



**US Army Corps
of Engineers**

Hydrologic Engineering Center

Runoff Prediction Uncertainty for Ungauged Agricultural Watersheds

December 1990

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to the Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE (DD-MM-YYYY) December 1990		2. REPORT TYPE Technical Paper		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Runoff Prediction Uncertainty for Ungauged Agricultural Watersheds				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) David M. Goldman, Miguel A. Marino, Arlen D. Feldman				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center (HEC) 609 Second Street Davis, CA 95616-4687				8. PERFORMING ORGANIZATION REPORT NUMBER TP-143	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/ MONITOR'S ACRONYM(S)	
				11. SPONSOR/ MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES This paper is part of the Journal of Irrigation and Drainage Engineering, Col. 116, No. 6, November/December 1990.					
14. ABSTRACT A physically based stochastic watershed model is used to estimate runoff prediction uncertainty for small agricultural watersheds in Hastings, Nebraska. The stochastic nature of the model results from postulating a probabilistic model for parameter estimation and input errors. The key factors assumed to contribute to prediction uncertainty are errors in estimating infiltration parameters and moisture conditions prior to a rainfall event. The error distributions for parameter estimates are inferred from soil survey information, and the error distribution for moisture conditions from a regression between antecedent precipitation indices and measured soil moisture. Comparison of model predicted and observed errors demonstrate that the model is conservative in that it is biased towards over-prediction of errors.					
15. SUBJECT TERMS runoff, rainfall, modeling, uncertainty, error, watershed, gagues, soil moisture					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 26	19a. NAME OF RESPONSIBLE PERSON
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER

Runoff Prediction Uncertainty for Ungauged Agricultural Watersheds

December 1990

US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

TP-143

Papers in this series have resulted from technical activities of the Hydrologic Engineering Center. Versions of some of these have been published in technical journals or in conference proceedings. The purpose of this series is to make the information available for use in the Center's training program and for distribution with the Corps of Engineers.

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

RUNOFF PREDICTION UNCERTAINTY FOR UNGAUGED AGRICULTURAL WATERSHEDS

By David M. Goldman,¹ Miguel A. Mariño,² and Arlen D. Feldman,³
Members, ASCE

ABSTRACT: A physically based stochastic watershed model is used to estimate runoff prediction uncertainty for small agricultural watersheds in Hastings, Nebraska. The stochastic nature of the model results from postulating a probabilistic model for parameter estimation and input errors. The key factors assumed to contribute to prediction uncertainty are errors in estimating infiltration parameters and moisture conditions prior to a rainfall event. The error distributions for parameter estimates are inferred from soil survey information, and the error distribution for moisture conditions from a regression between antecedent precipitation indices and measured soil moisture. Comparison of model predicted and observed errors demonstrates that the model is conservative in that it is biased towards overprediction of errors.

INTRODUCTION

A common approach to deriving flood-flow-frequency curves for an ungauged watershed is to simulate a design storm with an event-oriented watershed model. As with most models, a significant problem with this approach is model parameter estimation. One approach to the problem is to estimate watershed model parameters from generally available information such as topographic maps and soil maps. Probably the most difficult part of the problem is estimating loss rates from this type of information.

Loss rate parameter estimation for an event-oriented model consists of determining both the soil moisture condition prior to the rainfall event and the soil infiltration parameters. The particular focus of this study will be on determining the uncertainty in estimating initial moisture conditions from antecedent precipitation indices and infiltration parameters from commonly available soil survey information, particle-size distribution, and porosity, as proposed by Rawls and Brakensiek (1982).

An examination of the runoff prediction uncertainty caused by estimating loss rate parameters from simple indices such as particle-size distribution will be investigated using a physically based stochastic (PBS) watershed model (Klemes 1978). The PBS model will be formulated as a typical event-oriented distributed watershed model, except that the loss rate parameters will be considered stochastic (Goldman 1987). The stochastic nature of the loss rate parameters will be represented by the loss rate parameters' probability distributions. The parameter probability distribution represents the estimation

¹Hydr. Engr., Hydrologic Engrg. Ctr., Corps of Engrs., 609 Second St., Davis, CA 95616.

²Prof., Land, Air, and Water Sci., Dept. of Civ. Engrg., Univ. of California, Davis, CA 95616.

³Chf. Res. Div., Hydrologic Engrg. Ctr., Corps of Engrs., 609 Second St., Davis, CA.

Note. Discussion open until May 1, 1991. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on April 19, 1989. This paper is part of the *Journal of Irrigation and Drainage Engineering*, Vol. 116, No. 6, November/December, 1990. ©ASCE, ISSN 0733-9437/90/0006-0752/\$1.00 + \$.15 per page. Paper No. 25346.

uncertainty when depending on typically available information such as the simple indices proposed.

The PBS model prediction uncertainty is represented by the derived probability distribution for runoff volume and peak discharge. The derived probability distribution gives the runoff exceedance probabilities for any particular runoff event. In other words, the derived probability distributions give the chance that an observed runoff volume or peak discharge will exceed a given amount for a given rainfall event and antecedent moisture condition. The usefulness of the model-estimated prediction uncertainty, and in turn the estimated uncertainty in parameter values, will be verified by comparing predicted and observed exceedance probabilities for rainfall-runoff events recorded for small agricultural watersheds in Hastings, Nebraska.

TEST WATERSHED DESCRIPTION

The U.S. Department of Agriculture (USDA) maintained watersheds in Hastings, Nebraska (*The Central* no date), where rainfall-runoff, soil-moisture, and land-use data were collected from the period 1939–1967 and maintained in the REPHLEX data base (*REPHLEX* 1983). The seven watersheds used in this research were all about 4.0 acres in size with overland flow slopes ranging from 2.0 to 7.0%. The watershed soils are dominated by the Hastings silt loam and silt clay loam horizons. Although data for a number of different management practices existed, only runoff events from land surfaces with straight row contouring were considered, because this situation corresponds best to the assumptions that will be made in developing the PBS model.

There was always a rain gage within 200 ft of the border of any of the watersheds tested. Unfortunately, however, the rain gages were not shielded. The soil moisture data were obtained by analyzing fist-sized soil samples taken from field trenches. The major advantage of using the Hastings data is that they had a relatively long record, which was important for verifying the predictions of the PBS model.

MODEL FORMULATION

A single-event approach to modeling runoff was chosen to avoid the problem of simulating interstorm runoff dynamics such as evapotranspiration and long-term base flow. Assuming that overland flow will dominate the runoff process, a typical kinematic wave model will be used to model a watershed (Fig. 1). The watershed has two overland flow planes both with width W , and overland flow lengths and slopes equal to, respectively, l_1 , l_2 , and S_{01} , S_{02} . Rainfall excess is assumed to be uniformly distributed over each overland flow plane. The physical properties and the initial conditions for the watershed represented by the overland flow planes are assumed to be uniform both horizontally and vertically. Rainfall excess is calculated by first subtracting an initial surface loss

$$r(t) = 0 \quad \text{for } P(t) \leq I_a \quad t \geq 0 \dots\dots\dots (1)$$

$$r(t) = r_0(t) \quad \text{for } P(t) > I_a \quad t \geq 0 \dots\dots\dots (2)$$

where $P(t)$ = the cumulative precipitation over the watershed; $r(t)$ = the

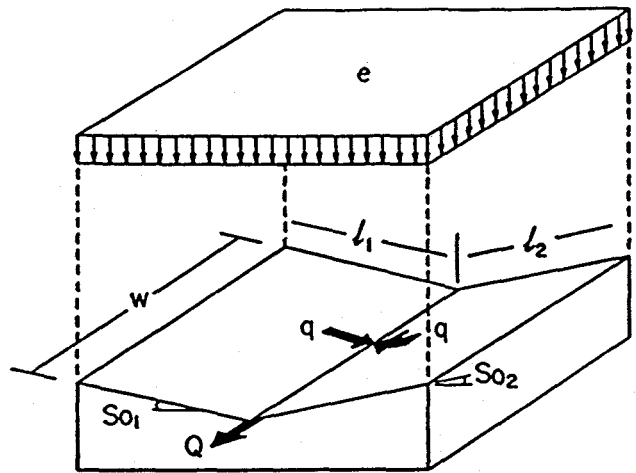


FIG. 1. Schematic of Watershed Model

rainfall intensity adjusted for surface losses; t = the time since the start of rainfall; $r_0(t)$ = the measured rainfall intensity; and I_a = the depth of surface loss assumed to be uniform over the watershed. Second, an infiltration loss is calculated by the Green and Ampt (GA) approach

$$F = \frac{\Omega}{\frac{i}{K_s} - 1} = \frac{K_s \Omega}{\frac{dF}{dt} - K_s} \quad i > K_s \dots \dots \dots (3)$$

where $dF/dt = i(t)$ is equal to the infiltration rate; F = the cumulative infiltration; K_s = the soil's saturated hydraulic conductivity; Ω = the product of the wetting front suction, ψ_f , and the soil volumetric deficit at the beginning of the storm, $\Delta\theta = \phi - \theta_i$; ϕ = the soil's porosity; and θ_i = the initial volumetric water content. The GA equation, as originally developed, is only strictly applicable to a uniform moisture condition at the soil surface or, in the case of rainfall infiltration, a ponded surface condition. Modifications were made as suggested by Mein and Larson (1973) and Morel-Seytoux (1980) to use the GA equation for unponded surface conditions and variable rainfall rates.

The rainfall excess is routed overland to the channel using the kinematic wave equations of motion

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} = e \quad \text{initial condition: } t = 0, y = 0$$

$$\text{boundary condition: } x = 0, y = 0 \dots \dots \dots (4)$$

$$q = \alpha y^m \dots \dots \dots (5)$$

where $q = q(x, t)$ is the flow per unit width; $\alpha = 1.49S_0^{1/2}/N$; S_0 = the slope along the overland flow length; N = a roughness coefficient for overland flow; $m = 1.67$; $y = y(x, t)$ is the depth of flow; and x = the distance along the direction of overland flow. The equations will be solved using a finite difference scheme proposed by Leclerc and Schaake (1973).

Flow entering the channel will be concentrated immediately to the watershed outlet to obtain the total outflow, Q . Channel routing of the flow

using the kinematic wave equations is a standard procedure. However, the channels of the test catchments used in this research are short and have little storage. Performing channel routing would add little in simulation capability, while adding greatly to the computational burdens in performing the uncertainty analysis. Consequently, a reasonable assumption was made that channel routing could be ignored.

PARAMETER ESTIMATION

Estimating Green and Ampt Parameters from Simple Indices

Rawls et al. (1981, 1982, 1983) and Rawls and Brakensiek (1982) reported on the relationship between simple soil indices and the Green and Ampt parameters. The general procedure involved has been to relate a simple soil index such as texture class to the Brooks and Corey parameters (Rawls et al. 1982), porosity ϕ , residual saturation, θ_r , bubbling pressure ψ_b , and the pore-size distribution, λ . These parameters are used to describe the soil matric suction curve by the relationship

$$S_e = \frac{\theta - \theta_r}{\phi - \theta_r} = \frac{\psi^\lambda}{\psi_b^\lambda} \dots \dots \dots (6)$$

where S_e = the effective saturation; and θ = the volumetric water content at matric suction ψ . The Brooks and Corey parameters are then used to calculate the wetting front suction, ψ_f , by

$$\psi_f = \psi_w + \frac{\psi_w^n}{1-n} [\psi_i^{(1-n)} - \psi_w^{(1-n)}] \dots \dots \dots (7)$$

where ψ_w = the water entry pressure; ψ_i = the water content corresponding to the initial soil moisture content of the soil prior to ponded infiltration; and ψ_w , the water entry pressure, and n are defined as

$$\psi_w = \frac{\psi_b}{2} \dots \dots \dots (8)$$

$$n = 3\lambda + 2 \dots \dots \dots (9)$$

Assuming that the initial moisture content is equal to the residual saturation, the formula finally derived by Brakensiek (1977) and applied by Rawls et al. (1982) is obtained as

$$\psi_f = \frac{n}{n-1} \psi_w \dots \dots \dots (10)$$

Since initial moisture conditions will be estimated using an API index, ψ_f will be calculated via Eq. 7 in model simulations of infiltration. The saturated hydraulic conductivity is calculated using Brutsaert's (1967) solution of the Childs and Collis-George permeability integral

$$K_s = \frac{a\theta_e^2\lambda^2}{\psi_b^2(\lambda+1)(\lambda+1)} \text{ (cm/s)} \dots \dots \dots (11)$$

where $\theta_e = \phi - \theta_r$. The parameter a was set equal to 21.0 by fitting Eq.

11 to an average of observed saturated hydraulic conductivity values for a full range of soil texture classes (Rawls et al. 1982). Rawls and Brakensiek (1989) developed the regression relationships shown here between simple soil indices; particle size distribution and total porosity, and the Brooks and Corey parameters.

The regression equations (Rawls and Brakensiek 1989) are

$$\begin{aligned} \theta_r = & -0.0182482 + 0.00087269(SA) + 0.00513488(CL) + 0.02939286(PR) \\ & - 0.00015395(CL^2) - 0.0010827(SA)(PR) - 0.00018233(CL^2)(PR^2) \\ & + 0.00030703(CL^2)(PR) - 0.0023584(PR^2)(CL) \dots \dots \dots (12) \end{aligned}$$

$$\begin{aligned} \lambda = \exp [& -0.7842831 + 0.0177544(SA) - 1.062498(PR) - 0.00005304(SA^2) \\ & - 0.00273493(CL^2) + 1.11134946(PR^2) - 0.03088295(SA)(PR) \\ & + 0.00026587(SA^2)(PR^2) - 0.0061052(CL^2)(PR^2) - 0.00000235(SA^2)(CL) \\ & + 0.00798746(CL^2)(PR) - 0.00674491(PR^2)(CL)] \dots \dots \dots (13) \end{aligned}$$

$$\begin{aligned} \psi_b = \exp [& 5.3396738 + 0.1845038(CL) - 2.48394546(PR) \\ & - 0.00213853(CL^2) - 0.04356349(SA)(PR) - 0.61745089(CL)(PR) \\ & + 0.00143598(SA^2)(PR^2) - 0.00855375(CL^2)(PR^2) - 0.00001282(SA^2)(CL) \\ & + 0.00895359(CL^2)(PR) - 0.00072472(SA^2)(PR) + 0.0000054(CL^2)(SA) \\ & + 0.50028060(PR^2)(CL)] \dots \dots \dots (14) \end{aligned}$$

where $PR = \phi =$ total porosity (vol/vol); $CL =$ % clay (particle size); $SA =$ % sand (particle size); $\psi_b =$ bubbling pressure (cm); $\lambda =$ pore-size distribution; and $\theta_r =$ residual saturation (vol/vol). The data for these regressions were obtained from the numerous soil surveys performed in the United States.

The data needed to apply these regressions can be conveniently obtained from the SOILS-5 data base compiled by the Soil Conservation Service and maintained by the Corps of Engineers (SOILS-5 1983). The relevant information provided by these data is the particle-size distribution, the percent sand, clay, and silt, and the porosity for different horizons of a soil series.

Selection of Soil Parameter Probability Distributions

In the case of the watershed model used in this research, the chosen parameters' probability distribution should describe the chance that the parameter will have a certain value for a given storm event. The random variation of a particular infiltration parameter between events might be affected by biologic (macropores), cultural (management practice), seasonal (crop growth), and meteorologic (rain-induced surface crusting) factors.

The distribution of soil properties within a given texture class or for a given particle-size distribution does not give information on the random variation of soil hydraulic properties in the field. Rather, the distribution of infiltration parameter values for a given soil property index is a measure of the uncertainty in predicting the infiltration properties of a field sample using that index. The correspondence between the probability distribution derived from a simple index and a field measurement program would be coincidental at best.

TABLE 1. Values for Watershed Model's Stochastic Parameters

Watershed (1)	Sand		Clay		Porosity	
	Mean (%) (2)	Range (%) (3)	Mean (%) (4)	Range (%) (5)	Mean (vol/vol) (6)	Coefficient of variation (7)
8	3.4	0.4-6.4	23.9	19.5-28.4	0.51	0.1
9	3.1	0.3-5.9	21.4	16.6-26.2	0.51	0.1
10	2.5	0.0-5.0	21.7	16.9-26.5	0.51	0.1
11	2.5	0.0-5.0	23.1	18.5-27.7	0.51	0.1
12	2.5	0.0-5.0	24.6	20.2-29.0	0.51	0.1
19	2.5	0.0-5.0	26.4	22.2-30.6	0.51	0.1
20	2.5	0.0-5.0	27.4	23.4-31.4	0.51	0.1

The probability distribution obtained from a simple index might be useful if the distribution of the parameter's values (e.g., the values of saturated hydraulic conductivity) bounds the range of the values for the actual field parameter. Furthermore, the parameter distribution obtained may be even more useful from an engineering perspective if it not only bounded the potential range of the field parameter, but also led to a conservative watershed model prediction of runoff. For example, the simple index probability distribution should overpredict the chance that the saturated hydraulic conductivity will be less than the true field value, which in turn will result in an overprediction of the chance that runoff will exceed a certain value. The overprediction resulting from the simple index may be considered to provide a safety factor that would be useful in design situations.

The probability distribution for the Green and Ampt infiltration parameters will be derived from assumed distributions for particle size distribution and total porosity via Eqs. 7, 11, 12, 13, and 14. The SOILS-5 data base provides the range in particle-size distribution and total porosity for the watershed soils (see Table 1). The particle-size distribution, as defined by the percentages of sand and clay, was assumed to be distributed uniformly over this range. The total porosity obtained from the SOILS-5 data base was assumed to have a normal distribution with a coefficient of variation equal to 0.1 in analogy to that found for variation within a texture class (McCuen et al. 1981).

Deriving the distributions of the Green and Ampt parameters K_s and ψ_f is an intermediate step in deriving the volume and peak discharge probability distributions. The probability distribution for K_s is independent of antecedent moisture and was derived using Monte Carlo simulation. The mean, standard deviation, skew, and kurtosis derived by Monte Carlo simulation are shown in Table 2.

The distribution of ψ_f is conditional on the antecedent moisture condition, and is not easily reported in general. However, the ψ_f corresponding to the mean infiltration parameters and initial moisture content equal to the residual saturation is shown in Table 3 for informational purposes. The derived mean values for K_s and ψ_f will not be equivalent to those calculated directly from average values of total porosity and particle distribution as can be seen, for example, by comparing the values of K_s shown in Tables 2 and 3.

No attempt will be made to assess the sensitivity of model predictions to

TABLE 2. Derived Values for Saturated Hydraulic Conductivity

Watershed (1)	Mean (in./hr) (2)	Standard deviation (in./hr) (3)	Coefficient of variation (4)	Skew (5)	Kurtosis (6)
8	0.055	0.044	0.80	1.6	6.6
9	0.061	0.045	0.74	1.6	6.5
10	0.058	0.044	0.76	1.6	6.2
11	0.055	0.042	0.76	1.6	6.4
12	0.051	0.041	0.80	1.7	6.6
19	0.047	0.039	0.83	1.7	7.0
20	0.045	0.038	0.84	1.8	7.2

Note: 1.0 in. = 2.54 cm, 1.0 in./hr = 2.54 cm/h.

the assumed probability distributions (i.e., normal or uniform) for particle-size distribution or total porosity. In verifying the model, the focus will be on comparing model predictions within one and two standard deviations about the mean prediction. Presumably, the standard deviation about the mean prediction will be most affected by the standard deviation assumed for model parameters. The tails of the assumed distributions, and consequently the shape, should be less important. Certainly, the best way to test sensitivity of model predictions to assumed parameter distributions is to try some different distributions. However, this was not possible given the computational burdens required to derive model predictions by Monte Carlo simulation.

Estimation of Initial Abstraction

The initial abstraction is defined as the water that is not free to flow overland to a stream. These losses are due to the interception of rain by crops and the depression storage due to the microrelief of the surface. Viessman et al. (1977) summarize studies that could be used to estimate interception loss. However, estimation of the depression storage from soil survey information is extremely difficult. Linden (1979) estimated depression storage for cultivated soils using a microrelief model. The key parameters in this model are random roughness and land surface slope (random roughness is essentially a measure of the variation of soil heights from the plane that would

TABLE 3. Deterministic Values for Watershed Green and Ampt and Brooks and Corey Parameters

Watershed (1)	Sand (%) (2)	Clay (%) (3)	Porosity ϕ (vol/vol) (4)	Residual saturation, θ_r (vol/vol) (5)	Effective saturation θ_e (vol/vol) (6)	Wetting front suction ψ_f (in.) (7)	Saturated hydraulic conductivity K_s (in./hr) (8)	Bubbling pressure ψ_b (in.) (9)	Pore size distribution λ (10)
8	3.4	23.9	0.51	0.080	0.430	18.62	0.0430	24.19	0.296
9	3.1	21.4	0.51	0.074	0.436	18.14	0.0487	23.67	0.306
10	2.5	21.7	0.51	0.075	0.435	18.41	0.0468	24.03	0.305
11	2.5	23.1	0.51	0.078	0.432	18.69	0.0435	24.35	0.299
12	2.5	24.6	0.51	0.082	0.428	19.02	0.0400	24.72	0.293
19	2.5	26.4	0.51	0.086	0.424	19.45	0.0364	25.19	0.286
20	2.5	27.4	0.51	0.088	0.422	19.69	0.0342	25.48	0.281

Note: 1.0 in. = 2.54 cm, 1.0 in./hr = 2.54 cm/h.

define zero cut and fill). Application of Linden's results are hampered because, as Allmaras et al. (1966) found, random roughness in an agricultural soil is a function of the plowing tool, initial water content prior to plowing, and soil preparation. Consequently, random roughness and, correspondingly, depression storage are very difficult to estimate from soil survey information.

Linden's results indicated that for the surface slopes of the test watersheds, 3–7%, the depression storage could vary between 0.08 and 0.40 in. (0.20 and 1.05 cm), corresponding to random roughness values between 0.3 and 1.6 in. (0.8 and 4.0 cm) (Linden 1979). Combining this depression storage with potential interception loss would lead to a surface loss that at the high end could account for the observed losses in 80% of the observed events.

Given that there are no simple indices for estimating random roughness from soil survey information and the large impact that assumptions about this parameter can have on predicted runoff, the assumption was made that the initial loss is zero. This assumption should lead to a model bias towards overprediction on the average. The actual bias can be observed by comparing mean predicted runoff with observed runoff values. Whether the bias is in a range reasonably attributed to surface loss can be judged in the context of future research. The advantage of this assumption is that the surface loss does not end up being a "fudge factor" that is varied to account for model bias.

Kinematic Wave Parameter Estimates

The estimates of overland flow lengths and slopes for overland flow planes were obtained from 2-ft contour interval topographic maps. The roughness values for overland flow were estimated as a best average value for all runoff events based on published values [summary given by Hjermfelt (1986)]. The values for these parameters are given in Table 4 for each test watershed.

Estimating Initial Moisture Content

An estimate of the average moisture conditions prior to a rainfall event is needed to implement the Green and Ampt method. The moisture condition was estimated by developing regression relationships between an antecedent precipitation index (API) and essentially point measurements of soil moisture. The regression relationships will then be used to predict the average moisture condition prior to a rainfall event given the API.

There are a number of difficulties with this approach. First, the use of soil moisture data to develop this relationship is a departure from the ungauged analysis procedure. However, soil moisture measurements are rarely available, and it was felt that investigating their usefulness was an important opportunity. Second, the assumption is made that the estimates of soil moisture obtained from grab samples (point measurements) are indicative of the general watershed moisture condition. Certainly, there will be spatial variation of soil moisture across a watershed. However, the point soil moisture is the best indicator of the average watershed moisture condition available, although it has drawbacks.

Third and finally, the assumption that an API can be used to assess average watershed conditions ignores the effect of evapotranspiration between storm events on available moisture. Again, API is not an ideal proxy for

TABLE 4. Kinematic Wave Parameters for Test Watersheds

Watershed (1)	Area ^a (acre) (2)	Overland flow length <i>l</i> (ft) (3)	Overland slope <i>S_o</i> (4)	Roughness coefficient <i>N</i> (5)	Initial abstraction <i>I_a</i> (in.) (6)
8	3.84	280	0.07	0.1	0
8	3.64	220	0.07	0.1	0
9	3.93	280	0.04	0.1	0
9	4.02	220	0.05	0.1	0
10	4.16	250	0.03	0.1	0
10	4.01	200	0.05	0.1	0
11	4.16	210	0.04	0.1	0
11	4.26	200	0.03	0.1	0
12	3.93	280	0.03	0.1	0
12	3.97	270	0.02	0.1	0
19	3.62	390	0.07	0.1	0
19	3.62	280	0.04	0.1	0
20	2.48	500	0.05	0.1	0
20	2.48	220	0.05	0.1	0

^aArea after 1959.

Note: 1.0 acre = 0.405 ha; 1.0 ft = 3.28 m, 1.0 in. = 2.54 cm.

soil moisture; but for ungauged analysis with a single-event model, it is probably the only one available.

The soil moisture data were obtained at various unreported locations within the test watersheds (*The Central* no date). The data were obtained by making gravimetric measurements of soil moisture for specimens taken from fist-sized field samples. The sampling interval was unevenly spaced over about 30 years of the measurement program. The volumetric water content was calculated from the reported gravimetric values, θ_D (fraction of dry unit weight), by applying the following formula:

$$\theta = \frac{\theta_D \gamma_{SD}}{\gamma_w} = 1.3622\theta_D \dots \dots \dots (15)$$

where θ = the volumetric water content; γ_w = the unit weight of water; and γ_{SD} = the dry unit weight of soil, taken as 85 lb/cu ft for all soils in the study area.

The soil measurements are most plentiful for the months during the growing season, April–October. The measurements were taken at depths between 0.0 and 6.0 ft. For the purposes of calculating infiltration, soil moisture measurements from 0.0 to 1.0 ft were considered most important. These soil moisture measurements covered a full range of soil moisture conditions. A linear regression relationship was established between the 5-, 15-, and 30-day API and the estimated soil moisture to explore the effects of short-, medium-, and long-term antecedent rainfall. Both multiple regression and simple regressions were explored, as can be seen from the results shown in Fig. 2. The multiple coefficient of determination, R^2 , is not tremendously impressive for any of the months examined. The results indicate that the best simple regression was not significantly poorer than the multiple regres-

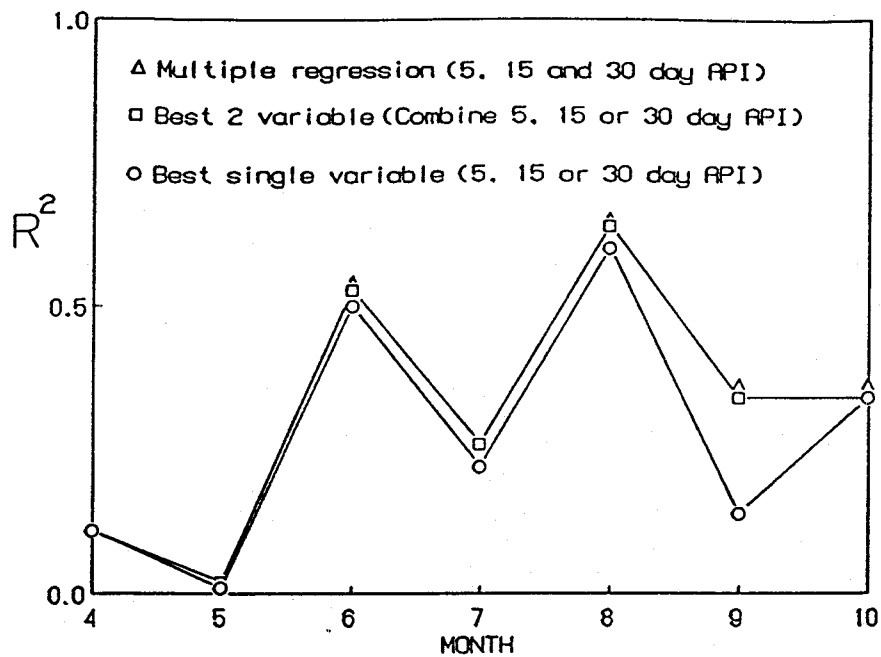


FIG. 2. Multiple Linear Regression between 5-, 15-, and 30-Day API and Soil Moisture at 0-1 ft Depth

sion relationships. Consequently, the best simple regression relationship was used for predicting average watershed moisture conditions.

The error made in estimating the average moisture condition via API is computed by using the final regression results shown in Table 5. The estimated error is modeled by a normal distribution whose mean value is given by the regression for each month and standard deviation is estimated by the standard error of the regression. Technically, the error distribution should be proportional to the product of the standard error and the student's *t*-distribution. However, the number of degrees of freedom available for the regression makes the difference between the normal and *t*-distribution small enough to be ignored.

TABLE 5. Simple Regression Equations for API and Soil Moisture Using Best Index

Month (1)	Abscissa intercept <i>a</i> (2)	Slope <i>b</i> (3)	Simple correlation, <i>R</i> (4)	Number of API days ^a (5)	Mean predicted moisture content (vol/vol) (6)	Standard error (vol/vol) (7)	Number of observations (8)
4	0.32	0.022	0.33	15	0.35	0.07	230
5	0.34	0.004	0.04	5	0.34	0.07	189
6	0.26	0.046	0.71	15	0.40	0.11	227
7	0.14	0.020	0.58	30	0.21	0.07	171
8	0.23	0.064	0.38	15	0.33	0.13	199
9	0.16	0.043	0.77	30	0.32	0.12	212
10	0.23	0.036	0.47	30	0.30	0.10	188

^a $\theta_t = a + b(P)$, where *P* is the antecedent precipitation for days designated in column 5.

STOCHASTIC ANALYSIS RESULTS

Stochastic model predictions were made by using Monte Carlo simulation to derive the probability of runoff volumes, peak discharge, and time-to-peak discharge for a given rainfall event. The distributions were estimated by performing sufficient Monte Carlo simulations to obtain stable estimates of the distribution's mean, standard deviation, skew, and kurtosis. The distributions were estimated for 101 events observed for the test watersheds. Other rainfall events were available from the test watershed records, but various observation errors excluded their use.

The statistics for the predicted volume and peak discharge stabilized in a reasonable number of simulations (5,000). However, the derived standard deviation, skew, and kurtosis for the time-to-peak discharge did not stabilize as readily, requiring at least 50,000 simulations. Since the estimation of time-to-peak discharge statistics led to onerous computer time, only the mean time-to-peak discharge was calculated.

The model was verified by comparing both model mean runoff predictions and predicted exceedance probabilities as determined from derived distributions with corresponding runoff observations and exceedance probabilities estimated from observations. A comparison of mean predicted and observed runoff resulted in a bias towards overprediction for runoff volumes of 0.20 in. and for peak discharge an overprediction of about 1.3 cfs. The prediction of time-to-peak discharge was biased towards an underprediction of about 24 minutes on the average. However, any individual prediction of volume, peak discharge, or time-to-peak discharge can differ from the observed value by a much larger amount than the average bias, as can be seen from Figs. 3-5.

The exceedance probability comparisons were made at plus or minus one or two standard deviations for the derived distributions (see Fig. 6). The observed exceedance or nonexceedance probabilities are defined as, respec-

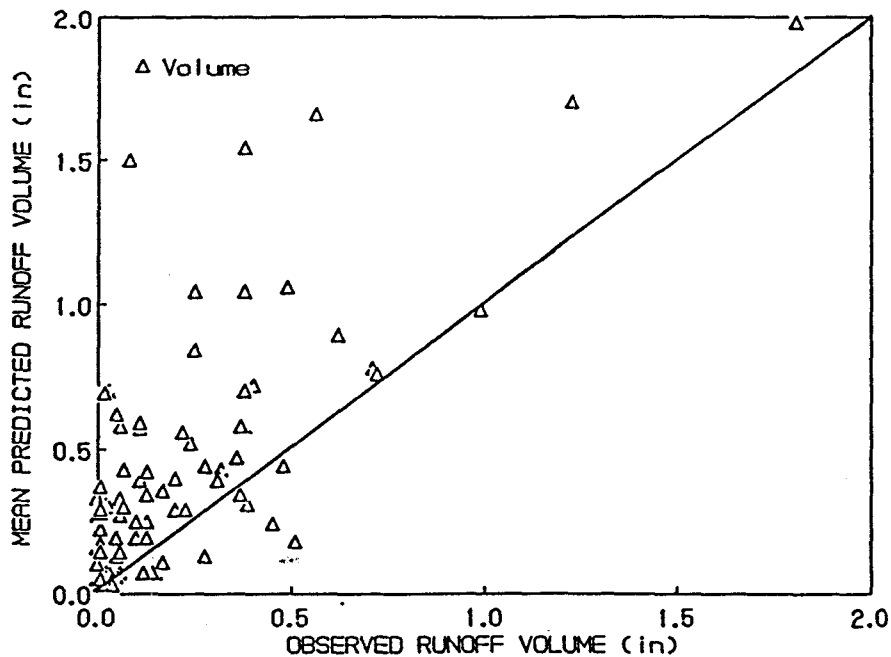


FIG. 3. Predicted Mean Volumes versus Observed Volumes

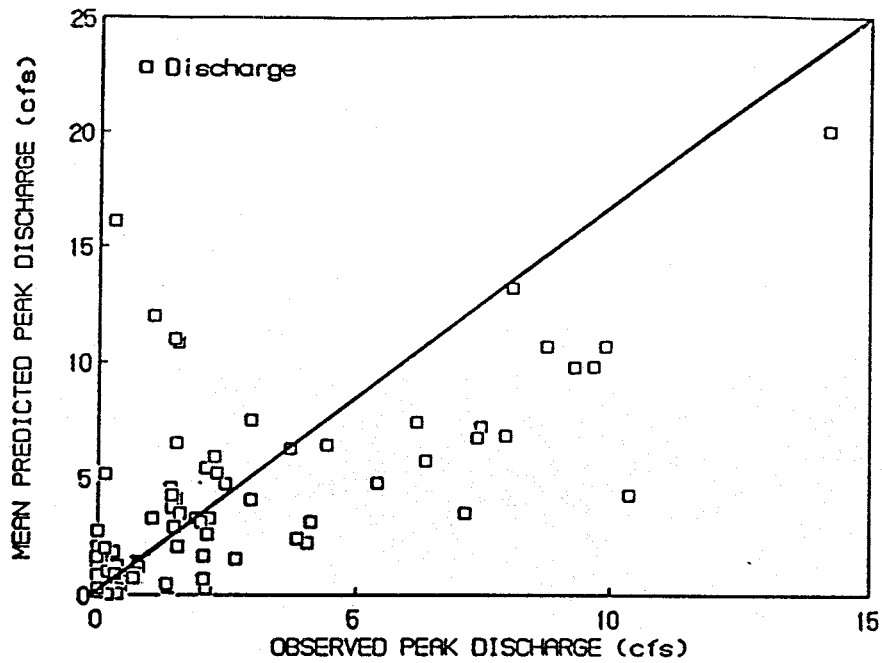


FIG. 4. Predicted Mean Peak Discharge versus Observed Volumes

tively, the fraction of observed occurrences that are greater than the mean prediction plus one or two standard deviations, and/or less than the mean prediction minus one or two standard deviations.

To estimate the predicted exceedance probability, a functional form for the derived distributions was determined by comparing the relationship of the coefficient of variation of the skew or kurtosis for the derived runoff distributions with that of the normal and lognormal distributions, as shown

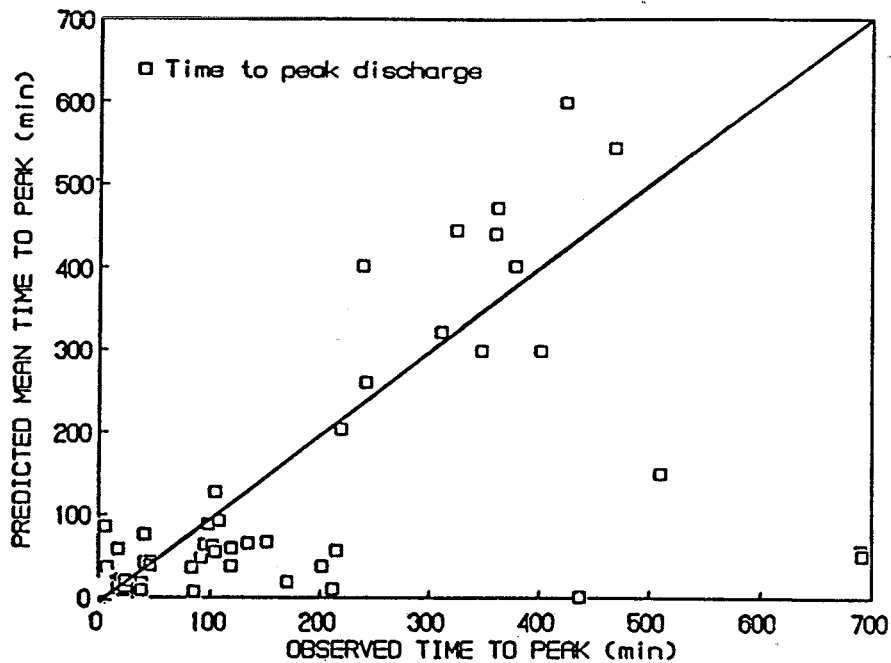


FIG. 5. Predicted Mean Time to Peak Discharge versus Observed Peak Discharge

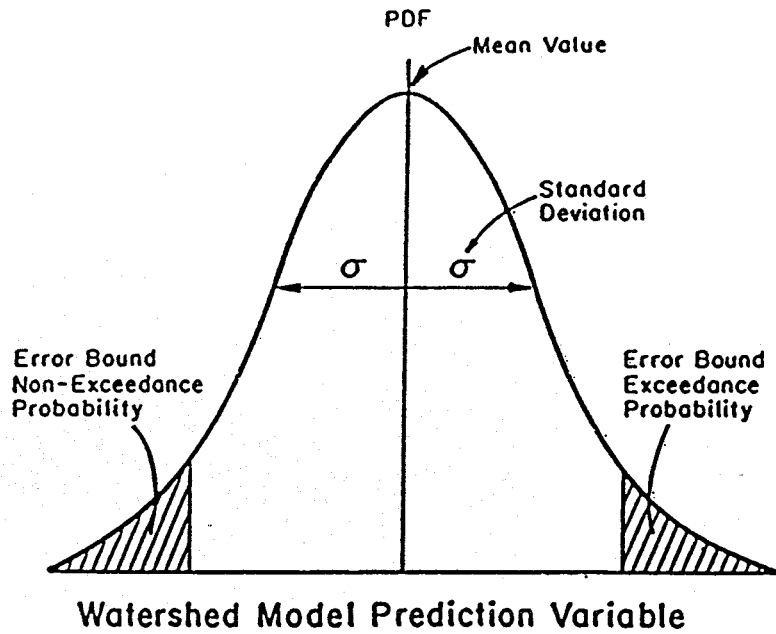


FIG. 6. Definition of Error Bounds and Corresponding Error Exceedance Probabilities

in Figs. 7 and 8. A comparison of the simulation results shows that the derived distributions for both runoff volume and peak discharge are better represented by a normal distribution than a lognormal distribution.

Assuming that the derived distributions are normal, model-predicted exceedance probabilities at plus or minus one and two standard deviations about the mean are equal to 16% and 2.5%, respectively. The estimated observed exceedance probabilities for the volume and peak discharge analysis are

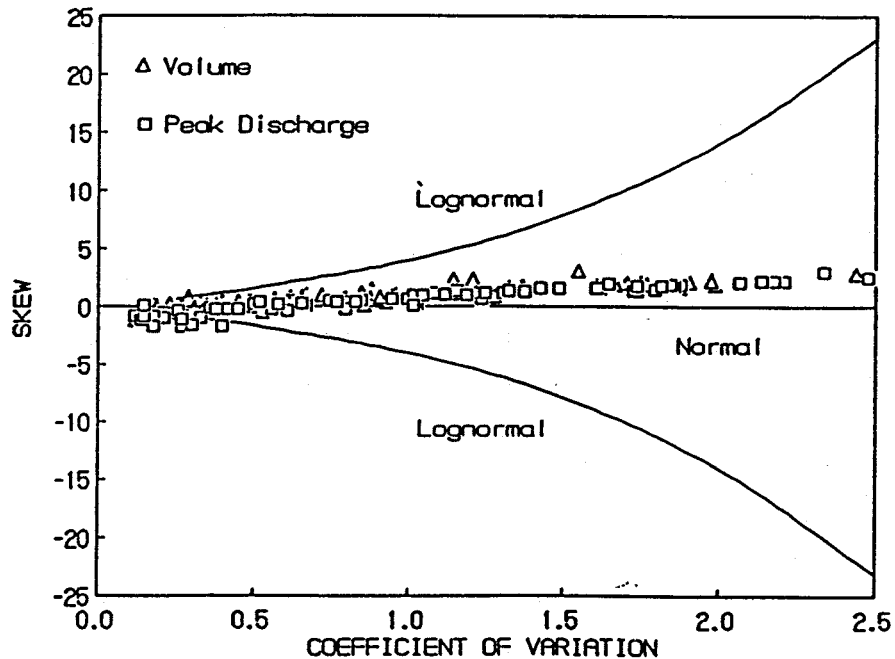


FIG. 7. Comparison of Derived Skew for Runoff Volumes and Peak Discharges with Those for Normal and Two-Parameter Lognormal Distributions

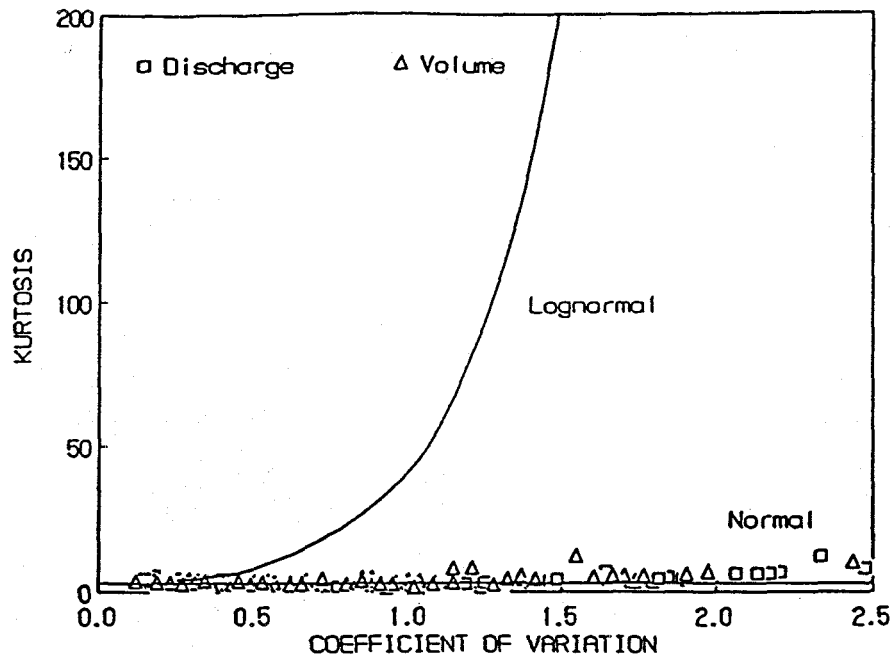


FIG. 8. Comparison of Derived Kurtosis for Runoff Volumes and Peak Discharges with Those for Normal and Two-Parameter Lognormal Distributions

compared to the predicted ones in Table 6. The comparisons indicate that the model conservatively predicts exceedance probability at plus one standard deviation for both prediction variables and at two standard deviations for runoff volume. However, the model prediction of discharge is not conservative at two standard deviations in that the estimated observed exceedance probability is 3.0%, whereas the predicted one is 2.5%. Consequently, the results demonstrate that the model is conservative at one standard deviation, but not necessarily at two standard deviations. A corresponding comparison of nonexceedance probabilities also shown in Table 6 indicates

TABLE 6. Comparison of Observed and Predicted Exceedance Probabilities (Based on 101 Events)

Number of standard deviations (1)	Exceedance (%) ^a		Nonexceedance (%) ^b	
	Predicted (2)	Observed (3)	Predicted (4)	Observed (5)
(a) Volume				
1.0	16.0	1.0	16.0	44.6
2.0	2.5	0.0	2.5	12.9
(b) Peak Discharge				
1.0	16.0	9.9	16.0	31.7
2.0	2.5	3.0	2.5	9.9

^aExceedance probability = the chance that runoff volume or peak discharge will exceed the mean prediction by the given number of standard deviations.

^bNonexceedance probability = the chance that runoff volume or peak discharge will be less than the mean minus the given number of standard deviations.

that the model underpredicts the chance that the runoff will be less than one or two standard deviations. Thus, the model is conservative in this respect.

CONCLUSIONS

The uncertainty in model predictions was conservatively estimated, for the most part, by considering the error resulting from using simple indices to estimate infiltration parameters. In other words, the assumed error model for infiltration parameter estimates resulted in estimated model prediction errors that were somewhat greater than the observed prediction error. This conservatism may be useful in that it could be used to obtain a safety factor in a design situation.

The conservatism of the estimated prediction uncertainty might be attributed to the assumptions made in choosing parameter probability distributions and in assuming zero surface loss. The conservatism in the estimated prediction uncertainty would be lessened if some type of peaked distribution were used instead of the uniform distribution assumed for particle-size distribution. Estimation of a surface loss may have helped in reducing the bias towards overprediction of runoff. However, further research in quantifying surface losses for ungauged watersheds would be helpful in attempts to estimate this parameter for the model. Additionally, the infiltration estimation procedure could be improved by finding a better indicator of soil moisture than an antecedent precipitation index.

The estimation procedure used for infiltration parameters could be useful when applying a PBS type model to derive flow-frequency curves (Eagleson 1972). However, application of this estimation procedure to more gauged basins would be necessary to determine whether it is consistently conservative and to determine the degree of conservatism.

APPENDIX I. REFERENCES

- Allmaras, R. R., et al. (1966). "Total porosity and random roughness of the interrow zone as influenced by tillage." *Conservation Res. Report No. 7*, Minnesota and South Dakota Agric. Exp. Sta., U.S. Dept. of Agr., Agric. Res. Svc., Washington, D.C. 22.
- Brakensiek, D. L. (1977). "Estimating the effective capillary pressure in the Green and Ampt infiltration equation." *Water Resour. Res.*, 13(3), 680-682.
- Brutsaert, W. (1967). "Some methods of calculating unsaturated permeability." *Trans. ASAE*, American Society of Agricultural Engineers, 10(3), 400-404.
- The Central Great Plains experiment watershed*. (No date). Agric. Res. Svc., U.S. Dept. of Agr., Beltsville, Md.
- Cosby, B. J., et al. (1984). "A statistical exploration of the relationship of soil moisture characteristics to the physical properties of soils." *Water Resour. Res.*, 20(6), 682-690.
- Eagleson, P. S. (1972). "Dynamics of flood frequency." *Water Resour. Res.*, 8(4), 878-897.
- Goldman, D. M. (1987). "Estimating runoff prediction uncertainty using a physically-based stochastic watershed model." Thesis presented to the University of California, at Davis, Calif., in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
- Hjemfelt, A. T., Jr. (1986). "Estimating peak runoff from field-size watersheds." *Water Resour. Bull.*, 22(2), 257-266.
- Klemes, V. (1978). "Physically based stochastic hydrologic analysis." *Adv. Hydrosci.*, 11(1), 285-352.

- Leclerc, G., and Schaake, J. C., Jr. (1973). "Methodology for assessing the potential impact of urban development on urban runoff and the relative efficiency of runoff control alternatives." *Ralph M. Parsons Lab., Dept. No. 167*, Massachusetts Inst. of Tech., Cambridge, Mass.
- Linden, R. L. (1979). "A model to predict soil water storage as affected by tillage practices." Thesis presented to the University of Minnesota, at Minneapolis, Minn., in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
- McCuen, R. H., Rawls, W. J., and Brakensiek, D. L. (1981). "Statistical analysis of the Brooks-Corey and the Green-Ampt parameters across soil textures." *Water Resour. Res.*, 17(4), 1005-1013.
- Mein, R. G., and Larson, C. L. (1973). "Modeling infiltration during a steady rain." *Water Resour. Res.*, 9(2), 384-394.
- Morel-Seytoux, H. J. (1980). "Application of infiltration theory in hydrologic practice, CEP80-81HJM2, Engrg. Res. Ctr., HYDROWAR program, Colorado State Univ., Fort Collins, Colo.
- Rawls, W. J., and Brakensiek, D. L. (1982). "Estimating soil water retention from soil properties." *J. Irrig. and Drainage*, ASCE, 108(2), 166-171.
- Rawls, W. J., and Brakensiek, D. L. (1989). "Estimation of soil water retention and hydraulic properties in unsaturated flow in hydrologic modeling, theory and practice." H. J. Morel-Seytoux, ed., *NATO ASI Series, Series C: Mathematical and Physical Sciences*, 275, Kluwer Academic Publishers, Boston, Mass.
- Rawls, W. J., Brakensiek, D. L., and Saxton, K. E. (1981). "Soil water characteristics." *Amer. Soc. Agric. Engrg. Paper No. 81-2510*.
- Rawls, W. J., Brakensiek, D. L., and Saxton, K. E. (1982). "Estimation of soil water properties." *Trans. ASAE*, 25(5), 1316-1320, 1328.
- Rawls, W. J., Brakensiek, D. L., and Soni, B. (1983). "Agricultural management effects on soil, water processes, part I: Soil water retention and Green-Ampt infiltration parameters." *Trans. ASAE*, 25(5), 1316-1320, 1328.
- REPHELEX: Retrieval procedures for hydrologic data from experimental watersheds in the United States.* (1983). Arm-NE-9, Agric. Res. Svc., U.S. Dept. of Agr., Beltsville, Md.
- "SOILS-5: An interactive soils information systems users manual." *Tech. Rept. N-163*, Constr. Engrg. Res. Lab., U.S. Army Corps of Engrs., Champaign, Ill.
- Weissman, W., Jr., et al. (1977). *Introduction to hydrology*. Dun-Donnelly, New York, N.Y.

APPENDIX II. NOTATION

The following symbols are used in this paper:

- F = cumulative infiltration (in.);
- I_a = initial abstraction (in.);
- i = infiltration rate (in./hr);
- K_s = saturated hydraulic conductivity (in./hr);
- l = length along overland flow plane (ft);
- P = cumulative precipitation (in.);
- Q = total watershed outflow (cfs);
- q = flow per unit width of channel (cfs/ft);
- m = kinematic wave discharge exponent = 1.67;
- N = roughness coefficient for overland flow;
- n = $3\lambda + 2$;
- r = rainfall intensity adjusted for surface loss (in./hr);
- r_0 = rainfall intensity (in./hr);
- S_0 = slope along overland flow plane (ft/ft);
- S_e = effective saturation;
- t = time (sec);

- W = width of overland flow plane (ft);
 x = distance along overland flow plane (ft);
 y = flow depth along overland flow plane (ft);
 α = $1.49S_0^{1/2}/N$;
 γ_{sd} = soil dry unit weight (lb/cu ft);
 γ_w = unit weight of water (lb/cu ft);
 $\Delta\theta$ = volumetric water deficit (vol/vol);
 θ = volumetric water content (vol/vol);
 θ_D = gravimetric water content (fraction of dry unit weight);
 θ_e = $\phi - \theta_r$ (vol/vol);
 θ_i = initial water content (vol/vol);
 θ_r = residual saturation (vol/vol);
 λ = pore-size distribution;
 σ = standard deviation;
 ϕ = porosity (vol/vol);
 ψ = matric suction (in.);
 ψ_b = bubbling pressure (in.);
 ψ_f = wetting front suction (in.);
 ψ_w = water entry pressure (in.); and
 Ω = $\psi_r\Delta\theta$ (in.).

APPENDIX III. CONVERSION TO SI UNITS

<u>To convert</u>	<u>To</u>	<u>Multiply by</u>
acre	ha	0.405
ft	cm	30.48
in.	cm	2.54
lb/cu ft	N/m ³	157.05
cu ft/sec	m ³ /s	0.0283

Technical Paper Series

TP-1	Use of Interrelated Records to Simulate Streamflow	TP-39	A Method for Analyzing Effects of Dam Failures in Design Studies
TP-2	Optimization Techniques for Hydrologic Engineering	TP-40	Storm Drainage and Urban Region Flood Control Planning
TP-3	Methods of Determination of Safe Yield and Compensation Water from Storage Reservoirs	TP-41	HEC-5C, A Simulation Model for System Formulation and Evaluation
TP-4	Functional Evaluation of a Water Resources System	TP-42	Optimal Sizing of Urban Flood Control Systems
TP-5	Streamflow Synthesis for Ungaged Rivers	TP-43	Hydrologic and Economic Simulation of Flood Control Aspects of Water Resources Systems
TP-6	Simulation of Daily Streamflow	TP-44	Sizing Flood Control Reservoir Systems by System Analysis
TP-7	Pilot Study for Storage Requirements for Low Flow Augmentation	TP-45	Techniques for Real-Time Operation of Flood Control Reservoirs in the Merrimack River Basin
TP-8	Worth of Streamflow Data for Project Design - A Pilot Study	TP-46	Spatial Data Analysis of Nonstructural Measures
TP-9	Economic Evaluation of Reservoir System Accomplishments	TP-47	Comprehensive Flood Plain Studies Using Spatial Data Management Techniques
TP-10	Hydrologic Simulation in Water-Yield Analysis	TP-48	Direct Runoff Hydrograph Parameters Versus Urbanization
TP-11	Survey of Programs for Water Surface Profiles	TP-49	Experience of HEC in Disseminating Information on Hydrological Models
TP-12	Hypothetical Flood Computation for a Stream System	TP-50	Effects of Dam Removal: An Approach to Sedimentation
TP-13	Maximum Utilization of Scarce Data in Hydrologic Design	TP-51	Design of Flood Control Improvements by Systems Analysis: A Case Study
TP-14	Techniques for Evaluating Long-Term Reservoir Yields	TP-52	Potential Use of Digital Computer Ground Water Models
TP-15	Hydrostatistics - Principles of Application	TP-53	Development of Generalized Free Surface Flow Models Using Finite Element Techniques
TP-16	A Hydrologic Water Resource System Modeling Techniques	TP-54	Adjustment of Peak Discharge Rates for Urbanization
TP-17	Hydrologic Engineering Techniques for Regional Water Resources Planning	TP-55	The Development and Servicing of Spatial Data Management Techniques in the Corps of Engineers
TP-18	Estimating Monthly Streamflows Within a Region	TP-56	Experiences of the Hydrologic Engineering Center in Maintaining Widely Used Hydrologic and Water Resource Computer Models
TP-19	Suspended Sediment Discharge in Streams	TP-57	Flood Damage Assessments Using Spatial Data Management Techniques
TP-20	Computer Determination of Flow Through Bridges	TP-58	A Model for Evaluating Runoff-Quality in Metropolitan Master Planning
TP-21	An Approach to Reservoir Temperature Analysis	TP-59	Testing of Several Runoff Models on an Urban Watershed
TP-22	A Finite Difference Methods of Analyzing Liquid Flow in Variably Saturated Porous Media	TP-60	Operational Simulation of a Reservoir System with Pumped Storage
TP-23	Uses of Simulation in River Basin Planning	TP-61	Technical Factors in Small Hydropower Planning
TP-24	Hydroelectric Power Analysis in Reservoir Systems	TP-62	Flood Hydrograph and Peak Flow Frequency Analysis
TP-25	Status of Water Resource System Analysis	TP-63	HEC Contribution to Reservoir System Operation
TP-26	System Relationships for Panama Canal Water Supply	TP-64	Determining Peak-Discharge Frequencies in an Urbanizing Watershed: A Case Study
TP-27	System Analysis of the Panama Canal Water Supply	TP-65	Feasibility Analysis in Small Hydropower Planning
TP-28	Digital Simulation of an Existing Water Resources System	TP-66	Reservoir Storage Determination by Computer Simulation of Flood Control and Conservation Systems
TP-29	Computer Application in Continuing Education	TP-67	Hydrologic Land Use Classification Using LANDSAT
TP-30	Drought Severity and Water Supply Dependability	TP-68	Interactive Nonstructural Flood-Control Planning
TP-31	Development of System Operation Rules for an Existing System by Simulation	TP-69	Critical Water Surface by Minimum Specific Energy Using the Parabolic Method
TP-32	Alternative Approaches to Water Resources System Simulation		
TP-33	System Simulation of Integrated Use of Hydroelectric and Thermal Power Generation		
TP-34	Optimizing flood Control Allocation for a Multipurpose Reservoir		
TP-35	Computer Models for Rainfall-Runoff and River Hydraulic Analysis		
TP-36	Evaluation of Drought Effects at Lake Atitlan		
TP-37	Downstream Effects of the Levee Overtopping at Wilkes-Barre, PA, During Tropical Storm Agnes		
TP-38	Water Quality Evaluation of Aquatic Systems		

- TP-70 Corps of Engineers Experience with Automatic Calibration of a Precipitation-Runoff Model
- TP-71 Determination of Land Use from Satellite Imagery for Input to Hydrologic Models
- TP-72 Application of the Finite Element Method to Vertically Stratified Hydrodynamic Flow and Water Quality
- TP-73 Flood Mitigation Planning Using HEC-SAM
- TP-74 Hydrographs by Single Linear Reservoir Model
- TP-75 HEC Activities in Reservoir Analysis
- TP-76 Institutional Support of Water Resource Models
- TP-77 Investigation of Soil Conservation Service Urban Hydrology Techniques
- TP-78 Potential for Increasing the Output of Existing Hydroelectric Plants
- TP-79 Potential Energy and Capacity Gains from Flood Control Storage Reallocation at Existing U.S. Hydropower Reservoirs
- TP-80 Use of Non-Sequential Techniques in the Analysis of Power Potential at Storage Projects
- TP-81 Data Management Systems of Water Resources Planning
- TP-82 The New HEC-1 Flood Hydrograph Package
- TP-83 River and Reservoir Systems Water Quality Modeling Capability
- TP-84 Generalized Real-Time Flood Control System Model
- TP-85 Operation Policy Analysis: Sam Rayburn Reservoir
- TP-86 Training the Practitioner: The Hydrologic Engineering Center Program
- TP-87 Documentation Needs for Water Resources Models
- TP-88 Reservoir System Regulation for Water Quality Control
- TP-89 A Software System to Aid in Making Real-Time Water Control Decisions
- TP-90 Calibration, Verification and Application of a Two-Dimensional Flow Model
- TP-91 HEC Software Development and Support
- TP-92 Hydrologic Engineering Center Planning Models
- TP-93 Flood Routing Through a Flat, Complex Flood Plain Using a One-Dimensional Unsteady Flow Computer Program
- TP-94 Dredged-Material Disposal Management Model
- TP-95 Infiltration and Soil Moisture Redistribution in HEC-1
- TP-96 The Hydrologic Engineering Center Experience in Nonstructural Planning
- TP-97 Prediction of the Effects of a Flood Control Project on a Meandering Stream
- TP-98 Evolution in Computer Programs Causes Evolution in Training Needs: The Hydrologic Engineering Center Experience
- TP-99 Reservoir System Analysis for Water Quality
- TP-100 Probable Maximum Flood Estimation - Eastern United States
- TP-101 Use of Computer Program HEC-5 for Water Supply Analysis
- TP-102 Role of Calibration in the Application of HEC-6
- TP-103 Engineering and Economic Considerations in Formulating
- TP-104 Modeling Water Resources Systems for Water Quality
- TP-105 Use of a Two-Dimensional Flow Model to Quantify Aquatic Habitat
- TP-106 Flood-Runoff Forecasting with HEC-1F
- TP-107 Dredged-Material Disposal System Capacity Expansion
- TP-108 Role of Small Computers in Two-Dimensional Flow Modeling
- TP-109 One-Dimensional Model for Mud Flows
- TP-110 Subdivision Froude Number
- TP-111 HEC-5Q: System Water Quality Modeling
- TP-112 New Developments in HEC Programs for Flood Control
- TP-113 Modeling and Managing Water Resource Systems for Water Quality
- TP-114 Accuracy of Computer Water Surface Profiles - Executive Summary
- TP-115 Application of Spatial-Data Management Techniques in Corps Planning
- TP-116 The HEC's Activities in Watershed Modeling
- TP-117 HEC-1 and HEC-2 Applications on the Microcomputer
- TP-118 Real-Time Snow Simulation Model for the Monongahela River Basin
- TP-119 Multi-Purpose, Multi-Reservoir Simulation on a PC
- TP-120 Technology Transfer of Corps' Hydrologic Models
- TP-121 Development, Calibration and Application of Runoff Forecasting Models for the Allegheny River Basin
- TP-122 The Estimation of Rainfall for Flood Forecasting Using Radar and Rain Gage Data
- TP-123 Developing and Managing a Comprehensive Reservoir Analysis Model
- TP-124 Review of U.S. Army corps of Engineering Involvement With Alluvial Fan Flooding Problems
- TP-125 An Integrated Software Package for Flood Damage Analysis
- TP-126 The Value and Depreciation of Existing Facilities: The Case of Reservoirs
- TP-127 Floodplain-Management Plan Enumeration
- TP-128 Two-Dimensional Floodplain Modeling
- TP-129 Status and New Capabilities of Computer Program HEC-6: "Scour and Deposition in Rivers and Reservoirs"
- TP-130 Estimating Sediment Delivery and Yield on Alluvial Fans
- TP-131 Hydrologic Aspects of Flood Warning - Preparedness Programs
- TP-132 Twenty-five Years of Developing, Distributing, and Supporting Hydrologic Engineering Computer Programs
- TP-133 Predicting Deposition Patterns in Small Basins
- TP-134 Annual Extreme Lake Elevations by Total Probability Theorem
- TP-135 A Muskingum-Cunge Channel Flow Routing Method for Drainage Networks
- TP-136 Prescriptive Reservoir System Analysis Model - Missouri River System Application
- TP-137 A Generalized Simulation Model for Reservoir System Analysis
- TP-138 The HEC NexGen Software Development Project
- TP-139 Issues for Applications Developers
- TP-140 HEC-2 Water Surface Profiles Program
- TP-141 HEC Models for Urban Hydrologic Analysis

- TP-142 Systems Analysis Applications at the Hydrologic Engineering Center
- TP-143 Runoff Prediction Uncertainty for Ungauged Agricultural Watersheds
- TP-144 Review of GIS Applications in Hydrologic Modeling
- TP-145 Application of Rainfall-Runoff Simulation for Flood Forecasting
- TP-146 Application of the HEC Prescriptive Reservoir Model in the Columbia River Systems
- TP-147 HEC River Analysis System (HEC-RAS)
- TP-148 HEC-6: Reservoir Sediment Control Applications
- TP-149 The Hydrologic Modeling System (HEC-HMS): Design and Development Issues
- TP-150 The HEC Hydrologic Modeling System
- TP-151 Bridge Hydraulic Analysis with HEC-RAS
- TP-152 Use of Land Surface Erosion Techniques with Stream Channel Sediment Models
- TP-153 Risk-Based Analysis for Corps Flood Project Studies - A Status Report
- TP-154 Modeling Water-Resource Systems for Water Quality Management
- TP-155 Runoff simulation Using Radar Rainfall Data
- TP-156 Status of HEC Next Generation Software Development
- TP-157 Unsteady Flow Model for Forecasting Missouri and Mississippi Rivers
- TP-158 Corps Water Management System (CWMS)
- TP-159 Some History and Hydrology of the Panama Canal
- TP-160 Application of Risk-Based Analysis to Planning Reservoir and Levee Flood Damage Reduction Systems
- TP-161 Corps Water Management System - Capabilities and Implementation Status

