APPLICATION OF THE U.S. GEOLOGICAL SURVEY RAINFALL-RUNOFF SIMULATION MODEL TO IMPROVE FLOOD-FREQUENCY ESTIMATES ON SMALL TENNESSEE STREAMS

by Herman C. Wibben

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 76-120

Prepared in cooperation with

Tennessee Department of Transportation

Bureau of Planning and Programming

and

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UNITED STATES DEPARTMENT OF THE INTERIOR

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APPLICATION OF THE U.S. GEOLOGICAL SURVEY RAINFALL-RUNOFF SIMULATION MODEL TO IMPROVE FLOOD-FREQUENCY ESTIMATES ON SMALL TENNESSEE STREAMS

By Herman C. Wibben

ABSTRACT

The U.S. Geological Survey rainfall-runoff simulation model was used in conjunction with National Weather Service climatological data to improve flood-frequency estimates for 52 small drainage basins in Tennessee. The basins range in size from 0.17 to 64 square miles (0.44 to 166 square kilometers) and are distributed throughout the State. Model parameters were determined by calibration with observed data from each site. Average error in peak discharge simulation was about 36 percent. Techniques used in screening data for calibration as well as those used to optimize parameter values are discussed. A scheme developed to assess the relative accuracy of the frequency curves based on observed and simulated data indicated that the simulated data are equivalent to 9 years of observed data in defining 2-year floods and 15 years in defining 100-year floods. Discharges corresponding to the best estimate of flows for selected recurrence intervals are tabulated for each modeled basin.

INTRODUCTION

Proper design of drainage structures relies on sound evaluation of the magnitude and frequency of floods. In the past, data on which this evaluation was made, was collected only on the larger streams. Most of the flood data currently available on streams smaller than 50 mi^2 (129.5 km^2) have record lengths less than 20 years.

The U.S. Geological Survey, in cooperation with the Tennessee Department of Transportation, began a study of flood-frequency characteristics of small rural watersheds in Tennessee during 1953. This project was the first major undertaking to eliminate the near void of small stream flood data. Crest-stage gages were initially installed at 87 sites ranging in size from 0.034 mi^2 (0.088 km^2) to 201 mi^2 (520 km^2). These gages provide a record of the annual peak stages. The approach used for analysis was to compute the annual peak discharges from stage-discharge ratings and subsequently to develop station flood frequency curves from these observed discharges. These curves can then be used in a regional analysis of flood-frequency characteristics. One drawback to this approach is the lag between the time data collection begins and the time at which events with a high recurrence interval can be reliably defined.

During 1963, an awareness of the shortage of small basin streamflow data was intensified by the large number of drainage structures being built under the interstate highway system. Since reliability of flood frequency characteristics derived from observed floods is dependent upon length of record, a lengthy data collection period would be necessary before data from new sites would produce reliable results using conventional techniques. This resultant time lag was greater than designers were willing to accept. Because of the urgency, the use of rainfall-runoff models was considered as a way to reduce the data collection period by extending the data base in time through the use of long-term climatological information.

A second cooperative program was initiated by the Geological Survey and the Tennessee Department of Transportation in 1965 to expand the small streams data network. This program was designed to provide concurrent rainfall and discharge data as input to the Geological Survey rainfall-runoff model developed by Dawdy, Lichty, and Bergmann (1972).

The purpose of this report is to present flood-frequency information on small streams in Tennessee resulting from application of the Geological Survey rainfall-runoff model. The feasibility of using the model to extend flood records in time is demonstrated, and general observations made during application of the model are documented for the benefit of future model users. Observed, simulated, and weighted discharges for selected recurrence intervals and calibrated model parameters are listed for each modeled basin. A discussion is included of techniques used to screen input data, to operate the model, and to assess the accuracy of the simulated data. Output from this study was combined with other streamflow data in a report prepared by Randolph and Gamble (1976) to define flood-frequency characteristics of Tennessee streams.

This report was prepared under the cooperative highway research program with the Tennessee Department of Transportation, Bureau of Planning and the U.S. Department of Transportation, Federal Highway Administration. The contents of this report reflect the views of the author. The Geological Survey is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. Insofar as the Federal Highway Administration is concerned, this report does not constitute a standard, specification, or regulation.

Daily precipitation and evaporation data and 5-minute incremental storm rainfall data for historic periods were obtained from the National Oceanic and Atmospheric Administration at Asheville, North Carolina. Streamflow and rainfall data collected at fourteen gaging stations under a cooperative program with the Metropolitan Government of Nashville-Davidson County were included in the analysis.

R. W. Lichty, research hydrologist with the U.S. Geological Survey provided advice and assistance during the study.

Use of Metric Units of Measurement

The analysis and compilations in this report were made with English units of measurements. The equivalent metric units are given in the text and illustrations where appropriate. English units only are shown in tables where, because of space limitations, the dual system of English and metric units would not be practicable. To convert English units to metric units, the following conversion factors should be used:

Multiply English units	by	To obtain metric units
inches (in)	25.4	millimeters (mm)
feet (ft)	0.305	meters (m)
miles (mi)	1.61	kilometers (km)
square miles (mi^2)	2.59	square kilometers (km^2)
feet per mile (ft/mi)	0.189	meters per kilometer (m/km)
cubic feet per second (ft^3/s)	0.0283	cubic meters per second (m^3/s)

DATA COLLECTION

Forty-nine gaging stations were established in clusters within the six physiographic provinces of the State. Sites were selected to represent the range of basin characteristics encountered in the field. The gages were to be operated for up to 10 years to collect sufficient data to calibrate the model. Stage-rainfall (circular-chart graphic) recorders were initially installed at 35 sites and analog digital recorders (paper-tape digital-punch) were installed at the other 14 sites. At most sites, the intakes were installed such that only storm flows were recorded in order to obtain a more reliable record of stream stage by reducing maintenance problems. Stage and rainfall data were collected concurrently at these sites.

The SR recorders proved to be less desirable than the ADR recorders even though they were considerably cheaper. Since both the stage pen and the rainfall pen of the SR recorders mark on the same chart to insure proper timing, all stations equipped with SR recorders had to have their stage wells and precipitation collectors mounted adjacent to each other. As a result of this constraint, compromises frequently had to be made in locating the stage well in order to provide adequate exposure for the rain gage. SR recorders were also less reliable than the ADR recorders. Although the chart drives operated satisfactorily, various problems with the recording pens and the float wheels resulted in considerable lost record. In addition, conversion of the storm data to a machine readable form was expensive and tedious. SR recorders were gradually replaced with ADR recorders as time and funds permitted.

At sites instrumented with ADR recorders more flexibility in locating the gages were permitted. The precipitation and stage recorders could be installed at separate locations when required. This distance was usually held to 100 ft (30.5 m) or less to insure reliability of the recorders since they were both activated with the same timer. Reliability and accuracy of these installations was better than that of the SR installations, and the data were recorded in a machine readable form. All ADR recorders were operated at a punch frequency of five minutes.

Most of the gages were placed in clusters such that increasingly larger segments of the basin were gaged. The decision to locate the sites in clusters has been a source of some controversy. One positive aspect of the cluster concept lies in providing a means to screen precipitation data for the model calibrations. Uniform rainfall rarely occurs in nature. Since the assumption that rainfall input is uniformly distributed throughout the basin is built into the Geological Survey rainfall-runoff model, it is helpful to know how closely this assumption is being met. With the gages located within a mile or so of each other, storm rainfall could be checked for uniformity. Storm rainfall could also be transferred to a nearby gage when one of them failed to function and the other gages indicated uniform rainfall. Another consideration for clustering the gages was to provide data for future stream-systems modeling. The clusters would allow for following a storm through a basin with discharge hydrographs available at each site to check theoretical routing techniques. The negative aspect of the cluster concept is the potential for extremely high inter-station correlation values since truly independent events are not being sampled by gaging increasingly larger segments of a basin.

Daily rainfall data from the closest ADR station were normally used for gage sites equipped with SR recorders since the daily values were not available from the circular charts. Daily rainfall from the closest National Weather Service reporting gage was used when record from a nearby gage was not available.

Daily pan evaporation data from the National Weather Service station at Center Hill Dam were used for all calibrations. This station was the only one that had been operated year-round for a long period of time. The record length of 25 years was significant in that the data would later be used to generate harmonic average evaporation data for those periods during which actual data were not available.

Long-term precipitation data used to simulate series of peak discharges were obtained from the National Weather Service. Rainfall stations and the periods for which data were used are listed below.

National Weather Service Station	Period
Memphis, TN	1898-1971
Nashville, TN	1898-1970
Chattanooga, TN	1901-1971
Knoxville, TN	1898-1971

Criteria for selecting storm events from the rainfall stations were based on an analysis of daily rainfall. A maximum of five storms per water year having a 2 day sum equal to or greater than 1 inch and a 1 day maximum ranking in the top five for the year were selected as the events likely to have caused the annual peak discharge. Five minute incremental rainfall for those events at Memphis, Nashville, and Knoxville were digitized by the National Weather Service from original charts. Comparable data at Chattanooga were processed by personnel in the Georgia District of the Geological Survey.

DESCRIPTION OF THE MODEL

The U.S. Geological Survey rainfall-runoff model is a parametric simulation model based on bulk-parameter approximations to the physical laws governing infiltration, soil moisture accretion and depletion, and surface streamflow. It was developed by Dawdy, Lichty, and Bergmann (1972) for use with point rainfall data and daily potential evapotranspiration data to predict flood volumes and peak rates of runoff for small drainage basins.

The model deals with three components of the hydrologic cycle-antecedent moisture, infiltration, and surface flow routing. A schematic outline of the model is shown in figure 1. Brief descriptions of the model parameters are listed below.

Parameter identifier code	Units	Application
PSP	Inches	Represents the combined effects of soil moisture contents and suction at the wetting front for soil moisture at field capacity.
RGF		Ratio of PSP for soil moisture at wilting point to that at field capacity.
KSAT	Inches per hour	The minimum saturated value of hydraulic conductivity used to determine infiltration soil rates.
BMSM	Inches	Soil moisture-storage volume at field capacity.
EVC		Coefficient to convert pan evaporation to potential evapotranspiration values.
DRN	Inches per hour	A constant drainage rate for redistribution of soil moisture.
RR		Proportion of daily rainfall that infiltrates the soil.
KSW	Hours	Time characteristic for linear reservoir storage.
TC	Minutes	Time base of the triangular translation hydrograph.
TP	Minutes	Time to peak of triangular translation hydrograph.

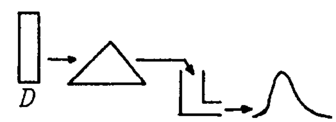
ANTECEDENT-MOISTURE ACCOUNTING COMPONENT	INFILTRATION COMPONENT	ROUTING COMPONENT
Saturated- unsaturated soil mositure regimes	Philip infiltration equation	Modified Clark instantaneous unit hydrograph
Parameter: *EVC*, *RR*, *BMSM*, *DRN* Variable: *BMS*, *SMS*	$\frac{di}{dt} = (l + \frac{P (m-m)}{i}$ Parmeter: *PSP*, *KSAT*, *RGF* Variable: *BMS*, *SMS*	 Parameter: *KSW*, *TC*, *TP*
	INPUT DATA	
Daily rainfall Daily pan evaportion Initial condition	Unit rainfall *BMS* *SMS*	Rainfall excess
	OUTPUT DATA	
BMS *SMS*	Rainfall excess	Discharge

Figure 1.--Schematic outline of the model, showing components, parameters, and variables.

The antecedent - moisture component is designed to determine the initial infiltration rate for a storm. The four parameters included within this component are EVC, RR, BMSM, and DRN. Input are daily rainfall and daily pan evaporation, and output is BMS (amount of base-moisture storage) and SMS (infiltrated surface-moisture storage). BMS represents a uniform antecedent-moisture content of the active soil column, and its range of values should simulate the moisture range from wilting-point conditions to field capacity. SMS represents the moisture content of the surface layer that forms during infiltration. Evaporation data is used as an index to seasonal variability of transpiration as well as evaporation.

The infiltration component uses the Philip (1954) equation, which is believed to be a somewhat better approximation to the differential equation for saturated flow than the classical Horton (1940) exponential-decay-infiltration equation. Input are storm rainfall, BMS, and SMS. Parameters consist of PSP, RGF, and KSAT. This component determines the amount of storm rainfall that infiltrates the soil and produces rainfall excess as output.

The third component, surface-runoff routing, is based on a modification of the Clark (1945) form of the instantaneous unit hydrograph. Input is the rainfall excess computed in the infiltration component, and output is the storm-runoff hydrograph. Three parameters, KSW, TC, and TP, are utilized within this component. It consists of a two-step procedure. First, the precipitation excess is converted into a triangular translation hydrograph representing the effects of varying travel times in the basin. In the second step, successive flow rates of the translation hydrograph are attenuated by routing through linear storage using a storage constant of KSW.

Output from one component is input to the next resulting in many interactions among the parameters. This interaction is particularly active in the antecedent-moisture-accounting and infiltration components, which constitute the loss functions of the model. Often adjustments of one parameter can be compensated for by adjustments in one or more other parameters. Over the same error range, many sets of parameter values may fit a given set of data equally well. Even though the model parameters are chosen so as to be analogous to the physical parameters in a basin, the degree of similarity in the optimum set of derived parameter values may mask the relation of the values to their supposed prototype. Thus, the conceptual physical equivalence of the model may be lost in the fitting process.

Calibration of the model for a basin involves trial and error adjustment of parameter values in order to improve the comparison between observed input and simulated output. The comparison is made by testing for the minimum value of an objective function, which is based on the sum of the squared deviations of the logarithms of peak flows, direct runoff volumes, or some combination of both. Starting values of parameters must be computed or estimated, and maximum and minimum parameter limits must be set. The observed rainfall and evaporation data serve as input and are used to generate a streamflow sequence that is compared with the observed streamflow record. Three separate phases of the calibrations optimize on three different objective functions. During phase one direct runoff volumes are used in the objective function, and parameters pertaining to the first two components of the model are varied. In phase two, the routing phase, peak flows are used in the objective function, and the hydrograph shape parameters are optimized. The peak flows are multiplied by the ratio of observed volumes to simulated volumes so that errors introduced by rainfall data and errors in the moisture-accounting and infiltration parameters are minimized. In phase three, peak flows are again used in the objective function while the parameters affecting the moisture-accounting and infiltration components are varied.

The current version of the model has been adapted for use on urban basins. Percent impervious cover is input to the model. It uses a simplified approach in handling impervious area. The impervious area is assumed to be uniformly distributed throughout the basin and is assumed to be capable of storing 0.05 in (1.27 mm) of precipitation. All precipitation in excess of 0.05 in (1.27 mm) is assumed to be direct runoff. Because the Survey model simulates only direct runoff, all other flow components are lumped together under the category of base flow. The term base flow is used rather loosely in this context. Two optional methods for separation of base flow from total runoff are available within the model for calibration use. The choice of options can be changed from storm to storm within a given calibration.

The "B" option requires estimation of a constant value of base flow for the duration of each hydrograph. Base flow is deducted from each discharge in order to estimate the volume of direct runoff and the magnitude of the peak discharge for each storm. This simple technique is adequate for base flow separation at most basins and requires little effort by the user prior to calibration since the direct runoff volume is computed within the model.

The "A" option permits much more flexibility in separating base flow. An estimate of the direct runoff volume and the peak discharge are input to the model instead of base flow. Any reasonable method for estimating base flow is then permissible. The estimated base flow must be sketched on the hydrograph plot. Direct runoff can be determined by planimetering the area between the discharge hydrograph and the base flow line. Peak discharge is computed as the maximum ordinate between the curves.

MODEL CALIBRATIONS

All data used in the model calibrations were stored on a computer accessible magnetic disk to facilitate retrieval of the massive quantities involved. Calibrations were made on the Geological Survey computer system. System memory requirements for operation of the model vary with the quantity and definition frequency of the storm data. Individual calibrations required as much as 500,000 bytes of storage.

Initial calibrations at all sites were made using the "B" version of the model. Selection of a starting and ending time for each storm event was required. In general, base flows selected were close to the average of the estimated base flow at the beginning and ending of the storm event. Departures from this average were based on hydrograph shape and ground-water recession slope. Starting times for the storms usually coincided with the beginning of storm rainfall. Ending times were normally based on a study of the recessions from select storm events to estimate how long direct runoff continued after rainfall ceased.

Starting model parameters were estimated on the basis of geology, soil type and hydrograph shape. Constraints were imposed on the range within which parameters were allowed to vary during calibration in an attempt to hold the values close to their range of occurrence in the basins. During the first calibration phase, parameters affecting antecedent moisture accounting and infiltration were optimized to achieve the best simulation of the observed runoff volumes. The optimization routine was not extensively used for the second phase. In general, KSW was picked from hydrograph plots of select storms. TP/TC was fixed at 0.5 after scanning results of initial calibrations since most of these calibrations had optimized TP/TC close to that value. This assumption is supported by the Tennessee data as well as O'Kelly's (1955) conclusions, from a study of drainage basins in Ireland, that the smoothing effect of storage on the translation hydrograph was so great that the latter could be replaced by an isosceles triangle without loss of accuracy. TC was hand fitted on the basis of the relative timing of the observed and simulated hydrographs of select storms or optimized within a narrow range. Optimization of parameters during the third phase was used only on the final calibration.

Selection of Data for Model Calibration

Data from 38 of the project stations and 14 of the Nashville urban stations were used with the U.S. Geological Survey rainfall-runoff model. These stations are listed in table 1, and the map in figure 2 shows their areal distribution. Eleven of the project gages were not used for model calibration due to various problems including questionable stage-discharge ratings, inadequate data from storms of sufficient magnitude to reliably separate direct runoff from total flow, or gross deviations of the observed hydrographs from assumptions intrinsic to linear unit hydrograph theory. All hydrographs used were defined at 5-minute intervals.

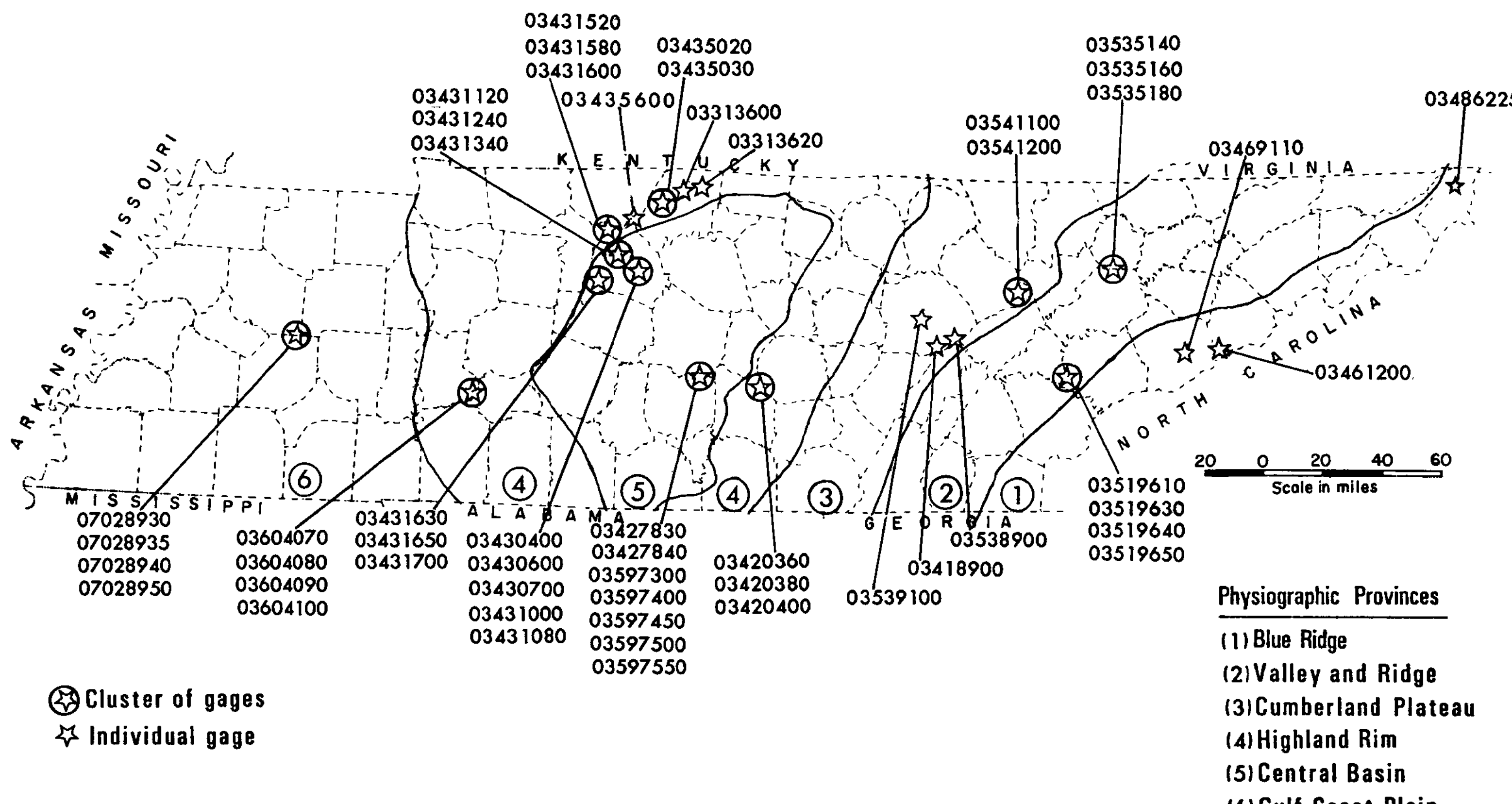


Figure 2. - Locations of modeled stations

Table 1.--Stations used to calibrate the U.S.

Station Number	Stream and Location	Drainage area (mi^2)	L (mi)
03313600	West Fork Drakes Creek tributary near Fountain Head, Tenn.	0.95	1.55
03313620	West Prong Caney Fork Creek near Oak Grove, Tenn.	3.03	3.12
03418900	Raccoon Creek near Old Winesap, Tenn.	1.52	1.88
03420360	Mud Creek tributary No. 2 near Summitville, Tenn.	2.28	2.46
03420380	Mud Creek tributary near Summitville, Tenn.	1.03	1.39
03420400	Mud Creek near Summitville, Tenn.	7.30	4.05
03427830	Short Creek tributary near Christiana, Tenn.	.17	0.56
03427840	Short Creek near Christiana, Tenn.	3.54	4.58
03430400	Mill Creek at Nolensville, Tenn.*	12.0	4.34
03430600	Mill Creek at Hobson Pike, near Antioch, Tenn.*	43.0	10.71
03430700	Indian Creek at Pettus Road, at Nashville, Tenn.*	3.86	2.51
03431000	Mill Creek near Antioch, Tenn.*	64.0	17.0
03431080	Sims Branch at Elm Hill Pike, near Donelson, Tenn.*	3.92	3.03
03431120	West Fork Browns Creek at General Bates Drive, at Nashville, Tenn.*	3.30	3.35
03431240	East Fork Browns Creek at Baird Ward Printing Company at Nashville, Tenn.*	1.58	2.36
03431340	Browns Creek at Factory Street, at Nashville, Tenn.*	13.2	6.51
03431520	Claylick Creek at Lickton, Tenn.*	4.13	3.01
03431580	Ewing Creek at Knight Road, near Bordeaux, Tenn.*	13.3	4.50
03431600	Whites Creek at Tucker Road, near Bordeaux, Tenn.*	51.6	11.13

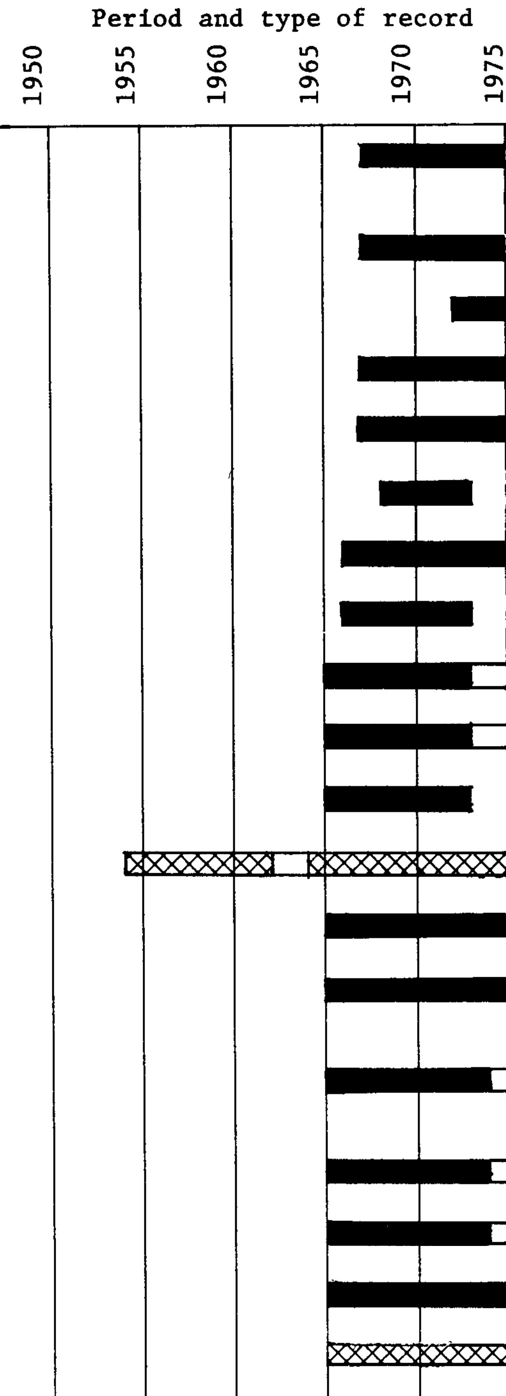
(cross-hatched bar) Continuous record

(solid bar) Flood hydrograph-rainfall record

(open bar) Crest-stage record

* Data collected under cooperative program with Metropolitan Government of

Geological Survey rainfall-runoff model.



S (ft/mi)	Impervious area (percent)	Basin lag time (hrs)	Station Number
73.92	0	1.08	03313600
52.80	0	1.23	03313620
182.27	0	3.58	03418900
35.38	0	2.24	03420360
46.46	0	3.10	03420380
30.62	0	5.15	03420400
100.32	0	0.54	03427830
73.92	0	1.54	03427840
30.58	3.0	1.68	03430400
16.11	3.0	4.16	03430600
45.92	3.0	1.58	03430700
11.40	4.2	5.39	03431000
57.80	22.4	1.08	03431080
77.05	22.3	0.92	03431120
65.59	37.3	1.08	03431240
42.60	31.5	1.92	03431340
69.26	8.2	1.54	03431520
46.70	14.2	2.00	03431580
21.49	8.0	3.48	03431600

Nashville-Davidson County.

Table 1.--Stations used to calibrate the U.S. Geological

Station Number	Stream and Location	Drainage area (mi^2)	L (mi)
03431630	Richland Creek at Lynnwood Blvd., at Belle Meade, Tenn. *	2.21	1.96
03431650	Vaughns Gap Branch at Percy Warner Blvd., at Belle Meade, Tenn. *	2.66	2.38
03431700	Richland Creek at Charlotte Avenue, at Nashville, Tenn. *	24.3	7.90
03435020	Red River near New Deal, Tenn.	9.32	4.00
03435030	Red River near Portland, Tenn.	15.1	6.70
03435600	Sulphur Fork Red River tributary near White House, Tenn.	3.50	3.52
03461200	Cosby Creek above Cosby, Tenn.	10.2	4.40
03469110	Ramsey Creek near Pittman Center, Tenn.	2.18	3.05
03486225	Powder Branch near Johnson City, Tenn.	4.88	3.87
03519610	Baker Creek tributary near Binfield, Tenn.	2.10	2.22
03519630	Griffitts Branch near Greenback, Tenn.	1.46	1.19
03519640	Baker Creek near Greenback, Tenn.	16.0	8.79
03519650	Little Baker Creek near Greenback, Tenn.	3.65	4.07
03535140	South Fork Beaver Creek at Harbison, Tenn.	1.23	1.72
03535160	Beaver Creek near Halls Crossroads, Tenn.	14.1	6.78
03535180	Willow Fork near Halls Crossroads, Tenn.	3.23	4.58
03538900	Self Creek near Big Lick, Tenn.	3.80	3.67
03539100	Byrd Creek near Crossville, Tenn.	1.10	1.66
03541100	Bitter Creek near Camp Austin, Tenn.	5.53	4.05

Continuous record

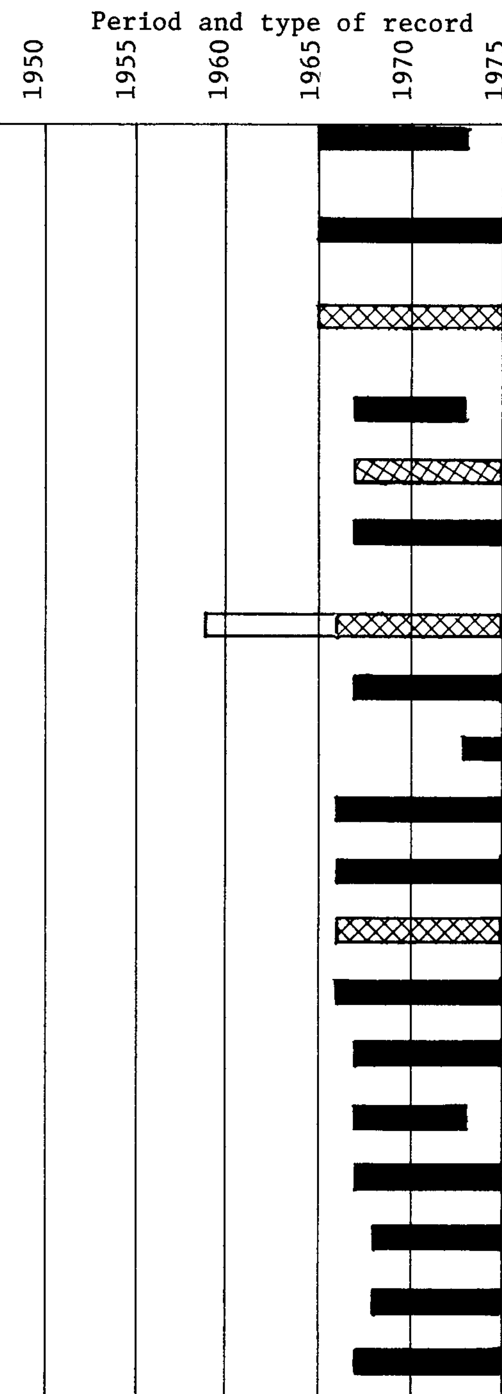
Flood hydrograph-rainfall record

Crest-stage record

* Data collected under cooperative program with Metropolitan Government of

Survey rainfall-runoff model.--Continued.

S (ft/mi)	Impervious area (percent)	Basin lag time (hrs)	Station Number
119.00	11.7	1.33	03431630
83.26	14.9	0.65	03431650
32.97	21.3	2.42	03431700
46.46	0	1.92	03435020
27.98	0	3.11	03435030
51.74	0	1.07	03435600
484.85	0	3.88	03461200
649.44	0	6.55	03469110
124.83	0	1.13	03486225
63.36	0	1.65	03519610
100.32	0	1.41	03519630
17.42	0	6.71	03519640
29.57	0	2.25	03519650
52.80	0	1.54	03535140
15.84	0	5.03	03535160
58.08	0	3.08	03535180
45.41	0	6.25	03538900
40.13	0	3.12	03539100
190.08	0	1.89	03541100



Nashville-Davidson County.

Table 1.--Stations used to calibrate the U.S. Geological

Station Number	Stream and Location	Drainage area (mi^2)	L (mi)
03541200	Forked Creek near Oakdale, Tenn.	2.44	3.03
03597300	Wartrace Creek above Bell Buckle, Tenn.	4.99	4.20
03597400	Wartrace Creek near Bell Buckle, Tenn.	9.59	6.08
03597450	Kelly Creek tributary near Bell Buckle, Tenn.	0.73	1.70
03597500	Wartrace Creek at Bell Buckle, Tenn.	16.3	8.30
03597550	Muse Branch near Bell Buckle, Tenn.	1.86	4.02
03604070	Coon Creek tributary near Hohenwald, Tenn.	0.51	0.87
03604080	Hugh Hollow Branch near Hohenwald, Tenn.	1.52	2.16
03604090	Coon Creek above Chop Hollow near Hohenwald, Tenn.	6.02	3.14
03604100	Coon Creek near Hohenwald, Tenn.	10.1	5.23
07028930	Turkey Creek at Medina, Tenn.	4.75	3.50
07028935	Turkey Creek tributary near Medina, Tenn.	1.08	1.80
07028940	Turkey Creek near Medina, Tenn.	7.87	4.56
07028950	Turkey Creek near Fairview, Tenn.	13.3	6.78

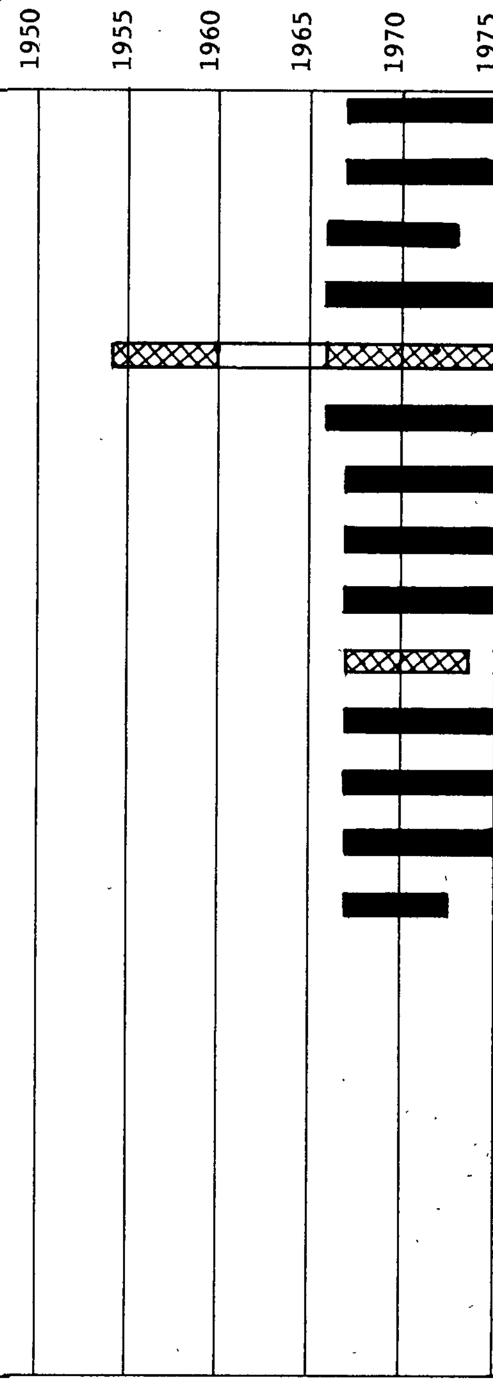
Continuous record

Flood hydrograph-rainfall record

Crest-stage record

Survey rainfall-runoff model.--Continued.

S (ft/mi)	Impervious area (percent)	Basin lag time (hrs)	Period and type of record	Station Number
237.60	0	2.58		03541200
49.63	0	1.79		03597300
31.68	0	2.42		03597400
132.00	0	0.83		03597450
25.71	0	3.33		03597500
58.08	0	1.71		03597550
200.48	0	1.76		03604070
105.60	0	1.33		03604080
73.92	0	1.50		03604090
49.63	0	2.32		03604100
34.32	0	1.70		07028930
52.80	0	1.12		07028935
26.93	0	2.10		07028940
18.48	0	2.86		07028950



Records were initially scanned for completeness and for the magnitude of the stage peaks recorded. This information was listed and was later used to select storms for processing. General criteria for selecting storm events for model calibration involved several factors that, due to wide variations in available data, were applied subjectively. A range of storm types and antecedent conditions was sought to be sure that data to which the different parameters were sensitive were included in the sample. A balance of data was desired that would represent short-duration, high-intensity storms and long-duration, low-intensity storms, dry and wet antecedent conditions, large and small peaks, as well as winter and summer storms. Another criterion in selecting storm events was that a reasonable separation of direct runoff from total flow could be made since the model calibrates only on direct runoff. Rainfall distribution over the basin was checked for uniformity, particularly on thunderstorm events which are usually very localized. Events having rainfall variations of more than 50 percent were eliminated. Deviations from the above criteria were permitted at some stations because of conflicts within the criteria, for example, the inability to separate base flow for extremely small storms at some stations precluded their use.

Calibration Results

Final values of the model parameters for the modeled basins are shown in table 2. Average error of simulated peak discharges was 36 percent, and no bias was evident from the results of the final calibrations. Accuracy of simulated peaks was better for larger peaks than for smaller peaks. This trend is assumed to be the result of an effectively simpler model simulating the larger peaks. Saturated soil conditions exist during most of the large storm events. Under these conditions, most of the parameters within the antecedent-moisture-accounting component and several of those within the infiltration component have a negligible effect upon losses. These parameters are effectively ignored within the model, and any error introduced by them would be negligible. These very parameters are the ones that should have major impact in simulating the smaller events, particularly with dry antecedent conditions. Calibration results from basins larger than about 15 mi^2 (38.8 km^2) were noticeably poorer than those from smaller basins. The sources of the increased error were in simulation of precipitation excess, and its cause apparently lies in the rainfall variation over these larger basins.

As previously mentioned, parameters affecting the loss components of the model were constrained during initial calibration with the range of reasonable occurence in the field. With only few exceptions, final parameter values are within those limits. The constraints were applied to prevent unreasonable parameter distortion from parameter interaction. Although several of the parameters resulted in variations consistent with their physical occurrence, it seems improbable that parameter values for ungaged basins can be predicted with accuracy. KSAT is a good example of the effects of parameter interaction. Basins having thin, tight soils generally produced smaller values of KSAT than did basins having thicker more permeable soils. This trend was consistent with expectations. Variation in KSAT between adjacent basins, however, was frequently over 100 percent, even though physical characteristics of the basins appear to be similar.

Because hydrograph shape parameters were either computed from selected hydrographs or severely constrained during optimization, very little of the parameter interaction so prevalent in the loss parameters was present in the routing parameters. Phase 2 error values were generally in the range of 15 to 20 percent, with some as low as 10 percent. With KSW and TC determined as mentioned previously and TP/TC assumed equal to 0.5, basin lag time can be computed from these parameters. A rigorous analysis of the model routing, O'Kelly (1955), shows that the time from the centroid of precipitation excess to the centroid of direct runoff is equal to one-half the base of the isosceles triangle translation hydrograph plus the linear storage constant. In terms of the model parameters, this relation reduces to

$$T_L = KSW + 1/2\ TC,$$

where T_L is basin lag time in hours. Units of both KSW and TC are in hours. Lag times for the calibrated basins are included in table 1.

Table 2. Summary of calibrated

Station number	PSP* (in.)	KSAT* (in./hr)	DRN*	RGF*	BMSM* (in.)	EVC*	RR*
03313600	3.210	0.085	0.551	18.300	5.100	0.945	0.868
03313620	8.710	0.109	0.123	14.900	1.490	0.839	0.922
03418900	3.070	0.103	0.367	10.200	2.350	0.621	0.980
03420360	5.060	0.081	0.338	13.500	6.860	0.829	0.880
03420380	1.560	0.034	0.338	15.100	5.060	0.960	0.979
03420400	2.610	0.058	0.339	10.300	1.930	0.850	0.990
03427830	5.770	0.072	0.412	19.900	3.110	0.801	0.810
03427840	1.450	0.034	0.250	12.000	0.917	0.850	0.900
03430400	1.260	0.029	0.124	14.900	3.980	0.829	0.911
03430600	2.520	0.061	0.260	10.000	1.580	0.590	0.910
03430700	2.230	0.087	0.462	4.720	2.520	0.811	0.899
03431000	1.260	0.078	0.400	6.900	3.460	0.900	0.900
03431080	5.850	0.112	0.131	15.500	1.580	0.791	0.980
03431120	2.020	0.087	0.634	6.990	1.050	0.845	0.759
03431240	7.990	0.123	0.152	24.700	7.880	0.829	0.979
03431340	8.940	0.082	0.526	15.300	8.990	0.829	0.980
03431520	5.820	0.077	0.532	12.300	6.580	0.747	0.911
03431580	1.940	0.043	0.437	8.390	2.660	0.829	0.870
03431600	3.250	0.062	0.242	4.400	4.730	0.622	0.203
03431630	2.520	0.075	0.913	20.800	5.000	0.822	0.928
03431650	7.770	0.128	0.123	9.740	3.460	0.720	0.980
03431700	2.690	0.090	0.345	19.900	3.940	0.845	0.878
03435020	3.030	0.073	0.566	15.600	3.080	0.850	0.900
03435030	2.990	0.085	0.430	9.320	1.500	0.850	0.900
03435600	6.710	0.094	0.823	17.600	4.760	0.890	0.983
03461200	2.880	0.080	0.222	26.800	1.120	0.980	0.888
03469110	3.750	0.095	0.968	10.400	1.800	0.760	0.979
03486225	6.900	0.168	0.490	27.200	6.150	0.727	0.880
03519610	7.880	0.137	0.367	13.700	3.070	0.990	0.894
03519630	7.100	0.232	0.488	7.310	3.120	0.924	0.900
03519640	7.220	0.164	0.385	4.270	2.680	0.824	0.830
	4.060	0.092	0.325	4.670	3.610	1.040	0.830
03519650	6.440	0.119	0.490	10.300	1.420	0.924	0.810
03535140	4.260	0.076	0.462	10.600	5.740	0.968	0.948
03535160	3.460	0.057	0.152	13.200	3.180	0.750	0.994
03535180	5.120	0.080	0.496	10.100	6.410	0.966	0.966
03538900	2.830	0.086	0.607	8.680	6.150	0.941	0.903
03539100	5.000	0.163	0.259	12.800	5.520	0.830	0.911
03541100	4.010	0.100	0.488	8.940	2.850	0.770	0.974
03541200	5.360	0.122	0.336	7.770	3.600	0.770	0.938

*See p. 6 for definitions of parameters

model parameters

KSW* (hrs)	TC* (min)	TP/TC*	Effective impervious area (percent)	Remarks	Station number
0.670	50	0.5	0		03313600
0.400	100	0.5	0		03313620
2.000	190	0.5	0		03418900
1.200	125	0.5	0		03420360
1.600	180	0.5	0		03420380
2.860	275	0.5	0		03420400
0.250	35	0.5	0		03427830
0.500	125	0.5	0		03427840
0.640	125	0.5	0		03430400
1.860	275	0.5	0		03430600
0.830	90	0.5	0		03430700
2.710	323	0.5	0		03431000
0.420	80	0.5	5		03431080
0.300	75	0.5	0		03431120
0.830	30	0.5	10		03431240
0.830	130	0.5	5		03431340
0.750	95	0.5	0		03431520
0.750	150	0.5	5		03431580
1.150	280	0.5	0		03431600
0.750	70	0.5	5		03431630
0.310	40	0.5	2		03431650
0.833	190	0.5	5		03431700
0.750	140	0.5	0		03435020
1.400	205	0.5	0		03435030
0.650	50	0.5	0		03435600
2.300	190	0.5	0		03461200
5.300	150	0.5	0		03469110
0.550	70	0.5	0		03486225
0.900	90	0.5	0		03519610
0.830	70	0.5	0		03519630
4.670	245	0.5	0	Summer storms	03519640
4.670	245	0.5	0	Winter storms	
1.500	90	0.5	0		03519650
1.000	65	0.5	0		03535140
3.200	220	0.5	0		03535160
1.750	160	0.5	0		03535180
4.170	250	0.5	0		03538900
1.570	186	0.5	0		03539100
1.170	87	0.5	0		03541100
1.500	130	0.5	0		03541200

Table 2. Summary of calibrated model

Station number	PSP* (in.)	KSAT* (in./hr)	DRN*	RGF*	BMSM* (in.)	EVC*	RR*
03597300	2.510	0.092	0.990	11.100	3.170	0.980	0.608
	1.430	0.052	0.506	9.090	2.520	0.945	0.900
03597400	1.940	0.029	0.419	8.630	2.580	0.850	0.900
03597450	5.670	0.180	0.320	11.700	1.420	0.924	0.608
	2.020	0.091	0.320	16.200	4.200	0.850	0.900
03597500	2.900	0.027	0.320	6.640	2.490	0.850	0.900
03597550	4.260	0.104	0.228	14.200	1.970	0.860	0.966
	2.960	0.030	0.698	10.000	1.700	0.828	0.920
03604070	7.350	0.145	0.779	23.800	3.820	0.946	0.945
03604080	6.490	0.138	0.077	25.600	5.930	0.840	0.858
03604090	9.560	0.243	0.365	34.200	8.050	0.964	0.850
	6.910	0.170	0.308	20.700	5.360	0.461	0.850
03604100	8.150	0.151	0.755	18.000	5.760	1.000	0.576
	8.030	0.048	0.409	19.000	4.860	0.850	0.792
07028930	2.110	0.061	0.958	17.900	5.360	0.905	0.900
07028935	1.580	0.030	0.338	29.300	6.520	0.850	0.900
07028940	1.640	0.033	0.175	20.300	4.720	0.821	0.900
07028950	1.840	0.043	0.230	6.350	2.290	1.020	0.810

*See p. 6 for definitions of parameters.

parameters.--Continued.

KSW* (hrs)	TC* (min)	TP/TC*	Effective impervious area (percent)	Remarks	Station number
0.920	90	0.5	0	Summer storms	03597300
0.920	120	0.5	0	Winter storms	
0.920	180	0.5	0		03597400
0.500	40	0.5	0	Summer storms	03597450
0.500	40	0.5	0	Winter storms	
1.250	250	0.5	0		03597500
1.000	85	0.5	0	Summer storms	03597550
1.000	85	0.5	0	Winter storms	
1.100	80	0.5	0		03604070
0.920	50	0.5	0		03604080
0.670	100	0.5	0	Summer storms	03604090
0.670	100	0.5	0	Winter storms	
1.100	120	0.5	0	Summer storms	03604100
1.030	185	0.5	0	Winter storms	
0.750	115	0.5	0		07028930
0.420	85	0.5	0		07028935
0.980	135	0.5	0		07028940
1.200	200	0.5	0		07028950

Notable Calibration Techniques

Most of the basins calibrated involved a straightforward application of the model. Data adequately fit within limits of model assumptions, and general calibration guidelines, as previously discussed, were sufficient to optimize the parameters. Situations arose, however, for which special techniques had to be established. Some of these situations involved judgment in interpreting the data so that model assumptions were not grossly violated. Others appear to be due to overstressing the model in handling particular circumstances. The following discussion points out the notable structures and describes how they were dealt with.

Separation of Base Flow

For most basins modeled, flow decreased rapidly after peaking and returned to a flow rate quite small in relation to the peak. Separating direct runoff from total runoff was fairly simple for this type of hydrograph. Figure 3 is a hydrograph from station 07028930 and is a good example of this type of response. Unsophisticated techniques for separating base flow produced acceptable estimates of direct runoff. This was mainly due to the base flow comprising a small part of the total flow. Errors in base flow estimates caused only minor errors in direct runoff estimates.

Figure 4, however, presents a hydrograph typical of those that require careful judgment for base flow separation. This hydrograph, from station 03541100, is one for which base flow separation is complex and potentially inaccurate. Flow components are indistinct and difficult to separate. The flow rate is high in relation to the peak flow long after the time direct runoff should have ceased. Direct runoff comprises a relatively small portion of total storm runoff, creating a situation in which appreciable errors in base flow estimates would cause appreciable errors in estimates of direct runoff. Therefore, when working with hydrographs of this type, some judgment must be made as to whether direct runoff can be reasonably estimated. Each hydrograph must be evaluated in this respect. Those for which direct runoff estimates cannot reasonably be made cannot be used for calibration.

Most hydrographs that had to be eliminated from the study because of problems with base flow separation were from small

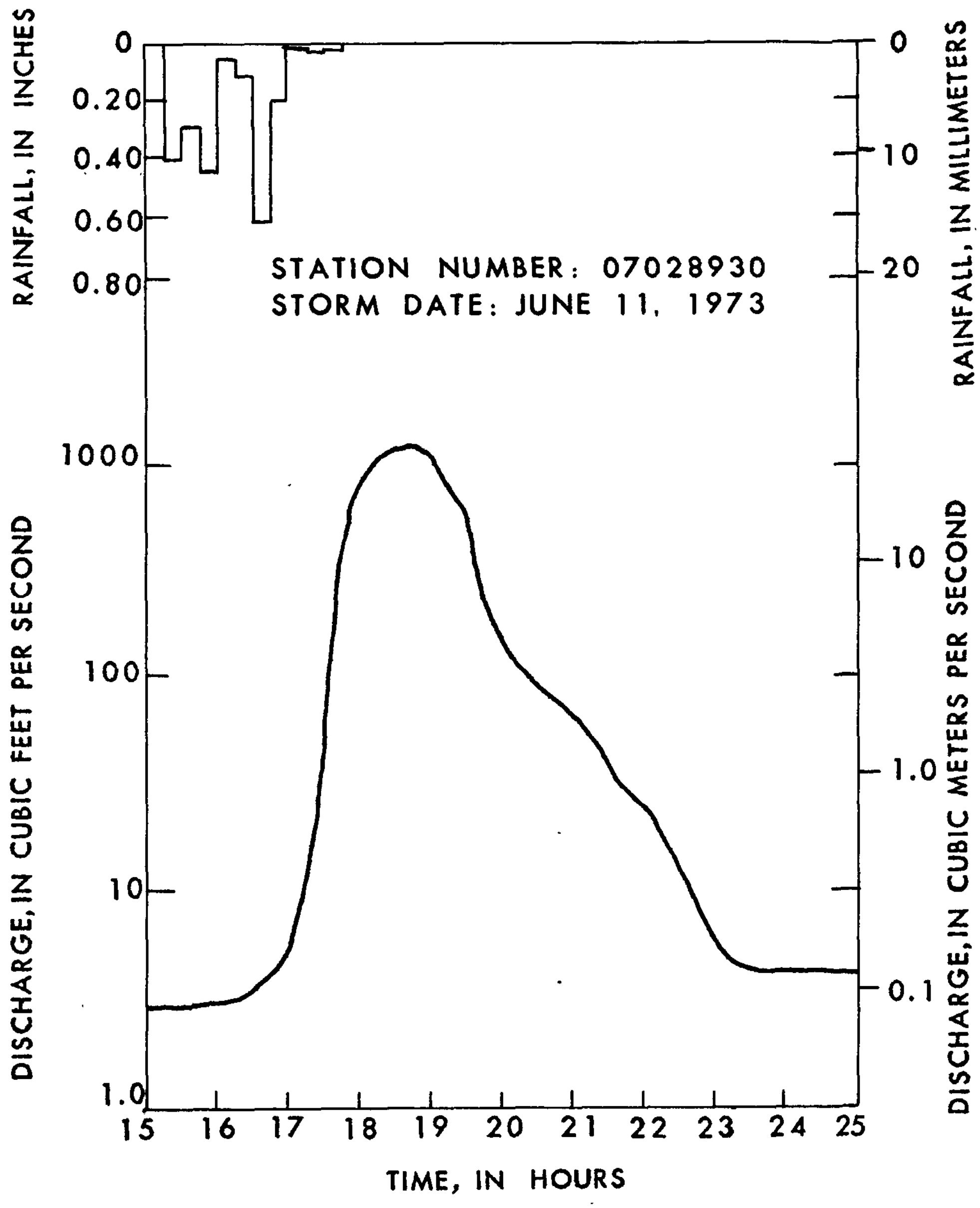


Figure 3.--Hydrograph for which base-flow separation can be made accurately.

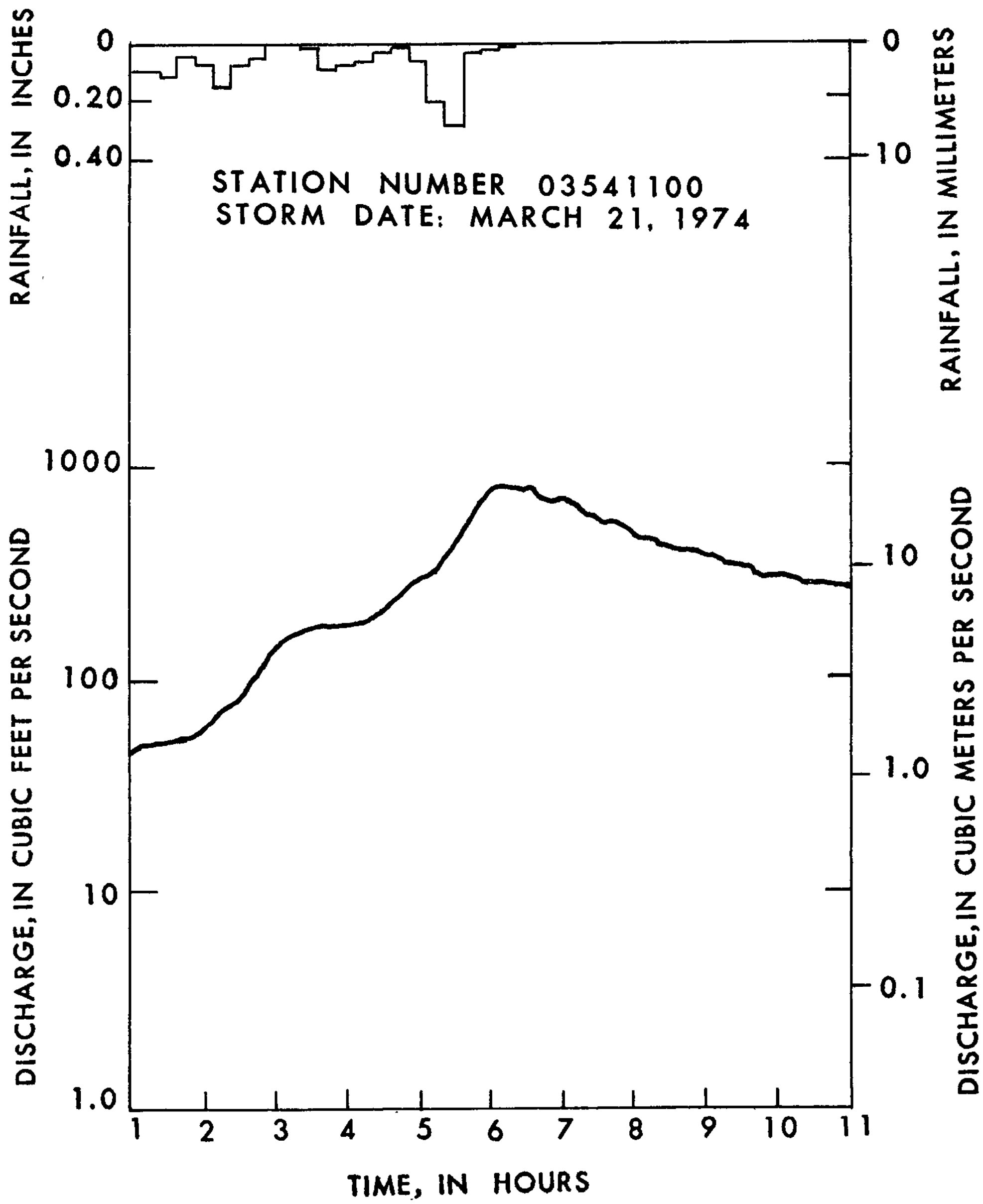


Figure 4.--Hydrograph for which base-flow separation is complex and potentially inaccurate.

storms in which secondary flow components dominate total flow. Hydrographs displaying this dominating secondary flow component appeared most frequently from stations in the eastern one-third of Tennessee. Impact upon model results due to systematic elimination of storms has not been evaluated, however, it seems reasonable to expect poorer results in simulation of the smaller events. The "A" option of the model was used extensively for base flow separation on the marginally usable hydrographs.

Non-Linearity

A second situation for which special calibration techniques had to be devised was one of apparent non-linearity of hydrographs from a number of East Tennessee basins. The adjective "apparent" is purposely used to describe this situation because it was most prevalent at basins that exhibited the dominating secondary flow components mentioned in the preceding section. It is possible that true basin lag time is partially masked on small storms from these basins and that actual non-linearity does not exist. However, based on the best estimate of the direct runoff hydrographs, variable hydrograph time and shape characteristics were indicated, and as such the basins do not fit with the definition of linearity as summarized by Dooge (1973). Unit hydrograph theory assumes a linear system in which basin lag time should be independent of both the intensity and duration of rainfall.

The hydrographs in figure 5 and figure 6 are typical of the variation encountered. The larger, higher-intensity storms tend to produce more consistent and steeper hydrograph recession slopes and shorter lag times than do the smaller, lower-intensity storms. The Survey model routing scheme, however, utilizes unit hydrograph theory which assumes basin response time to be a constant. Therefore, judgment must be made on each station as to the extent of deviation of the hydrographs from linearity. If the deviation is minor, model routing parameters can be determined from typical hydrographs or optimized by the model. If the deviation is considerable, only two choices can be made. One choice would be to eliminate the station from the analysis. The other would be to pick routing parameters from larger storms in cases where these storms indicate more consistent lag times. This second choice was generally used in handling the problem stations during the study. The storms used for selecting the model routing parameters typically had rainfall of short duration, with respect to basin lag time, that ended abruptly, and had peak flows within the range of the annual peaks. The resultant routing parameters should produce more representative annual peaks than if the smaller storms had been given

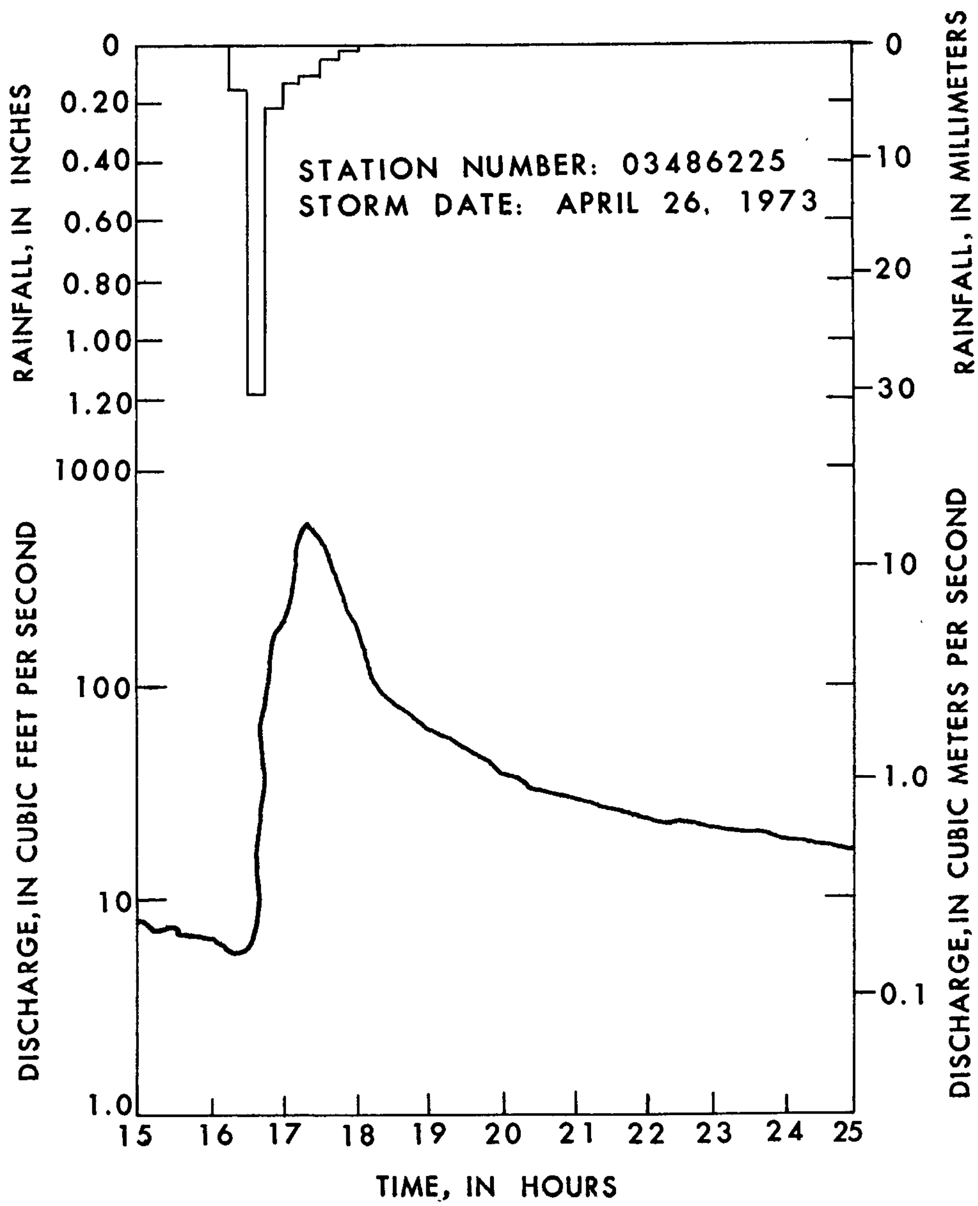


Figure 5.--Hydrograph typical of those on which model routing parameters should be determined.

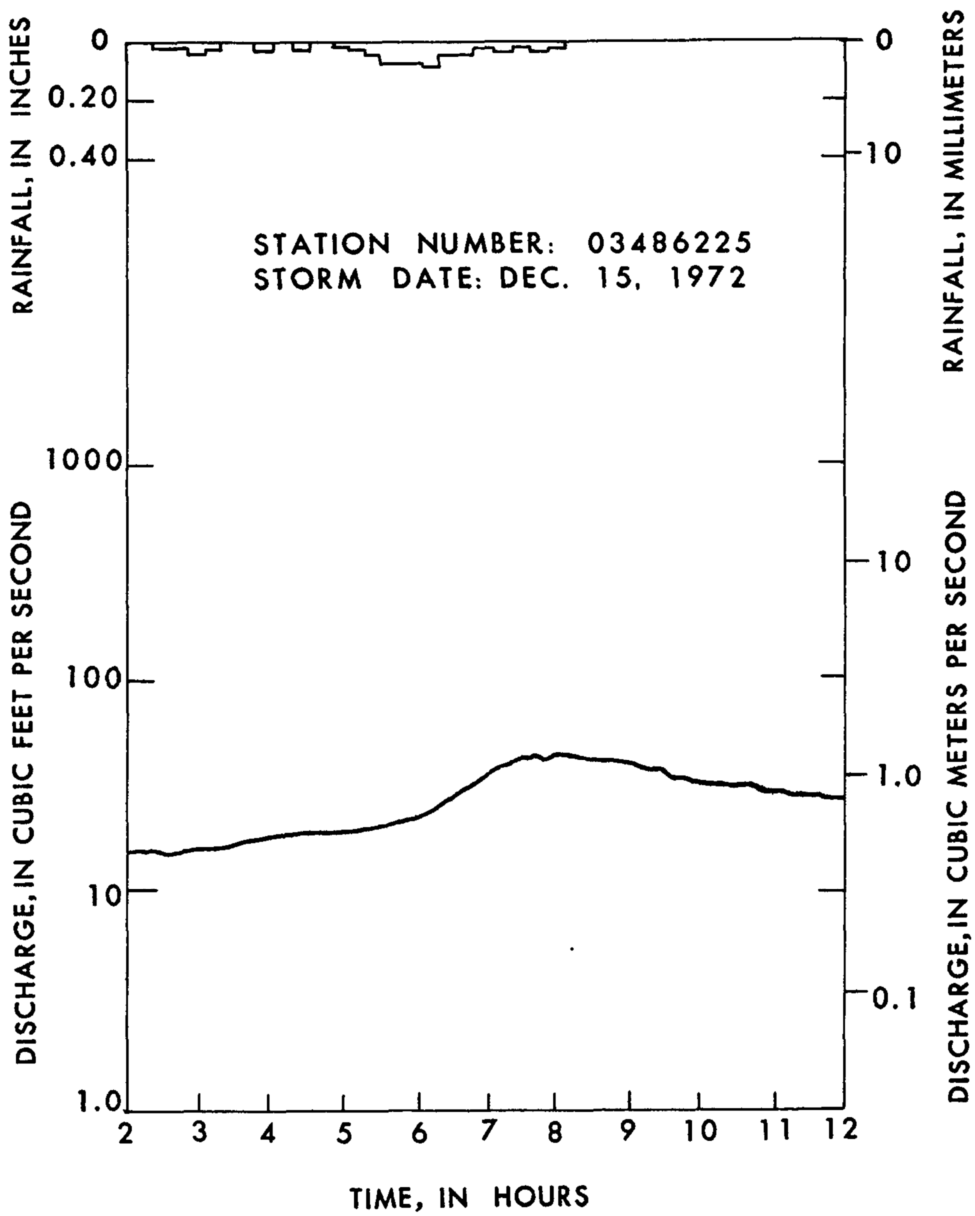


Figure 6.--Hydrograph typical of those that should not be used to determine model routing parameters.

weight. This technique for determining routing parameters would have a tendency to sacrifice simulation accuracy of the smaller storms in order to better reproduce the larger ones.

Potentially the most serious problem in modeling basins that deviate from linearity, is not having sufficient data to define the basin response of the larger storms. If the data were collected in a short period or during an unusually dry period such that few, if any, large storms are available for analysis, resultant routing parameters could be grossly over estimated. The peak discharge from most of the large storms would then be underestimated during simulation.

Seasonal Bias

A tendency for seasonal bias was indicated in simulating direct runoff volumes for some of the basins. It was relatively insignificant on most basins, however it was extensive on six of them. Calibrations for several of the six problem basins produced phase one errors in excess of 50 percent. The majority of the direct runoff volumes of events occurring from about mid-April through October were overestimated, and most of those during the rest of the year were underestimated.

The basins for which seasonal bias resulted varied considerably in physical characteristics. Forest cover ranged from 3.7 to 95.9 percent and main channel slope ranged from 17.4 to 132 ft/mi (3.28 to 24.9 m/km). Soil cover ranged from a thin layer of tight clay overlying limestone to a thicker, more permeable clay overlying deep overburden. Consequenty, it was not possible to generalize the type of basin from which seasonal bias could be expected and restructure the model to minimize this bias.

As an example of this bias, phase one results from station 03597300, are presented in figure 7. The fitting error was 43 percent. Eight of the summer-storm direct runoff volumes were overestimated and one was underestimated. The direct runoff volumes of fourteen winter storms were underestimated and three were overestimated. Figures 8 and 9 are the phase one results from separate calibrations of the summer and winter storms respectively, with events occurring between April 15 and October 31 being designated summer storms and those occurring between November 1 and April 14 being designated winter storms. Phase one fitting error was 27.5 and 19.9 percent for the summer and winter calibrations respectively. Bias within each storm group was eliminated, and the resultant parameters should produce more reliable simulated runoff within their respective periods of the year.

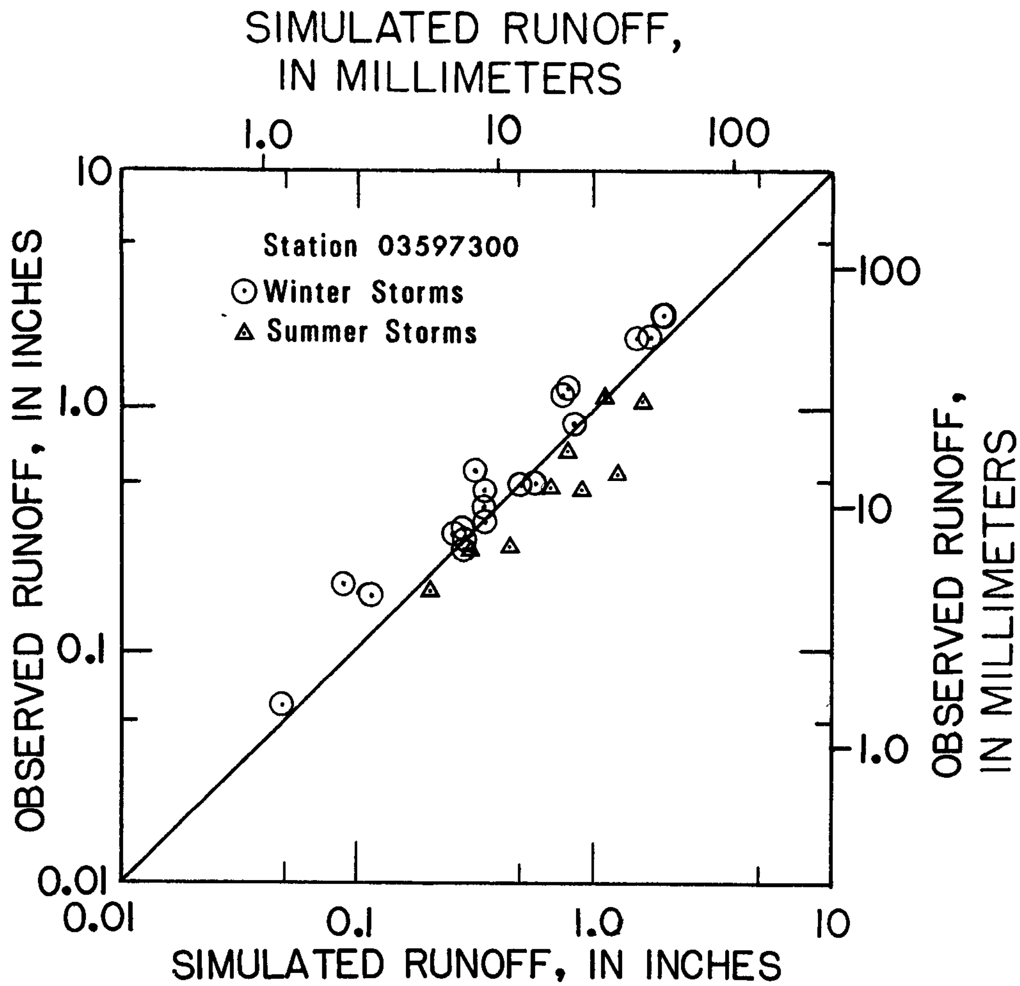


Figure 7.--Results of volumetric optimization using both summer and winter storms.

The net effect of differences between the sets of parameters from the six stations having significant seasonal bias was that the loss functions of the model were increased significantly by the summer parameters as compared with the winter parameters. KSAT was the parameter that consistently changed the most. The ratio of summer KSAT to winter KSAT ranged from 1.43 to 3.47 for these stations. Whether a seasonal variation of KSAT of this magnitude is realistic or not is difficult to assess. Other factors, such as extremes in antecedent moisture and vegetal cover, undoubtedly have an impact upon summer storm losses being greater than those for winter storms. In addition, summer rainfall is normally the result of thunderstorm activity and as such is generally of

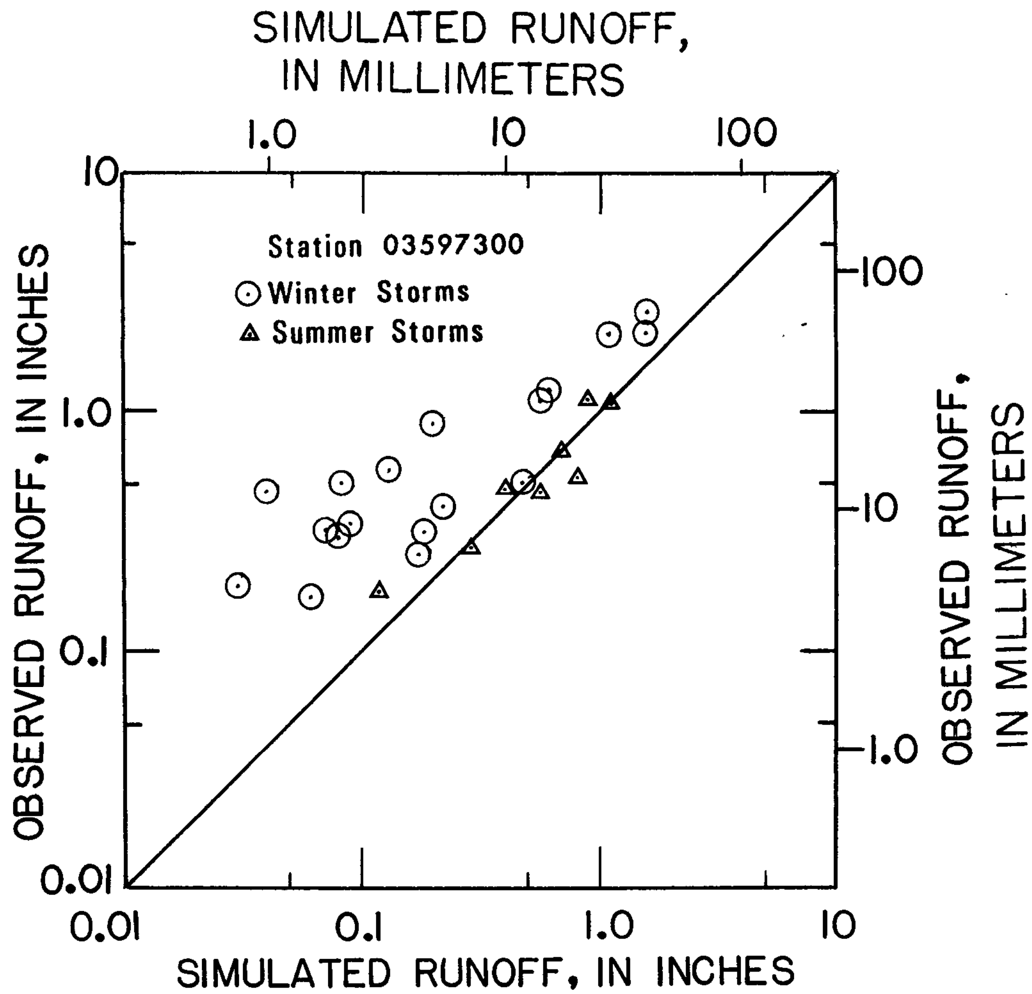


Figure 8.--Results of volumetric optimization using summer storms only.

short duration and high intensity. Winter rainfall, however, is most frequently of longer duration and lower intensity as the result of major frontal storms. The impact of these variations may be masked within and show up as a factor affecting KSAT.

Effective Impervious Area

Studies of other urban areas have indicated that not all the man-made impervious cover was effective in producing additional runoff. Essentially the same situation was indicated by data in the vicinity of Nashville. For all the urban basins calibrated, small storm direct runoff volumes were grossly

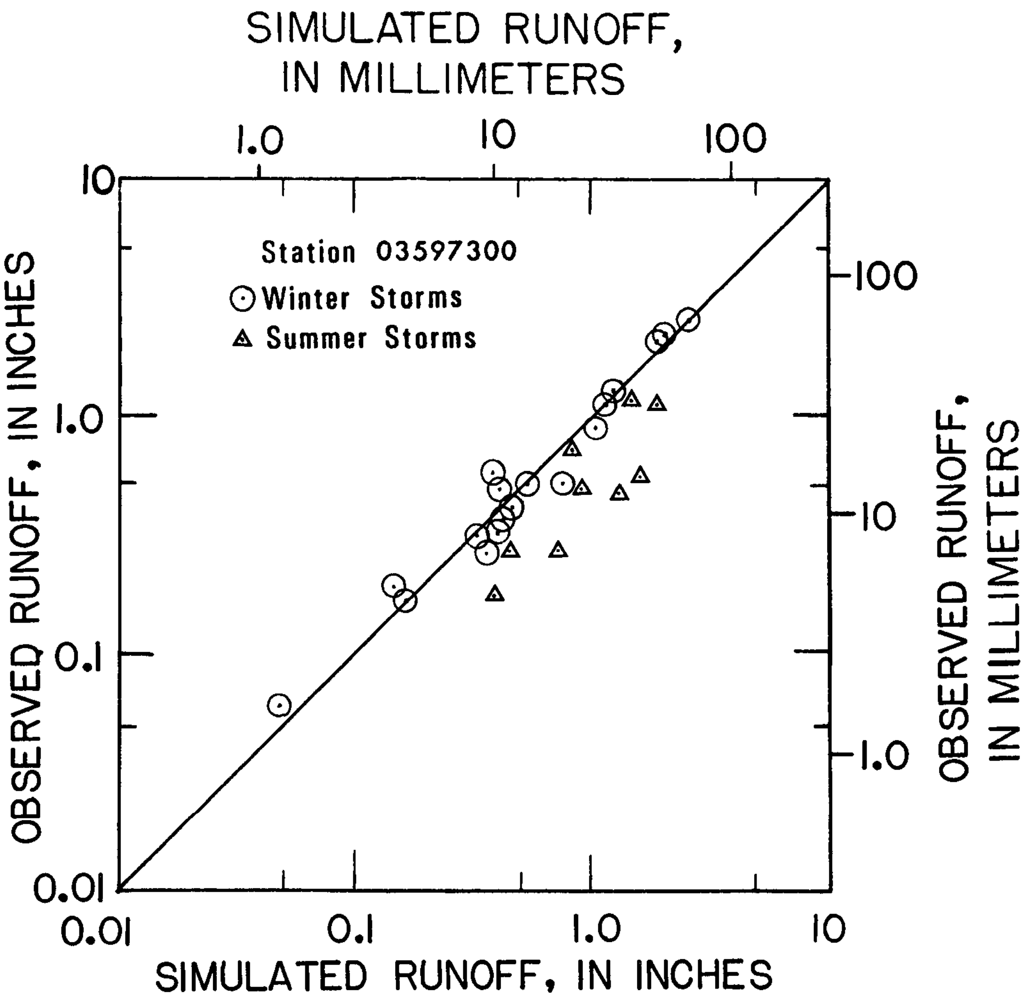


Figure 9.--Results of volumetric optimization using winter storms only.

overestimated when the measured percent of impervious area was given as input to the model. The phase one results from station 03431080 shown in figure 10 are typical.

In attempting to achieve a better fit of the smaller storm runoff volumes, the larger storm runoff volumes were frequently underestimated. In addition to this bias, several model parameters, mainly PSP, KSAT, and RGF, were forced outside a reasonable range of occurrence during optimization. The net effect of the unusual parameter values was to drastically reduce runoff from the pervious areas to compensate for the increased runoff from the impervious areas.

Data from the Nashville area do not support runoff volumes

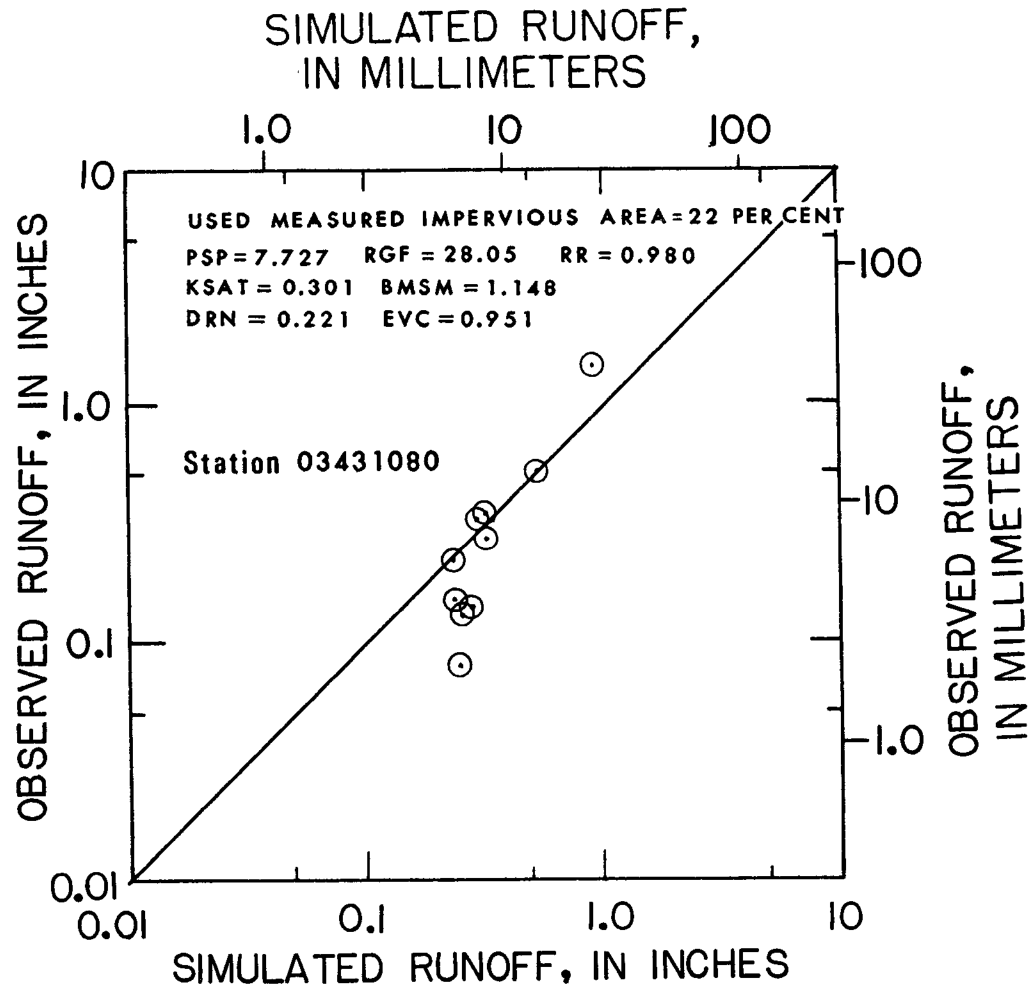


Figure 10.--Results of volumetric optimization using measured impervious area.

as large as those produced by the model. It seemed evident that either the impervious surfaces were storing more than 0.05 in (1.27 mm) of precipitation or portions of the flow from the impervious surfaces were subsequently infiltrated while being routed over pervious areas enroute to the stream channels.

Selection of final parameters was based on the assumption that only part of the impervious area was effective in increasing runoff. This approach was similar to that used by Durbin (1974) in his study of the Upper Santa Ana Valley in California. During subsequent calibrations, the percent impervious area was successively reduced until small runoff events were satisfactorily reproduced. As a result of applying this technique, basins having less than 5 percent man-made impervious area were calibrated with no effective impervious area. The average effective impervious area of the other urban basins was 22 percent of the measured impervious area. The values of effective impervious area for individual basins were fairly close to those given by Durbin's curve relating the effective impervious area in drainage basins to the area affected by urban development. Figure 11 shows the phase 1 results from station 03431080 using a reduced value of impervious area.

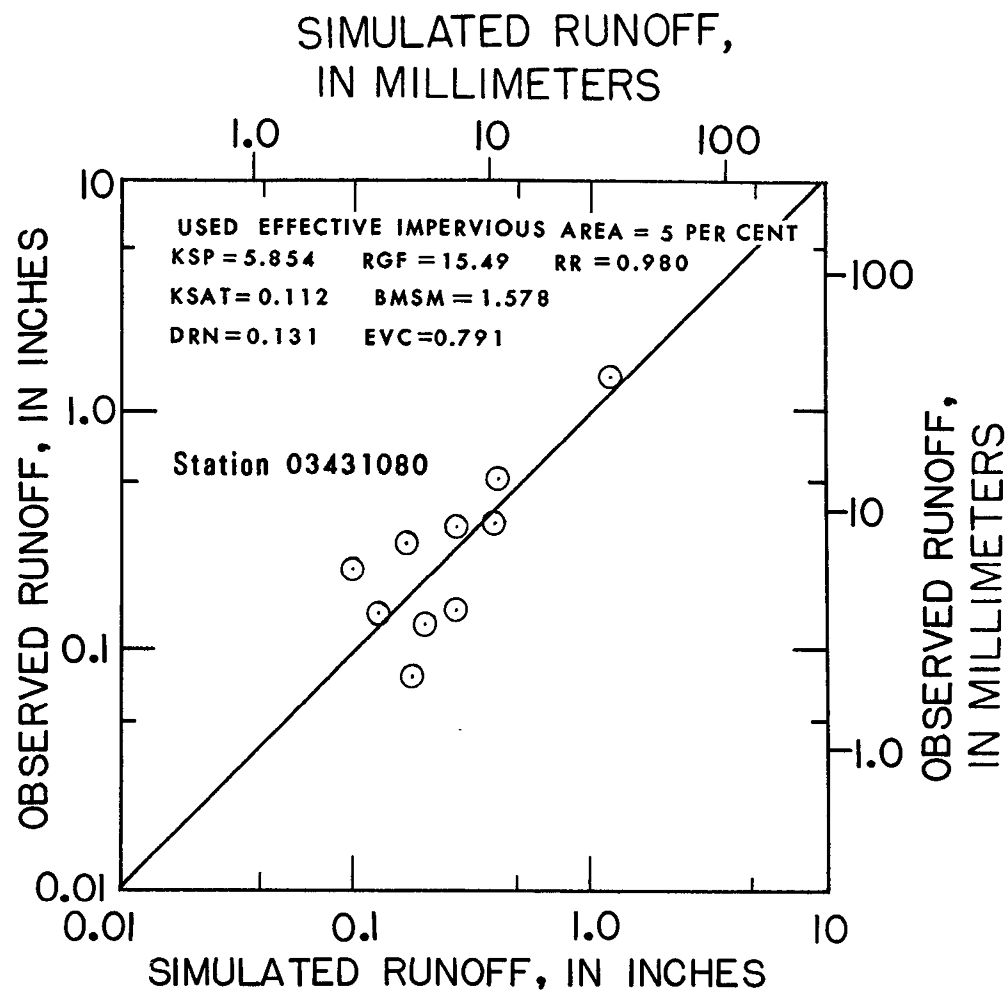


Figure 11.--Results of volumetric optimization using reduced value of impervious area.

PEAK DISCHARGE SIMULATIONS

Model parameters, drainage area, and percent of effective impervious area of each calibrated basin along with the Center Hill Dam pan evaporation data were used successively with each of the long-term precipitation stations to develop four series of peak discharges for each basin. The highest simulated peak for each water year was used to compute four log-Pearson type III discharge-frequency curves for each of the calibrated gage sites.

Annual peak discharge determination was handled a little differently at stations for which seasonal calibrations were made. Two series of peak discharges were simulated; one using summer parameters and one using winter parameters. For each water year the highest discharge from the winter and summer periods was chosen as the annual peak.

Simulation Results

The simulated frequency curves produced estimates of t-year discharges for individual stations that varied with the long-term rainfall data used. A t-year discharge is that discharge corresponding to a specific recurrence interval. Because of the variation, a technique was needed to form a composite curve from the four simulated curves. Table 3 presents the simulated discharges from the four long-term rainfall records for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals for each model basin. Figure 12 shows the simulated curves for station 03597500 along with the frequency curve based on 22 years of observed annual peaks.

The simulated data were analyzed by two methods to determine relative trends. The first method tested the four series of annual peaks in pairs for identical distributions via the Cramer-von-Mises-Two-Sample test as described by Conover (1971). Test results indicated that Memphis, Nashville, and Chatanooga rainfall data would produce simulated flood series from the same distribution but that Knoxville data would not.

The second analysis was essentially an overview of the four sets of frequency curves and indicated that identical distributions as determined from the above test do not necessarily produce comparable discharge-frequency curves. In general, Memphis and Knoxville data produced comparable 100-year flood estimates. Nashville and Chattanooga data also produced comparable 100-year flood estimates, however, they were usually lower than those based on Memphis and Knoxville data. At the 2-year flood level, Memphis data consistently produced the highest values, and Knoxville data produced the

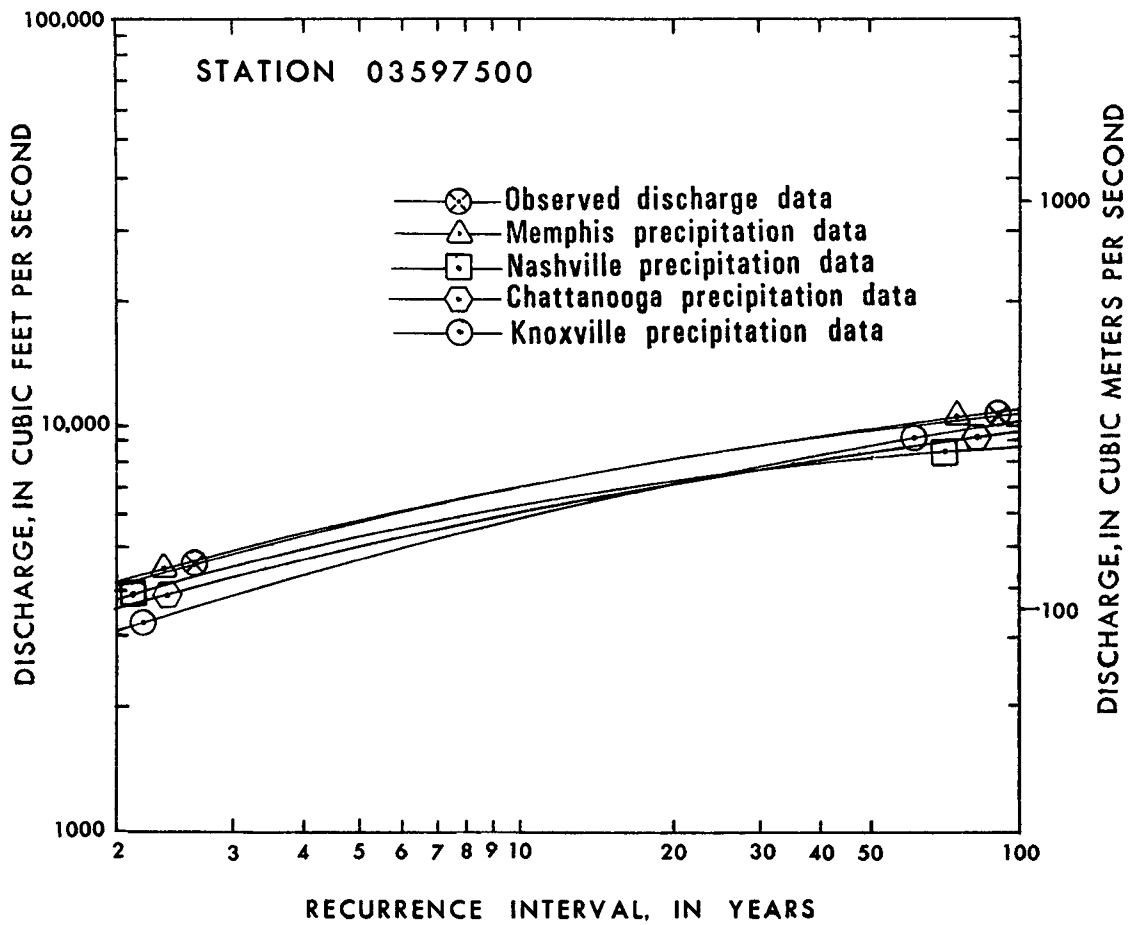


Figure 12.--Frequency curves based on observed and simulated data.

lowest ones. Nashville and Chattanooga data resulted in comparable 2-year flood estimates within the discharge range established by Memphis and Knoxville data.

The average spread between highest and lowest values among the sets of 100-year discharge estimates was 28 percent of the lowest values. The maximum was 64 percent, and the minimum was 7 percent. At the 2-year recurrence interval, average difference in extremes was 79 percent. Elimination of the t-year estimate based on the most distant rainfall record reduced the scatter considerably. Average spread of extremes decreased to 19 percent for the 100-year values and decreased to 47 percent for the 2-year values.

As a result of the above comparisons, a method for developing composite curves was selected that utilized frequency

Table 3.--Summary of simulated flood frequency values for modeled basins.

Station number	Drainage area (mi^2)	Long-term rainfall station	Simulation results						
			Q_2 (ft^3/s)	Q_5 (ft^3/s)	Q_{10} (ft^3/s)	Q_{25} (ft^3/s)	Q_{50} (ft^3/s)	Q_{100} (ft^3/s)	Skew coefficient
03313600	0.95	Memphis	260	416	528	677	792	912	-0.127
		Nashville	213	371	477	606	697	784	-0.603
		Chattanooga	256	401	493	604	682	755	-0.499
		Knoxville	148	286	404	583	739	914	-0.001
03313620	3.03	Memphis	480	884	1200	1640	1990	2370	-0.218
		Nashville	356	692	936	1250	1480	1700	-0.599
		Chattanooga	458	822	1090	1440	1710	1990	-0.366
		Knoxville	259	520	760	1150	1510	1930	-0.165
03418900	1.52	Memphis	237	357	442	552	638	725	-0.053
		Nashville	212	328	394	464	508	545	-0.871
		Chattanooga	203	306	384	496	589	691	0.339
		Knoxville	160	267	353	478	585	703	0.191
03420360	2.28	Memphis	389	631	804	1030	1200	1380	-0.212
		Nashville	302	530	685	878	1020	1150	-0.556
		Chattanooga	371	578	713	876	991	1100	-0.451
		Knoxville	221	422	594	856	1090	1350	0.045
03420380	1.03	Memphis	252	354	426	522	598	677	0.221
		Nashville	229	327	387	459	508	555	-0.412
		Chattanooga	229	315	375	452	512	574	0.151
		Knoxville	184	278	352	459	549	648	0.401
03420400	7.30	Memphis	1060	1540	1870	2300	2630	2970	0.029
		Nashville	932	1380	1630	1910	2090	2250	-0.733
		Chattanooga	894	1280	1560	1950	2260	2590	0.282
		Knoxville	752	1150	1460	1890	2250	2630	0.243
03427830	0.17	Memphis	68	115	148	192	226	259	-0.311
		Nashville	54	101	132	170	196	221	-0.694
		Chattanooga	66	109	138	173	199	223	-0.486
		Knoxville	36	71	101	145	183	226	-0.064
03427840	3.54	Memphis	1510	2050	2440	2970	3400	3860	0.449
		Nashville	1370	1970	2350	2800	3120	3420	-0.374
		Chattanooga	1390	1940	2330	2850	3260	3690	0.251
		Knoxville	1170	1800	2260	2900	3420	3970	0.121
03430400	12.0	Memphis	4890	6680	7930	9600	10900	12300	0.274
		Nashville	4500	6390	7590	9040	10100	11100	-0.289
		Chattanooga	4530	6290	7550	9260	10600	12000	0.322
		Knoxville	3830	5800	7270	9300	11000	12700	0.195
03430600	43.0	Memphis	7950	11400	13800	16900	19400	21600	0.074
		Nashville	7060	10300	12200	14300	15700	16900	-0.682
		Chattanooga	6640	9470	11600	14600	17200	19900	0.479
		Knoxville	5660	8660	11000	14500	17500	20900	0.446
03430700	3.86	Memphis	1360	1910	2290	2780	3170	3560	0.106
		Nashville	1220	1840	2220	2680	3000	3290	-0.478
		Chattanooga	1240	1800	2210	2760	3200	3670	0.222
		Knoxville	1000	1620	2100	2760	3300	3880	0.058
03431000	64.0	Memphis	10500	14900	18000	22200	25500	28900	0.147
		Nashville	9310	13400	15900	18800	20800	22700	-0.475
		Chattanooga	8860	12500	15100	18600	21300	24100	0.203
		Knoxville	7560	11200	14100	18100	21400	25000	0.367

Table 3.--Summary of simulated flood frequency values for modeled basins.--Continued

Station number	Drainage area (mi^2)	Long-term rainfall station	Simulation results						
			Q_2 (ft^3/s)	Q_5 (ft^3/s)	Q_{10} (ft^3/s)	Q_{25} (ft^3/s)	Q_{50} (ft^3/s)	Q_{100} (ft^3/s)	Skew coefficient
03431080	3.92	Memphis	958	1550	1990	2570	3040	3520	-0.104
		Nashville	766	1330	1710	2180	2520	2840	-0.540
		Chattanooga	935	1500	1880	2360	2710	3060	-0.355
		Knoxville	566	1040	1450	2100	2690	3380	0.248
03431120	3.30	Memphis	1600	2290	2780	3410	3910	4420	0.099
		Nashville	1420	2220	2750	3410	3870	4330	-0.411
		Chattanooga	1550	2260	2750	3360	3830	4300	-0.095
		Knoxville	1210	2010	2610	3410	4040	4690	-0.162
03431240	1.58	Memphis	307	508	659	868	1030	1210	-0.058
		Nashville	232	408	550	738	934	1130	0.048
		Chattanooga	294	500	659	885	1070	1270	-0.012
		Knoxville	175	311	430	619	792	995	0.385
03431340	13.2	Memphis	2060	3500	4580	6030	7180	8380	-0.179
		Nashville	1560	2900	3950	5430	6620	7880	-0.223
		Chattanooga	1970	3290	4250	5550	6570	7610	-0.187
		Knoxville	1150	2200	3130	4580	5880	7390	0.149
03431520	4.13	Memphis	954	1530	1920	2410	2770	3120	-0.377
		Nashville	771	1370	1790	2330	2720	3110	-0.495
		Chattanooga	915	1450	1830	2310	2680	3050	-0.234
		Knoxville	540	1000	1410	2040	2600	3250	0.179
03431580	13.3	Memphis	4560	6310	7560	9230	10600	11900	0.282
		Nashville	4160	6010	7190	8610	9630	10600	-0.315
		Chattanooga	4110	5780	7010	8700	10100	11500	0.366
		Knoxville	3480	5330	6730	8690	10300	12000	0.222
03431600	51.6	Memphis	10300	15100	18700	23700	27800	32100	0.323
		Nashville	8880	13800	16800	20300	22800	25000	-0.583
		Chattanooga	8750	12800	15900	20100	23500	27100	0.270
		Knoxville	7310	11800	15400	20400	24600	29200	0.161
03431630	2.21	Memphis	641	974	1210	1510	1740	1970	-0.119
		Nashville	569	923	1150	1400	1580	1740	-0.653
		Chattanooga	644	971	1190	1460	1650	1850	-0.296
		Knoxville	416	726	980	1360	1690	2060	0.151
03431650	2.66	Memphis	903	1490	1890	2390	2770	3130	-0.400
		Nashville	743	1380	1850	2460	2910	3360	-0.493
		Chattanooga	879	1460	1870	2410	2820	3240	-0.288
		Knoxville	497	961	1370	2010	2580	3250	0.128
03431700	24.3	Memphis	4570	7140	8990	11500	13400	15400	-0.050
		Nashville	3890	6230	7690	9410	10600	11700	-0.629
		Chattanooga	4320	6540	8010	9840	11200	12500	-0.288
		Knoxville	3000	5110	6800	9250	11300	13600	0.105
03435020	9.32	Memphis	2110	3310	4160	5280	6160	7050	-0.115
		Nashville	1890	3050	3730	4470	4940	5360	-0.836
		Chattanooga	1990	3030	3770	4750	5510	6290	-0.036
		Knoxville	1430	2480	3280	4390	5290	6250	-0.117
03435030	15.1	Memphis	2710	4070	5060	6390	7440	8540	0.081
		Nashville	2330	3640	4420	5280	5840	6330	-0.760
		Chattanooga	2350	3480	4280	5350	6190	7060	0.051
		Knoxville	1840	3080	4050	5460	6630	7910	0.098

Table 3.--Summary of simulated flood frequency values for modeled basins.--Continued.

Station number	Drainage area (mi^2)	Long-term rainfall station	Simulation results						
			Q_2 (ft^3/s)	Q_5 (ft^3/s)	Q_{10} (ft^3/s)	Q_{25} (ft^3/s)	Q_{50} (ft^3/s)	Q_{100} (ft^3/s)	Skew coefficient
03435600	3.50	Memphis	669	1190	1580	2120	2540	2980	-0.253
		Nashville	528	1020	1360	1790	2090	2370	-0.700
		Chattanooga	684	1210	1580	2040	2370	2700	-0.514
		Knoxville	334	695	1040	1630	2190	2890	0.257
03461200	10.2	Memphis	1080	1740	2190	2780	3210	3640	-0.316
		Nashville	874	1590	2050	2570	2920	3230	-0.843
		Chattanooga	980	1580	1970	2450	2790	3120	-0.484
		Knoxville	729	1300	1730	2330	2820	3330	-0.189
03469110	2.18	Memphis	175	271	340	432	504	578	-0.046
		Nashville	150	240	292	346	379	407	-0.944
		Chattanooga	150	231	291	374	442	513	0.126
		Knoxville	112	193	260	359	444	541	0.194
03486225	4.88	Memphis	561	1160	1660	2400	3010	3690	-0.241
		Nashville	409	929	1360	1990	2490	3020	-0.477
		Chattanooga	560	1200	1740	2540	3200	3910	-0.326
		Knoxville	243	565	903	1520	2160	2990	0.306
03519610	2.10	Memphis	214	419	589	842	1060	1290	-0.129
		Nashville	161	327	455	627	759	892	-0.520
		Chattanooga	198	378	524	738	918	1110	-0.123
		Knoxville	109	222	323	483	628	794	0.031
03519630	1.46	Memphis	148	283	396	563	705	864	-0.058
		Nashville	119	242	337	465	563	662	-0.521
		Chattanooga	137	264	369	524	655	799	-0.100
		Knoxville	74	167	260	424	585	787	0.222
03519640	16.0	Memphis	1230	1890	2370	3040	3570	4130	0.095
		Nashville	1030	1650	2000	2390	2630	2840	-0.873
		Chattanooga	1060	1600	2000	2540	2970	3430	0.147
		Knoxville	813	1310	1680	2190	2600	3030	-0.014
03519650	3.65	Memphis	421	732	964	1280	1530	1800	-0.204
		Nashville	319	605	809	1070	1260	1440	-0.591
		Chattanooga	375	644	847	1130	1350	1590	-0.127
		Knoxville	242	471	672	983	1260	1580	0.067
03535140	1.23	Memphis	301	465	577	722	830	939	-0.217
		Nashville	250	416	526	661	756	847	-0.538
		Chattanooga	292	436	526	636	713	786	-0.410
		Knoxville	179	331	462	663	841	1040	0.140
03535160	14.1	Memphis	1910	2790	3390	4160	4750	5340	-0.065
		Nashville	1710	2520	2970	3440	3740	3990	-0.843
		Chattanooga	1640	2400	2960	3720	4330	4970	0.218
		Knoxville	1360	2080	2630	3440	4120	4880	0.382
03535180	3.23	Memphis	452	729	930	1200	1410	1620	-0.146
		Nashville	361	608	774	977	1120	1260	-0.527
		Chattanooga	425	645	781	938	1050	1150	-0.564
		Knoxville	266	496	688	979	1230	1510	0.050
03538900	3.80	Memphis	386	593	739	930	1080	1230	-0.095
		Nashville	323	508	623	758	850	935	-0.602
		Chattanooga	347	507	607	726	809	888	-0.417
		Knoxville	250	421	553	740	893	1060	0.011

Table 3.--Summary of simulated flood frequency values for modeled basins.--Continued.

Station number	Drainage area (mi^2)	Long-term rainfall station	Simulation results						
			Q_2 (ft^3/s)	Q_5 (ft^3/s)	Q_{10} (ft^3/s)	Q_{25} (ft^3/s)	Q_{50} (ft^3/s)	Q_{100} (ft^3/s)	Skew coefficient
03539100	1.10	Memphis	102	180	238	316	378	442	-0.274
		Nashville	77	142	188	247	291	333	-0.545
		Chattanooga	93	161	209	271	318	364	-0.407
		Knoxville	54	107	155	232	303	385	0.128
03541100	5.53	Memphis	1180	1820	2260	2830	3260	3690	-0.201
		Nashville	1050	1710	2100	2540	2820	3060	-0.838
		Chattanooga	1090	1680	2100	2670	3120	3590	-0.021
		Knoxville	746	1330	1820	2540	3150	3840	0.084
03541200	2.44	Memphis	351	574	729	927	1070	1220	-0.336
		Nashville	295	507	645	808	920	1020	-0.677
		Chattanooga	321	514	650	829	966	1110	-0.190
		Knoxville	209	388	541	778	987	1230	0.138
03597300	4.99	Memphis	1370	1990	2430	3040	3530	4040	0.230
		Nashville	1200	1810	2180	2610	2890	3160	-0.596
		Chattanooga	1250	1750	2090	2540	2880	3230	0.094
		Knoxville	944	1500	1920	2520	3020	3560	0.171
03597400	9.59	Memphis	3020	4170	5020	6180	7120	8120	0.422
		Nashville	2790	3980	4730	5640	6290	6920	-0.281
		Chattanooga	2720	3790	4580	5650	6520	7440	0.387
		Knoxville	2360	3520	4400	5630	6650	7750	0.306
03597450	0.73	Memphis	233	362	447	554	631	706	-0.367
		Nashville	125	244	328	434	509	581	-0.672
		Chattanooga	246	372	440	508	549	582	-0.983
		Knoxville	120	202	267	362	442	530	0.126
03597500	16.3	Memphis	4130	5760	6940	8570	9880	11300	0.381
		Nashville	3780	5360	6350	7540	8370	9160	-0.344
		Chattanooga	3600	5010	6040	7470	8610	9830	0.409
		Knoxville	3150	4640	5790	7430	8810	10300	0.436
03597550	1.86	Memphis	482	701	854	1050	1210	1370	0.022
		Nashville	438	664	802	963	1070	1170	-0.566
		Chattanooga	476	671	792	934	1030	1130	-0.367
		Knoxville	327	507	643	831	984	1150	0.128
03604070	0.51	Memphis	38	81	118	177	230	289	-0.077
		Nashville	29	63	90	128	156	185	-0.574
		Chattanooga	38	79	112	158	193	230	-0.490
		Knoxville	18	40	63	105	147	202	0.299
03604080	1.52	Memphis	191	374	523	739	917	1110	-0.215
		Nashville	128	265	373	522	638	758	-0.477
		Chattanooga	176	345	476	655	795	938	-0.407
		Knoxville	88	194	293	459	615	801	0.076
03604090	6.02	Memphis	627	1290	1760	2330	2730	3090	-0.806
		Nashville	356	845	1300	2010	2650	3360	-0.244
		Chattanooga	605	1130	1530	2070	2510	2980	-0.249
		Knoxville	286	538	765	1130	1470	1880	0.363
03604100	10.1	Memphis	1250	2200	2900	3810	4500	5200	-0.363
		Nashville	872	1740	2400	3270	3920	4580	-0.541
		Chattanooga	1080	1880	2400	3020	3440	3820	-0.707
		Knoxville	624	1180	1640	2340	2950	3630	0.021

Table 3.--Summary of simulated flood frequency values for modeled basins.--Continued.

Station number	Drainage area (mi^2)	Long-term rainfall station	Simulation results						
			Q_2 (ft^3/s)	Q_5 (ft^3/s)	Q_{10} (ft^3/s)	Q_{25} (ft^3/s)	Q_{50} (ft^3/s)	Q_{100} (ft^3/s)	Skew coefficient
07028930	4.75	Memphis	1310	1970	2430	3060	3550	4060	0.034
		Nashville	1160	1820	2220	2680	2990	3270	-0.665
		Chattanooga	1280	1870	2240	2700	3020	3330	-0.326
		Knoxville	870	1510	2020	2780	3430	4140	0.107
07028935	1.08	Memphis	491	691	827	1000	1130	1270	0.017
		Nashville	444	664	806	978	1100	1220	-0.372
		Chattanooga	478	675	814	996	1140	1290	0.141
		Knoxville	360	581	752	997	1200	1420	0.147
07028940	7.87	Memphis	2450	3430	4120	5020	5720	6440	0.138
		Nashville	2240	3220	3830	4540	5030	5490	-0.449
		Chattanooga	2280	3160	3790	4620	5270	5950	0.227
		Knoxville	1800	2770	3520	4610	5530	6540	0.347
07028950	13.3	Memphis	3640	5070	6120	7560	8730	9980	0.409
		Nashville	3290	4740	5660	6790	7610	8390	-0.279
		Chattanooga	3190	4480	5410	6700	7740	8850	0.366
		Knoxville	2750	4130	5180	6700	7970	9360	0.383

curves produced by data from the three closest rain gages. The t-year discharges were weighted on the inverse ratios of the distances from the rainfall stations to the discharge site. Use of this weighting scheme recognizes the potential rainfall variation with geographical location and as such assigns more weight to discharges based on the closer rain gages.

Weighting Observed and Simulated Frequency Curves

Log-Pearson type III curves were computed from observed data in accordance with current Water Resources Council recommendations (1976) for all stations having seven or more annual peaks. Each of these gaging stations then had two estimates of its flood-frequency characteristics, one on the basis of observed annual peaks and one on the basis of a composite of simulated annual peaks. In order to objectively proportion the two estimates rather than averaging them, some measure of their relative accuracy at various recurrent intervals was needed. The technique selected (R. W. Lichty, oral commun., 1976) was to weight the pairs of t-year discharges on the inverse ratios of their relative error. The scheme used to compute the relative error is analogous to a variance analysis except that the expected value of mean square error was used as an indicator of error instead of regression variance. The method is outlined below:

1. The measure of error between the observed and simulated discharges was computed for each recurrence interval using

$$E = \frac{\Sigma(\log Q_{obs} - \log Q_{sim})^2}{n} = \overline{V}_{ts} + \overline{V}_m$$

in which

E = mean square error, in log units,

Q_{obs} = observed t-year station discharge, in ft^3/s,

Q_{sim} = simulated t-year station discharge, in ft^3/s,

n = number of stations,

$\overline{V}_{ts}$ = average error associated with the observed discharge, in log units,

$\overline{V}_m$ = average error associated with the simulated discharge, in log units.

$\overline{V}_{ts}$ was assumed to result mainly from time-sampling errors since the average record length was only about 10 years. It is referred to as the average time-sampling variance.

2. From log-Pearson type III statistics of observed station data, the time sampling variance was estimated for each station for selected recurrence intervals using a modification to the equation developed by Hardison (1971) as follows:

$$V_{ts} = \frac{(R)^2(I_v)^2}{N}$$

where V_{ts} = station time-sampling variance, in log units,

R = factor relating standard error of a t-year event to I_v and N,

I_v = standard deviation of logarithms of annual events, in log units,

N = number of annual peaks.

The average time-sampling variance was computed from the station values.

3. $\overline{V}_m$ was computed as the difference between E and $\overline{V}_{ts}$ for each recurrence interval.

4. The simulated data error for each recurrence interval cannot be estimated for individual stations since it encompasses a multitude of sources, such as model errors and long-term rainfall data errors, whose impact cannot be evaluated. For this analysis, the assumption was made that the simulated data error for individual stations (V_m) closely approximates the average ($\overline{V}_m$). Using this assumption the discharges can be weighted by the inverse ratio of V_{ts}/V_m such that

$$Q_{weighted} = \frac{(V_{ts} \times Q_{sim}) + (V_m \times Q_{obs})}{V_{ts} + V_m}$$

Although the above technique is arbitrary, it does remove subjectivity from the process of combining the pairs of curves. It assigns less weight to Q_{obs} values as the standard deviation of the observed data increases and more weight as the standard deviation decreases. It assigns less weight to Q_{obs} values from short records than it does long ones. The weighting technique also gives more weight to Q_{obs} values at lower recurrence intervals than it does at higher ones. These trends are consistent with those normally associated with the relative accuracy of discharge-frequency curves.

Average record length of the observed data is about 10 years. The average weight given to simulated discharges at the 100-year recurrence interval was 1.5 times the average weight given to the observed discharges. At the 2-year recurrence interval the average weight assigned to the simulated data was 0.9 times that of the observed data. Use of these weighting factors implies that the effective record length of the composite simulated data is 15 years for 100-year floods and 9 years for 2-year floods. Accuracy of the weighted discharges in terms of equivalent years of record should be greater than either the length of the observed data or the effective length of the composite simulated data, but is probably less than their total. It should be noted that the accuracy estimates are relative to the particular period of data collection and, as such, are not absolute values.

Discharges for selected recurrence intervals from frequency curves developed on the basis of observed data, composite simulated data, and the above weighting technique are presented in table 4, where applicable. Observed frequency curves were not computed for stations that did not have sufficient data to adequately define them. The composite simulated data are the only date available at these stations, and, consequently, only the discharges based on the simulated data are listed. The weighted discharges should be used as the best estimate of t-year floods at stations for which they are available.

EVALUATION OF MODELING

Application of the Geological Survey rainfall-runoff model has added greatly to the quantity of information available for definition of flood frequency characteristics of small Tennessee streams. In a flood-frequency study for Tennessee by Randolph and Gamble (1976), the modeled basins comprised 42 percent of the basins less than 50 mi^2 (129.5 km^2) and 56 percent of those less than 20 mi^2 (51.8 km^2) that were used. No bias due to modeling was detected in the study. The t-year discharges from modeled stations did exhibit less variance than those from stations with observed discharges only. This trend is undoubtedly due, in part, to the long-term precipitation data being common to all simulations. Also, the various weighting techniques would tend to filter out extremes and as such would be a factor in reducing variance.

Although the average record length of observed annual peaks was about 10 years, the average length of flood hydrograph collection was less than 10 years as shown in table 1. Stations 03418900 and 03486225 had only 3 years of record when the model was calibrated for them. The particular period during which these two gages were operated provided a sufficient quantity and variety of storms for calibration. Modeling experience with the Tennessee stations indicates that a 3-year-data-collection period is probably close to the minimum record length needed to adequately sample storm types. Maximum length of data collection required will vary from station to station and will vary with the particular period of data collection, but a period of about 7 years should suffice.

Approximately one-fourth of the project gages were continued in some capacity, mainly as crest-stage stations, to provide further evaluation of the simulated data. These gages will be operated until 20 to 25 annual peaks are available to define their flood frequency estimates. An updated comparison of the simulated and observed frequency is planned to be made at that time.

Table 4.--Summary of observed, composite and weighted T-year discharge for modeled basins.

Station number	Drainage area (mi^2)	Type of frequency curve	Q_2 (ft^3/s)	Q_5 (ft^3/s)	Q_{10} (ft^3/s)	Q_{25} (ft^3/s)	Q_{50} (ft^3/s)	Q_{100} (ft^3/s)	Skew coefficient
03313600	0.95	Observed	155	368	571	905	1210	1580	-0.110
		Composite	211	364	469	602	701	798	
		Weighted	194	365	495	672	818	972	
03313620	3.03	Composite	356	686	933	1260	1520	1780	
03418900	1.52	Composite	190	297	376	482	568	660	
03420360	2.28	Observed	312	593	831	1190	1500	1850	0.010
		Composite	311	526	677	873	1020	1170	
		Weighted	311	554	735	982	1180	1390	
03420380	1.03	Observed	246	407	530	702	843	993	0.010
		Composite	220	313	376	457	518	581	
		Weighted	234	361	448	563	655	751	
03420400	7.30	Observed	1150	2540	3830	5960	7930	10300	0.010
		Composite	882	1300	1570	1920	2180	2450	
		Weighted	954	1600	2050	2680	3230	3850	
03427830	0.17	Observed	65	104	133	173	205	239	-0.010
		Composite	55	98	129	167	195	222	
		Weighted	61	101	131	170	200	230	
03427840	3.54	Observed	1570	2590	3350	4420	5290	6210	-0.010
		Composite	1340	1940	2330	2830	3200	3580	
		Weighted	1460	2250	2780	3470	4030	4590	
03430400	12.0	Observed	3700	5280	6330	7670	8660	9650	-0.100
		Composite	4460	6340	7560	9080	10200	11300	
		Weighted	3880	5550	6680	8120	9150	10200	
03430600	43.0	Observed	4210	6150	7470	9160	10400	11700	-0.100
		Composite	6970	10200	12100	14300	15900	17300	
		Weighted	4930	7290	8910	10900	12300	13700	
03430700	3.86	Observed	612	893	1080	1320	1510	1690	-0.100
		Composite	1210	1820	2210	2690	3020	3350	
		Weighted	790	1190	1480	1850	2100	2350	
03431000	64.0	Observed	6330	9830	12300	15600	18100	20700	-0.100
		Composite	9250	13300	15800	18800	20800	22800	
		Weighted	6890	10600	13100	16400	18800	21300	
03431080	3.92	Observed	620	1230	1760	2540	3220	3970	-0.100
		Composite	766	1320	1710	2180	2520	2850	
		Weighted	698	1280	1730	2310	2770	3250	
03431120	3.30	Observed	864	1500	1990	2680	3240	3840	-0.100
		Composite	1420	2220	2750	3400	3880	4340	
		Weighted	1100	1830	2360	3060	3580	4110	
03431240	1.58	Observed	231	323	383	459	514	569	-0.100
		Composite	233	409	551	759	935	1130	
		Weighted	231	343	426	546	637	737	
03431340	13.2	Observed	1980	2650	3070	3600	3970	4340	-0.100
		Composite	1570	2900	3940	5410	6600	7860	
		Weighted	1910	2700	3250	4030	4600	5200	

Table 4.--Summary of observed, composite and weighted T-year discharge for modeled basins.--Continued.

Station number	Drainage area (mi^2)	Type of frequency curve	Q_2 (ft^3/s)	Q_5 (ft^3/s)	Q_{10} (ft^3/s)	Q_{25} (ft^3/s)	Q_{50} (ft^3/s)	Q_{100} (ft^3/s)	Skew coefficient
03431520	4.13	Observed	838	1510	2040	2810	3430	4110	-0.100
		Composite	768	1350	1770	2310	2710	3110	
		Weighted	806	1430	1900	2530	3020	3540	
03431580	13.3	Observed	2920	3950	4610	5410	6000	6580	-0.100
		Composite	4120	5960	7150	8620	9700	10800	
		Weighted	3130	4350	5170	6200	6920	7660	
03431600	51.6	Observed	5310	7910	9700	12000	13800	15500	-0.100
		Composite	8810	13600	16700	20300	22900	25300	
		Weighted	6300	9630	12000	15000	17200	19200	
03431630	2.21	Observed	414	661	840	1080	1270	1460	-0.100
		Composite	566	916	1140	1400	1600	1770	
		Weighted	474	768	977	1240	1430	1620	
03431650	2.66	Observed	537	801	982	1220	1390	1570	-0.100
		Composite	739	1360	1820	2420	2880	3340	
		Weighted	594	970	1260	1660	1940	2240	
03431700	24.3	Observed	2720	4290	5420	6920	8090	9300	-0.100
		Composite	3870	6190	7670	9420	10600	11800	
		Weighted	3110	4970	6310	8000	9180	10400	
03435020	9.32	Observed	2200	3580	4590	5960	7040	8170	-0.110
		Composite	1850	2970	3680	4500	5070	5610	
		Weighted	2030	3270	4100	5120	5900	6660	
03435030	15.1	Observed	2520	3900	4870	6140	7120	8130	-0.110
		Composite	2270	3540	4350	5310	6000	6650	
		Weighted	2430	3760	4650	5760	6600	7440	
03435600	3.50	Observed	639	1110	1460	1960	2360	2780	-0.120
		Composite	527	1010	1360	1800	2130	2460	
		Weighted	583	1060	1400	1860	2220	2580	
03461200	10.2	Observed	816	1170	1420	1760	2020	2290	0.150
		Composite	805	1400	1830	2390	2830	3260	
		Weighted	814	1220	1510	1920	2240	2560	
03469110	2.18	Observed	132	245	341	491	624	776	0.150
		Composite	125	207	270	360	436	518	
		Weighted	128	223	297	404	497	600	
03486225	4.88	Composite	366	819	1230	1900	2520	3250	
03519610	2.10	Observed	214	483	743	1180	1600	2110	0.080
		Composite	119	240	346	512	659	826	
		Weighted	152	314	453	671	872	1100	
03519630	1.46	Observed	149	291	415	610	783	982	0.080
		Composite	85	184	279	438	592	780	
		Weighted	115	228	330	496	654	844	
03519640	16.0	Observed	775	1550	2240	3330	4320	5460	0.080
		Composite	864	1380	1750	2260	2660	3080	
		Weighted	824	1450	1930	2600	3180	3800	

Table 4.--Summary of observed, composite and weighted T-year discharge for modeled basins.--Continued.

Station number	Drainage area (mi^2)	Type of frequency curve	Q_2 (ft^3/s)	Q_5 (ft^3/s)	Q_{10} (ft^3/s)	Q_{25} (ft^3/s)	Q_{50} (ft^3/s)	Q_{100} (ft^3/s)	Skew coefficient
03519650	3.65	Observed	286	697	1120	1870	2610	3530	0.080
		Composite	267	506	707	1010	1270	1570	
		Weighted	273	557	803	1190	1530	1940	
03535140	1.23	Composite	204	357	479	658	811	981	
03535160	14.1	Observed	981	1560	1990	2600	3100	3630	0.100
		Composite	1440	2170	2710	3480	4120	4800	
		Weighted	1180	1860	2370	3100	3700	4320	
03535180	3.23	Observed	230	484	719	1100	1460	1880	0.100
		Composite	298	529	710	973	1190	1440	
		Weighted	271	514	713	1010	1260	1550	
03538900	3.80	Observed	385	755	1080	1570	2010	2510	0.030
		Composite	306	476	591	738	849	961	
		Weighted	338	578	750	983	1180	1390	
03539100	1.10	Observed	122	232	325	466	590	729	0.030
		Composite	74	136	183	250	306	364	
		Weighted	96	176	236	324	400	482	
03541100	5.53	Observed	1210	2480	3620	5450	7110	9040	0.050
		Composite	883	1480	1940	2570	3090	3650	
		Weighted	1010	1840	2480	3400	4210	5100	
03541200	2.44	Observed	414	733	992	1370	1700	2050	0.050
		Composite	250	437	584	795	971	1160	
		Weighted	335	576	758	1020	1250	1490	
03597300	4.99	Observed	1490	2920	4140	6000	7640	9480	0.000
		Composite	1170	1740	2110	2570	2910	3240	
		Weighted	1310	2200	2840	3690	4410	5170	
03597400	9.59	Observed	2310	3880	5100	6820	8220	9740	0.000
		Composite	2700	3840	4620	5640	6420	7220	
		Weighted	2510	3860	4820	6090	7090	8140	
03597450	0.73	Observed	395	467	509	559	594	627	0.000
		Composite	160	275	351	444	509	573	
		Weighted	378	451	493	546	584	620	
03597500	16.3	Observed	4080	5880	7110	8710	9920	11200	0.000
		Composite	3620	5140	6170	7500	8520	9560	
		Weighted	4020	5760	6940	8470	9630	10900	
03597550	1.86	Observed	501	718	866	1060	1200	1350	0.000
		Composite	430	638	771	931	1040	1160	
		Weighted	482	694	834	1010	1140	1280	
03604070	0.51	Observed	56	121	180	273	356	450	-0.100
		Composite	34	72	103	148	184	223	
		Weighted	42	88	126	182	230	283	
03604080	1.52	Composite	155	312	436	609	746	889	
03604090	6.02	Observed	822	1670	2410	3530	4500	5590	-0.100
		Composite	484	1030	1470	2110	2640	3200	
		Weighted	619	1270	1790	2550	3210	3910	

Table 4.--Summary of observed, composite and weighted T-year discharge for modeled basins.--Continued.

Station number	Drainage area (mi^2)	Type of frequency curve	Q_2 (ft^3/s)	Q_5 (ft^3/s)	Q_{10} (ft^3/s)	Q_{25} (ft^3/s)	Q_{50} (ft^3/s)	Q_{100} (ft^3/s)	Skew coefficient
03604100	10.1	Observed	1080	2010	2770	3870	4790	5800	-0.100
		Composite	1020	1900	2530	3350	3960	4560	
		Weighted	1050	1950	2620	3530	4240	4970	
07028930	4.75	Observed	1660	2370	2830	3390	3800	4200	-0.220
		Composite	1260	1900	2330	2860	3260	3660	
		Weighted	1550	2230	2670	3200	3610	4010	
07028935	1.08	Observed	486	905	1230	1690	2070	2460	-0.220
		Composite	473	679	818	993	1120	1260	
		Weighted	479	779	989	1250	1480	1710	
07028940	7.87	Observed	2760	3460	3870	4340	4660	4970	-0.220
		Composite	2350	3310	3960	4790	5410	6040	
		Weighted	2700	3440	3880	4420	4790	5160	
07028950	13.3	Observed	3190	4550	5440	6540	7340	8120	-0.200
		Composite	3440	4850	5840	7160	8180	9260	
		Weighted	3274	4650	5590	6800	7680	8590	

Using a rainfall-runoff model with 3 to 7 years of data instead of using conventional techniques which require 20 to 25 years of data is advantageous if there is an urgent need for flood information. The Geological Survey rainfall-runoff model seems to fulfill the validity requirements of such a model. No bias was detected when residuals of the regression equations for the stations studied in this report were compared with residuals of the previously mentioned flood-frequency study in Tennessee.

SUMMARY

Data from 52 small drainage basins in Tennessee were used to calibrate the U.S. Geological Survey rainfall runoff model. Average error of peak discharge simulation on the final calibrations was about 36 percent, however peak simulation was generally more accurate for larger peaks than for the smaller ones. The calibrated model parameters were used with long-term precipitation data from Memphis, Nashville, Chattanooga and Knoxville to simulate four discharge-frequency curves for each modeled basin. Composite simulated frequency curves were computed on the basis of a distance weighting of the simulated curves from the three closest stations having long-term precipitation data. Discharge-frequency curves were also computed from observed annual peaks for stations that had sufficient data. For those stations, t-year discharges from the composite simulated curves and the observed curves were weighted on the basis of their relative accuracy to make up the best estimate of the flood characteristics that can currently be made.

Average record length at the modeled basins was 10 years. Results of this study indicate that accuracy of the simulated data is equivalent to 9 years of data at the 2-year recurrence interval and 15 years at the 100-year recurrence interval. The effective record length of the weighted frequency curves should be greater than either the observed data period or the effective length of the simulated data but probably less than their total. It should be noted that the accuracy estimate is relative to the particular period during which the data was collected, and, as such, is not an absolute value.

The modeled basins comprise 42 percent of the basins less than 50 mi^2 (129.5 km^2) and 56 percent of those less than 20 mi^2 (51.8 km^2) that are currently available for definition of flood-frequency characteristics of Tennessee streams. These basins were analyzed along with other basins having observed data only in a recent flood-frequency study for Tennessee. No bias due to modeling was detected.

Regionalization of model parameters does not appear to be promising at this time. Although general trends of several parameters were consistent with expectations, actual values were significantly affected by parameter interaction. This interaction was expected since, within some error range, many sets of parameter values may fit a given set of data equally well. These sets of parameters should produce comparable simulated annual peaks.

This report illustrates that rainfall-runoff modeling can be an effective way to extend observed data in time. Quality of the simulated data is dependent upon how closely the observed data fit within the assumptions inherent to the hydrologic components of the model. Consequently, model users should be familiar with these components and should exercise careful judgment in selecting input data. The Survey model performed acceptably over a wide range of conditions when the above guidelines were followed.

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GLOSSARY

antecedent moisture.--moisture stored within a drainage basin before a storm.

baseflow.--in context of the usage in this report baseflow is all runoff except direct runoff; sustained flow.

continuous-record gaging station.--site on a stream where stage discharge data are obtained continuously over a period of time.

crest-stage partial-record gaging station.--site on a stream where only flood peak data are collected systematically over a period of years.

direct runoff.--that runoff that enters stream channels promptly after rainfall.

dual-digital gaging station.--site on a stream equipped with two recorders to measure the stage and concurrent rainfall associated with a flood event.

flood-frequency curve.--graphic relationship between recurrence interval and flood-magnitude.

harmonic average evaporation data.--simulated evaporation values, used during periods of no actual evaporation data, based on a curve fitted through actual data.

instantaneous unit hydrograph.--a hydrograph with direct runoff equal to one inch from a storm uniformly distributed over the drainage basin and occurring within a unit time of zero.

lag time.--the time interval between the centroid of rainfall excess and the centroid of direct runoff.

linear storage.--that characteristic of storm hydrographs having storage conceptualized as being within a fictitious reservoir in which the storage is directly proportional to outflow.

mean square error.--a measure of error between the observed discharges and the simulated discharges that is equal to the sum of the squared deviations divided by the number of discharge values tested.

<u>multiple regression</u>.--statistical technique for defining the relationship between a dependent variable and two or more independent variables.

<u>physiographic provinces</u>.--areas within the State of Tennessee where soils and drainage patterns have been developed on geologically similar materials.

<u>recurrence interval</u>.--average interval of time, in years, within which the given flood event is expected to be exceeded once. The reciprocal of the recurrence interval is the probability of occurrence during any one year. (A 50-year flood, Q_{50}, has a 2 percent chance of being exceeded in any given year). Recurrence intervals imply no regularity of occurrence; a 50-year flood event might be exceeded in consecutive years, or it might not be exceeded in a period many times 50 years in length.

<u>regional analysis, regionalization</u>.--a method of combining records within a region which reduces the sampling error, bases the results on a uniform period of experience, and produces flood-frequency relations generally applicable within the region.

<u>standard deviation</u>.--a measure of the dispersion or precision of a series of statistical values such as precipitation, streamflow, etc. It is the square root of the mean of the sum of the squares of the deviations from the arithmetic mean.

<u>standard error of estimate</u>.--range of error such that the value estimated by the regression equation is within this range at about two out of three sites and is within twice the range at about 19 out of 20 sites.

<u>skew coefficient</u>.--one of the measures of the distortion of the data from a normal distribution about the mean.

<u>water year</u>.--the 12-month period from October 1 through September 30, designated by the calendar year in which it ends.