(12)

US Army Corps
of Engineers
Hydrologic Engineering Center

Application of Rainfall-Runoff Simulation for Flood Forecasting

Technical Paper No. 145

June 1993

APPLICATION OF RAINFALL-RUNOFF SIMULATION FOR FLOOD FORECASTING[1]

John Peters[2]

INTRODUCTION

Hydrologic simulation models provide a means for extending the lead time associated with flood warnings. Following a brief discussion of warning objectives and approaches to short-term hydrologic forecasting, characteristics of rainfall-runoff models for forecast applications are discussed. HEC-1 and HEC-2 are described as illustrations of models that can be applied to develop warning criteria; HEC1F and the Sacramento Method are described as illustrations of models for real-time application. Finally, aspects of model selection and use are discussed.

WARNING OBJECTIVES

The value of a flood-threat recognition system depends to a large extent on the *lead time* it provides for issuing warnings, enabling evacuation, etc.. A minimum lead time must be provided for a system to be practically useful. The lead time that is potentially achievable depends on (1) the spatial and temporal characteristics of storm rainfall and the ability to sample/forecast these, (2) rainfall-runoff response characteristics of the watershed and the ability to simulate these, and (3) the time required to recognize and evaluate the flood threat and take appropriate action. The value of a warning system depends also, of course, on its reliability. Consider Figure 1, which illustrates aspects of reliability. Sets of storm events are labeled {A}, {B}, {C} and {D}, where:

{A}	=	storm events that cause flooding
{B}	=	storm events that do not cause flooding
{C}	=	storm events that cause flooding but for which warnings are not issued
{D}	=	storm events that do not cause flooding but for which warnings are issued

[1] Paper presented at the United States - Republic of China Workshop on Natural Disaster Reduction, Taipei, Taiwan, June 24-26, 1993.

[2] Senior Engineer, US Army Corps of Engineers, Hydrologic Engineering Center, Davis, California, 95616, USA.

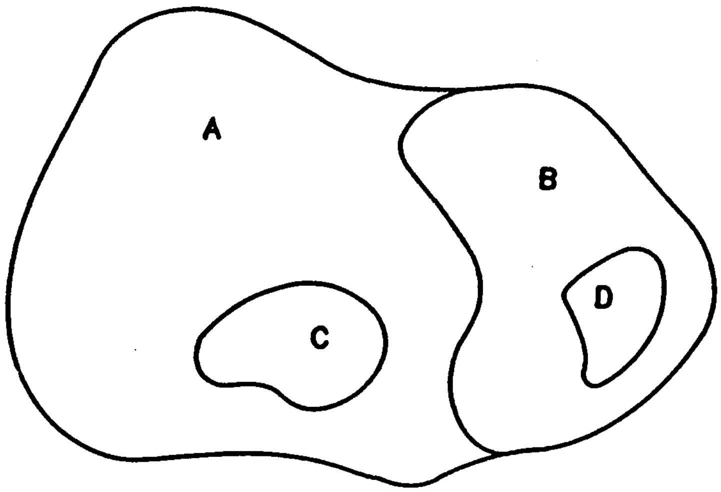


Figure 1. RELIABILITY OF FLOOD WARNINGS

The goal of a warning system is to minimize both {C} and {D}. Events from {C} can cause damage and loss of life that could possibly be prevented; events from {D} increase the likelihood that future warnings will be ignored. Alternative warning systems will be reflected by different configurations of {C} and {D}.

The basis for a warning can range from measured river stage (elevation) at an index gage to results of a rainfall-runoff simulation that incorporates recent rain data and estimates of future rainfall. Although the more sophisticated warning systems may provide longer lead times, their reliability is not necessarily greater than that associated with simpler systems. Both lead time and reliability should be evaluated when analyzing alternative warning systems.

The tradeoff between lead time (warning time) and warning reliability can be illustrated by considering a simple threshold-stage method of warning, as shown in Figure 2 . The warning stage is sensed at location A. The primary flood threat is downstream at location B. The problem is to choose a threshold (index) stage for location A such that when that stage is exceeded, a warning for flooding at location B is to be issued. It is desired that the lead time to prepare for the flood threat be as long as possible. The lower the index stage at A, presumably the more lead time will be provided. However, if the threshold stage is too low, there will be too many false warnings, so that genuine warnings will not be heeded. In terms of Figure 1, as {C} becomes smaller, {D} becomes larger.

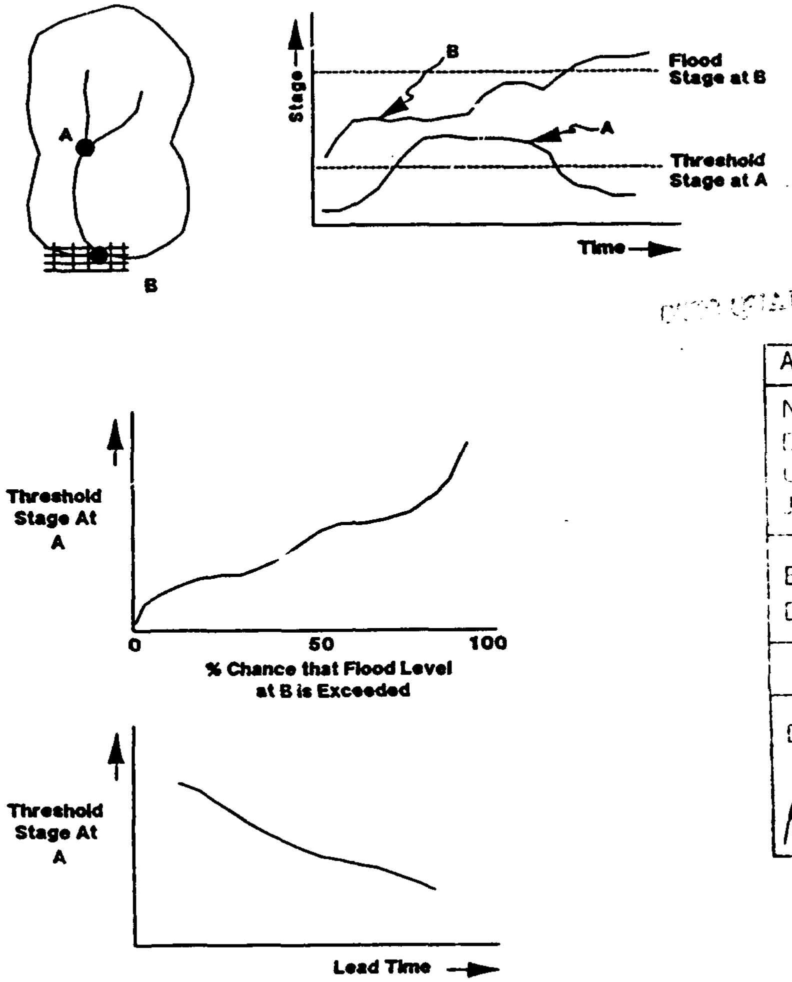


Figure 2. LEAD TIME VS. WARNING RELIABILITY

The graphs in the lower portion of Figure 2 represent relationships that could be developed by analyzing a set of historical storm events (Dotson and Peters, 1990). Lead time is a variable that depends on event-specific storm and runoff characteristics. Storm and streamflow data from historical events provide useful information for assessing the magnitude and variability of lead time.

APPROACHES TO SHORT-TERM HYDROLOGIC FORECASTING

"Short-term" here refers to forecasts with lead times of hours to several days, as required for flood warning purposes. By contrast, long-term forecasts, which provide lead times up to a year or more, are useful for water management decisions.

Hydrologic models for short-term forecasting may employ channel routing, rainfall-runoff simulation, or both. Choice of a model type depends on required forecast lead time, the response characteristics of the basin, and the scale of meteorological events. Lettenmaier and Wood (Maidment, 1993) list four cases, as follows:

<u>Case 1.</u> Required lead time is larger than the hydrologic response time (the sum of the time of concentration for the basin and the time of travel through the river system). In this case, a forecast of precipitation is required, because future precipitation will reach the forecast point within the lead time. Rainfall-runoff modeling is required.

<u>Case 2.</u> Required lead time is smaller than the hydrologic response time, and the time of concentration is substantially smaller than the time of travel through the river system. This is the case for large river systems for which forecasts can be based on channel routing of upstream observed (gauged) flows.

<u>Case 3.</u> Required lead time is smaller than the hydrologic response time, and the time of concentration is substantially larger than the time of travel through the river system. A rainfall-runoff model is required, but forecasts of future precipitation are not required.

<u>Case 4.</u> This case is one in which the scale of the meteorological event is significantly smaller than the scale of the basin. This would occur, for example, on large basins subject to convective storms. In this situation, it is necessary to subdivide the basin or employ a model that permits specification of precipitation as a distributed input. Also it is desirable to telemeter data from stream gages on major tributaries. Rainfall-runoff modeling and channel routing of observed and/or forecasted tributary flows are required.

For quick-responding watersheds (i.e. Case 1 above), lead times are very short, and the time available for processing forecasts is extremely limited. In such situations, real-time modeling may not be practical, and it may be more appropriate to apply pre-established warning criteria with real-time observed and forecasted rainfall depths/durations as inputs. Historical events can be analyzed to develop such criteria. The hydrologic models used for this purpose do not require the special functionality associated with real-time applications.

Another approach for quick-responding watersheds is to automatically compute forecasts at frequent intervals (e.g., every 10 minutes), and to include in those forecasts a set of pre-specified (fixed) future rainfall amounts, as illustrated in Figure 3. The amount of forecasted rainfall can then be used to interpolate a discharge hydrograph (and associated inundated area) from the most recent pre-computed set of forecasts. Automated forecasting requires a well calibrated, robust model. The state-of-the-art of modeling is such that generally an experienced modeler must be involved in model applications and interpreting model results.

VENTURA COUNTY FLOOD ADVISORY

PROVIDED BY THE

CALIFORNIA-NEVADA RIVER FORECAST CENTER OF THE NATIONAL WEATHER SERVICE

FORECAST PEAK FLOWS IN THOUSAND CFS RESULTING FROM 3 HOUR PRECIPITATION

	3 HOUR PRECIPITATION (IN INCHES)				
	1	2	3	4	5
SESPE CREEK NEAR FILLMORE	.45	2.70	10.89	19.39	27.98
SANTA PAULA CR	.12	1.59	5.35	9.04	12.72
CALLEGUAS CREEK AT CAMARILLO	.23	2.16	8.88	29.19	50.90
REV. SLOUGH (CAL CK PARM)	.27	.85	4.02	8.36	12.82
FAGAN CANYON	.02	.09	.36	.54	.71
SANTA ANA CREEK	.00	.06	.13	3.98	6.81
COYOTE CREEK	.01	.10	1.37	5.70	9.47
MATILIJA CR 100% BURNED	.18	.48	6.11	14.50	22.52
MATILIJA CR IF UNBURNED	.05	.11	.27	2.39	11.09
ARROYO SIMI NR SIMI	.26	.63	9.95	35.18	55.67

(Taylor and Weikel 1991)

Figure 3. FORECASTS BASED ON PRE-SPECIFIED DEPTHS OF FUTURE RAINFALL

HYDROLOGIC MODELING - GENERAL

A large number of hydrologic models are available for developing rainfall hyetographs, simulating runoff and determining inundated areas for historical and/or hypothetical storm events. Such models can be used effectively in the development of hydrologic criteria for flood warning. Characteristics of two such models, and associated data management software, are described in the following sections. The programs are well documented and can be used on IBM-compatible microcomputers as well as UNIX-based workstations. Either metric or English units may be used.

HEC-1, Flood Hydrograph Package

Capabilities - The fundamental capability of HEC-1 (Hydrologic Engineering Center, 1990a) is to develop discharge hydrographs for historical or hypothetical storm events at specific locations in a basin. The basin can be subdivided into any number of subbasins, and modeling elements such as uncontrolled reservoirs and diversions can be accommodated. The program includes options to:

- optimize values for unit hydrograph and/or loss rate parameters
- optimize values for routing parameters
- simulate snow pack/snow melt
- simulate dam overtopping/breaching
- incorporate alternative land use/development conditions, and multiple storm events, in a single program application

A variety of alternative methods are available for simulating precipitation, losses, base flow, runoff transformation and routing.

Precipitation Computations - The spatial averaging of precipitation can be performed externally to HEC-1 and input for direct use. Alternatively, precipitation for individual recording and non-recording gages can be specified, along with associated weighting factors for each subbasin. Additional weighting to accommodate gauge bias (e.g., difference in normal annual precipitation for a gauge vs. a subbasin) can be employed.

Losses and Base Flow - Losses can be specified in terms of (1) an initial loss and constant loss rate, (2) a four parameter exponential loss function (unique to HEC-1), (3) an initial loss and a "curve number" based on land use and US Soil Conservation Service (SCS) soil classifications (Soil Conservation Service 1972), (4) the Holtan method, and (5) the Green and Ampt method. Base flow is specified by means of three input variables.

Runoff Transform - Precipitation excess can be transformed to direct runoff with a unit hydrograph or kinematic wave techniques. Unit hydrograph options allow a unit hydrograph to be input directly or to be expressed in terms of Clark, Snyder or SCS parameters. The kinematic wave option permits depiction of subbasin runoff with elements representing up to two overland-flow planes, two collector channels and a main channel.

Routing - Primary routing options are the Muskingum-Cunge, Modified Puls and Muskingum methods. For the Muskingum-Cunge and Modified Puls methods, a routing reach can be specified in terms of a length, slope, three Manning *n* values (for a main channel and left and right overbanks), and a cross section defined with eight pairs of coordinates.

HEC-2, Water Surface Profiles

HEC-2 (Hydrologic Engineering Center, 1991) is intended for calculating water surface profiles for *steady, gradually varied flow* in natural or man-made channels. Both subcritical and supercritical profiles can be calculated. The effects of various obstructions such as bridges, culverts, weirs, and structures in the flood plain may be simulated. The computational procedure is based on the solution of the one-dimensional energy equation with energy losses due to friction evaluated with Manning's equation. The energy and energy-loss equations are solved iteratively between each pair of cross sections with the "standard step" method (Henderson, 1966).

Data Storage System (HEC-DSS)

Data management is a significant aspect of hydrologic evaluations. The DSS software (Hydrologic Engineering Center, 1990) is intended for efficient management of time series data of any type, such as rainfall hyetographs and discharge or stage hydrographs. Paired-function data, such as stage-discharge rating curves, discharge-frequency or stage-frequency relationships, can also be accommodated. The DSS system includes a set of utility programs intended for data entry, data editing and graphic displays. Figure 4 illustrates the role of DSS in data management. A typical application with HEC-1 is to first store observed precipitation and discharge data in a DSS file with a data entry utility program, and then to automatically retrieve such data as part of an HEC-1 execution. Simulation results can be written to the same DSS file, and another utility program can be used to develop graphs or tabulations of any data in the file.

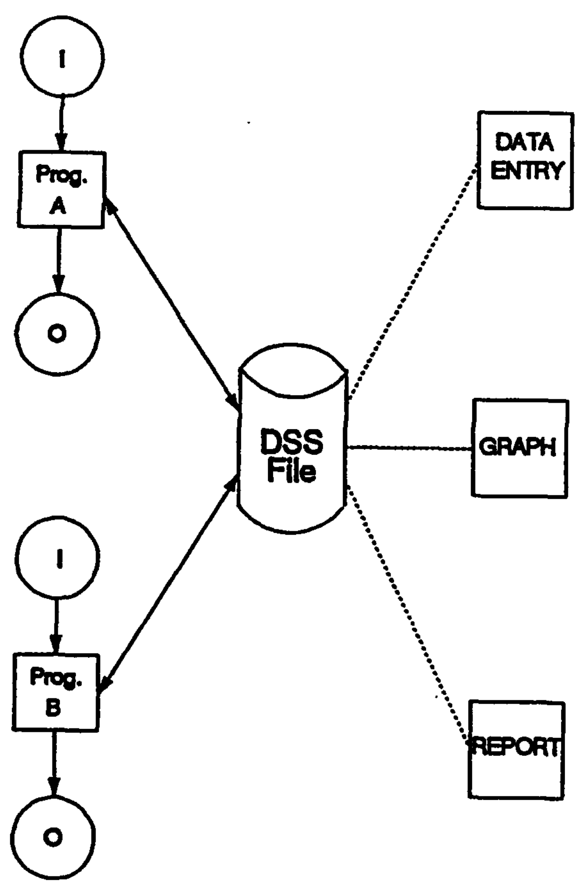


Figure 4. ROLE OF DSS IN DATA MANAGEMENT

REAL-TIME HYDROLOGIC MODELING

Simulation models are of two types, *event* and *continuous*. Continuous modeling generally attempts a continuous accounting of soil moisture, whereas event models require specification of initial conditions (e.g., loss rates) that pertain to the "event". Advantages of event-type approaches are that they generally do not require representation of evapotranspiration and subsurface water balances. Because event-type approaches are simpler, they generally use fewer parameters and are easier to calibrate. However for short-term forecasts, there may be substantial uncertainty with respect to initial conditions, especially after dry periods. The following sections describe first an event-type model, HEC1F, and then a continuous-type model, the Sacramento Watershed Model. Comments on model updating are also provided.

Event-type Modeling

The event-type approach involves the following steps in determining runoff from a basin:

- o specification of precipitation (spatial and temporal distribution)
- o specification of "losses" and rainfall excess
- o transformation of rainfall excess to direct runoff
- o specification of base flow
- o combining of base flow and direct runoff to obtain total runoff

If a basin is divided into subbasins, the above steps are performed for each subbasin, and routing and combining of hydrographs are performed as required.

HEC1F, which is an adaptation of computer program HEC-1, is an example of an event-type model used for forecasting (Peters and Ely, 1985). The basic HEC-1 capabilities for calculating runoff with a unit hydrograph approach from a multi-subbasin watershed, and for parameter optimization, are retained in HEC1F. However, HEC1F contains additional capabilities that facilitate the task of runoff forecasting. Aspects of application of HEC1F are as follows:

1. Forecasting with HEC1F is intended to involve a "hands-on" process by which the analyst can readily compare simulated hydrographs with observed hydrographs (up to the time-of-forecast) and adjust loss rates, or perhaps other parameters, to improve results.

2. Forecasting is generally performed in two separate executions of HEC1F. In the first, unit hydrograph, loss rate and base flow parameters are optimized for gauged headwater subbasins. The time window "T" in Figure 5 is the period over which an objective function to optimize the above parameters is evaluated. The window is approximately equal to the time base of the unit hydrograph for the subbasin. An objective func-

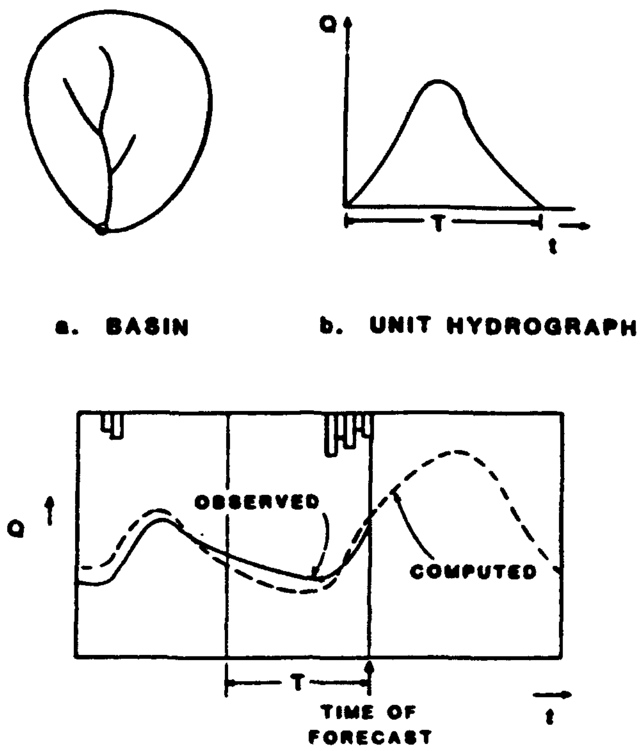


Figure 5. PARAMETER ESTIMATION WITH HEC1F

time base of the unit hydrograph for the subbasin. An objective function is minimized by a univariate gradient technique (Ford et al, 1980). The objective function is as follows:

$$STDER = \sqrt{\frac{\sum_{i=1}^{N}(QOBS_i - QCOMP_i)^2 * WT_i}{N}}$$

where STDER = objective function
$QOBS_i$ = ordinate i of the observed hydrograph
$QCOMP_i$ = ordinate i of the computed hydrograph
WT_i = weighting factor applied at ordinate i
N = total number of hydrograph ordinates encompassed by the objective function

The equation defining the weighting factor is as follows:

$$WT_i = \left(\frac{J}{N-1}\right)^2$$

where J = number of Δt intervals from the beginning of the time period for parameter estimation (T) to the time of ordinate i

The objective function is a quantitative measure of the goodness of fit of the calculated hydrograph to the observed hydrograph. The weighting factor has a value of 1 at the time-of-forecast, and diminishes to a value of 0 at the beginning of the time window "T". The purpose of the weighting is to insure a relatively close fit of the calculated to the observed hydrograph in the vicinity of the time-of-forecast.

The optimization process has built-in constraints that prevent physically unreasonable values for the parameters to be optimized (Hydrologic Engineering Center, 1989). For example, if the rainfall is concentrated very near the time-of-forecast, there will be little hydrograph "rise" with which to optimize parameters. In this case, the optimization is permitted only for base flow parameters.

3. Following the parameter optimization application of HEC1F, the analyst reviews optimization results and parameter estimates as an aid to setting values of loss rate and base flow parameters for the remainder of the basin.

4. The second application of HEC1F performs runoff computations, and routing and combining operations throughout the basin. At each location for which an observed hydrograph is available, "blending" can be performed. A blended hydrograph consists of the observed hydrograph up to the time-of-forecast and an adjusted simulated hydrograph after the time-of-forecast. The adjustment is made either by a vertical shifting of the simulated hydrograph with a constant increment of discharge (positive or negative), or by providing a smooth transition from the observed to the unadjusted simulated hydrograph over six time intervals following the time-of-forecast. The transition is computed by linearly diminishing the "error" (difference between the observed and computed discharge) at the time-of-forecast to zero over the six time intervals. The two types of blending are illustrated in Figure 6. The blended hydrograph is used in subsequent routing computations.

HEC1F is generally used in conjunction with the program PRECIP (Hydrologic Engineering Center, 1989) for processing gauged rainfall data, and DSS. The PRECIP program develops hyetographs of spatial-average rainfall for each subbasin using an inverse distance-squared weighting procedure. If data for a gauge is missing, the program automatically obtains data for the next nearest gauge. The DSS graphics utility program facilitates data review and analysis, as well as evaluation of forecast results. Runoff forecasts based on scenarios of future (forecasted) rainfall can be readily evaluated.

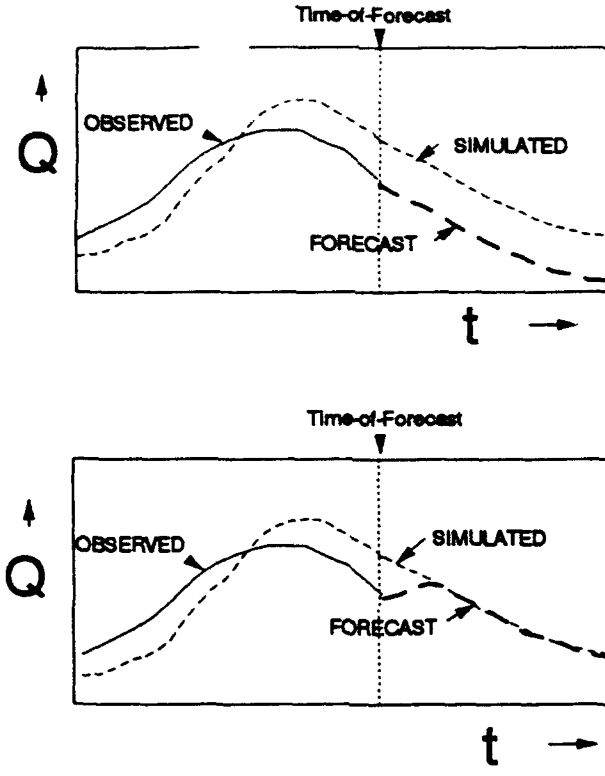


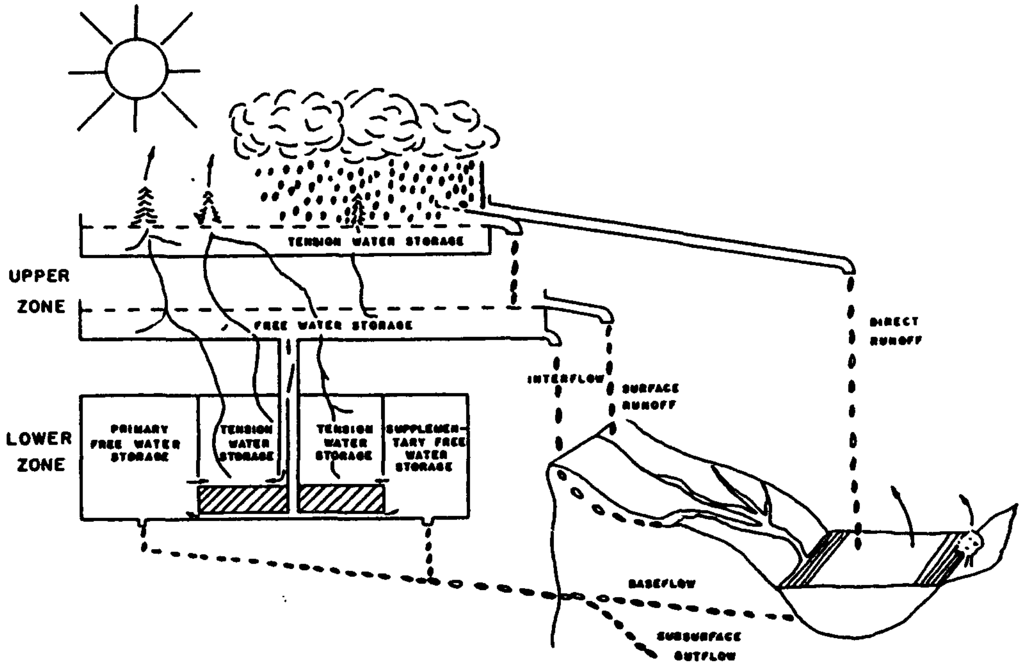
Figure 6. TWO METHODS FOR BLENDING

Continuous-type Modeling

An example of a continuous-type model used for real-time applications is the Sacramento Watershed Model (Burnash et al, 1973), developed by the California-Nevada River Forecast Center of the US National Weather Service. It has been in use for a number of years by that agency and is also a component of the National Weather Service River Forecasting System (NWSRFS).

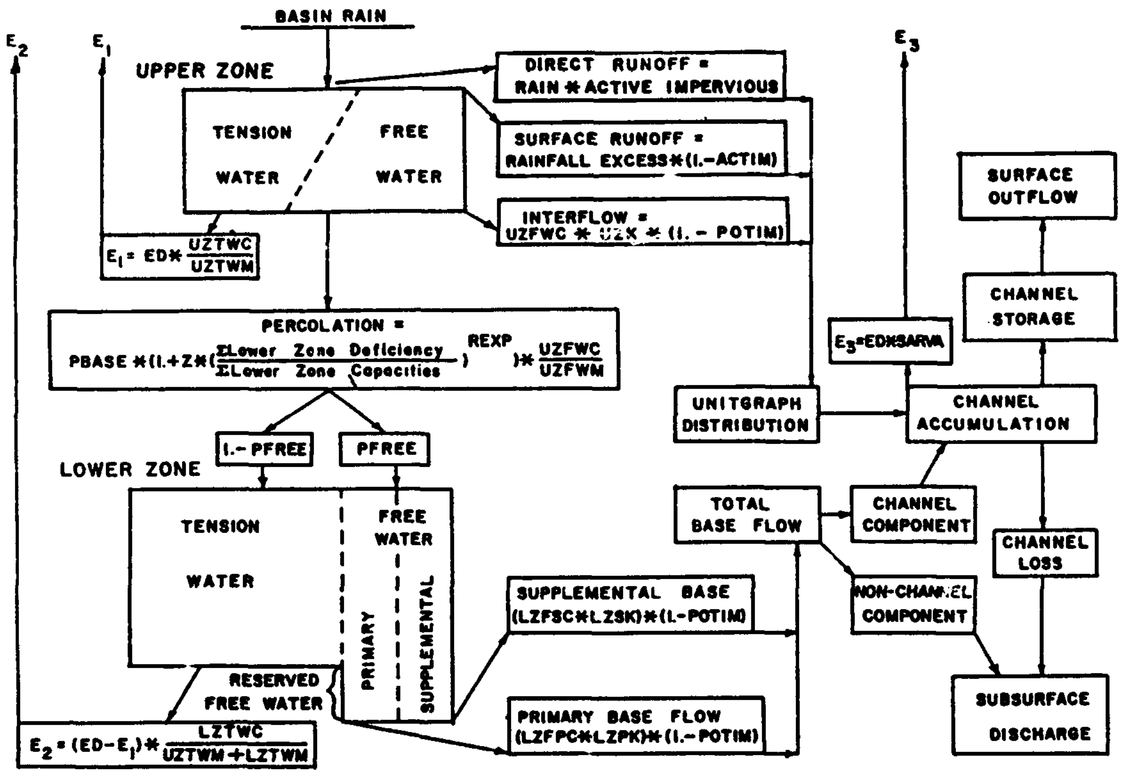
The Sacramento Model simulates runoff processes in headwater basins. It provides a conceptual representation of (1) soil moisture storage (as both *tension* and *free* water) at two levels, an upper zone and a lower zone; (2) direct runoff from impervious surfaces, water bodies and saturated ground; (3) percolation from the upper zone free water storage to the lower zone; (4) evaporation from surface water and evapotranspiration from tension water storage; (5) interflow from upper zone free water storage; and (6) baseflow and subsurface outflow (out of the basin) from lower zone free water storage. A unit hydrograph can be applied to surface runoff and interflow, and the resulting flow can optionally be routed with a non-linear "layered" Muskingum method. Figure 7 illustrates storage and runoff components of the Sacramento Model.

Figure 8 is a schematic representation of analytical aspects of the Sacramento Model. Processes are characterized in terms of storages of specified capacities which are filled from precipitation and percolation, and depleted by percolation, evapotranspiration and lateral drainage. Table 1 contains brief definitions of 17 parameters for defining the production of runoff from rainfall. The Table does not include parameters associated with a unit hydrograph or channel routing.



(Burnash et al 1973)

Figure 7. CONCEPTUAL REPRESENTATION OF THE SACRAMENTO MODEL



(Burnash et al 1973)

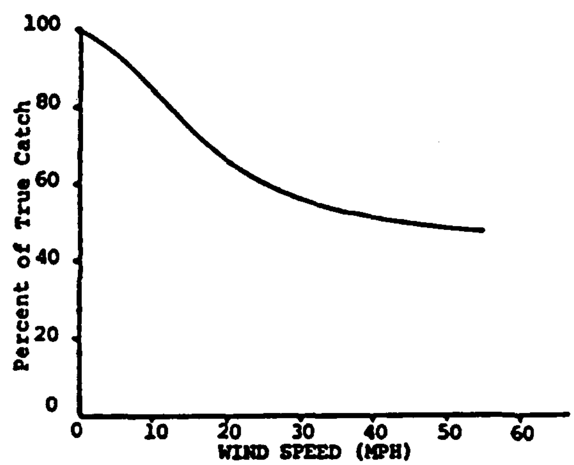
Figure 8. COMPONENTS OF THE SACRAMENTO MODEL

Table 1. Parameters for the Sacramento Watershed Model

PCTIM	Permanently impervious fraction of basin contiguous with stream channels. Rainfall on this portion of the basin bypasses storages and contributes instantly to runoff.
ADIMP	Fraction of the basin which becomes impervious when upper-zone tension storage becomes filled (i.e., behavior is same as for PCTIM).
SARVA	Fraction of basin covered by streams, lakes, and riparian vegetation (generally about 40% to 100% of PCTIM). Evapotranspiration occurs at the potential rate from this portion of the basin.
UZTWM	Maximum depth (over non-impervious areas) of upper zone tension water storage. This storage must be filled before any water becomes available for free water storage. Water from this storage is "lost" by direct evaporation from the soil surface or by evapotranspiration by shallow-rooted vegetation.
UZFWM	Maximum depth (over non-impervious areas) of upper zone free water. Water from this zone feeds the upper zone tension water storage, percolates to the lower zone or contributes to interflow. When the free water storage is full, rainfall contributes to surface runoff.
UZK	Depletion coefficient for upper zone free water storage. Upper zone lateral drainage (i.e. interflow) is determined on a daily basis as the product of this coefficient and available contents. Percolation from the upper zone (during a time interval) is accommodated prior to determination of interflow.
PFREE	Proportion of water percolating from the upper zone to the lower zone which passes directly to the free water storages without contributing to the tension water storage.
LZTWM	Maximum capacity of lower zone tension storage. Water stored here can only be removed by evapotranspiration.
LZFSM	Maximum capacity of lower zone supplemental free water storage. Water stored here contributes to baseflow at the "supplemental" rate.
LZSK	Depletion coefficient for lower zone supplemental free water storage. Supplemental baseflow (daily rate) is determined as the product of this coefficient and available contents.
LZFPM	Maximum capacity of lower zone primary free water storage. Water stored here contributes to baseflow at the "primary" rate.
LZPK	Depletion coefficient for lower zone primary free water storage. Primary baseflow (daily rate) is determined as the product of this coefficient and available contents.
RSERV	Decimal fraction of lower zone free water storage which is not available for supplying lower zone tension water storage. This portion of the lower zone free water storage is considered to be below the root system that reaches to the lower zone.
SIDE	Decimal fraction of baseflow (entering the river) that exits the basin without passing through the river channel. For example, a value of 0.5 indicates that a quantity of baseflow equal to 50% of that which enters the river leaves the basin without affecting baseflow in the river.
SSOUT	Constant streamflow loss term representing flow through porous material below the channel bottom. This term is commonly zero. Rivers in glaciated areas may require use of this parameter.
ZPERC	Proportional increase in percolation from saturated to dry condition.
REXP	Exponent in percolation equation which determines rate at which percolation demand changes from the dry condition, (ZPERC + 1)*PBASE, to the wet condition, PBASE.

The parameters in Table 1 provide substantial flexibility for representing rainfall-runoff processes. However calibration of these parameters can be a very challenging task, and there is the potential for mis-calibration such that the model is treated essentially as a "black box" without due regard for representation of the essential runoff characteristics of the basin. A poorly calibrated model is ill-suited for prediction, especially where conditions differ significantly from those used for calibration. It is generally necessary to have, as a minimum, several years of continuous precipitation and streamflow data as a basis for calibration.

A simple water balance of annual quantities of runoff, rainfall and evapotranspiration over a period of several years can be used to gain insight into the runoff characteristics of a basin. Such an evaluation can facilitate recognition of subsurface outflows that bypass the river channel, or problems in definition of rainfall volumes. Runoff (streamflow) measurements are generally the most accurate data source for this evaluation. Spatially-averaged rainfall data may be highly uncertain because of large sampling errors (due to sparse gage networks) and because of errors inherent in the measurement of rainfall. Wind effects (e.g., turbulence over the gage opening) tend to cause rainfall measurements to be biased on the low side, as illustrated in Figure 9. Underestimates of point rainfall depths of 15% or more are typical.



(Burnash, undated)

Figure 9. RAINFALL CATCH VS. WIND SPEED

Evapotranspiration must be estimated, as it is not measured. Actual evapotranspiration can differ significantly from evapotranspiration potential, depending on water availability. Evapotranspiration potential is sometimes based on application of monthly or seasonal coefficients applied to measured pan evaporation. However there is much uncertainty in this approach, as the physical processes and energy fluxes associated with pan evaporation can be substantially different from those associated with evapotranspiration. The Sacramento Model lumps evaporation from water bodies and moist soil with evapotranspiration from vegetation. Generally the latter is the dominant process. Because of the difficulty in using pan evaporation data as a surrogate for the total basin evapotranspiration, applications of the Sacramento Model commonly utilize direct estimates of basin evapotranspiration, for example using data such as that provided in Figure 10 (Burnash, undated).

IN MM

	SPRING		SUMMER		FALL		WINTER	
	WET	DRY	WET	DRY	WET	DRY	WET	DRY
HOT	3	4	6	7	3	4	2	2
WARM	2	3	5	6	2	3	1	1
COOL	1	1	3	4	1	2	0	1
COLD	1	1	2	2	1	1	0	0

(Burnash, undated)

Figure 10. **AVERAGE DAILY EVAPOTRANSPIRATION DEMAND**

Burnash (Burnash, undated) suggests initial (typical) values for the 17 parameters listed previously. He also provides a rationale for estimating values for several of the parameters from direct analysis of carefully selected portions of historical rainfall and streamflow data. For example, PCTIM, the impervious fraction of the basin contiguous with stream channels, can be estimated on the basis of small runoff events following long dry periods. Presumably surface runoff from the events is from the impervious fraction of the basin. PCTIM can be estimated from the ratio of surface runoff to rainfall accumulated for several such events.

Because of interdependence of parameters and uncertainty associated with rainfall data and evapotranspiration estimates, caution must be exercised in attempts at automated calibration. Burnash recommends review of monthly error summaries with due consideration of uncertainties in the driving inputs. Application of a model like the Sacramento Model requires substantial knowledge of the runoff characteristics of a basin and skill in interpreting cause and effect relationships among essential processes. Experience in applying a model of this type can itself be a means for acquiring understanding of basin rainfall-runoff behavior.

Model Updating

A real-time gauging network provides observed streamflow data up to the time-of-forecast. This data can used to adjust model inputs, states (i.e. volumes of water in storage) and/or parameter values so that the model is more "in tune" with current conditions. One such approach is to apply Kalman filtering for automated adjustment (Georgakakos, 1986). For flash floods, automated adjustment may not be practical because by the time a stream rise occurs, the time at which the forecast is required may already have passed. For an event-type model like HEC1F, model updating can be achieved using a combination of optimization for headwater subbasins and manual adjustment.

MODEL SELECTION AND USE

Factors to consider in selecting a model are (1) the knowledge and skills of the model user, (2) the hydrologic regime to which the model will be applied, and (3) data availability and data requirements. A widely cited study by the World Meteorological Organization (World Meteorological Organization, 1975b) indicates that in humid environments, soil moisture accounting models may not offer much advantage over simpler "event" approaches because of the relatively stable moisture conditions. However for arid and semi-arid climates, use of explicit soil moisture accounting models (like the Sacramento Watershed Model) can be advantageous.

Because of the complex nature of physical processes that constitute the hydrologic cycle, the heterogeneous characteristics of a watershed (including the subsurface), and the uncertainty associated with model inputs, rainfall-runoff modeling is a difficult and challenging task. The skills of the analyst applying the model can be significantly more important than the model itself. This is supported by Loague and Freeze, who in conclusion to a paper describing a comparison of modeling techniques on small upland catchments, state the following:

> "In many ways, hydrologic modeling is more an art than a science, and it is likely to remain so. Predictive hydrologic modeling is normally carried out on a given catchment using a specific model under the supervision of an individual hydrologist. The usefulness of the results depends in large measure on the talents and experience of the hydrologist and his understanding of the mathematical nuances of his particular model and the hydrologic nuances of his particular catchment. ..." (Loague and Freeze, 1985).

The above comments should be borne in mind when considering the role of rainfall-runoff modeling in flood forecasting. Modeling can provide valuable information which, when considered in relation to the current state of a basin and meteorological forecasts, can aid in the making of reasonable flood warning decisions. However, there will always be significant uncertainty associated with model predictions, and careful interpretation of model results is essential.

BIBLIOGRAPHY

Anderson, M.G. and T.P. Burt (editors) 1985. *Hydrological Forecasting*, John Wiley & Sons Ltd.

Burnash, Robert J.C. undated. "The Sacramento Watershed Model", River Forecast Center, National Weather Service, Sacramento, California.

Burnash, Robert J.C., R.L. Ferral, and R.L. McGuire 1973. *A Generalized Streamflow Simulation System*, National Weather Service, California Department of Water Resources, Sacramento, California.

Charley, W. and J. Peters 1988. "Development, Calibration and Application of Runoff Forecasting Models for the Allegheny River Basin," *Computerized Decision Support Systems for Water Managers*, Proceedings of the 3rd Water Resources Operations Management Workshop, American Society of Civil Engineers. (Also *Technical Paper No. 121*, Hydrologic Engineering Center, Davis, California.)

Dotson, H.W. and J. Peters 1990. "Hydrologic Aspects of Flood Warning-Preparedness Programs," Paper presented at the American Society of Civil Engineers Conference on Hydraulic Engineering, August 1990, San Diego, California. (Also *Technical Paper No. 131*, Hydrologic Engineering Center, Davis, California.)

Ford, D.T., E. Morris and A. Feldman 1980. "Corps of Engineers' Experience with Automatic Calibration of a Precipitation-runoff Model," *Water and Related Land Resource Systems*, (Y. Haimes and J. Kindler, eds.), Pergamon Press, New York. (Also *Technical Paper No. 70*, Hydrologic Engineering Center, Davis, California.)

Georgakakos, K.P. 1986. "A Generalized Stochastic Hydrometeorological Model for Flood and Flash-Flood Forecasting: 2. Case Studies," *Water Resources Research*, vol. 22, no. 13, pp. 2096-2106.

Henderson, F.M. 1966. *Open Channel Flow*, Macmillan Co., New York.

Kitanidis, P.R. and R.L. Bras 1980. "Real-Time Forecasting with a Conceptual Hydrologic Model, 2: Application and Results," *Water Resources Research*, Vol. 16, No. 6, pp. 1034-1044.

Kraijenhoff, D.A. and J.R. Moll (editors) 1986. *River Flow Modelling and Forecasting*, D. Reidel Publishing Company, Dordrecht, Holland.

Loague, Keith M. and R. Allan Freeze, 1985. "A Comparison of Rainfall-Runoff Modeling Techniques on Small Upland Catchments," *Water Resources Research*, vol. 21, no. 2, pp. 229-248.

Maidment, David R. (ed.) 1993, *Handbook of Hydrology*, (Chapter 26, Hydrologic Forecasting by D.P. Lettenmaier and E.F. Wood), McGraw-Hill.

Nemec, Jaromír 1986. *Hydrological Forecasting*, D. Reidel Publishing Company, Dordrecht, Holland.

Pabst, Arthur 1986. "State-of-the-Art Flood Forecasting Technology," *Proceedings of a Seminar on Local Flood Warning-Response Systems*, US Army Corps of Engineers, Hydrologic Engineering Center, Davis, California.

Pabst, A. and J. Peters 1983. "A Software System to Aid in Making Real-Time Water Control Decisions," paper presented at the Technical Conference on Mitigation of Natural Hazards Through Real-Time Data Collection and Hydrological Forecasting, *Technical Paper No. 89*, Hydrologic Engineering Center, Davis, California.

Peters, J. and P. Ely 1985. "Flood-Runoff Forecasting with HEC1F," *Water Resources Bulletin*, 21(1), pp. 7-13, (Also *Technical Paper No. 106*, Hydrologic Engineering Center, Davis, California.)

Sittner, W.T., C.E. Schauss, and J. Monroe 1969. "Continuous Hydrograph Synthesis with an API-Type Hydrograph Model", *Water Resources Research*, Vol. 5, No. 5, pp. 1007-1022.

Sittner, W.T. 1985. "Catchment Response in the Computer Age," *Computer Applications in Water Resources*, Harry C. Torno, ed., American Society of Civil Engineers, pp. 749-757.

Soil Conservation Service 1972. *National Engineering Handbook*, Section 4, US Department of Agriculture, Washington, D.C.

Sweeney, Timothy L. 1988. "Flash Flood Hydrologic Forecast Model, ADVIS," *Computerized Decision Support Systems for Water Managers*, Proceedings of the 3rd Water Resources Operations Management Workshop, American Society of Civil Engineers, pp. 683-692.

Taylor, Dolores B. and J. G. Weikel 1991. "Ventura County ALERT System - A Case Study", lecture notes for a training course on Flood Warning Preparedness Programs, Hydrologic Engineering Center, Davis, California.

US Army Corps of Engineers, Hydrologic Engineering Center 1989. "Water Control Software - Forecast and Operations," unnumbered software documentation, Davis, California.

US Army Corps of Engineers, Hydrologic Engineering Center 1990a. "HEC-1, Flood Hydrograph Package - User's Manual," *CPD-1A*, Davis, California.

US Army Corps of Engineers, Hydrologic Engineering Center 1990b. "HECDSS - User's Guide and Utility Program Manuals," *CPD-45*, Davis, California.

US Army Corps of Engineers, Hydrologic Engineering Center 1991. "HEC-2, Water Surface Profiles - User's Manual," *CPD-2A*, Davis, California.

US Army Corps of Engineers, North Pacific Division 1991. "Streamflow Simulation and Reservoir Regulation (SSARR) User's Manual" Portland, Oregon.

World Meteorological Organization 1973a. "Automatic Collection and Transmission of Hydrological Observations," *Operational Report No. 2, WMO No. 337*, Secretariat of the World Meteorological Organization, Geneva, Switzerland.

World Meteorological Organization 1973b. "Benefit and Cost Analysis of Hydrological Forecasts," *Operational Hydrology Report No. 3, WMO No. 341*, Secretariat of the World Meteorological Organization, Geneva, Switzerland.

World Meteorological Organization 1974. "Guide to Hydrologic Practices, 3rd edition," *WMO No. 168*, Secretariat of the World Meteorological Organization, Geneva, Switzerland.

World Meteorological Organization 1975a. "Hydrological Forecasting Practices," *Operational Hydrology Report No. 6, WMO No. 425*, Secretariat of the World Meteorological Organization, Geneva, Switzerland.

World Meteorological Organization 1975b. "Intercomparison of Conceptual Models Used in Operational Hydrological Forecasting," *Operational Hydrology Report No. 7, WMO No. 429*, Secretariat of the World Meteorological Organization, Geneva, Switzerland.

TECHNICAL PAPER SERIES
($2 per paper)

TP-1 Use of Interrelated Records to Simulate Streamflow
TP-2 Optimization Techniques for Hydrologic Engineering
TP-3 Methods of Determination of Safe Yield and Compensation Water from Storage Reservoirs
TP-4 Functional Evaluation of a Water Resources System
TP-5 Streamflow Synthesis for Ungaged Rivers
TP-6 Simulation of Daily Streamflow
TP-7 Pilot Study for Storage Requirements for Low Flow Augmentation
TP-8 Worth of Streamflow Data for Project Design - A Pilot Study
TP-9 Economic Evaluation of Reservoir System Accomplishments
TP-10 Hydrologic Simulation in Water-Yield Analysis
TP-11 Survey of Programs for Water Surface Profiles
TP-12 Hypothetical Flood Computation for a Stream System
TP-13 Maximum Utilization of Scarce Data in Hydrologic Design
TP-14 Techniques for Evaluating Long-Term Reservoir Yields
TP-15 Hydrostatistics - Principles of Application
TP-16 A Hydrologic Water Resource System Modeling Techniques
TP-17 Hydrologic Engineering Techniques for Regional Water Resources Planning
TP-18 Estimating Monthly Streamflows Within a Region
TP-19 Suspended Sediment Discharge in Streams
TP-20 Computer Determination of Flow Through Bridges
TP-21 An Approach to Reservoir Temperature Analysis
TP-22 A Finite Difference Method for Analyzing Liquid Flow in Variably Saturated Porous Media
TP-23 Uses of Simulation in River Basin Planning
TP-24 Hydroelectric Power Analysis in Reservoir Systems
TP-25 Status of Water Resource Systems Analysis
TP-26 System Relationships for Panama Canal Water Supply
TP-27 System Analysis of the Panama Canal Water Supply
TP-28 Digital Simulation of an Existing Water Resources System
TP-29 Computer Applications in Continuing Education
TP-30 Drought Severity and Water Supply Dependability
TP-31 Development of System Operation Rules for an Existing System by Simulation
TP-32 Alternative Approaches to Water Resource System Simulation
TP-33 System Simulation for Integrated Use of Hydroelectric and Thermal Power Generation
TP-34 Optimizing Flood Control Allocation for a Multipurpose Reservoir
TP-35 Computer Models for Rainfall-Runoff and River Hydraulic Analysis
TP-36 Evaluation of Drought Effects at Lake Atitlan
TP-37 Downstream Effects of the Levee Overtopping at Wilkes-Barre, PA, During Tropical Storm Agnes
TP-38 Water Quality Evaluation of Aquatic Systems
TP-39 A Method for Analyzing Effects of Dam Failures in Design Studies
TP-40 Storm Drainage and Urban Region Flood Control Planning
TP-41 HEC-5C, A Simulation Model for System Formulation and Evaluation
TP-42 Optimal Sizing of Urban Flood Control Systems
TP-43 Hydrologic and Economic Simulation of Flood Control Aspects of Water Resources Systems
TP-44 Sizing Flood Control Reservoir Systems by Systems Analysis
TP-45 Techniques for Real-Time Operation of Flood Control Reservoirs in the Merrimack River Basin
TP-46 Spatial Data Analysis of Nonstructural Measures
TP-47 Comprehensive Flood Plain Studies Using Spatial Data Management Techniques
TP-48 Direct Runoff Hydrograph Parameters Versus Urbanization
TP-49 Experience of HEC in Disseminating Information on Hydrological Models
TP-50 Effects of Dam Removal: An Approach to Sedimentation
TP-51 Design of Flood Control Improvements by Systems Analysis: A Case Study
TP-52 Potential Use of Digital Computer Ground Water Models
TP-53 Development of Generalized Free Surface Flow Models Using Finite Element Techniques
TP-54 Adjustment of Peak Discharge Rates for Urbanization
TP-55 The Development and Servicing of Spatial Data Management Techniques in the Corps of Engineers
TP-56 Experiences of the Hydrologic Engineering Center in Maintaining Widely Used Hydrologic and Water Resource Computer Models
TP-57 Flood Damage Assessments Using Spatial Data Management Techniques
TP-58 A Model for Evaluating Runoff-Quality in Metropolitan Master Planning
TP-59 Testing or Several Runoff Models on an Urban Watershed
TP-60 Operational Simulation of a Reservoir System with Pumped Storage
TP-61 Technical Factors in Small Hydropower Planning
TP-62 Flood Hydrograph and Peak Flow Frequency Analysis
TP-63 HEC Contribution to Reservoir System Operation
TP-64 Determining Peak-Discharge Frequencies in an Urbanizing Watershed: A Case Study
TP-65 Feasibility Analysis in Small Hydropower Planning
TP-66 Reservoir Storage Determination by Computer Simulation of Flood Control and Conservation Systems
TP-67 Hydrologic Land Use Classification Using LANDSAT
TP-68 Interactive Nonstructural Flood-Control Planning
TP-69 Critical Water Surface by Minimum Specific Energy Using the Parabolic Method
TP-70 Corps of Engineers Experience with Automatic Calibration of a Precipitation-Runoff Model
TP-71 Determination of Land Use from Satellite Imagery for Input to Hydrologic Models
TP-72 Application of the Finite Element Method to Vertically Stratified Hydrodynamic Flow and Water Quality

TP-73 Flood Mitigation Planning Using HEC-SAM
TP-74 Hydrographs by Single Linear Reservoir Model
TP-75 HEC Activities in Reservoir Analysis
TP-76 Institutional Support of Water Resource Models
TP-77 Investigation of Soil Conservation Service Urban Hydrology Techniques
TP-78 Potential for Increasing the Output of Existing Hydroelectric Plants
TP-79 Potential Energy and Capacity Gains from Flood Control Storage Reallocation at Existing U. S. Hydropower Reservoirs
TP-80 Use of Non-Sequential Techniques in the Analysis of Power Potential at Storage Projects
TP-81 Data Management Systems for Water Resources Planning
TP-82 The New HEC-1 Flood Hydrograph Package
TP-83 River and Reservoir Systems Water Quality Modeling Capability
TP-84 Generalized Real-Time Flood Control System Model
TP-85 Operation Policy Analysis: Sam Rayburn Reservoir
TP-86 Training the Practitioner: The Hydrologic Engineering Center Program
TP-87 Documentation Needs for Water Resources Models
TP-88 Reservoir System Regulation for Water Quality Control
TP-89 A Software System to Aid in Making Real-Time Water Control Decisions
TP-90 Calibration, Verification and Application of a Two-Dimensional Flow Model
TP-91 HEC Software Development and Support
TP-92 Hydrologic Engineering Center Planning Models
TP-93 Flood Routing Through a Flat, Complex Flood Plain Using a One-Dimensional Unsteady Flow Computer Program
TP-94 Dredged-Material Disposal Management Model
TP-95 Infiltration and Soil Moisture Redistribution in HEC-1
TP-96 The Hydrologic Engineering Center Experience in Nonstructural Planning
TP-97 Prediction of the Effects of a Flood Control Project on a Meandering Stream
TP-98 Evolution in Computer Programs Causes Evolution in Training Needs: The Hydrologic Engineering Center Experience
TP-99 Reservoir System Analysis for Water Quality
TP-100 Probable Maximum Flood Estimation - Eastern United States
TP-101 Use of Computer Program HEC-5 for Water Supply Analysis
TP-102 Role of Calibration in the Application of HEC-6
TP-103 Engineering and Economic Considerations in Formulating
TP-104 Modeling Water Resources Systems for Water Quality
TP-105 Use of a Two-Dimensional Flow Model to Quantify Aquatic Habitat
TP-106 Flood-Runoff Forecasting with HEC-1F
TP-107 Dredged-Material Disposal System Capacity Expansion
TP-108 Role of Small Computers in Two-Dimensional Flow Modeling
TP-109 One-Dimensional Model For Mud Flows
TP-110 Subdivision Froude Number
TP-111 HEC-5Q: System Water Quality Modeling
TP-112 New Developments in HEC Programs for Flood Control
TP-113 Modeling and Managing Water Resource Systems for Water Quality
TP-114 Accuracy of Computed Water Surface Profiles - Executive Summary
TP-115 Application of Spatial-Data Management Techniques in Corps Planning
TP-116 The HEC's Activities in Watershed Modeling
TP-117 HEC-1 and HEC-2 Applications on the MicroComputer
TP-118 Real-Time Snow Simulation Model for the Monongahela River Basin
TP-119 Multi-Purpose, Multi-Reservoir Simulation on a PC
TP-120 Technology Transfer of Corps' Hydrologic Models
TP-121 Development, Calibration and Application of Runoff Forecasting Models for the Allegheny River Basin
TP-122 The Estimation of Rainfall for Flood Forecasting Using Radar and Rain Gage Data
TP-123 Developing and Managing a Comprehensive Reservoir Analysis Model
TP-124 Review of the U.S. Army Corps of Engineering Involvement With Alluvial Fan Flooding Problems
TP-125 An Integrated Software Package for Flood Damage Analysis
TP-126 The Value and Depreciation of Existing Facilities: The Case of Reservoirs
TP-127 Floodplain-Management Plan Enumeration
TP-128 Two-Dimensional Floodplain Modeling
TP-129 Status and New Capabilities of Computer Program HEC-6: "Scour and Deposition in Rivers and Reservoirs"
TP-130 Estimating Sediment Delivery and Yield on Alluvial Fans
TP-131 Hydrologic Aspects of Flood Warning - Preparedness Programs
TP-132 Twenty-five Years of Developing, Distributing, and Supporting Hydrologic Engineering Computer Programs
TP-133 Predicting Deposition Patterns in Small Basins
TP-134 Annual Extreme Lake Elevations by Total Probability Theorem
TP-135 A Muskingum-Cunge Channel Flow Routing Method for Drainage Networks
TP-136 Prescriptive Reservoir System Analysis Model - Missouri River System Application
TP-137 A Generalized Simulation Model for Reservoir System Analysis
TP-138 The HEC NexGen Software Development Project
TP-139 Issues for Applications Developers
TP-140 HEC-RAS/HEC-2 Comparison Study
TP-141 HEC-RAS Conveyance Comparison
TP-142 Systems Analysis Applications at the Hydrologic Engineering Center
TP-143 Runoff Prediction Uncertainty for Ungauged Agricultural Watersheds
TP-144 Review of GIS Applications in Hydrologic Modeling
TP-145 Application of Rainfall-Runoff Simulation for Flood Forecasting

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Distribution of this document is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Technical Paper No. 145	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION US Army Corps of Engineers Hydrologic Engineering Ctr 6b. OFFICE SYMBOL (If applicable) CEWRC-HEC	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) 609 Second Street Davis, California 95616	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Application of Rainfall-Runoff Simulation for Flood Forecasting

12. PERSONAL AUTHOR(S)
John C. Peters

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical Paper	FROM ______ TO ______	1993 JUNE	20

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Flood-flow forecasting; rainfall-runoff simulation

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Flood-warning objectives, approaches to short-term hydrologic forecasting, and characteristics of rainfall-runoff models for forecast applications, are discussed. HEC-1 and HEC-2 are described as illustrations of models that can be applied to develop warning criteria; HEC1F and the Sacramento Model are described as illustrations of models for real-time application. Finally, aspects of model selection and use are discussed.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL John C. Peters	22b. TELEPHONE (Include Area Code) (916) 756-1104 22c. OFFICE SYMBOL CEWRC-HEC