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DISTRIBUTED MODEL FOR SMALL SEMIARID WATERSHEDS

By Leonard J. Lane,[1] A. M. ASCE

ABSTRACT: A distributed model for estimation of runoff volumes and peak rates of flow from small semiarid watersheds is shown to produce reasonable estimates for mean runoff and flood frequency distributions. The model is simplified and constructed to require a minimum of observed data for calibration. The model simulates runoff volume and peak discharge rates for individual storm events. It can also be used to estimate water yield and a surface water balance incorporating transmission losses in ephemeral stream channels. Experimental data are compared with the simulation model predictions. Individual components of the model could be improved with further research and data. However, based on available information contained in soils and topographic maps and published sources, the distributed model can be used to estimate runoff rates and amounts from ungaged watersheds in semiarid regions.

INTRODUCTION

The needs for water resources are becoming more critical each year in the southwestern United States and in other areas as increasing urban and expanding industry and agriculture demands put more pressure on existing water supplies. Flood prevention and control and sedimentation problems add to the need for development of practical approaches to the problems of water yield, flood frequency analysis, sediment yield, and channel stability.

Solutions to each of these problems require the development of practical methods to predict runoff rates and amounts from semiarid watersheds. Runoff from upland areas is often in response to intense, short-duration thunderstorms of limited areal extent (9,24,26). Various procedures have been developed to predict runoff from upland areas on semiarid watersheds. These procedures range from development of regression equations (23) to application of the Soil Conservation Service Runoff Equation (27) on semiarid watersheds (8,28), to infiltration models (31), and to distributed infiltration-runoff routing models (18,30).

Many semiarid watersheds have alluvial channels that abstract large quantities of streamflow (3,4,5,26). These abstractions, or transmission losses, are important because water is lost as the flood wave travels downstream. Thus, runoff

[1]Hydro., United States Dept. of Agriculture, Southwest Watershed Research Center, 442 East Seventh St., Tucson, Ariz. 85705.

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volumes are reduced. Although these abstractions are called transmission losses, they are an important part of the water balance, because they support riparian vegetation and recharge local aquifers and regional ground water (26). Procedures are needed to estimate runoff and transmission losses in ephemeral streams. Several procedures have been developed to estimate transmission losses. These procedures range from inflow-loss rate equations (4,5,27), to simple regression equations (16), to simplified differential equations for loss rate (12,15), to storage-routing as a cascade of leaky reservoirs (14,25,33), and to kinematic wave models incorporating infiltration (29).

Therefore, there is a range of complexity in procedures for estimating runoff from upland areas and from ephemeral streams with transmission losses. As a rule, the simplified procedures require less information about physical features of the watersheds but are less general in their application. The more complex procedures may be more physically based, but they require correspondingly more data and more complex computations.

The distributed simulation model presented herein represents an attempt to develop a procedure for practical applications. The model represents a compromise between the more physically based deterministic models and the more simplified procedures. The resulting model is constructed to require a minimum of observed data for calibration, while providing a means of making predictions on ungaged watersheds.

Scope and Limitations.—The model described herein is intended for application on small semiarid watersheds up to a few tens-of-square kilometers in size where channels are ephemeral and transmission losses occur. Runoff on such watersheds generally follows periods of thunderstorm rainfall. At other times the stream channels are normally dry. Runoff is accompanied by substantial infiltration losses in the stream channels. These losses, and the usually steep slope of the channels, tend to produce sharply peaked runoff hydrographs. The resulting hydrograph consists of a fairly narrow triangular peak followed by a relatively longer recession of low flow. The time to peak (time from beginning of runoff to the hydrograph peak) is usually shorter than the recession time. This characteristic shape of the runoff hydrographs suggests that they can be fairly well approximated if the runoff volume, peak rate, and duration of flow are known. Based on these observations, the model described herein simulates a runoff volume and flow duration, and then a peak rate of flow as a function of runoff volume and flow duration.

Development and Analysis

Runoff from Upland Areas.—The Soil Conservation Service (SCS) method is used to estimate runoff volume. A National Engineering Handbook (27) is available to aid in selecting parameters, and improved estimates of runoff curve numbers are available for semiarid watersheds (28). The advantages of this procedure include: (1) It is a one-parameter model; (2) handbook values of runoff curve numbers (CN's) are available for many soils and management practices; and (3) collectively, hydrologists and engineers have a great deal of experience in estimating curve numbers in the absence of observed rainfall and runoff data.

Runoff volume, V, is estimated using the SCS procedure as

$$V = \begin{cases} 0 & P \le 0.2S \\ \dfrac{(P - 0.2S)^2}{(P + 0.8S)} & P > 0.2S \end{cases} \qquad (1)$$

in which: V = runoff volume in in. (mm); P = rainfall depth in in. (mm); and S = retention in in. (mm). The linkage between CN and the S parameter, in in., is

$$\mathrm{CN} = \frac{1{,}000}{10 + S} \qquad (2)$$

Notice that the values of CN may range between 0.0 (no runoff) and 100 (all rainfall becomes runoff). Estimates of curve numbers for semiarid watersheds are given in the SCS Handbook (27), by Simanton, Renard, and Sutter (28), and by Hanson, Neff, and Nicks (10).

Routing flow through the channel network, it is necessary to know peak discharge as well as runoff volume from the upland and lateral flow areas. Peak discharge is assumed to be a function of runoff volume and time characteristics of the runoff hydrograph. Peak discharge of a unit hydrograph from small areas can be estimated from runoff volume and time to peak (27) as

$$Q = \frac{484\, V A}{T_p} \qquad (3)$$

in which, in English units, the variables are: Q = peak rate in cfs; V = runoff volume in in.; A = drainage area in square miles; and T_p = time to peak in hours. The conversion factor 484 converts units of square mile-in./hr to cfs. If time to peak, T_p, is assumed to be a constant proportion of flow duration, D, and discharge is expressed in in./hr, then Eq. 3 becomes

$$Q = \frac{484\, \alpha\, V}{640 D} \qquad (4)$$

in which Q = peak discharge in in./hr; D = flow duration in hr; $T_p = D/\alpha$; and α = the ratio of flow duration to time to peak. The conversion factor 640 is the number of acres per square mile. For a constant, α, Eq. 4 is of the form

$$Q = \frac{C_5 V}{D} \qquad (5)$$

in which C_5 can be interpreted as a parameter expressing hydrograph shape.

The use of a double triangle unit hydrograph as a model for unit hydrographs of small watersheds has been proposed by Ardis (1,2), with results for a number of watersheds published in a report by TVA (32). These procedures were applied to a small semiarid watershed by Diskin and Lane (7). Based on the analysis of ten hydrographs from a 4 acre (1.6 ha) watershed, they found for a 1 min hydrograph

$$u = \frac{6.6\, V}{\bar{D}} \qquad (6)$$

in which u = the peak of the unit hydrograph; V = runoff volume in in.; and $\bar{D}$ = the duration of the mean unit hydrograph in hr. By convoluting the unit hydrograph with observed rainfall excess patterns, the relation between runoff volume, mean duration of flow, and peak rate of runoff was

$$Q = \frac{4.82\,V}{\bar{D}} \qquad (7)$$

which suggested a value of 4.82 for the hydrograph shape parameter.

Using data from 15 semiarid watersheds in Arizona with 10–35 years of record, Murphey, Wallace, and Lane (22) found that mean flow duration was related to drainage area as

$$\bar{D} = C_1 A^{C_2} = 2.53\,A^{0.2} \qquad (8)$$

in which $\bar{D}$ = mean duration of flow in hr; A = drainage area in square mile; and C_1, C_2 = parameters. The coefficient of determination for Eq. 8 was 0.78 with a standard error of estimate of 21%. They also found that mean runoff volume per runoff event was related to drainage area as

$$\bar{V} = C_3 A^{C_4} = 0.05\,A^{-0.2} \qquad (9)$$

in which $\bar{V}$ = mean runoff volume in in.; A = drainage area in square mile; and C_3, C_4 = parameters. The coefficient of determination for Eq. 9 was 0.61 with a standard error of estimate of 28%.

A similar equation for mean peak discharge was found to be

$$\bar{Q} = 0.10\,A^{-0.38} \qquad (10)$$

in which $\bar{Q}$ = mean peak discharge in in./hr; and A = drainage area in square mile. Combining Eqs. 8, 9, and 10 from Murphey, Wallace, and Lane (22), the equation corresponding to Eq. 5 is approximately

$$\bar{Q} = \frac{5.06\,\bar{V}}{\bar{D}} \qquad (11)$$

or C_5 = 5.06. This is quite close to the value of 4.82 found by Diskin and Lane (7) in an independent analysis.

The procedure used to compute runoff volume and peak rate from the upland and lateral flow areas is as follows. Given a CN, Eq. 2 is used to compute S. The value of S is then used in Eq. 1 to compute runoff volume for a given rainfall depth. This volume of runoff and the mean flow duration from Eq. 8 are used in Eq. 5 to compute peak discharge. The runoff volume and peak discharge are then taken as upland or lateral input into a channel segment for the routing calculations. As will be shown in the next section, estimates of mean runoff volume and mean flow duration are also used to compute transmission loss parameters for a channel segment.

The Channel Component.—In the absence of lateral inflow, if observed inflow-outflow data for a channel reach are related by regression analysis (14), then the resulting equation is

$$V(x,w) = \begin{cases} 0; & V_{up} \le V_o(x,w) \\ a(x,w) + b(x,w)V_{up}; & V_{up} > V_o(x,w) \end{cases} \qquad (12)$$

in which: $a(x,w)$ = regression intercept (acre-ft or m^3); $b(x,w)$ = regression slope; $V_o(x,w)$ = threshold volume (acre-ft or m^3); $V(x,w)$ = outflow volume (acre-ft or m^3); V_{up} = inflow volume (acre-ft or m^3); x = length of channel reach (mile or km); and w = average width of flow (ft or m). By setting $V(x,w)$ = 0.0 and solving for V_{up}, the threshold volume is

$$V_o(x,w) = \frac{-a(x,w)}{b(x,w)} \qquad (13)$$

This is the volume of inflow required before outflow begins. Inflow volumes less than $V_o(x,w)$ will all be lost or infiltrated into the channel alluvium.

Based on the preceding empirical observations and the work of Jordan (12), using an ordinary differential equation, Lane (15) approximated the rate of change in runoff volume with distance as

$$\frac{dV}{dx} = -wc - wk\,V(x,w) \qquad (14)$$

in which c and k = parameters as described in the following and the other variables are as described previously. The solution to Eq. 14 is

$$V(x,w) = \frac{-c}{k}[1 - e^{-kxw}] + V_{up}e^{-kxw} \qquad (15)$$

in which $V_{up} = V(x = 0, w)$ = the upstream inflow volume. By letting $x = w = 1$, Lane (15) defined $a(1,1) = a$, $b(1,1) = b$, and $c = -k\,a/(1 - b)$, so that Eq. 15 becomes

$$V(x,w) = \frac{a}{1-b}[1 - e^{-kxw}] + V_{up}e^{-kxw} \qquad (16)$$

Notice that, if the following equivalence is made

$$b(x,w) = e^{-kxw} \qquad (17)$$

and $$a(x,w) = \frac{a}{1-b}[1 - e^{-kxw}] = \frac{a}{1-b}[1 - b(x,w)] \qquad (18)$$

Then Eq. 16 is identical to the regression model described by Eq. 12. Therefore, given observed inflow data for a channel reach, least squares analysis can be used to estimate parameters in the differential equation (Eq. 14) or its solution (Eq. 16).

If lateral flow areas contribute flow along the channel reach, and if this flow can be considered approximately uniform with distance along the channel reach, then Eq. 14 becomes

$$\frac{dV}{dx} = -wc - wk\,V(x,w) + \frac{V_{LAT}}{x} \qquad (19)$$

in which V_{LAT} = the volume of lateral inflow. The solution to Eq. 19 is

$$V(x,w) = a(x,w) + b(x,w)\,V_{up} + \frac{V_{LAT}}{kwx}[1 - b(x,w)] \qquad (20)$$

in which $a(x,w)$ and $b(x,w)$ are defined by Eqs. 17 and 18. If the quantity $[1 - b(x,w)]/kw$ is denoted $F(x,w)$, then Eq. 20 becomes

$$V(x,w) = a(x,w) + b(x,w)\,V_{up} + F(x,w)\frac{V_{LAT}}{x} \quad \text{(21)}$$

in which $a(x,w)$, $b(x,w)$, and $F(x,w)$ are parameters to be determined for a particular channel reach.

Peak discharge of the outflow hydrograph from a stream reach is computed as a function of the time average loss rate in the channel reach and the peak discharge of the inflow hydrograph. The average loss rate is inflow volume minus outflow volume divided by the mean duration of flow, $\bar{D}$. The inflow volume minus outflow volume in the absence of lateral inflow is

$$V_{up} - V(x,w) = -a(x,w) + [1 - b(x,w)]V_{up} \quad \text{(22)}$$

so that the outflow peak discharge is

$$Q(x,w) = \frac{12.1}{\bar{D}}[a(x,w) - (1 - b(x,w))V_{up}] + b(x,w)Q_{up} \quad \text{(23)}$$

in which $Q(x,w)$ = peak discharge of the outflow hydrograph (cfs or m^3/sec); Q_{up} = peak discharge of the inflow hydrograph (cfs or m^3/sec); and $\bar{D}$ = mean duration of flow in the channel reach (hr). The conversion factor 12.1 converts acre-ft/hr to cfs. For uniform lateral inflow along the channel reach, the peak discharge equation becomes

$$Q(x,w) = \frac{12.1}{\bar{D}}[a(x,w) - (1 - b(x,w))V_{up}]$$

$$+ b(x,w)\,Q_{up} + F(x,w)\frac{Q_{PLAT}}{x} \quad \text{(24)}$$

in which $F(x,w)$ is defined in Eq. 20; and Q_{PLAT} = the peak discharge of the lateral inflow hydrograph in cfs. As an alternative, runoff volume from Eq. 21 could be used in Eq. 5 to estimate peak discharge.

Significance of Transmission Losses.—As an example of the significance of transmission losses in reducing outflow volumes and peak rates, hydrographs were analyzed for a 4.1 mile (6.6 km) channel reach on the Walnut Gulch Experimental Watershed. This channel reach has a mean width of 38 ft (11.6 m), with the channel alluvium consisting of sands and gravel with a median particle size of 1.5 mm.

On July 30, 1966 a storm occurred which produced runoff only on the drainage area above the upper gaging station. The resulting runoff traveled the dry channel reach producing the hydrographs shown in Fig. 1. Transmission losses reduced the runoff volume by 31%, and the corresponding peak discharge was reduced by 30%. The transmission loss equations (Eqs. 12 and 23) predicted a reduction in volume of 30% and a reduction in peak rate of 27%, respectively. The dashed line in Fig. 1 represents a double-triangle approximation to the outflow hydrograph matching the predicted volume and peak rate. Notice that the hydrographs are plotted on a common time scale and that the double triangle underestimates

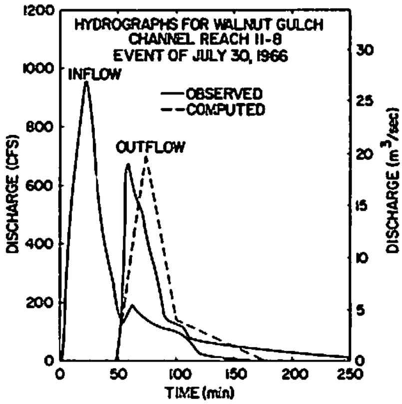

FIG. 1.—Inflow-Outflow Hydrographs for Walnut Gulch Showing the Influence of Transmission Losses

the observed duration of outflow. However, the double triangle produced a reasonable approximation of the outflow hydrograph closely matching the observed volume and peak rate of outflow.

Calibration of the Transmission Loss Equations.—Observed data representing 139 hydrographs in 14 channel reaches were analyzed to evaluate the transmission loss equations or channel component (15). The procedure was to select events with little or no lateral inflow in a number of reaches and to estimate $a(x, w)$ and $b(x, w)$ in Eq. 12, using linear regression on observed inflow-outflow data. Given the derived regression parameters, the differential equation parameters (a, b, k) in Eqs. 16–18 could then be derived and related to physical features of the channel systems. Data from 14 channel reaches in Arizona, Kansas-Nebraska, and Texas were analyzed (Table 1). The Walnut Gulch data are from USDA-ARS observations; the Queen Creek data are from Babcock and Cushing (3); the Kansas-Nebraska data are from Jordan (12); and the Texas data are from the Texas Board of Water Engineers (6). The first column in Table 1 shows the location, and the second column cites references for description of the channel reaches and data. The third column shows the numbers of channel reaches at each location, while the fourth column shows the number of events analyzed, and the fifth column shows the range in estimates of the decay factor, k. The last column shows the range of the coefficients of determination from the regression analysis. Additional details on the analysis are presented by Lane elsewhere (15). In general, higher values of the decay factor, k, represent higher loss rates in the channels.

Data representative of the peak discharge predictions from Eq. 23 are shown in Fig. 2. The data from Trinity River, Texas, represent a stream with insignificant or very small loss rates. The Queen Creek data represent large flows and high flow rates. The data from Walnut Gulch represent a wider range of flow conditions including very small events. Analysis has shown that for very small inflows, where the volume of losses is on the same order of magnitude as the volume of inflow, the peak discharge equation (Eq. 23) overestimates the peak

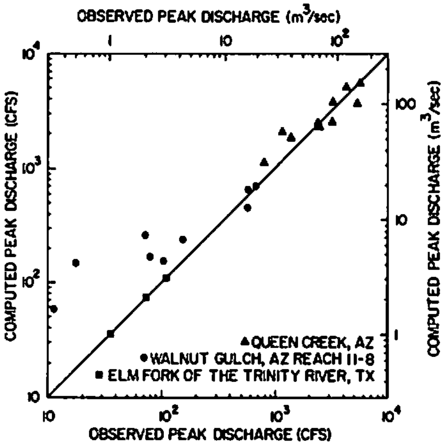

FIG. 2.—Observed vs. Computed Peak Discharge of the Outflow Hydrograph

rate of outflow. Subsequent analysis has shown that, for the small events, the mean duration of flow used in Eq. 23 overestimates the actual flow duration. This results in the underestimation of the average loss rate. Thus, overestimation of the peak discharge of the outflow occurs. Correcting the average loss rate estimates would reduce the prediction errors. However, the estimates are conservative in that they overpredict the smallest events but perform well on the larger events.

Parameter Estimation on Ungaged Channels.—Relationships were found (15), between the unit channel intercept parameter, a, the decay factor, k, and characteristics of the inflow and an effective hydraulic conductivity, K. The effective hydraulic conductivity, K, was defined as the channel infiltration rate averaged over the total area wetted by the flow and over the total duration of flow. Since the effective hydraulic conductivity represents a space-time average, it incorporates the influence of temperature, sediment concentration, flow irregularities, errors in the data, and variations in wetted area. For these reasons, it is not the same as the saturated hydraulic conductivity for clear water under steady-state conditions.

Analyzing the data listed in Table 1, the relation between the unit channel intercept, a, and the average volume of losses, $K\bar{D}$, was

$$a = -0.00465\,K\bar{D} \qquad (25)$$

with $R^2 = 0.87$. The equation for the decay factor, k, in terms of the average volume of losses divided by the average volume of inflow was

$$k = -1.09 \ln\left[1 - 0.00545\,\frac{K\bar{D}}{\bar{V}}\right] \qquad (26)$$

with $R^2 = 0.83$. Given the value of k, the unit channel regression slope is

$$b = e^{-k} \qquad (27)$$

TABLE 1.—Summary of Transmission Loss Data Analyzed by Lane (15)

Location (1)	Reference (2)	Number of channel reaches (3)	Number of events (4)	Range in decay factor, k^a in feet-mile^{-1} (5)	Range of R^2 values (6)
Walnut Gulch Arizona	Renard (26)	6	98	0.000674–0.001521	0.84–0.98
Queen Creek Arizona	Babcock and Cushing (3)	1	10	0.0000783	0.98
Kansas-Nebraska	Jordan (12)	4	22	0.000144–0.000800	0.81–0.99
Texas	Texas Board of Water Engineers (6)	3	9	0.000013[b]	—[b]

[a]Conversion: 1 ft-mile = 0.4904 m-km.
[b]Data limited to three events per reach.

With values of a, k, and b determined from Eqs. 25–27, the transmission loss parameters for a channel of length, x, and width, w, are:

$$b(x,w) = e^{-kxw} \quad \text{(28)}$$

$$a(x,w) = \frac{a}{1-b}[1 - b(x,w)] \quad \text{(29)}$$

and $$F(x,w) = \frac{1 - b(x,w)}{kw} \quad \text{(30)}$$

These parameters $a(x,w)$, $b(x,w)$, and $F(x,w)$ are then used in Eqs. 21 and 24 to predict outflow volume and peak discharge for a channel reach.

Even though parameters from Eqs. 28–30 are used to compute outflow for any upstream runoff event, with or without lateral inflow, only mean values of $\bar{D}$, K, and $\bar{V}$ are used in Eqs. 25–27. This is because K represents an average infiltration rate over the wetted channel area for the average flow duration, $\bar{D}$, and the average volume of flow, $\bar{V}$.

If inflow-outflow data are available, then $\bar{D}$ and $\bar{V}$ can be computed as the mean values of the observed flow durations and volumes for the channel reach. The effective hydraulic conductivity can be computed as the average loss rate from the mean difference between inflow and outflow volume divided by the mean duration of flow.

In the absence of observed data, Eq. 8 can be used to compute $\bar{D}$, and Eq. 9 can be used to compute $\bar{V}$ where A is the drainage area above the point of outflow on a channel reach. Values of K tend to increase with median particle size and decrease with increasing silt-clay content of the bed material. Values of K for various bed material classifications are shown in Table 2.

Basin-Scale Simulation Model

Program Logic.—The program logic or computational structure of the model follows the channel network from upland areas to the watershed outlet. Each primary channel can receive input from any combination of an upland and two lateral flow areas. Secondary channels receive input from two or, perhaps, one upstream channels and one or two lateral flow areas. Each upland and lateral flow area can receive a different rainfall input and can have different infiltration parameters. Thus, the model is distributed in that a watershed is represented by discrete upland lateral flow areas.

Each channel segment is described by its contributing area above the point of interest, the length of the segment, the average width of channel segment, the effective hydraulic conductivity of the channel bed material, its upstream contributing area, and its lateral contributing areas. Outflow from a channel segment

TABLE 2.—Effective Hydraulic Conductivity for Transmission Losses in Channel Alluvium[a]

Bed material group (1)	Bed material characteristics (2)	Effective Hydraulic Conductivity[b] in: Inches per hour (3)	Centimeter per hour (4)
1 Very high loss rate	Very clean gravel and large sand. $d_{50} > 2$ mm	>5.0	>12.7
2 High loss rate	Clean sand and gravel under field conditions. $d_{50} > 2$ mm	2.0–5.0	5.1–12.7
3 Moderately high loss rate	Sand and gravel mixture with less than a few percent silt-clay. Walnut Gulch data represent this group.	1.0–3.0	2.5–7.6
4 Moderate loss rate	Mixture of sand and gravel with significant amounts of silt-clay. Queen Creek data represent this group.	0.25–1.0	0.64–2.5
5 Very low loss rate	Consolidated bed material with high silt-clay content. Elm Fork of the Trinity River, Texas data represent this group.	0.001–0.1	0.0025–0.25

[a]Based on analysis of data from 14 channel reaches summarized in Table 1, data from 14 other channel reaches in Arizona, and canal seepage rates in unlined canals (15).

[b]Values of effective hydraulic conductivity reflect the flashy, sediment-laden character of many ephemeral streams, and thus do not represent clear water infiltration rates at steady-state.

becomes input to a downstream segment until the watershed outlet is reached. Transmission losses for each channel segment are accumulated to produce a total transmission loss for the basin. A surface water balance is computed by accounting for rainfall, infiltration on the upland lateral flow areas, transmission losses, and runoff for the entire basin.

The procedures just described were applied to the watershed shown in Fig. 3. This figure shows a 3.18-square mile (8.24-sq km) semiarid watershed on

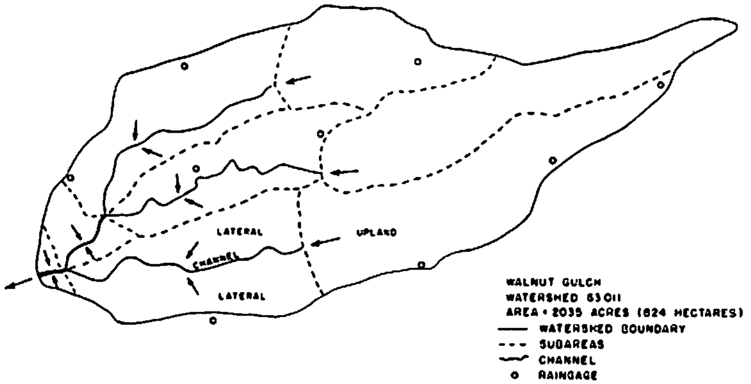

FIG. 3.—Demonstration of Contributing Areas and Channel Segments Used to Represent Watershed 63.011

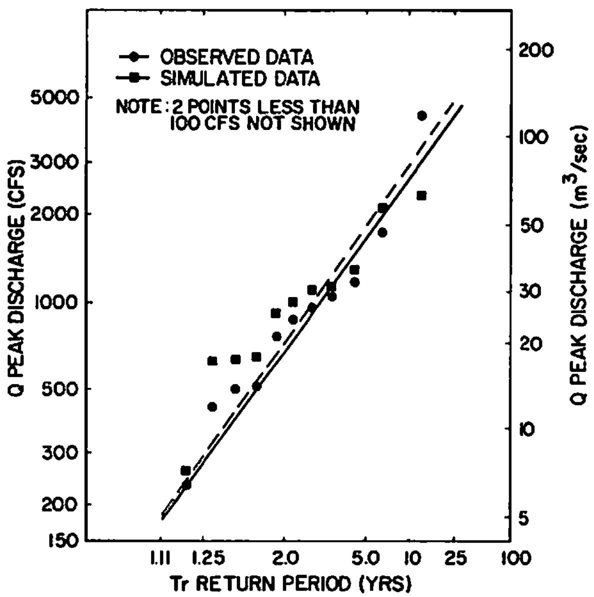

FIG. 4.—Observed and Simulated Flood Frequency Using Observed Rainfall Data. Watershed 63.011 on Walnut Gulch

Walnut Gulch and how it is represented for modeling purposes. This map shows the location of nine recording raingages, five channel segments, the three upland areas contributing to three primary channels, and the 10 lateral areas contributing to the primary and secondary channels. The arrows in Fig. 3 indicate contributing areas for each channel segment. Runoff curve numbers for the 13 upland and lateral flow areas were estimated following procedures outlined by Simanton, Renard, and Sutter (28) and varied from 82–87 with an area weighted average value of 85. The effective hydraulic conductivity was selected from Table 2 as 2.0 in./hr, or 5.1 cm/hr. Mean duration and volume of flow were computed using Eqs. 8 and 9, respectively. Observed rainfall data were used for the maximum annual floods from 1963–1975, and runoff data were simulated. A plot of observed and simulated flood frequency is shown in Fig. 4. The observed and simulated values agree quite well for return periods up to 25 years (Fig. 4). Although the simulated and observed flood frequencies agree closely, the coefficient of determination between observed and predicted volumes was $R^2 = 0.75$, and between observed and predicted peaks was $R^2 = 0.78$. This suggests that the model predicted the distribution of flood peaks better than it predicted for individual events. There was a tendency to overpredict for the smaller events and to underpredict for the largest event (Fig. 4). However, this was not a completely independent test, because data from Walnut Gulch were used to develop the curve number estimation procedure (28), to develop the mean duration and volume estimates (22), and to develop the transmission loss model (15).

As a second test of the procedure, the model was applied to eight small watersheds (1.6–4.0 ha) on the Santa Rita Experimental Range, near Tucson, Arizona (19,20). Parameters of the model were estimated at just described, and rainfall data from 222 runoff-producing summer storms on the eight experimental watersheds were used to simulate runoff volumes and peak discharges. Values of observed and predicted run-off volumes and peak rates were compared. For the individual events on the eight watersheds, the coefficient of determination ranged from 0.45–0.80 with a mean of 0.60 for runoff volumes. The coefficients of determination for peak discharge ranged from 0.30–0.64 with a mean value of 0.47. Therefore, on the average, the model explained 60% of the variation in runoff volumes and 47% of the variation in peak rates for individual events. Mean runoff volume and peak rate were computed for each of the eight watersheds. The relation between mean observed runoff volume, $\bar{V}$, and predicted mean runoff volume, $\bar{V}_e$, was

$$\bar{V}_e = -0.006 + 1.02\,\bar{V} \quad (31)$$

with $R^2 = 0.96$. The corresponding relation between mean observed peak rate, $\bar{Q}$, and predicted mean peak rate, $\bar{Q}_e$, was

$$\bar{Q}_e = 0.007 + 0.86\,\bar{Q} \quad (32)$$

with $R^2 = 0.82$. The model reproduced trends in mean values of runoff volume and peak rate, explaining 96% and 82% of the variation in the means, respectively.

Therefore, the model can be used to predict runoff volumes and peak discharge rates. From the analysis of 222 runoff events, the model explained about 50%–60% of the variance in runoff for individual events. When the model was used to predict mean values of runoff volume and peak rate for the eight watersheds, it explained about 80%–96% of the variance in the means. Based on the analyses summarized previously, the distributed model described herein can be used to predict water yield (mean volumes and peaks), and to simulate flood frequency distributions for small semiarid watersheds using handbook and other published values for the parameters and observed rainfall data.

Detailed site-specific sensitivity analysis of model input parameters and variables have been conducted [see Knisel (13) for a detailed sensitivity analysis for runoff curve numbers as used in Eq. 1]. However, model sensitivity is a function of specific parameter values which, in turn, are functions of site-specific conditions. Relative sensitivity of the model is summarized in Table 3. The degree of model sensitivity to errors in input data or parameter values is denoted as moderate or significant, depending upon whether relative errors in input are damped (moderate sensitivity) or magnified (significant sensitivity) when the distributed model is used to compute peak discharge of the mean annual flood from small semiarid watersheds, as described earlier (Fig. 3 and 4).

Example of Practical Applications

The distributed simulation model described herein is being used as the hydrologic basis of a rangeland resource model. Since the model estimates vari-

TABLE 3.—Relative Sensitivity of Computed Peak Discharge for the Mean Annual Flood Using the Distributed Model

Input parameter or variable (1)	Source of estimate (2)	Model sensitivity degree[a] (3)	References (4)
Watershed geometry	Topographic map	—[b]	Lane and Woolhiser (17)
Channel geometry	Topographic map, field measurements	moderate	Lane (15)
Effective hydraulic conductivity	Table 2 and field measurements	moderate	Lane (15)
Runoff curve number	Handbook values based on soils, land use, etc.	significant	NEH-4 (27), Simanton, Renard, and Sutter (28)
Hydrograph shape parameters	Hydrograph analysis, synthetic hydrographs	moderate	Murphey et al. (22), Zeller (34)
Rainfall depth	Rainfall frequency data	significant	Miller et al. (21)

[a]Qualitative estimates based on site specific-conditions. Moderate denotes an input value such that errors are usually damped by the model; percent error in computed peak discharge is less than, or equal to, the percent error in the input value. Significant sensitivity denotes the case where percent error in computed peak discharge is usually as large as, or larger than, the percent error in the input value.

[b]Moderate to significant, depending upon the degree of correspondence between model and prototype watershed; see cited reference and Fig. 3.

ations of peak discharge in the downstream direction, calculation of depth, hydraulic radius, and velocity, at a given cross section, is possible. These hydraulic variables, in turn, can be used to estimate sediment transport. Based on the concept of minimum stream power and an assumed sediment transport formula, the model has been used to derive hydraulic geometry for ephemeral streams. However, an obvious application is in estimating flood frequency distributions for ungaged watersheds.

Simulation of Flood Frequency Distributions.—Based on soils and vegetation data and a topographic map, runoff curve numbers, mean duration of flow, mean runoff volume, and effective hydraulic conductivity were estimated for a small, semiarid watershed near Safford, Arizona. Watershed 45.001 is a 519 acre (210 ha) watershed with sparse vegetation consisting of shrubs and some short grasses. Approximately 85% of the area is bare, and the watershed is classification as sparsely vegetated rangeland. A more complete description is given in a USDA Miscellaneous Publication (11).

Maximum one-hour rainfall depths for return periods of 2, 5, 10, 25, 50, and 100 years were estimated using a rainfall frequency atlas (21). These rainfall data were then used to simulate flood events for the given return periods. As a comparison, annual flood flows for the period 1939–1968 were tabulated and used to derive a flood frequency curve.

The observed and simulated flood frequency curves are shown in Fig. 5. The solid line represents the observed flood peaks, and the dashed line represents the predicted values from estimated rainfall frequency data. The predicted two-year flood is about 14% higher than the observed data suggest, while the predicted 50-year flood is about 7% higher. These approximations to the observed flood series are actually quite close, as differences of this magnitude could easily result from selecting a different distribution (e.g., extreme value rather than log-normal) for the observed data. That is, the predicted flood peaks, shown by the dashed line in Fig. 5, easily fall within the range of variability of the observed data for return periods greater than two years.

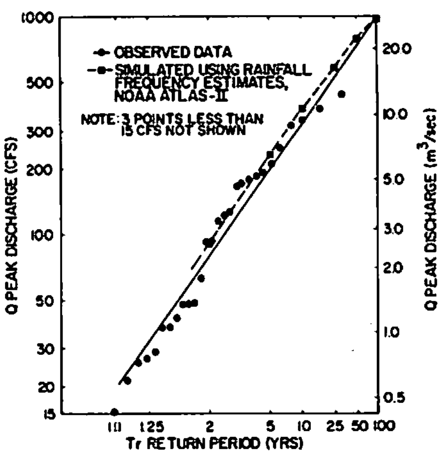

FIG. 5.—Observed and Simulated Flood Frequency for Watershed 45.001

Conclusions

The distributed model described herein represents an attempt to develop a procedure for practical applications. The model is constructed to require a minimum of observed data for calibration and to provide a means of making hydrologic predictions on ungaged watersheds. The parameters are selected using published sources of information, but runoff data, if available, can be used to improve the parameter estimates.

Rainfall data and infiltration parameters can vary over the watershed to the extent that a given drainage area is represented by upland and lateral flow areas. The model simulates runoff volume and peak discharge rates for individual storm events but can also be used to estimate water yield and a surface water balance incorporating transmission losses.

Components of the distributed model have been developed and tested using hydrologic data from Arizona, Kansas, Nebraska, and Texas. The entire model has been tested using data from ten experimental watersheds in Arizona representing over 260 individual rainfall-runoff events. The model reproduces trends in runoff rates and amounts and can be used to predict flood frequency distributions by using rainfall data from a rainfall frequency atlas.

Individual components of the model could be improved with further research and data. However, based on available information contained in soils and topographic maps and published sources, the distributed model can be used to estimate runoff rates and amounts from ungaged watersheds in semiarid regions as described herein.

Appendix I.—References

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Appendix II.—Notation

The following symbols are used in this paper:

A = watershed area;
a = unit channel parameter, intercept;
$a(x,w)$ = regression intercept for a channel of length x and width w;
b = unit channel parameter, slope;
$b(x,w)$ = regression slope for a channel of length x and width w;
C_1 = coefficient in the mean duration of flow equation;
C_2 = exponent in the mean duration of flow equation;
C_3 = coefficient in the mean runoff volume equation;
C_4 = exponent in the mean runoff volume equation;
C_5 = coefficient in the peak rate-volume equation;
CN = runoff curve number;
c = parameter in the differential equation for loss rate;
D = duration of flow;
$\bar{D}$ = mean duration of flow;
d_{50} = median particle diameter;
$F(x,w)$ = lateral inflow coefficient;
K = effective hydraulic conductivity;
k = decay factor in the differential equation for loss rate;
P = depth of rainfall;
Q = peak rate of flow;
$\bar{Q}$ = mean peak rate of flow;
$\bar{Q}_e$ = predicted mean peak rate of flow;
$\bar{Q}_{PLAT}$ = peak discharge of the lateral inflow hydrograph;

Q_{up} = peak discharge of the inflow hydrograph;
S = retention parameter;
T_p = time to peak of the hydrograph;
u = peak of the unit hydrograph;
V = volume of runoff from the upland or lateral areas;
$\bar{V}$ = mean volume of runoff;
$V(x,w)$ = volume of outflow from a channel reach;
$\bar{V}_e$ = predicted mean volume of runoff;
V_{LAT} = volume of lateral inflow;
$V_o(x,w)$ = threshold volume of runoff in a channel reach;
V_{up} = volume of inflow;
x = distance or length of a channel reach;
w = mean width of a channel reach; and
α = ratio of flow duration to time to peak.