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United States
Department of
Agriculture

Agricultural
Research
Service

ARS-63

December 1987

SPUR
Simulation of Production and Utilization of Rangelands

Documentation and User Guide

3. HYDROLOGY COMPONENT: UPLAND PHASES

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INTRODUCTION

The hydrology component of the model is designed to use inputs from the climate component and produce outputs for use unto its own (for example, runoff and sediment yield) or inputs for other components of the SPUR model (for example, estimates of available soil moisture for forage production). The hydrology component is divided into three parts: an upland phase, a snowmelt phase, and a channel phase. The upland phase is discussed in this chapter.

In streams draining rangeland areas of the Western United States, extreme spatial and temporal variability in physiographic and climatic conditions require that a hydrologic model consider such conditions. For example, an individual storm event occurring as rain at low elevations and snow at high elevations is a possibility. Airmass thunderstorms dominating the rainfall-runoff process in the semiarid Southwest have extreme variations in precipitation depth in short distances (1 in/mi is not rare).

A hydrologic model component should be capable of simulating the effects of management changes on streamflow for streams that may have influent or effluent characteristics, have flow conditions that are subcritical or supercritical, and have a wide variety of slopes up to steep, rocky, pool-riffle systems.

The objectives of the upland phase of the hydrology model are to (1) be capable of predicting changes in water quantity and quality resulting from management changes; (2) be physically based, so that model parameters can be evaluated from available data for ungaged areas; (3) have sufficient detail to allow simulation on subdivided watersheds to coincide more or less with ranch and pasture boundaries; (4) be computationally efficient to enable long-term simulation for frequency analyses; (5) be capable of providing input to other SPUR model components, such as soil moisture for plant-forage-yield; and (6) be used for environmental impact analysis, nonpoint pollution assessment, and other types of resource utilization and environmental-protection-problem solutions.

Although these objectives may seem overly ambitious, significant improvements have been made in water resource models in recent years (Crawford and Donigian 1976; Williams and LaSeur 1976; Beasley et al. 1977; Simons et al. 1977; Knisel 1980a, 1980b) which facilitate such a development.

The upland phases of the hydrology model for SPUR draw heavily from a model called SWRRB (Williams et al. 1985), which has been modified and improved to consider the essential features known to affect the hydrologic response from rangelands. The SWRRB model includes the major processes of surface runoff, percolation, return flow, evapotranspiration, pond and reservoir storage, and erosion and sedimentation. The well known curve number technique (USDA 1972) is used to predict surface runoff for any given precipitation event because (1) many years of use have given confidence in its validity; (2) it relates runoff, soil type, vegetation, land use and management; and (3) it is computationally efficient. The use of rainfall data for short time increments (minutes and/or hours), which is required with infiltration equations to compute precipitation excess, is not generally available for most areas of the United States, and especially not on the rangelands with the orographic precipitation effects, sparsity of recording rain gages, etc. Finally, daily rainfall estimates are computationally more efficient than similar operations with shorter time increments.

MODEL DESCRIPTION

Water Balance

The SPUR model maintains a continuous water balance on a daily computational basis using the equation:

$$SW = SW_o + P - Q - ET - PL - QR \qquad (1)$$

where:

SW = current soil water content (in),
SW_o = initial soil water content (in),
P = cumulative rainfall (in),
Q = cumulative amount of surface runoff (in),
ET = cumulative amount of evapotranspiration (in),
PL = cumulative amount of percolation loss to ground water storage (in),
QR = cumulative amount of return flow (in).

In maintaining the continuous water balance, complex watersheds are subdivided to reflect such diverse factors as different vegetation or soils, topography, and stream morphology. In other words, runoff is computed for each subarea, and the water is routed to the outlet of the basin to obtain the total runoff. This accounting allows changing management practices of only part of the area and should improve the model's accuracy, yet, provide a more detailed physical preservation of the watershed details.

Soil/Plant Water Relationship

The plant component of SPUR requires soil water tensions for the 6 in (15 cm) depth, and for the wettest layer in the root zone to simulate plant growth (chapter 6). Several relationships are available which describe the soil water characteristic curve (Brooks and Corey 1966; van Genuchten 1980). The functional form was deemed necessary for SPUR, because range vegetation can operate at tensions significantly greater than the 15-bar lower limit used in agronomic situations, so an extrapolation to some lower limit had to be conducted. Also, limited information available for soils found on range sites stipulated that requiring more data than is already in the model, which is porosity, 1/3-bar water content, and 15-bar water content, would limit potential application of the model. Therefore, the simple power function model proposed by Campbell (1974) was used because it has only two parameters.

Campbell's equation is:

$$h_s = h_a \left(\frac{T}{T_s}\right)^b \tag{2}$$

where:

h_s = soil water tension (cm),
h_a = air entry tension (cm),
T = volumetric soil water content,
T_s = saturated volumetric soil water content, and
b = parameter.

By using a logarithmic transformation, equation 1 can be rewritten to solve for h_a and b using the porosity, 1/3-bar and 15-bar water contents. The solution for b, assuming 1020 cm/bar, is:

$$b = \frac{\ln(340) - \ln(15300)}{\ln(S_3) - \ln(S_{15})} \tag{3}$$

where:

S_3 = T(at 1/3 bar)/porosity, and
S_{15} = T(at 15 bars)/porosity.

The value for h_a is found by solving equation 2 using the 1/3-bar tension and water content. These parameters are computed for each layer.

The 15-bar water content has traditionally been set as the lower bound of available water for agronomic crops. Rangeland vegetation, particularly perennials and shrubs, are capable of functioning at tensions much lower than 15 bars. There are essentially no soils data available at this tension, so equation 2 was extrapolated to provide the 50-bar volumetric water content. Users should be cautioned that these values are an extrapolation of the data. The definition of available water in the model is changed to reflect the 50-bar water content (see following section).

Soil-Layer Water Storage

The soil in each subarea of the watershed is divided into layers (user-specified number of layers (up to eight) and layer thickness for each subarea). Water balance is done on a daily basis using rainfall excess, evapotranspiration, percolation, and return flow, as described in equation 1. Total storage, field capacity, and initial water storage in the various layers are expressed in terms of plant available water and are computed from input parameters as follows:

$$UL_i = (SM0_i - SM50_i)\, THK_i \tag{4}$$

$$FC_i = (SM3_i - SM50_i)\, THK_i \tag{5}$$

$$SW_{oi} = FC_i\, STF \tag{6}$$

where:

UL_i = upper limit of water storage in layer i (in),
FC_i = field capacity in layer i (in),
SW_{oi} = initial soil water in layer i (in),
$SM0_i$ = soil porosity for layer i (in/in),
$SM3_i$ = 1/3-bar water content for layer i (in/in),
$SM50_i$ = 50-bar water content for layer i (in/in),
THK_i = soil layer thickness for layer i (in), and
STF = initial soil water content as a fraction of field capacity for the entire soil profile.

Runoff

The traditional three antecedent moisture levels (I - dry, II - normal, III - wet), as used by the Soil Conservation Service (SCS), have been modified in the model by allowing soil moisture to be updated daily and by computing daily curve numbers based on soil-water storage, rather than using the three curve numbers associated with their moisture classes. Thus, each day has a curve number (Williams and LaSeur 1976), and the soil moisture changes between runoff events with estimates of evapotranspiration and percolation using routines very similar to those used in CREAMS (Knisel 1980b). From the curve number method, surface runoff is estimated on a daily basis from:

$$Q = \frac{(P - I_a)^2}{P + s - I_a} = \frac{(P - 0.2s)^2}{P - 0.8s} \tag{7}$$

where:

Q = daily runoff (in),
P = daily rainfall (in),
s = a retention parameter (in), and
I_a = 0.2s = initial abstraction.

The maximum value, s_{mx}, for the retention parameter, s, is computed with the following SCS curve number relationship (USDA 1972):

$$s_{mx} = \frac{1000}{CN_I} - 10 \tag{8}$$

where CN_I is the dry-antecedent-moisture-condition curve number. If handbook curve numbers are available for the normal moisture condition, CN_{II}, the following polynomial may be used to estimate CN_I:

$$CN_I = -16.91 + 1.348\, CN_{II} - 0.01379\, CN_{II}^2 + 0.0001177\, CN_{II}^3 \quad (9)$$

The soil retention parameter is computed daily as a weighted average of the unused storage in the various soil layers scale from zero to s_{mx}. It is:

$$s = s_{mx} \sum_{i=1}^{n} \left(W_i \frac{UL_i - SW_i}{UL_i}\right) \quad (10)$$

where:

n = number of soil layers,
SW_i = current water storage in layer i (updated daily) (in), and
W_i = weighting factor.

The weighting factors decrease exponentially to give greater dependence of s on the upper soil layers, so:

$$W_i = a\, e^{-4.16\, d_i} \quad (11)$$

where:

d_i = (depth to bottom of layer i)/(depth to bottom of last layer), and

a = constant adjusted so $\sum_{i=1}^{n} W_i = 1$

Peak Flow Calculation

Peak discharge for daily runoff events is calculated using some relationships discussed in the channel routing process (chapter 5):

$$Q_p = C_5 \frac{Q}{D} \quad (12)$$

where:

Q_p = peak flow rate (in/h),
Q = daily runoff volume (in),
D = duration of runoff (h), and
C_5 = a constant.

Runoff duration (D is in h) is obtained from:

$$D = C_1 A^{C_2} \quad (13)$$

where:

A = watershed area (acres); and C_1 and C_2 are constants.

Combining equations and converting units gives:

$$Q_p = 1.00833 \frac{C_5}{C_1} Q\, A^{-C_2} \quad (14)$$

where the constant (1.00833) allows conversion to give Q_p in cubic feet per second. The constants C_1, C_2, and C_5 are data input to the program.

Percolation

The percolation component of SPUR uses a storage routing model combined with a crack-flow model to predict flow through the root zone. These models are similar to those used in CREAMS (Knisel 1980b) and SWRRB. Water moving below the root zone becomes ground water, or appears as return flow that is routed into the channel network.

In the following, $PL1_i$ is percolation flow out of the bottom of layer i from the storage routing model. The variable $PL2_i$ is the crack flow out of the same layer. The variable PL_i is equal to $PL1_i$ plus $PL2_i$ and is the total flow out of layer i (ignoring return flow). The variable PL_0 is computed as being equal to precipitation minus rainfall excess; it is the amount of water flowing into the first layer.

Flow through a soil layer may be restricted by a lower layer which is saturated or nearly saturated. The variable PL_i, as subsequently computed, may exceed the projected available storage in the next layer ($UL_{i+1} - SW_{i+1}$ + projected evapotranspiration losses from layer i + 1), in which case, PL_i is set to this projected value. There is no "succeeding" layer to the bottom layer. Crack-flow computations use bottom layer values where the bottom layer needs succeeding layer values. The value of PL2 is not limited by the succeeding layer.

Storage Routing

The storage routing model uses an exponential function with the percolation computed by subtracting the soil water in excess of field capacity at the end of the day from that at the beginning of the day, or:

$$PL1_i = \begin{cases} (SW_i - FC_i)(1 - e^{-\frac{\Delta t}{T_i}}) & SW_i > FC_i \\ 0 & SW_i \le FC_i \end{cases} \quad (15)$$

where:

$PL1_i$ = amount of percolate (in),
SW_i = the soil water content at the beginning of the day for layer i (in)
Δt = time interval (24 h),
T_i = travel time through a particular layer (h),
FC_i = the field capacity water content for layer i, (in), and
i = soil layer number increasing with depth.

The travel time through each soil layer is computed with the linear storage equation:

$$T_i = \frac{SW_i - FC_i}{H_i} \quad (16)$$

where:

H_i = the hydraulic conductivity of layer i (in/h).

Hydraulic conductivity is varied from the specified saturated conductivity value by:

$$H_i = SC_i\left(\frac{SW_i}{UL_i}\right)^{\beta_i} \qquad (17)$$

where:

SC_i = saturated conductivity for layer i (in/hr), and
β_i = parameter that causes H_i 0.0022 SC_i as SW_i FC_i.

The equation for estimating β_i is:

$$\beta_i = \frac{-2.655}{\log\left(\frac{FC_i}{UL_i}\right)} \qquad (18)$$

where the constant (-2.655) assures that $H_i = 0.0022\ SC_i$ at field capacity.

Crack Flow

The crack-flow routine is used in the model to allow percolation of infiltrated precipitation, even though the soil water content may be less than field capacity. Given a dry soil with cracks, infiltration can move through the cracks of a layer without becoming part of the soil water in the layer, while the portion that becomes part of a layer's stored water cannot percolate by the storage-routing model until the storage exceeds field capacity.

Crack-flow percolation uses the equation:

$$PL2_i = d_c\, PL_{i-1}\left(1 - \frac{SW_{i+1}}{UL_{i+1}}\right)^2 \qquad (19)$$

where d_c is a soil parameter that expresses degree of cracking. Crack flow occurs only on days when water enters the layer (PL_{i-1}) and is greatest when the next lower layer is dry.

Since the daily time increment is relatively long for routing the flow through soils, it is desirable to route the water in volume increments. The increments to be routed are variable and are a function of the difference between the UL_i minus FC_i and the total amount to be routed. By dividing the layer inflow into several "slugs," each slug may be routed through the layer, thus allowing SW_i to be updated during the calculation.

Return Flow

Return flow is calculated as coming from the bottom soil layer, n. The return-flow function used for SWRRB is also used in SPUR (note the similarity to equation 15). Thus:

$$QR = (SW_n - FC_n)(1 - e^{\frac{1}{T_R}}) \qquad (20)$$

where:

QR= return flow (in),
T_R= return-flow travel time (days), and
n = last soil layer.

Return-flow time, T_R, is the time required for subsurface flow from the centroid of the basin to the basin outlet. The value of T_R is input for each subarea by the SPUR user instead of being calculated from soil hydraulic properties. Experienced hydrologists familiar with the base-flow characteristics of watersheds within a region should have little problem in assigning reasonable values to T_R.

Evapotranspiration

The evapotranspiration (ET) component in SPUR is the same as that used in CREAMS and SWRRB and is based on work by Ritchie (1972). Potential evaporation is computed with the equation:

$$E_o = \frac{0.0504\, H_o \Delta}{\gamma + \Delta} \qquad (21)$$

where:

E_o = potential evaporation (in),
Δ = slope of the saturation-vapor-pressure curve at the mean air temperature,
H_o = net solar radiation (ly), and
γ = a psychrometric constant,

and Δ is computed with the equation:

$$\Delta = \frac{5304}{T_k^2} e^{(21.255 - \frac{5304}{T_k})} \qquad (22)$$

where:

T_k = daily temperature (degrees Kelvin).

The variable H_o is calculated with the equation:

$$H_o = \frac{(1 - \lambda) R}{58.3} \qquad (23)$$

where:

R = daily solar radiation (ly) and
λ = albedo.

Soil Evaporation

The model computes soil evaporation and plant transpiration separately. Potential soil evaporation is computed with the equation:

$$E_{so} = \min \begin{cases} E_o e^{-0.4\,LAI} \\ E_o GR \end{cases} \qquad (24)$$

where:

E_{so} = potential evaporation at the soil surface (in),
LAI = leaf area index defined as the area of plant leaves relative to the soil surface (in/in), and
GR = mulch (residue) cover factor. (We suggest using a value of 0.5 for most range plant communities, and 1.0 for bare soil.)

Actual soil evaporation (E_s) is computed in two stages based on the soil moisture status in the upper soil profile. In stage 1, soil evaporation is limited only by the energy available at the surface and, thus, is equal to the potential (eq. 24). When the accumulated soil evaporation exceeds the first-stage upper limit, the stage-2 evaporation begins (the reader is referred to Ritchie (1972) for additional explanation of the procedure). The first-stage upper limit is estimated from:

$$U = 1.38\,(\alpha - 0.118)^{0.42} \tag{25}$$

where:

U = stage-1 upper limit (in) and
α = soil evaporation parameter dependent on soil-water transmission characteristics (ranges from 0.13 to 0.22 in/day$^{1/2}$).

Ritchie (1972) suggests using α = 0.14 for clay soils, 0.18 for loamy soils, and 0.13 for sandy soils. Similar values were obtained for data from Jackson et al. (1976). A wider distribution of values for most soil textural classes is given by Lane and Stone (1983).

Stage-2 soil evaporation is predicted by:

$$E_s = \alpha\left[t^{\frac{1}{2}} - (t-1)^{\frac{1}{2}}\right] \tag{26}$$

where:

E_s = soil evaporation for day t (in) and
t = days since stage-2 evaporation began.

Plant Transpiration

Potential transpiration (E_{po}) from plants is computed with the equations:

$$E_{po} = \frac{E_o\,LAI}{3} \qquad 0 \le LAI \le 3 \tag{27}$$

$$E_{po} = E_o - E_s \qquad LAI > 3 \tag{28}$$

(If $E_{po} + E_s > E_o$, E_s is reduced so $E_{po} + E_s = E_o$.) Because the LAI is generally considerably less than three in rangeland plant communities that SPUR is intended to consider, equation 27 will be used most of the time. If soil water is limited, plant transpiration is reduced with the equation:

$$E_p = \frac{E_{po}\,SW}{0.25\,FC} \qquad SW \le 0.25\,FC \tag{29}$$

where:

E_p = plant transpiration reduced by limited soil moisture (in) and
SW = current soil water in the root zone (in).

(If SW > 0.25 (FC), $E_p = E_{po}$, and if $E_p + E_s$ exceeds available water, E_s is reduced so $E_p + E_s$ = available water.)

Evapotranspiration (ET), then, is the sum of plant transpiration (eq. 27, 28 or 29) plus soil evaporation (eq. 25 or 26), and cannot exceed available soil water.

Distribution of ET in the Soil Profile

Soil-water evaporation is removed uniformly from the soil profile down to a maximum depth (ESD). The variable ESD is set in the SPUR code. If the soil profile does not contain sufficient water to meet soil-water evaporation demand, the actual amount of evaporation is reduced accordingly.

Transpiration is initially distributed through the soil layers by the following equation:

$$v = v_o\, e^{-v_1 D} \tag{30}$$

where:

v = water-use rate by crop at depth D (in/day),
v_o = water-use rate at the surface (in/day),
v_1 = 3.065, and
D = soil depth/depth to bottom of last soil layer with roots.

The total water use within any depth can be computed by integrating equation 30. The value of v_o is determined for the root depth each day, and the water use in each soil layer is computed with the equations:

$$v_o = \frac{v_1\,ET}{1 - e^{-v_1}} \tag{31}$$

$$UW_i = \frac{v_o}{v_1}\left(e^{-v_1 D_{i-1}} - e^{-v_1 D_i}\right) \tag{32}$$

where:

UW_i = water use in layer i (in), and

D_{i-1} and D_i = the fractional depths at the top and bottom of layer i.

When calculating actual uptake, transmission demand for a layer that cannot be satisfied by the available water in that layer is added to the demand of the next layer. This process is continued until the transpiration demand is satisfied or the bottom of the root zone is reached.

(The UW_i vector contains the initial estimates of ET which are to be subtracted from the various soil layers. If a layer has insufficient water, the excess ET is taken out of the first layer containing available water and having roots present.)

Water Balance for Ponds

Water for grazing animals in rangeland watersheds is often supplied by small earth dams, which create small ponds. These ponds can hold a considerable part of the runoff from the contributing watershed, depending upon how full the pond is when runoff begins. In addition, the retention of water in such ponds can result in a significant delay or reduction in the downstream runoff and a distortion of the time/flow-rate relationship. The SPUR model uses a component of SWRRB that was designed to account for the effects of farm/ranch ponds on water yield. The water balance equation is:

$$VM = VM_o + QI - QO - EV - SP \qquad (33)$$

where:

VM = volume of water stored in pond at end of day (acre-ft),
VM_o = volume of water in pond at beginning of day (acre-ft),
QI = inflow to the pond during the day (acre-ft),
QO = outflow from the pond during the day (acre-ft),
EV = evaporation from pond (acre-ft), and
SP = seepage from pond (acre-ft).

(The amount of water consumed by grazing animals is assumed to be negligible compared with seepage and evaporation losses.)

Inflow, QI, is considered to be surface runoff from the watershed area draining into the pond plus precipitation on the pond's water surface. Outflow from the pond occurs from either an emergency spillway or a principal spillway and occurs when the permanent pool storage is exceeded. Evaporation from the pond is computed with the equation:

$$EV = \frac{1}{12} \alpha E_o SA \qquad (34)$$

where:

α = evaporation coefficient (≈0.6), and
SA = surface area of the pond (acres).

Seepage from the pond is computed with the equation:

$$SP = 2\ SC\ SA \qquad (35)$$

where:

SC = saturated-soil conductivity of the pond bottom (in/h).

No effort was made to make SC vary with water depth and other factors, like soil stratification or sediment distribution, in the pond. These modifications were felt to be unwarranted because of the need for additional detailed user-supplied information to implement them.

Since pond surface area is required for computing evaporation (eq. 34) and seepage (eq. 35), a relationship between pond volume and surface area is necessary. Data from many stock ponds and small reservoirs in Texas and Oklahoma (USDA 1957) indicate that surface area can be calculated with the equation:

$$SA = SA_{max} \left[\frac{VM}{VM_{max}} \right]^{\delta} \qquad (36)$$

where:

δ = a parameter determined to be 0.9,
VM_{max} = maximum pond volume (acre-ft), and
SA_{max} = maximum pond surface area (acre).

Other research by Hanson et al. (1975) indicated that, in Montana and South Dakota, the exponent should be about 0.7.

Sediment Yield

Estimating soil loss from the upland areas of rangelands is difficult (Renard 1980) because most of the technology currently used was developed for cultivated cropland areas. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) and the modification to this equation (MUSLE) (Williams and Berndt 1977) are used in the basin-scale version of SPUR. The equation used is:

$$Y = \eta (Q\ Q_p)^{0.56}\ K\ C\ P\ LS \qquad (37)$$

where:

Y = sediment yield from upland area (tons/acre),
η = coefficient = 95,
Q = upland runoff volume (in),
Q_p = peak-flow rate (ft^3/s),
K = soil erodibility factor,
C = cover/management factor,
P = erosion control practice factor, and
LS = slope length and steepness factor.

Determining the LS factor in this equation is critical to calculating sediment yield. The model elements must be carefully selected to describe prototype configuration. As the model is used to describe larger and larger elements, some detail is lost. Thus, the way the LS term is evaluated may change with the size of the area to be simulated. The average land slope of any subarea or subwatershed can be estimated by field measurements or by measurements from a topographic map with the Grid-Contour Method (Williams and Berndt 1976) using the equations:

$$S_d = N_d \frac{H}{D_d} \tag{38}$$

$$S = [S_l^2 + S_w^2]^{\frac{1}{2}} \tag{39}$$

where:

- S_d = slope in one grid direction,
- S = average land slope of a subarea or subwatershed,
- N_d = total number of contour crossings from all grid lines in direction d,
- H = contour interval,
- D_d = total length of all grid lines within the subarea in direction d,
- S_l = slope in the length grid direction obtained from equation 38 and,
- S_w = slope in the width direction obtained from equation 38.

The average slope length can be estimated for each subarea or subwatershed by field measurements, or with the Contour-Extreme Point Method (Williams and Berndt 1976) by:

$$L = \frac{LC}{2EP} \tag{40}$$

where:

- EP = number of extreme points (channel crossings) on the contours of a topographic map,
- LC = total length of all contours within the subarea or subwatershed, and,
- L = average slope length (ft).

The LS factor is computed with the equation:

$$LS = \left[\frac{L}{72.6}\right]^M [65.41 \sin^2(\theta) + 4.56 \sin(\theta) + 0.065] \tag{41}$$

where:

- θ = angle of slope (Note: S is often substituted for sin θ) and,
- M = exponent proportional to steepness.

The exponent, M, varies with slope and is computed with the equation:

$$M = 0.6\,(1 - e^{-35.835\,S}) \tag{42}$$

The value of the C factor for each crop is determined from the tables in Agriculture Handbook 537 (Wischmeier and Smith 1978). In many rangeland areas, erosion pavement (rocks larger than a half in) on the surface is very effective in absorbing the kinetic energy of rainfall. We recommend including an estimate of the percentage of the soil surface covered by the erosion pavement and including it with the plant basal area to arrive at a C factor (for example, by using table 10 in Agriculture Handbook 537). Values of K and P can also be obtained for each subwatershed using Agriculture Handbook 537 or using the conservation report of SCS for each State.

Sediment Routing in Ponds

The SPUR model assumes that the sediment coming into the pond with the inflow is retained there. Thus, the outflow from the pond is assumed to be clear, and any water leaving the pond thus picks up sediment again from the channel boundaries below the pond.

APPLICATION OF THE SPUR UPLAND-HYDROLOGY MODEL

The hydrology part of the SPUR model is designed to operate with the climatic portion of the SPUR model providing the input and with the channel-routing portions for both the runoff and sediment transport. Thus, the user of the technology must be familiar with considerations in these parts of the program as well.

The conceptual configuration of a surface topography for input to the model is given in figure 3.1. In this conceptualization, there were four channel reaches (C1 . . . C4), eight lateral inputs (L1, L2 . . . L8), two upland regions (U1 and U2), and one pond (P1). The constraints shown at the bottom of the figure illustrate requirements for the computer model. These constraints allow simulation of almost any topographic or land use variation patterns into a fairly rigorous reproduction of the prototype.

Illustrations of the model application to a small watershed on Walnut Gulch follow. Walnut Gulch is an ephemeral tributary of the San Pedro River in southeastern Arizona. The watershed is an intermountain alluvial basin typical of mixed grass-brush areas encountered in Major Land Resource Area 41, the Southwestern Arizona Basin and Range. Figure 3.2 illustrates the features of stock pond watershed 23 (known locally as the Lucky Hills Watershed) on Walnut Gulch. The watershed was conceptualized for the model as one 9.1-acre upland area discharging to a 4,000-ft long channel (C1 and C2) having lateral contributing areas L1 (49.2 acres) and L2 (49.7 acres), or a total drainage of 108 acres into the pond (P1).

Tables 3.1, 3.2, and 3.3 contain the input data used in the upland hydrology part of the SPUR model for the 108-acre watershed used in the test application for the hydrology component only. The 100-day return-flow travel time was used to ensure that there was no baseflow. Similarly, the use of zero for the crack-flow factor means that the model in the test application did not consider this type of flow situation (table 3.1).

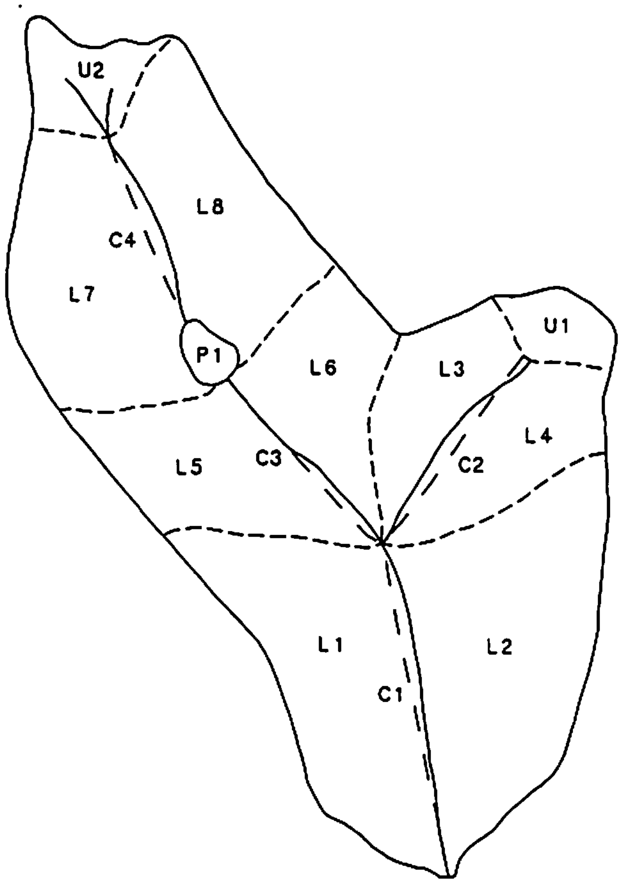


Figure 3.1
Concept of a watershed into upland areas (U1-U2), lateral areas (L1-L8), stream channel reaches (C1-C4), and ponds (P1). Model constraints are (1) each channel must have an input, either an upland region or up to two channels; (2) each channel must have one or more lateral inputs; and (3) each channel may output through a pond.

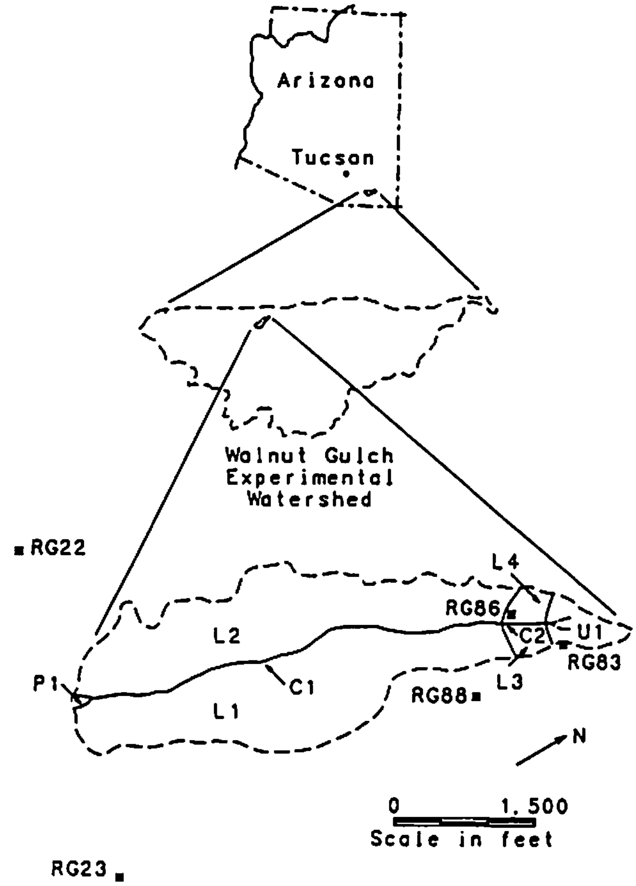


Figure 3.2
Lucky Hills Watershed used in the model evaluation showing two lateral areas (L1-L2), one upland area (U1), and a single channel reach (C1) draining into one pond (P1).

The soils data in Table 3.2 are for a Rillito-Laveen gravelly loam soil. Gelderman (1970) described this association as occurring on moderately sloping ridges formed by the deep dissection of old alluvial fans and valley plains.

These soils generally consist of deep, well-drained, medium and moderately coarse-textured gravelly soils. Because the same soil occurred in each of the three field elements simulated in the model, only one data set is included in table 3.2. The seventh layer of the model was assumed to have zero saturated hydraulic conductivity to simulate the caliche layer which persists through the area. This layer is synonymous with the limit of the most active root layers. In our experience, using greater soil depth results in the creation of an artificially large soil moisture reservoir, and, in turn, a low curve number which, therefore, simulates lower runoff than the prototype records indicate.

A sample of the output from the hydrology part of the SPUR model is given in table 3.4 for 1973. The 10.33 inches of precipitation is very near the average annual for the period of record but below the normal for the long-term record at the Tombstone, AZ gage, about 3 miles from the watershed. Monthly values of infiltration, evaporation, and plant transpiration are very representative of those for normal conditions in this environment. The table summarizes what the model predicts will happen from the fields (upland and lateral areas), from the soil profile, in the channels, and, finally, the net yield of sediment from the fields, as well as the fine material (silt and clay) and coarse material (bed load) from the channels. The output from the channel routing is documented in chapter 5.

A 17-year simulation with the SPUR hydrology component was compared with actual data from the Lucky Hills watershed for 1965-81. Figures 3.3 and 3.4 illustrate the agreement between the predicted and observed runoff for the upland area and that of the entire area. The relatively poor agreement between the observed and predicted data, as evidenced by the regression statistics in figure 3.3, results largely from the 1975 data, where the 2.10-in simulation seriously underestimates the 2.96 in of observed runoff. Without this one year, the slope of the regression line is much closer to unity.

In figure 3.5, the cumulative observed and predicted annual runoff are compared for two curve numbers. Again, the problem of the 1975 data shows with the large departure from the one-to-one line. With the curve number equal to 87, the cumulative runoff at the end of the 17 years overpredicted the observed results. The sensitivity of the curve number model is illustrated with this figure.

Figure 3.6 illustrates the annual variability of precipitation, evapotranspiration, and transmission losses from the upland area and the entire 108-acre Lucky Hills watershed. As expected, the ET follows the precipitation fairly closely, with some noticeable exceptions like that in 1966. In 1966, the computed ET actually exceeds the precipitation because of some soil moisture carry-over from the fall of 1965. In addition, the underestimation of the runoff meant there was additional soil moisture for evaporation and transpiration in 1966. Transmission losses are notably larger on the larger and more variable watershed, as expected.

To test agreement of simulated and actual sediment yield with the MUSLE relationship in SPUR, data from the upland area (9.1 acres) (figs. 3.2 and 3.7) for 1965 through 1981 was used. The correlation coefficient of 0.90, and an intercept near zero with a slope of 1.1, indicates a close relationship between field-measured and simulated values.

CONCLUSIONS

A model has been developed which facilitates describing the spatial variability of soils, vegetation, and topography. By allowing such spatial physiographic variability, differences in hydrologic process magnitudes can be accommodated, including those which are restricted to the upland areas as contrasted with those that happen in stream channels. The fundamental precepts behind the development are felt to be in sufficient detail to facilitate describing the heterogeneity encountered in most rangeland conditions.

Table 3.1.
Parameter values input for the upland areas of the Lucky Hills Watershed

Parameter	Unit	Field		
		1	2	3
Field type		Upland	Lateral	Lateral
Soil layers	Number	8	8	8
Field area	Acres	9.1	49.2	49.7
Curve number		86	86	86
Return-flow time	Days	100	100	100
MUSLE parameters				
K		.10	.10	.10
C		.10	.13	.13
P		1.00	1.00	1.00
LS		1.30	1.30	1.30
Soil evaporation	In/day$^{1/2}$	.122	.122	.122
Crack-flow factor		0	0	0

Table 3.2
Soil data for the upland areas of the Luck Hills Watershed

Soil data	Soil-layer parameters							
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
Soil porosity (in/in)	0.430	0.430	0.430	0.430	0.460	0.470	0.470	0.450
Water at 1/3 bar (in/in)	.200	.200	.200	.200	.200	.200	.200	.200
Water at 15 bar (in/in)	.037	.043	.049	.049	.059	.065	.065	.055
Saturated-soil conductivity (in/h)	.500	.500	.500	.500	.500	.500	.000	.300
Soil depth, accumulative (in)	3.000	6.500	10.000	15.000	20.000	22.500	25.000	27.000
Field capacity (in)	.535	.607	.590	.843	.799	.386	.386	.327
Maximum storage (in)	1.225	1.412	1.395	1.993	2.099	1.061	1.061	0.827

Note: Soil data for Rillito-Laveen gravelly loam soil.

Table 3.3
Climate generator input parameters and generated mean monthly max-min temperatures (°F) and solar radiation (ly) by month, Walnut Gulch, AZ

Maximum temperature	
TXMD	= 80.000
ATX	= 17.500
CVTX	= 0.085
ACVTX	= -0.040
TXMW	= 70.000
Minimum temperature	
TN	= 48.900
ATW	= 17.000
CVTN	= 0.110
ACVTN	= -0.050
Solar radiation	
RMD	= 525.000
AR	= 207.000
RMW	= 380.000

Temperature and solar radiation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum temperature (°F)	32.14	33.46	39.55	47.96	56.68	63.17	65.35	63.17	56.83	49.84	41.18	34.51
Maximum temperature (°F)	61.91	62.59	69.12	78.47	87.71	93.77	92.97	91.61	85.99	80.60	71.48	64.07
Solar radiation (ly)	330.26	399.08	484.64	610.20	686.98	721.90	647.37	597.32	510.20	435.89	342.82	298.82

Table 3.4
Sample output from the simulation with the SPUR hydrology model on the 9.1-acre Lucky Hills watershed using measured daily precipitation, by month, 1973

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
							FIELDS						
RAINFALL	0.360	1.150	2.490	0.000	0.370	0.790	3.670	0.890	0.400	0.000	0.210	0.000	10.330
INFILTRATION	0.360	1.008	2.367	0.000	0.370	0.788	2.958	0.877	0.400	0.000	0.210	0.000	9.337
RUNOFF	0.000*	0.142	0.123	0.000	0.000	0.002	0.712	0.013	0.000	0.000	0.000	0.000	0.993
							SOIL						
RETURN FLOW	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SOIL EVAP	0.137	0.557	1.538	0.383	0.256	0.535	1.451	0.894	0.303	0.000	0.131	0.055	6.241
PLANT EVAP	0.006	0.156	0.503	0.393	0.161	0.267	1.004	0.488	0.097	0.000	0.020	0.004	3.098
DEEP PERC	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
STORAGE	0.312	0.607	0.933	0.157	0.109	0.096	0.598	0.093	0.093	0.093	0.152	0.093	
							CHANNEL						
LOSSES	0.000	0.010	0.020	0.000	0.000	0.002	0.043	0.006	0.000	0.000	0.000	0.000	0.081
RUNOFF	0.000*	0.133	0.103	0.000	0.000	0.000	0.669	0.008	0.000	0.000	0.000	0.000	0.913
PEAK	0.0	3.8	1.5	0.0	0.0	0.0	15.2	0.2	0.0	0.0	0.0	0.0	15.2
BASIN WE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
LIVE VEG	133.67	151.01	226.96	299.67	327.76	392.06	661.23	596.53	343.88	177.31	137.41	110.48	
DEAD VEG	750.44	573.10	380.99	527.78	577.57	627.48	525.72	820.69	997.54	981.41	821.61	705.62	
							SEDIMENT						
FIELD SED	0.00	0.38	0.29	0.00	0.00	0.00	2.14	0.03	0.00	0.00	0.00	0.00	2.84
SILT-CLAY	0.00	0.74	0.40	0.00	0.00	0.00	4.28	0.02	0.00	0.00	0.00	0.00	5.98
BEDLOAD	0.00	1.24	0.71	0.00	0.00	0.00	7.15	0.02	0.00	0.00	0.00	0.00	9.12

* When there is no runoff for the month in question, the computer program produces the indicated values.

NOTE: Water = inches; WE = snow water equivalent in inches; peak flow = ft^3/s; veg = lb/ac; and sediment = tons. An acre-ft of water is 0.111 inches over the watershed.

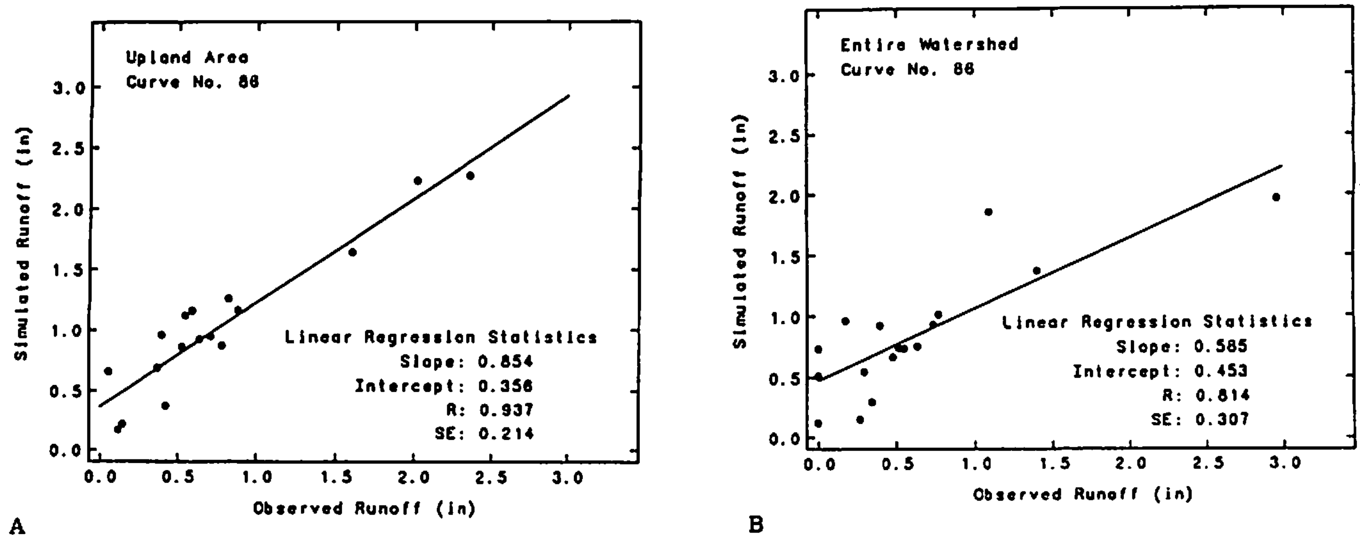


Figure 3.3
Simulated versus observed annual runoff from the 9.1-acre area and the entire 108-acre Lucky Hills watershed, 1965-1981.

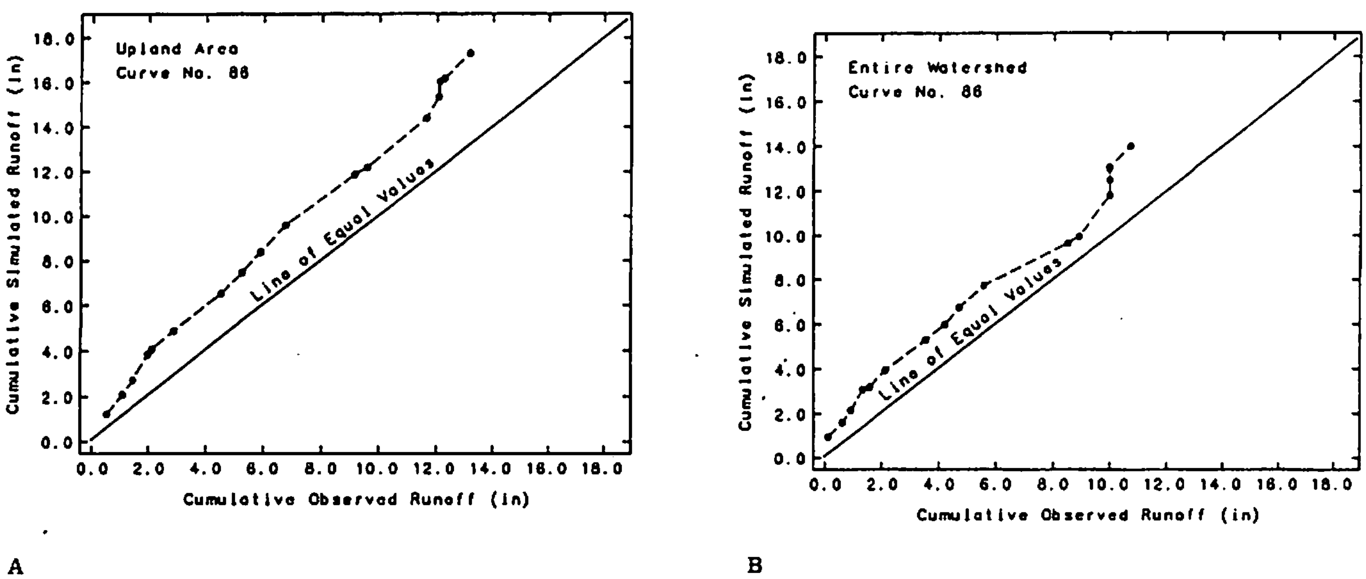
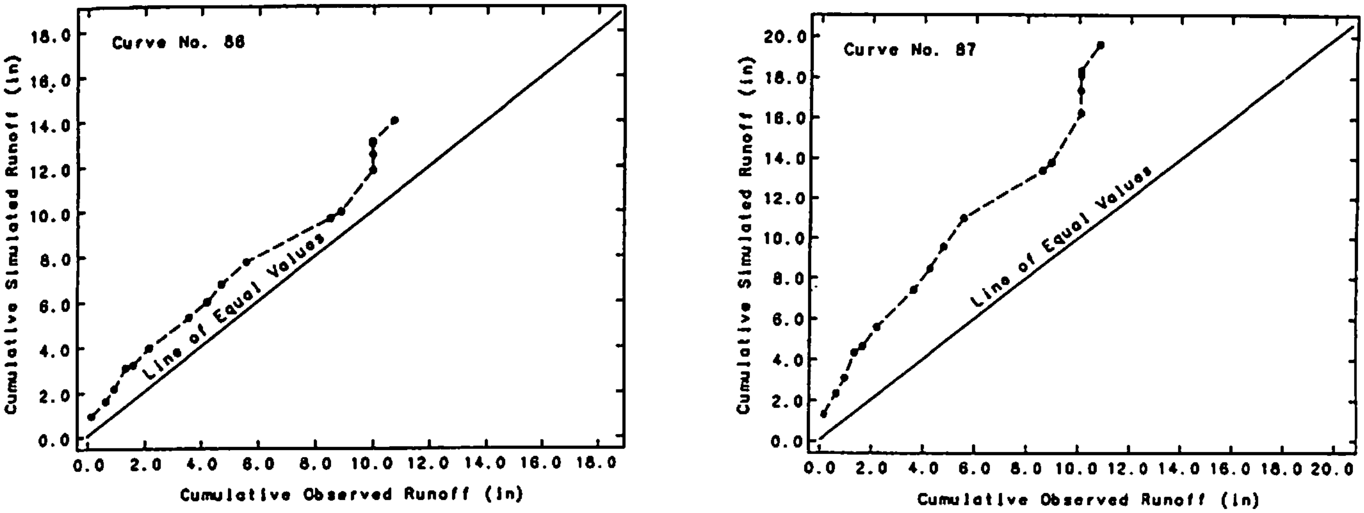
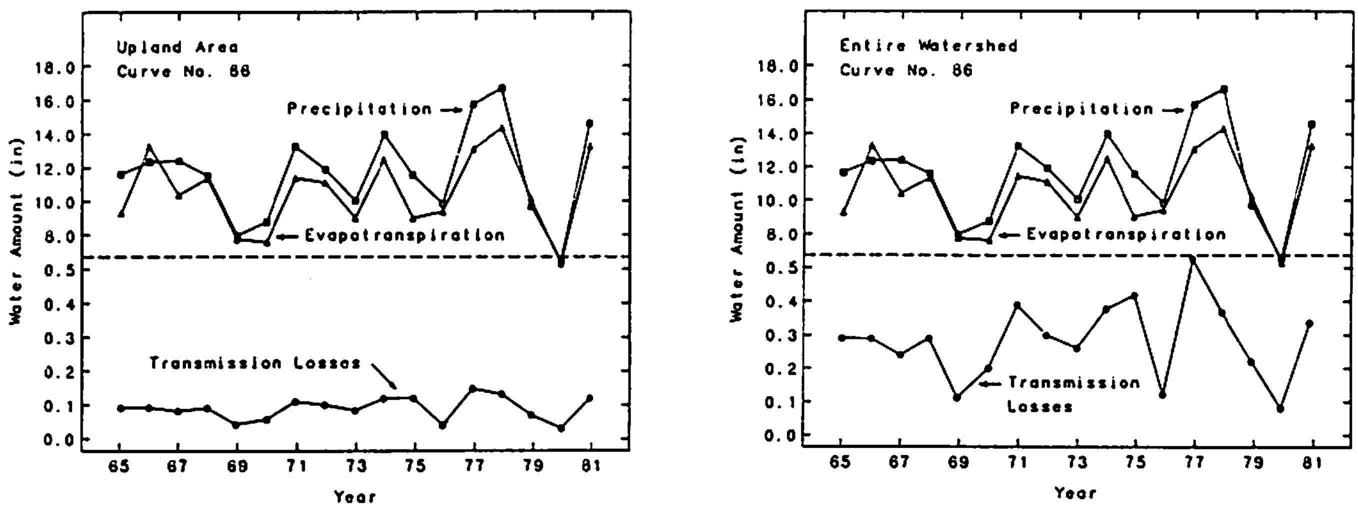


Figure 3.4
Cumulative annual predicted versus actual runoff from the 9.1-acre upland area and the entire 108-acre Lucky Hills watershed, 1965-1981.



A B

Figure 3.5
Cumulative annual predicted versus actual runoff for the 108-acre Lucky Hills watershed for two curve numbers, 1965-1981.



A B

Figure 3.6
Precipitation, evapotranspiration, and transmission losses for the 9.1-acre upland area and the entire watershed, 1965-1981.

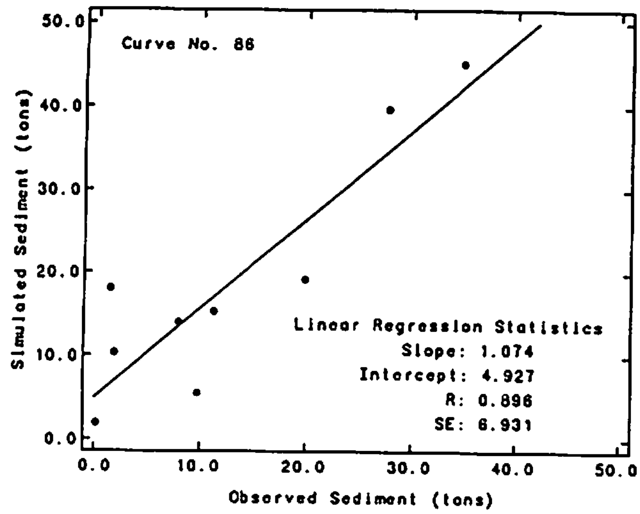


Figure 3.7
Simulated versus observed annual sediment yield using the MUSLE for the 9.1-acre upland area of the Lucky Hills watershed, 1965-1981.

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