**US Army Corps
of Engineers**
Hydrologic Engineering Center

Flood Hydrograph and Peak Flow Frequency Analysis

March 1979

TP-62

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)* March 1979	2. REPORT TYPE Technical Paper	3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE Flood Hydrograph and Peak Flow Frequency Analysis	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) 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-62

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
Presented at Engineering Foundation Conference on Improved Hydrologic Forecasting and also published in their proceedings, Asilomar, California, March 1979.

14. ABSTRACT

Several methods for estimating flood hydrographs and flood peaks of various frequencies are discussed. The methods include frequency analysis of historical streamflows, statistical equations, empirical formulas, single event watershed models, and continuous watershed models. Methods for computing modified frequency curves due to changing watershed conditions and water management activities are described.

15. SUBJECT TERMS
flood hydrology, flood frequency, peak discharge, regional methods, design storms, continuous simulation, math model, river basin hydrology

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U	UU	28	19b. TELEPHONE NUMBER

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

Flood Hydrograph and Peak Flow Frequency Analysis

March 1979

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-62

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.

Flood Hydrograph and Peak Flow Frequency Analysis

Arlen D. Feldman*

The accurate prediction of streamflows is essential to the planning of our water resource systems. This paper addresses the practical state-of-the-art of techniques to predict flood peaks and their associated frequency of occurrence; and techniques for predicting critical flood hydrographs (or series of hydrographs) and their frequencies of occurrence. Statistical relationships, empirical equations, and watershed models will be investigated as means for predicting the peak discharges and flood hydrographs.

Peak discharge information is required to determine the appropriate size of water conveyance systems such as natural channels, diversion canals, storm drains, bridge openings, etc. The frequency of the peak discharges is necessary to determine how often the conveyance system capacity is exceeded. Criteria for sizing conveyance systems are derived from socio-economic responses to the inconveniences associated with the exceedence of system conveyance capacities and the cost of providing those systems.

Flood control studies usually base flood damages on peak discharges as representative of damage due to several associated flood problems. It is especially convenient to be able to express flood damages in terms of discharge (stage), however, other factors such as flow velocities and duration of flooding may need to be considered separately. Flood control measures may take the form of increasing the capacity of conveyance systems or regulating the flood waters through storage, diversions, or local control measures. Flood damage reduction measures include these items plus nonstructural measures such as flood proofing structures, etc.

The tradeoff between conveyance capacity and storage in a flood control system is a classic consideration. This analysis is appropriate for small urban drainage systems (storm and combined sanitary) up to the large river/reservoir networks. Many techniques have been developed, tested, and implemented for sizing these systems. In general, the larger or more complex the drainage system becomes, the more the analysis shifts from predicting peaks to predicting the whole hydrograph. The

techniques addressed in this paper are separated into the following catagories:

> Frequency analysis of historical streamflows
> Statistical equations
> Empirical formulae
> Single event watershed models
> Continuous watershed models

The single event watershed models are further broken down into techniques using hypothetical storms and historical storms. Continuous watershed models are discussed in terms of relatively simple models and also the more complex complete soil moisture accounting models. In one of the proposed methods of analysis, a simple continuous model is used to screen the historical rainfall-runoff record to determine important individual events which are then simulated in more detail with a single event model. A distinction will also be made between techniques which predict peak flows from urban and nonurban areas. Much emphasis has been placed on urban runoff in recent years and several techniques have been developed to meet those needs (1).

The statistical equations and empirical formulae are best used to predict peak flow rates for small areas, less than 50 mi^2. When analyzing larger areas, the storage and routing effects in the basin usually require the use of a watershed model for adequate definition of the hydrograph.

Peak Flow Estimation Techniques.--Peak flows may be estimated directly as functions of historical streamflow records or statistical/empirical relationships. The peak flow techniques referred to in this paper are those techniques which predict only the peak flow - not including the whole hydrograph. The techniques which predict the whole hydrograph or series of hydrographs also compute a peak flow but they will be discussed in the Watershed Modeling sections. The peak flow techniques are functions of rainfall intensity or runoff frequency and various geographic characteristics of the basin. Usually the annual peak flow frequency curve is derived either directly from an equation or by estimating a series of flood peaks which are then analyzed with standard frequency techniques.

Frequency Analysis of Historical Streamflows.--Historical streamflow records may be used directly to estimate discharges at various frequencies. If adequate streamflow records exist and the watershed has remained relatively unchanged during the course of that record, then those observed streamflows are probably the best indicator of the potential flood responses of the watershed in its present condition. The Water Resource Council's guidelines (2) describe the currently recommended techniques. Those guidelines describe the use of the Pearson Type III distribution and associated topics of high and low outliers, generalized skew, two-station comparisons, mixed populations, confidence limits, flood estimates from precipitation data, and equivalent accuracy for independent estimates for analysis of historical flood peaks.

2

If it is desired to predict the magnitude-frequency of streamflows under some future watershed land use development or regulated condition, then the historical streamflow records cannot be used directly. In this case one must usually resort to a watershed model. The same requirement arises where long term historical streamflow records exist but the watershed has undergone significant changes during that time. Thus, a nonstationary streamflow series exists and cannot be used directly in the frequency analysis. The nonstationary series problem can also be unraveled through the use of watershed models (3).

If a stationary series of data is available, but not at the specific locations of interest, then a regional frequency analysis may be undertaken (4). The regional analysis allows one to transfer the parameters of the flood frequency distribution at gaged locations to other locations of interest. This is accomplished through relating frequency parameters to geographic and meteorologic characteristics which are known at the gaged and ungaged locations.

Water Resource Council's Ungaged Areas Flood Frequency Study.--The Water Resources Council - Hydrology Committee, work group for peak flow frequency for ungaged areas, has recently begun a study of the following eight flood frequency estimation techniques.

> Statistical estimation of Qp
> Statistical estimation by moments
> Index flood method
> Transfer method
> Empirical equations
> Single storm
> Multiple discrete events
> Continuous simulation

The first phase of the WRC study has just been completed for selected watersheds in the northwestern and central U.S. and they expect to publish a report in November 1979 (personal communication with John Miller, National Weather Service). The methods reported in the pilot tests are: USGS Equations, FHWA, Reich, Snowmelt, Index Flood, Rational Formula, TR55, (RP149), TR55 (TC), TR20, and HEC-1. They are encouraging the widest possible review of this work before going on with similar applications in the southwestern and southeastern U.S. A later phase of the WRC studies will include urban areas.

Preliminary results of the WRC study show there to be a fair amount of variation within the application of the same method on the same watershed by different participants. This was observed even with the apparently straight forward methods such as the USGS State Equations and FHWA where all that is needed is drainage area and other simple geographic location parameters. The results varied even more, as one would expect, as more judgement/experience factors were required to use the methods such as SCS' TR-20 and The Corps of Engineers' HEC-1. The above observations were made from a very preliminary review of the pilot study raw data. The WRC Ungaged Watershed Group is now in the process of editing and analyzing that data and preparing their report.

Statistical Flood Peak Estimation Techniques.--Statistical flood peak
estimation techniques predict instantaneous peak flows of prescribed
frequencies through a regression analysis of geographic variables affect-
ing the flood runoff. An excellent discussion of drainage basin and
meteorologic characteristics which can be used to explain behavior of
streamflows is given in Thomas and Benson (21). They analyzed over
twenty characteristics and discuss the relative affects of each. Drain-
age basin area and normal annual precipitation were among the most signi-
ficant. Certainly some of the most widely available examples of these
techniques are the U.S. Geological Survey (USGS) "State Regression
Equations," (5).

Patterson and Gamble (5), developed relationships between drainage
area and mean annual flood in different hydrologic areas. The mean
annual flood is reduced in proportion to the lake storage in the basin if
applicable, and the peak flows for recurrence intervals from 1.1 to 50
years may be determined from a graph of recurrence interval vs. ratio of
discharge to mean annual flood as in figure 1.

A generalized procedure is also used by the Federal Highway Adminis-
tration (FHWA), (6) for small rural watersheds, generally less than 100
square miles. In this procedure the 10-year event is determined as a
function of the drainage area, an iso-erodent factor, and a difference
in elevation in the watershed. Separate equations are given for each of
twenty four hydrophysiographic zones in the U.S. and Puerto Rico. A
fixed relationship is given between the 2-year, 100-year peaks and the
10-year peak.

Other techniques use watershed runoff characteristics and precipi-
tation intensities to predict the peak runoff rates. A time on concen-
tration and infiltration index may be determined directly from watershed
characteristics such as length and elevation change of main channel, soil
characteristics, and land cover. The x-minute rainfall intensity for
the desired frequency is obtained from TP40 or HYDRO-35 (7). A peak
discharge per square mile may be derived from the time-of-concentration,
infiltration index, and peak 30-minute intensity. Adjustments can be
made for antecedent precipitation. This method is subject to the
standard criticisms of assuming the frequency of the runoff is the same
as the rainfall.

Empirical Equations.--The most popular and long lasting of the
empirical equations is the Rational formula (8). Despite the many more
sophisticated methods available today, the rational formula is still
popular because of its easy and economic use. The regression equations
previously discussed are similar to this except that the coefficients
in the equations are determined by a minimum error statistical tech-
niques. Application of the Rational method has even been inconsistent (37).

Runoff vs. Rainfall Based Methods.--Many of the statistical estima-
tion techniques for peak flow are directly streamflow based and do not
go through the rainfall-to-runoff analysis. The flow estimates are
determined by analyzing streamflows of known frequencies in a hydrologic
region and relating them to basin characteristics, primarily drainage
area and sometimes general meteorologic measures such as average annual

4

Mean
Annual
Flood
(cfs)

Hydrologic area A

B

C

Drainage Area mi^2

Ratio
of
Discharge
to
Mean
Annual
Flood

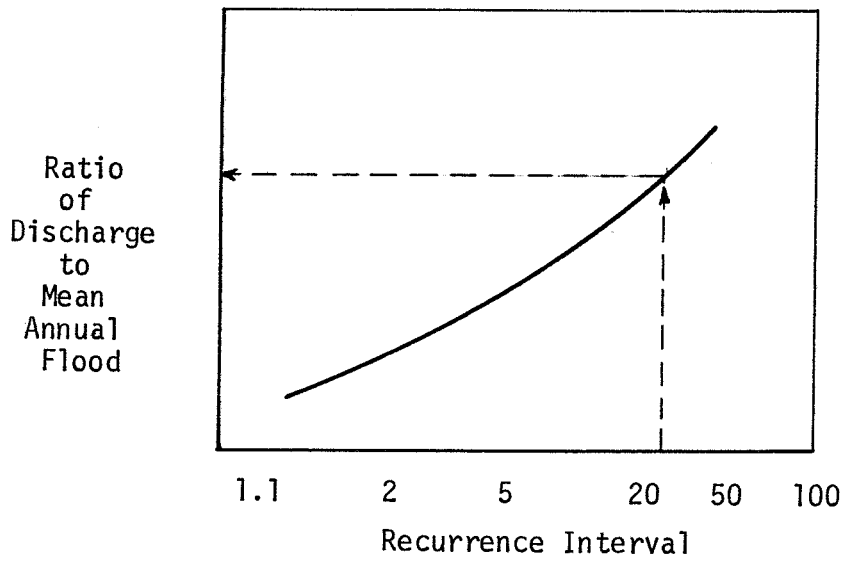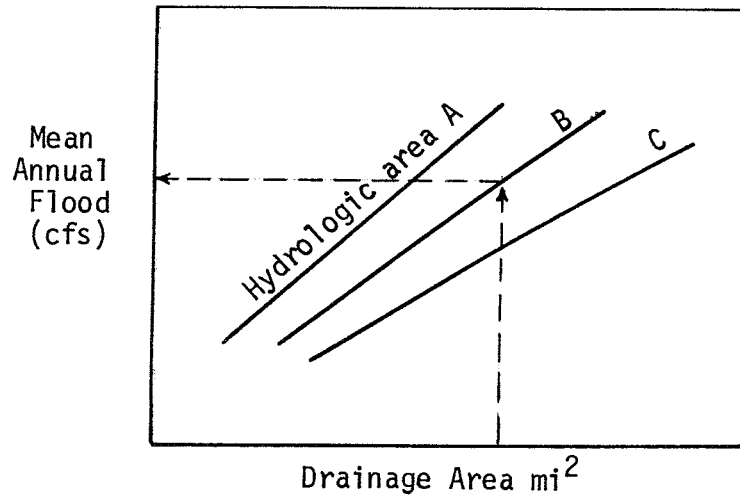1.1   2   5   20   50   100

Recurrence Interval

Figure 1. Area Regression Equation Method

precipitation. It is generally more difficult to develop these relationships in urbanizing basins because of the nonhomogeneous nature of the runoff series.

As urbanization occurs the rainfall runoff response function changes and additional parameters must be brought into the relationship to explain that variation. Usually the percent of impervious area and watershed conveyance factors are found to be suitable measures of urbanization (9). Rainfall is also brought into these relationships so that impact of changed precipitation loss rates can be analyzed directly instead of trying to reflect change only in the routing parameters.

There are two general classes of rainfall based flood prediction methods: 1) runoff frequency is assumed to be the same as the rainfall frequency, and 2) the runoff frequency is computed independently of the rainfall frequency. The assumption that runoff frequency equals rainfall frequency is generally agreed to be undesireable (10) but is oftentimes used because it simplifies the required analysis. Precipitation frequency analysis is discussed in a later section. Rainfall of some frequency can be applied to several different antecedent moisture conditions in the same watershed and largely different runoff may result. As the frequency of the event becomes more rare, the runoff is less affected by the antecedent moisture condition and the ensuing loss rates. The single event models can be used on many historic events and then the runoff peaks ranked and the frequencies determined by standard methods. Continuous simulation models take the final step of analyzing the entire precipitation runoff record maintaining consistency with respect to soil moisture storages. The continuous process modelers claim to have the most realistic basis for computing flood frequencies.

Watershed Modeling.--When is it necessary and/or desirable to use a watershed model instead of the simplified statistical and empirical techniques? The watershed models are generally required when: an entire hydrograph is desired; analyzing complex areas; or when the past or proposed future watershed response functions are changing. Watershed models are particularly desirable when analyzing the effect of various water management schemes.

Watershed models range widely in complexity. Brandstetter (1), compares many different models for urban storm runoff and many of these models are equally good for nonurban cases. Some are nothing more than simple empirical equations within a subbasin network routing/combining framework. Others perform a complex accounting of soil moisture and water in various stages of runoff. The following discussion of watershed modeling looks at the practical state-of-the-art in single event and continuous models and combinations thereof. The attendent precipitation analyses required with both techniques is also discussed.

Hydrographs are necessary when storage projects (reservoirs of different forms) are being investigated as flood control measures. A frequency analysis of runoff can be made to determine the expected frequency of various flow durations (4). If a certain flow-duration relationship is desired for project design, it can be determined separately, as just mentioned, and then the simulated hydrograph can be

balanced (11) to conform to that flood duration. Continuous event
simulation models are often preferred for storage analysis if it is a
sequence of storms which cause the flood problem as opposed to one
large, single event.

Single Event Models.--A single event model is one that is used
primarily for individual storm events, although it may be of long
duration and multi-peaked. Two factors usually constrain their use to
single events: the continuity of soil moisture (loss rates) is not
simulated, and/or the model simulates in such detail and requires time
consuming computations so that it is not economical to run over long
periods. Many of the single event models can be used equally well in
urban and nonurban areas but have usually been developed for a specific
purpose and then generalized to meet more needs. Some of the most
widely used single event models are:

HEC-1: Flood Hydrograph Package (11)

TR-20: Computer Program for Project
Formulation Hydrology (12)

MITCAT: MIT Catchment Model (13)

USGS Rainfall-Runoff Simulator (14)

SWMM: Storm Water Management Model (15)

Many other models exist and some contain more advanced representation
of various aspects of the precipitation-runoff process. Many comparisons
of such models have been made (1, 16). Few models are more comprehensive
and/or widely used than those above. These models are generally well
supported by government agencies or private engineering consultants and
are continually being improved to meet new needs. The HEC-1 model, for
example, goes beyond the basic rainfall/snowmelt runoff simulation pro-
cess and has special options for computation of expected annual flood
damages, automatically sizing components of a flood control system for
maximum net benefits, and simulation of dam overtopping and failure per
the requirements of the National Dam Safety Inspection Program.

The current tendency in watershed modeling, both single event and
continuous, is to incorporate parameters with realistic relationships to
the physical process and that can be determined directly from readily
available geographic data. Because of this strong interest in relating
watershed model parameters to geographic characteristics, the Soil
Conservation Service's (SCS) curve number technique has received much
increased interest and usage. The SCS curve number technique is the
only one in which both the precipitation loss rate and the water excess-
to-runoff transformation (unit hydrograph) can be determined from readily
available geographic data. The data used are: land cover, hydrologic
soil type, average slope of the watershed, and length of the main water
course. Curve numbers have been recommended for various land cover -
hydrologic soil group combinations in both urban and nonurban areas (17)
as shown in Table 1. Calibration with observed rainfall runoff data is
still required. The curve number technique, although a rather simplistic

representation of the runoff process, appears to work well in many cases. Further research is being currently undertaken by the HEC and Espey, Huston & Assoc. to test the validity of the technique in urbanizing watersheds.

Table 1.   Runoff Curve Numbers for

Selected Land Uses (from Table 2.2 (17))

Land Use	Hydrologic Soil Group			
	A	B	C	D
Cultivated land	72	81	88	91
Pasture or range land	68	79	86	89
Wood or Forest land	25	55	70	77
Residential, 1/4 acre lots	61	75	83	87
Commercial (85% imperv.)	89	92	94	95
Industrial (72% imperv.)	81	88	91	93
Paved parking lots, roofs, driveways, etc.	98	98	98	98

A particularly interesting and powerful benefit of using geographically related watershed parameters is that of interconnecting watershed models with geographic information systems. This concept was used in a project for Fairfax County, VA in which a geographic grid cell information system was used as the basis for computation of watershed model parameters (18). This study made use of the MITCAT watershed model and parameters were estimated from a geographic data bank of land use, etc.

The Hydrologic Engineering Center, (19), made a practical application of a geographic information system for automatically computing hydrologic and economic parameters in the Oconee River Expanded Flood Plain Information study, figure 2. This concept has been expanded into a comprehensive flood plain planning tool (20), and is now being implemented as a regular tool in Corps of Engineers' project investigation.

As single event models became more geographically based and capable of easily predicting starting conditions, (initial values of model parameters), the less necessary continuous watershed models would appear to be. With this capability, the single event model could be started before every significant event. Statistical analysis of the output peak flows and volumes could be performed to make predictions for design purposes. Using a single event model for many storm events and using the resulting frequency curve, overcomes the common criticism of single event models - that runoff frequency equals rainfall frequency.

Map Data

Grid Cell Data Bank

1. location
2. basin
3. subbasin
4. Soil
5. land use
6. etc.

Economic
Utility Program
for
Damage functions

Hydrologic
Utility Program
for
Runoff functions

Watershed Model
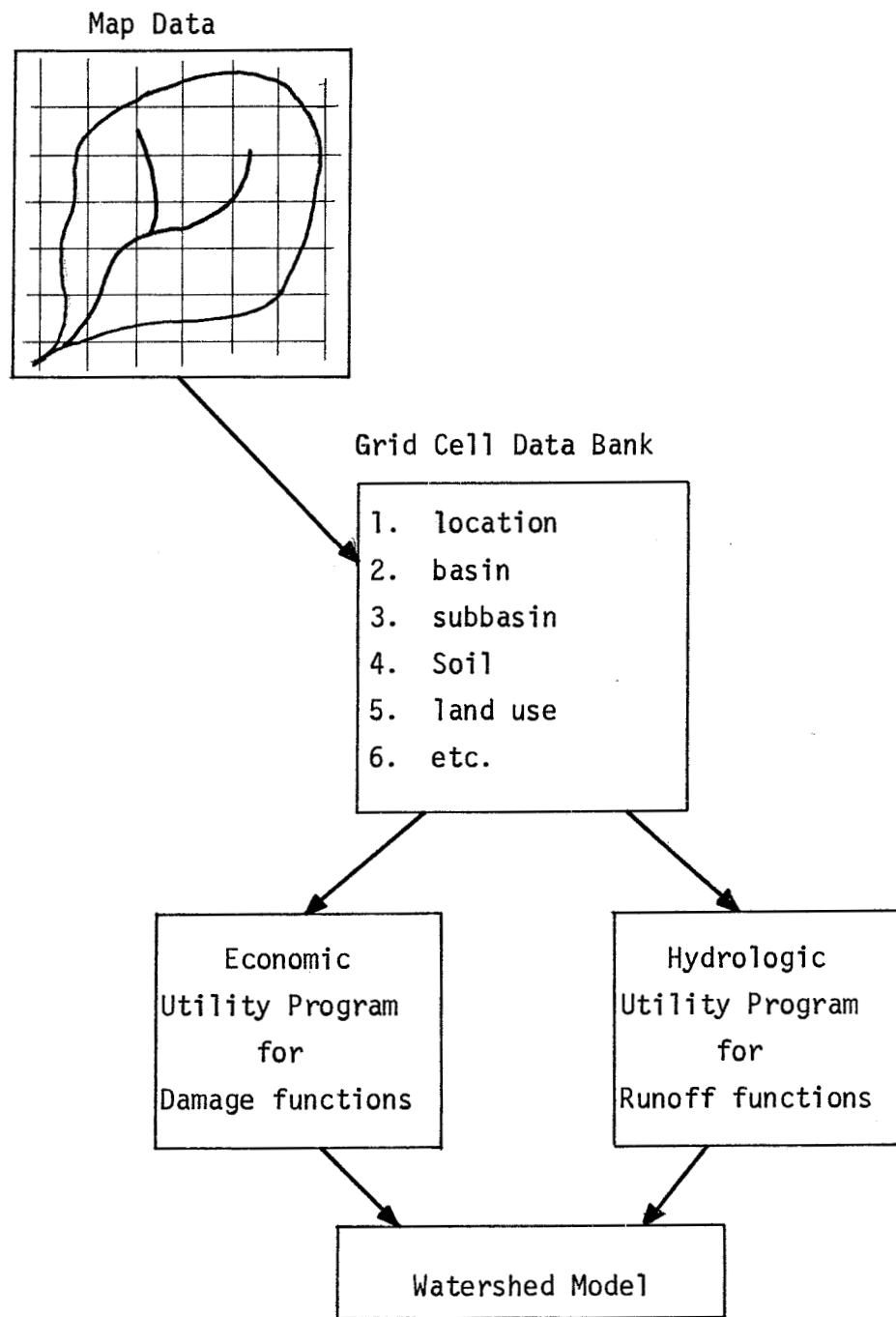
Figure 2.   Spatial Data Management and Hydrologic Analysis System

9

Analysis of Flood Control Measures and Land Use Changes.--The hydro-
logic engineer is often asked to determine the impact of land use changes
or flood control management measures on specific design floods and the
entire flow frequency curve. This can be accomplished with either the
single event or continuous watershed model. Both methods require the
ability to change watershed parameters to reflect new watershed response
functions.

Watershed modelers use many different characteristics affecting the
runoff process with which to predict the parameters of the model. The
common procedure is to establish a relationship between the model para-
meters, say loss rates, and runoff transformations (unit graph
and kinematic wave), and basin characteristics. Basin characteristics
are discussed in relation to runoff production by Thomas and Benson (21).
Urbanization factors are included if the basin has been or is being devel-
oped (9).

For evaluating flood control management alternatives, the watershed
modelers simply run the model in the with and without project control
modes to determine the impact of the project. In the continuous models,
one usually simulates the entire record with and without the modified
land use and/or flood control projects. The annual peak flows, for each
case, are subjected to traditional frequency analysis and the modified
frequency curve is obtained.

Single event models can be used to develop a modified frequency
curve by simulating several storms, of varying magnitude, under each dev-
elopment condition (11). A base case frequency curve is required and can
be developed by any preferred method. Usually a frequency curve is
"adopted" which may be some specific curve or combination of curves.
The frequency of the base case computed peak flow, for each storm mag-
nitude, is determined from the adopted frequency curve, figure 3. The
same storm is simulated again under the modified conditions and the
frequency of the runoff is assumed to be the same. The modified fre-
quency curve is determined as shown in figure 3. A potential fallacy
with this approach is that the storm runoff may change in frequency for
the modified watershed development. That is, the ranking of peaks flows
might change under the modified condition.

Precipitation Frequency Analysis.--Many studies have been made of
precipitation frequency and critical design events such as the probable
maximum precipitation and various frequency intensity-duration relation-
ships of the National Weather Service (NWS) (7). A recent analysis by
Marsalek (10) reviewed the Chicago and Illinois design storm methods
and compared them with results obtained from continuous simulation.
Marsalek reinforced those common feelings about the pitfalls of design
storms, at least for the limited geographic area analyzed.

Nevertheless, design storms are a commonly used tool and must be
given serious consideration, especially because of their economic
attractiveness. Several single event watershed modelers have developed
their own rainfall frequency analysis techniques (22) and link these
techniques directly with their watershed models. These techniques as
well as the NWS (7) publications can be used effectively as long as the

10

Figure 3.   Modifying Frequency Curves
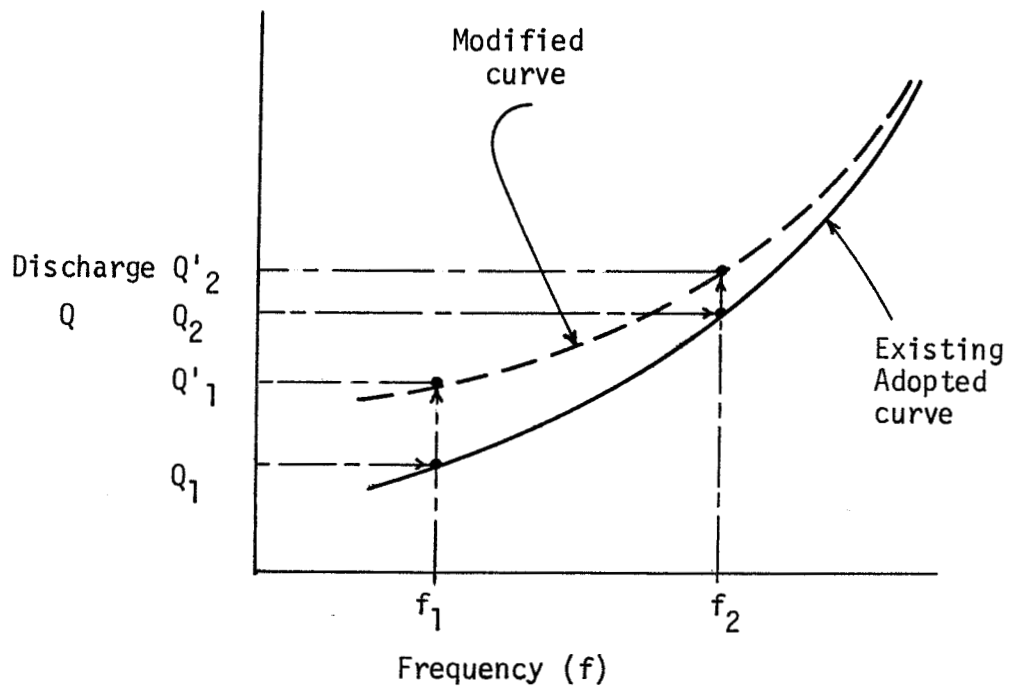
Q_i = peak discharge for design storm i

f_i = frequency of Q_i from given curve

Q'_i = peak discharge from design storm i under modified watershed condition

impact of the antecedent precipitation assumptions are fully realized. A study by Yen (23) demonstrates the use of synthetic storms in designing projects for the Federal Highway Administration. One of the major problems occurs when the particular sequence of precipitation events causes the critical flood situation as opposed to the magnitude of any one part of the multiple events. This type of problem leads one to prefer the analysis found in the continuous models.

The use of continuous watershed models does not solve all of one's rainfall analysis problems. Granted, it is the most comprehensive analysis of the hydrology of the basin and much is to be gained from that insight. These models have a major dependence upon the precipitation measured or synthetically generated; and the precipitation data are usually the least well known part of the runoff process. The difficulty comes in the spatial variation of precipitation; point measurements are made and spatial averages are inferred.

The construction of a long-record precipitation series is a difficult task. As one goes back in time, the observation stations become fewer, and one must make more and more assumptions about the spatial and temporal variation of the precipitation. The National Weather Service maintains tape files of daily precipitation records since 1948 and shorter interval precipitation measurements for selected stations and time periods. Before 1948, most precipitation data were not in computer compatible format and thus, extensive preparation by the analyst is required. The Hydrologic Engineering Center estimated that approximately 4 to 6 person-months of effort would be required to construct the precipitation record from 1900 to 1948 for a 130 mi^2 basin near Chicago, IL.

Continuous Watershed Models.--Most of today's highly sophisticated continuous watershed models are derived from the Stanford Watershed Model (24). Another model, developed at about the same time, is the SSARR model of the Corps of Engineers (25). The SSARR model does not have all of the complexity of the Stanford derived models, but has been shown to be comparable in results with the more comprehensive models (26).

The Stanford Watershed Model has been elaborated upon at several universities: Kentucky (27); Texas (28); Ohio (20); and others. Notable among these is the Kentucky version, entitled OPSET, where the parameters of the model are derived automatically by an optimization routine. The National Weather Service also used the Stanford Watershed Model as the basis for its NWSRFS model (30). The National Weather Service Sacramento Model (31) has more comprehensive soil moisture accounting algorithms, but may be considered less sophisticated in its runoff transformation via linear unit graphs and the fact that it does not route stream flows in a comprehensive river system.

One of the most highly developed versions of the Stanford Watershed Model existing today is the Hydrocomp HSP Model (32). The HSP system of programs incorporates the precipitation-runoff model as one piece of an array of study tools ranging from water quality simulation to unsteady flow dam break flood routings. The technical analysis tools all link together with a comprehensive data management system which arranges input and saves output for further analysis.

Efficient data management in continuous watershed simulation models is an exceedingly important requirement. The HSP system is probably the most advanced and comprehensive in this regard. The continuous models are frequently criticized for their enormous appetite for data. In fact, the cost of assembling the necessary data often negates the use of these models in all but the most comprehensive studies which require a well orchestrated analysis of competing interdisciplinary uses of water.

One of the simplest and most economical to run continuous watershed models is the STORM program (33). The model was originally developed by Water Resource Engineers, Inc. in connection with stormwater runoff in the city of San Francisco. The original model was essentially a long term hyetograph analysis with a simple rational formula type transformation to runoff. Long term, say 50 years or more, of hourly precipitation data can easily be analyzed at an affordable computer cost. The original model was limited to a single subbasin analysis but later versions incorporate multibasin routing and combining.

The STORM program was studied by Brandstetter (1) and its characteristics can easily be compared with other models in that report. Another comparison of several continuous and single event watershed models was recently published by the ASCE Urban Water Resources Research Program (16). While this comparison was not an exhaustive testing of the models, it does give good insight into the relative performance, attributes, and difficulties one may find in these models. Another comparison of continuous models was made by Lumb (34).

The Hydrologic Engineering Center has undertaken a detailed analysis of the HSP watershed model (35). The purpose of this analysis was to see how well and practically a comprehensive continuous simulation model could be used in a standard Corps of Engineers flood frequency study. The HSP model was chosen as a state-of-the-art model and applied to the DuPage River Basin near Chicago, IL. This study drew several conclusions:

1) The model can produce reasonable results when properly calibrated. Annual flood events, when analyzed together, exhibited characteristics similar to recorded flows, although individual years were significantly different from the observed.

2) The model can account for urbanization but more in theory than was able to be accomplished in practice. The application was begun with five land uses for runoff production, but this was soon reduced to two, nonurban and urban, together with an impervious area. Without runoff data to distinguish the urban and nonurban contributions to runoff it was furthermore not possible to make that land use distinction. The final model was constituted of an urban/rural mixture land use and an impervious area. The theory of the model would lead one to believe that several different land use runoff segments could be used but in the end only one could be realistically used.

3) The model is relatively easy to operate in terms of input instructions, file organization and manipulation.

13

4) The model is difficult to calibrate because of the large number of parameters and the mass of data processing. Many of the parameters were found to be more empirical than one would expect and their best values could only be determined by calibration. It was difficult to know the starting values for several parameters, but this would be easier with experience. It would certainly be desirable to have parameter values more directly derivable from geographic data.

5) The data requirements are extensive both in quantity and in the labor necessary for preprocessing.

6) The use of such a model produces a major benefit of becoming very knowledgeable about the full complexity of the watershed's hydrologic cycle; that knowledge will surely permit a greater number/variety of water resource management alternatives to be considered.

7) The general conclusion of this application was that continuous simulation models can be used for the flood frequency study, but, considering the amount of work and data required, it is doubtful that they are the best tool for such limited studies. These models are best suited for comprehensive river basin studies requiring analysis of both high and low flows.

Hybrid Single Event/Continuous Watershed Modeling.--The previous discussion has noted that single event models used with design storms have certain difficulties in estimating the frequency of the runoff. Single event models can be used on historical storms and could be taken to the limit of analyzing all storms of record. That task would be quite expensive and receive the same criticism as the data and manpower intensive comprehensive continuous simulation models. Is it possible, then, that a blend of the single event and continuous models could fulfull this need?

The Hydrologic Engineering Center has recommended the use of a simple continuous simulation model to screen the history of precipitation runoff events in a watershed (36). The STORM model or other similar simple model is used to simulate the entire historic record, figure 4. Different amounts of storage in a simple linear reservoir model could also be used to see if basin storage, natural and/or artifical, would bring about different series of critical events (22).

The simulated runoff events are then ranked according to magnitude and/or volume. A conventional flood frequency analysis is performed for those simulated flood events. This yields a gross estimate of the flood frequency curve. This rough estimate of the frequency curve is then improved with detailed runoff analysis by a single event model.

Several representative storm events are selected across the range of computed floods. These storm events are then simulated in detail using models such as MITCAT or HEC-1. The antecedent moisture conditions prior

screening model simulation for period of record
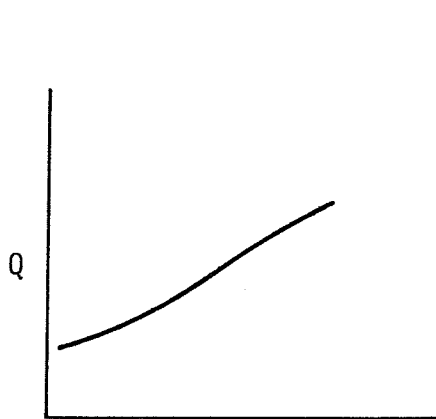
frequency
screening model results
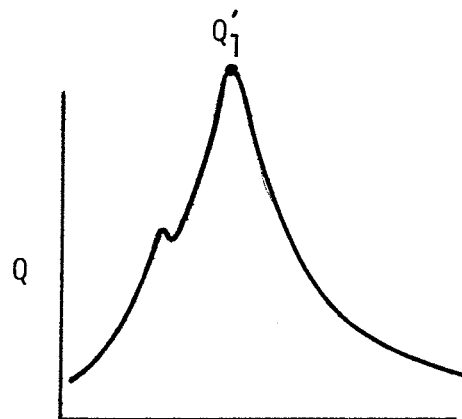
time
single event in detail
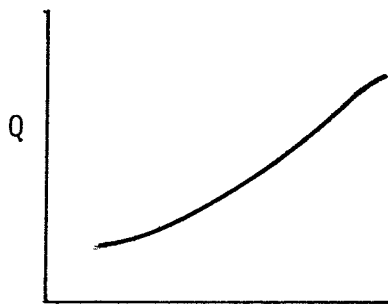
adjusted frequency
curve by (Q_i, Q_i')
function

frequency

Figure 4. Hybrid Single Event/Continuous Model Analysis

to each storm can be estimated from the continuous simulation results. A statistical analysis of the simple continuous model peak flows and the detailed single event model's peak flows is made and a regression equation is developed. The regression equation is used to determine a better value for the other simple continuous model peak flows not simulated in detail. This results in an adjusted frequency curve based on the detailed simulation of a few significant flood events, figure 4.

Conclusions.--There are numerous techniques for predicting peak flood discharges/volumes of prescribed frequencies. The budget of one's study and one's familiarity with different analytical techniques usually determine which approach is used.

Statistical and empirical flood peak estimation techniques may be good for small areas where river routing/storage effects are not significant. For larger watersheds and studies requiring analysis of alternative flood control/watershed management procedures, the watershed simulation model is the best tool. The advantages and disadvantages of single event models with design storms and complex continuous simulation models have been discussed. A hybrid approach using a simple continuous model to identify significant events and a single event model to analyze those events in detail is a promising method of analysis.

Watershed models are tending to become more directly based on readily measurable geographic parameters. The need for continuous accounting of soil moisture conditions would appear to be less necessary as one becomes better able to predict watershed model parameters from direct geographic/ meteorologic measurements. With this capability, single event models theoretically could be easily started for any event in question.

Geographic information systems and utility programs to compute automatically the watershed model parameters are a promising technology for comprehensive river basin studies. This technique is particularly powerful in analyzing many land use and watershed and flood damage reduction management alternatives.

If one uses a subjective measure of flood severity, such as general public inconvenience, then projects may be sized by methods which are not dependent on a true estimate of a flood frequency. That is, the projects are designed by some consistent method, say design storms, and the severity of the storms is changed dependent upon the public's reaction to flooding inconvenience. This is generally the case in urban storm sewer design.

If an objective estimate of expected economic damage is to be the design criterium, then realistic flood frequencies must be computed. Projects based on specific flood frequencies, say the 100-year flood of the flood insurance studies, would require consistent, but not necessarily precise, estimates of flood frequencies. In that case, insurance premiums could be adjusted, as actuarial experience indicates, to made the project viable. The landowners, however, would argue for the use of a precise frequency.

References

1. Brandstetter, Albin, "Assessment of Mathematical Models for Storm and Combined Sewer Management," for Environmental Protection Agency, Technology Series, EPA-600/2-76-175a, August 1976.

2. Water Resources Council, "Guidelines for Determining Flood Flow Frequency," Bulletin 17A, Hydrology Committee, June 1977.

3. Gundlach, David L., "Adjustments of Peak Discharge Rates for Urbanization," Irrigation and Drainage Journal, American Society of Civil Engineers, Vol. 104, No. IR3, September 1978.

4. Beard, Leo R., "Statistical Methods in Hydrology," U.S. Army Corps of Engineers, Sacramento District, January 1962.

5. Patterson, James L. and C.R. Gamble, "Magnitude and Frequency of Floods in the United States, Part 5. Hudson Bay and Upper Mississippi River Basins," U.S. Geological Survey, Water Supply Paper 1678, Washington, D.C. 1968.

6. Trent, R.E., "FHWA Method for Estimating Peak Flow Rates of Runoff from Small Rural Watersheds," Federal Highway Administration, Offices of Research and Development, Environmental Design and Control Division, Washington, D.C., 1978.

7. U.S. Weather Bureau, "Rainfall Frequency Atlas of the United States," Dept. of Commerce, Technical Paper No. 40, May 1961, and National Weather Service, "Five to 60-Minute Precipitation Frequency for the Eastern and Central United States," NOAA Technical Memo NWS HYDRO-35, Silver Spring, MD, June 1977.

8. Gregory, R.L., and C.E. Arnold, "Rational Runoff Formulas," Transactions, American Society of Civil Engineers, Vol. 96, 1932.

9. Espey, William H. Jr., Duke G. Altman, and Charles B. Graves, Jr., "Nomographs for Ten-Minute Unit Hydrographs for Small Urban Watersheds," American Society of Civil Engineers Urban Water Resources Research Program Technical Memo No. 32, New York, 1977.

10. Marsalek, Jiri, "Research on the Design Storm Concept," American Society of Civil Engineers Urban Water Resources Research Program, Technical Memo No. 33, New York, 1978.

11. Hydrologic Engineering Center, "Flood Hydrograph Package, HEC-1," U.S. Army Corps of Engineers, California, 1973.

12. Soil Conservation Service, "Computer Program for Project Formulation Hydrology," Technical Release No. 20, U.S. Dept. of Agriculture, Washington, D.C., 1965.

13. Resource Analysis, Inc., "MITCAT Catchment Simulation Model," Description and Users Manual, Version 6, Massachusetts, 1975.

14. Dawdy, David R., Robert W. Lichty, and James M. Bergmann, "A Rainfall-Runoff Simulation Model for Estimation of Flood Peaks for Small Drainage Basins," U.S. Geological Survey Professional Paper 506-B, Washington, D.C., 1972.

15. Heaney, James P. and Wayne C. Huber, "Storm Water Management Model: Refinements, Testing, and Decision-Making," University of Florida, 1973.

16. Abbott, Jesse W., "Testing of Several Runoff Models on an Urban Watershed," American Society of Civil Engineers Urban Water Resources Research Program Technical Memo No. 34, New York, October 1978.

17. Soil Conservation Service, "Urban Hydrology for Small Watersheds," Technical Release No. 55, U.S. Dept. of Agriculture, Washington, D.C., January 1975.

18. Michel, Henry L. and William P. Henry, "Flood Control and Drainage Planning in the Urbanizing Zone: Fairfax Co. Virginia," in Urban Runoff Quantity and Quality, Engineering Foundation and American Society of Civil Engineers, New York, 1974.

19. Hydrologic Engineering Center, "Phase 1 Oconee Basin Pilot Study, Trail Creek Test," U.S. Army Corps of Engineers, California, 1975.

20. Davis, Darryl W., "Comprehensive Flood Plain Studies Using Spatial Data Management Techniques," Water Resources Bulletin, Vol. 14, No. 3, June 1978.

21. Thomas, H. and M. Benson, "Generalization of Streamflow Characteristics," U.S. Geological Survey Water Supply Paper No. 1975, Washington, D.C., 1970.

22. Resource Analysis, Inc., "Rainfall Analysis and Generation Model Description and Theoretical Background," Boston, MA, March 1975.

23. Yen, Ben Chie and Ven Te Chow, "Feasibility Study on Research of Local Design Storms," Prepared for Federal Highway Administration, Report No. FHWA-RD-78-65, Washington, D.C., November 1977.

24. Crawford, Norman H. and Ray K. Linsley, "Digital Simulation in Hydrology: Stanford Watershed Model IV," Stanford University, Civil Engineering Technical Report No. 39, July 1966.

25. Rockwood, David M., "Streamflow Synthesis and Reservoir Regulation," U.S. Army Engineer Division, North Pacific, Technical Bulletin No. 22, January 1964.

26. World Meteorological Organization, "Intercomparison of Conceptual Models Used in Operational Hydrological Forecasting," Operational Hydrology Report No. 7, WMO-No. 429, Geneva, 1975.

27. James, L. Douglas, "An Evaluation of Relationships Between Stream-flow Patterns and Watershed Characteristics Through the Use of OPSET," Research Report No. 36, Water Resources Institute, University of Kentucky, Lexington, 1970.

28. Claborn, B.J., and W.L. Morre, "Numerical Simulation of Watershed Hydrology," Hydrologic Engineering Laboratory, Civil Engineering Dept., University of Texas, Technical Report HYD-14-7001, 1970.

29. Ricca, V.T., "The Ohio State University Version of the Stanford Streamflow Simulation Model," Water Resources Research Center, Ohio State University, 1972.

30. National Weather Service, "National Weather Service River Forecast System Forecast Procedures," NOAA Technical Memo, NWS HYDRO-14, Silver Spring, MD, 1972.

31. Burnash, Robert J.C., R. Larry Ferral and Richard McGuire, "A Generalized Streamflow Simulation System," Joint Federal-State River Forecast Center, Sacramento, CA 1973.

32. Hydrocomp, Inc., "Hydrocomp Simulation Programming Operations Manual, Fourth Edition," Palo Alto, California, January 1976.

33. Hydrologic Engineering Center, "Storage, Treatment, Overflow, Runoff Model, STORM," U.S. Army Corps of Engineers, California, 1976.

34. Lumb, Alan M., "Comparison of the Georgia Tech, Kansas, Kentucky, Stanford, and TVA Watershed Models in Georgia," Georgia Institute of Technology, January 1976.

35. Cermak, Robert J., "Continuous Hydrologic Simulation of the West Branch DuPage River Above West Chicago: An Application of Hydro-comp's HSP," Hydrologic Engineering Center, U.S. Army Corps of Engineers, California, Draft, November 1978.

36. Peters, John C., "Techniques for Developing Frequency Curves in Urban Areas," Lecture Notes, Hydrologic Engineering Center, U.S. Army Corps of Engineers, California 1978.

37. Ardis, Colby V., K.J. Dueker, and A.T. Lenz, "Storm Drainage Practices of Thirty-Two Cities," American Society of Civil Engineers, Journal of the Hydraulics Division, Vol. 95, No. 1, January 1969.

Technical Paper Series