CALIBRATION PROCEDURES USED WITH THE NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM

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Abstract. The National Weather Service River Forecast System consists of a set of interrelated computer programs developed to provide continuous hydrologic forecasting. The catchment model is conceptual in design and generally must be calibrated for each watershed. Current calibration procedures consist of a combination of trial-and-error and automatic-parameter optimization techniques. Initial parameter values are determined from analyses of the hydrometeorological data base of a catchment. Soil moisture storage components, depletion coefficients, and other appropriate parameters are adjusted based on the results of trial-and-error simulations. An automatic-parameter optimization program utilizing a direct-search technique is used to make final modifications to the parameter values. The calibration procedures and results of a case study are presented in the paper to show how the techniques are applied. Current and important future research areas, including initial parameter estimation, physically based automatic parameter optimization, interactive computer graphics applications, and estimation theory techniques such as maximum likelihood and stochastic approximations, are discussed.

Keywords. Hydrologic modeling; parameter estimation; hydrologic model calibration; optimization; computer graphics; optimal filtering.

INTRODUCTION

The National Weather Service (NWS), National Oceanic and Atmospheric Administration (NOAA), is responsible for providing accurate and timely hydrologic information and forecasts for watersheds and rivers throughout the United States. The hydrology program of the NWS is under the direction of the Office of Hydrology (O/H). Thirteen River Forecast Centers (RFC's) located throughout the country (Fig. 1) issue hydrologic forecasts for over 2,500 forecast locations. Each RFC is staffed by professional hydrologists responsible for the preparation of river forecasts within the RFC's forecast area. The information is used for the issuance of flood forecasts and warnings and for daily operational forecast needs such as those required for decisions concerning water supply, irrigation, reservoir operation, power production, navigation, recreation, and water quality. In addition to the daily river forecasts, several of the RFC's prepare seasonal snowmelt forecasts for areas where snowmelt constitutes a major portion of the streamflow.

Individual RFC's were originally largely responsible for formulating their own forecast techniques. In the late 1960's the decision was made to develop a system of hydrologic components which could be used by all the RFC's for forecasting under a wide variety of hydrologic conditions. The Hydrologic Research Laboratory (HRL), within O/H, which is responsible for research and development in support of the NWS river forecasting services, tested several models and began developing the National Weather Service River Forecast System (NWSRFS). In 1972 a description of the initial system and the steps involved in developing operational river forecast procedures was published (NOAA, 1972). Later publications have described early tests made on the system and some of the suggested calibration techniques (Monro and Anderson, 1974) and the many improvements and additions to NWSRFS (Curtis and Smith, 1976 and Ostrowski, 1979).

Nationwide implemention of a forecasting system such as NWSRFS is a large and time-consuming task. One of the most difficult problems faced is the calibration of the models within NWSRFS for the various parts of the country. Research is being performed to develop improvements in calibration procedures and to determine new automatic parameter estimation techniques. The purpose of this paper is to describe the NWSRFS and some of the current calibration procedures as well as to discuss current and future research designed to enhance parameter estimation.

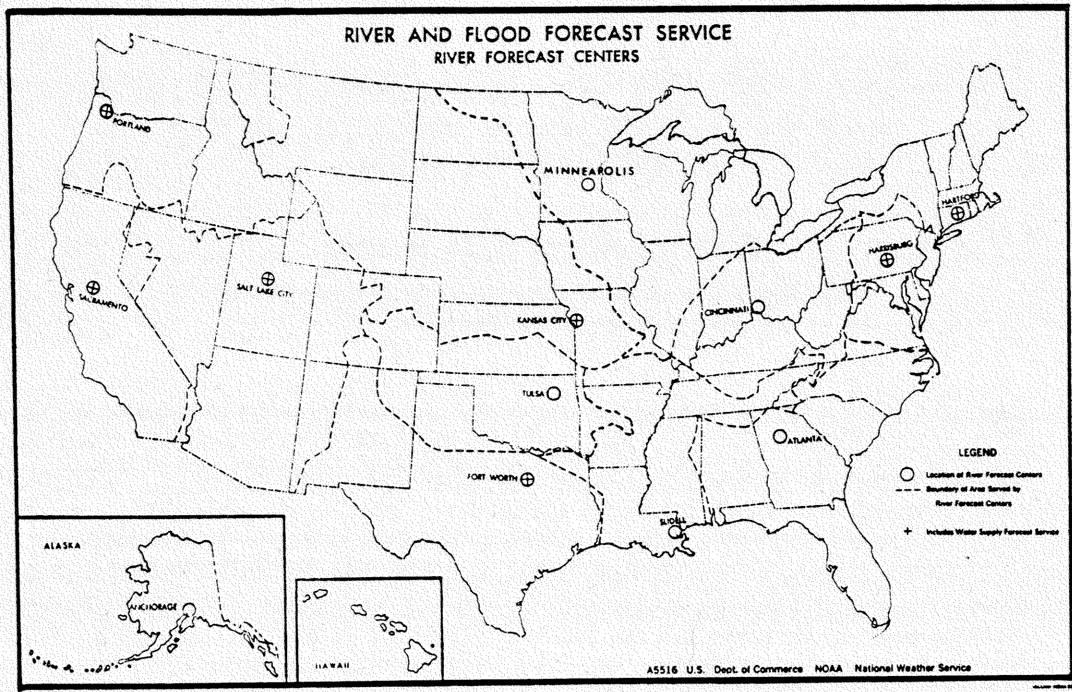

Fig. 1. The 13 NWS River Forecast Centers and their respective forecast areas (from NOAA, 1979).

NATIONAL WEATHER SERVICE
RIVER FORECAST SYSTEM

The NWSRFS is a collection of interrelated computer programs capable of a wide variety of hydrologic, hydraulic and data processing functions. The various software components and their interrelationships are shown in Fig. 2.

Most of the early forecast models generated simulated streamflows from rainfall-runoff relationships based on index type response functions (for example, the antecedent precipitation index (Kohler and Linsley, 1951)). In the 1960's physically-based conceptual models gained acceptance, however, no one model was supported for use by all the RFC's. When the NWS made the commitment to develop

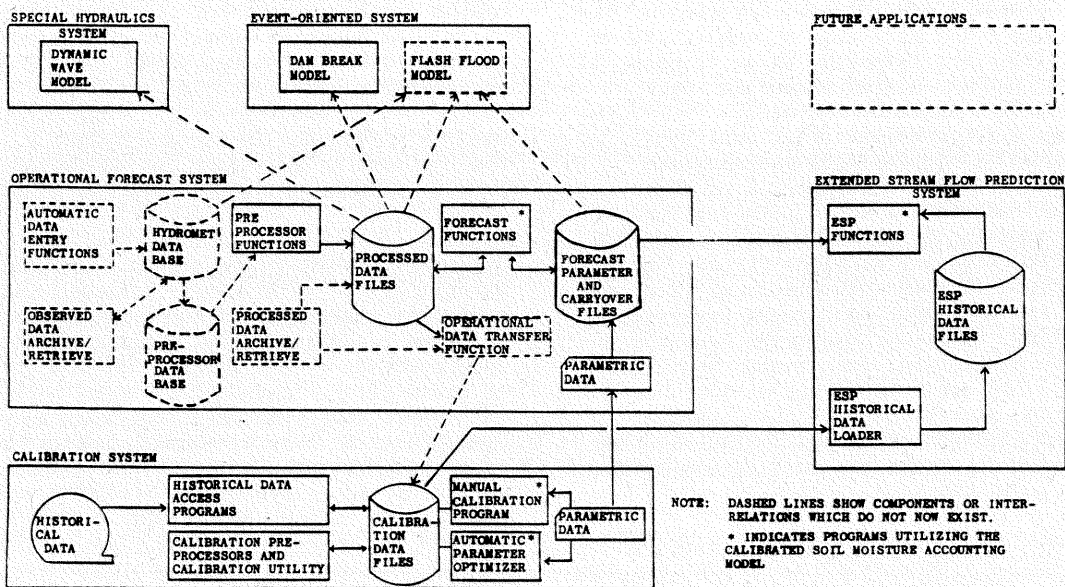

Fig. 2. Block diagram of the various components of the NWS River Forecast System.

the NWSRFS, the decision was made to move from purely index methods to a system which includes continuous conceptual hydrologic models. The version of the NWSRFS forecast program currently under development has the flexibility to include both conceptual and index relationships, leaving the user to decide which modeling technique is more appropriate in a given location and situation. The physically-based conceptual models have several advantages (Schaake, 1976). Some of them are:

1. Conceptual models have an enhanced probability of predicting future events, especially events of a magnitude that never, or rarely, have been experienced in the past.

2. Parameters related to basin characteristics may be adjusted to reflect land use changes.

3. Conceptual models offer potential of application to problems other than streamflow prediction (e.g., capability to model the movement of pollutants through the watershed system).

For simplicity, the forecast component of the NWSRFS can be thought of as having two general types of programs: 1) hydrologic programs which simulate the runoff and in-channel routing processes, and 2) hydraulic programs which utilize the complete momentum and continuity equations, also known as dynamic routing programs.

The current version of the hydrologic portion of the NWSRFS is composed of three basic computational elements, a soil moisture accounting model, a snow accumulation and ablation model, and a set of hydrologic channel routing routines. This paper describes only those parts of the NWSRFS which are used in conjunction with the soil moisture accounting model.

Calibration of the soil moisture model involves the use of preprocessing programs for converting meteorological data from point inputs to areal inputs and the use of basic computational programs to determine soil moisture model parameter values. These programs are:

1. Mean Areal Precipitation Program -- routines to convert point precipitation values to areal mean precipitation.

2. Mean Areal Evapotranspiration Program -- routines to compute mean areal evapotranspiration from point values.

3. Manual Calibration Program -- routines that are used through trial and error to "manually" determine model parameter values.

4. Optimization Program -- routines to further refine model parameter values automatically.

SOIL MOISTURE ACCOUNTING MODEL

The soil moisture accounting model used in the NWSRFS is a modified version of the Sacramento model (Burnash, et al., 1973) and its components are shown schematically in Fig. 3. The model is deterministic and has

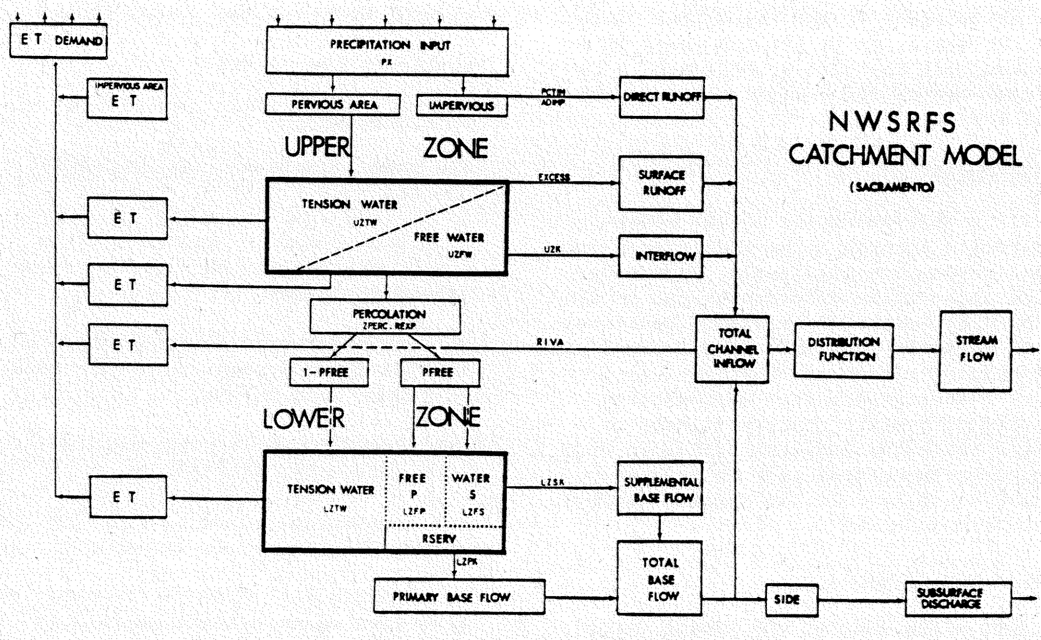

Fig. 3. Schematic diagram of the NWSRFS soil moisture accounting model (after Peck, 1976).

lumped input and lumped parameters within a soil moisture accounting area. A catchment may be modeled with distributed input and parameters by dividing the watershed into several soil moisture accounting areas.

The model divides the soil vertically into two main soil moisture accounting zones. The upper zone represents interception storage and the upper soil layers, while the lower zone accounts for the bulk of the soil moisture and ground-water storage capacity.

Soil Moisture Storage

The upper and lower zones are conceptualized as storing both "tension" and "free" water. Tension water is the water which is tightly bound to the soil particles and not readily available for movement, whereas free water can move both horizontally and vertically through the soil profile. Tension water requirements must be met in the upper zone before water can be transferred to the upper zone free water storage. Tension water can be depleted only by evapotranspiration, while free water can be transferred through percolation, interflow, evapotranspiration, and tension water replenishment. Within the lower zone, a fraction of the incoming water can be placed directly in the free water storage without fulfilling tension water requirements. This feature allows a realistic simulation for basins where lower zone drainage is significant and area-wide lower zone tension water requirements have not been met.

Percolation

The movement of water from the upper zone to the lower zone is determined by a complex percolation function, relating capacities and contents of both zones and free water depletion coefficients. The percolation algorithm is the key element in the transfer of water within the model, as it affects water movement throughout the soil profile and is itself dependent on the current state of the storage system.

Evapotranspiration

An accurate representation of the evapotranspiration process is necessary to insure accurate streamflow simulation, particularly in rural areas where evapotranspiration can be a dominant factor in the hydrologic cycle. The soil moisture model can accept two types of evapotranspiration information: 1) a seasonal evapotranspiration demand curve consisting of average monthly values, or 2) actual potential evapotranspiration data with monthly adjustment factors to account for seasonal changes in the vegetative cover and ground conditions.

Variable Impervious Area

Generally, a fraction of the precipitation falling on a catchment will be deposited on impervious areas directly connected to the stream. This water contributes directly to the streamflow without traveling through the soil. As some soils near the stream become saturated, they begin to act as impervious areas. The soil moisture accounting model represents this process through the use of an algorithm which evaluates the state of the soil moisture storage system. The program allows the percentage of impervious area to fluctuate between two extremes determined from parameters specified by the user.

Model Computational Technique

The movement of water through a soil matrix is a continuous process and is a function of the soil moisture system and the state of the moisture supply. The soil moisture accounting model simulates the natural continuous motion with a set of quasi-linear computations performed at user-specified time steps. Movement of water during a time step is determined by the conditions of the system at the beginning of the time step. Generally, a computational time interval of six hours currently is used for the calibration simulations and for the operational forecasts. Six-hour increments have been found in most cases to adequately define runoff events without causing excessive computations for the space scales presently used operationally. Future service requirements and data availability may necessitate the use of time steps of less than six hours. Time intervals as small as one hour may be specified in the calibration and operational forecast programs currently being developed. The model also contains a check so that no more than 5 millimeters of water are involved in a single execution of a computational loop. Thus, the model may actually perform several computational loops within the specified time increment if a large amount of precipitation is being input.

Flow Components

The model generates five components of channel flow:

1. Direct runoff — resulting from precipitation applied to the impervious and temporary impervious areas.

2. Surface runoff — resulting from precipitation input applied at a rate greater than the upper zone intake.

3. Interflow -- lateral drainage from upper zone free water storage.

4. Supplemental base flow — drainage from lower zone free water supplemental storage.

5. Primary base flow — drainage from lower zone free water primary storage.

The sum of the flow components for each computational interval is the runoff or channel inflow for that interval. A user-specified unit hydrograph is used to convert channel inflow to stream discharge.

Model Parameters

The soil moisture accounting model has 19 user-specified parameters (Table 1). The parameters control the following components of the model: direct runoff, upper zone tension and free water capacities, interflow, percolation, lower zone tension water capacity, lower zone primary and supplemental capacities, lower zone water transfer rates, primary and supplemental base-flow depletion rates, and precipitation and evapotranspiration adjustment. The user also must specify ordinates for the unit hydrograph. There are six state variables in the model representing the contents of the various soil moisture zones (Table 1).

CALIBRATION DATA AND DATA PREPROCESSING

The NWSRFS requires a large amount of data for implementation. The calibration program for the soil moisture accounting model uses mean areal precipitation, daily streamflow data, and evapotranspiration information. The raw data, from which these inputs are derived, are obtained from the National Climatic Center (NCC) and the U.S. Geological Survey (USGS), (Peck, Monro, and Snelson, 1977).

A set of data management programs is used to inventory the data on the NCC and USGS tapes, to copy selected data to direct-access data files, and to maintain and access the data on the data files. The four types of data currently stored on the magnetic tapes are: 1) synoptic meteorological observations, 2) hourly precipitation readings, 3) daily climatological observations, and 4) daily streamflow information. Once the data are stored on direct access disk, the data file utility system also can be used to edit data, copy selected parts of files, and plot one or more chronological data series as a function of time or another time series.

Mean Areal Precipitation

The soil moisture accounting model requires as input an estimate of the average precipitation over the entire soil moisture accounting area. The mean areal precipitation (MAP) program transforms hourly and daily point

TABLE 1 Parameters and State Variables Included in the Soil Moisture Accounting Model

Parameter	Description
PXADJ	Precipitation adjustment factor
PEADJ	ET-demand adjustment factor
UZTWM	Upper zone tension water capacity (mm)
UZFWM	Upper zone free water capacity (mm)
UZK	Fractional daily upper zone free water withdrawal rate
PCTIM	Minimum impervious area (decimal fraction)
ADIMP	Additional impervious area (decimal fraction)
RIVA	Riparian vegetation area (decimal fraction)
ZPERC	Maximum percolation rate coefficient
REXP	Percolation equation exponent
LZTWM	Lower zone tension water capacity (mm)
LZFSM	Lower zone supplemental free water capacity (mm)
LZFPM	Lower zone primary free water capacity (mm)
LZSK	Fractional daily supplemental withdrawal rate
LZPK	Fractional daily primary withdrawal rate
PFREE	Decimal fraction of percolated water going directly to lower zone free water storage
RSERV	Decimal fraction of lower zone free water not transferrable to lower zone tension water
SIDE	Ratio of deep recharge to channel baseflow
ET Demand or PE Adjust	Daily ET demand (mm/day) or PE adjustment factor for 16th of each month
State Variables	**Description**
ADIMC	Tension water contents of the ADIMP area (mm)
UZTWC	Upper zone tension water contents (mm)
UZFWC	Upper zone free water contents (mm)
LZTWC	Lower zone tension water contents (mm)
LZFSC	Lower zone free supplemental contents (mm)
LZFPC	Lower zone free primary contents (mm)

precipitation measurements into areal means, estimates missing data from nearby stations, and determines the hourly distribution of daily data.

The MAP program has three options for distributing precipitation gage data throughout an area. Each method places weights on the gage information. The first technique determines a gage's relative importance to an area in proportion to $1/d^2$, where d is the distance from each grid point within the area to the closest gage in each quadrant surrounding the grid point. The proportional weight assigned each gage is determined by normalizing to the sum of $1/d^2$ for all gages entering the solution for a given grid point; normally, four gages are used when at least one is available from each quadrant. Additional details of this technique have been published elsewhere, e.g., NOAA (1972). Another method for estimating mean areal precipitation uses predetermined weighting factors for distributing point precipitation. This technique is particularly effective in areas where the pattern of precipitation may not be accurately represented by the gage network (i.e., mountainous areas). The third method used by the MAP program utilizes Thiessen weighting factors.

Techniques using $1/d^2$ weighting, analogous to that described above for distributing point measurements over an area, also are included in the MAP program for estimating missing data and distributing daily records into hourly and six-hourly estimates. An option exists in the program to allow the user to specify characteristic station adjustments in cases where missing data may be incorrectly estimated using the standard technique (e.g., where orographic effects are apparent).

Evapotranspiration

The soil moisture accounting model requires as input information on the amount of water removed from a basin through evaporation and transpiration. This input may be in the form of average daily evapotranspiration demand or as daily mean areal potential evapotranspiration rate. The mean areal evapotranspiration program (MAPE) will compute mean areal potential evapotranspiration from selected point values. The procedure uses weighted climatological point measurements to estimate missing observations. The final product of the MAPE program is a time series of daily areal potential evapotranspiration.

CURRENT CALIBRATION TECHNIQUES

The soil moisture accounting model generally must be calibrated for each watershed before it can be used as a component in the operational forecast program for river forecasting. Both trial-and-error and automatic optimization techniques are used to determine the model parameters. The trial-and-error procedures require subjective parameter adjustments based on the results of previous simulation runs. The automatic techniques use a direct-search algorithm for optimizing parameter values.

Experience with the NWSRFS, and in particular with the soil moisture model, has shown that the best calibration strategy involves a combination of trial-and-error and automatic optimization procedures. Monro and Anderson (1974) showed that a combination of the techniques takes advantage of the strengths of both while minimizing the weaknesses in the two procedures. To satisfactorily derive a set of parameter values, the hydrologist must understand the physical processes occurring in the watershed and the way the model mathematically represents a catchment. Manual adjustment of parameters by an experienced hydrologist produces good results, but the process requires a great deal of time. Automatic optimization procedures require a relatively small amount of manpower, however there are disadvantages to the automatic methods. Direct search techniques determine parameter adjustments, generally on the basis of a single objective criterion function. If the user specifies poorly selected initial parameter values in the optimization program, the procedure may produce suboptimal results. The direct search procedure also may produce slow convergence if there is considerable interaction among the model parameters.

A proper combination of the trial-and-error and automatic calibration procedures can provide satisfactory model results. The Hydrologic Research Laboratory has experimented with both types of calibration techniques, and has developed a three-part calibration strategy which is designed to overcome the disadvantages associated with manual and automatic methods. The three parts consist of an initial stage that includes initial parameter estimation and trial-and-error calibration, an intermediate stage employing automatic parameter optimization, and a final stage of manual and/or automatic parameter "fine tuning."

Initial Stage — Manual Calibration

Initial parameter values are generally computed based on the characteristics displayed in observed streamflow records. Determination of initial values is a critical part of the overall calibration process. If emphasis is given to this stage, many of the initial values can be determined within reasonable limits directly from hydrometeorological data, and the representativeness of other parameters determined by automatic optimization will be enhanced by careful selection of all initial parameter values. Burnash, et al. (1973) and Peck (1976) give guidance for estimating initial values for most of the parameters from streamflow records. Armstrong (1978) has prepared a technique for estimating parameter values related to soil properties from soil data type.

The length of record to be used for model calibration depends on the location of the watershed, but in general should be long enough to contain climatic and hydrologic variety (extreme dry to extreme wet conditions) and should be recent enough to reflect current land use conditions. Varying conditions in the hydrologic record allow the model to apply its functional relationships over a large range of conditions. Experience with the model has shown that the most recent ten years of record is a suitable calibration period for most watersheds. A portion of the calibration period is often set aside to be used for verification of the model after final parameter values have been determined.

Model simulation runs made with the initial parameter values typically reveal significant errors between observed and simulated streamflows. Statistical summaries and plotted hydrographs are provided by the manual calibration program (MCP) and are used to determine the appropriate parameter adjustments during the trial-and-error calibration runs. Manual calibration continues until the simulated hydrograph resembles the observed streamflow data. The initial stage of calibration also should provide parameter sensitivity information so that parameters having little effect on the model output will not be included in the optimization stage.

Intermediate Stage — Automatic Parameter Optimization

The automatic parameter optimization program (OPT) uses a direct search optimization procedure known as Pattern Search (Hooke and Jeeves, 1961 and Monro, 1971). The Pattern Search algorithm attempts to establish a pattern of parameter adjustment so that the size of the adjustment can be increased at each stage of optimization and the model performance can be improved rapidly. Performance of the model is described by a single-valued objective function. The objective function commonly used is the sum of the squares of the differences between simulated and observed mean daily streamflow. However, the current version of OPT includes a choice of four evaluation criteria: 1) the most commonly used criterion, i.e., the daily root mean square (RMS) error, 2) monthly volume RMS error, 3) sum of the absolute value of the differences of the observed and simulated mean daily streamflows, raised to a user-specified exponent, and 4) same as option 3 except with logs of the mean daily streamflow values. The daily RMS error is recommended for use in most situations. Although the daily RMS error tends to be influenced more by large errors, which typically are associated with high flows, experience with the model has shown that use of this function normally results in a parameter set that allows the model to adequately simulate a variety of flows.

Because of the iterative nature of OPT, the amount of computer time required to run the program often may necessitate that the calibration period for the automatic optimization procedure be considerably less than that used for manual calibration. The period of record should contain hydrologic variety and the data errors should have zero mean to insure stable calculations. A period of about 4 years is generally recommended for automatic parameter optimization. A start-up buffer period of 2 to 6 months also is suggested to allow the model to adjust to initial conditions.

The OPT program requires as input initial parameter values for the parameters being optimized, initial parameter adjustment increments, upper and lower bounds on the optimized parameter values, and limits to control the number of iterations. Users are encouraged to keep initial adjustment increments small so that the program can quickly seek a reliable adjustment pattern. Once a pattern is established the procedure can automatically increase the adjustment increment and begin to converge more rapidly. Experience with the model has shown that the program generally will have reached an acceptable set of parameter values within 10-15 iterations per parameter. Results from using OPT on many watersheds have shown that when reasonable initial parameter values are specified, the program provides realistic computed parameter values that substantially improve the accuracy of the simulations.

Final Stage — "Fine Tuning"

In the final stage the manual calibration program is run for the entire period of record. Simulated and observed streamflows are compared to determine if bias is present in any particular flow range. Occasionally, additional trial-and-error or automatic optimization model runs are performed. When no bias appears in the model results, the calibration is considered complete.

CASE STUDY

The soil moisture model was calibrated for the Leaf River near Collins, Mississippi. The Leaf River watershed is primarily forested and that portion above Collins has a drainage area of 1,948 square kilometers and an average yearly runoff of 450 millimeters. The normal three-stage calibration procedure described in the previous section was used to determine parameter values. Computer

TABLE 2 Results of Parameter Optimization Tests for Four Sets of Initial Parameter Values for the Leaf River above Collins, Mississippi

Parameter	Run A		Run B		Run C		Run D	
	Initial Value	Opt. Value	Initial Value	Opt. Value	Initial Value	Opt. Value	Initial Value	Opt. Value
PEADJ	1.0	0.98	1.0		1.0		1.0	
UZTWM	20.0	12.	20.0	16.	125.0	144.	20.0	
UZFWM	25.0	34.	25.0		25.0		25.0	
UZK	0.35	0.33	0.30	0.38	0.35		0.10	0.30
ZPERC	200.0	214.	150.0	150.	30.0	28.	200.0	
REXP	3.3	3.2	2.5	2.5	1.5	1.8	3.3	
LZTWM	200.0	208.	150.0	190.	75.0	91.	200.0	
LZFSM	45.0	43.	45.0	39.	45.0		150.0	126.
LZFPM	140.0	166.	175.0	171.	140.0		250.0	126.
LZSK	0.15	0.11	0.15	0.13	0.15		0.02	0.03
LZPK	0.004		0.004		0.004		0.004	
PFREE	0.1	0.15	0.1		0.1		0.1	
UG Peak[1]	7.2	7.1	7.2	7.1	7.2		14.4	4.4
UG Timing[2]	60.0	56.	60.0	58.	60.0		24.0	41.
Statistics								
Daily RMS Error[3]	18.07	16.89	19.05	17.60	21.49	20.98	43.35	19.60
% Bias	-2.71	-0.01	2.14	-0.21	1.10	-2.19	-4.46	-2.73
R Coefficient	0.9685	0.9729	0.9660	0.9704	0.9551	0.9571	0.8039	0.9630

[1]Units=cms } These two parameters are not parameters of the soil moisture accounting
[2]Units=hr } model (see Table 1), but often are included in the optimization process.
[3]Units=cmsd

runs also were made using the optimization program to show that poorly selected initial values can cause the Pattern Search routine to produce suboptimal results. Results of the optimization runs for four sets of initial values are shown in Table 2.

For all four runs included in Table 2, parameters with values shown in the optimized column were selected for optimization, and the period of record used for calibration was October 1956 to September 1962. Run A shows fourteen of the parameters resulting from the "manual" calibration trials and the changes that were made to them by the automatic optimization program. The results reveal that the parameter values were changed somewhat by the optimization program and the model errors were reduced. For Run B, some of the initial parameter values were distorted slightly to see if the automatic optimization program would move the parameter values in the "correct" direction. Table 2 shows that most of the parameters optimized in Run B changed as expected, however, the statistics illustrate that only a local optimum was attained and the model errors for Run B were greater than those for Run A.

Changes were made to selected initial parameter values for Runs C and D to demonstrate results of a different interpretation of historical records during initial parameter estimation. In Run C the relative sizes of the upper and lower zone tension water storages were switched, but the overall approximate tension water capacity was maintained. Also, in Run C the percolation curve, determined by ZPERC and REXP, was made considerably flatter. Table 2 shows that the optimization program was unable to make the major parameter changes required to reach the level of optimization achieved in Run A. Selected initial parameter values were changed for Run D to show a misrepresentation of interflow. The UZK and LZSK coefficients were lowered, the lower zone free water storages were increased, and the unit hydrograph was changed so as to have a peak that occurred earlier and was larger in magnitude. In this case most of the parameter values were considerably altered by the optimization program resulting in a greatly improved simulation. However, again the statistics showed that the model fit was not as close as that for Run A.

This case study reveals that use of the optimization program and the Pattern Search technique generally can improve calibration results. However, the case study also illustrates that the automatic optimizer could not completely correct for major mistakes in the estimation of initial parameter values. In conclusion, it must be emphasized that the results from any automatic optimization technique will be critically dependent on the representativeness of the initial parameter values and on the quality of the input data.

CALIBRATION RESEARCH

A number of calibration research projects currently are being conducted or are planned for the future. Research ideas include the development of techniques which utilize computer-generated graphics, computer algorithms to improve the efficiency and reduce the manual interpretation effort required to derive initial parameter values, physically based optimization procedures, and estimation theory techniques such as maximum likelihood and stochastic approximations.

The field of computer generated graphics has several applications to calibration. The results of optimization runs can be stored in the computer and later plotted in three dimensions (e.g., two parameter dimensions and one objective criterion dimension) to show interaction among parameters. This type of analysis could be useful in determining the sensitivity of the model to simultaneous parameter changes. Interactive calibration programs which show graphically the response of the model to parameter adjustments are planned. In an interactive system the user could immediately see the reaction to his input. Another application of computer graphics is in the area of calibration training. As mentioned previously, a thorough understanding of the catchment model is essential to good calibration work. A program which could display on a graphics scope the changing states of the soil moisture accounting model would be a valuable training tool. It is evident that the rapidly expanding field of computer graphics offers numerous calibration applications.

Research activities designed to incorporate many of the current manual calibration steps into an improved automatic optimization program are planned. This would involve establishing decision rules to automatically isolate the portions of the hydrograph that can best be used to estimate the values of each parameter. For example, it should be possible to formulate a computer algorithm that could automatically estimate the minimum impervious area (PCTIM) for a given watershed by identifying one or more dry periods of minimum specified length followed by small rainfall events that produce surface runoff from the impervious areas only. For some parameters, once the portions of the record are isolated, the parameter value could be computed directly without using iterative techniques similarly to the current procedure for determining initial parameter estimates. Other parameters would still require the use of an iterative procedure like Pattern Search; however, the optimization criterion and portion of the record used could be different for each parameter. Also, research is planned to develop an objective function, which may be useful for some conditions, that would be a weighted combination of several criterion.

The Hydrologic Research Laboratory currently is supporting contractual work in several areas of application of estimation theory to hydrologic forecasting. The Civil Engineering Department, Massachusetts Institute of Technology (MIT) and The Analytic Sciences Corporation (TASC) are collectively developing state-space formulations for the NWS soil moisture model and unit hydrographs. Also, these contractors are examining various ways of applying estimation theory techniques to parameter estimation. Among the candidate methods, maximum likelihood parameter estimation is being explored by TASC, and MIT in addition is examining the application of suboptimal filters, e.g., the method of stochastic approximations.

A calibration system based on estimation theory would attempt to recursively determine a range of optimal parameter values so that the difference between the best estimate of the model states and the true values of those states is minimized. Recursive in this context means that critical parameters are optimally updated at successive time steps without the need to iterate through previous time steps.

The combination of in-house and contractual research in the area of parameter estimation should lead to significant improvements in calibration of the NWS River Forecast System. Also, several of the research efforts hold promise of improving the efficiency with which calibrations may be achieved and thus should significantly accelerate the model implementation schedules.

CONCLUDING REMARKS

Components of the NWS River Forecast System provide the means for processing data into useable model inputs, for performing calibration to determine suitable model parameters, and for performing hydraulic and hydrologic computations for a wide variety of conditions. Accurate calibration of the soil moisture model for various watersheds often is a complex and time-consuming process. Experience with the soil moisture accounting model has shown that the model can produce very accurate simulations and streamflow forecasts when calibrated according to the procedures described. However, at the time of this writing, calibrations are complete for only about 20 percent of the headwater basins.

The techniques currently used for calibration consist of three stages: 1) initial stage, including hand computations to determine initial parameter values from observed hydrologic data and trial-and-error computer runs using the manual calibration program, 2) intermediate stage, consisting of parameter adjustment using the automatic optimization program, and 3) final stage, including final parameter adjustments using the optimization and/or manual calibration programs. To speed up the implementation of the soil moisture accounting model at the

13 RFC's, future research must be directed toward the development of a better understanding of the physical processes represented in the model and toward improved consideration of these physical processes in model calibration. Potentially, improvements are possible at all stages of the current calibration procedure. Research work designed to improve the first stage of calibration includes applications of computer graphics and the development of computer algorithms to automatically estimate initial parameter values. The intermediate stage could be improved by incorporating into the calibration procedures physically based optimization routines and recursive calibration techniques utilizing estimation theory. Current research in the estimation theory area includes consideration of the maximum likelihood method and the use of suboptimal filtering techniques such as the method of stochastic approximations.

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