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Corps of Engineers' Experience with Automatic Calibration of a Precipitation-Runoff Model

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David T. Ford, Edward C. Morris, Arlen D. Feldman

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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

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CORPS OF ENGINEERS' EXPERIENCE WITH AUTOMATIC CALIBRATION OF A PRECIPITATION-RUNOFF MODEL[1]

David T. Ford

Hydraulic Engineer, Training & Methods Branch, The Hydrologic Engineering Center, Davis, California

Edward C. Morris

Research Hydraulic Engineer, Research Branch, The Hydrologic Engineering Center, Davis, California

Arlen D. Feldman

Chief, Research Branch, The Hydrologic Engineering Center, Davis, California

Abstract. Computer program HEC-1, a precipitation-runoff model widely used throughout the United States, includes the capability to estimate automatically any of twelve parameters necessary to model the precipitation-runoff process and the channel routing process. The parameter estimation scheme employs Newton's method to minimize a weighted sum of squares of differences between observed and computed hydrograph values. Applications of this parameter estimation procedure are presented, and typical steps of the procedure for determining optimal parameter estimates are outlined. Recent efforts to improve the estimation algorithm and recent use of the calibration capability to update sequentially parameter estimates in a flood forecasting application are discussed.

Keywords. Water Resources, Hydrology, Rainfall-Runoff Modelling, Parameter Estimation, Computer Applications.

INTRODUCTION

Computer program HEC-1, which simulates the hydrologic response of urban and rural watersheds, was developed as a tool to assist the staff of the U.S. Army Corps of Engineers in meeting their water management responsibilities. The basic concepts embodied in the program were conceived in 1966 when Beard and other members of The Hydrologic Engineering Center (HEC) developed a set of small programs that could be used independently to solve the individual tasks typically required in a hydrologic study. Included in the set of programs was one which employed a univariate version of Newton's technique to calibrate automatically unit hydrograph and loss rate parameters (HEC, 1967). In 1967, when the set of programs was combined into the single computer program entitled HEC-1 Flood Hydrograph Package, this technique was adopted and has been retained through subsequent revisions, including the latest 1973 version. Over 400 copies of the latest version have been distributed to private consulting firms, universities, and governmental agencies in both the United States and other countries. The program has been executed nearly 4000 times annually by Corps personnel using the Lawrence Berkeley Laboratory computer.

The automatic parameter estimation option of the program has been extensively used for several reasons. First, the Hydrograph Analysis Package is composed of a set of simple conceptual procedures employing lumped parameters that are intended to model the general behavior of hydrologic phenomena. The parameters of the conceptual procedures are inferred from precipitation and streamflow records rather than by direct measurement of physical watershed characteristics. As a result of inaccuracies in the modelling process and in the measurement of input data, even experienced users have difficulty in determining precise parameter values. Second, many users are inexperienced with the model, and the automatic calibration feature eliminates the frustrating trial and error approach to estimating acceptable parameter values.

This paper describes the major technical components of the program and details the basic structure of its calibration technique. The strategy for employing the automatic calibration features of the program in regional studies is discussed, and several typical applications are described. A flood forecasting

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application is summarized that involves sequentially updating the model's parameters as successive forecasts are calculated during a storm event. In addition, application of an alternative optimization scheme, involving the random search method of Box (1965), is presented.

DESCRIPTION OF THE HEC-1 FLOOD HYDROGRAPH PACKAGE

The HEC-1 computer program consists of three major hydrologic components that determine the average precipitation and snowmelt and the amount of effective precipitation contributing to direct runoff from a subbasin, compute the subbasin runoff hydrograph from the effective precipitation, and route and combine the subbasin runoff hydrographs. All components in HEC-1 employ lumped parameters for each subbasin or routine reach. This means that the model's input, parameters, and output are considered to be average values over the entire subbasin of interest. When subbasin averages are not appropriate, smaller subbasins can be defined to obtain a better spatial definition.

The first computational step in the program determines the average subbasin precipitation from either historical gaged data or hypothetical storms. This is followed by an accounting of interception and accumulation of soil moisture by a loss rate function to compute the subarea rainfall or snowmelt excess. The moisture excess is then distributed in time by a unit hydrograph function, added to a base flow function, and recessed by a logarithmic decay function once a specified recession flow rate is reached on the falling limb of the hydrograph. This yields the total runoff hydrograph at the subbasin's outlet. Next, the runoff hydrograph from the subbasin is conveyed downstream using a streamflow routing function. Tributary streamflows are added at the confluences as the simulation proceeds downstream. Snowfall and snowmelt are simulated in each subarea according to temperatures in various elevation bands. Either the degree-day or energy budget method may be used to compute the snowmelt. Complex stream systems can be simulated if the unit graph, loss rate and routing parameters are specified along with either observed precipitation or a specified precipitation depth-area relationship. In addition, expected annual damages can be calculated at any point in the stream system where flow-frequency and flow-damage relationships are provided. The model's automatic calibration features can be used to select unit hydrograph and loss rate parameters in a single subbasin or choose the routing parameters in an individual river reach. In both cases the optimization scheme is based on comparisons with the observed and simulated hydrographs.

Loss Rate Functions

Precipitation losses to interception, depression storage and infiltration may be simulated by one of three loss rate functions: initial loss followed by a constant loss rate, the SCS curve number technique (Soil Conservation Service, 1972), or the HEC exponential loss rate function. The latter computes precipitation losses as a function of antecedent soil moisture, precipitation intensity, and an infiltration rate that is a non-linear function of accumulated losses, as shown in Fig. 1. For a snow-free basin the equations for the HEC-1 exponential loss rate are as follows:

$$ALOSS = (AK + DLTK)\ (RAIN)^{ERAIN} \quad (1)$$

$$AK = (STRKR)/(RTIOL)^{0.1\ CUML} \quad (2)$$

$$DLTK = 0.2\ DLTKR\ [1-(CUML/DLTKR)]^2$$

$$\text{for } (CUML/DLTKR) < 1;$$

$$\text{otherwise } DLTK = 0. \quad (3)$$

where ALOSS is the loss rate in mm/hr; AK is the basic loss coefficient, DLTK is the incremental loss coefficient; RAIN is the rainfall intensity in mm/hr; ERAIN is an exponent that reflects the influence of precipitation intensity on the basin average loss characteristics; STRKR is the starting value of the basic loss index on the exponential recession curve in mm/hr; RTIOL is the ratio of the loss rate coefficient AK to that after 254 mm more of accumulated loss occurs; CUML is the accumulated loss in mm; and DLTKR is an incremental loss index.

The program contains a separate set of loss rate equations that are employed when the snowmelt capabilities of the program are desired:

$$ALOSS = AK\ (RAIN + SNWMT)^{ERAIN} \quad (4)$$

$$AK = (STRKS)/(RTIOK)^{0.1\ CUML} \quad (5)$$

where SNWMT is the snowmelt in mm/hr, STRKS is the basic loss coefficient for snowmelt in mm/hr, and RTIOK is similar to RTIOR for snowmelt conditions. Equations 4 and 5 are used in lieu of equations 1 and 2 whenever snowmelt occurs. The amount of snowmelt is calculated separately in each elevation zone based on the air temperature which is calculated from a base temperature at the lowest elevation and a user supplied adiabatic lapse rate. The degree-day method for computing snowmelt is:

$$SNWMT = COEF\ (TMPR - FRZTP) \quad (6)$$

where TMPR is the air temperature in ^{o}C lapsed to the midpoint of the elevation zone, FRZTP is the temperature in ^{o}C at which snow melts, and COEF is the melt coefficient in mm per

degree-day (^{o}C). Energy-budget equations for melt during rain or melt during rainfree periods can also be employed. The losses are subtracted from rainfall and snowmelt in each zone, and the excesses are summed to yield the excess precipitation from the subbasin.

In the loss rate and snowmelt equation, the following parameters must be determined by calibration: STRKR, RTIOL, DLTKR, ERAIN, COEF, STRKS, RTIOK, and FRZTP.

Unit Hydrograph Functions

The precipitation excess-to-runoff transformation is accomplished by the use of the unit hydrograph. Sherman (1932) defined the unit hydrograph as follows:

> If a given one-day rainfall produces a one-inch depth of runoff over the given drainage area, the hydrograph showing the rates at which the runoff occurred can be considered a unit graph for the watershed.

Application of this technique to precipitation excess amounts other than one inch is accomplished by multiplying precipitation excess amounts by the unit hydrograph ordinates because the runoff ordinates for a given duration are assumed to be directly proportional to the rainfall excess. Unit hydrograph ordinates can be supplied directly to the program or the unit hydrograph can be calculated using techniques proposed by Clark (1945), Snyder (1938) or the SCS (1972).

The Clark method uses two parameters and a time-area relationship to define an instantaneous unit hydrograph. Experience by the HEC has indicated that the use of a detailed time area relationship is usually not warranted and that one based on a generalized watershed shape (contained within the program) is satisfactory in most instances. When used in this fashion, Clark's technqiue requires only TC, the time of concentration, and R, a storage constant, to define the ordinates of the unit hydrograph. This function is attractive because it avoids the difficulties associated with the calibration of many individual unit graph ordinates. The general shape of the hydrograph is fixed and problems associated with negative ordinates and infeasible fluctuations of the unit hydrograph are eliminated.

In addition to the Clark parameters, Snyder's coefficients TP and CP, which define the peak of the unit hydrograph, can be provided as input. The program internally uses the Clark procedure by interatively varying TC and R until the peak of the unit hydrograph corresponds to the one described by the specified Snyder's parameters. The SCS dimensionless unit hydrograph technique, which uses a single lag parameter TLAG to define the shape of a triangular unit hydrograph, can also be used.

The unit hydrograph parameters required for calibration are TC and R, or TP and CP, or TLAG.

Streamflow Routing

Subbasin runoff is routed downstream using one of the following 'hydrologic' routing techniques: Muskingum, working R&D, straddle-stagger, Tatum, modified Puls or multiple storage. Parameters for the first four methods can be automatically calibrated. These parameters include the following:

1. Number of routing steps to be used for routing by the Tatum method, Muskingum method, or modified Puls method (NSTPS).

2. Number of ordinates to be averaged in the straddle-stagger routing (NSTDL).

3. Number of intervals the hydrograph is to be lagged in the straddle-stagger routing (LAG).

4. Coefficients of the Muskingum routing function (AMSKK and X).

5. Time-of-storage coefficient for the multiple storage routing (TSK).

The non-linear storage outflow relationship required for the modified Puls and working R&D methods can be obtained using steady-state water surface profile computations or using a separate optimization program such as the one suggested by Slocum and Dandekar (1975).

PARAMETER ESTIMATION TECHNIQUES

If HEC-1 were a perfect model of watershed hydrology, and if total precipitation and total direct runoff could be measured accurately, the parameters of the precipitation-runoff transformation functions for a particular storm event could be determined directly by inverse solution of the transformation equations. However, these conditions are not satisfied in reality, and inverse solution of the equations is difficult, so the parameters are found instead by selection of those values that yield the "best" reproduction of a measured runoff event with the available measured precipitation data and the available model. This parameter selection has often been accomplished by a systematic trial-and-error procedure: parameter values are selected, the model is exercised with these values, and, the resulting runoff hydrograph is compared with the observed hydrograph. If the "fit" is less than satisfactory, different parameter values are selected, the model is exercised with these values, and, the resulting runoff hydrograph is compared with the observed hydrograph. If the "fit" is less than satisfactory, different parameter values are selected, and the entire process is repeated.

An alternative to the trial-and-error approach to parameter selection is an automatic calibration approach in which the necessary tasks for calibration are automated. Automatic calibration requires selection of an explicit index of the acceptability of alternative parameter estimates, definition of the range of feasible values of the parameters, and development of some techniques for correction of the parameter estimates until the "best" estimates are determined. Thus the parameter estimation problem can be classified as an optimization problem: there is an objective function for which an optimal value is sought, subject to certain constraints on the decision variables (the parameters). The HEC-1 program includes the capability to solve this optimization problem, thereby automatically determining optimal parameter estimates.

Objective Function

The objective function of the parameter estimation optimization problem must define the difference between the computed runoff hydrograph (with any parameter estimates) and the recorded runoff hydrograph. Presumably, this difference will be at a minimum for the optimal parameter estimates. In HEC-1, the following objective function is employed as an index of the errors:

$$STDER = \sqrt{\sum_{i=1}^{N} [(QOBS_i - QCOMP_i)^2 * WT_i] / N} \quad (7)$$

where STDER = the error index; $QOBS_i$ = observed runoff hydrograph ordinate for time period i; $QCOMP_i$ = the runoff hydrograph ordinate for time period i, computed by HEC-1 with the current parameter estimates; N = total number of hydrograph ordinates; WT_i = a weight for the hydrograph ordinate. The weight, WT_i, is defined as follows:

$$WT_i = (QOBS_i + QAVE) / (2 * QAVE) \quad (8)$$

where QAVE = the average computed discharge. This weighting function emphasizes accurate reproduction of peak flows rather than low flows by biasing the objective function. Any errors for discharge ordinates that exceed the average discharge will be weighted more heavily, and hence the optimization scheme should focus on reduction of these errors.

Constraints

The range of feasible values of the parameters is bounded because of physical limitations on the values that the various unit hydrograph, loss rate, and snowmelt parameters may have, and also because of numerical limitations imposed by the mathematical functions employed to model watershed behavior. In addition to bounds on the maximum and minimum values of certain parameters, the interaction of some parameters is also restricted because of physical or numerical limitations. These constraints are summarized in Table 1. The constraints shown here are limited to those imposed explicity in the program. Additional constraints may be appropriate in certain circumstances; however, these must be imposed externally to the program when the user must decide whether to accept, to modify, or to reject a given parameter set, based on engineering judgment.

TABLE 1 Constraints on HEC-1 Unit Hydrograph and Loss Rate Parameters

$(TC + R) \geq 1.03/(1. - [R/(TC + R)])$
$R/(TC + R) < 0.52/(TC + R)$
$R/(TC + R) \leq 1.0 - (1.03/(TC + R))$
$ERAIN \leq 1.0$
$RTIOL \geq 1.0$
$RTIOK \geq 1.0$
$FRZTP \geq -1.11$ °C
$FRZTP \leq 3.33$ °C

OPTIMIZATION TECHNIQUE

The constrained optimization scheme employed in HEC-1 is a univariate search technique that uses Newton's method. Application of such a technique permits use of the simulation capabilities of HEC-1 in a traditional manner and does not require development of analytical derivatives. Steps in application of this technique, as implemented in HEC-1, are as follows:

1. Initial values are assigned for all parameters. These values may be assigned by the program user, or program-assigned default values may be used. The default parameter values are shown in Tables 2 and 3.

2. The response of the watershed is simulated with the initial parameter estimates, and the value of the objective function is computed by comparison of the ordinates of the computed and observed runoff hydrographs.

3. In the order shown in Tables 2 and 3, each parameter to be estimated is decreased by one percent and then by two percent, the system response is evaluated, and the objective function calculated for each change, respectively. This gives three separate system evaluations at equally-spaced values of the parameter with all other parameters held constant. The "best" value of the parameter is then estimated using Newton's method.

4. Step 3 is repeated, using the "best" estimates of the parameters.

5. Step 3 is repeated for the parameter that most improved the value of the objective function in its last change until no single change in any parameter yields a

reduction of the objective function of more than one percent.

6. One more complete search of all parameters is made.

7. Step 5 is repeated, and the final parameter estimates are identified as optimal.

For the integer-valued parameters, the estimate is increased or decreased for each in turn until a minimum is determined.

The scheme employed for estimating the "best" value of each parameter in Step 3 is based on the concept that the optimum of the objective function occurs at a root of the first partial derivative of the function with respect to each of the parameters. These derivatives cannot easily be evaluated analytically because the objective function indirectly includes all the functions and equations contained in the HEC-1 watershed response. Therefore, numerical approximations of the derivatives are used.

TABLE 2 Program HEC-1 Default Initial Unit Hydrograph and Loss Rate Parameter Estimates

Parameter Number	Parameter Number	Initial Value
1	TC+R	$\sqrt{(TAREA)}/TRHR$
2	R/(TC+R)	0.5
3	COEF	0.07
4	STRKR	0.2
5	STRKS	0.2
6	RTIOK	2.0
7	ERAIN	0.5
8	FRZTP	0.0
9	DLTKR	0.5
10	RTIOL	2.0

TAREA = Drainage area, in square miles
TRHR = Computation interval, in hours

TABLE 3 Program HEC-1 Default Initial Routing Parameter Estimates

Parameter Name	Initial Value
NSTPS	1
NSTDL	1
LAG	1
AMSKK	TRHR
X	.2
TSK	3*(TRHR)

APPLICATION OF THE CALIBRATION CAPABILITY

Due to the varying quantity and form of data available for precipitation-runoff analysis, the exact sequence of steps in application of the automatic calibration capability of HEC-1 varies from study to study. An often-used strategy employs the following steps when using the complete exponential loss rate equation:

1. Determine for each storm selected for use in calibration the base flow and recession parameters that are event dependent and are not included in the set of parameters that can be estimated automatically. These parameters are the recession flow for antecedent runoff (STRTQ), the discharge at which recession flow begins (QRCSN), and the recession coefficient that is the ratio of flow at some time to the flow ten time periods later (RTIOR). These parameters are illustrated in Fig. 2. The HEC-1 Users Manual (HEC, 1973) suggests techniques for estimating these parameters.

2. For each storm at each gage, determine the optimal estimates of all unknown unit hydrograph and loss rate parameters using the automatic calibration feature of HEC-1.

3. If ERAIN is to be estimated, select a regional value of ERAIN, based on analysis of the results of Step 2 for all storms for the representative gages.

4. Using the optimization scheme, estimate the unknown parameters with ERAIN now fixed at the selected value. Select an appropriate regional value of RTIOL if RTIOL is unknown. If the temporal and spatial distribution of precipitation is not well defined, an initial loss, followed by a uniform loss rate may be appropriate. In this case, ERAIN = 0 and RTIOL = 1. If these values are used, as they often are in studies accomplished at HEC, Steps 2, 3, and 4 are omitted.

5. With ERAIN and RTIOL fixed, estimate the remaining unknown parameters using the optimization scheme. Select a value of STRKR for each storm being used for calibration. If parameter values for adjacent basins have been determined, check the selected value for regional consistency.

6. With ERAIN, RTIOL, and STRKR fixed, use the parameter estimation algorithm to compute all remaining unknown parameters. DLTKR can be generalized and fixed if desired at this point, although this parameter is considered to be relatively event-dependent.

7. Using the calibration capability of HEC-1, determine values of TR+R and R/(TC+R). Select appropriate values of TC+R for each gage. In order to determine TC and R, an average value of R/(TC+R) is typically selected for the region.

8. Once all parameters have been selected, the values should be verified by simulating the response of the gaged basins to other events for which precipitation and runoff records are available.

APPLICATIONS OF HEC-1 AT THE HEC

The HEC-1 optimization scheme has been used by the HEC in numerous studies for nearly 10 years. The applications have focused on developing frequency curves for ungaged locations and on modelling the impact of basin modifications, of channel improvements, or of additional control measures at selected locations.

Many of the recent applications of HEC-1 accomplished at the Hydrologic Engineering Center have employed the automatic calibration scheme in development of data for ungaged areas. Typically in these studies data are available from stream and precipitation measurement stations in the proximity of a location for which detailed stage and discharge data are unavailable but are desired. The automatic calibration technique is used to estimate unit hydrograph, loss rate, and routing parameters for the gaged locations, and this data is "transferred" to the ungaged locations using regression techniques. The particular strategy for estimating parameters and the methods for transferring the parameters to ungaged locations is a function of the basin characteristics, the available data, the parameters that are found via calibration, and the time and money available for the study.

While the sequence of steps for estimation of all parameters of this rainfall-runoff model has been employed in at least one major study, the flexibility gained by use of four parameters in the exponential loss rate equation is not always necessary. Often ERAIN is set to zero, RTIOL is set to one, and calibration proceeds with Step 5 to this sequence. This approach has been employed in studies of the Shellpot and Naaman Creeks (HEC, 1976), the Schuylkill River (HEC, 1976), the Maurice River (HEC, 1976), and the Lehigh River (HEC, 1978). In a hydrologic study on the Oconee River Basin, ERAIN and DLTKR were set to zero, yielding a simple exponential decay loss function (1976).

The Soil Conservation Service's dimensionless unit graph and rainfall-runoff relationship based on the soil classification curve numbers were recently added to HEC-1. An application was made on the Pennypack Creek as part of an expanded flood plain information report (HEC, 1978). The 145 km^2 study area was broken into 65 subareas, each requiring unit graph, loss rate, and channel storage parameters. The curve number (CN) and lag parameters, which are the only variables necessary to define the SCS unit graph and loss rate, were estimated via optimization for the gaged basins. These were used as a guide in establishing CN and LAG values for the ungaged subareas.

FORECASTING APPLICATION

In addition to the previously described applications of HEC-1, the model has recently been applied to develop reservoir inflow forecasts for W. Kerr Scott Reservoir on the Yadkin River of North Carolina. For this application, the basic model was modified so that the calibration technique could be used to update sequentially the model parameters. The parameters are then used to calculate forecasted streamflows.

In the W. Kerr Scott system, 20 gages, nine of them recording, were available to determine mean areal precipitation in the 900 km^2 basin. Seven storm events were modelled, using the optimization procedure to estimate TC, R, ERAIN, RTIOL, and STRKR for the basin. Conceptually, these parameters will remain constant from storm to storm on the same basin, with DLTKR alone indicating the antecedent basin wetness. In reality, all the parameters vary due to storm centering, to inaccuracies in precipitation data, to nonhomogeneity of the basin, and to the approximate nature of the hydrologic model. Three combinations of estimated and fixed parameters were investigated. In the first case, basin average values of TC and R were used, and the four loss rate parameters were established by calibration. In the second case, ERAIN was set to zero and RTIOL was set to one, while the remaining parameters were estimated by calibration. Finally, all six parameters were estimated via calibration. When tested for seven storm events, the latter approach provided more accurate predictions when the time of forecast occurred before the peak of the hydrograph. In each case, the parameters were estimated using the computed reservoir inflows and observed mean areal precipitation that were available at the time of forecast. The purpose of the calibration was to adjust loss rates to reflect the antecedent conditions and fine tune the unit graph parameters to best fit each storm.

Forecast Procedure

In order to test the procedure in a realistic forecasting application, data from four storms were used in a situation that is similar to that encountered by Corps' field offices. Whenever the calculated reservoir inflow exceeded 50 cms (twice the long term average inflow for Scott Reservoir), a forecast was calculated using the data available at that time. Subsequent forecasts were calculated every two hours, using additional data observed between forecasts, until the inflow hydrograph started to recede. In addition, forecasts were issued whenever subsequent rises occurred during the receding limb. Thus forecasts were made for all the peaks in a complex hydrograph.

Two strategies were investigated for establishing the initial values for calibration of the unit graph and loss rate parameters.

The initial values for TC, R, ERAIN, RTIOL for method 1 were based on average values determined from the calibration of seven storms while program default values were used for STRKR and DLTKR. These starting values were used for every forecast during the event, and did not consider the results of the previous forecast. Method 2 employed the same starting values for the first forecast of each storm, but initial values for subsequent forecasts were set equal to optimal parameter values from the previous forecast.

Analysis of Forecasting Results

The performance of a flood forecast model can be fully evaluated only after the event has occurred and the complete observed inflow hydrograph is available. For reservoir operation, both the shape and the volume of the flood hydrograph are important. The following statistical measures were defined to measure discrepancies between the forecasted and observed inflows, beginning when the forecast is issued and ending when the observed flow recedes to 20% of the peak flow:

Volume Error =

$$\sum_{i=1}^{N} (QS_i - QO_i) / \sum_{i=1}^{N} QO_i \qquad (9)$$

Average Discharge Error =

$$1/N \sum_{i=1}^{N} (|QS_i - QO_i| / QO_i) * 100 \qquad (10)$$

where QO_i = observed discharge at ordinate i; QS_i = simulated discharge at ordinate i; N = number of hydrograph ordinates.

The overall accurancy of the forecasts is a function of storm type and intensity, representativeness of the computed basin average precipitation, and the degree of storm development. Despite the difficulties in providing high quality data for the calibration, the forecasted volumes for the four storms are reasonable; the predicted inflow volumes are within 25 percent of the observed values 8 to 10 hours prior to the peak. As expected, forecasts made before the total precipitation had fallen generally underestimated the total runoff volume.

In order to improve the performance of the forecasting scheme, the sources of differences between the observed and forecasted discharge must be isolated. Typically these sources include errors inherent within the forecasting procedure, errors in the basin hydrologic model, and errors in the model calibration.

Errors inherent within any forecasting procedure include uncertainty in measurement of precipitation and streamflow data, and underestimation of the hydrograph before the total precipitation occurs. In the Yadkin application, inflow into the W. Kerr Scott Reservoir was calculated using the change in elevation of the pool level, elevation-storage tables, and the reservoir releases determined by the gate-discharge rating tables. Fluctuations in the reservoir pool due to wind set-up and seiching, combined with an unknown amount of gate slippage caused the calculated inflows to oscillate considerably. The adopted inflow hydrograph used for calibrating and forecasting was based on a smoothed curve, so considerable errors could occur in the slope of the rising limb. Because this early portion of the observed hydrograph is used to verify and adjust the simulated hydrograph, the calibration scheme could have forced a fit with erroneous data and thus could have degraded the forecasted hydrograph.

The basic structure of the hydrologic model and the manner it is applied can also lead to errors. Because of the appreciable lag time between the measurement of rainfall on the basin and its occurrence at the streamgage, when a forecast is issued early in the flood event, only a small portion of the recorded precipitation may contribute to the simulated discharge prior to the time of forecast. When this occurs it is possible that the optimization scheme may cause substantial changes in the model's parameters without a corresponding change in the fit between the simulated and observed discharge. This effect was evident when alternative initial parameter values were employed. In 17 of 25 forecasts, method 2 exhibited a lower calibration error (error prior to forecast), while in all but two cases method 1 exhibited a lower total error for the event. In seven of the cases for which method 2 had the lower calibration error, the total event error was two to five times greater than that with method 1. This demonstrates that an excellent fit between the observed and simulated discharges does not necessarily lead to a correspondingly good forecast.

Several characteristics of the parameter estimation scheme can influence the amount of forecast error. First, if the unit hydrograph and loss rate parameters are constrained too loosely, as in the HEC-1 scheme, the adopted parameters may be unreasonable. Method 2, which consistently yielded better results during calibration, often calculated unrealistic values of TR, R and RTIOL. A second factor is the allowable error between the observed and simulated values in the calibration step. To reduce the calibration error, the parameter estimation algorithm may produce significant fluctuations in parameters when only a small portion of precipitation and discharge data are available. However, if the allowable tolerance is increased sufficiently early in the storm event and is gradually reduced, the number and magnitude of parameter modifications would be reduced. This concept was adopted for a flood forecasting model developed by the National Weather Service (1979).

In summary, the performance of the calibration scheme was only one contributing factor to the accuracy of the flood forecast. While the addition of a variable tolerance or more limiting constraints to the present method may be beneficial, the results of the HEC-1 model were quite satisfactory.

ALTERNATIVE OPTIMIZATION ALGORITHMS FOR CALIBRATION

In 1978 the Hydrologic Engineering Center began a study of alternative techniques for estimation of parameters for HEC-1. This study was motivated by increasing use by Corps field offices of the automatic calibration feature of the model. In these many applications of the model, any significant improvement in the parameter estimation technique is desirable, in terms of a reduction in the cost of calibration or in terms of a reduction in the error of the parameter estimates.

Analysis of the existing univariate search technique employed for parameter estimation in HEC-1 indicated that the technique often does not effectively handle constraints on the parameters, so a nonlinear programming algorithm that does was sought. An additional restriction on selection of an optimization scheme is imposed by the number of parameters that must be estimated. If all parameters of the precipitation-runoff process are to be estimated, the optimization algorithm must be capable of solving efficiently a problem of as many as ten variables.

The alternative optimization technique selected for initial trial application was a version of the random search method of Box (1965), as suggested by Johnston and Pilgrim (1976), Chu and Bowers (1978), and Sorooshian and Dracup (1978). This technique is an extension of the polyhedron search of Nelder and Mead (1965), and as programmed at HEC, uses the precipitation-runoff model directly in evaluation of the objective function. Implementation of the technique requires definition of explicit upper and lower bounds on the variables; this proved to be a formidable task because the parameters of the rainfall-runoff model are not related clearly to physical attributes of the drainage basin. Currently the constraints are defined on the basis of knowledge of the limitations of the mathematical functions combined with experience in manual calibration of the model for Corps' studies nation-wide.

Although the investigation of alternative optimization techniques or calibration schemes is not yet complete, preliminary analyses indicate the following: (1) the Box technique does not select an optimal set of parameter values in significantly less time or with fewer function evaluations than does the univariate gradient algorithm currently employed; and (2) the Box technique does not select parameter values that yield a significantly better reconstitution of runoff events, as measured by the least-squares objective function. As a result of the research, the following conclusions were reached regarding the parameter estimation procedure: (1) for efficiency, an automatic calibration technique should allow specification of and should exploit the availability of appropriate initial values of the parameters; and (2) the least-squares objective function is relatively insensitive to variations of the parameters of HEC-1.

The Box technique is executed by initially evaluating the objective function for sets of parameter values scattered randomly throughout the feasible region (a "complex"). Box recommends that 2n sets of values be established for the initial complex where n equals the number of unknown parameters. For ten parameters, this requires 20 evaluations of the objective function, each requiring simulation of watershed response. The univariate technique, with certain heuristic rules for dealing with violated constraints and with good initial estimates often selects near-optimal, acceptable parameter estimates with approximately the same number of function evaluations. Furthermore, the random search techniques does not exploit the knowledge of good initial estimates of the parameters. Experience at HEC indicates that this is critical because these estimates often reduce substantially the effort to calibrate and because automatic calibration schemes may chose an unreasonable, false optimum otherwise.

The least-squares objective function, although widely accepted for application in model calibration, in many cases is insensitive to variations in the parameters of HEC-1 and causes premature termination of the search. This difficulty is related also to interaction among the variables of the watershed model. However, acceptance of any modifications to the model is not likely, so alternative objective functions are being evaluated. These functions include those suggested by Manley (1978) and other functions suggested through research at HEC.

Additional tasks to be completed in the area of parameter estimation for the HEC-1 watershed model include the following: (1) programming and testing other nonlinear programming algorithms for parameter estimation; (2) programming and testing alternative objective functions for calibration; (3) further comparing the existing parameter estimation algorithm with the alternative algorithms; and (4) applying the knowledge gained from parameter estimation research with program HEC-1 to other programs developed and supported by the HEC.

SUMMARY

To satisfy the need for a precipitation-runoff model for application in water resources planning and management by the Corps of

Engineers, computer program HEC-1 was developed. This model includes algorithms to accomplish the following tasks necessary to simulate watershed response:

1. Determine effective precipitation.

2. Compute the subarea runoff due to the effective precipitation.

3. Route and combine the subarea runoff hydrographs.

In addition, HEC-1 includes the capability to determine automatically the parameters of the functions employed in the simulation. This is accomplished using Newton's technique to minimize a weighted least-squares objective function. Currently, alternative optimization techniques and alternative objective functions are being evaluated.

The parameter estimation capability of program HEC-1 has been employed in a variety of studies at the Hydrologic Engineering Center. These applications have focused on modelling the impact of basin modifications, of channel improvements, of various flood-control measures, and on developing frequency curves for ungaged watersheds.

The parameter estimation technique of HEC-1 has been extended recently to update sequentially parameter estimates for flood forecasting. In these applications, computed reservoir inflows and observed mean areal precipitation available at the time of forecast are used to estimate model parameters. These parameters are used then to estimate future reservoir inflows, using the simulation capability of the program. The results of the applications are satisfactory for application to flood-control reservoir operation.

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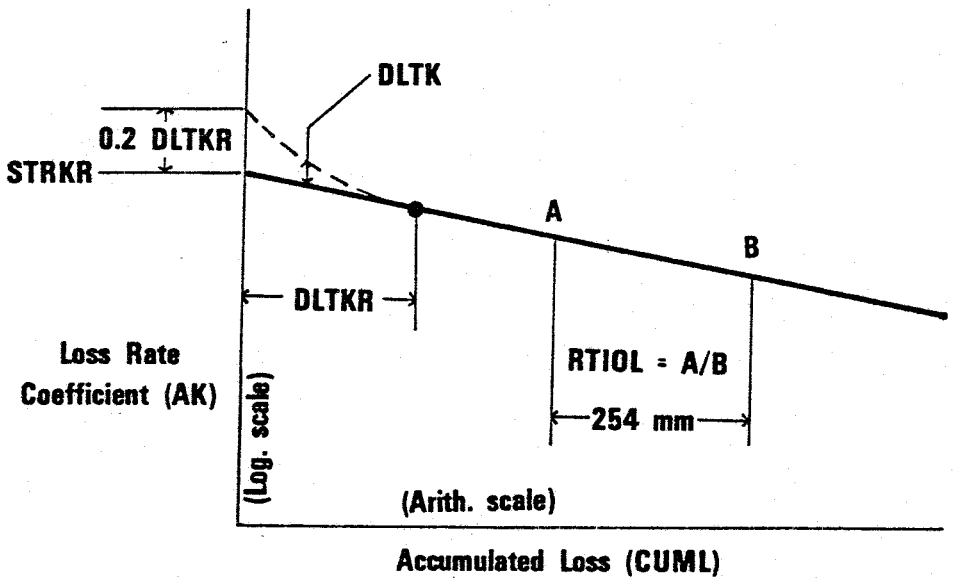

Fig. 1. HEC-1 exponential loss rate function

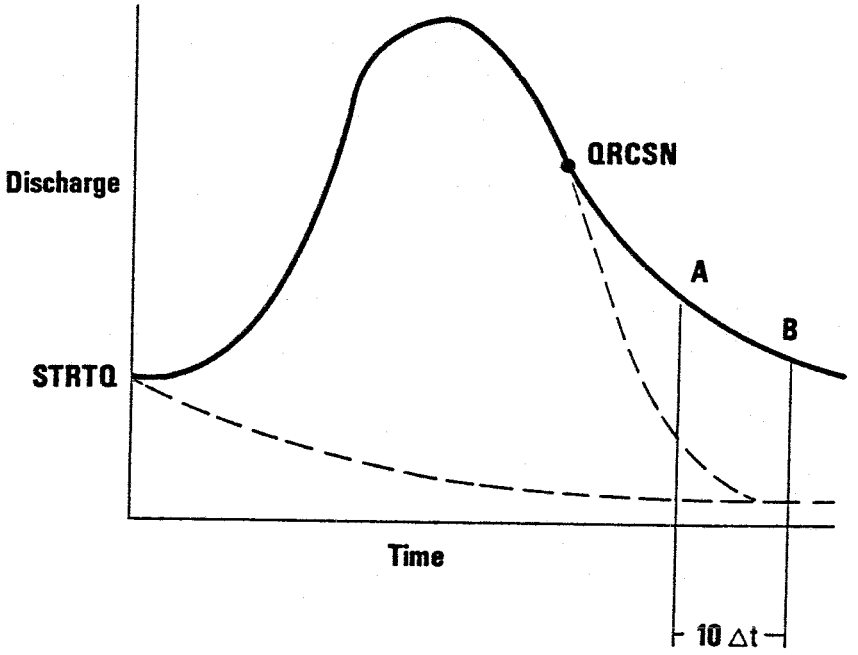

Fig. 2. Base flow and recession parameters

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