Presently, the infiltration submodel considers the process for the single layered soil profile. Therefore, the submodel was modified for the two-layered soil profile infiltration process.

Moore (1981) and Moore and Eigel (1981) modified the Green-Ampt-Mein-Larson infiltration equations for two-layered soil profile. Equations (14) and (15) are shown in review of literature chapter.

From finite difference perturbation Equations (14) and (15) can be rewritten as Equation (47) and Equation (48).

$$\Delta F - G_1 D_1 \ln\left(1 + \frac{\Delta F}{G_1 D_1 + F}\right) = K_1 \Delta t; \text{ for } L \leq L_1 \qquad (47)$$

$$\Delta F - (E-H) \ln\left(1 + \frac{\Delta F}{H - F_1 + F}\right) = K_2 \Delta t; \text{ for } L > L_1 \qquad (48)$$

Solving the Equations (47) and (48) for the change in cumulative infiltration volume, ΔF, in time interval of Δt by series and rearranging Equations (49) and (50) were obtained.

$$\Delta F = -\left(F - \frac{K_1 \Delta t}{2}\right) + \left[\left(F - \frac{K_1 \Delta t}{2}\right)^2 + (F_1 + G_1 D_1)(2k_1 \Delta t)\right]^{\frac{1}{2}}$$

$$\text{for } L \leq L_1 \qquad (49)$$

$$\Delta F = -\left(2H + F - F_1 - E - \frac{K_2 \Delta t}{2}\right) + \left[\left(2H + F - F_1 - E - \frac{K_2 \Delta t}{2}\right)^2 - (F_1 - F - H)(2k_2 \Delta t)\right]^{\frac{1}{2}} \text{ for } L > L_1 \qquad (50)$$

where:

$E = L_1 D_2 (\frac{k_2}{k_1})$

$H = D_2(L_1 + G_2)$

$F_1 = L_1 D_1$

K_1 = hydraulic conductivity of wetting zone behind the wetting front in the surface layer

G_1 = effective suction at the wetting front in the surface layer

D_1 = initial soil moisture deficit in the surface layer

L_1 = depth of surface layer

K_2 = hydraulic conductivity of wetting zone behind the wetting front in the subsurface layer

G_2 = effective suction at the wetting front in the subsurface layer

D_2 = initial soil moisture deficit in the subsurface layer

L_2 = depth of subsurface layer

F = cumulative infiltration volume

t = time elapsed

Equations (49) and (50) were incorporated in the infiltration submodel, which replaced Equation (7) in the submodel. These equations required three additional input parameters: (1) effective saturated hydraulic conductivity of subsoil (2) effective capillary tension of subsoil and (3) soil porosity of subsoil.

After incorporating the equations and additional input parameters, a computer run was made for Guthrie W-V watershed. The results from the simulation run showed a very high cumulative runoff error. Therefore, the hydraulic conductivity of surface soil and subsoil (input parameters) were varied such that the best fit was obtained.

The simulated runoff obtained from the best fit of the modified model did not show any improvement compared to the simulated runoff of the original model.

Therefore, the modification of the Green-Ampt-Mein-Larson infiltration equation for two-layered soil profile did not show improvement in continuous simulation of runoff.

Two-Phase Infiltration. The Green-Ampt infiltration equation considers the water flow phase only. Chu and Engman (1982) modified the Green-Ampt infiltration equation based on two phase flow formulation of Darcy's Law. They found effective hydraulic conductivity to be directly proportional to fillable porosity as shown in Equation (51).

$$K_s = K_1 D \tag{51}$$

where:

K_s = effective hydraulic conductivity

K_1 = constant (hydraulic conductivity)

D = fillable porosity

Theoretical justification of Equation (51) is based on the concept of a two-phase infiltration process.

Two schematic diagrams I and II are shown in Figure 17 for illustration purpose. The vertical dimension shows the depth of soil profile

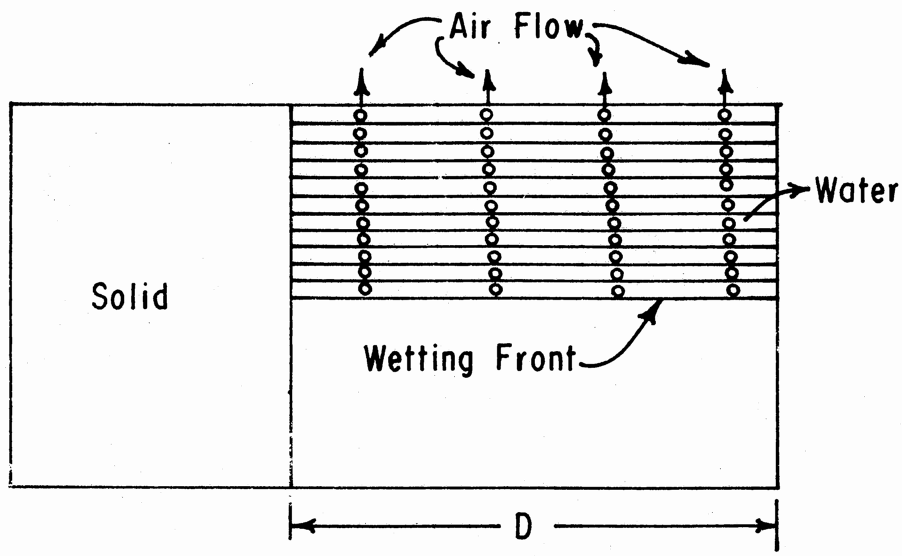

DIAGRAM I

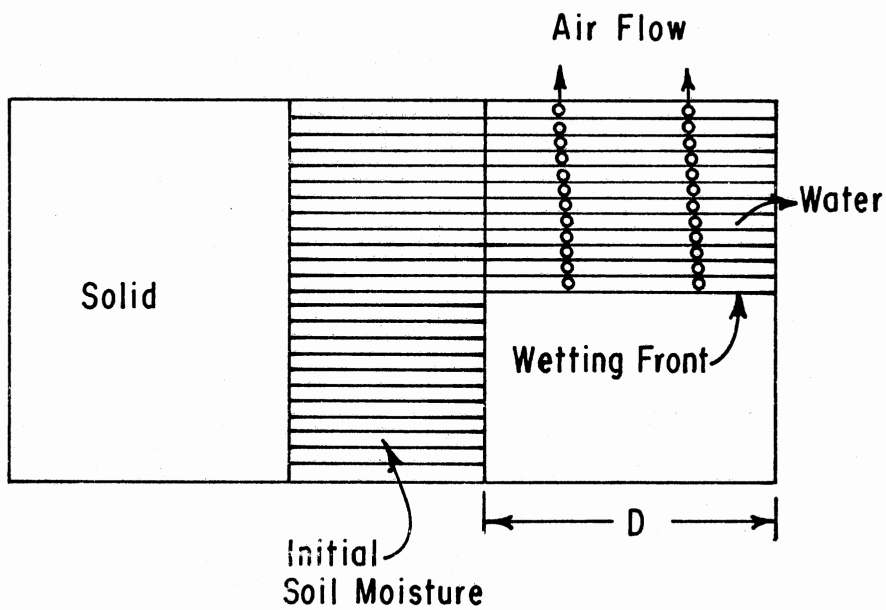

DIAGRAM II

Figure 17. Schematic Diagrams of Two Phase Infiltration Process

and moving depth of the wetting front, whereas the horizontal dimension shows the portions of soil cross-sectional area contained with solids, water and air. In Figure 17, the diagram I represents a dry state and diagram II a wet state of the same soil. The depths of wetting front are kept the same for both diagrams.

The two phase process can be considered as an exchange of water flow into the soil with the air flow out of the soil. The amount of air flow can be determined by the fillable porosity because the air in the soil pores represents the extent of air supply. Based on this viewpoint, the infiltration rate in a dry state should be greater than that in a wet state for the same soil at a specific depth of wetting front, since the air supply is more extensive in a dry state.

This process can be represented by considering the effective hydraulic conductivity as a dependent variable of initial soil moisture. Equation (51) is an adequate description of such a relationship.

Equation (51) was incorporated in the infiltration submodel. Subsequently, computer runs were made for Guthrie W-V watershed. The modification involved the input of constant hydraulic conductivity parameter instead of effective hydraulic conductivity parameter; therefore, the parameter was varied such that the best fit was achieved. All other parameters, which were obtained by the best fit from the original model, were kept the same.

For the modified model, the final value of the hydraulic conductivity parameter, RC, was 0.22 inches per hour.

The monthly simulated and observed runoff values are shown in Table XXV. Means and standard deviations of monthly simulated and observed runoff are shown in Table XXVI. The annual water balance summary is shown in Table XXVII.

The relative performance of the modified and original model was determined for the Guthrie W-V watershed. Regression analysis of monthly runoff using the modified model gave intercept, slope, correlation coefficient and standard deviation values of 0.06, 0.81, 0.89 and 0.32 as compared to the original model which gave the values of 0.08, 0.76, 0.87 and 0.33 respectively. The monthly simulated and observed runoff and their respective regression lines for both versions of the model are shown in Figure 18. In most months, the modified model simulated runoff relatively closer to observed runoff than the original model, as shown in Figure 19. The annual runoff regression analysis from modified model (Figure 20) showed intercept, slope, correlation coefficient and standard deviation values of 0.36, 0.91, 0.87 and 1.19 respectively, whereas the original model produced the values of 0.64, 0.83, 0.85 and 1.22 respectively.

Thus, the modified model caused an improved relationship between the observed and simulated runoff compared to the original model for the Guthrie W-V watershed.

In order to confirm the improved performance of the modified model, computer runs were made for the other three watersheds. The best fit was obtained for each watershed by varying the RC parameter.

The summary of linear regression analyses of runoff from modified and original models for all the watersheds is shown in Table XXVIII. The intercepts, slopes, correlation coefficients, and standard deviations of monthly and annual runoff were compared for the modified and original models.

For the Chickasha R-7 watershed the monthly runoff regression slope

TABLE XXV

SIMULATED MONTHLY RUNOFF FROM MODIFIED CREAMS MODEL AND OBSERVED MONTHLY RUNOFF FOR GUTHRIE W-V WATERSHED

Year	Runoff* Type	Runoff Values for the Specified Month of the Year (in)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1942	QM_s	0	0.17	0	1.00	0.25	0.50	0	0.27	0.59	0.01	0	0.01	2.81
	Q_o	0	0.02	0	2.74	0.13	0.03	0	0.07	0.47	0.02	0	0.01	3.44
1943	QM_s	0	0	0.02	0.01	1.42	0.11	0	0	0.01	0.75	0	0.01	2.34
	Q_o	0	0	0	0	2.45	0.08	0	0	0	0.22	0	0	3.25
1944	QM_s	0	0	0.26	0.67	0.77	0.13	0.02	0	0.53	0.43	0.01	0.02	2.86
	Q_o	0	0	0.25	0.70	0.74	0.12	0	0	0.04	0.65	0.01	0.27	2.78
1945	QM_s	0.01	0.06	0.14	0.45	0.01	3.37	0.26	0	1.16	0	0	0	5.47
	Q_o	0	0.01	0.04	0.62	0	2.17	0.09	0	1.46	0	0	0	4.38
1946	QM_s	0.01	0.09	0.04	0.06	0.80	0.29	0	0.62	0	0.61	0.57	0.03	3.14
	Q_o	0.02	0.04	0.01	0	0.46	0.11	0	0.22	0	0.21	0.45	0	1.52
1947	QM_s	0.06	0	0	1.67	1.00	0.02	0.10	0	0	0	0	0.02	2.88
	Q_o	0	0	0	3.81	1.65	0	0.06	0	0	0	0	0	5.52
1948	QM_s	0	0.03	0.44	0.46	0.01	2.21	0.14	0.01	0	0	0.02	0	3.32
	Q_o	0	0.17	0.71	0.71	2.21	0	0	0	0	0	0	0	3.10

TABLE XXV (Continued)

Year	Runoff* Type	Runoff Values for the Specified Month of the Year (in)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1949	QM_s	0.11	0.01	0.03	0	5.96	2.12	1.04	0	0.84	0.01	0	0.01	10.14
	Q_o	0.25	0.02	0	0	5.37	2.60	0.79	0	0.38	0.01	0	0	9.42
1950	QM_s	0.02	0.04	0	0	0.17	1.22	1.05	0.07	0	0	0	0	2.59
	Q_o	0	0	0	0	0.13	1.37	1.89	0	0	0	0	0	3.39
1951	QM_s	0	0.07	0	0.07	0.74	1.72	0.17	1.22	0.92	0.08	0.06	0	5.07
	Q_o	0	0.14	0	0.44	1.18	1.27	0.28	0.79	0.37	0	0.12	0	4.59
1952	QM_s	0	0	0	0.01	0.06	0.04	0.46	0	0	0	0.03	0.06	1.09
	Q_o	0	0.01	0.44	0.01	0.32	0	0.01	0.08	0	0	0	0	0.87
1953	QM_s	0.01	0.09	0.21	0.03	0.11	0	0.54	1.12	0.30	0.53	0	0.11	3.07
	Q_o	0	0.28	0.28	0.05	0.07	0	0.12	0.74	0.14	0.29	0.19	0.15	2.03
MEAN	QM_s	0.02	0.05	0.09	0.37	0.94	0.98	0.31	0.31	0.36	0.20	0.06	0.02	3.71
	Q_o	0.02	0.02	0.10	0.76	1.08	0.83	0.27	0.16	0.23	0.12	0.06	0.03	3.74

*QM_s - stands for simulated runoff from modified CREAMS model.

Q_o - stands for observed runoff.

TABLE XXVI

MEANS AND STANDARD DEVIATIONS OF SIMULATED RUNOFF FROM MODIFIED MODEL AND OBSERVED RUNOFF FOR GUTHRIE W-V WATERSHED FOR 1942-1953

Month	Simulated Runoff Mean (in)	Simulated Runoff S.D. (in)	Observed Runoff Mean (in)	Observed Runoff S.D. (in)	Error (pct)
Jan	0.02	0.03	0.02	0.07	0
Feb	0.05	0.05	0.02	0.04	150
Mar	0.09	0.14	0.10	0.15	-10
Apr	0.37	0.52	0.76	1.23	-51
May	0.94	1.64	1.08	1.61	-13
Jun	0.98	1.13	0.83	1.03	+18
Jul	0.31	0.38	0.27	0.56	+15
Aug	0.31	0.45	0.16	0.29	+93
Sep	0.36	0.43	0.23	0.42	+56
Oct	0.20	0.29	0.12	0.20	+66
Nov	0.06	0.16	0.06	0.13	0
Dec	0.02	0.03	0.03	0.08	-33

TABLE XXVII

ANNUAL SUMMARY OF WATER BALANCE FROM MODIFIED CREAMS MODEL FOR GUTHRIE W-V WATERSHED

Year	Rain (in)	Observed Runoff (in)	Simulated Runoff (in)	Error (pct)	ET (in)	Percolation (in)
1942	31.09	3.44	2.81	- 18	30.97	1.03
1943	22.32	3.25	2.34	- 28	18.92	0.0
1944	30.87	2.78	2.86	+ 3	27.33	0.0
1945	31.92	4.38	5.47	+ 25	27.15	0.0
1946	26.71	1.52	3.14	+106	23.66	0.0
1947	25.60	5.52	2.88	+ 49	22.95	0.66
1948	22.88	3.10	3.32	+ 7	19.95	0.0
1949	41.43	9.42	10.14	+ 7	31.08	0.0
1950	26.65	3.39	2.59	- 23	25.28	0.0
1951	32.27	4.59	5.07	+ 10	26.48	0.0
1952	19.03	0.87	1.09	+ 25	17.67	0.0
1953	31.86	2.03	3.07	+ 51	26.76	0.0
MEAN	28.46	3.74	3.73	-0.2	24.85	0.14

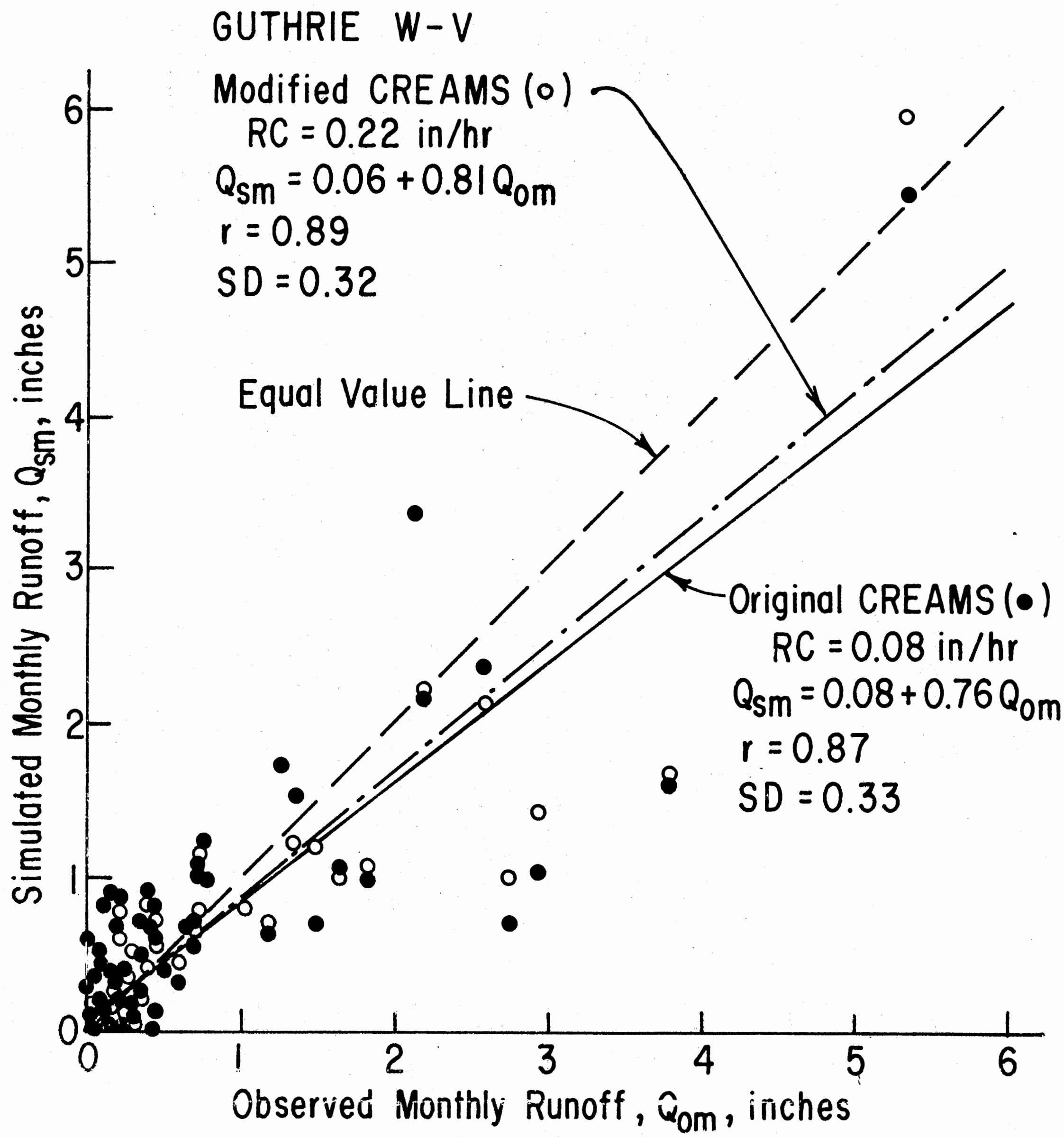

Figure 18. Simulated and Observed Monthly Runoff for Guthrie W-V Watershed From Modified and Original CREAMS Models From 1942 to 1953

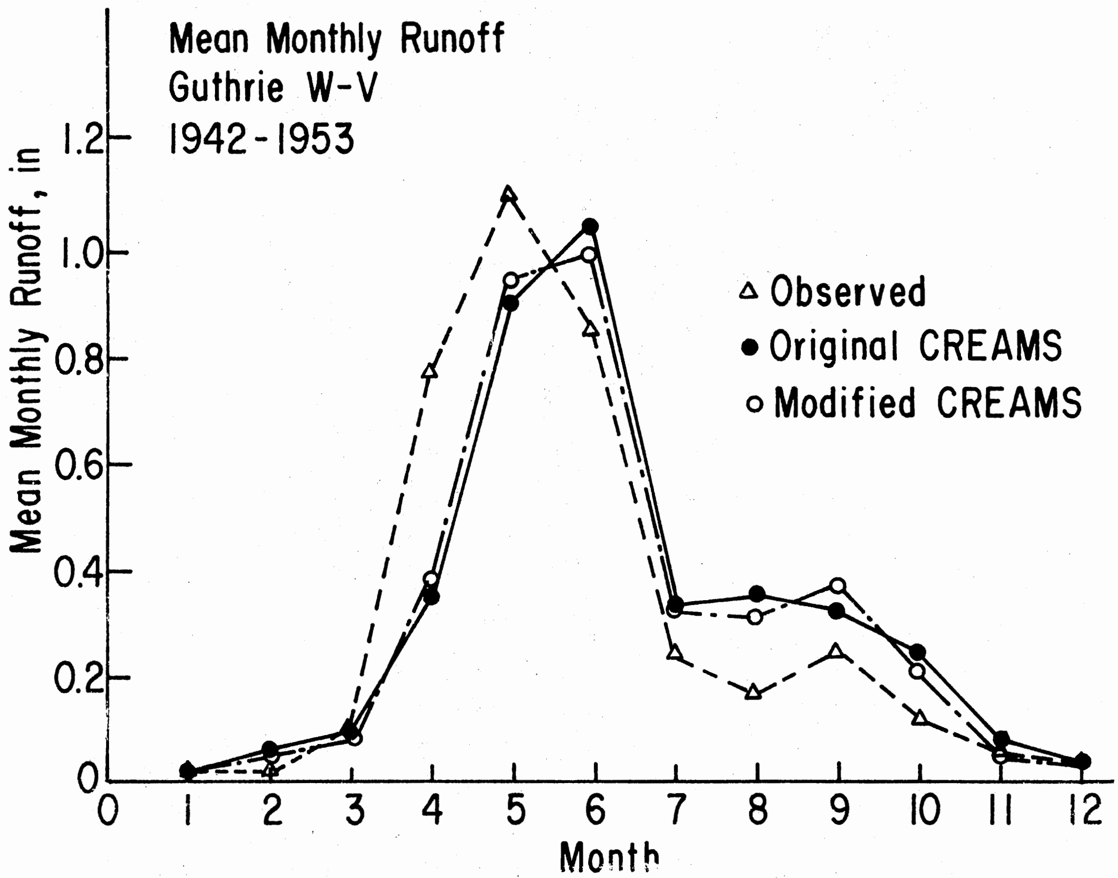

Figure 19. Monthly Mean Simulated and Observed Runoff for Guthrie W-V Watershed From Modified and Original CREAMS Models From 1942 to 1953

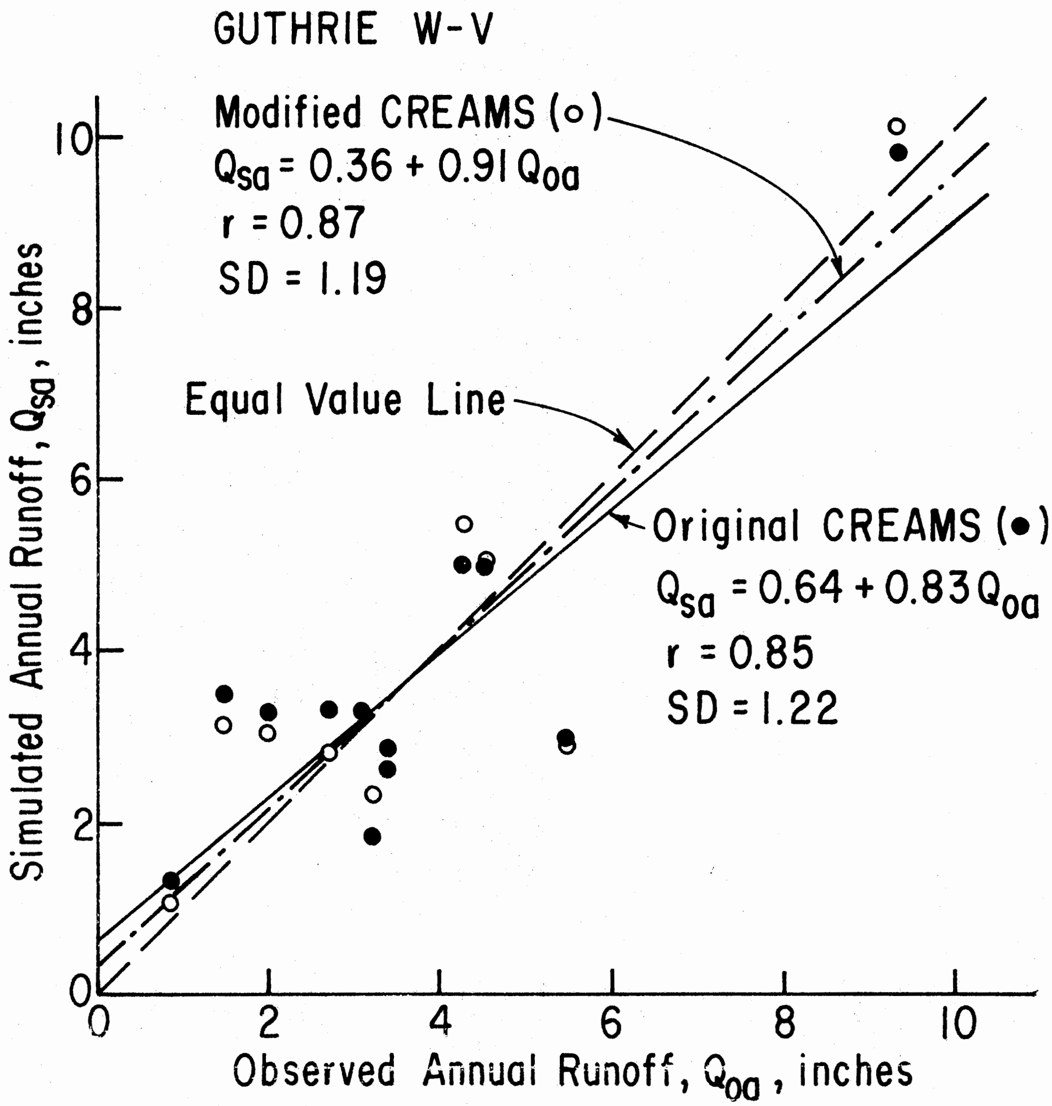

Figure 20. Simulated and Observed Annual Runoff for Guthrie W-V Watershed From Modified and Original CREAMS Models From 1942 to 1953

TABLE XXVIII

SUMMARY OF LINEAR REGRESSION ANALYSES OF RUNOFF FROM MODIFIED AND ORIGINAL CREAMS MODELS

		Monthly Runoff Regression				Annual Runoff Regression			
Watershed	Model	Intercept (in)	Slope	r	S.D. (in)	Intercept (in)	Slope	r	S.D. (in)
Guthrie	Modified	0.06	0.81	0.89	0.32	0.36	0.91	0.87	1.19
W-V	Original	0.07	0.76	0.87	0.33	0.64	0.83	0.85	1.22
Chickasha	Modified	0.04	0.94	0.88	0.37	1.86	0.72	0.90	1.31
R-7	Original	0.05	0.91	0.88	0.37	1.89	0.69	0.90	1.25
Stillwater	Modified	0.14	0.61	0.81	0.39	1.96	0.55	0.88	1.19
W-4	Original	0.15	0.55	0.78	0.39	2.02	0.51	0.87	1.14
Stillwater	Modified	0.20	0.52	0.74	0.52	2.53	0.50	0.85	1.53
W-3	Original	0.22	0.49	0.72	0.52	2.67	0.48	0.84	1.51

was 0.94 for the modified model compared to 0.91 for the original model. The correlation coefficients were 0.88 and 0.87 respectively. The standard deviations were the same for both models. The annual runoff regression showed the slopes of 0.72 and 0.69 for modified and original models. The standard deviations were 1.31 and 1.26 inches respectively.

For Stillwater W-4 watershed the monthly runoff regression slopes were 0.61 and 0.55 for modified and original models. The correlation coefficients were 0.81 and 0.78. The annual regression analysis slopes were 0.55 and 0.51 for modified and original models. The correlation coefficients were 0.88 and 0.87 and the standard deviations were 1.19 and 1.14 inches respectively.

For Stillwater W-3 watershed, the monthly runoff the regression slopes were 0.52 and 0.49 for modified and original model. The correlation coefficients were 0.74 and 0.72. The standard deviations were the same for both the models. The annual runoff regression slopes were 0.50 and 0.48 for modified and original models with correlation coefficients of 0.85 and 0.84. The standard deviations were 1.53 and 1.50 inches for modified and original models respectively.

Therefore, it was found that the modification of Green-Ampt infiltration equation for the two-phase flow improved the runoff simulation.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

A study of the performance of the CREAMS hydrologic model to simulate runoff was conducted on four grassland watersheds in central Oklahoma. The watersheds were divided into two groups, namely, (1) Guthrie W-V and Chickasha R-7 watersheds which have relatively small sizes and homogenous soils, and (2) Stillwater W-4 and W-3 watersheds which are relatively large in size and have heterogenous soils. The study utilized the available information on rainfall, temperature, solar radiation, and runoff data. The data base varied from 8 to 20 years.

The objectives of the study were (1) to assess the capability of the CREAMS hydrologic model to simulate the runoff from small native grassland watersheds in central Oklahoma, (2) to identify the problem sources and propose modifications of the components of the model for the improvement of runoff simulation, and (3) to modify the model and test the revised model.

The model was assessed with respect to simulated and observed monthly and annual runoff. The parameters that were varied were effective hydraulic conductivity, effective capillary tension and soil porosity. They were varied until the cumulative simulated runoff was within ±1 percent error of the cumulative observed runoff, and until the best possible fit of the monthly runoff regression line and equal value line were achieved.

The simulation period for the Guthrie W-V watershed was 12 years (from 1942 to 1953). The relationship between the monthly simulated and observed runoff was expressed by Equation (35).

$$Q_{sm} = 0.08 + 0.76\ Q_{om} \qquad (35)$$

with r = 0.87 and s.d. = 0.33 inches. The annual runoff regression analysis produced Equation (36)

$$Q_{sa} = 0.64 + 0.83\ Q_{oa} \qquad (36)$$

with r = 0.85 and s.d. = 1.22 inches.

The analysis of monthly simulated and observed runoff for the period of 8 years (from 1967 to 1974) on Chickasha R-7 watershed gave the relationship expressed by Equation (37).

$$Q_{sm} = 0.05 + 0.91\ Q_{om} \qquad (37)$$

with r = 0.88 and s.d. = 0.38 inches. The annual simulated and observed runoff were related by Equation (38).

$$Q_{sa} = 1.89 + 0.69\ Q_{oa} \qquad (38)$$

with r = 0.90 and s.d. = 1.25 inches.

For Stillwater W-4 watershed, the monthly runoff relationship for the period from 1953 to 1972 was given by Equation (39).

$$Q_{sm} = 0.16 + 0.55\ Q_{om} \qquad (39)$$

with r = 0.78 and s.d. = 0.39 inches. The annual runoff relationship was given by Equation (40).

$$Q_{sa} = 2.02 + 0.51\, Q_{oa} \tag{40}$$

with r = 0.87 and s.d. = 1.14 inches.

For the Stillwater W-3 watershed, the monthly simulated and observed runoff were related by Equation (41).

$$Q_{sm} = 0.22 + 0.49\, Q_{om} \tag{41}$$

with r = 0.72 and s.d. = 0.52 inches. The annual runoff regression analysis gave Equation (42).

$$Q_{sa} = 2.67 + 0.48\, Q_{oa} \tag{42}$$

with r = 0.84 and s.d. = 1.51 inches.

The best estimate of the effective hydraulic conductivity parameter was found to be equal to the saturated hydraulic conductivity of least permeable soil layer in the root zone.

It was noted that the high runoff amounts were underestimated and low runoff amounts were overestimated on both monthly and annual basis. The annual simulated runoff had more dispersion, underestimation, and overestimation than the monthly simulated runoff. The extremely high and low monthly simulated runoff occurred in the months with higher than the average rainfall. The mean monthly runoff amounts were overestimated in July and August, and underestimated in March, May and October.

It was found that the fillable porosity, which is directly related with the antecedent soil moisture, is the most sensitive parameter in the Green-Ampt infiltration equation. The overestimations of the runoff were identified to be associated with high simulated soil moisture and underestimations were associated with low simulated soil moisture.

The model was modified for soil moisture distribution, evapotranspiration, two-layer soil profile infiltration and two-phase infiltration.

For the Guthrie W-V watershed, the modified model for two-phase infiltration simulated the monthly runoff, which was related with the observed runoff by Equation (52).

$$Q_{sm} = 0.06 + 0.81\, Q_{om} \tag{52}$$

with r = 0.89 and s.d. = 0.32 inches. The regression analysis of annual runoff gave Equation (53).

$$Q_{sa} = 0.36 + 0.91\, Q_{oa} \tag{53}$$

with r = 0.87 and s.d. = 1.19 inches.

Comparison of the simulated runoff between the modified and original models on four watersheds indicated that the modification of the Green-Ampt infiltration equation for two-phase infiltration improved the accuracy of the simulated runoff.

Conclusions

1. The model simulated runoff more accurately on Guthrie W-V and Chickasha R-7 watersheds, which are small in size and have homogenous soils, than on Stillwater W-4 and W-3 watersheds.

2. The effective hydraulic conductivity, a model input parameter, was found to be equal to the saturated hydraulic conductivity of the least permeable soil layer of root zone.

3. The annual simulated runoff had more dispersion and variability than the monthly simulated runoff.

4. The model overestimated the small runoff amounts and underestimated the large runoff amounts.

5. Antecedent soil moisture, a built-in model parameter, was identified as an important parameter for accurately simulating runoff amounts.

6. The modifications in the soil moisture distribution, evapotranspiration and infiltration (two-layered soil profile infiltration) submodels did not improve the simulated runoff.

7. The two-phase infiltration modification in the Green-Ampt infiltration equation produced improvement in continuous simulation of runoff.

Recommendations for Future Research

1. The large watersheds should be divided into small sections based on homogenous soils and then the model performance should be studied.

2. Measurement of soil moisture in situ in the soil profile should be made after which the simulated and observed soil moisture content should be compared.

3. Empirical relationships for computing plant transpiration from grassland watersheds should be established through field measurements.

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APPENDIXES

APPENDIX A

MONTHLY RAINFALL DATA FOR THE GUTHRIE W-V, CHICKASHA R-7 AND STILLWATER W-4 WATERSHEDS

TABLE XXIX

OBSERVED MONTHLY RAINFALL FOR GUTHRIE W-V WATERSHED (INCHES)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1942	0.16	1.44	0.61	8.05	1.29	5.59	0.11	4.20	5.34	2.22	0.43	1.65
1943	0	0.62	0.93	1.37	9.28	2.34	0.19	0.23	0.96	3.72	0.18	2.50
1944	0.92	1.12	2.87	4.48	3.83	2.80	2.08	1.69	3.08	4.20	1.71	2.09
1945	0.91	1.79	2.27	3.53	0.71	10.37	3.00	0.71	8.09	0.51	0	0.03
1946	2.55	1.60	2.44	2.07	4.43	2.81	0	2.76	0.50	2.45	4.18	0.92
1947	0.33	0.01	0.27	10.11	7.04	0.70	2.29	0.05	1.20	0.61	1.20	1.79
1948	0.07	1.47	3.23	2.97	2.42	6.77	1.34	1.77	0	0.99	1.75	0.10
1949	4.20	0.90	1.42	1.22	12.37	8.20	3.93	1.24	3.87	3.04	0	1.04
1950	0.89	1.37	0.31	0.94	4.79	4.99	8.92	2.38	1.18	0.27	0.59	0.02
1951	0.82	1.76	0.98	2.96	5.48	5.79	3.57	2.53	4.02	2.60	1.75	0.01
1952	0.38	1.35	2.87	2.30	3.43	1.45	2.25	2.23	0.29	0	1.58	0.90
1953	0.53	1.29	4.02	2.62	1.77	1.39	5.12	5.26	2.31	5.60	0.83	1.12

TABLE XXX

OBSERVED MONTLY RAINFALL FOR CHICKASHA R-7 WATERSHED (INCHES)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	0.10	0.10	2.34	6.43	4.32	1.95	1.54	1.12	5.42	2.13	0.23	1.02
1968	2.50	1.09	1.90	2.12	4.98	3.37	2.29	1.04	2.97	2.39	4.29	1.29
1969	0.71	2.36	1.95	1.05	4.76	3.95	3.82	2.42	3.41	1.63	0.37	1.49
1970	0.17	0.67	2.25	2.60	3.23	1.18	1.03	1.87	6.79	2.96	0.99	0.32
1971	0.57	1.67	0.16	0.55	4.14	5.00	1.72	3.82	6.15	5.54	0.49	2.91
1972	0.08	0.60	0.95	4.69	2.94	0.72	1.02	1.66	1.47	9.30	1.76	0.69
1973	3.12	0.44	6.07	2.56	7.95	5.93	3.69	2.15	6.43	3.41	3.55	0.12
1974	0.16	1.79	1.62	4.01	2.61	1.04	0.71	5.04	3.49	4.78	1.63	1.43

TABLE XXXI

OBSERVED MONTHLY RAINFALL FOR STILLWATER W-4 WATERSHED (INCHES)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1953	0.19	0.91	3.09	2.68	3.91	3.69	6.60	0.56	2.22	2.42	3.35	1.00
1954	0	0.68	0.15	2.80	3.97	1.38	0.25	2.17	0.87	1.81	0.30	1.79
1955	0.77	1.54	2.08	0.64	14.00	3.11	0.27	7.30	1.39	4.59	0.09	0
1956	0.50	0.81	0.52	1.62	1.90	1.98	3.34	0.73	0.15	1.52	1.75	1.46
1957	0.60	1.96	2.49	8.11	9.64	11.50	1.60	1.02	4.48	1.40	2.38	0.66
1958	1.13	1.05	4.40	1.40	1.71	3.97	6.23	3.46	3.30	0.20	0.67	0.79
1959	0.27	0.84	1.73	3.38	5.01	3.74	10.53	2.41	8.27	10.00	0.15	1.87
1960	0.76	2.48	1.21	1.05	7.48	1.98	6.76	2.19	0.55	4.14	0.10	1.75
1961	0	1.08	2.57	0.24	8.26	4.67	4.58	2.60	8.57	2.35	3.30	1.06
1962	0.71	0.63	1.34	1.10	1.44	8.10	4.51	0.93	3.53	2.41	1.34	1.44
1963	0.45	0.01	3.18	1.56	3.59	1.89	5.84	4.61	5.12	2.70	1.66	0.57
1964	0.52	1.39	1.03	3.58	3.60	1.43	1.11	8.33	2.68	0.86	5.06	0.86
1965	0.85	0.66	0.89	1.13	3.75	2.39	2.95	1.76	3.91	0.28	0	2.34
1966	0.22	1.59	0.19	2.05	1.65	1.64	5.71	4.18	1.60	0.52	0.04	1.04
1967	1.37	0.45	1.23	2.46	3.68	6.95	4.08	1.67	6.64	2.33	0.78	0.80
1968	1.15	0.59	2.65	4.12	7.08	2.81	0.69	3.03	1.67	1.98	5.23	1.22
1969	0.63	1.89	2.59	2.84	3.72	6.85	1.16	3.43	4.78	2.48	0.29	1.62
1970	0.21	0.20	2.94	4.50	1.12	2.71	1.00	0.17	5.49	1.83	0.28	0.90
1971	1.46	1.80	0.05	2.70	2.83	5.22	5.33	1.07	9.09	3.24	0.58	2.25
1972	0.16	0.39	0.70	3.47	1.51	5.77	2.26	1.88	2.40	5.46	2.12	1.21

APPENDIX B

MONTHLY TEMPERATURE DATA FOR THE GUTHRIE W-V

CHICKASHA R-7 AND STILLWATER W-4

WATERSHEDS

TABLE XXXII

MONTHLY TEMPERATURE FOR GUTHRIE W-V WATERSHED (DEG F)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1942	41.7	41.0	45.5	54.2	64.6	74.0	80.0	80.7	76.2	67.5	57.0	47.6
1943	39.2	37.5	42.6	53.0	66.0	78.2	86.1	87.7	82.6	72.2	59.2	47.0
1944	41.7	39.8	43.7	52.3	63.4	73.8	80.9	82.8	78.9	70.3	59.3	48.8
1945	43.7	42.1	45.5	53.0	62.5	71.6	77.7	79.3	76.0	68.5	59.0	49.9
1946	43.9	43.6	48.4	57.2	67.5	76.5	82.0	82.2	77.4	68.6	58.4	49.3
1947	38.2	35.5	39.3	48.7	61.2	73.3	81.8	84.6	80.7	70.3	58.9	46.7
1948	40.9	40.7	45.3	53.5	63.0	71.4	76.2	76.4	71.8	63.6	54.0	45.7
1949	36.2	36.2	42.1	52.4	64.2	74.4	80.3	80.3	74.4	64.1	52.3	42.0
1950	40.4	39.3	43.3	51.2	61.0	70.2	76.0	77.2	73.2	65.2	55.4	46.3
1951	37.5	36.6	41.6	51.2	62.8	73.2	79.7	80.6	75.6	66.0	54.4	44.0
1952	39.9	39.0	43.9	53.2	64.6	74.9	81.3	82.2	77.3	68.0	56.6	46.3
1953	40.0	39.3	44.1	53.0	63.8	73.5	79.4	80.0	75.3	66.3	55.6	46.0

TABLE XXXIII

MONTHLY TEMPERATURE FOR CHICKASHA R-7 WATERSHED (DEG F)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	45.7	46.0	50.9	59.1	68.5	76.5	80.9	80.6	75.7	67.5	58.1	50.2
1968	40.4	39.3	43.7	52.5	63.4	73.3	79.7	80.8	76.3	67.5	56.7	46.7
1969	40.3	39.1	43.9	53.2	64.6	75.0	81.7	82.8	78.1	68.8	57.4	46.9
1970	38.8	38.0	43.5	53.8	66.0	77.0	83.8	84.5	79.0	68.8	56.5	45.5
1971	41.4	40.7	45.4	54.3	64.9	74.6	80.6	81.3	76.6	67.8	57.1	47.4
1972	41.6	41.4	46.7	56.0	67.0	76.5	82.1	82.3	77.0	67.6	56.7	47.2
1973	42.2	41.0	45.1	53.4	63.7	73.2	79.4	80.7	76.6	68.3	58.0	48.4
1974	41.4	42.2	47.9	57.2	67.4	75.8	80.3	79.5	73.8	64.6	54.4	45.9

TABLE XXXIV

MONTHLY TEMPERATURE FOR STILLWATER W-4 WATERSHED (DEG F)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1953	45.0	44.2	48.6	56.9	67.0	76.1	81.8	82.6	78.2	69.9	59.8	50.7
1954	45.2	43.3	47.4	56.2	67.6	78.3	85.6	87.5	83.5	74.6	63.3	52.5
1955	44.0	43.3	48.0	56.9	67.7	77.3	83.3	84.0	79.2	70.3	59.6	50.0
1956	43.2	41.8	46.6	56.4	68.5	79.6	86.8	88.2	83.4	73.6	61.5	50.4
1957	39.8	39.4	44.8	54.5	65.9	75.9	81.9	82.2	76.8	67.1	55.7	45.7
1958	40.6	38.9	43.2	52.4	64.1	75.0	82.3	84.0	79.6	70.4	58.8	47.9
1959	40.0	40.0	45.7	55.3	66.5	76.1	81.6	81.5	75.8	66.2	55.0	45.4
1960	40.4	38.3	42.3	51.2	62.7	73.8	81.4	83.5	79.5	70.6	59.1	48.0
1961	43.2	42.8	47.3	55.6	65.4	74.1	79.3	79.7	75.1	66.8	57.0	48.4
1962	42.2	41.7	46.8	56.1	67.0	76.8	82.7	82.2	78.1	68.8	57.9	48.1
1963	42.8	42.3	47.6	57.2	68.5	78.6	84.7	85.2	80.0	70.4	59.0	48.9
1964	43.0	42.5	47.6	56.8	67.8	77.5	83.4	83.9	78.9	69.6	58.7	48.9
1965	43.0	41.8	46.1	54.8	65.6	75.6	82.0	83.2	78.9	70.1	59.4	49.4
1966	41.1	40.2	44.9	53.9	64.8	74.7	80.9	81.8	77.1	68.1	57.2	47.3
1967	44.8	45.2	50.1	58.2	67.4	75.1	79.3	78.9	74.0	65.9	56.7	49.0
1968	41.7	40.9	45.6	54.5	65.2	74.9	80.9	81.7	77.0	68.0	57.4	47.7
1969	39.1	37.9	42.7	52.2	63.8	74.5	81.4	82.6	77.8	68.3	56.7	46.0
1970	36.4	36.0	42.0	52.8	65.4	76.5	83.1	83.4	77.4	66.7	54.1	43.0
1971	39.0	37.9	42.7	52.1	63.6	74.0	80.7	81.7	76.9	67.5	56.1	45.6
1972	39.5	39.6	45.3	55.2	66.5	76.3	81.9	81.8	76.1	66.2	54.9	45.1

APPENDIX C

MONTHLY SOLAR RADIATION DATA FOR OKLAHOMA

CITY AND STILLWATER

TABLE XXXV

MEAN MONTHLY SOLAR RADIATION FOR OKLAHOMA CITY AND STILLWATER (LANGLEY'S)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Oklahoma City	319	409	494	536	615	610	593	487	377	291	240	
Stillwater	205	289	390	454	504	600	596	545	455	354	269	209

VITA

Chandra Shekhar Pathak

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Doctor of Philosophy

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