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APPLICATION OF REMOTE SENSING TO HYDROLOGY

FINAL TECHNICAL REPORT

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APPLICATION OF REMOTE SENSING TO HYDROLOGY

FINAL TECHNICAL REPORT

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IBM Federal Systems Division, Electronics Systems Center/Huntsville, Alabama

PREFACE

This report is expected to receive wider distribution than any published previously on the same study. It therefore incorporates much of the material contained in those prior reports, for the convenience of readers who have not had access to them. Those already familiar with the study concept and prior progress are entreated to understand and forgive the duplications.

The study is the first part (a feasibility investigation) of a longer-range application development project whose concept has evolved from an idea suggested at the International Astronautical Congress in Brussels in 1971[1]. Since it was initiated under NASA contract in July 1971, it has focused on the same objective even though (as in all such research) the technical scope, methodology and manpower levels have from time to time been revised. A brief history of the study appears in Appendix A.

The study objective and concept are described in Section 1, with a summary of results. Section 2 supports the choice of simulation model and describes its use in the study. Section 3 presents the study methodology and describes each task and the results of each task. Recommendations for additional research and validation efforts appear in Section 4. Appendices contain a summary project history, a list of references and the basic distribution list for the report.

The authors are grateful to many individuals for initiation and support of and contributions to the study. Dr. Peter A. Castruccio (presently president of Ecosystems International, Inc.) and Mr. Andrew Adelman of IBM were energetic in promoting the basic idea. Dr. George McDonough of NASA's George C. Marshall Space Flight Center sponsored the project and was instrumental in securing funds to support it. Dr. William D. Clarke, as NASA-MSFC technical manager, made several helpful suggestions and first recognized the potential value to others of the processed and integrated data base which is a by-product of the study.

The advice of authorities in many areas related to streamflow forecasting and hydrologic modeling was available to the study team. Dr. L. Douglas James of the Environmental Research Center, Georgia Institute of Technology, provided the basic simulation and calibration programs, advised us in their implementation and reviewed interim results of the study. In obtaining historical and physiographic data, selecting watersheds for study, and understanding the objectives and methods of operational river forecasting, the authors have received invaluable assistance from personnel of the Tennessee Valley Authority; National Weather Service Hydrology Office and Lower Mississippi River Forecast Center; U. S. Geological Survey, in several locations; U. S. Soil Conservation Service; and the U. S. Army Corps of Engineers.

Mrs. Becky Robinson of IBM deserves a special measure of thanks. In a remarkable exhibition of versatility, in addition to performing as departmental secretary, she:

- secured storage facilities for the tons of data acquired and generated in the study;
- constructed photomosaics and overlay graphics;
- identified and maintained hundreds of maps and aerial photographs;
- made special trips to TVA in Knoxville to obtain historical data;
- prepared illustrations for presentations and reports;
- typed, edited and assembled technical reports, including this one.

These acknowledgements of assistance do not imply any endorsement or approval by those whose help we appreciate so much. The conduct of the study, the results achieved and the content of this report are the responsibility of the authors. Any errors of fact, methodology or logic should be attributed solely to us.

Reuben Ambaruch
Principal Investigator

John W. Simmons
Study Manager

CONTENTS

CONTENTS (Continued)

CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

SECTION 1

INTRODUCTION

1.1 OBJECTIVE

The objective of the study whose results are reported herein is to assess the feasibility of using the data produced by remote observation from space and/or aircraft to reduce the time and expense normally involved in achieving the ability to predict the hydrological behavior of an ungaged watershed. Such a capability will enhance effective planning for urban and industrial development, flood control, hydroelectric power, navigation, and water resources management. Traditionally, the ability to predict streamflow rates, in response to given precipitation, is attainable only after installation of extensive instrumentation and collection of data for several years to estimate the operating parameters of a model of the basin or watershed system. This project was aimed at developing techniques for using the large amounts of data acquired by earth observation missions to determine those parameters more directly.

1.2 BASIN MODELING AND STREAMFLOW FORECASTING

That aspect of hydrology known as Streamflow Forecasting undertakes to predict the outflow from a given catchment, in terms of flow rate as a function of time, in response to a given precipitation event under given initial conditions. This capability is vital to effective planning for urban/industrial development, flood control hydroelectric power, navigation, and water resources management.

Figure 1 depicts the cross section of a somewhat idealized rural catchment and identifies the principal phenomena at work in the rainfall-runoff relationship. The input (precipitation) is partially intercepted by vegetation and water retention areas. Moisture reaching pervious surfaces divides between overland flow, infiltration and evaporation. Through subsurface processes, interflow and groundwater flow contribute ultimately to streamflow, with some losses due to transpiration through plant life.

All the phenomena involved in the hydrological cycle are widely and well understood qualitatively, and several empirical relationships have

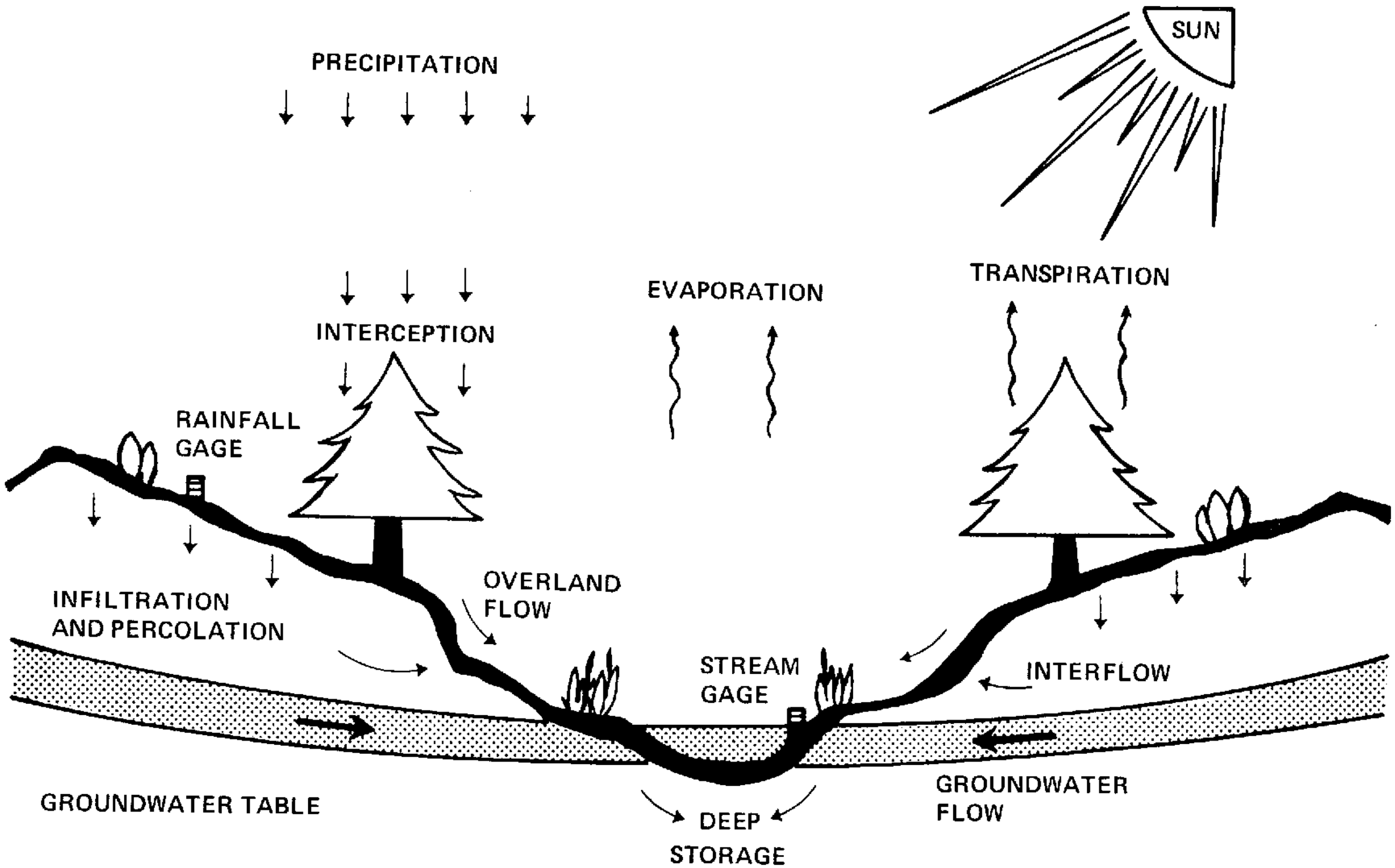

Figure 1. Cross Section of Idealized Rural Catchment

been developed. Integrating them into comprehensive parametric models has been achieved by several investigators, developments which were facilitated by the availability of large, high-speed digital computers. Of these, the Stanford Watershed Model is probably the best known. In order to apply any model to a given catchment, however, it is necessary that it be calibrated. That is, several years of streamflow are simulated using actual precipitation data, synthesized flows are then compared to actual recorded flows, model parameters (as well as seasonal factors) adjusted by hydrologists and the process repeated until acceptable simulation accuracy has been achieved. More recently, self-calibrating models have been developed which use trial and error routines to optimize model and seasonal parameters, but the calibration still required historical streamflow data. If a stochastic model or technique is used instead of a parametric model, several dozen storm events in the form of previously measured rainfall and runoff data must be used in multivariate statistical analyses in order to establish confidence in the results.

Whatever the model or analytical techniques used, current methods of streamflow forecasting require installation and maintenance of a system of instruments so that data may be collected for several years. The basin of a major river must be divided into hundreds of watersheds of manageable size and each one provided its own stream gage. Although the installation and maintenance expenses may not be objectionable, waiting for several years of data collection to initiate a new development may be intolerable. There is a real need for a method of predicting the hydrological behavior of a previously ungaged catchment quickly (within two months, say, rather than three to five years) and with reasonable accuracy.

1.3 POTENTIAL APPLICATION OF REMOTE SENSING

There has been increasing interest in recent years in the relationship between hydrological behavior of a watershed and a unique set of physiographic features by which it might be characterized. One would like to be able to quantify simulation model parameters, either directly or inferentially, from observations of catchment morphology and climate, taking advantage of all available prior knowledge of the area. Earth observation spacecraft, manned or unmanned, make observations using a variety of sensors, covering large areas in a short time. The objective of the study whose results are reported herein is to assess the extent to which the data provided by earth observation missions can be used to reduce the time, effort, and cost of predicting the hydrological behavior of a given catchment.

1.4 FEASIBILITY STUDY METHODOLOGY

The study was conducted in three phases as shown in Figure 2, aimed at devising a set of widely applicable prediction model parameters in terms of photographically observable characteristics (such as climatology, areas, elevations, and land use) and inferable characteristics (such as soil depth and porosity).

1.4.1 PRINCIPAL STUDY ELEMENTS

The principal elements of the study are a simulation and a calibration model, a study area, and a complete historical and physiographic data base pertaining to the study area. They are as follows:

- Simulation Model. The continuous simulation model chosen for the study, for the reasons discussed in Section 2, is known as the Kentucky Watershed Model (KWM). This model is based upon the well-known Stanford Watershed Model IV, and has been further adapted and refined by IBM for application to this project.

- Calibration Program. A calibration program known as OPSET (because it estimates the optimum set of watershed model parameters) is a companion to the KWM. It has also been refined and modified for application to this study. By a trial and error process it estimates values for 13 simulation model parameters which are further refined by manual operations. This program is also described in Section 2.

- Study Area. The area from which test watersheds are chosen for the study is the Tennessee River Valley, a major watershed of approximately 104,000 square kilometers in the southeastern United States. This is a well-instrumented, thoroughly photographed and mapped area for which copious historical data records are available.

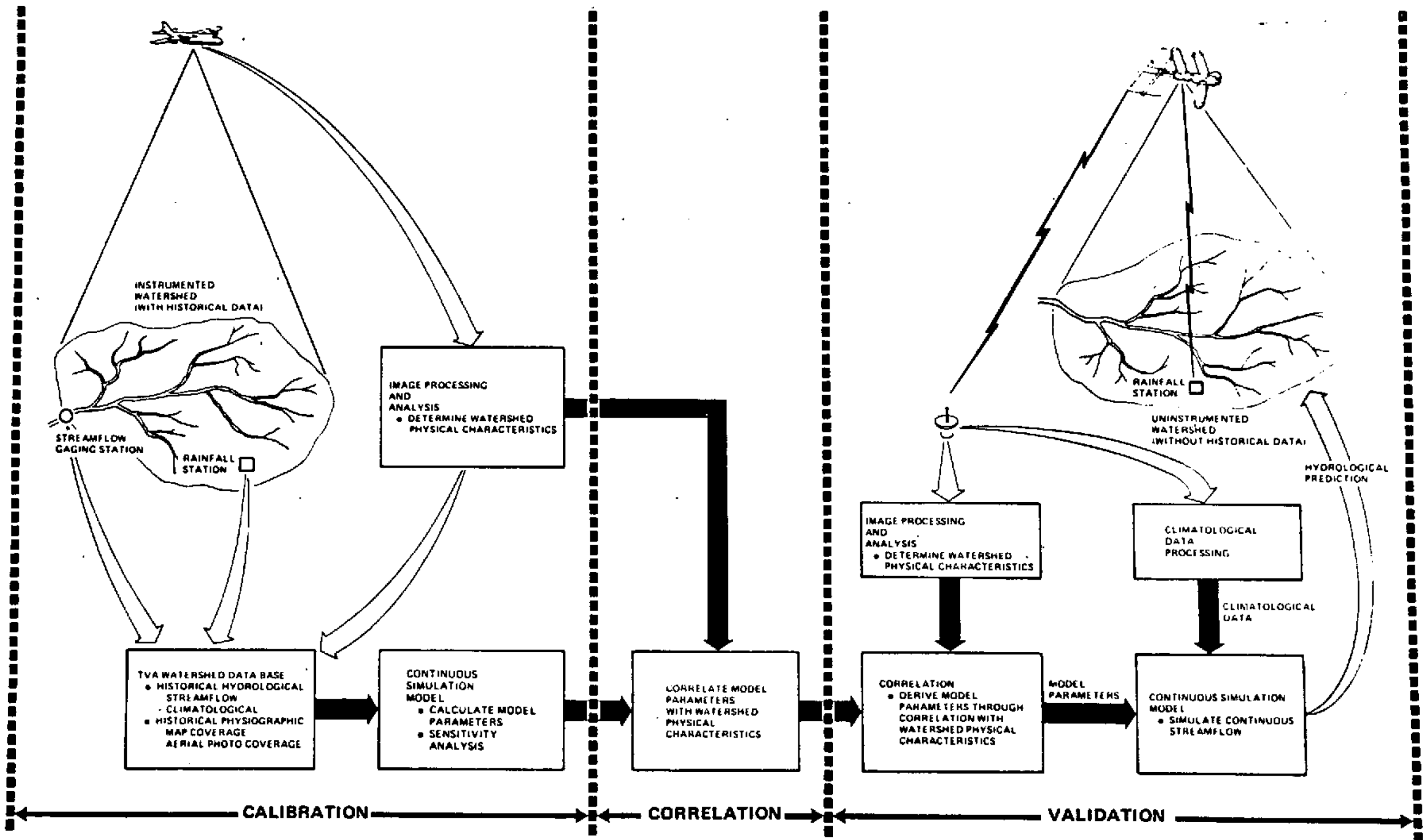

Figure 2. Study Methodology

Within the Tennessee Valley 55 watersheds have been identified as suitable to the purposes of the project, representing all six physiographic provinces of the valley. It was estimated that 35 watersheds would be needed for confidence in the results of the correlation process. Of these, 25 were to be used for calibration and 10 for tests of simulation accuracy. Table 1 lists the limited set actually used in the study. Figure 3 indicates their locations in the region. These represent five of the six physiographic provinces and range in area from 7 to 365 square kilometers. The average overland flow surface slopes are indicative of the varying ruggedness of the region, from the Nashville Basin to the Blue Ridge Mountains. For all except the smallest watersheds, hourly rainfall station records are supplemented by daily rainfall records for the sake of accuracy.

- Historical Data Base. The study requires accumulation of a comprehensive data base consisting of streamflow, precipitation, and evaporation records for the study area. The Tennessee Valley watershed is one which is extensively instrumented and for which ample historical data are available. It contains approximately 560 rainfall stations, both hourly and daily. Almost 1,000 streamflow records have been accumulated in the past several decades; approximately 360 streamflow stations are currently active, and some 600 have been discontinued. Other climatological data such as temperature, evaporation, wind and humidity have been carefully collected and catalogued.

- Physiographic Data Base. The study also requires the accumulation of a comprehensive physiographic data base for the study area. Complete topographic map coverage is available, consisting almost entirely of 7.5 minute quadrangle maps derived from aerial photographs at a scale of 1:24,000. The Tennessee Valley has also been completely surveyed by aerial photography, and black and white photographs are available for every watershed, mainly at a scale of 1:24,000. Some photographic coverage is also recently available in pseudocolor infrared taken from high altitude aircraft, at a scale of 1:63,000. Excellent images from the Earth Resources Technology Satellite (ERTS) have also been obtained.

Table 1. Selected Watersheds

	CATCHMENT NAME	PHYSIOGRAPHIC PROVINCE	AREA (SQUARE KILOMETERS)	AVERAGE SLOPE	NUMBER OF RAINFALL STATIONS		USE*
					Hourly	Daily	
1.	WHITE CREEK NEAR SHARPS CHAPEL, TN (WHITE HOLLOW)	Valley and Ridge	6.94	.300	1	–	C
2.	LITTLE CHESTUEE CREEK BELOW WILSON STATION, TN	Valley and Ridge	21.30	.237	1	1	C
3.	SOUTH FORK MILLS RIVER AT PINK BEDS, NC	Blue Ridge	25.70	.315	2	1	C
4.	NOLAND CREEK NEAR BRYSON CITY, NC	Blue Ridge	35.70	.500	2	–	V
5.	WEST FORK PIGEON RIVER ABOVE HAZELWOOD, NC	Blue Ridge	37.30	.413	1	1	C
6.	BIG BIGBY CREEK AT SANDY HOOK, TN	Highland Rim	45.30	.185	1	1	V
7.	BIG ROCK CREEK AT LEWISBURG, TN	Nashville Basin	64.50	.155	1	–	C
8.	LITTLE RIVER ABOVE HIGH FALLS, NEAR CEDAR MTN., NC	Blue Ridge	69.50	.246	1	2	V
9.	TRACE CREEK NEAR DENVER, TN	Highland Rim	78.70	.129	1	2	C
10.	PINEY CREEK NEAR ATHENS, AL	Highland Rim	145.00	.033	1	4	V
11.	RUTHERFORD CREEK NEAR CARTERS CREEK, TN	Nashville Basin	178.00	.133	1	2	U
12.	EMORY RIVER NEAR WARTBURG, TN	Cumberland Plateau	215.00	.298	1	3	C
13.	SEWEE CREEK NEAR DECATUR, TN	Valley and Ridge	303.00	.165	2	2	C
14.	TOWN CREEK NEAR GERALDINE, AL	Cumberland Plateau	365.00	.062	2	5	C
15.	POPLAR CREEK NEAR OAK RIDGE, TN	Cumberland Plateau	214.00	.329	1	3	C
16.	EAST FORK POPLAR NEAR OAK RIDGE	Cumberland Plateau	50.50	.215	1	1	V

*USE: C = CALIBRATION; V = VALIDATION; U = UNUSEABLE (INADEQUATE DATA)

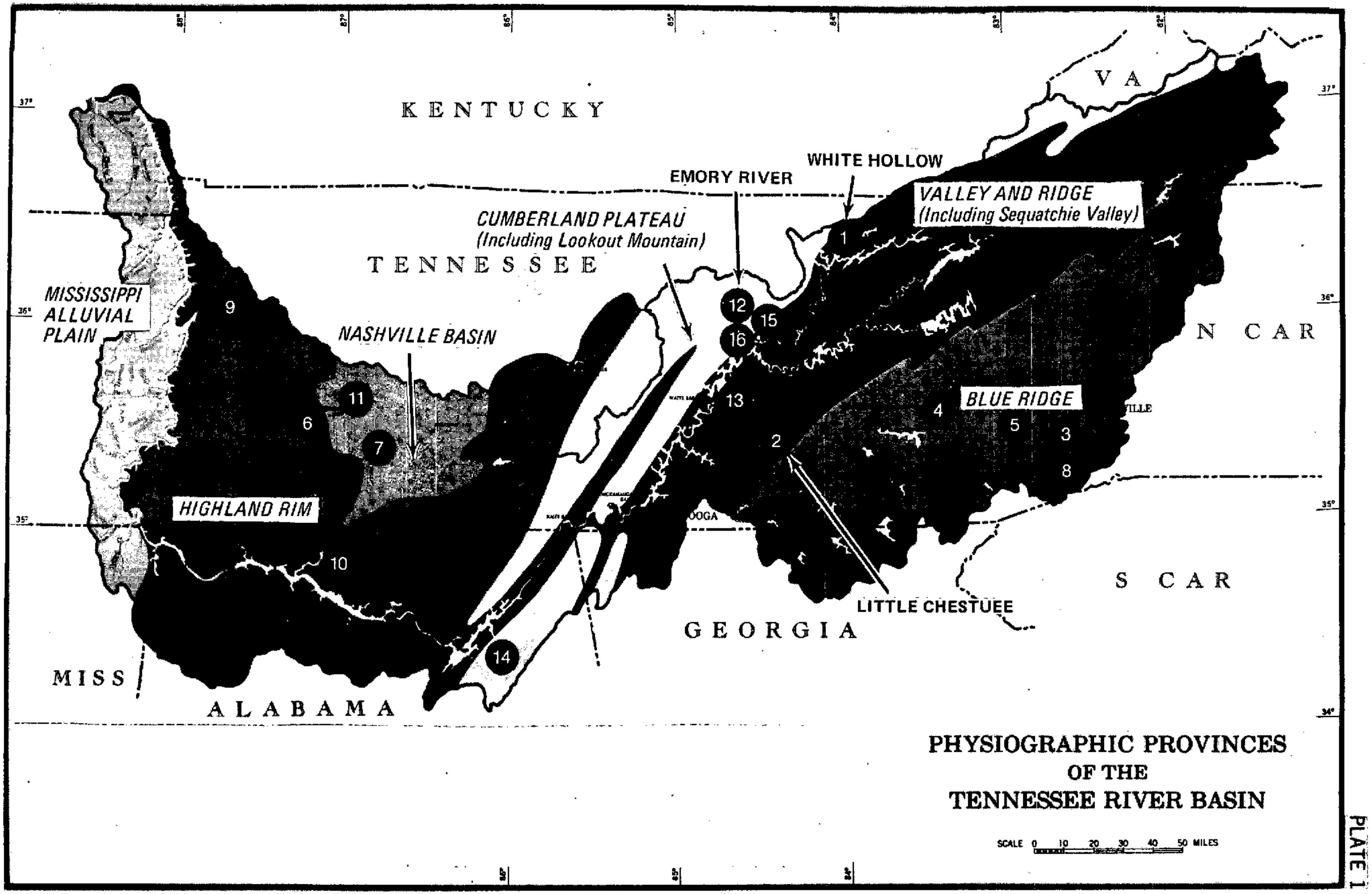

FIGURE 3 LOCATIONS OF STUDY WATERSHEDS

1.4.2 CALIBRATION

In the calibration phase the model parameters and their related observables were quantified and adjusted for ten selected watersheds from five of the six physiographic provinces of the Tennessee Valley. These sets of satisfactory model parameter values are those which yield simulated streamflows which best correlate with actual recorded flows for periods of five to ten years. A sensitivity analysis of two watersheds provided guidance for final manual adjustments of the model parameters, thereby minimizing the time and effort spent in the calibration phase.

1.4.3 CORRELATION

In the correlation phase, satisfactory model parameters were correlated with observable physiographic characteristics in a multiple regression analysis, using the results of ten calibrations as a data base. The product of this phase is a set of regression equations, each of which is an expression for a model parameter as a linear combination of other parameters.

1.4.4 VALIDATION

In the validation phase, the relationships produced by the correlation analysis were tested on five watersheds from different physiographic provinces of the region. No calibrations were performed on these basins; they were treated as "ungaged" watersheds. Their simulation model parameters were quantified by using the regression equations, and then the simulation model was run, using those parameters and historical climatological data as input. The simulated streamflows compared well with observed streamflows, in respect to most indices of performance indicating the feasibility of the technique.

1.5 SUMMARY OF RESULTS

1.5.1 FEASIBILITY CLEARLY INDICATED

The five validation runs produced simulated streamflows which correlated remarkably well with observed streamflow. Daily correlation coefficients ranged from 0.83 to 0.87; monthly, from 0.92 to 0.97. Many major storms were reasonably well matched with respect to peak flows and timing of peaks. For a multi-year open-loop simulation, this is adequate for most applications, and it strongly indicates the feasibility of using remotely sensed data to forecast the hydrologic performance of an ungaged watershed.

This happy conclusion should be kept in the perspective shaped by the following facts and circumstances.

- The initial study plan envisioned using 25 watersheds for calibration and ten for validation to provide statistical confidence in the results. The study actually used ten and five respectively, leaving some (undefined) uncertainty in the validity of the result.

- The remote sensing imagery used to determine watershed physical characteristics was actually aerial photographs, mostly at a scale of 1:24,000. No interpretation of higher-altitude (RB-57F, U-2) or space (ERTS) images was done in the study.

- Some ground truth was necessary, in this instance soil data. This is not considered a disqualifying fact, because the need for some ground truth probably cannot be obviated in future applications.

- The correlation (i. e., multiple regression) analysis deserves some refinement, based on an enlarged appreciation by the statistical analyst of the hydrologic processes and relationships found in a watershed.

1.5.2 SIGNIFICANT BY-PRODUCTS

There are two by-products of the study which the authors believe to be of potential value to other investigators in hydrologic modeling and related fields.

1.5.2.1 Integrated Data Base

As in most applications using simulation models, the preponderant share of the study effort was devoted to acquiring, verifying, formatting, and preprocessing input data to construct a data basis. As a result of this study, a data base now exists in the form of a magnetic tape. The tape has a capacity of up to 50 files, one file per basin. Each file has fields allocated for up to ten years of historical climatological data (mean basin hourly rainfall, evaporation, temperature), mean daily streamflow, and selected storm events (up to ten per year, characterized by peak flow and time of peak). Each file also has fields for watershed features, simulation model parameters and program control options.

At present, the data base contains data, except temperature, pertinent to the 15 Tennessee Valley basins used in the study. To any other investigator interested in doing similar studies in the same area, the integrated data base may be of great value.

1.5.2.2 The IBM System for Simulation and Analysis of Watersheds

Since the study team began adapting the Kentucky Watershed Model and its companion calibration program, OPSET, to the feasibility study, several programming additions and modifications have been made. The result is a system of methods and software, built around the basic simulation and calibration models, which is a powerful hydrologic research tool readily adaptable to operational use. Features of the system are as follows.

- Input data preprocessing and verification.
- Plot outputs.
- Tabular summaries.
- Storm analysis.
- Statistical analysis routines.
- Terminal operation for
  - set up and initiation of calibration/simulation runs, with a batch-processing computer, or
  - real-time interaction, with a time sharing computer.

The effort required to develop this system for efficient operation has been more than compensated by the manpower saved in manipulation of data, handling many large decks of cards, and analyzing raw simulation outputs. In fact, the study could not have been completed without it.

1.6 A GLIMPSE OF THE FUTURE

Section 4 of this report summarizes research efforts worthy of consideration as sequels to this feasibility study. Several years will be required for the idea tested preliminarily here to be reduced to practice in another region. Nevertheless, one can readily visualize the sequence of events.

- A set of spacecraft sensors observe an ungaged region concurrent with aircraft underflights and ground truth patrols.
- The data so acquired are analyzed and interpreted to yield watershed characteristics.
- Statistically derived relations are used to quantify simulation model parameters from observed characteristics.

- The simulation model is run, using climatological inputs typical of the region, to generate multiyear streamflow predictions and statistics, for planning purposes.

This can be done in a short time, two to three months, without extensive instrumentation or the need to take calibration data for three or more years. Residual benefits will derive from implementing the system for periodic short-term river forecasting, using a few well-placed stream gages for "closed-loop" operation and a forecasting accuracy within five per cent.

SECTION 2

SELECTION OF SIMULATION MODEL

2.1 OBJECTIVE

The spreading availability of high-performance computers has stimulated remarkable progress in development of hydrological models. An individual investigator may prefer one model or another on the basis of several criteria, with emphasis on the objectives of his research. We have selected a model with which we can accomplish the calibration, correlation, and validation phases within the study schedule time and manpower budgets. The models and procedures developed must be capable of predicting the hydrological performance of an ungaged basin with parameters derived from space or aerial imagery, sparse ground samples, precipitation and evaporation data.

2.2 STOCHASTIC MODELS

The project first considered stochastic models, which involved the use of multivariate regression analysis to develop predictions of runoff as a function of a limited number of observable variables: storm duration, storm intensity, time of the year, and initial moisture conditions--the last estimated empirically from recent precipitation experience. Techniques were identified for deriving rainfall-runoff relations using observable or inferable physiographic features. Synthetic hydrograph* methods were considered for determining streamflow as a function of time. Methods were identified for statistically correlating observable physiographic features with unit hydrograph parameters.

2.3 PARAMETRIC MODELS

Parametric models were also considered and found to be preferable to stochastic models for the following reasons:

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*A hydrograph is simply a plot of streamflow in volume per unit time or river height as a function of time. See Reference 2, Chapter 9.

1. The cause and effect relationships among the conditions and processes in a watershed are obscured in the stochastic model but are used explicitly in the design of the parametric model, many of whose parameters are observable directly from remote sensed imagery.

2. In using a stochastic rainfall-runoff (RF-RO) model, it is necessary to analyze some 50 observations (storm events) per watershed to obtain confidence in the validity of the derived relationship. In determining RF-RO relationships based upon physiographic parameters, approximately 50 watersheds are needed, each one having 50 associated storm events.

3. In order to take into account all practical variations in and interrelations among watershed parameters, a prohibitive amount of data is required for thorough statistical analysis. Thomas and Benson[3] identified 71 physiographic and statistical variables of interest in relating streamflow characteristics to basin physical characteristics.

4. A parametric model that is capable of simulating continuous flows over a long period of time supports a larger variety of planning objectives than a method which is intended to estimate or predict a single variable or isolated event (e.g., flood peak or total runoff from a storm).

2.4 STANFORD WATERSHED MODEL (SWM)

The Stanford Watershed Model[4,5] is probably the best known of the parametric hydrological models and, in all its modifications, is probably the most widely used. Since it was originally published in 1962, several reports have appeared in literature describing modified versions and applications (References 5, 6, 7, 8, 9, 10, and others). As a proven tool it was attractive to our project, whose scope does not embrace advances in hydrological modeling.

The Stanford Watershed Model uses a moisture accounting system to synthesize a continuous hydrograph from the following:

1. Recorded climatological data, precipitation, evaporation and (for snowmelt situations) temperature,

2. Measurable watershed characteristics such as drainage area and friction of the watershed in impervious surfaces, and

3. Parameters used in the computation process which are known to vary in magnitude among watersheds but have not been quantitatively tied to specific measurable watershed properties. For example, one parameter indexes the capacity of the soil of the watershed as a whole to retain water.

The third class of inputs requires a trial and error series of calibration runs to quantify a set of model parameters which will synthesize flows with acceptable accuracy.

Figure 4 depicts the accounting of moisture entering the watershed until it leaves by streamflow, evapotranspiration, or subsurface outflow. A series of relations each based on empirical observation or theoretical description of a specific hydrologic process, is used to estimate rates and volumes of moisture movement from one storage category to another, in accordance with current storage states and the calibrated watershed parameters. The model routes channel inflow from the point where it enters a tributary channel to the downstream point for which a hydrograph is required. A subroutine exists for including snow in the accounting but is not needed in the present study.

2.5 KENTUCKY WATERSHED MODEL (KWM) AND OPSET PROGRAM

The Stanford Watershed Model was originally written in the Burroughs Computer Language (BALGOL) then in use at the Stanford Computer Center. It has subsequently been translated into Fortran IV, and a number of adaptations were introduced in one version to suit the climate and geography of Kentucky as representative of the eastern United States. In a recent research program a version of the model using an initial set of model parameter values and a number of control options was developed for use with a self-calibrating streamlined version of the model. These models are referred to as the Kentucky Watershed Model (KWM) and OPSET (because it estimates the OPtimum SET of model

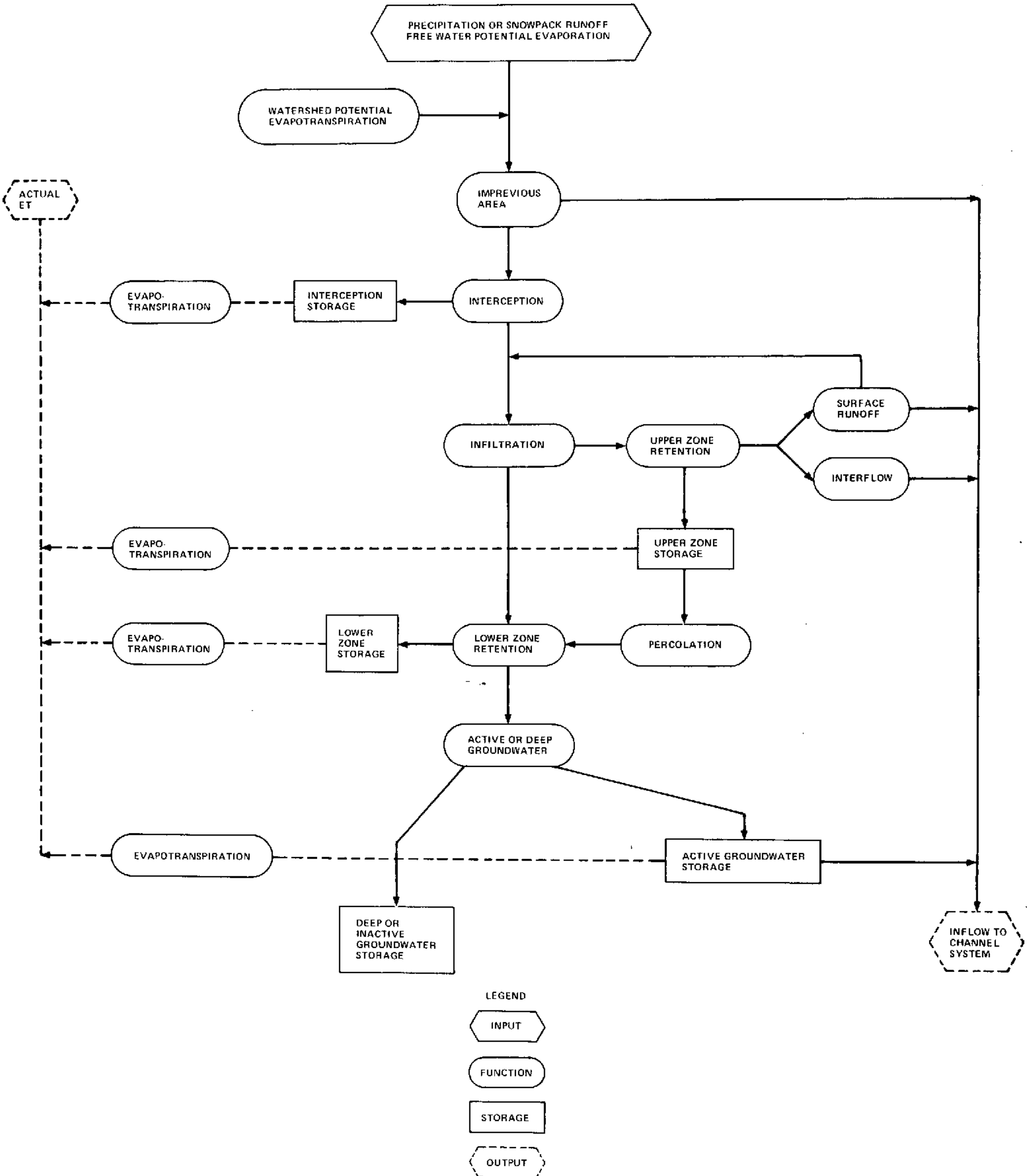

Figure 4. Moisture Accounting in the Stanford Watershed Model

parameters). The availability and utility of these models and reports describing them [11,12,13] led to their use in the IBM project.

2.5.1 KENTUCKY WATERSHED MODEL

Figure 5 lists the inputs (exclusive of control options) used by the Kentucky Watershed Model to simulate streamflow. Climatological data can be obtained from precipitation records or can be hypothetical, the latter being useful in generating rainfall-runoff predictions. The inputs classed as "Overland Flow Parameters" and "Watershed Parameters" are readily obtainable from analysis and interpretation of images (maps and/or photographs). The inputs on the right side of the figure are estimated in the calibration phase by OPSET. Some additional manual calibration is necessary to develop a set of model parameters that best represents the watershed.

2.5.2 OPSET

When a user applies a simulation model to a watershed, there are several parameters whose values he must initially guess and subsequently adjust, between trial runs of the model and comparisons of synthesized with observed flows. This trial and error calibration requires ingenuity, familiarity with how the parameters interact within the model, and some understanding of the sensitivity of simulated flows to specific parameter adjustments. The process is aided greatly by a thorough understanding of the hydrologic process and by the guidance published by Crawford and Linsley[4,5]. Through careful parameter adjustment, one can cause simulated flows to approximate recording flows but never to match them exactly. Several combinations of parameter values can produce comparable results from an overall viewpoint, and the final choice may well hinge on whether a particular comparison emphasizes flood peaks, annual runoff volume, or some other hydrograph feature. The final acceptance of a set of parameters may depend heavily on subjective factors.

In developing OPSET, Liou[12] provided a tool for calibrating the KWM with a minimum of subjective decisions. The parameter optimization concept is depicted in flow chart form in Figure 6. The input data consists of control options and initial conditions as well as the inputs listed in Figure 7. A simulation is performed, one year at a time, using

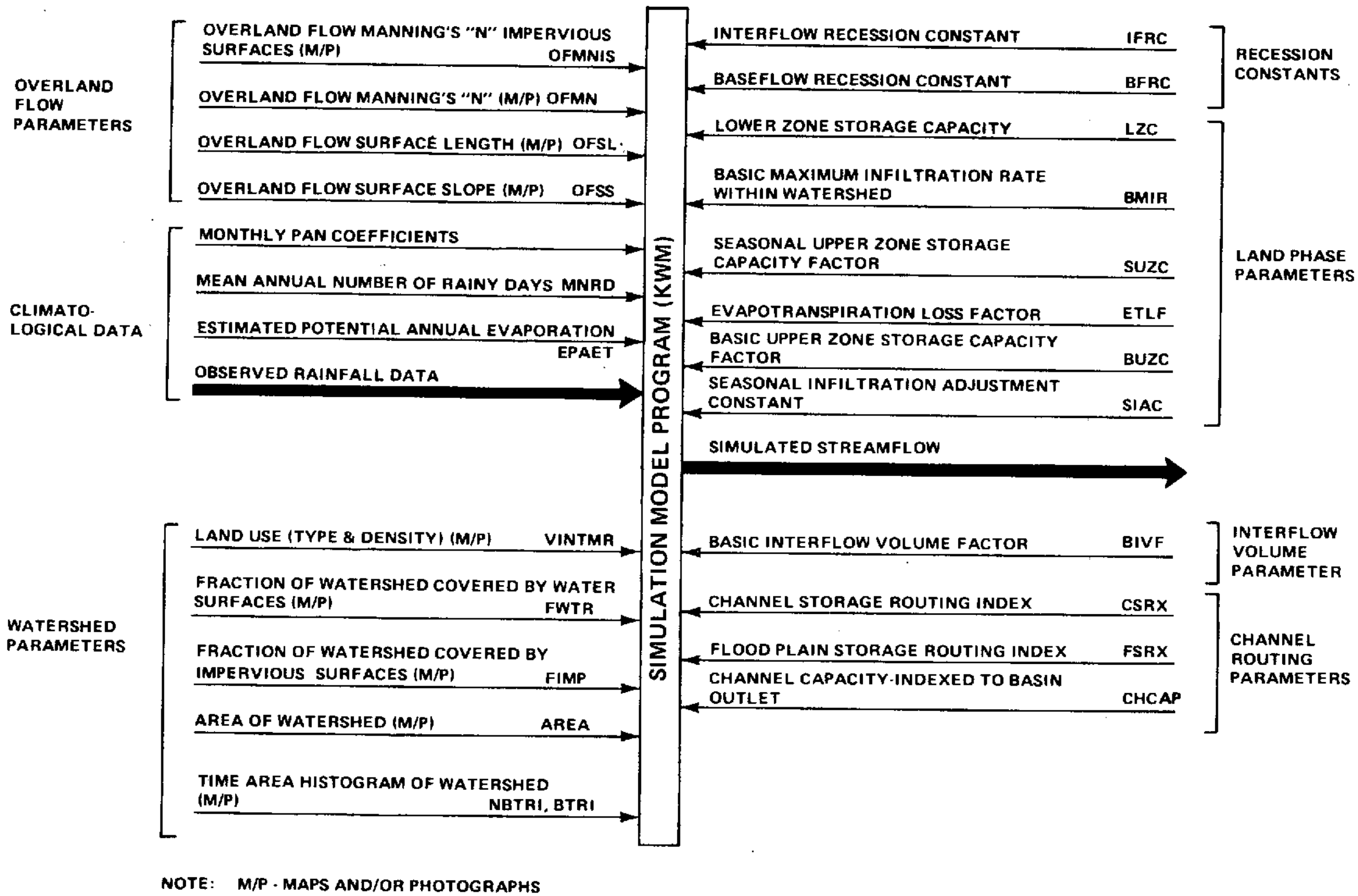

Figure 5. Simulation Model (KWM) Inputs and Output

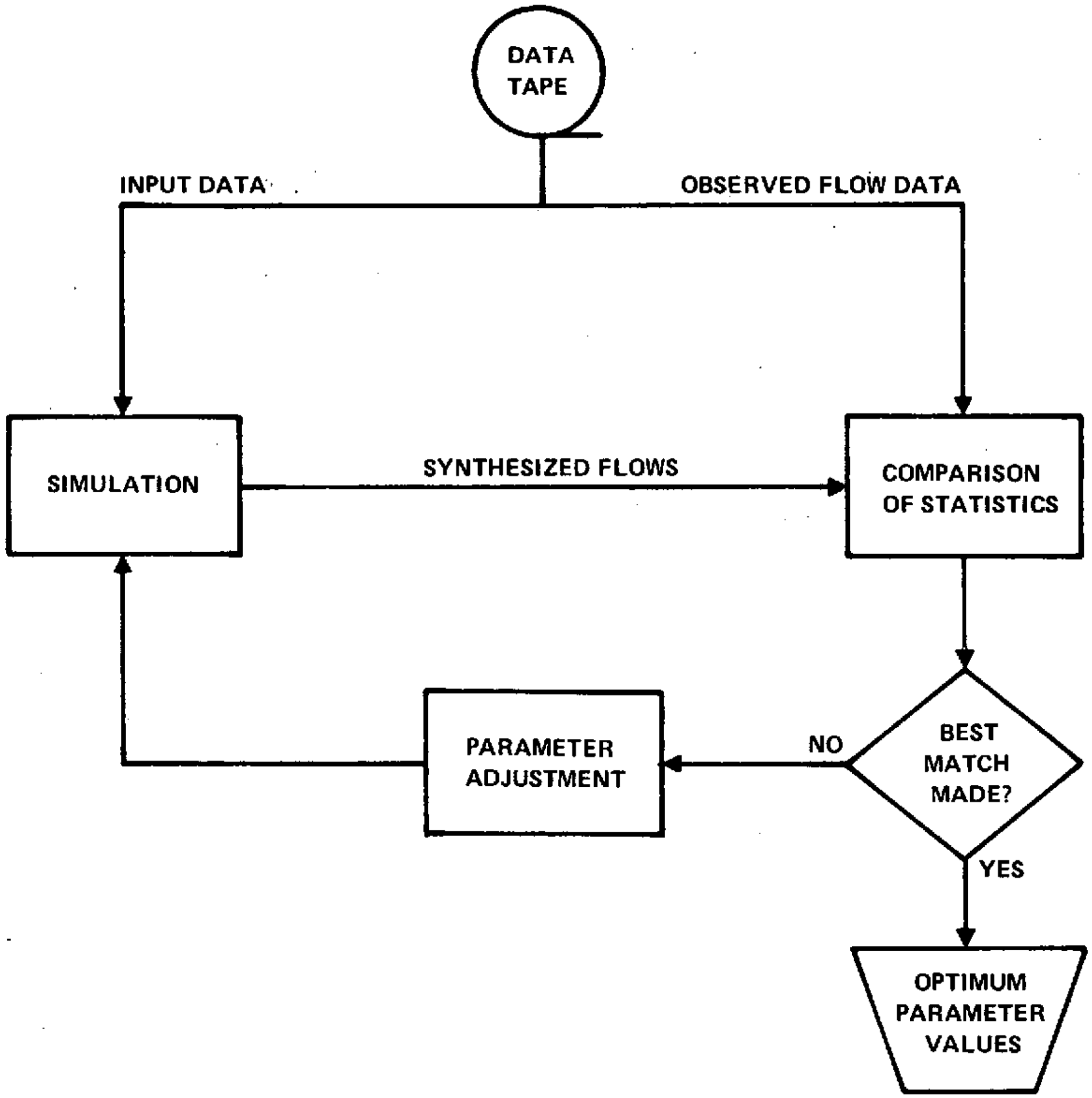

Figure 6. Parameter Optimization Concept

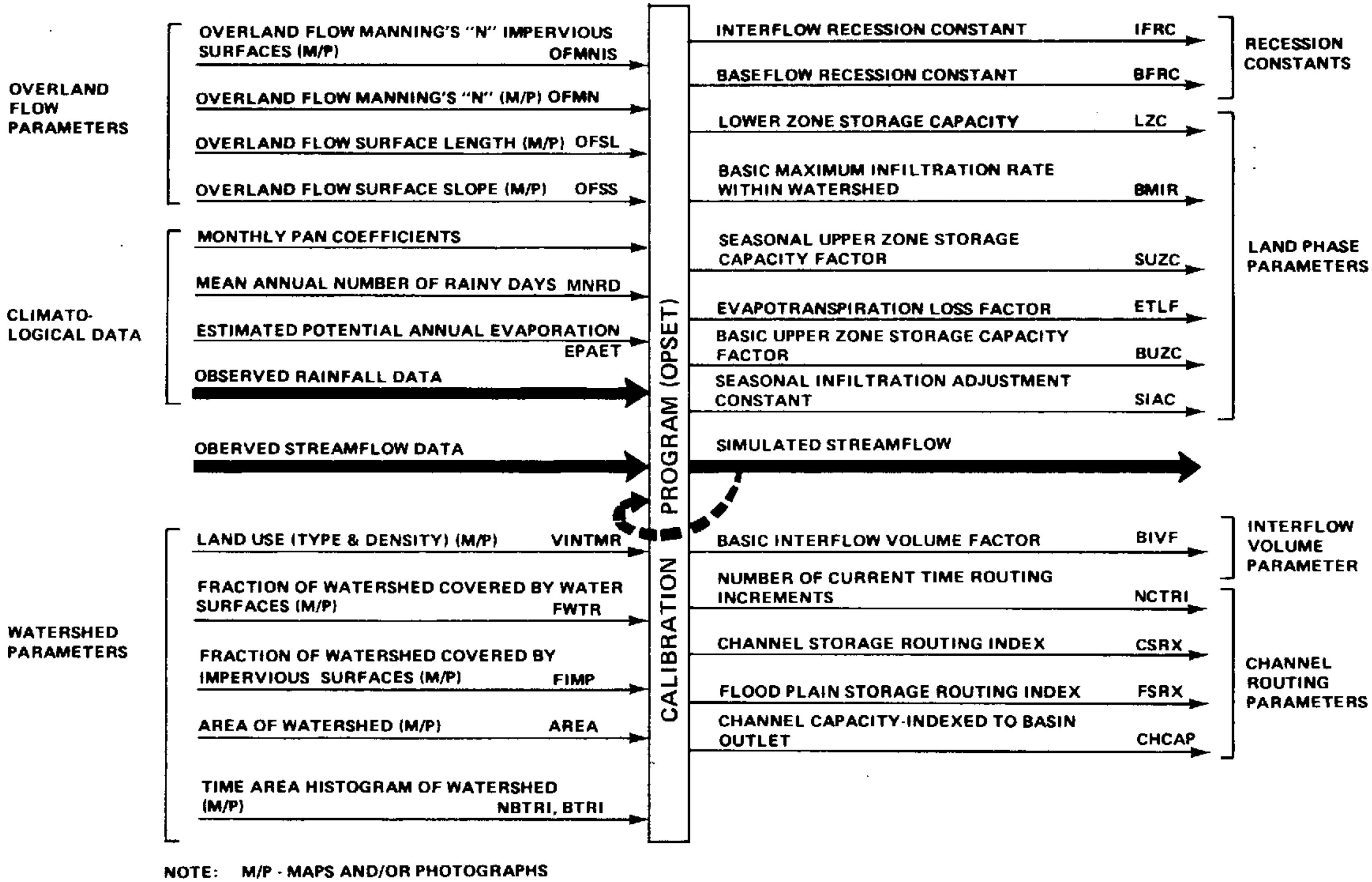

Figure 7. Calibration Program (OPSET) Inputs and Outputs

a "streamlined" KWM. The synthesized flows are compared with the observed flows. An objective function is used to determine when an optimum set of parameters has been found. If the best match has not been achieved, parameters are again adjusted and the simulation run again. This sequence is repeated until a satisfactory parameter set has been quantified.

Figure 7 also lists the 13 outputs of OPSET, in addition to simulated streamflow. (Comparison with Figure 5 shows the relationship to KWM.) These parameters are the most difficult to measure directly and ones to which simulated flow values are sensitive. Yet they, too, must be estimated from observation and correlation in the future, to apply the simulation model to an ungaged watershed. The calibration process should be based on three separate water years for the same basin. Simulation model parameters are then derived by averaging the results of the three calibration runs. A minor modification to OPSET has been implemented to generate a more precise Base Flow Recession Constant (BFRC). As it is presently designed, OPSET estimates parameters which produce accurate simulations of major winter storms (with respect to flood peak magnitude and timing) but misses summer and autumn storm peaks by significant factors. Manual adjustments are required to achieve accurate simulation in the latter. An improvement in OPSET efficiency could be achieved by modifying it to calibrate on the basis of several consecutive years rather than one year at a time.

2.6 MODIFICATIONS AND ADDITIONS TO KWM AND OPSET

In adapting the KWM and OPSET programs to the project, several additions and modifications were implemented by IBM for improved flexibility and efficiency, both in running the program and evaluating results. They are listed as follows:

1. The subroutine called READ was modified to operate on any current System/360 installation.

2. Both models are in the Production Library, and the input data is in a partition data set (PDS) based operation which will (a) avoid the need for maintaining several thousand cards for each watershed, and (b) permit operation from a terminal, giving the investigator quick access to the data base for modifications.

3. A subroutine designated INT has been added to convert historical stream gage height information from strip charts to streamflow rates (volume per unit time), applying the gage rating tables. It also analyzes the peaks and calculates the runoff.

4. A subroutine designated STAT has been added to provide statistical analysis of monthly and daily data for a single year, and multiple years. Sample output for a yearly statistical summary is shown in Figure 8, and the total statistical summary output for seven years of simulation is presented in Figure 9.

5. An Output Summary routine tabulates all the end results of a calibration or simulation run for a particular watershed so that the investigator need not search through several pages of printout to compare and evaluate results. Figure 10 presents an Output Summary.

6. As it was originally received, the KWM could perform simulations only for one year at a time, and it was necessary to re-establish initial conditions as well as re-read watershed descriptive data before each run. The capability has been introduced to simulate any number of successive years with only one reading of the watershed description and retaining simulated moisture conditions at the end of each year to serve as initial conditions for the succeeding year, thereby providing more accurate simulation results.

7. A Plot Output routine with several options was introduced in order to minimize manpower and time needed for evaluation of results, sensitivity analysis and calibration "fine tuning." Plots shown in a subsequent section of this report were produced by this program. Vertical (flow rate) and horizontal (time) scales may be specified or automatically chosen. Plots are available for simulated flow, observed flow or the two superimposed on the same scale. Time intervals available are one year (mean daily streamflows), one month (mean daily streamflows) and storm duration (hourly streamflows for the duration of the selected storm runoff).

*LITTLE CHESTUEE,BELOW WILSON,TENN. (8.24 SQ.MI.) WY51 STUDY LC08

YEARLY STATISTICAL SUMMARY

	MONTHLY		DAILY	
	OBSERVED	SIMULATED	OBSERVED	SIMULATED
MEAN	426.05	380.88	14.01	12.52
MAXIMUM	1301.00	1156.07	388.00	400.84
VARIANCE	123591.00	90998.56	780.48	1039.80
STANDARD DEVIATION	351.56	301.66	27.94	32.25

	MONTHLY	DAILY
SUM OF (OBSERVED - SIMULATED)	542.01	541.97
ROOT SUM SQUARE	329.05	192.07
SUM SQUARED	1.34	134.05
SUM SQUARED (IBM METHOD)	1.36	136.00
CORRELATION COEFFICIENT	0.9758	0.9553

Figure 8. Example of Yearly Statistical Summary

*LITTLE CHESTUEE,BELOW WILSON,TENN.(8.24 SQ. MI.) WY56 STUDY LC08

TOTAL STATISTICAL SUMMARY

	MONTHLY		DAILY	
	OBSERVED	SIMULATED	OBSERVED	SIMULATED
MEAN	395.90	424.25	13.01	13.94
MAXIMUM	1638.00	1458.49	388.00	507.47
VARIANCE	114971.44	123118.50	607.70	1071.79
STANDARD DEVIATION	339.07	350.88	24.65	32.74
SUM OF (OBSERVED - SIMULATED)	-2381.21		-2381.01	
ROOT SUM SQUARE	957.08		751.03	
SUM SQUARED	12.58		1169.41	
SUM SQUARED (IBM METHOD)	12.59		1192.33	
CORRELATION COEFFICIENT	0.9576		0.9044	

Figure 9. Example of Multi-Year Statistical Summary

LITTLE CHESTUEE,BELOW WILSON,TENN. (8.24 SQ.MI.) WY51 STUDY LC08

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	ANNUAL	
PRECIPITATION	3.300	2.210	3.210	4.440	4.960	9.330	4.200	1.850	4.870	3.970	2.270	6.520	51.130	INCHES
EVP/TRAN-NET	2.409	1.510	0.881	0.723	0.727	1.044	2.370	3.983	4.757	4.776	3.653	3.549	30.384	INCHES
-POTENTIAL	2.968	1.568	0.887	0.723	0.727	1.044	2.448	4.658	5.975	6.638	6.864	5.028	39.530	INCHES
SURFACE RUNOFF	0.050	0.060	0.141	0.791	2.086	3.363	1.011	0.064	0.346	0.114	0.031	0.245	8.301	INCHES
INTERFLOW	0.0	0.0	0.0	0.025	0.188	0.599	0.299	0.010	0.001	0.0	0.0	0.0	1.121	INCHES
BASE FLOW	0.728	0.593	0.642	0.680	0.846	1.256	1.543	1.286	1.115	1.075	0.811	0.631	11.206	INCHES
STREAM EVAP.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	INCHES
TOTAL RUNOFF(SIM)	0.778	0.653	0.783	1.497	3.120	5.218	2.852	1.360	1.462	1.190	0.862	0.876	20.629	INCHES
TOTAL RUNOFF(REF)	0.947	0.813	1.617	1.867	3.643	5.872	3.429	1.212	0.980	1.053	0.735	0.908	23.075	INCHES
OBSERVED TOTALS	209.8	180.2	358.3	413.6	807.1	1301.0	759.7	268.6	217.1	233.2	162.8	201.2	5112.6	CFS
SIMULATED TOTALS	172.4	144.6	173.6	331.7	691.2	1156.1	631.9	301.3	323.9	263.6	186.5	194.0	4570.6	CFS

BALANCE -0.0229 INCHES

MONTHLY FLOW CORRELATION COEFFICIENT 0.9758
MEAN DAILY FLOW CORRELATION COEFFICIENT 0.9553

Figure 10. Example of Output Summary

The subroutine INT, added to KWM for storm analysis, constitutes a major modification. It has the following capabilities:

- Converts gage height (ft) to streamflow (cfs), a task which formerly had to be done manually.
- Calculates the total runoff volume resulting from each storm.
- Summarizes the characteristics of each selected storm: peak flow rate, time of peak, etc.

Evaluation and analysis of hydrograph characteristics requires observed hourly streamflow data. An example of available observed* hydrograph data is shown in Figure 11. The observed hydrograph data is in terms of stream gage height (ft), but the simulated hydrograph data is in streamflow (cfs). Therefore the observed data must be converted to cfs, which requires rating tables for for that period of time. A sample rating table is shown in Figure 12. This rating table is valid for the period from February 11, 1953, to March 9, 1953. The present study uses seven years of historical data (1950-1956) and requires 17 rating tables. The subroutine INT uses the proper rating table to convert stream height to flow rate. Operating with selected major storms, rather than a continuous 8,760 hours of data per year, reduced the effort associated with observed input data (manual translation of gage height hydrographs) and processing time by a factor of 40, assuming an average storm duration of 48 hours and five major storms per year. The subroutine INT has the capability of integration to calculate the runoff volume produced by observed and simulated storms.

The calibration and simulation models and their data base have been adapted to operation from data terminals in the IBM-Huntsville facility. Access to an IBM System/360 Model 75 is afforded from a Model 2260 terminal, from which an operator can call up sections of the data base

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*Throughout this report, the term "observed" refers to recorded historical data, distinguished from the "simulated" or "synthesized" results produced by the simulation model.

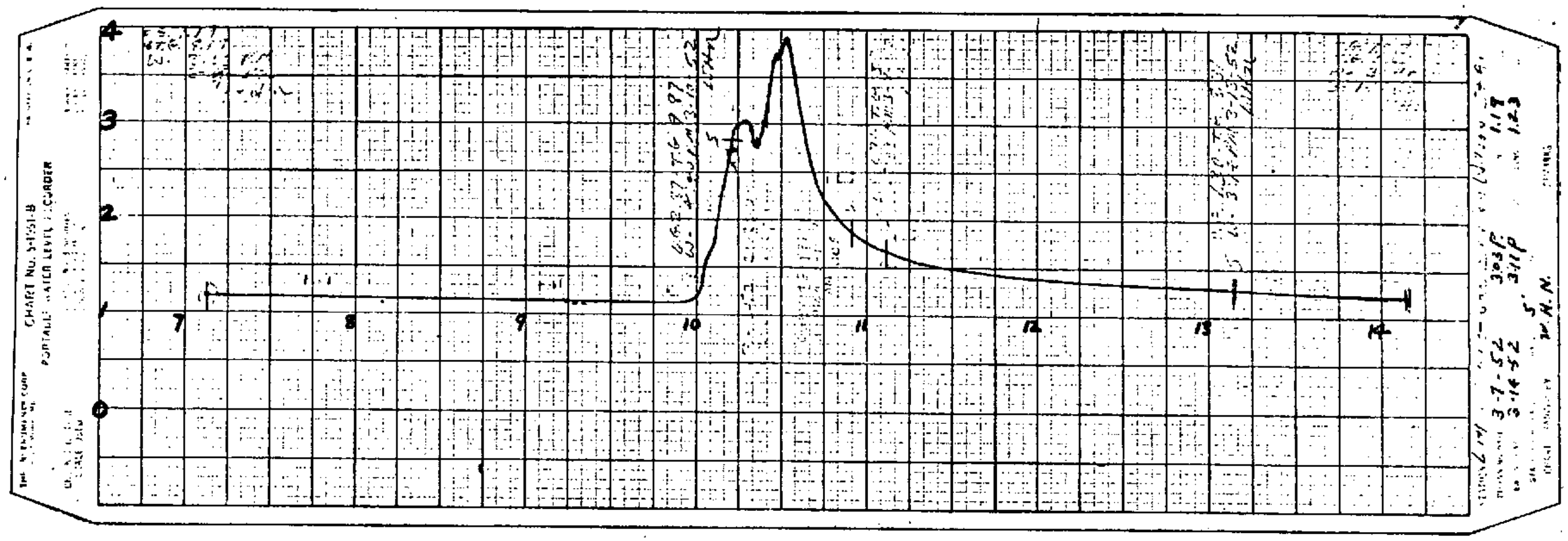

Figure 11. Example of Observed Hydrograph Data

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9-210
(Sept. 1952)

Tennessee Valley Authority
Hydraulic Data Branch

File No. { Washington .... Field ....

Rating table for Little Chestuee Creek Below Wilson station

from Feb. 11, 1953, *to* March 9, 1953

Gage height	Discharge	Difference	Gage height	Discharge	Difference	Gage height	Discharge	Difference	Gage height	Discharge	Difference	Gage height	Discharge	Difference
Feet	*Cfs*	*Cfs*	*Feet*	*Cfs*	*Cfs*	*Feet*	*Cfs*	*Cfs*	*Feet*	*Cfs*	*Cfs*	*Feet*	*Cfs*	*Cfs*
1.00			3.00	238	22.	.00			.00			.00		
.10			.10	260	21.	.10			.10			.10		
.20			.20	281	24.	.20			.20			.20		
.30			.30	305	25.	.30			.30			.30		
.40			.40	330	25.	.40			.40			.40		
.50	30.0	7.0	.50	355	28.	.50			.50			.50		
.60	37.0	7.7	.60	383	29.	.60			.60			.60		
.70	44.7	8.3	.70	412	33.	.70			.70			.70		
.80	53.0	9.8	.80	445	35.	.80			.80			.80		
.90	62.8	10.2	.90	480	35.	.90			.90			.90		
2.00	73.6	10.4	4.00	515	35.	.00			.00			.00		
.10	84.0	13.0	.10	550		.10			.10			.10		
.20	97.0	14.0	.20			.20			.20			.20		
.30	111.	16.0	.30			.30			.30			.30		
.40	127	17.	.40			.40			.40			.40		
.50	144	17.	.50			.50			.50			.50		
.60	161	19.	.60			.60			.60			.60		
.70	180	19.	.70			.70			.70			.70		
.80	199	19.	.80			.80			.80			.80		
.90	218	20.	.90			.90			.90			.90		

The above table is not applicable for ice or obstructed channel conditions. It is based on .... discharge measurements made during ....

and is .... well defined between .... cfs and .... cfs.

Below 1.50 until 12/5/52 – [illegible]
Above 4.10 until March 9 [illegible]

Computed by G C F

Checked by ....

Date 3-9-53

U. S. GOVERNMENT PRINTING OFFICE 16--63517-2

Figure 12. Typical Stream Gage Rating Table

and modify elements thereof, enter control options in the program, change model parameters, and enter the program in the computer system queue, without having to manipulate punched cards. In the sensitivity analysis (explained in a subsequent section of this report), several runs can be set up and initiated at one setting. It is conservatively estimated that this terminal operation approach has obviated the storage and maintenance of 500,000 punched cards and improved the efficiency of operation by a factor of ten.

SECTION 3

TECHNICAL RESULTS

This section describes the principal and secondary accomplishments of the feasibility study. The study consists of nine tasks, identified as shown in Figure 13, which illustrates the flow of study activities. In the remaining pages of this section, each task is described with respect to its objective, the technical approach used, and the results achieved.

Physiographic data were collected (Task 1) in the form of topographic maps, aerial photographs, and other documents for 15 watersheds of the Tennessee Valley. The historical data (Task 2) consists of observed streamflow, precipitation, and evaporation data related to the same 15 watersheds. All these physiographic and historical data are digitized and integrated into the Master Data Bank (Task 3). (Note: Although only 15 basins were used in the study, the study team's accumulation of raw data pertains to some 50 basins.)

Ten of the test watersheds were modeled, and the models were calibrated using OPSET and manual adjustments (Task 4) in order to derive a set of optimum model parameters for each watershed. This process was aided by the sensitivity analysis (Task 5), which was performed on two of the selected watersheds. The sensitivity analysis shows quantitatively how the accuracy of the simulation model is affected by variations in the model parameters.

The physiographic data base yields watershed characteristics for each of the 10 basins on which a calibration will have been performed. These watershed characteristics, which are the observable or the inferable characteristics determined from remote sensing, were used with the optimum model parameters to perform a correlation analysis (Task 6) and thereby determine statistical relationships between optimum model parameters and observable physical characteristics of the watershed.

Five watersheds were reserved and used to test the relationships developed in the calibration and correlation tasks. Observable characteristics were used, together with the relationships determined by Task 6, to generate sets of simulation model parameters. For each of these watersheds, the simulation model was then run, using actual climatological data as input. The simulated streamflow was then compared to the actual historical streamflow, to yield an evaluation or validation (Task 7) of the relationships.

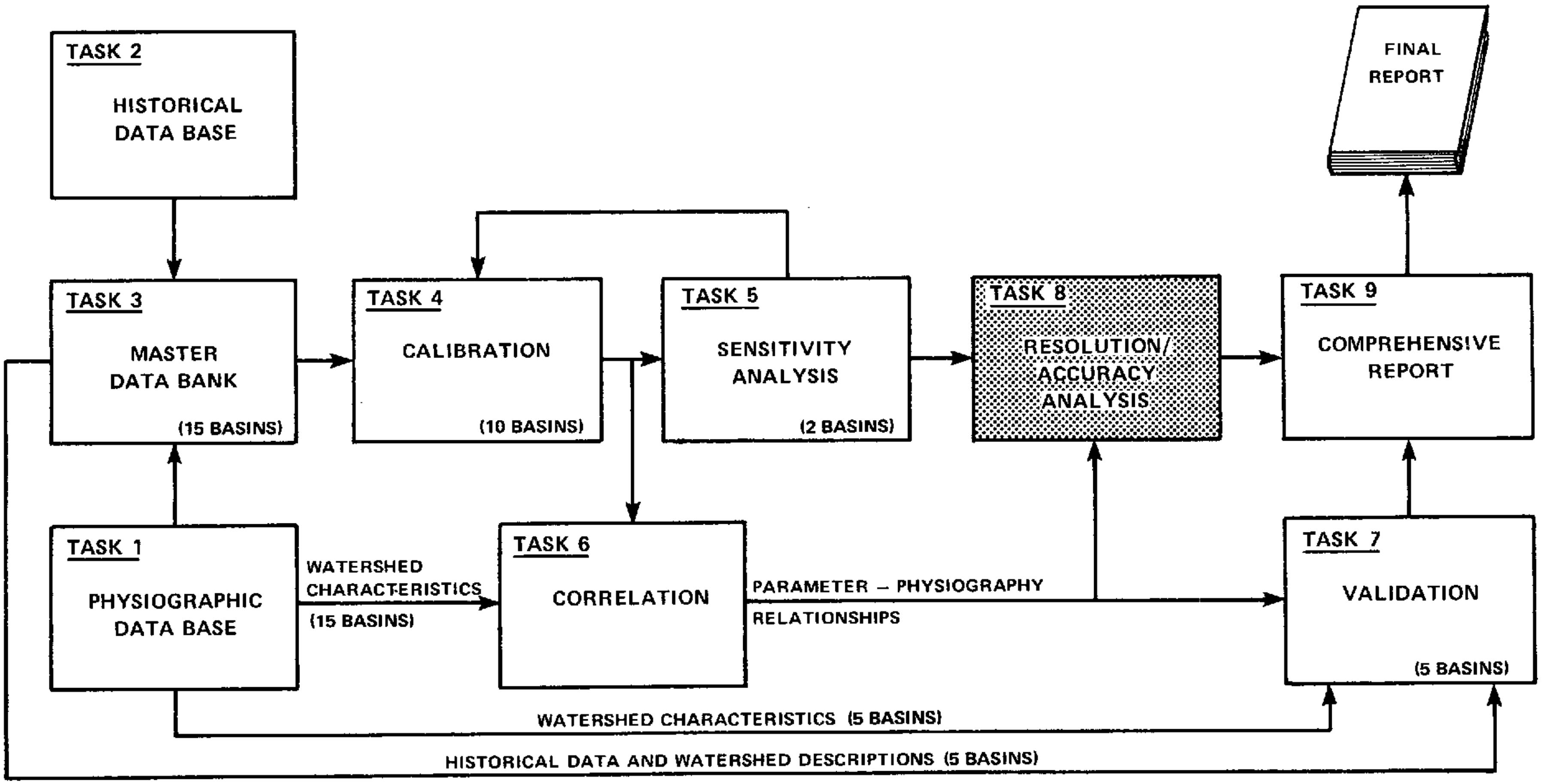


Figure 13. Feasibility Study Flow

Task 8, Resolution/Accuracy Analysis, was to be a determination of the performance characteristics of remote sensors needed to make application of the techniques practicable. The study was not able to address this task within the originally planned budget and schedule, but a very similar task is to be performed under another contract.

This report is the result of Task 9.

3.1 PHYSIOGRAPHIC DATA BASE

Operation of the mathematical models (both OPSET and KWM) used in the hydrological simulation activity is governed by certain input parameters which are related to the physical nature of the watersheds being simulated. These parameters must be measured or in some instances inferred from existing documentation such as topographical maps, aerial photographs, soil catalogs, survey reports, and other a priori information. This collected documentation, together with certain measured or inferred information therefrom, constitutes the physiographical data base whose construction is the objective of Task 1. Figure 14 depicts the activities involved in establishing the physiographic data base. Table 2 is a summary of the applicable documentation presently available in IBM files, and Table 3 is a physiographic data base status summary for the 15 watersheds utilized in the feasibility study.

The physiographic data required by the mathematical models is a series of parameters as listed and defined in Table 4. The methodology employed to derive these parameters from the physiographic documentation is discussed in the following paragraphs.

3.1.1 AREA

The first step in determining the area of any given watershed is to locate on a topographical map or photomosaic the streamflow gage associated with that particular watershed. Then beginning at the stream gage location, an outline of the watershed is manually drawn by following contour lines and ridges until the area perimeter closes on itself back at the stream gage. Visualization of ridges, slopes, and drainage patterns is considerably enhanced by accentuating the waterways associated with a particular watershed. Accentuation is easily accomplished by darkening the rivers and streams on the map with a dark blue pencil. Once the watershed perimeter is determined, the area can be measured with a planimeter.

3.1.2 OVERLAND FLOW SURFACE LENGTH (OFSL)

The overland flow surface length is defined as the average distance excess precipitation, or runoff, must travel from ground impact until it reaches a permanent water course such as a river, stream, creek, branch, or crevasse. The average value of OFSL is determined by selecting 10 to 20 points at random throughout the watershed as outlined on the topographical map. A line perpendicular to the contour lines is then drawn from the

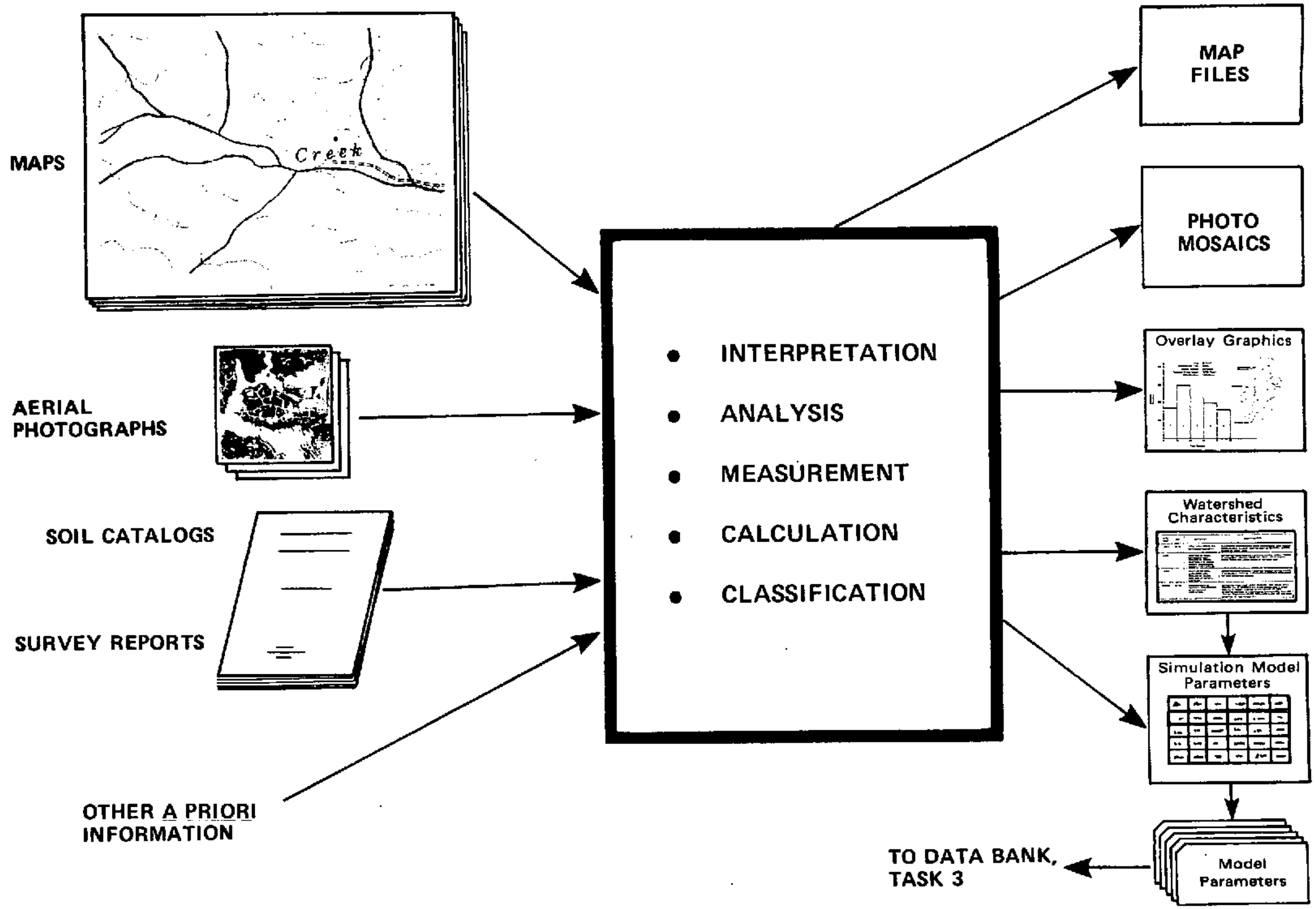


Figure 14. Physiographic Data Base

Table 2. "Raw" Physiographic Data Acquired
(Tennessee Valley Region)

146	TOPOGRAPHIC MAPS, 7.5′ QUADRANGLE
385	AERIAL PHOTOGRAPHS, USDA B&W; 1:15,000, 1:24,000, and 1:36,000
45	AERIAL PHOTOGRAPHS, NASA RB–57F, B&W PRINTS FROM IR NEGATIVES, 1:120,000
250	GEOLOGIC AND MINERAL RESOURCE SUMMARIES
MISCELLANEOUS SPECIAL REPORTS AND DOCUMENTS	

Table 3. Physiographic Data Base Status

WATERSHED	MAP COVERAGE	PHOTO COVERAGE	PARAMETERS QUANTIFIED*	REMARKS
WHITE HOLLOW	↑	NONE	12/12	PHOTOS REQUIRED TO
LITTLE CHESTUEE		PARTIAL	12/12	ESTIMATE VALUES FOR:
S. FORK MILLS RIVER		PARTIAL	7/12	(1) FIMP
NOLAND CREEK		PARTIAL	7/12	(2) VINTMR
W. FORK PIGEON RIVER		PARTIAL	7/12	(3) OFMN
BIG BIGBY		PARTIAL	7/12	(4) OFMNIS
BIG ROCK	100%	PARTIAL	7/12	
LITTLE RIVER		PARTIAL	7/12	ALL OTHER PHYSICAL
TRACE CREEK		NONE	7/12	PARAMETERS (EXCEPT
PINEY CREEK		NONE	7/12	CHANNEL CAPACITY–
RUTHERFORD CREEK		NONE	7/12	CHCAP) CAN BE
EMORY RIVER		NONE	12/12	DETERMINED OR
SEWEE CREEK		NONE	7/12	INFERRED FROM
TOWN CREEK	↓	NONE	7/12	TOPOGRAPHIC MAPS.

*Expressed as a fraction of the total number of parameters to be quantified.

Table 4. Physiographic Data Parameters

AREA	Area of the Watershed in Square Miles
OFSL	Average Overland Flow Surface Length in Feet
OFSS	Average Overland Flow Surface Slope
TAH	Time Area Histogram Parameters
FIMP	Fraction of Total Watershed Area Covered by Impervious Surface
FWTR	Fraction of Total Watershed Area Covered by Water Surface
VINTMR	Vegetative Interception Maximum Rate in Inches/Hour
OFMN	Overland Flow Manning's "N" for Pervious Surfaces
OFMNIS	Overland Flow Manning's "N" for Impervious Surfaces
GWETF	Ground Water Evapotranspiration Factor
SUBWF	Subsurface Water Factor

(The significance and methods of quantification of these parameters are described in the text.)

selected point to the nearest water course. The length of that line is then measured and tabulated. This same procedure is repeated for all selected points and the average distance of the 10 to 20 points is calculated and recorded as OFSL.

3.1.3 OVERLAND FLOW SURFACE SLOPE (OFSS)

The OFSS is the average slope of the land contained within the boundaries of the watershed and is determined as follows. For convenience, the same points selected for OFSL may be used to determine OFSS. From each point selected, the height differential from that point to the nearest watercourse can be determined by counting the contour lines and multiplying by the contour scale. Since the length of the overland flow surface at that point was measured when determining OFSL, OFSS is then equal to the change in height (Δh) divided by the average of the local OFSS values.

Table 5 is a sample worksheet showing the final average OFSS and OFSL values for a typical watershed.

3.1.4 TIME AREA HISTOGRAM

A time area histogram requires the division of the watershed into "n" subareas where each area is defined as a function of drainage time. Boundaries of subareas are known as isochrones, which may represent 15-minute or one-hour intervals depending on the size of the watershed. A minimum of four isochrones is desired for operation in the simulation model. The steps required to develop a time area histogram are as follows:

1. Utilizing the topographical map of the watershed, determine the longest watercourse in units of feet from the stream gage location to the furthermost point of the defined watershed. This will be noted as a stream length (L).

Table 5. Worksheet for OFSS/OFSL (Typical)

Site Selected (No.)	Overland Distance (Ft.)	Altitude Change (Ft.)	Local Slope ($\Delta H/S$)
1	1,000	160	0.160
2	900	100	0.110
3	1,400	260	0.186
4	1,200	120	0.100
5	2,000	120	0.060
6	1,100	80	0.073
7	1,500	160	0.107
8	700	160	0.229
9	2,000	180	0.090
10	700	180	0.258
	12,500		1.333

OFSL = 12,500 ÷ 10 = 1,250 ft.

OFSS = 1.333 ÷ 10 = 0.1333

NOTE: Above values are actuals for Rutherford Creek near Carters Creek, Tennessee

2. Determine the change in elevation in feet between the stream gage location and the furthermost point in the basin as established in Step 1. This change will be noted as Δh.

3. Calculate the concentration time (T_c) in minutes utilizing the empirical equation[14]

$$T_c = 0.0078 \left(\frac{L}{\sqrt{\frac{\Delta h}{L}}} \right)^{0.77}$$

where L is stream length and Δh is altitude difference as defined previously. Concentration time is the time it takes for a drop of water to reach the gaging station from the watershed extreme perimeter. If L and Δh are measured in meters rather than feet, then the coefficient should be 0.0195 rather than 0.0078. When T_c is equal to or greater than 240 minutes, the isochrone intervals should be one hour. This will provide the minimum subareas required to operate in the simulation models. When T_c is less than 240 minutes, then the isochrone interval should be 15 minutes. Since it is very unlikely that T_c will calculate in exact multiples of 15 minutes, the concentration time should be arbitrarily adjusted to the nearest number divisible by 15.

4. Calculate the number of subareas or isochrones by dividing the concentration time by either 15 minutes or 60 minutes.

5. Calculate the average stream velocity ($\overline{V}$) by dividing the stream length (L) by the concentration time (T_c).

$$\overline{V} = \frac{L}{T_c}$$

6. Calculate the average overland flow distance per isochrone by multiplying $\overline{V}$ by either 15 minutes or 60 minutes.

NOTE: Figure 15 shows an example of the calculations used to establish a time area histogram.

Once the average overland flow distance per isochrone has been determined, the actual subdivision of the subdivision of the watershed can be accomplished as follows:

1. Beginning at the stream gage location on the topographical map and using a map measuring meter, track several watercourses from the gage station inland to a distance equal to the average overland flow length per isochrone for that particular watershed. Measured distances must always follow the watercourses. Several measurements should be made radially from the stream gage and a mark placed at each overland flow distance milestone. A line connecting these marks should then be drawn from perimeter to perimeter and this area identified as Isochrone 1. This isochrone identifies that area of the basin which would drain within the first 15 minutes (or one hour) after a storm. Then measuring from the first isochrone line, repeat the process to establish the second isochrone area. This is the area that would be drained from 15 to 30 minutes after a rain. Continue the process until the entire basin is subdivided into "n" areas. Figure 16 is an illustration of a typical watershed so divided.

2. Once the watershed is subdivided, measure with a planimeter the area of each isochrone. These areas should be tabulated as both absolute magnitude in square miles and also as a fractional portion of the entire watershed. Table 6 is a typical data sheet with this information. Each isochrone area and fractional portion value is converted to punch cards and entered into the simulation model.

3.1.5 IMPERVIOUS SURFACE FRACTION (FIMP)

This is a fraction of the total watershed area covered by pavings, rooftops, streets, etc., whose runoff contributes directly to a stream. This value is usually estimated from aerial photography. The value is usually zero for rural areas except where there are large areas of exposed rock adjacent to watercourses.

Maximum Stream Length (measured): 110,000 Ft.

Maximum Altitude Drop — H(Map Scale): 480 Ft.

$$T_c = 0.0078 \left(\frac{L}{\sqrt{\frac{\Delta H}{L}}} \right)^{0.77} = 0.0078 \left(\frac{110{,}000}{\sqrt{\frac{480}{110{,}000}}} \right)^{0.77}$$

$$= 482 \text{ Minutes} \cong 480 \text{ Minutes}$$

$$N_{isochrones} = 480 \div 60 = 8$$

$$\overline{V} = 110{,}000 \text{ Ft./480 Minutes} = 229 \text{ Ft./Minutes}$$

Average Overland Flow Distance/Isochrone: 229 Ft./Min. x 60 Minutes = 13,750 Feet

NOTE: Above calculations are actuals for Sewee Creek Watershed near Decatur, Tennessee.

Figure 15. Time Area Histogram Calculation (Typical)

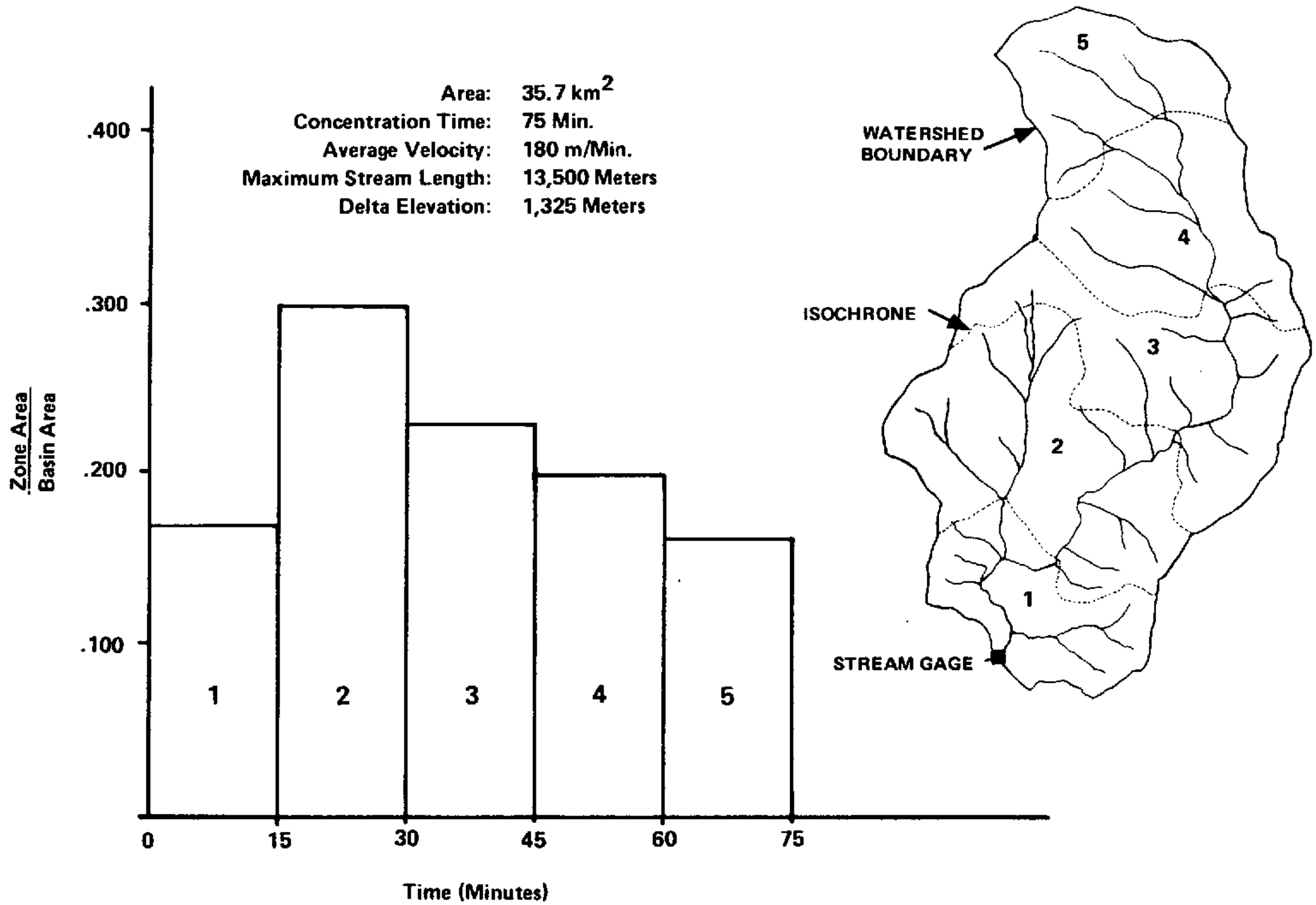


Figure 16. Typical Watershed (Noland Creek, N.C.) Divided by Isochrones

Table 6. Time Area Histogram Worksheet (Typical)

Isochrone No.	Area (Sq. Miles)	Fraction of Total
1	3.9	0.034
2	16.9	0.144
3	6.8	0.058
4	11.0	0.094
5	18.3	0.156
6	23.2	0.198
7	15.3	0.131
8	21.6	0.185
	117.0	1.000

NOTE: Above values are actuals for Sewee Creek Watershed near Decatur, Tennessee

3.1.6 WATER SURFACE FRACTION (FWTR)

This is a fraction of the total watershed area covered by water surfaces at normal low flow conditions. The value is estimated from aerial photos and is virtually zero for watersheds containing neither lakes nor swamps.

3.1.7 VEGETATIVE INTERCEPTION MAXIMUM RATE (VINTMR)

VINTMR is the maximum rate of rainfall interception by the watershed vegetation expressed in inches per hour. The values range from 0.10 for grasslands to 0.20 for heavy forest and is estimated from land cover interpretation from aerial photographs. A weighted average is used for watersheds having more than one type of vegetative cover. See reference 13.

3.1.8 OVERLAND FLOW MANNING'S "N" FOR PERVIOUS SURFACES (OFMN)

This is a roughness coefficient for overland flow derived from published tables dependent on estimated vegetative cover and soil usage. Weighted averages are used where different types of cover are in evidence. Values range from 0.018 for smooth earth to 0.100 for heavy forest. (See Table 7 for more details.)

3.1.9 OVERLAND FLOW MANNING'S "N" FOR IMPERVIOUS SURFACES (OFMNIS)

Derivation is the same as for OFMN but applies to impervious surfaces. Values are derived from published tables and vary from 0.013 for smooth asphalt to 0.017 for unfinished concrete. (See Table 7.)

3.1.10 GROUND WATER EVAPOTRANSPIRATION FACTOR (GWETF)

GWETF is a factor used to estimate the current rate at which swamp vegetation draws water from below the water table. This value is usually zero unless aerial photographs reveal a significant area of swamps within the watershed perimeter. In this case an appropriate value may be estimated using methods analogous to that used in determining FIMP.

Table 7. Manning's Roughness Coefficient for Overland Flow for Various Surface Types

Watershed Surface	Manning's "N"
Smooth Asphalt	0.013
Concrete (Trowel Finish)	0.013
Rough Asphalt	0.016
Concrete (Unfinished)	0.017
Smooth Earth	0.018
Firm Gravel	0.020
Cemented Rubble Masonry	0.025
Pasture (Short Grass)	0.030
Pasture (High Grass)	0.035
Cultivated Area (Row Crops)	0.035
Cultivated Area (Field Crops)	0.040
Scattered Brush, Heavy Weeds	0.050
Light Brush and Trees (Winter)	0.050
Light Brush and Trees (Summer)	0.060
Dense Brush (Winter)	0.070
Dense Brush (Summer)	0.100
Heavy Timber	0.100

SOURCE: Reference 15, pp. 110–113.

3.1.11 SUBSURFACE WATER FACTOR (SUBWF)

SUBWF is the fraction of moisture entering groundwater storage which leaves the basin through subsurface flow (underground rivers, subterranean caverns) not measured by the stream gage. This value is usually zero unless such subterranean geophysical anomalies are known to exist.

3.2 HISTORICAL DATA BASE

The historical data required by the simulation and calibration models is similar in format to the physiographic data described in paragraph 3.1. The basic difference is that while all physiographic data is either measured or inferred from observations, historical data is converted from existing written records to a digital format for input to the models. Where precipitation gages are not uniformly distributed about a given watershed and are a combination of hourly and daily gages, Thiessen analysis is used to derive "weighting factors" to apply to the historical data.

The historical data base generated by IBM for this hydrology application study is constructed primarily from five different specific types of data:

1. Precipitation data
2. Stream stage charts
3. Stream gage rating tables
4. Daily discharge data
5. Evaporation data

The conversion of this data to the digital forms usable by the simulation and calibration models is represented in Figure 17. Table 8 is a listing of the historical data collected and presently on file in IBM, and Table 9 is a summary of the utilization of that data base as applied to the initial 15 watersheds being studied. The following paragraphs describe in some detail the procedures used to extract the desired information from the historical data base.

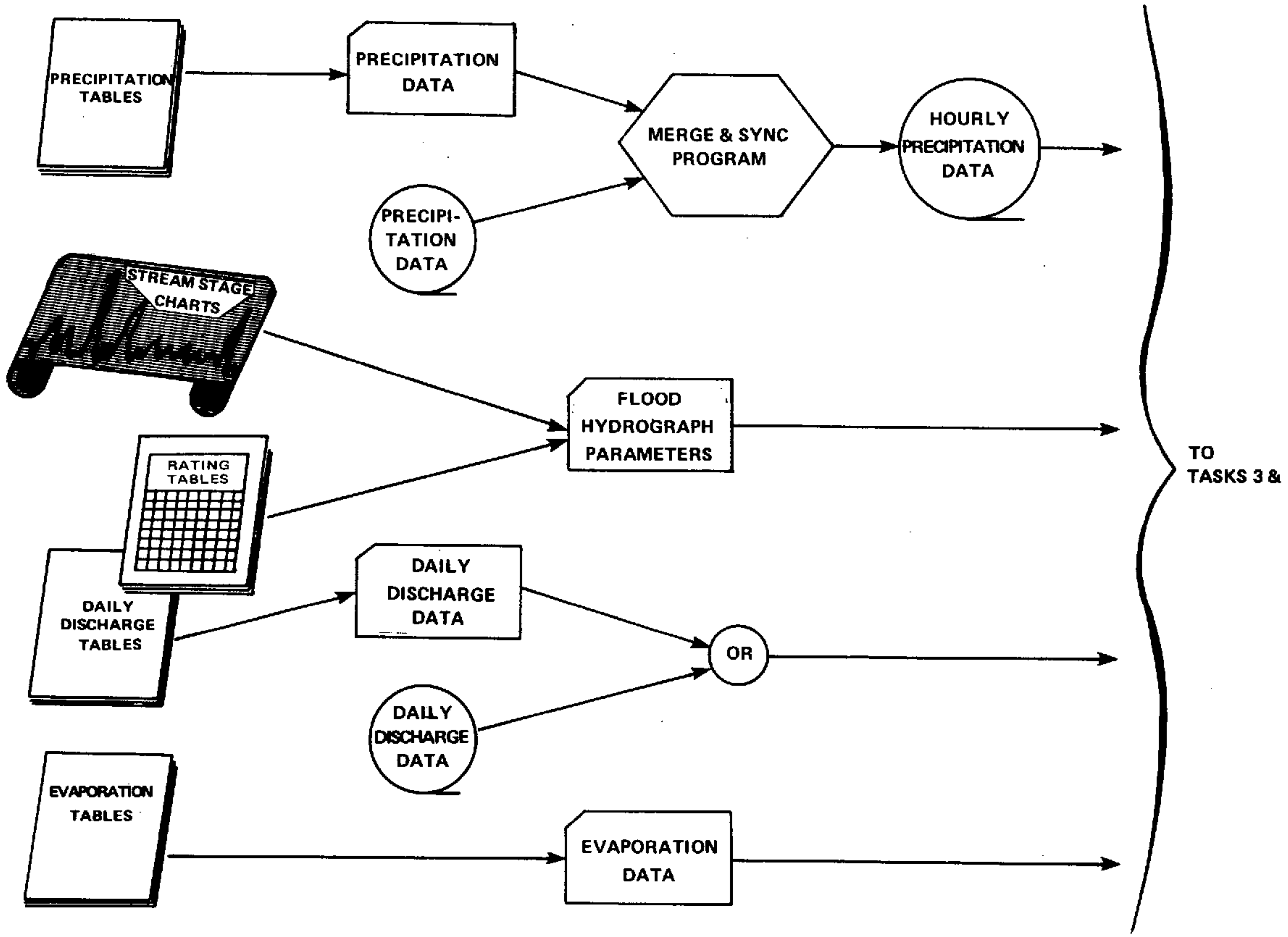


Figure 17. Task 2: Historical Data Base

Table 8. "Raw" Historical Data Acquired (Tennessee Valley Region)

NWS DAILY CLIMATOLOGICAL DATA TABLES, 1948–70

TVA DAILY PRECIPITATION TABLES, 1948–70

NWS HOURLY PRECIPITATION DATA TAPES (5 REELS), 1960–70

NWS DAILY PRECIPITATION DATA TAPES (9 REELS), 1963–70

TVA DAILY PRECIPITATION DATA TAPE (1 REEL), 1968–71

USGS DAILY SURFACE WATER RECORDS, 1961–70

TVA DAILY DISCHARGE TABLES, 1940–70

USGS DAILY DISCHARGE DATA TAPE (1 REEL), 1939–70

SELECTED STREAM STAGE RECORDER CHARTS

Table 9. Processed Historical Data

MEAN BASIN/HOURLY PRECIPITATION

- 15 MERGED RECORDS
- 100 WATER YEARS
- 294 WATER YEARS INPUT DATA

DAILY DISCHARGE

- 15 RECORDS
- 100 WATER YEARS

STORM EVENT HYDROGRAPHS

- PEAK DAY, HOUR, MAGNITUDE
- 500 SIGNIFICANT STORMS

EVAPORATION

- 15 RECORDS
- 100 WATER YEARS

3.2.1 DATA AVAILABILITY SUMMARY

Precipitation data is gathered throughout the Tennessee Valley by many precipitation stations which are owned and/or managed by either TVA, the National Weather Service (NWS), or private corporations. In all cases the data is recorded either hourly or daily and the information stored on magnetic tape and/or written documents. Magnetic tape storage is limited primarily to data collected from certain stations since 1960; therefore, most precipitation data of value to the study is recorded in tables. The following paragraphs detail the step-by-step procedures necessary to obtain the hourly precipitation data required by the models for a given watershed.

Once a subject watershed has been identified, several initial questions must be answered:

1. How many precipitation stations exist within the boundaries of the watershed?

2. How many precipitation stations are closely adjacent to the watershed and how close are they?

3. How many of the stations are hourly and how many are daily?

4. What are the years of operation for the stations?

5. How much of the existing historical data exists as written tables and how much on magnetic tape?

The answers to the above questions exist in different reports, lists, maps, documents, etc., and require considerable manual effort to compile. Figure 18 is a sample of a matrix type data worksheet developed to correlate the answers to the questions. The following paragraphs explain the notation used in Figure 18.

The watershed name, approximate latitude and longitude boundaries, centroid, and station names are self-explanatory. The station descriptions are (1) S.G. for stream gage (required to determine the operational years to be selected for input to the simulation model), (2) PG-H and PG-D for precipitation gage-hourly and daily, respectively, and (3) E.S. for evaporation station.

WATERSHED NAME: NOLAND CREEK NEAR BRYSON CITY, NORTH CAROLINA (13.8 SQ. MILES)

WATERSHED BOUNDARIES (APPROX.) LATITUDE 3528 TO 3534 ; LONGITUDE 8327 TO 8331

WATERSHED CENTROID (APPROX.) LATITUDE 3531 ; LONGITUDE 8329

STATION NAME	Station Descr.	TVA No.	NWS No.	LOCATION Lat.	LOCATION Long.	Read Time	Data Type	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
NOLAND CREEK	S.G	(3-5135)		3529	8330	R	T/D	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
NOLAND CREEK	PG-H	183		3529	8330	R	D	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
NEWFOUND GAP	PG-H	819		3535	8327	R	D																			■	■	■	■
GATLINBURG	PG-H	209A	3420	3541	8332	R	D																			■	■	■	■
TOWNSEND	PG-H	715A		3538	8345	R	D			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
CADES COVE	PG-D	177A		3534	8348	0900	D							■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
GATLINBURG	PG-D	209		3540	8330	0990	D	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
MT. LE CONTE	PG-D	210		3535	8328	0900	D	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
ELA	PG-D	525		3529	8325	0900	D	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
JEFFERSON CITY, TENN	E.S.			3607	8330			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Hourly Discharge Data Available.																													

Figure 18. Historical Data Availability

The station latitude and longitude are important in determining the proximity of the precipitation gages to the watershed. The location of the various gages is required for the merging and synchronizing process described in paragraph 3.2.2. The read time is either "R" for continuous recording or is specified for daily stations (e.g., 2400 means the gage is read daily at midnight).

The data type is either "T" meaning magnetic tape and/or "D" for written documentation. In those instances where both types are indicated, the upper line of the adjacent bar chart represents those operational years where the data exist on magnetic tape. The lower line of the bar chart reflects the years that the station has been in operation and for which precipitation data (tape and/or table) is available. The "hourly discharge data available" entry at the bottom of the charts represents those years for which strip chart hydrographs are available.

Once this worksheet is completed, the water years to be used for that particular basin can be selected, utilizing available stream gage data and the best of the available precipitation gages. After selection of operational water years and precipitation stations, conversion of the raw data to the digital data required by the models can begin.

3.2.2 HOURLY PRECIPITATION DATA

Hourly precipitation data in digital form is the primary input to KWM and OPSET. In a very small watershed having its own hourly precipitation gage (e.g., White Hollow) one can with reasonable safety assume that the gage reading applies uniformly to the entire watershed. This assumption (which is implicit in both programs) departs from reality more and more with increase in watershed size. It has been necessary, as part of the study, to implement a method whereby several precipitation records are used to synthesize a single hourly rainfall history for each basin.

The number of precipitation stations associated with any given watershed may vary from one station located 20 or 30 miles from the watershed centroid to 5 or 6 stations located within or closely adjacent to the watershed boundaries.

Typically, a watershed will have one or two hourly stations, and one or more daily stations. In addition to the varying distances of these stations from the centroid, the reading time for the daily stations might be different. It is also quite likely that data will appear from the several gages in both magnetic tape and tabular formats. The latter must be manually extracted from the tables and converted to punched data card format.

The precipitation gage outputs are assigned weighting factors, using the Thiessen technique[2,15], in accordance with their physical locations relative to the basin centroid. A software program, designated MERGE AND SYNC in Figure 17 which was developed by IBM Huntsville, automatically performs the interpolation and correlation of the precipitation data. This program accepts all precipitation data, the reading time for each daily station, and the weighting factor developed from the Thiessen Analysis, and produces an hourly precipitation record for the applicable water years associated with a given watershed. This hourly precipitation data record is then used as one of the climatological inputs required by the models.

3.2.3 SELECTED STORM DATA

For operation of the OPSET program it is necessary to select up to five flood hydrographs for each of the years for which the model is to be calibrated. This requires a manual search of precipitation and discharge records to select storms useful to the calibration. The digitized input data include the number of hydrographs chosen and three parameters related to each hydrograph: day of occurrence of the flood peak, hour of occurrence of the flood peak, and flow rate at the peak. These hydrographs parameters are essential for the OPSET program to determine watershed model routing parameters, so that total flows will represent accurate predictions, with respect to the time of occurrence of hydrograph peaks as well as the total volume of flow for a given period of time. In practice the selected storm hydrograph parameters are not available in daily discharge records. It is necessary to obtain them from the strip charts produced by the stream gage recorders. Rating tables are also digitized and stored for conversion of gage height readings into flow rate.

The procedure employed to obtain this data requires manual analysis of each strip chart and manual recording of the rise and fall of the stream gage on an hourly basis. The time frame should extend from midnight of the day in which the storm occurred until some time at which the stream height returns to or approaches its initial stage. This hourly height recording is then formatted for entry into the computer where a subroutine will fetch the appropriate rating table into memory and convert the data to cubic feet per second. This flood hydrograph data is then in a usable form when required by the simulation model.

3.2.4 DAILY DISCHARGE DATA

Daily discharge data is the volume in cubic feet of water per day that flows past any given stream gage. This data exists on magnetic tape and/or written tables for all stream gages in the Tennessee Valley. The data format which exists on magnetic tape must be altered to be compatible with the simulation model. Where the data exists in written tables, it is necessary to manually extract that information, convert to punched card format, and develop a listing compatible with model requirements.

3.2.5 EVAPORATION TABLES

Evaporation data appear in Climatological Data publications of the National Weather Service. Unfortunately, the number of pan evaporation stations is too limited to provide complete coverage. The nearest evaporation station may be as much as 100 miles from the watershed. Additionally, the station may be associated with a large lake or reservoir which has evaporation rates different from those of an interior watershed in a predominantly mountainous region. Preparation of the evaporation data is similar to that for daily discharge data in that the rates and pan evaporation coefficients are read from published tables, punched onto cards, and a computer-compatible listing generated for the identified watershed.

3.3 MASTER WATERSHED DATA BANK

The digital products of Task 1 (Physiographic Data Base) and Task 2 (Historical Data Base) are stored in a Master Watershed Data Bank, which is in a digital tape format, along with control options and other logical inputs needed for the operation of OPSET and KWM as indicated in Figure 19 . This tape-based data bank provides flexibility in operating the models and obviates storage of some 1,200,000 punched cards.

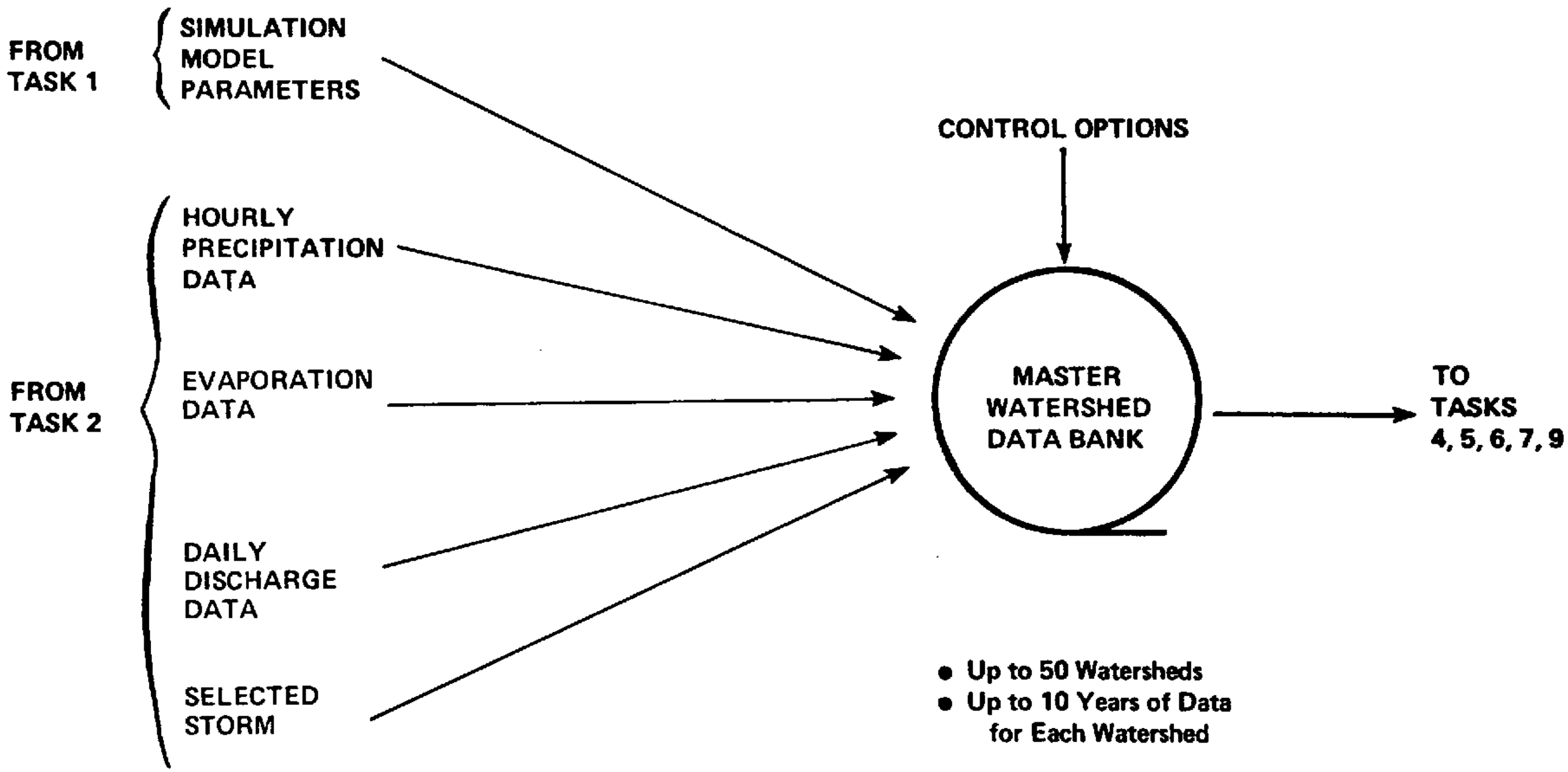


Figure 19. Task 3: Master Watershed Data Bank

Considerable effort has been devoted to acquiring and formatting the raw data and creating this master data bank. It is a by-product of the study which is potentially valuable to others engaged in hydrologic or related research using the same geographic area.

3.4 CALIBRATION (TASK 4)

3.4.1 USE OF OPSET

The OPSET model is used to calibrate a set of watersheds chosen from a region, generally using three water years of historical data for each basin, determining a set of model parameters from the calibration runs, and testing the accuracy of the calibration using the KWM. Calibration of several watersheds using OPSET generated sets of model parameters that produced accurate simulations on a daily flow and monthly flow basis which unfortunately did not accurately simulate the low flows. The subroutine that estimates the Base Flow Recession Constant (BFRC) has been modified, and results indicate an improvement in accuracy of simulation of low flows. Some manual "fine tuning" has been used to obtain a set of model parameters that represents the watershed very well.

Figure 21 shows the activities involved in Task 4 (Calibration). Data pertaining to the watershed to be calibrated are fed into the OPSET program, which is then run to estimate a set of model parameters. This step gets the task "into the ballpark." A simulation is then run using KWM and the IBM analysis/evaluation routines. Simulation accuracy is evaluated with respect to total annual runoff, monthly flow, daily flow, statistical indices, and selected storm hydrograph characteristics. Based on these evaluations, parameters are adjusted, and a new simulation run, followed by another evaluation. This process goes through several iterations until simulated flow matches observed flow with acceptable accuracy in all criteria of interest to the analyst. The choice of parameters to adjust, direction and magnitude of the adjustments depend upon the judgment of the analyst.

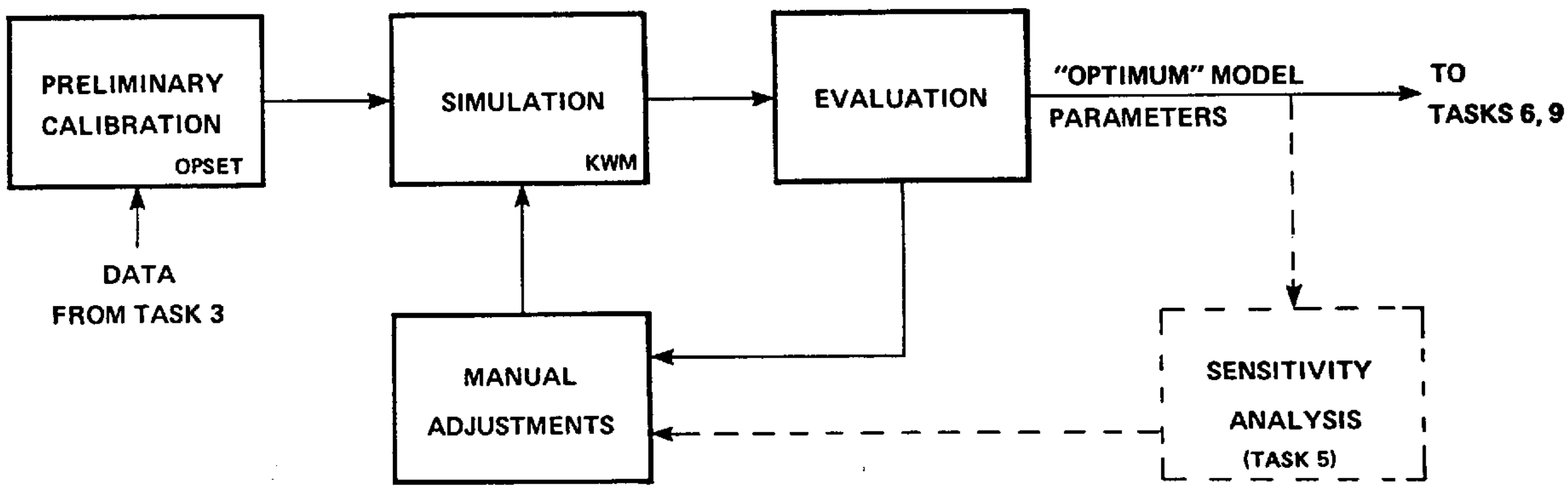


Figure 20. Task 4: Calibration

Sensitivity analyses performed to date have produced invaluable guidance to the manual-adjustment activity, reducing the subjectivity and eliminating the requirement that the analyst be skilled in hydrology.

3.4.2 PARAMETERS ESTIMATED BY CALIBRATION

The calibration process (a combination of automatic and manual adjustments as summarized above) was used to quantify the following simulation model parameters for each of ten watersheds. See Reference 13 for more complete description.

1. BFRC, Base Flow Recession Constant, governs the rate at which groundwater flow recedes in the model.

2. IFRC, Interflow Recession Constant, governs interflow recession.

3. BUZC, Basic Upper Zone Capacity, is an index for estimating the capacity of the soil surface (upper zone) to store water in interception and depression storage.

4. SUZC, Seasonal Upper Zone capacity adjustment constant, is used to adjust upper zone variations in vegetation and cultivation.

5. LZC, Lower Zone Capacity, is an estimate of the capacity of the basin soil to hold water. Decreasing LZC in the model has the effect of increasing synthesized runoff.

6. BMIR, Basic Maximum Infiltration Rate, is the index used to control the basic rate of moisture inflitration. This is a parameter to which simulation accuracy is very sensitive, particularly as it affects storm peaks.

7. SIAC, the Seasonal Infiltration Adjustment Constant, is an evaporation-infiltration factor relating infiltration rates to evaporation rates to account for more rapid infiltration during warmer periods.

8. ETLF, Evapotranspiration Loss Factor, is an index used to estimate the maximum rate of evapotranspiration which could accur within the watershed under current conditions of soil moisture content.

9. BIVF, Basic Interflow Volume Factor, controls time distribution and quantities of moisture entering interflow. Increasing

BIVF tends to reduce storm runoff peaks and extend hydrograph recession limbs.

10. NCTRI, Number of Current Time Routing Increments, is the number of subareas into which the basin should be divided, given 15 minute or one hour separation between isochrones.

11. CSRX, Channel Storage Routing Index, is used to account for channel storage when channel flows are less than half of channel capacity (CHCAP). Channel storage effects are simulated by having the hydrograph time routed to the mouth of the watershed through an imaginary reservoir.

12. FSRX, Flood plain Storage Routing Index, is used to account for channel storage plus flood plain storage when streamflows are greater than twice the channel capacity. Between one-half and twice channel capacity, the program interpolate values between FSRX and CSRX.

13. CHCAP, Channel Capacity, is that value of streamflow, measured at the gage, at which a transistor is made from channel routing to flood plain routing. In mountainous watersheds, this is not an oritical parameter, and OPSET seldom adjusts it.

After OPSET has adjusted the parameters listed above to achieve a "best match" based on mean daily streamflow, it is usually found that synthesized flood peaks fail to match observed peaks, in magnitude and/or time. Since the study attempted to address as wide a variety of applications as practicable, some manual "fine tuning" was undertaken to achieve an acceptable match between synthesized and observed flood peaks while maintaining an acceptable correlation between synthesized and observed mean daily and monthly flows. This manual adjustment process requires some knowledge of the hydrologic processes occurring in the watershed and some subjective judgment. No firm rules or recipes have been developed, but the following are useful guidelines.

1. Overall results are affected by soil moisture capacities and infiltration rates (LZC, BUZC, BMIR) and their related seasonal adjustment constants (SUZC, SIAC).

2. Initial storages (LZS and UZS) can be varied to improve accuracy in the first two months of the multiyear simulation.

3. Summer storm peaks are affected more than winter storm peaks by changes in SIAC and SUZC, and the latter has more influence on mean daily flow in drier months than the former.

4. Consistent phasing errors (differences in times of occurrence between synthesized and observed flood peaks) can usually be reduced by adjustment if the number and sizes of subareas in the time-area histogram. Phasing errors which appear random are attributable to errors in input precipitation and/or evaporation data.

5. Since there are parameter interactions, all performance indices should be re-checked after any parameter adjustment and others re-adjusted as needed until a "best simulation" is realized.

3.4.3 CALIBRATION RESULTS

The calibration process was applied to ten Tennessee Valley watersheds to derive the sets of parameters shown in Table 10. Parameter definitions are listed in Table 11. Each set is the one which produces simulations that are acceptable with respect to all indices of performance, as shown in Table 12. The mean monthly and daily streamflows show good correlation coefficients.

From each multi-year simulation, the largest winter storm was included in the table, even though others showing more felicitous results could have been chosen. For some of the large winter storms (e.g., Sewee Creek, 3-13-63), simulated flood peaks vary from the observed peaks by factors in magnitude and several hours in time. Experience in the study shows that (1) input data are often erroneous and (2) good simulation fidelity with respect to storm/flood events should not be expected in a free-running or "open loop" model. In an operational application, moisture storage conditions and simulated flow rate would be periodically adjusted in accordance with actual observed conditions and in a short-term forecast (24 to 72 hours), a prediction accuracy within five per cent could confidently be expected.

Several plots were generated early in the study after the first calibrations were completed. They were useful at first, but more time-consuming than the information they yielded would justify. It was found that simulated and observed storm events could be compared effectively, for evaluation purposes, on the basis of peak flow magnitude and time. Some

Table 10. Simulation Model Parameters After Calibration

WATERSHED		WATERSHED PARAMETERS			PARAMETERS QUANTIFIED BY CALIBRATION																SOIL CHARACTERISTICS	
					SOIL MOISTURE							CHANNEL ROUTING AND GROUNDWATER				OVERLAND FLOW						
NO.	NAME	AREA	FIMP	FWTR	BMIR	LZC	ETLF	SUZC	SIAC	BUZC	BIVF	CSRX	FSRX	BFRC	BFNLR	OFSL	OFSS	OFMN	IFRC	OFMNIS	AWC	PERM-A
1	WHITE HOLLOW	2.68	.001	.001	9.0	6.0	.20	.50	.40	.90	.50	.99	.97	.98	.85	1000	.30	.10	.10	.015	3.71	1.70
2	LITTLE CHESTUEE	8.26	.013	0.0	10.0	6.0	.20	.20	.40	.50	0.0	.93	.97	.99	.85	630	.237	.061	.10	.002	8.75	1.20
3	SOUTH FORK MILLS	9.99	.001	0.0	12.9	7.6	.07	.20	.20	.20	.58	.96	.97	.99	.85	1140	.315	.05	.10	.015	7.90	4.54
5	WEST FORK PIGEON	27.6	.001	.008	4.0	7.0	.10	.15	.15	.15	0.0	.95	.95	.99	.85	1380	.413	.05	.10	.015	8.82	4.0
7	BIG ROCK CREEK	24.9	.033	.005	5.0	4.0	.07	.15	.15	.40	0.0	.94	.95	.70	.50	980	.155	.04	.10	.015	5.30	.77
9	TRACE CREEK	30.4	.039	.005	6.5	4.6	.11	.70	.90	.39	0.0	.97	.97	.96	.85	850	.129	.05	.10	.015	1.80	1.43
12	EMORY CREEK	83.2	.005	.001	7.0	3.9	.10	.20	.20	.30	.78	.94	.94	.84	.85	1270	.298	.07	.10	.010	5.55	2.67
13	SEWEE CREEK	117	.001	.001	4.0	3.5	.10	.25	.15	.25	.50	.98	.99	.99	.85	1060	.165	.05	.10	.015	4.92	.50
14	TOWN CREEK	141	.002	.001	7.0	4.0	.25	.25	.30	.25	.50	.94	.90	.93	.85	1550	.062	.05	.10	.014	6.19	4.3
15	POPLAR CREEK	82.5	.010	.001	4.0	3.0	.15	.20	.15	.15	1.0	.97	.98	.98	.85	1320	.329	.05	.10	.015	2.02	1.08

NOTE: Watershed parameters and soil characteristics are included in the table to make a complete base for correlation.

Table 11. Model Parameter Definitions

SYMBOL	DEFINITION/SIGNIFICANCE
BIVF	Basic Interflow Volume Factor; indexes distribution and quantities of moisture entering interflow.
BFNLR	Base Flow Nonlinear Recession Adjustment Factor
BFRC	Base Flow Recession Constant
BMIR	Basic Maximum Infiltration Rate; relates to "A" horizon permeability.
BUZC	Basic Upper Zone Storage Capacity
CHCAP	Channel Capacity Indexed to Basin Outlet; flow rate indicated at transition from channel routing to flood plain routing.
CSRX	Channel Storage Routing Index; used to account for channel storage when channel flows are less than half of CHCAP.
ETLF	Evapotranspiration Loss Factor; indexes moisture depletion rate through evapotranspiration.
FSRX	Flood Plain Storage Routing Index; used to account for channel plus flood plain storage when streamflows are greater than twice CHCAP. The model synthesizes a routing index when streamflow is between ½*CHCAP and 2*CHCAP.
IFRC	Interflow Recession Constant; indexes interflow recession rate, effective only in conjunction with a non-zero BIVF.
LZC	Lower Zone Capacity; indexes lower zone soil moisture storage capacity; relates to plant-available water capacity.
NBTRI	Number of Base Time Routing Increments; used by the model in routing by Clark's method.
SIAC	Seasonal Infiltration Adjustment Constant; relates to changes in vegetative cover with changes in season.
SUZC	Seasonal Upper Zone Storage Capacity Factor; BUZC and SUZC together regulate the capacity of the upper zone to hold moisture.
VINTMR	Vegetative Interception Maximum Rate.

Table 12. Simulation Accuracy After Calibration

WATERSHED				YEARS OF RECORDS			STREAMFLOW						LARGEST WINTER STORM				
							CORRELATION COEFFICIENT		DAILY, CFS				DATE	PEAK			
NO.	SHORT NAME	AREA							MEAN		MAX			FLOW, CFS		TIME, HR	
		MI²	KM²	YRS	FROM	THRU	M'LY	D'LY	OBS	SIM	OBS	SIM		OBS	SIM	OBS	SIM
1	WHITE HOLLOW	2.7	6.9	7	57	63	.95	.91	3.79	3.69	147	78	3-12-63	270	98	6	4
2	LITTLE CHESTUEE	8.2	21.3	7	50	56	.92	.87	13.0	13.9	388	447	4-15-56	1,030	895	18	18
3	SOUTH FORK MILLS	9.9	25.7	3	66	68	.84	.80	32.2	32.5	713	706	2-13-66	1,618	1,273	6	8
5	WEST FORK PIGEON	27.6	37.3	9	56	64	.93	.82	78.1	79.1	1600	2641	3-5-64	4,714	3,368	25	27
7	BIG ROCK CREEK	24.9	64.5	7	55	61	.95	.93	40.3	40.9	3800	3895	3-7-61	6,518	5,923	24	26
9	TRACE CREEK	30.4	78.7	6	64	69	.93	.88	39.8	37.5	2310	1547	12-4-64	3,524	2,579	8	8
12	EMORY RIVER	83.2	215	4	53	56	.95	.83	142	145	5460	3150	3-22-55	13,000	8,925	3	1
13	SEWEE CREEK	117	303	9	60	68	.93	.84	192	142	6450	5658	3-13-63	20,400	8,561	35	46
14	TOWN CREEK	141	365	6	61	66	.95	.90	282	216	9260	8384	3-25-64	10,699	9,233	48	49
15	POPLAR CREEK	82.5	214	7	62	68	.96	.90	157	142	6200	4068	3-12-63	6,389	5,252	38	31

of the plots generated early in the study are shown in Figures 21 (whose time scale is unavoidably too small for good interpretation) through 25. Except for some graphical enhancement for the sake of good reproduction, all the plots except that of Figure 23 were generated automatically.

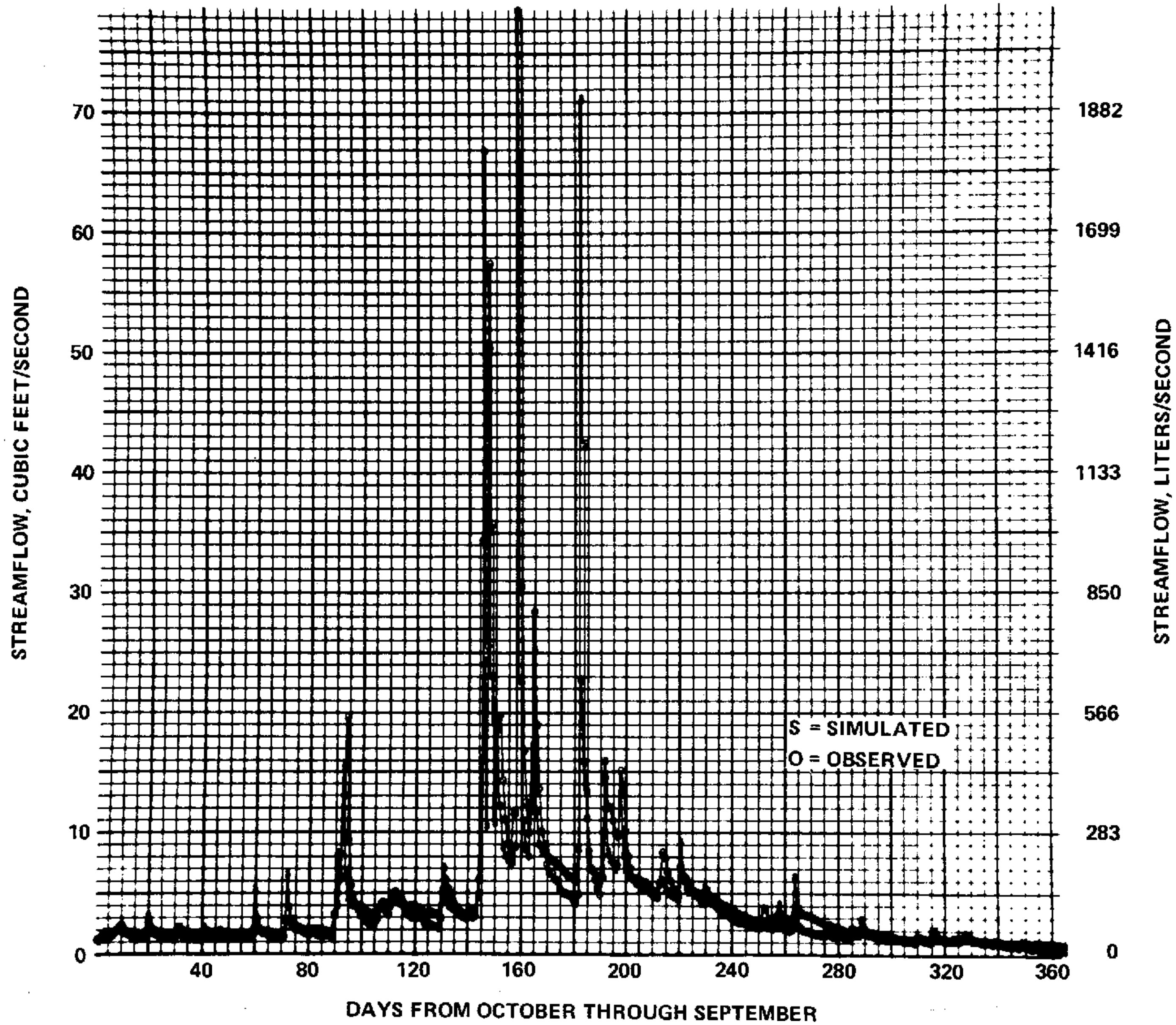


Figure 21. One Year Simulated and Observed Flow, White Hollow, 1961

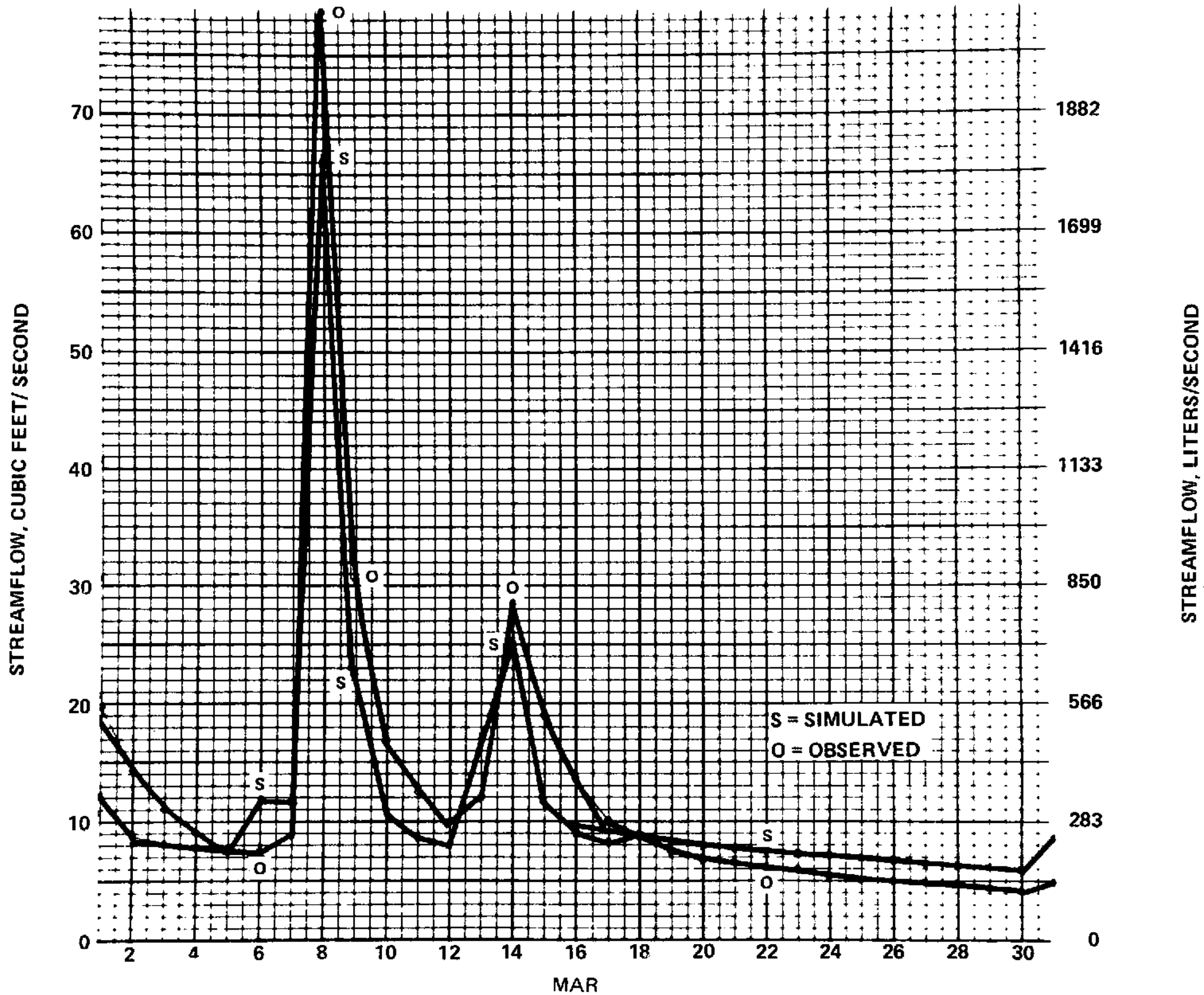


Figure 22. One Month Simulated and Observed Flow, White Hollow, March 1961

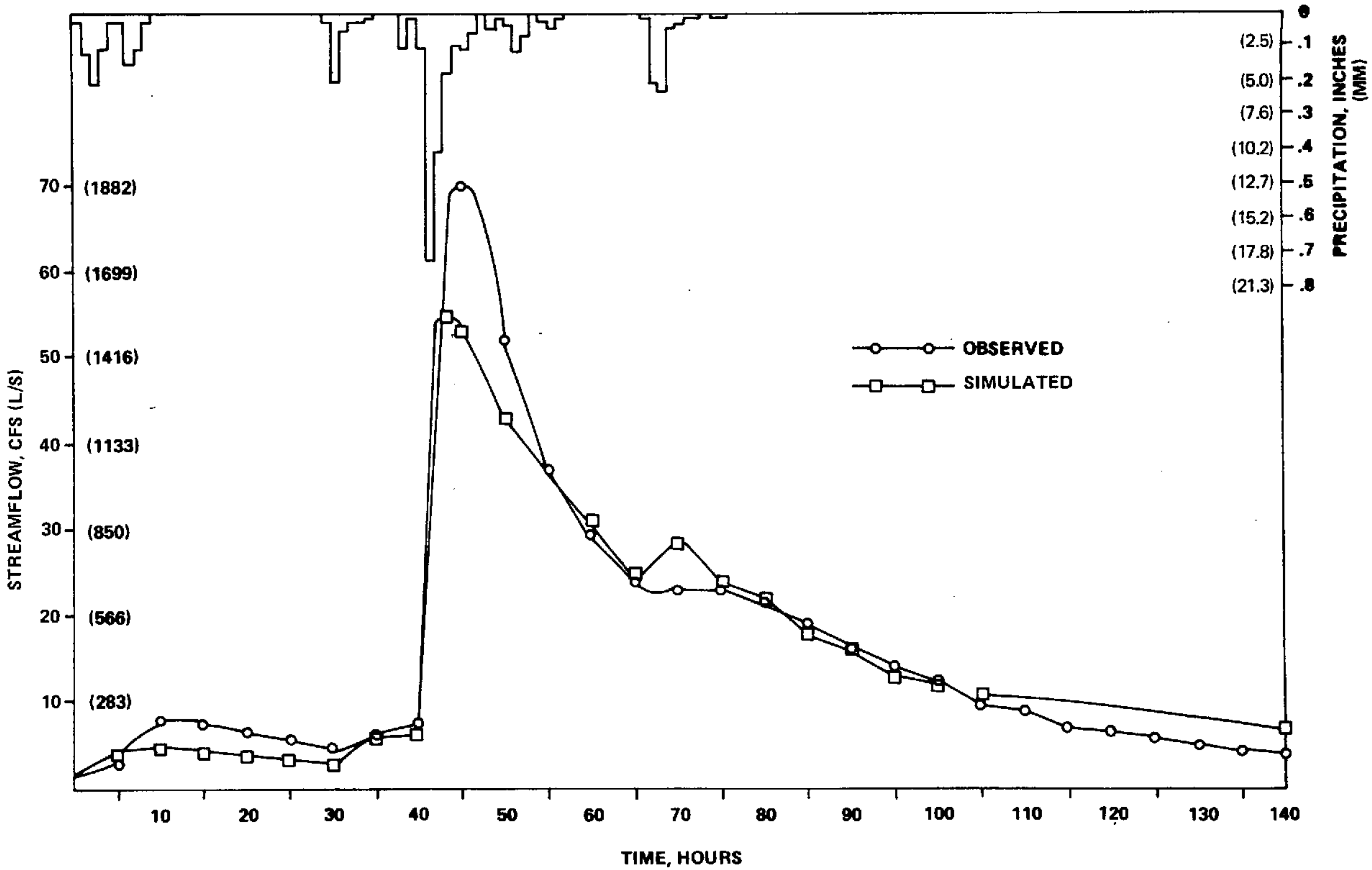
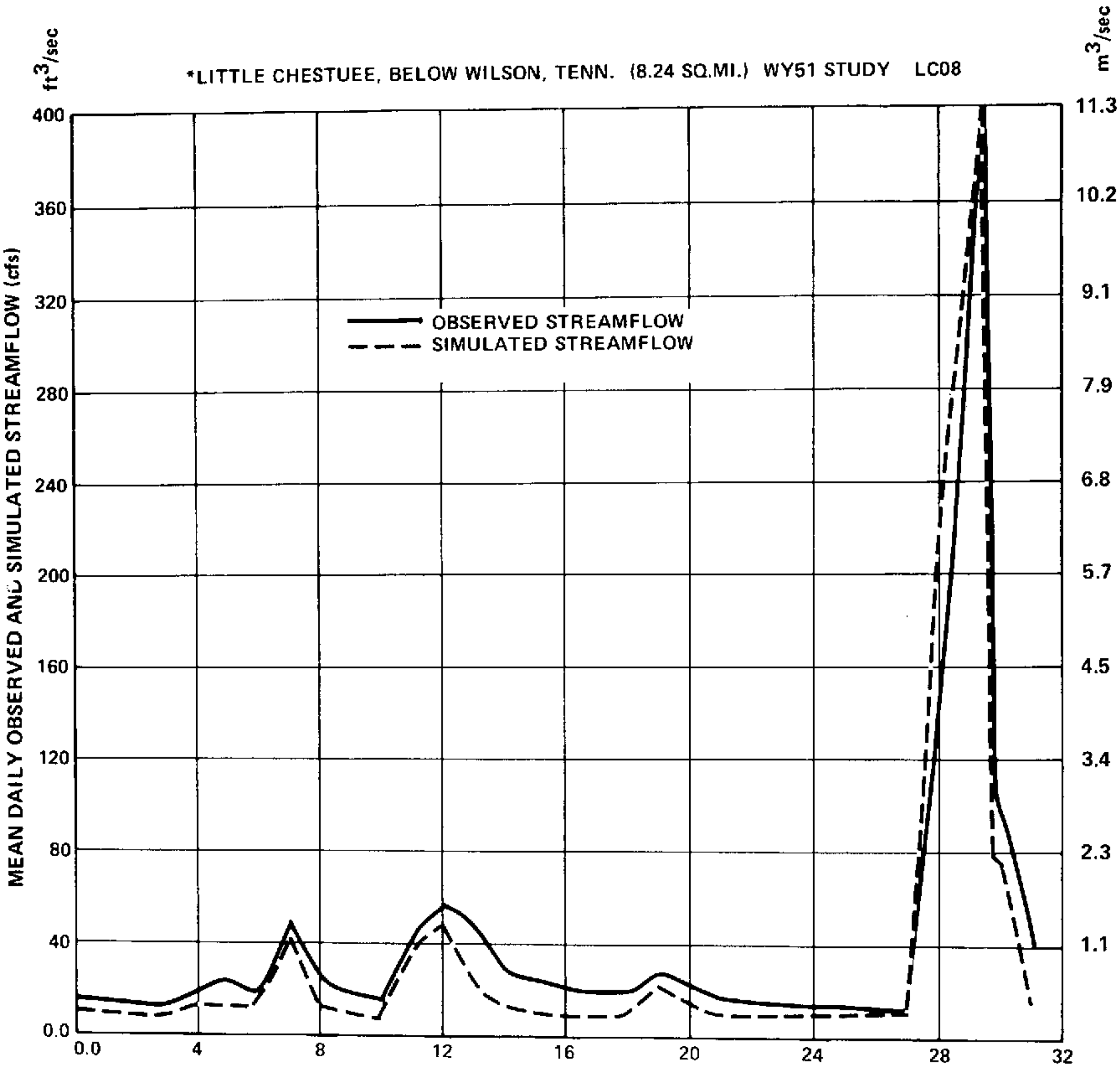


Figure 23. Selected Storm, November 16-23, 1957, White Hollow



OBSERVED MONTHLY STREAMFLOW = 1301 CFS SIMULATED MONTHLY STREAMFLOW = 1156 CFS

Figure 24. One Month Simulated and Observed Flows, Little Chestuee, March 1951

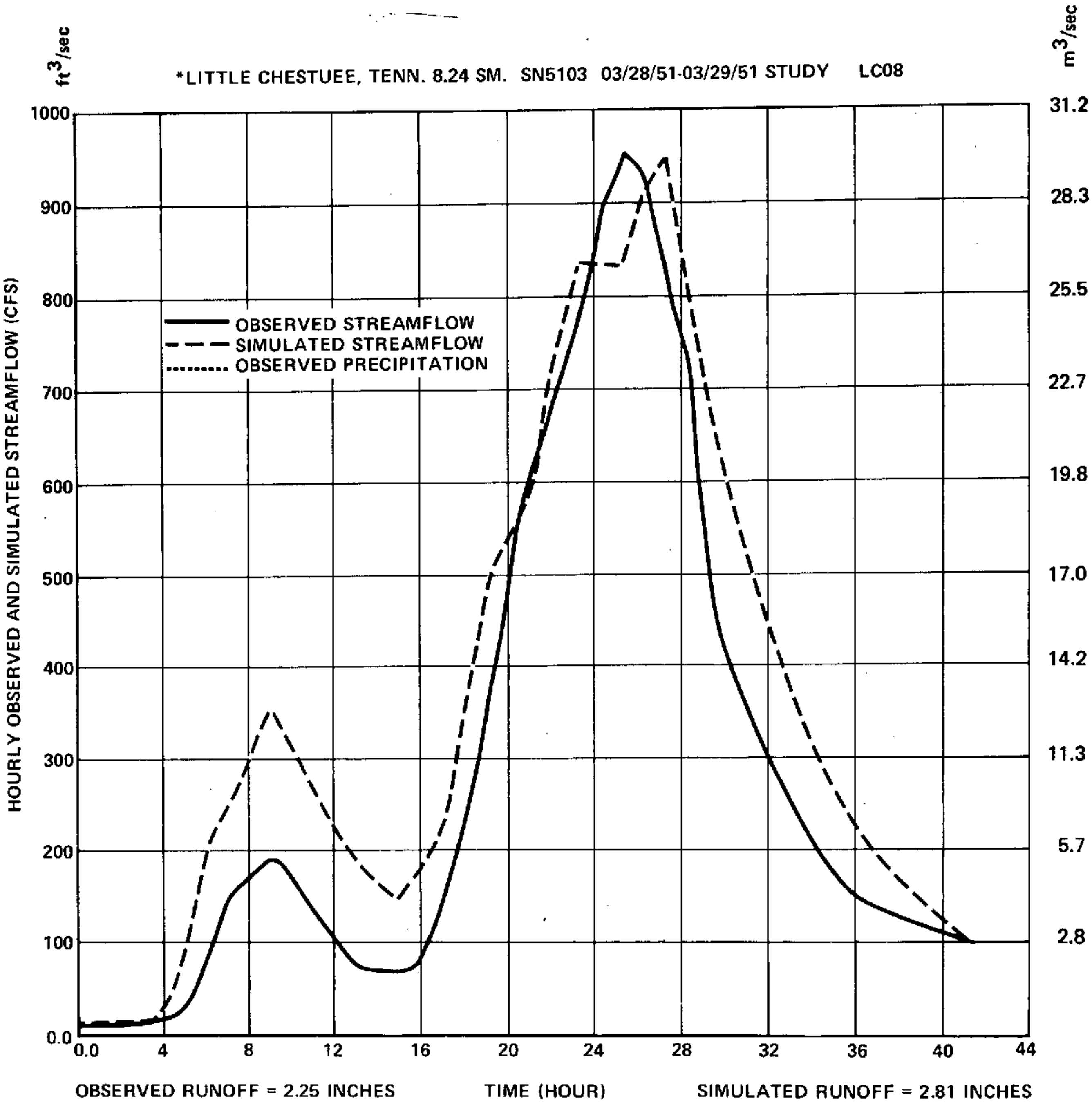


Figure 25. Simulated and Observed Runoff, Major Winter Storm, Little Chestuee, March 28-29, 1951

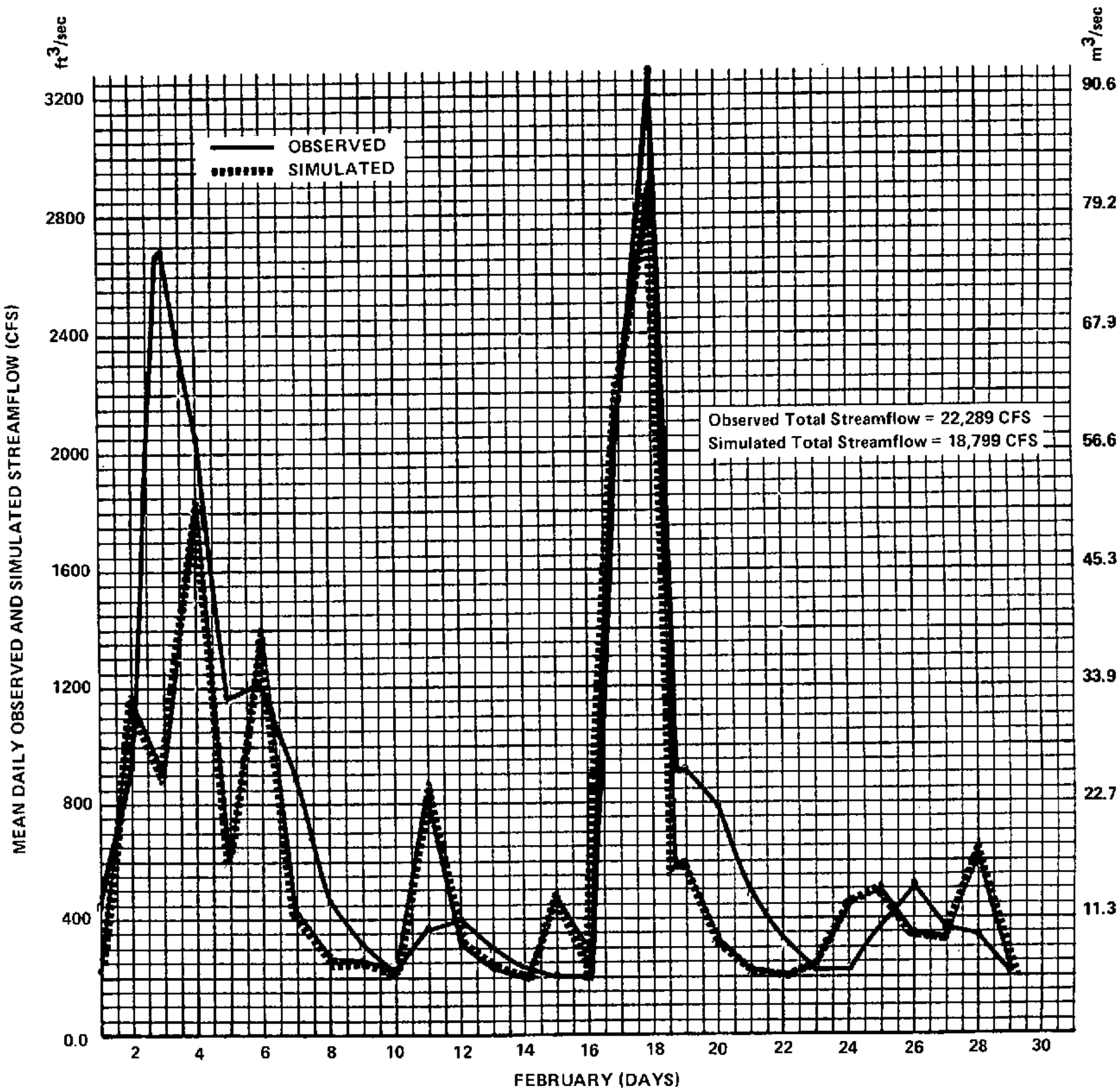


Figure 26. Simulated and Observed Flows, Emory River, February 1956

3.5 SENSITIVITY ANALYSIS (TASK 5)

The success of a general hydrologic model is measured by its ability to simulate streamflow sequences that match observed records. The model utilizes time sequences of climatological data, information on the physical watershed, and a set of values for model parameters. These model parameters theoretically relate to watershed physical characteristics; operationally, those values are estimated by a sequence of trials and adjustments ending in an acceptable match. The quality of a given trial is determined by the closeness with which the observed and simulated flows agree during every simulation period. The manifest impracticality of making all these comparisons in evaluating a trial simulation requires selection of a small number of quality indices. One such index is the total annual flow; however, a large number of combinations of parameter values will give the same total annual flow. Therefore we need to differentiate in selecting among these combinations by adding other indices such as mean, standard deviations, root sum squares, daily correlation coefficients, low and high flows, and hydrograph characteristics.

If one is to adjust a trial set of model parameter values in order to improve the matching of the observed and simulated streamflows, he needs information on the effect a given change in a given parameter value will have on the simulated streamflows. The universe of such information is a multidimensional response surface of values for each index at points representing each set of parameter values. The response surface of interest is bounded by the reasonable range for each individual parameter. Comprehensive mapping is impractical.

The information on the direction and the rate of change of the index values per unit change of each parameter at the point representing the set is important and very useful. Theoretically an infinite number of points could be analyzed, but a good one to start with is one accepted after trial and error modeling to achieve a "best" match.

The advantages of the sensitivity analysis lie in its ability to: (1) guide manual adjustments or programmed adjustments in a computerized optimization routine, indicating how much to change a given mode parameter to effect a given correction in a statistical index and/or hydrograph characteristic, and also the effect it will have on other indices; (2) show which parameters need to be estimated carefully and which ones require only rough approximation; (3) indicate the critical parameters on which effort should be concentrated to find a correlation with watershed physical characteristics that can be observed by remote sensing; and (4) provide guidance on what difference in runoff characteristics to expect from a given difference in physical characteristics of two watersheds.

Sensitivity analysis is time consuming and costly because of the large number of computer runs required. Also, a completed sensitivity analysis may be invalidated by a change in the model, but recently the models have been stabilized sufficiently to make the analysis worthwhile. Figure 27 shows the interfaces of Task 5 (Sensitivity Analysis) with other study tasks.

Two sensitivity analyses were performed, for the purpose of guiding manual calibrations, on two small basins: White Hollow and Little Chestuee. The results of the latter are tabulated in Table 13. The column headings represent various mean daily streamflow statistics and hydrograph characteristics that were selected to assess the closeness of simulated flow to recorded flow. No single statistical quality index can be used in reckoning the quality of a match. Different users need to match different statistical indices depending on their objective, interest, or application (e.g., flood control, low flows, water supply). None of the parameters except NBTRI affect flood peak timing. Flood peak times are therefore not included in Table 13. Parameter values producing the "best" simulation appear in parentheses in the PARAM column.

The data shown in Table 13 need further interpretation to be informative. A "Unit Sensitivity", defined by the following division

US = (percent change in simulation result)/(percent change in parameter)

was calculated for each parameter with respect to the simulation result of interest, as a measure of parameter effectiveness. The results for the Little Chestuee basin are summarized in Table 14.

Examination of the results suggests a general scheme of parameter change that should improve accuracy of low flow simulation, and the peak of the biggest storm. Increasing the BFRC value from 0.98 to 0.99 would improve the summer low flow simulation. A reduction in ETLF from 0.165 to 0.05 would increase the annual flow volume, and counteract the reduction due to BFRC increase. Reducing the CSRX value from 0.97 to 0.96 should increase the peaks of all floods and therefore better the peak of the biggest storm. Results of experiments with these combinations were used to advantage in the calibration task.

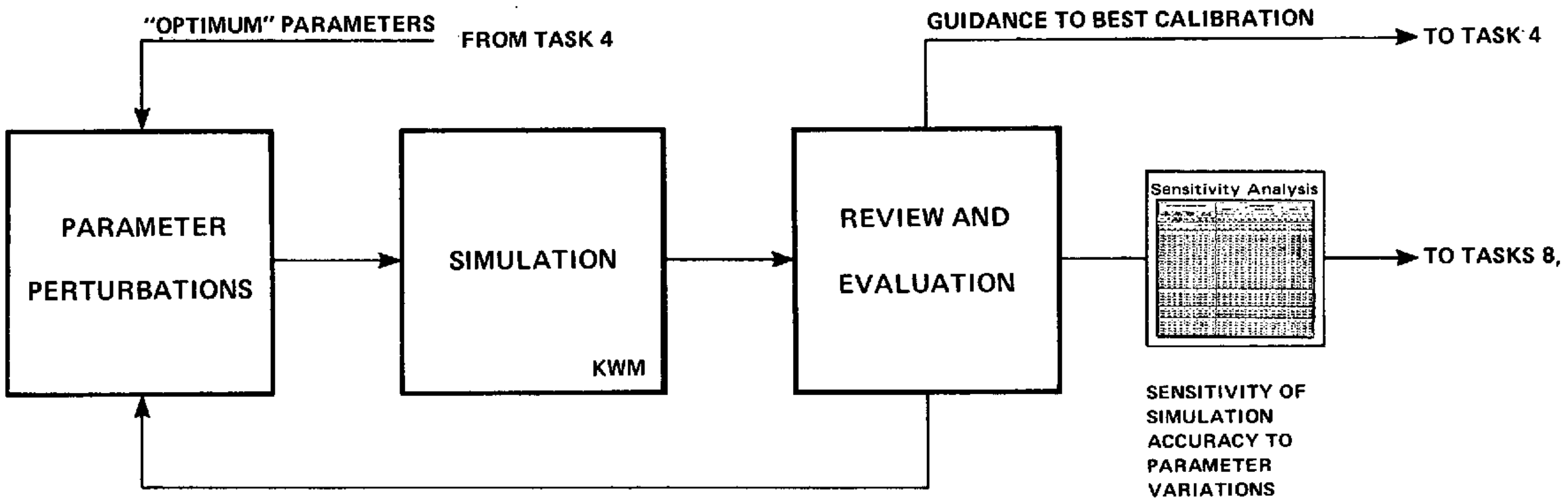


Figure 27. Task 5: Sensitivity Analysis

Table 13. Sensitivity Analysis of Little Chestuee (Part 1 of 4)

SENSITIVITY ANALYSIS FOR LITTLE CHESTUEE WATERSHED WATER YEAR 1951 DRAINAGE AREA 8.24 Square Miles

I D	PARAM	VALUE	DAILY STREAMFLOW STATISTICAL SUMMARY: FLOW STATISTICS MEAN	FLOW STATISTICS STD DEV.	ERROR STATISTICS ROOT SUM SQUARE	ERROR STATISTICS DAILY CORR. COEFF.	AVERAGE ERRORS LOW FLOWS (4.5)	AVERAGE ERRORS HIGH FLOWS (33.1)	LOW FLOW STATISTICS MEAN OF (Aug.)	LOW FLOW STATISTICS MEAN OF (June)	LOW FLOW STATISTICS LOWEST OF (Feb.)	STORM ANALYSIS SUMMARY: STORM OF 1/14/51 #1 PEAK (CFS)	#1 PEAK (HOUR)	#1 R/O (IN)	STORM OF 2/1/51 #2 PEAK (CFS)	#2 PEAK (HOUR)	#2 R/O (IN)	STORM OF 3/29/51 #3 PEAK (CFS)	#3 PEAK (HOUR)	#3 R/O (IN)	STORM OF 9/22/51 #4 PEAK (CFS)	#4 PEAK (HOUR)	#4 R/O (IN)
	OBSERVED CONFIGURATION		14.01	27.9					5.25	7.24	11.0	191	21	0.49	798	9	1.61	954	2	2.25	230	15	.20
	BEST SIMULATED CONFIGURATION		14.78	33.67	194	.963	+0.7	+1.6	4.50	10.97	9.7	222	19	0.61	950	8	1.86	954	4	2.83	231	16	.28
			WATERSHED PARAMETERS																				
51	AREA	4.12	7.38	16.83	271	.963	-2.5	-21.7	2.24	5.46	4.9	111	19	.30	475	8	.93	477	4	1.41	115	16	.14
52	(8.24)	12.36	22.17	50.41	498	.963	+3.9	+24.9	6.74	16.46	14.6	333	19	.91	1424	8	2.80	1432	4	4.24	346	16	.43
53	FIMP	0.00	14.59	33.33	188	.963	+0.6	+0.2	4.36	10.71	9.9	219	19	.60	944	8	1.85	950	4	2.80	216	16	.26
57	(0.013)	0.052	15.36	34.74	216	.959	+0.9	+5.8	4.90	11.76	9.4	232	19	.64	966	8	1.91	969	4	2.90	273	16	.35
58		0.10	16.07	36.17	249	.952	+1.1	+11.0	5.39	12.75	9.1	244	19	.68	987	8	1.98	987	4	2.99	326	16	.43
59		0.20	17.56	39.48	330	.930	+1.7	+21.8	6.42	14.81	8.1	269	19	.75	1030	8	2.10	1023	4	3.19	437	16	.55
60		0.50	22.04	51.20	612	.852	+3.2	+54.0	9.54	21.15	5.5	343	19	.99	1158	8	2.48	1134	4	3.77	775	16	1.09
63	FWTR	0.01	14.67	33.95	198	.962	+0.4	+2.5	4.09	10.71	9.6	224	19	.61	954	8	1.88	958	4	2.84	240	16	.30
65	(0.0)	0.10	14.30	36.44	248	.952	-1.1	+10.1	3.34	8.95	8.2	244	19	.67	989	8	1.97	989	4	2.99	327	16	.42
67		0.50	18.20	49.27	557	.862	+0.4	+44.3	7.24	15.27	2.4	332	19	.93	1144	8	2.41	1128	4	3.67	717	16	.98
			SOIL MOISTURE PARAMETERS																				
2	BMIR	3.15	15.31	41.36	339	.942	-0.6	+18.0	3.44	10.59	6.8	307	19	.76	1109	8	2.25	1099	4	3.38	356	16	.43
3	(6.3)	9.45	14.53	28.36	132	.970	+1.4	-6.6	5.08	11.54	11.6	165	19	.51	803	8	1.57	825	4	2.38	161	16	.21
6	LZC	4.00	16.67	41.42	328	.954	+0.3	+16.8	4.29	11.57	7.4	254	19	.83	1045	8	2.30	1044	4	3.24	199	16	.25
7	(8.0)	12.00	12.59	28.21	157	.958	0.0	-7.8	4.50	10.64	8.9	159	19	.45	814	8	1.51	856	4	2.43	274	16	.34
10	ETLF	0.125	15.42	34.26	211	.958	+1.1	+6.3	5.18	11.68	9.7	225	19	.62	957	8	1.89	960	4	2.85	420	16	.51
11	(0.25)	0.375	14.55	33.51	192	.963	+0.5	-0.4	4.24	10.70	9.8	221	19	.60	947	8	1.86	953	4	2.82	141	16	.18
14	SIAC	0.15	14.77	31.81	171	.964	+0.8	+0.2	4.59	11.58	10.7	200	19	.57	891	8	1.74	909	4	2.66	256	16	.31
15	(0.30)	0.45	14.80	35.41	221	.961	+0.6	+3.3	4.40	10.37	9.1	244	19	.65	1001	8	1.98	995	4	2.97	205	16	.26
18	SUZC	0.15	15.32	33.94	211	.955	+1.0	+3.8	5.40	13.24	9.8	222	19	.61	949	8	1.86	954	4	2.82	328	16	.40
19	(0.30)	0.45	14.32	33.77	191	.965	+0.3	-1.2	4.03	9.76	9.6	225	19	.61	955	8	1.88	959	4	2.84	138	16	.18
22	BUZC	0.21	14.81	33.68	195	.963	+0.7	+1.9	4.53	11.02	9.7	222	19	.61	949	8	1.86	954	4	2.82	244	16	.30
23	(0.42)	0.63	14.75	33.67	194	.963	+0.7	+1.4	4.46	10.91	9.7	222	19	.61	949	8	1.86	955	4	2.83	216	16	.27
40	BIVF	0.20	14.77	33.78	205	.957	+0.7	+1.7	4.51	11.05	9.8	229	19	.60	965	8	1.87	972	4	2.87	231	16	.29
41	(0.40)	0.60	14.82	33.21	166	.975	+0.5	+1.6	4.37	10.95	9.5	173	19	.61	855	8	1.84	900	4	2.70	229	16	.28
68	VINTMR	0.00	14.88	33.18	184	.965	+1.0	-0.2	4.77	11.32	10.2	208	19	.56	939	8	1.82	955	4	2.80	230	16	.29
69	(0.149)	0.075	14.79	33.53	191	.963	+0.8	+1.0	4.54	11.03	9.9	219	19	.59	947	8	1.85	954	4	2.82	230	16	.29
71		0.224	14.76	33.82	197	.962	+0.7	+1.9	4.48	10.96	9.7	225	19	.62	954	8	1.88	955	4	2.84	231	16	.28

955-2426-2

Table 13. Sensitivity Analysis of Little Chestuee (Part 2 of 4)

SENSITIVITY ANALYSIS FOR LITTLE CHESTUEE WATERSHED WATER YEAR 1951 DRAINAGE AREA 8.24 Square Miles

ID	PARAM	VALUE	DAILY STREAMFLOW STATISTICAL SUMMARY: FLOW STATISTICS: MEAN	FLOW STATISTICS: STD DEV.	ERROR STATISTICS: ROOT SUM SQUARE	ERROR STATISTICS: DAILY CORR. COEFF.	AVERAGE ERRORS: LOW FLOWS (4.5)	AVERAGE ERRORS: HIGH FLOWS (33.1)	LOW FLOW STATISTICS: MEAN OF (Aug.)	LOW FLOW STATISTICS: MEAN OF (June)	LOW FLOW STATISTICS: LOWEST OF (Feb.)	STORM ANALYSIS SUMMARY: STORM OF 1/14/51 #1: PEAK (CFS)	#1 PEAK (HOUR)	#1 R/O (IN)	STORM OF 2/1/51 #2: PEAK (CFS)	#2 PEAK (HOUR)	#2 R/O (IN)	STORM OF 3/29/51 #3: PEAK (CFS)	#3 PEAK (HOUR)	#3 R/O (IN)	STORM OF 9/22/51 #4: PEAK (CFS)	#4 PEAK (HOUR)	#4 R/O (IN)
	OBSERVED CONFIGURATION		14.01	27.9					5.25	7.24	11.0	191	21	0.49	798	9	1.61	954	2	2.25	230	15	.20
	BEST SIMULATED CONFIGURATION		14.79	33.67	194	.963	+0.7	+1.6	4.50	10.97	9.7	222	19	0.61	950	8	1.86	954	4	2.83	231	16	.28
			SOIL MOISTURE PARAMETERS (CONTINUED)																				
72		0.298	14.75	33.98	200	.961	+0.6	+2.0	4.43	10.90	9.6	228	19	.63	958	8	1.89	955	4	2.85	231	16	.28
74		1.00	14.64	34.56	214	.958	+0.4	+2.1	4.20	10.66	9.3	228	19	.63	964	8	1.91	962	4	2.92	234	16	.29
122	SUBWF	0.05	14.38	33.60	194	.962	+0.4	+1.0	4.28	10.56	9.3	222	19	.60	949	8	1.86	954	4	2.82	230	16	.28
123	(0.0)	0.10	13.97	33.52	193	.962	+0.1	+0.4	4.07	10.14	8.8	221	19	.60	948	8	1.85	953	4	2.81	230	16	.28
124		0.20	13.17	33.38	194	.961	-0.4	-0.9	3.64	9.32	8.0	221	19	.59	947	8	1.84	951	4	2.80	230	16	.28
125		0.30	12.37	33.25	197	.960	-1.0	-2.1	3.21	8.50	6.8	220	19	.58	946	8	1.83	949	4	2.79	230	16	.28
126	GWETF	0.05	13.53	33.77	194	.964	-0.8	+0.7	2.31	8.50	9.3	222	19	.60	949	8	1.86	954	4	2.82	229	16	.28
127	(0.0)	0.10	12.72	33.80	195	.963	-1.6	-0.0	1.34	6.94	8.8	221	19	.60	949	8	1.86	953	4	2.81	229	16	.27
128		0.20	11.68	33.77	199	.964	-2.6	-1.1	0.63	5.26	8.0	221	19	.59	948	8	1.85	952	4	2.81	228	16	.27
129		0.30	11.01	33.71	202	.963	-3.1	-2.0	0.41	4.46	7.4	220	19	.58	948	8	1.84	951	4	2.80	228	16	.27
			OVERLAND PARAMETERS																				
46	IFRC	0.05	14.78	33.77	197	.962	+0.7	+1.8	4.49	10.97	9.7	223	19	.61	952	8	1.87	959	4	2.84	231	16	.28
47	(0.10)	0.15	14.78	33.58	192	.963	+0.7	+1.5	4.49	10.97	9.7	222	19	.61	948	8	1.86	951	4	2.81	231	16	.28
77	OFSS	0.118	14.75	33.49	190	.964	+0.8	+0.9	4.56	10.89	9.9	219	19	.60	950	8	1.85	958	4	2.82	230	16	.28
78	(0.237)	0.355	14.79	33.77	197	.962	+0.7	+2.1	4.46	11.02	9.7	224	19	.61	950	8	1.87	953	4	2.83	231	16	.29
79		0.474	14.81	33.83	198	.962	+0.6	+2.3	4.44	11.03	9.6	225	19	.61	950	8	1.87	952	4	2.83	231	16	.29
81		0.948	14.83	33.98	202	.961	+0.6	+3.0	4.39	11.06	9.5	227	19	.62	951	8	1.88	951	4	2.84	231	16	.29
82	OFSL	1.0	14.88	34.45	212	.958	+0.4	+5.5	4.26	11.10	9.1	232	19	.64	952	8	1.90	951	4	2.86	231	16	.29
83	(630.0)	315.0	14.83	33.98	202	.961	+0.6	+3.0	4.39	11.06	9.5	227	19	.62	951	8	1.88	951	4	2.84	231	16	.29
84		945.0	14.74	33.46	189	.964	+0.8	+0.7	4.57	10.88	9.9	218	19	.60	950	8	1.85	959	4	2.82	229	16	.28
85		1260.0	14.71	33.28	185	.965	+0.8	-0.2	4.63	10.85	10.0	214	19	.59	951	8	1.84	962	4	2.81	216	16	.27
87		3150.0	14.60	32.56	169	.969	+1.0	-3.7	4.86	10.77	10.5	187	19	.54	948	8	1.80	966	4	2.78	164	16	.21
88	OFMN	0.030	14.83	33.99	202	.961	+0.6	+3.0	4.39	11.06	9.5	227	19	.62	951	8	1.88	951	4	2.84	231	16	.29
89	(0.061)	0.091	14.75	33.46	189	.964	+0.8	+0.7	4.57	10.88	9.9	218	19	.60	950	8	1.85	959	4	2.82	229	16	.28
92		0.305	14.60	32.56	169	.969	+1.0	-3.7	4.86	10.77	10.5	187	19	.54	948	8	1.80	967	4	2.78	164	16	.21
93	OFMNIS	0.0006	14.78	33.67	194	.963	+0.7	+1.6	4.49	10.97	9.7	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
97	(0.002)	0.01	14.78	33.67	194	.963	+0.7	+1.6	4.49	10.97	9.7	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28

955-2426-2

Table 13. Sensitivity Analysis of Little Chestuee (Part 3 of 4)

SENSITIVITY ANALYSIS FOR LITTLE CHESTUEE WATERSHED WATER YEAR 1951 DRAINAGE AREA 8.24 Square Miles

ID	PARAM	VALUE	DAILY STREAMFLOW STATISTICAL SUMMARY									STORM ANALYSIS SUMMARY											
			FLOW STATISTICS		ERROR STATISTICS		AVERAGE ERRORS		LOW FLOW STATISTICS			STORM OF 1/14/51 #1			STORM OF 2/1/51 #2			STORM OF 3/29/51 #3			STORM OF 8/22/51 #4		
			MEAN	STD DEV.	ROOT SUM SQUARE	DAILY CORR. COEFF.	LOW FLOWS (4.5)	HIGH FLOWS (33.1)	MEAN OF (Aug.)	MEAN OF (June)	LOWEST OF (Feb.)	PEAK (CFS)	PEAK (HOUR)	R/O (IN)	PEAK (CFS)	PEAK (HOUR)	R/O (IN)	PEAK (CFS)	PEAK (HOUR)	R/O (IN)	PEAK (CFS)	PEAK (HOUR)	R/O (IN)
	OBSERVED CONFIGURATION		14.01	27.9					5.25	7.24	11.0	191	21	0.49	798	9	1.61	954	2	2.25	230	15	.20
	BEST SIMULATED CONFIGURATION		14.78	33.67	194	.963	+0.7	+1.6	4.50	10.97	9.7	222	19	0.61	950	8	1.86	954	4	2.83	231	16	.28
			CHANNEL ROUTING AND GROUND WATER PARAMETERS																				
28	CSRX	0.925	14.81	34.28	218	.953	+0.7	+2.7	4.50	10.98	9.7	294	19	.61	979	8	1.88	962	4	2.90	312	16	.29
29	(0.95)	0.975	14.76	31.87	133	.982	+0.7	-1.4	4.48	10.91	9.8	132	19	.59	637	8	1.77	742	4	2.49	128	16	.25
32	FSRX	0.925	14.78	33.67	194	.963	+0.7	+1.6	4.49	10.97	9.7	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
33	(0.95)	0.975	14.82	34.06	182	.972	+0.7	+1.6	4.49	10.97	9.7	222	19	.61	729	8	1.86	781	4	2.78	230	16	.29
36	BFRC	0.97	14.97	34.06	195	.965	+0.4	+3.1	3.17	9.75	10.4	223	19	.62	952	8	1.88	958	4	2.84	230	16	.28
37	(0.98)	0.99	13.87	33.11	198	.956	+0.8	-1.2	6.63	11.92	7.7	220	19	.58	946	8	1.84	949	4	2.79	232	16	.30
99	CHCAP	50.0	14.78	33.67	194	.963	+0.7	+1.6	4.49	10.97	9.7	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
103	(200.0)	300.0	14.78	33.67	194	.963	+0.7	+1.6	4.49	10.97	9.7	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
104		400.0	14.78	33.67	194	.963	+0.7	+1.6	4.49	10.97	9.7	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
130	EXQPV	0.01	14.78	33.67	194	.963	+0.7	+1.6	4.49	10.97	9.7	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
131	(0.30)	0.15	14.78	33.67	194	.963	+0.7	+1.6	4.49	10.97	9.7	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
132		0.45	14.78	33.67	194	.963	+0.7	+1.6	4.49	10.97	9.7	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
134		1.00	14.78	33.67	194	.963	+0.7	+1.6	4.49	10.97	9.7	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
135	BFNLR	0.1	14.83	33.97	194	.965	+0.4	+2.7	3.90	10.11	10.0	223	19	.61	951	8	1.87	957	4	2.84	230	16	.28
136	(0.85)	0.3	14.80	33.83	194	.964	+0.5	+2.2	4.18	10.52	9.9	222	19	.61	950	8	1.87	956	4	2.83	230	16	.28
137		0.5	14.79	33.75	194	.963	+0.6	+1.9	4.33	10.73	9.8	222	19	.61	950	8	1.87	955	4	2.83	230	16	.28
138		0.7	14.78	33.70	194	.963	+0.7	+1.7	4.43	10.88	9.8	222	19	.61	950	8	1.87	955	4	2.83	231	16	.28
139		0.9	14.78	33.66	194	.963	+0.7	+1.6	4.51	10.99	9.7	222	19	.61	950	8	1.86	954	4	2.82	231	16	.28
			STARTING MOISTURE STORAGE VALUES AS OF OCTOBER 1																				
141	GWS	0.01	14.57	33.71	195	.963	+0.4	+1.5	4.49	6.51	4.64	222	19	.60	949	8	1.86	954	4	2.83	231	16	.28
142	(0.355)	0.18	14.67	33.69	194	.963	+0.5	+1.6	5.05	6.82	4.49	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
143		0.54	14.89	33.65	194	.963	+0.9	+1.7	6.26	7.46	4.64	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
144		0.71	14.99	33.64	194	.963	+1.0	+1.7	6.82	7.77	4.64	222	19	.61	950	8	1.87	954	4	2.83	231	16	.28
145	UZS	0.1	14.81	33.76	196	.963	+0.7	+1.8	5.70	7.17	4.65	223	19	.61	952	8	1.87	956	4	2.83	231	16	.29
146	(0.0)	0.5	14.96	34.14	201	.962	+0.7	+2.7	5.97	7.32	4.67	227	19	.62	959	8	1.90	962	4	2.86	233	16	.29
147		1.0	15.22	34.33	205	.962	+1.0	+3.2	7.09	7.92	4.53	229	19	.63	964	8	1.91	965	4	2.87	235	16	.29
150	LZS	0.01	9.37	25.19	201	.942	-1.8	-17.4	1.48	0.92	3.81	53	19	.14	630	8	1.08	8.36	4	2.33	200	16	.25
151	(11.88)	6.0	11.92	29.00	164	.958	-0.7	-9.1	2.31	2.85	4.28	150	19	.41	813	8	1.50	884	4	2.54	210	16	.26

955-2426-2

Table 13. Sensitivity Analysis of Little Chestuee (Part 4 of 4)

SENSITIVITY ANALYSIS FOR LITTLE CHESTUEE WATERSHED WATER YEAR 1951 DRAINAGE AREA 8.24 Square Miles

ID	PARAM	VALUE	DAILY STREAMFLOW STATISTICAL SUMMARY: FLOW STATISTICS MEAN	FLOW STATISTICS STD DEV.	ERROR STATISTICS ROOT SUM SQUARE	ERROR STATISTICS DAILY CORR. COEFF.	AVERAGE ERRORS LOW FLOWS (4.5)	AVERAGE ERRORS HIGH FLOWS (33.1)	LOW FLOW STATISTICS MEAN OF (Aug.)	LOW FLOW STATISTICS MEAN OF (June)	LOW FLOW STATISTICS LOWEST OF (Feb.)	STORM ANALYSIS SUMMARY: STORM OF 1/14/51 #1 PEAK (CFS)	#1 PEAK (HOUR)	#1 R/O (IN)	STORM OF 2/1/51 #2 PEAK (CFS)	#2 PEAK (HOUR)	#2 R/O (IN)	STORM OF 3/29/51 #3 PEAK (CFS)	#3 PEAK (HOUR)	#3 R/O (IN)	STORM OF 9/22/51 #4 PEAK (CFS)	#4 PEAK (HOUR)	#4 R/O (IN)
OBSERVED CONFIGURATION			14.01	27.9					5.25	7.24	11.0	191	21	0.49	798	9	1.61	954	2	2.25	230	15	.20
BEST SIMULATED CONFIGURATION			14.78	33.67	194	.963	+0.7	+1.6	4.50	10.97	9.7	222	19	0.61	950	8	1.86	954	4	2.83	231	16	.28
			STARTING MOISTURE STORAGE VALUES AS OF OCTOBER 1 (CONTINUED)																				
154		18.0	16.83	41.82	345	.946	+0.5	+20.0	10.05	8.22	4.84	288	19	.83	1092	8	2.32	1075	4	3.32	315	16	.39
155		24.0	17.72	41.90	347	.948	+0.5	+24.6	10.36	8.29	5.12	231	19	.83	1007	8	2.29	1023	4	3.19	483	16	.59
156	BNFX	0.01	14.78	33.67	194	.963	+0.7	+1.6	5.63	7.13	4.49	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
157	(0.747)	0.40	14.78	33.67	194	.963	+0.7	+1.6	5.63	7.13	4.49	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
159		1.00	14.78	33.67	194	.963	+0.7	+1.6	5.64	7.13	4.49	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
162	IES	0.1	14.84	33.66	195	.962	+0.8	+1.6	6.35	7.13	4.49	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
164	(0.0)	0.5	15.08	33.89	213	.954	+1.4	+1.6	9.21	7.13	4.49	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
165		1.0	15.38	34.77	264	.927	+2.0	+1.6	12.79	7.13	4.49	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
167		5.0	17.81	57.81	931	.544	+7.4	+1.6	41.37	7.13	4.49	222	19	.61	950	8	1.86	954	4	2.83	231	16	.28
			EVAPORATION DATA																				
106	EPAET	19.14	18.44	37.79	304	.935	+2.6	+18.6	8.60	16.63	10.4	246	19	.70	998	8	2.03	993	4	3.07	566	16	.70
108	(31.9)	25.52	16.35	35.40	234	.954	+1.6	+9.1	5.98	13.45	10.0	235	19	.65	974	8	1.95	973	4	2.94	377	16	.46
111		38.28	13.48	32.18	169	.966	-0.1	-4.7	3.57	9.24	9.4	210	19	.56	927	8	1.79	935	4	2.71	139	16	.18
113		44.66	12.35	30.83	157	.967	-0.7	-10.8	2.89	7.93	9.0	196	19	.51	904	8	1.71	915	4	2.62	75	16	.10
114	MNRD	81.0	15.60	34.98	220	.958	+1.1	+6.2	5.10	12.18	9.7	233	19	.64	973	8	1.93	974	4	2.92	303	16	.37
116	(135.0)	108.0	15.17	34.30	207	.961	+0.9	+3.8	4.77	11.54	9.7	228	19	.62	961	8	1.90	964	4	2.87	263	16	.32
119		162.0	14.40	33.06	183	.964	+0.5	-0.5	4.25	10.46	9.7	217	19	.59	938	8	1.83	945	4	2.78	200	16	.25
121		189.0	14.04	32.46	174	.966	+0.3	-2.5	4.01	10.00	9.7	212	19	.57	927	8	1.80	935	4	2.73	170	16	.21

955-2428-2

Table 14. Summary of Sensitivity Analysis for Little Chestuee (Part 1 of 3)

WY '51

ID	PARAMETERS: PARAMETER	PARAMETERS: PERCENT VARIATION	#3 MAJOR WINTER STORM 3/29/51 PEAK % CHANGE	U/S	R/O % CHANGE	U/S	#4 MAJOR SUMMER STORM 9/22/51 PEAK % CHANGE	U/S	R/O % CHANGE	U/S	TOTAL FLOW % CHANGE	U/S	MEAN DAILY FLOW DRIEST MO./Aug. % CHANGE	U/S
	WATERSHED PARAMETERS													
51	AREA	-50	-50	+1.00	-50	+1.00	-50	+1.00	-50	+1.00	-50	+1.00	-50	+1.00
52	(8.24)	+50	+50	+1.00	+50	+1.00	+50	+1.00	+54	+1.07	+50	+1.00	+50	+1.00
53	FIMP	-100	-0.42	+0.004	-1.05	+0.010	-6.5	+0.065	-7.14	+0.071	-1.3	+0.013	-3.1	+0.031
57	(0.013)	+300	+1.57	+0.005	+2.47	+0.008	+18.2	+0.061	+25.0	+0.083	13.9	+0.013	+8.9	+0.030
		FIMP												
58		0.10	+3.5		+5.6		+41		+54		+8.7		+20	
59		0.20	+7.2		+13		+89		+111		+19		+43	
60		0.50	+18.9		+33		+235		+289		+49		+112	
		FWTR												
63	FWTR	0.01	+0.42		+0.35		+3.9		17.1		-0.7		-9.1	
65	(0.0)	0.10	+3.67		+5.65		+42		+50		-3.2		-26	
67		0.50	+18.2		+29.6		+210		+250		+23		+51	
	SOIL MOISTURE PARAMETERS													
2	BMIR	50	+15	-0.30	+19	-0.38	+54	-1.08	+54	-1.08	+3.6	-0.07	-24	+0.48
3	(6.3)	+50	-14	-0.28	-16	-0.32	-30	-0.60	25	-0.50	-1.7	-0.03	+13	+0.26
6	LZC	-50	+09	-0.18	+14	-0.28	-14	+0.28	-11	+0.22	+13	-0.26	-05	+0.09
7	(8.0)	+50	-10	-0.20	-14	-0.28	+19	+0.38	+21	+0.42	-15	-0.30	0.0	0.0
10	ETLF	-50	+1.0	-0.02	+0.7	-0.01	+82	-1.64	+82	-1.64	+4.3	-0.09	+15	-0.30
11	(0.25)	+50	-0.1	0.0	-0.4	-0.01	-39	-0.78	-36	-0.72	-1.6	-0.03	-5.8	-0.12
14	SIAC	-50	-05	+0.10	-06	+0.12	+11	-0.22	+11	-0.22	-0.7	+0.001	+2.0	-0.04
15	(0.30)	+50	+04	+0.09	+05	+0.10	-11	-0.22	-07	-0.14	+0.10	+0.002	-2.2	-0.04
18	SUZC	-50	+0.0	0.0	-0.4	+0.01	+42	-0.84	+43	-0.86	+3.7	-0.07	+20	-0.40
19	(0.30)	+50	+0.5	+0.01	+0.4	+0.01	-40	-0.81	-36	-0.71	-3.1	-0.06	-11	-0.22
22	BUZC	-50	0.0	0.0	-0.35	+0.01	+5.6	-0.11	+7.1	-0.143	+0.2	-0.004	+0.6	-0.01
23	(0.42)	+50	+0.1	0.0	0.00	0.0	-6.5	-0.13	-3.6	-0.70	-0.2	-0.004	-0.9	-0.02
40	BIVF	-50	+1.9	-0.04	+1.4	-0.03	0.0	0.0	+3.6	-0.071	-0.07	+0.001	+0.2	-0.004
41	(0.40)	+50	-5.7	-0.11	-4.6	-0.09	-0.87	-0.02	0.0	0.00	-0.30	+0.006	-2.9	-0.058
68	VINTMR	-100	+0.1	-0.001	-1.1	+0.01	-0.4	+0.004	+3.6	-0.036	+0.7	-0.007	+5.0	-0.050
69	(0.149)	-50	0.0	0.00	-0.4	+0.01	-0.4	+0.009	+3.6	-0.072	+0.1	-0.001	+0.9	-0.018
71		+50	+0.1	+0.002	+0.4	+0.01	0.0	0.00	0.0	0.00	-0.1	-0.002	-0.9	-0.018
72		+100	+0.1	+0.001	+0.7	+0.01	0.0	0.00	0.0	0.00	-0.2	-0.002	-1.6	-0.016
74		+571	+0.8	+0.001	+3.2	+0.01	+1.3	+0.002	+3.6	+0.006	-0.9	-0.002	-6.7	-0.012
		SUBWF												
122	SUBWF	0.05	0.00	0.00	-0.35	-0.070	-0.43	-0.086	0.00	0.00	-2.7	-0.540	-4.9	-0.98
123	(0.0)	0.10	-0.10	-0.01	-0.71	-0.071	-0.43	-0.043	0.00	0.00	-5.5	-0.550	-9.6	-0.96
124		0.20	-0.31	-0.02	-1.05	-0.052	-0.43	-0.022	0.00	0.00	-11	-0.545	-19	-0.95
125		0.30	0.52	-0.02	-1.41	-0.047	-0.43	-0.014	0.00	0.00	-16	-0.533	-29	-0.97
		GWETF												
126	GWETF	0.05	0.00	0.00	-0.35	-0.070	-0.87	-0.174	0.00	0.00	-8.5	-1.70	-49	-9.8
127	(0.0)	0.10	-0.10	-0.01	-0.71	-0.071	-0.87	-0.087	-3.57	-0.357	-14	-1.40	-70	-7.0
128		0.20	-0.21	0.01	-0.71	-0.036	-1.30	-0.065	-3.57	-0.179	21	-1.05	-86	-4.3
129		0.30	-0.31	0.01	-1.05	-0.035	-1.30	-0.043	-3.57	-0.119	-26	-0.857	-91	-3.0

Table 14. Summary of Sensitivity Analysis for Little Chestuee (Part 2 of 3)

WY '51

ID	PARAMETERS		CHANGE IN RESPONSE TO PARAMETER VARIATION											
	PARAMETER	PERCENT VARIATION	#3 MAJOR WINTER STORM 3/29/51				#4 MAJOR SUMMER STORM 9/22/51				TOTAL FLOW		MEAN DAILY FLOW DRIEST MO./ Aug.	
			PEAK		R/O		PEAK		R/O					
			% CHANGE	U/S	% CHANGE	U/S	% CHANGE	U/S	% CHANGE	U/S	% CHANGE	U/S	% CHANGE	U/S
· · · · OVERLAND FLOW PARAMETERS · · · ·														
46	IFRC	-50	+0.52	-0.010	+0.35	-0.007	0.00	0.00	0.0	0.00	0.0	0.00	-0.2	+0.004
47	(0.10)	+50	-0.31	-0.006	-0.71	-0.014	0.00	0.00	0.0	0.00	0.0	0.00	-0.2	-0.004
77	OFSS	-50	+0.42	-0.008	-0.35	+0.007	-0.43	+0.009	0.0	0.00	-0.2	+0.004	+1.3	-0.026
78	(0.237)	+50	-0.10	-0.002	0.00	0.00	0.00	0.00	+3.6	+0.071	+0.07	+0.001	-0.9	-0.018
79		+100	-0.21	-0.002	0.00	0.00	0.00	0.00	+3.6	+0.036	+0.2	+0.002	-1.3	-0.013
81		+300	-0.31	-0.001	+0.35	+0.001	0.00	0.00	+3.6	+0.012	+0.3	+0.001	-2.4	-0.008
82	OFSL	-100	-0.31	+0.003	+1.05	-0.010	0.0	0.0	+3.6	-0.036	+0.7	-0.007	-5.3	+0.053
83	(630.0)	-50	-0.31	-0.006	+0.35	-0.007	0.0	0.0	+3.6	-0.071	+0.3	-0.007	-2.4	+0.048
84		+50	+0.52	+0.010	-0.35	0.007	-0.9	-0.2	0.0	0.0	-0.3	-0.006	+1.6	+0.032
85		+100	+0.84	+0.008	-0.71	-0.007	-6.5	-0.06	3.6	-0.04	-0.5	-0.005	+29	+0.029
87		+400	+1.26	+0.003	-1.77	-0.004	-29	-0.07	-25	-0.06	-1.2	0.003	+8.0	+0.020
88	OFMN	-51	0.31	+0.006	+0.35	-0.007	0.0	0.0	+3.6	-0.07	+0.34	-0.007	-2.4	+0.047
89	(0.061)	+49	+0.52	+0.011	-0.35	-0.007	-0.9	-0.02	0.0	0.0	-0.2	-0.004	+1.6	+0.033
92		+400	+1.36	+0.003	-1.77	-0.004	-29	-0.07	-25	-0.06	-1.2	-0.003	+8.0	+0.020
93	OFMNIS	-75	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.00	-0.2	+0.003
97	(0.002)	+400	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.00	-0.2	0.000
· · · CHANNEL ROUTING AND GROUND WATER PARAMETERS · · ·														
28	CSRX	-50	+0.8	-0.02	+2.47	-0.05	+35.0	-0.70	+3.6	-0.071	+0.2	-0.004	0.0	0.00
29	(0.95)	+50	-22	-0.44	-12.0	-0.24	-44.6	-0.89	-10.7	-0.214	-0.1	-0.002	-0.4	-0.01
32	FSRX	-50	0.0	0.00	0.00	0.00	0.00	0.0	0.00	0.00	0.0	0.00	0.0	+0.004
33	(0.95)	+50	-18	-0.36	-1.77	-0.04	-0.43	-0.01	+3.6	+0.071	+0.3	+0.006	-0.2	-0.004
36	BRFC	-50	+0.4	-0.01	+0.35	-0.01	-0.43	+0.01	0.00	0.00	+1.3	0.026	30	+0.60
37	(0.98)	+50	-0.5	-0.01	-1.41	-0.03	+0.43	-0.01	+7.14	+0.14	-6.2	-0.124	+47	+0.94
99	CHCAP	-75	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.0	0.0	0.00	-0.2	+0.003
103	(200.0)	+50	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.0	0.0	0.00	-0.2	-0.004
104		+100	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.0	0.0	0.00	-0.2	-0.002
130	EXQPV	-97	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.0	0.0	0.00	-0.2	+0.002
131	(0.30)	-50	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.0	0.0	0.00	-0.2	+0.004
132		+50	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.0	0.0	0.00	-0.2	-0.004
134		+233	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.0	0.0	0.00	-0.2	-0.001
135	BFNLR	88	+0.31	-0.004	+0.35	-0.004	-0.43	+0.005	0.0	0.0	+0.34	-0.004	-13	+0.147
136	(0.85)	-65	+0.21	-0.003	0.00	0.000	-0.43	+0.006	0.0	0.0	+0.14	-0.002	-7.1	+0.110
137		41	+0.10	-0.002	0.00	0.000	-0.43	+0.010	0.0	0.0	+0.07	-0.002	-3.8	+0.092
138		-18	+0.10	-0.006	0.00	0.000	0.00	0.00	0.0	0.0	0.00	0.00	-1.6	+0.091
139		+5.9	0.00	0.00	-0.35	-0.059	0.00	0.00	0.0	0.0	0.00	0.00	+0.2	+0.034

Table 14. Summary of Sensitivity Analysis for Little Chestuee (Part 3 of 3)

WY '61

ID	PARAMETERS		CHANGE IN RESPONSE TO PARAMETER VARIATION											
	PARAMETER	PERCENT VARIATION	#3 MAJOR WINTER STORM 3/29/51 PEAK		R/O		#4 MAJOR SUMMER STORM 9/22/51 PEAK		R/O		TOTAL FLOW		MEAN DAILY FLOW DRIEST MO./Aug.	
			% CHANGE	U/S	% CHANGE	U/S	% CHANGE	U/S	% CHANGE	U/S	% CHANGE	U/S	% CHANGE	U/S
· · STARTING MOISTURE STORAGE VALUES AS OF OCTOBER 1 · ·														
141	GWS	-97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.4	+0.014	+3.3	-0.034
142	(0.355)	-49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.7	+0.014	0.0	0.00
143		+52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	+0.7	+0.013	+3.3	+0.063
144		+100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	+1.4	+0.014	+3.3	+0.033
		UZS												
145	UZS	0.1	+0.21		0.0		0.00		+3.6		+0.2		+3.6	
146	(0.0)	0.5	+0.84		+1.05		+0.87		+3.6		+1.2		+4.0	
147		1.0	+1.15		+1.41		+1.73		+3.6		+3.0		+0.9	
150	LZS	-100	-12.4	+0.124	-17.7	+0.177	-13.4	+0.134	-10.7	+0.107	-37	+0.37	-15.0	+0.150
151	(11.88)	-50	-7.3	+0.148	-10.2	+0.205	-9.1	+0.184	-7.14	+0.144	-19	+0.38	-4.7	+0.095
154		+52	+12.6	+0.245	+17.3	+0.336	+36.4	+0.707	+39.3	+0.763	+14	+0.27	+7.8	+0.151
155		+102	+7.2		+12.7	+0.125	+109	+1.07	+111	+1.09	+20	+0.20	+14	+0.137
156	BFNX	-99	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0	0.00	0.0	0.00
157	(0.747)	-47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0	0.00	0.0	0.00
159		+34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0	0.00	0.0	0.00
		IFS												
162	IFS	0.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	+0.4	+4.0	0.0	0.00
164	(0.0)	0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	+2.0	+4.0	0.0	0.00
165		1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	+4.1	+4.1	0.0	0.00
167		5.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	+16.4	+3.3	0.0	0.00
· · · · EVAPORATION DATA · · · ·														
106	EPAET	-40	+4.1	-0.10	+8.5	-0.210	+145	-3.62	+150	-3.75	+25	-0.62	+91	-2.28
108	(31.9)	-20	+2.0	-0.10	+3.8	-0.190	+63	-3.15	+64	-3.20	+11	-0.55	+33	-1.65
111		+20	-2.0	-0.10	-4.2	-0.210	-40	-2.00	-35	-1.75	-8.8	-0.44	-21	-1.05
113		+40	-4.1	-0.10	-7.4	-0.186	-68	-1.70	-64	-1.60	-16	-0.40	-36	-0.90
114	MNRD	-40	+2.1	-0.05	+3.2	-0.080	+31	-0.775	+32	-0.80	+5.5	-0.14	+13	-0.325
116	(135.0)	-20	+1.1	-0.05	+1.4	-0.075	+14	-0.695	+14	-0.72	+2.6	-0.13	+6.0	-0.300
119		+20	-0.9	-0.05	-1.8	-0.088	-13	-0.670	-11	-0.54	-2.6	-0.13	-5.6	-0.280
121		+40	-2.0	-0.05	-3.5	-0.088	-26	-0.660	-25	-0.62	-5.0	-0.12	-11	-0.275

3.6 CORRELATION (TASK 6)

The data base for the Correlation task consists of (1) the ten sets of "best" model parameters from the Calibration task and (2) ten sets of Watershed Parameters (i.e., observable or inferable characteristics) from the Physiographic Data Base Task, as indicated in Figure 28. The objective of the task was to derive a statistically based set of formulas for quantifying those parameters which are normally estimated by the calibration process previously described.

A linear correlation coefficient was calculated for each of 88 pairs of parameters. In each pair, one parameter was chosen from the set of calibrated model parameters and the other from the set of "observable" parameters. These correlation coefficients, for a linear relationship ($y = a + bx$), were found to be generally rather low, the exceptions (up to 0.8) being associated with parameters whose values lie in narrow ranges. The results of this step provided a basis for selection of combinations of observable parameters for the multivariate linear regression analysis. It was necessary to accept linear correlation coefficients as low as 0.39 in order to generate a useable expression for each calibrated parameter.

The result of the multivariate regression analysis[16] is the set of equations listed in Table 15. They were used to estimate model parameters for the Validation task. The parameters FIMP, OFSS, OFMN, OFSL, and OFMNIS can be determined from remotely sensed image data, provided resolution (not yet determined precisely) is adequate and relative elevations can be discerned. The soil parameters AWC (Available Water Capacity) and PERM-A (Permeability of the A Horizon) were obtained from County Soil Surveys of the U.S. Soil Conservation Service; they are not remotely sensible at present. In a future application in an ungaged area, some ground truth data related to soil characteristics will be required unless those characteristics can be inferred from surrogate information[17,18].

The data base sample points are widely scattered in all cases. This is evident from the statistical indices calculated and shown in Table 16. It would obviously be worthwhile to refine the Correlation Analysis. Additional observables should be introduced, carefully chosen with regard both to hydrologic phenomena and remote sensing system capabilities. Additionally, interaction between independent variables should be resolved through translation into an intermediate set of composite variables. Nevertheless, this simplified analysis produced results which led to acceptable validation runs and a strong indication of the feasibility of the technique.

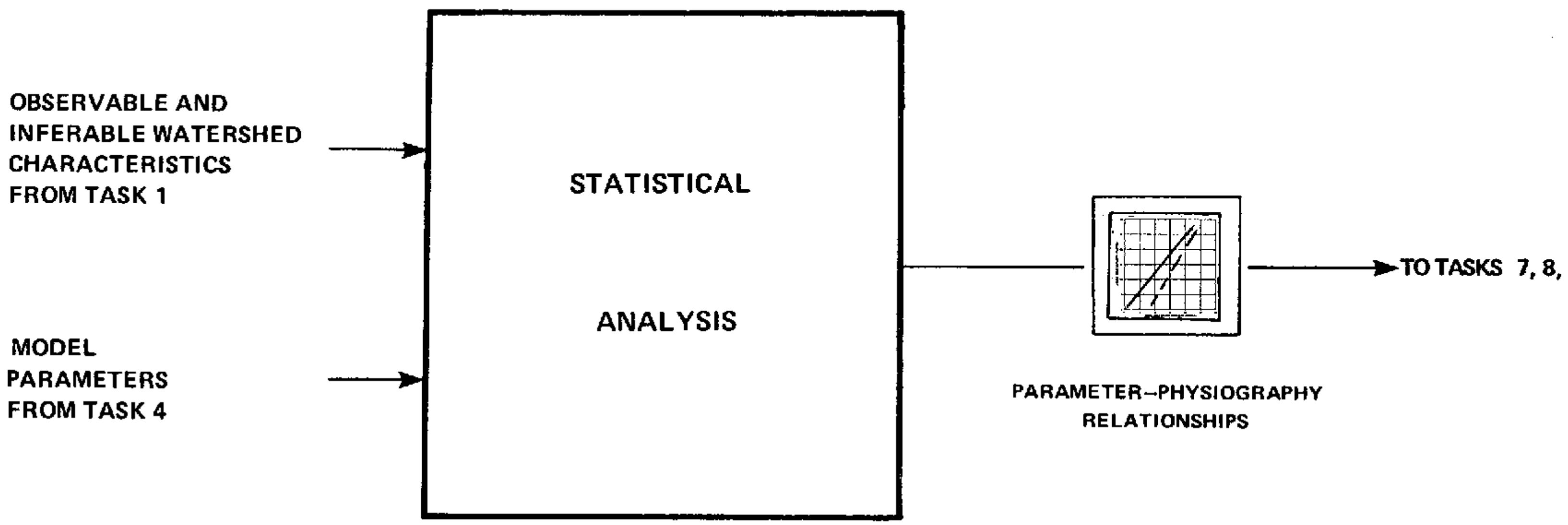


Figure 28. Task 6: Correlation

Table 15. Correlation Results (Multiple Regression Analysis)

BMIR	=	5.27	+	0.75 PERM A						
LZC	=	1.80	+	4.73 OFSS	+	2.63 AWC	+	0.26 PERM A		
ETLF	=	0.05	+	1.49 OFMN						
SUZC	=	0.46	+	2.51 FIMP	–	0.04 AWC				
SIAC	=	0.80	+	3.84 FIMP	–	0.02 AWC	–	0.37 OFSS	–	0.0003 OFSL
BUZC	=	0.18	+	9.69 OFMN	–	0.0003 OFSL				
BIVF	=	–0.02	–	9.25 FIMP	+	0.0004 OFSL				
CSRX	=	0.95	+	1.92 OFMNIS	–	0.003 AWC				
FSRX	=	1.01	–	0.006 PERM A	–	0.00003 OFSL				
BFRC	=	0.97	–	3.29 FIMP						
BFNLR	=	0.86	–	4.38 FIMP						

Table 16. Statistical Characteristics, Regression Equations

PARAMETER	S.M.	S.E.E.	S.M.C.C.
BMIR	6.94	2.89	0.15
LZC	4.96	1.26	0.58
ETLF	0.135	0.060	0.17
SUZC	0.290	0.153	0.42
SIAC	0.300	0.227	0.47
BUZC	0.349	0.109	0.82
BIVF	0.296	0.332	0.36
CSRX	0.957	0.016	0.50
FSRX	0.959	0.022	0.43
BFRC	0.935	0.088	0.24
BFNLR	0.815	0.097	0.31

S.M. = Sample Mean

S.E.E. = Standard Error of Estimate

S.M.C.C. = Square of Multiple Correlation Coefficient

3.7 VALIDATION (TASK 7)

Five basins of the Tennessee Valley were identified for the Validation task. They were exempt from calibration and treated as "ungaged" watersheds. The watershed description and historical data from the integrated data base, and the model parameters estimated by the linear regression equations generated in the Validation task, are inputs, as indicated in Figure 29. For each basin, a multiyear simulation was run, the synthesized streamflow results compared with observed streamflow, and analyses of the results printed out in tabular and plot formats.

Results of the validation runs are summarized in Table 17. Mean monthly streamflow correlation coefficients indicate generally good agreement between simulated and observed values. For each basin, the largest winter storm event was chosen for comparison of simulated streamflow peaks with observed peaks.

Examples of daily and hourly plots are shown in Figures 30 and 31 respectively. In the latter, the observed storm event is represented only by the flood peak. Peak magnitude and timing are the basis for judging the effectiveness of the model with respect to storm events. Plotting an observed runoff hydrograph at one-hour intervals would require a prohibitively expensive manual translation of strip-chart records into hourly runoff for every selected storm event.

The result of the Validation task is a strong indication of the feasibility of making streamflow forecasts for an ungaged basin, at least with respect to mean daily streamflow. With respect to storm runoff peaks, the result is inconclusive. Further refinement of the technique will lead to the ultimate method depicted in Figure 32.

3.8 RESOLUTION/ACCURACY ANALYSIS (TASK 8)

This task was not performed in the study because of budgetary limitations. It is being addressed in a separate NASA study, the results of which will be available in the second quarter of 1974.

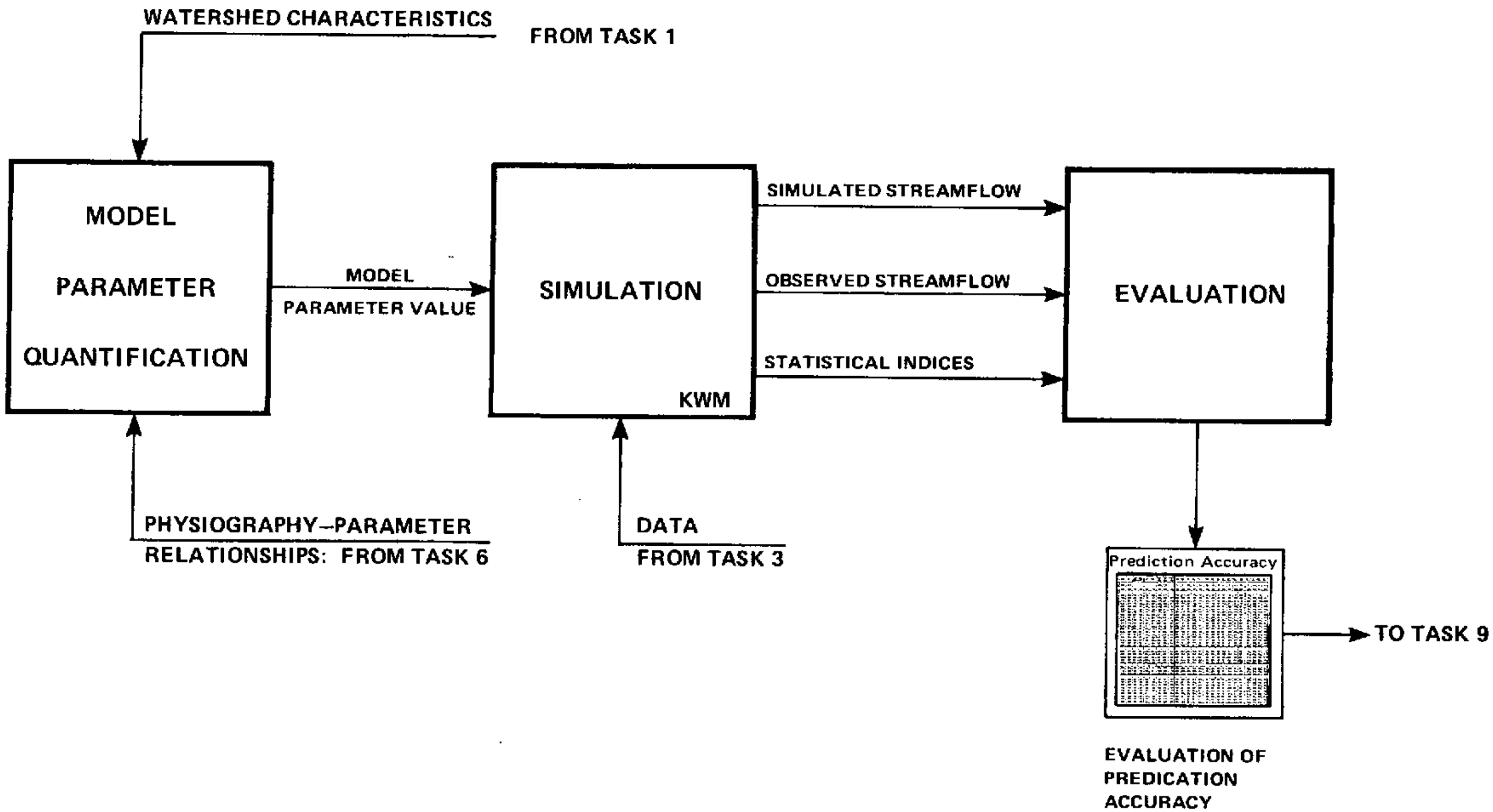


Figure 29. Task 7: Validation

C-2

Table 17. Validation Results

WATERSHED				YEARS OF RECORDS			STREAMFLOW						LARGEST WINTER STORM				
							CORRELATION COEFFICIENT		DAILY, CFS				DATE	PEAK			
NO.	SHORT NAME	AREA							MEAN		MAX			FLOW, CFS		TIME, HR	
		MI^2	KM^2	YRS	FROM	THRU	M'LY	D'LY	OBS	SIM	OBS	SIM		OBS	SIM	OBS	SIM
4	NOLAND CREEK	13.8	35.7	9	56	64	.95	.83	47.2	37.7	923	982	12–12–61	1,371	1,375	1	1
6	BIG BIGBY CREEK	17.5	45.3	5	64	68	.92	.86	27.0	24.4	1020	1707	3–6–67	1,510	1,069	40	35
8	LITTLE RIVER	26.8	69.5	5	65	69	.96	.87	108	92	2840	3675	2–13–66	4,049	7,727	7	6
10	PINEY CREEK	55.8	145	8	61	68	.96	.86	94	98	4220	6242	3–12–63	12,900	13,597	25	28
16	EAST FORK POPLAR	19.5	50.5	8	62	69	.93	.87	47	31	1450	1456	3–12–63	1,802	2,013	20	5

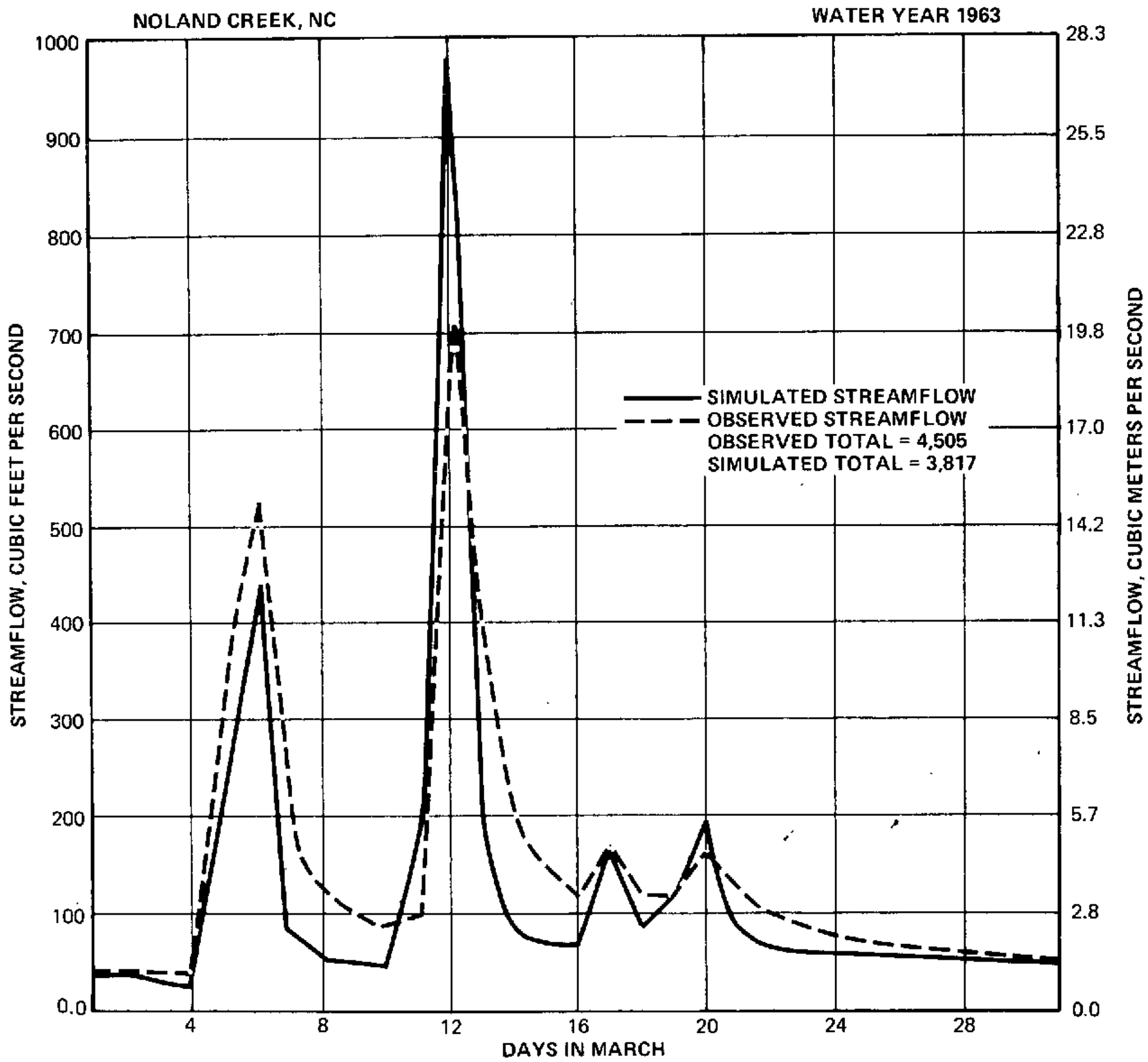


Figure 30. Example of Mean Daily Streamflow Plots

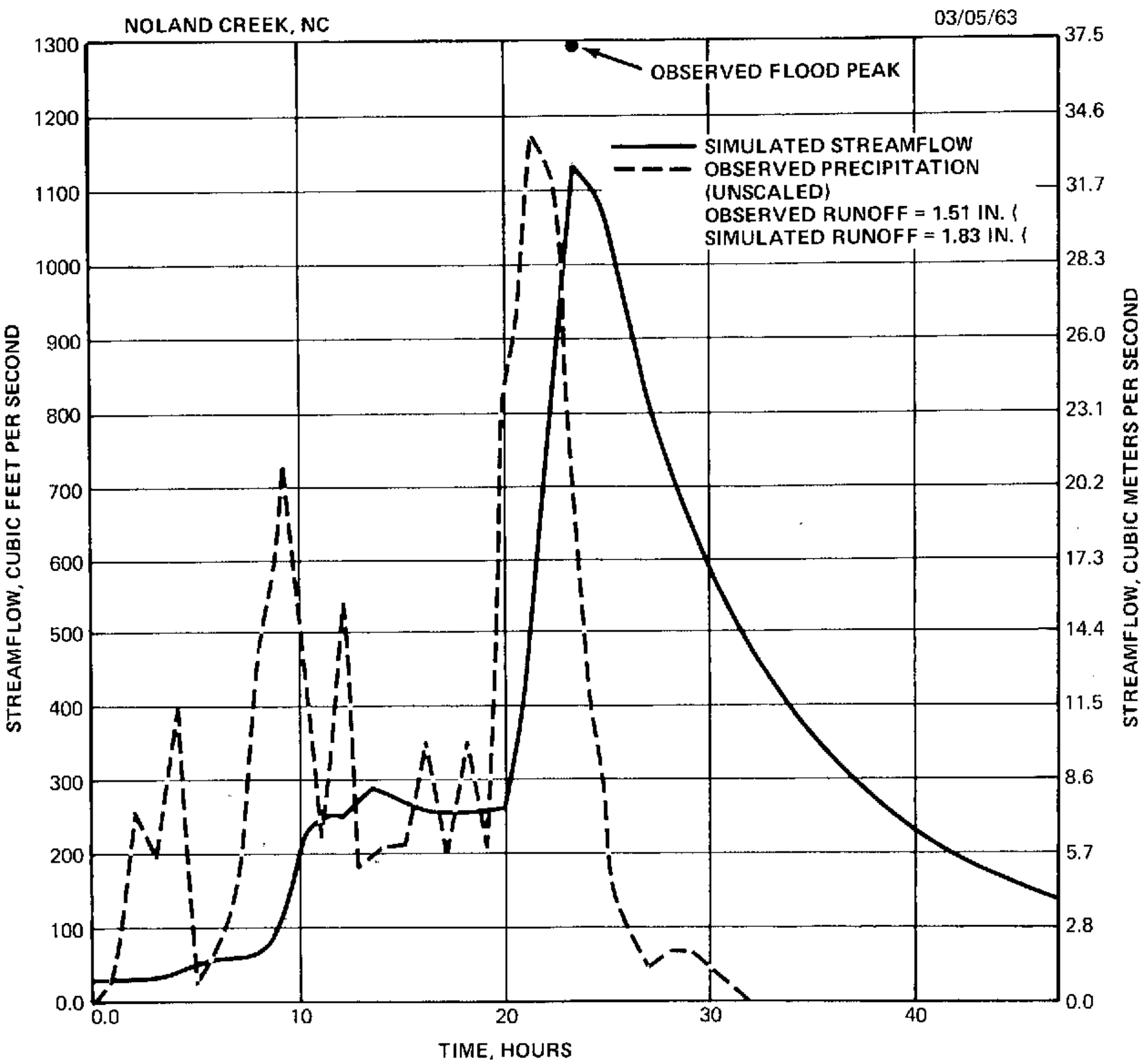


Figure 31. Example of Hourly Streamflow Plots

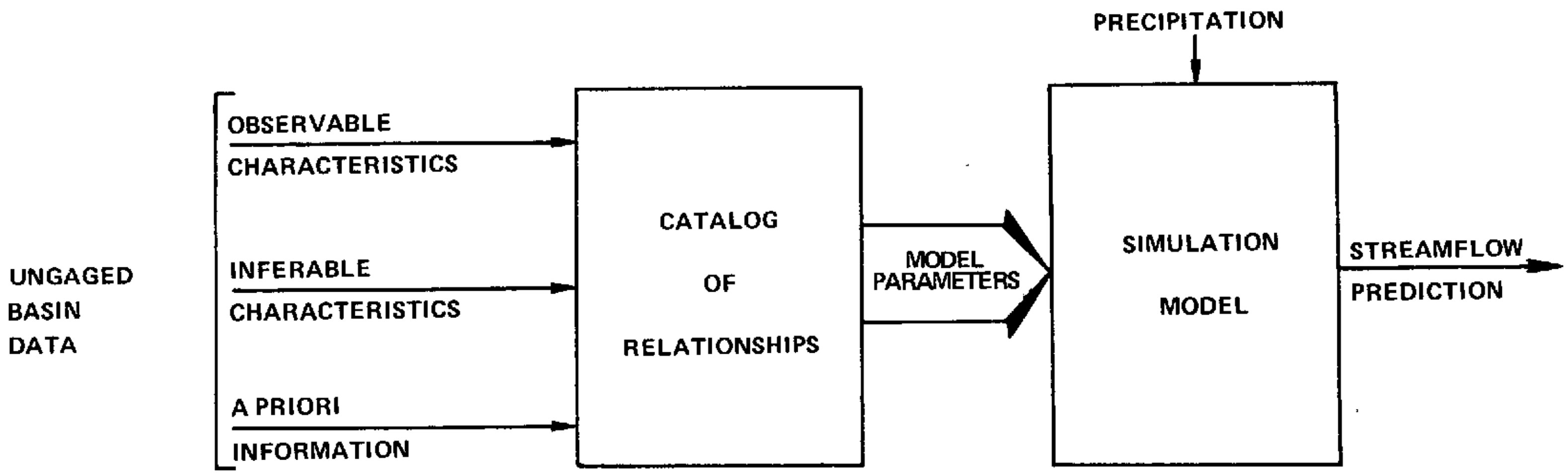


Figure 32. Ultimate Method

SECTION 4

RECOMMENDED ADDITIONAL RESEARCH

As in all such research, this feasibility study revealed several topics deserving further study. Also, the investigators believe that some tasks should be done more thoroughly and/or more efficiently with the benefit of experience gained in subsequent tasks. The following paragraphs summarize topics the authors recommend for additional research.

4.1 EXPANDED CORRELATION DATA BASE

The five validation runs used data derived from the results of a correlation analysis which was in turn based on calibration of only ten basins. The size of the sample population limits confidence in the results; the good correlations scored in the validation runs may well have been "good luck". It is suggested that the following tasks be performed.

- Collect historical and physiographic data for twenty additional watersheds of the Tennessee Valley, including five from the Mississippi Alluvial Plain Region.
- Preprocess and format the new data and integrate it into the Master Data Bank.
- Rework the Correlation Analysis using the expanded data base (15 basins).
- Quantify parameters for ten basins, the five used for validation in the basic study and five reserved for the purpose from the new set.
- Perform ten validation runs and analyze the results.
- Revise this report or issue a supplementary report.

4.2 REFINED CORRELATION STUDY

Even with the limited population sample (ten sets of parameters) used in the basic feasibility study, the correlation analysis should be redone with a more rigorous methodology to achieve more refined results. It is desirable, for instance, to remove the sub-surface aspects, such as permeability and water holding capacity, because they are not directly measurable or inferrable from remote sensing. Additional physical characteristics which lend themselves to determination by remote sensing, even from satellite altitudes, should be introduced into the study. Hydrologic expertise should be brought to bear in the selection of combinations of observable characteristics. Intermediate or composite variables should also be derived in order to eliminate the effects of interaction among the selected independent parameters. This additional research task should produce a report which is supplementary to this one.

4.3 VALIDATE TECHNIQUE IN OTHER REGIONS

A similar study could be performed in another region which is physiographically and climatically very different from the Tennessee Valley, as a further validation of the feasibility of the technique. This additional work should concentrate in an area in which snowfall is a significant form of precipitation.

4.4 DOCUMENT THE SYSTEM FOR SIMULATION AND ANALYSIS OF WATERSHEDS

The system for simulation and analysis of watersheds, developed by IBM around the KWM and OPSET programs, is an effective tool for research and hydrologic modeling, river forecasting, and water resources management. However, it is presently useful only to those who are involved in the development of the system, who are familiar with its operation. Inadequate documentation exists to transfer the tool to another investigating team without an extensive period of learning and familiarization. It is suggested that the system for simulation and analysis of watersheds be documented by the preparation of operating instructions and users' manuals containing flowcharts, program description, and step by step instructions of how another user could take advantage of this system of programs and methods.

4.5 PILOT DEMONSTRATION, OPERATIONAL RIVER FORECAST APPLICATION

Accepting the results of the study as a strong indication of the feasibility of the technique the study originally set out to investigate, it appears appropriate for NASA to leave further refinement of the technique to potential users and other researchers. A more appropriate step for NASA to take may well be pursuit of a study jointly with a potential user agency, aimed at implementation of a pilot demonstration of operational river forecasting utilizing the models, methods, and other results of the feasibility study. The first product of such an undertaking would be a specification for the demonstration system, to be followed by implementation of the pilot system. For a period of time the pilot system could be operated in parallel with the user agency's normal river forecast methods. Then the two systems could be compared with respect to accuracy and efficiency. Should the demonstration prove successful, complete documentation of the system, as a NASA product available to potential user agencies, would be the final task.

APPENDIX A

SUMMARY OF STUDY HISTORY

The feasibility study reported herein began in mid-1971. At the beginning of 1972, it was reduced to a low-level sustaining effort and then resumed at an appropriate manning level in July 1972. It is appropriate to summarize those three segments of the study in this Appendix.

A.1 LAST HALF, CALENDAR YEAR 1971

During the months July through December 1971, with the support of the Research Institute of the University of Alabama in Huntsville, IBM

- Selected a family of 55 Tennessee Valley Watersheds, with the advice and assistance of the Tennessee Valley Authority (TVA)
- Collected 30 percent of historical data needed for the study
- Acquired 80 percent of the applicable topographical maps and photographic coverage
- Programmed and operated the statistical rainfall-runoff correlation technique sometimes referred to as the "API Method"
- Programmed and operated three basic synthetic hydrograph regeneration methods, those of Clark, Nash, and Decoursey, with two additional variations on the Nash method
- After a review of available simulation models, selected the Kentucky Watershed Model and its companion calibration program for continuation of the study.
- Established a mutually beneficial technical liaison with the Tennessee Valley Authority and orally reported the study concept and progress to other organizations: World Bank; U. S. Army Corps of Engineers; U. S. Departments of Interior (Geological Survey), Agriculture (Agricultural Research Service), and Commerce (National Oceanic and Atmospheric Administration); and National Academy of Sciences.

A.2 FIRST HALF, CALENDAR YEAR 1972

The initial funding authorization expired at the end of 1971, and the study was reduced to a sustaining effort funded at a one-man level from January through June 1972. Highlights of this interim effort were as follows:

- The Kentucky Watershed Model and its optimization program were acquired and operated in the IBM-Huntsville facility. Additionally, the Tennessee Valley Authority Daily Flow Model, an experimental simulation program, was acquired, set up, and run.

- Modifications and improvements in the KWM and OPSET were begun during this interim period in order to adapt it to the purposes of the feasibility study. These additions and improvements included preprocessing routines for input data and implementation of several plot and tabular output options.

- The historical data base was expanded by the acquisition of digital daily streamflow tapes from USGS and digital precipitation data tapes from the National Weather Service. In order to provide hourly precipitation data for the master data bank, a computer program to merge and synchronize rainfall data from several hourly and daily precipitation gages was completed and made operable.

A.3 SECOND HALF, CALENDAR YEAR 1972

In July 1972 the study was resumed at a five-man funding level, which was reduced to three in mid-September. Highlights of the last six months of 1972 are as follows:

- The design of an integrated data bank consisting of historical data and model parameters derived from the physiographic data base was completed. A master data tape was established and data pertaining to three TVA watersheds were entered on the tape. The master data tape has the capacity for storage of up to 50 watersheds, with data related to 10 years of historical experience for each one.

- The calibration program and simulation model were tested using actual data from TVA watersheds. After calibration the simulation model is capable of synthesizing streamflows which are accurate within five percent of observed flows. Accurate simulation of flood peaks with respect to magnitude and time of peak require additional manual adjustments after model parameters have been estimated by OPSET.

- A sensitivity analysis task was introduced into the study in order to determine what effects on accuracy of simulation variations in the different model parameters have. This analysis was performed on two small watersheds of the test area. It helped expedite calibration of the remaining watersheds.

- The data base and models were implemented in the IBM facility with a Terminal Assistance Package which allows an operator to set up programs, modify the data base, and initiate program operations from a terminal without having to handle several thousands of data cards.

A.4 CALENDAR YEAR 1973

The study was continued at a three-man funding level from January 1 through September 21, 1973, and was completed, with the results as summarized in Section 1.5 and detailed in Section 3. Most of the effort during this time was spent on formatting and integrating the data base for 15 watersheds. Calibration of ten watersheds required the next largest proportion of time, after which the correlation analysis and validation runs were quickly completed.

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