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DEVELOPMENT, CALIBRATION AND APPLICATION OF RUNOFF FORECASTING MODELS FOR THE ALLEGHENY RIVER BASIN

By William J. Charley and John C. Peters

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DEVELOPMENT, CALIBRATION AND APPLICATION OF RUNOFF FORECASTING MODELS FOR THE ALLEGHENY RIVER BASIN[2]

William J. Charley and John C. Peters [1]

Introduction

The U.S. Army Corps of Engineers is responsible for operating several hundred reservoirs throughout the United States. Many of the reservoirs are multiple purpose, with flood control as a primary purpose. Day-to-day operational decisions are generally made in water control centers located in the Corps' district offices. Some of these offices utilize a water-control software system developed by the Hydrologic Engineering Center (Pabst and Peters, 1983), which facilitates the decision-making process with capabilities for processing meteorologic and hydrologic data, forecasting runoff and simulating reservoir system performance. A component of the software system is computer program HEC1F (Peters and Ely, 1985), which performs runoff forecasting. The focus of this paper is on application of HEC1F in making short-term (3 to 5 day) forecasts for the 11,733 square mile (30,440 sq. km.) Allegheny River Basin, which contains nine flood control reservoirs operated by the Pittsburgh District, Corps of Engineers. Following a brief overview of the nature and scope of the water control software system, the intended application of HEC1F is provided. The characteristics of the Allegheny Basin, data collection networks, and forecast needs are described, as well as the approach used for model calibration and initial results. Finally, comments are made regarding the present status of model development and usage, and plans for the future.

Nature and Scope of the Software System

Figure 1 illustrates the major elements of the water control software system. A key component is the Hydrologic Engineering Center's Data Storage System (DSS), which is designed for efficient storage of time series data. Data stored in the DSS may consist of raw data, processed data (i.e., data that has been transformed, verified, filled-in, etc.), and data developed by various simulation programs (e.g., subbasin-average hyetographs, discharge hydrographs, reservoir elevation or reservoir storage versus time relationships, etc.). Rating curves and other similar data can also be stored in the DSS (HEC, 1987a).

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[2]Presented at the ASCE 3rd Water Resources Operations and Management Workshop, June 1988, Fort Collins, Colorado.

Sources of data encompassed by the Data Acquisition element of Figure 1 include data obtained

1. directly by satellite telemetry and other radio-based systems,

2. by computer-to-computer link with the National Weather Service's Automated Field Operations Service (AFOS),

3. from telemark and other sources (entered automatically or manually into DSS),

4. from dam-tenders and other field offices.

The "analysis" element of Figure 1 contains 3 primary programs: (1) PRECIP, which performs spatial averaging of gaged precipitation data to provide subbasin-average hyetographs, (2) HEC1F, which computes runoff from precipitation, and (3) HEC-5, which simulates and computes releases for a reservoir system. Another component, SNOSIM (Hoggan et al., 1987), is used to simulate snow accumulation and snowmelt for use in conjunction with HEC1F.

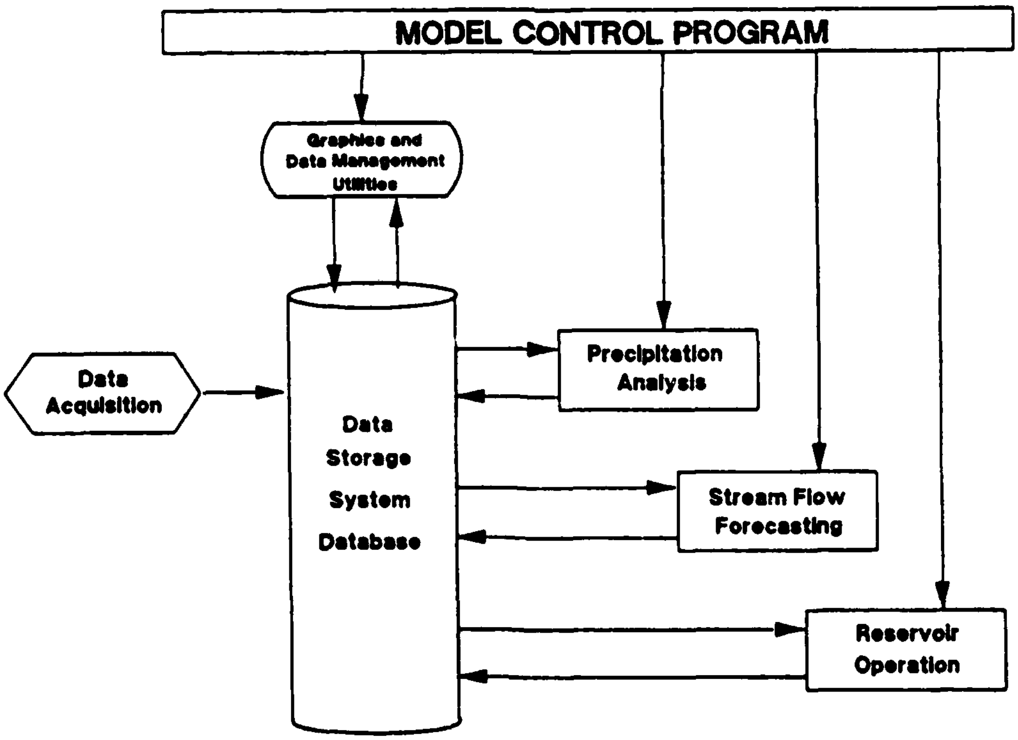


Figure 1. Water Control Software System Diagram

Associated with the DSS is a set of data management utility programs that enable plotting, tabulating, editing, etc., of stored data. To facilitate use of the software system, the interactive program MODCON (for Model Control) provides capabilities to review current data availability, set parameters for forecasts and operations simulations, execute forecasting models, review results, and set future precipitation and operations parameters.

Allegheny River Basin and Reservoir System

The Allegheny River Basin, with a drainage area of 11,733 square miles (30,390 sq. km.), is located in the northwest corner of Pennsylvania and extends into the southwest corner of New York as depicted in Figure 2. The basin is about 160 miles (257 km.) long and 73 miles (117 km.) wide, with topography that varies from narrow canyons to wide flood plains. Elevations range from 710 feet (216 meters) at Pittsburgh to almost 3000 feet (914 meters) in the Allegheny Mountains, which form the eastern border of the basin. The vegetation varies from grasslands to dense forest. The Allegheny River joins the Monongahela River at Pittsburgh to form the Ohio River.

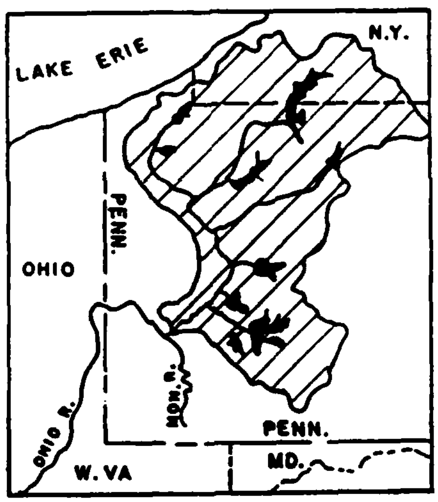


Figure 2. Allegheny River Basin

The climate of the Allegheny Basin is temperate and humid with a substantial seasonal variation in temperature. Frequent and rapid changes in weather are due to frontal air mass activity. Precipitation is distributed throughout the seasons with a normal annual total of about 40 inches (100 cm.). The normal monthly precipitation is highest in July with 4.3 inches (11 cm.) and lowest in February with 2.6 inches (6.6 cm.). Average seasonal snowfall ranges from 40 inches (100 cm.) near Pittsburgh to 170 inches (430 cm.) in New York. Snow cover is generally subject to melting throughout the winter season and is frequently a contributing factor to winter and early spring flood runoff. Winter ice jams on the upper Allegheny have caused significant flooding.

A key element of the flood control reservoir system is Allegheny Reservoir, which controls runoff from 2180 square miles (5650 sq. km.), representing 19 percent of the basin. (A Basin Schematic is provided in Figure 3.) Flood control storage in the reservoir provides an equivalent depth of 5.22 inches (13.3 cm.) of water over the upstream area. The reservoir is located 135 miles from the confluence with the Monongahela River at Pittsburgh. Eight additional Corps reservoirs within the basin also provide flood control. The area upstream of all nine reservoirs is 45 percent of the total basin area. Four of the nine reservoirs are multi-purpose; five are essentially dedicated to flood control. Two reservoirs are operated for water quality purposes. Conemaugh, the second largest reservoir, limits releases to minimize effects of acid mine drainage, and East Branch Reservoir maintains releases to insure adequate dissolved oxygen downstream.

The Corps maintains 57 data collection platforms (DCPs) in the basin. Solar panels provide power to DCPs which enables them to operate in remote areas without access to commercial power or telephone service. Typically, the DCPs record stage, precipitation and air temperature data every hour, then transmit that data to the Corps' Ohio River Division office in Cincinnati once every four hours, via the GOES (Geostationary Operational Environmental Satellite) system. The Cincinnati office decodes the data, then transmits it to the District office where it is stored in a data base until a forecast is made. The District also receives precipitation data from the National Weather Service AFOS, and reservoir storage and related data from the field offices at the reservoirs.

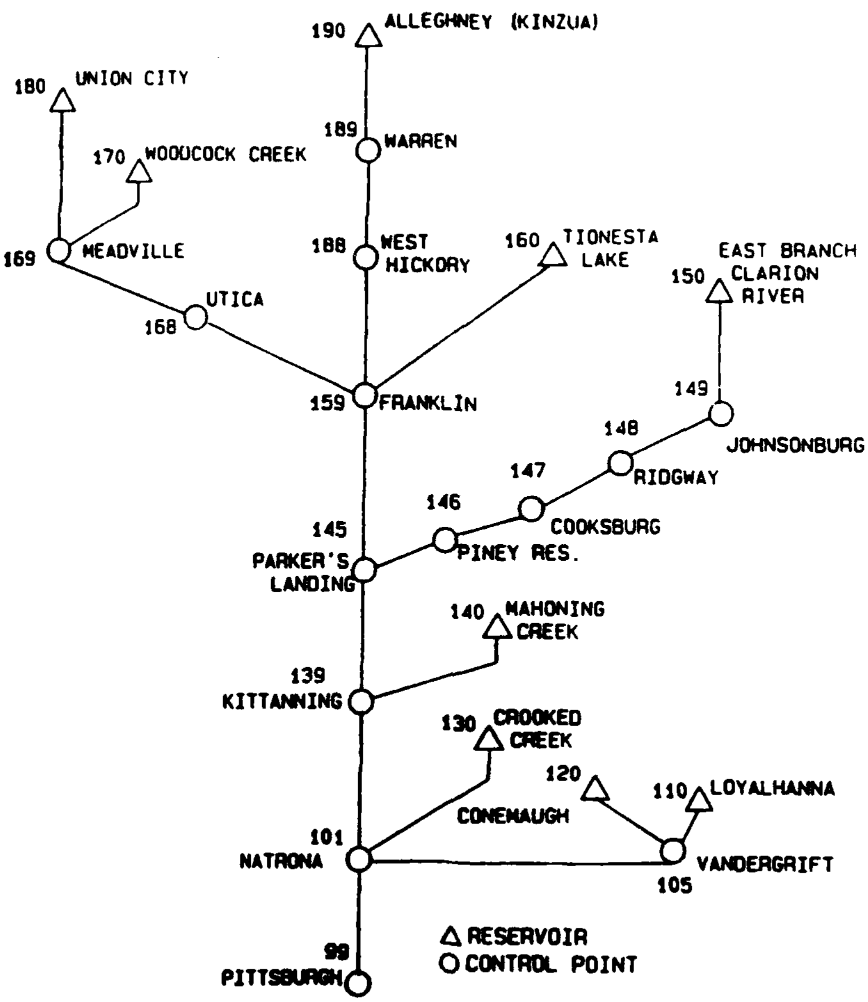


Figure 3. Allegheny Basin Reservoir System

Capabilities and Intended Application of HEC1F

Computer program HEC1F is an adaptation of computer program HEC-1 (HEC, 1985), which is widely-used in flood-runoff analysis for purposes such as project planning, flood-plain delineation and hydraulic-structure design. 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 for forecasting 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. Subbasins are aggregated into groups (called zones) for purposes of specifying values for loss rate and base flow parameters. For example, a watershed with 30 subbasins might be subdivided into 4 or 5 zones. Loss rate and base flow parameters may then be specified on a zonal basis, rather than a subbasin basis.

2. Forecasting is performed in two separate executions of HEC1F. In the first, unit hydrograph, loss rate and base flow parameters are optimized for gaged headwater subbasins. The time window "T" in Figure 4 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. The objective function that is minimized by a univariate gradient technique (Ford et al., 1980) is as follows:

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

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:

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

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 given in equation (1) is a quantitative measure of the goodness of fit of the calculated hydrograph to the observed hydrograph. The weighting factor defined by equation 2 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.

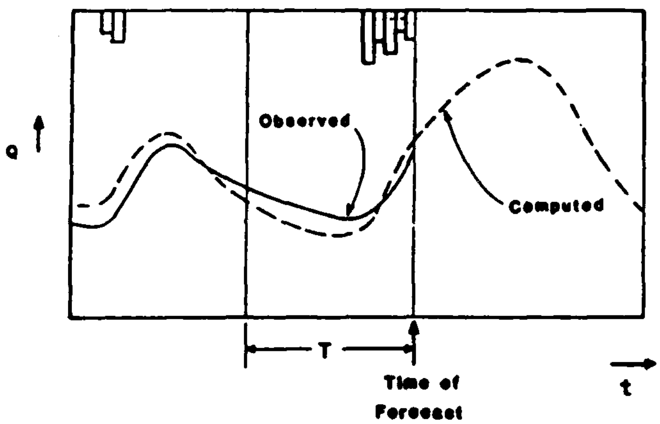


Figure 4. Parameter Estimation of Gaged Headwater Subbasins

The optimization process has built-in constraints that prevent physically unreasonable values for the parameters to be optimized (HEC, 1987b). For example if the rainfall is concentrated very near the time-of-forecast, there will be little hydrograph "rise" with which to optimize parameters, so that 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 zonal 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, a transition from the observed to the computed hydrograph for six time

intervals following the time-of-forecast, and the computed hydrograph from the end of the transition through the remainder of the forecast period. 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 blended hydrograph is used in subsequent routing computations.

5. Forecasts may be evaluated by reviewing several summary tables (examples of which are provided in Figure 5) and by viewing plots of computed and observed hydrographs for locations of interest. If necessary, zonal values for parameters can be adjusted and an additional HEC1F "run" executed to improve results.

Forecasts developed with HEC1F take into account precipitation and reservoir releases up to the time-of-forecast. The software system provides the capacity to specify future precipitation and future reservoir releases so that "what if" conditions can be readily evaluated. In order for future reservoir releases to be included in the forecasts, such releases can be manually entered with the MODCON program for use by HEC1F. Alternatively, future releases can be determined with the reservoir system simulation program, HEC-5.

PARAMETER ESTIMATION ERROR SUMMARY

RUN DATE: 10MAY88 TIME: 12:52

TIME OF FORECAST --- 0600 4 APR (PRECIPITATION ALT A)

LOCATION	AREA SQ MI	--- FORECAST TIME --- OBS FLOW CFS	CALC FLOW CFS	ERROR PCT	TIME FRAME HRS	------- FOR TIME FRAME ------- AVERAGE FLOW OBS CFS	CALC CFS	AVG ABS ERROR PCT	PPT EXCESS INCHES
PALP	263	1440	882	-39	105	759	728	17	.20
BRFP	100	---	1120	---	33	---	411	---	.24
GUFP	46	570	544	-5	33	199	210	14	.27

PARAMETER ESTIMATES

RUN DATE: 10MAY88 TIME: 12:52

TIME OF FORECAST --- 0600 4 APR PPT ALT A INITIAL ESTIMATES

LOCATION	BFFCST CFS/SQ MI	RTIOR	B.F. ZONE	STRTL INCHES	CNSTL IN/HR	L.R. ZONE	TP HOURS	CP
PALP	2.58	1.0011	1	0.000	0.110	1	20.00	0.30
	1.65	1.0083		0.000	0.110		20.00	0.30
BRFP	1.65	1.0083	1	0.000	0.110	1	5.00	0.40
	1.65	1.0083		0.000	0.110		5.00	0.40
GUFP	2.04	1.0016	1	0.000	0.111	1	5.01	0.38
	1.65	1.0083		0.000	0.110		5.00	0.40

Figure 5. Parameter Estimation Summary Table

Development and Calibration of HEC1F Models

Models for HEC1F are developed to provide information at key locations such as reservoirs and downstream control points, and must accommodate essential watershed and data network features. Development tasks include delineation of subbasins, and initial estimation of parameters for each subbasin and routing reach. These parameters are then calibrated with data from historic events. The models are subsequently "fine-tuned" with data from the current data collection network.

The delineation of subbasins involves consideration of the locations of current and anticipated DCPs which transmit stage, and hydrologic and meteorologic variability in the basin. Based on these considerations, the basin was divided into 53 subbasins, as depicted in Figure 6, of which 49 subbasins have stage gages at the outlet. Twenty of these are headwater subbasins (shaded in Figure 6) for which it is possible to optimize runoff parameters.

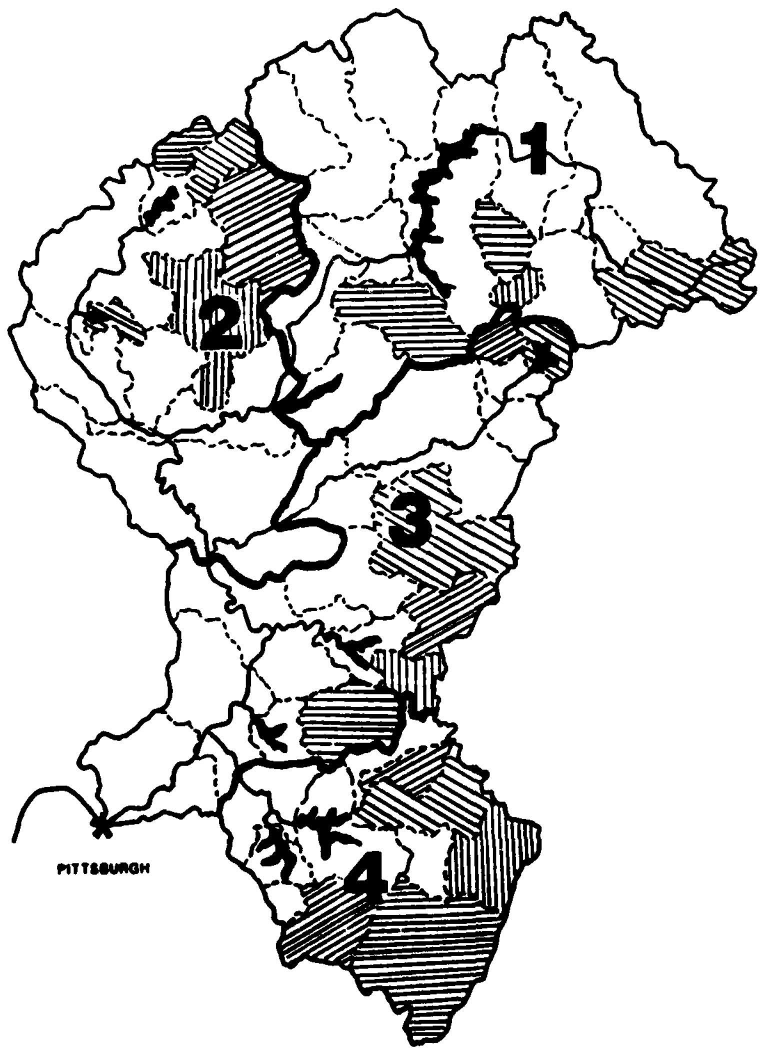


Figure 6. Allegheny Basin Subbasins and Zones

Values for unit hydrograph, loss rate and base flow parameters are required for each subbasin for which runoff is to be calculated. Values chosen are ultimately based on calibration. However, the adoption of reasonable initial values greatly facilitates the calibration process. Generally extensive hydrologic investigations are involved in planning and designing reservoirs, and results of these past studies can be very useful as an aid for developing initial parameter estimates. Such is the case for this study; substantial data, including unit hydrographs, were available.

The Pittsburgh District provided six-hour unit hydrographs for 36 of the subbasins. Although it is possible to use unit hydrographs expressed in coordinate form in HEC1F, a unit hydrograph must be defined in terms of the two Snyder parameters, TP and CP, if the optimization capabilities of the program are to be used. Unit hydrographs for all gaged headwater subbasins must therefore be represented by Snyder parameters for HEC1F. Snyder parameters are used for other subbasins to facilitate the making of adjustments during the calibration process, and to enable development of regional relations by regression analysis. The parameters are derived for a given unit hydrograph by using the optimization option of HEC1F to develop values for TP and CP to best fit the unit hydrograph. This procedure involves specifying one inch of rain with a duration equal to the duration of the unit hydrograph, and setting losses and base flow equal to zero.

Unit hydrograph parameters for remaining subbasins were derived with a variety of methods. In some cases, simple routing and combining or subtracting operations with available unit hydrographs was all that was required. In other cases, regional correlation relationships were used. For a number of the subbasins, parameters were estimated based on parameters for nearby subbasins and modified during the calibration process.

Muskingum routing criteria were available for most of the routing reaches from previous studies. Where criteria were not available, initial values were estimated by adjusting values for nearby reaches for travel-time differences as reflected in the length and slope of the reach. Calibration confirmed most of the routing coefficients provided, but changes were required for a few reaches to improve the fit of observed and calculated hydrographs at some downstream locations. It should be noted that the coefficients have been developed for periods of significant runoff. Experience with similar watersheds has indicated that different routing coefficients may be required for low flow conditions.

Three historical events (occurring in the years 1972, 1977 and 1983) were selected by the District office for purposes of calibration. Hourly flow data was supplied for those events for about one-half of the locations of the current DCPs. Hourly and daily precipitation records were obtained for a number of additional locations from the National Weather Service. The latter data was transferred from magnetic tape to a DSS file by use of the utility program NWSDSS (HEC, 1987a).

Two input files for HEC1F were developed. The first enables parameter optimization for gaged headwater subbasins, and the second enables calculation of runoff at all reservoirs, stream gages and other locations of interest. The first file was used to optimize parameters directly with data for the historical events. Figure 7 shows values for Snyder unit hydrograph parameters for the McCormick subbasin (labeled MCRP), a typical gaged headwater subbasin. A single set of values was adopted for the subbasin based on factors such as the quality of the historical data, and the goodness of fit of the computed to the observed hydrographs. This task was performed for each gaged headwater subbasin for which historical data exists. The adopted values are used as initial estimates when observed flow data is available for real-time optimization. If observed flow data is not available, the values are used without adjustment.

PARAMETER	INITIAL ESTIMATE	1972 EVENT	1977 EVENT	1983 EVENT	ADOPTED
TP (HOURS)	15.0	14.7	11.7	11.9	13.7
CP	0.50	0.51	0.41	0.73	0.45

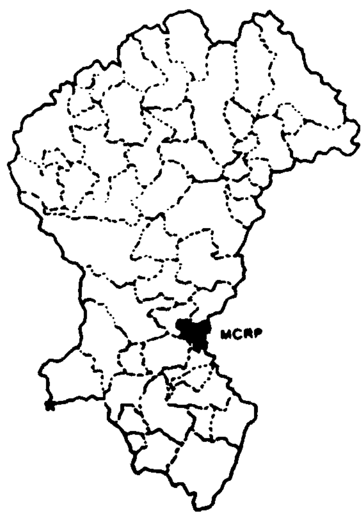


Figure 7. Optimized and Adopted Values for Synder Parameters at a Typical Headwater Subbasin

The second input file was used to calibrate parameters for the remaining (non-headwater) subbasins. The problem here is that there can be a large number of parameters that influence the simulated runoff at a given location, and calibration requires substantial judgment and trial and error adjustment. In general, the approach is to look for consistent bias in the comparison of calculated and observed hydrographs at a given location, and then adjust routing and/or unit hydrograph parameters in an attempt to obtain more consistent results.

During a real-time event, the forecaster needs to be able to quickly assign a reasonable estimate of loss rates and base flow parameters to each subbasin. To facilitate specification of parameters, the basin is divided into zones of similar hydrologic characteristics. During a forecast, HEC1F produces optimized loss rate and base flow parameters for each gaged headwater subbasin. The forecaster reviews these parameters and the associated forecasts, then selects the "best" estimate for each zone. These estimates are then used with the second input file to make basin-wide runoff forecasts. Although some flexibility is sacrificed by lumping subbasins into zones, it is necessary from the point of view of efficiency in making forecasts for a large basin with numerous subbasins.

The next step in the calibration process is to evaluate performance of the models by stepping through historical events as if they were occurring in real time. This involves optimizing parameters up to the time-of-forecast, assigning best fit parameters to each zone, then executing the forecast model and examining the results. Generally only minor adjustments to parameters are made at this stage.

As indicated previously, historical data are available for only about one half of the locations in the DCP network. It is therefore necessary to test the models and zonal subdivisions using the current data network. To accomplish this task, data is automatically retrieved every morning from the Pittsburgh District using a high speed modem. Forecasts made with this data provide information to enable additional model adjustments. An example of a forecast with data from the present network is shown in Figure 8 for April 3, 1988 at Natrona, a key downstream control point. Rain fell over the entire basin on the evening of the third. A plot of the forecasted hydrograph for the first forecast, made at 9 p.m., is depicted in Figure 8a. The dashed vertical line indicates the time-of-forecast; no data was known past the forecast time. The observed flows were added in later for comparison purposes, and reflect rain that occurred after the time-of-forecast as well as reservoir releases that had not been anticipated at the time-of-forecast. For this forecast, the peak was predicted to occur about 24 hours in the future, and was about 25% low. Another forecast, made three hours later at 12 midnight, as shown in Figure 8b, shows a substantial increase in the peak as compared to the earlier forecast. With the additional precipitation information over the three hours between forecasts, it was possible to forecast the peak more accurately. The forecasted peak is slightly early because routing coefficients are based on calibration with higher flows.

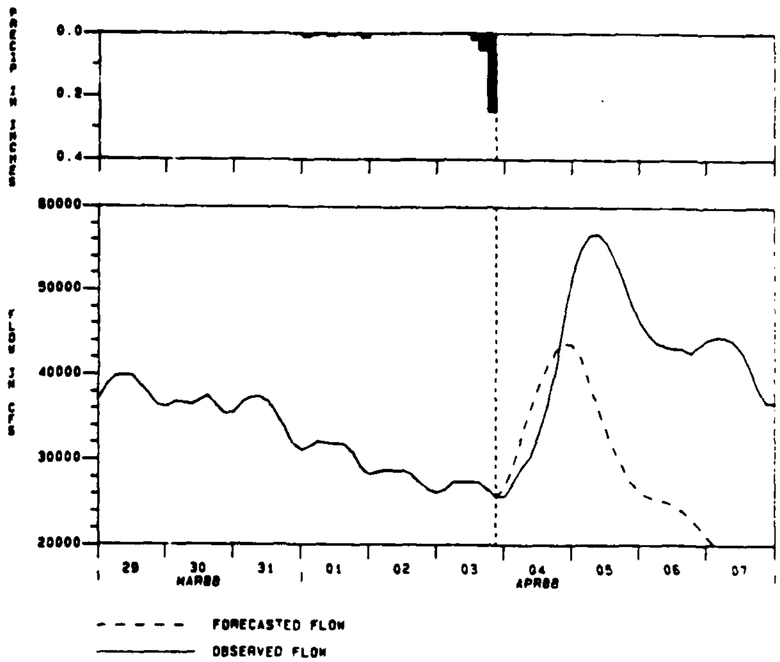
The calibrated HEC1F models are now in day-to-day use in the Pittsburgh District. As experience is gained in applying the models, and as further knowledge of the hydrologic response of the basin is acquired, additional adjustments to the models will be made.

Summary and Plans for the Future

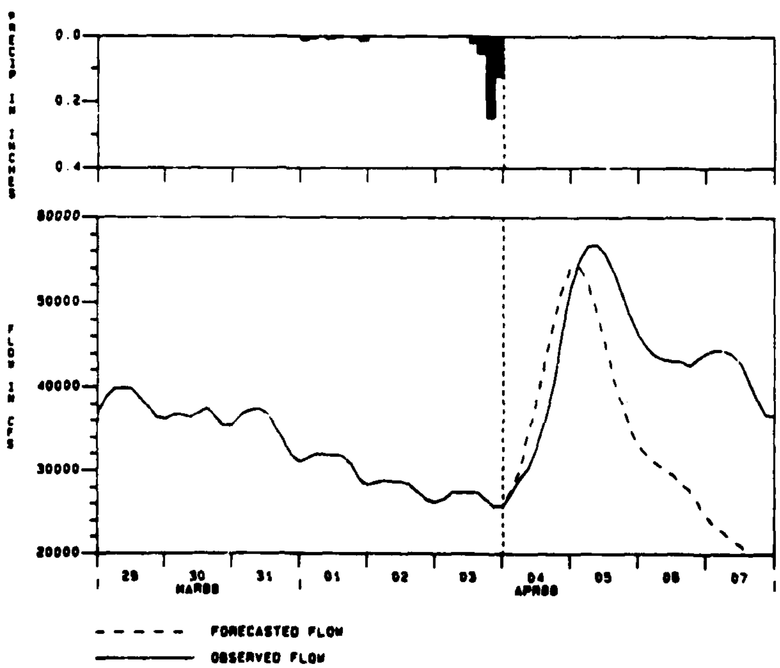
The development and calibration of HEC1F models for the Allegheny River Basin, and their use in conjunction with a water control software system, have been described. Similar models are in day-to-day use for several other basins tributary to the Ohio River, including the Scioto, Kanawaha, Muskingum and Monongahela. As experience is gained in using the capabilities described, the need for software enhancements and new tools becomes apparent.

The models seem to perform reasonably well for significant rainfall events, but simulation of minor rises is subject to substantial error because of uncertainty in estimating effective rainfall and limited capability for representing base flow. A new version of HEC1F that employs continuous soil moisture accounting is presently being tested. It is expected that with such a model the accuracy of forecasts for small events will improve, as will the accuracy of early forecasts in large events.

Components of the software system are being adapted for use on microcomputers. It is anticipated that a substantial portion of forecasts for operational purposes will be made on microcomputer using a local area network in the not-to-distant future.



(a) 9 p.m. Time-of-Forecast



(b) 12 Midnight Time-of-Forecast

Figure 8. Forecasted verses Observed Hydrographs at Natrona on April 3, 1988

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