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INSTITUTO NACIONAL DE RECURSOS
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UNIVERSIDAD DEL
ESTADO DE COLORADO
(CSU)

ESTUDIOS SOBRE LA OPERACION Y SEGURIDAD DEL SISTEMA DE EMBALSES DE VALDESIA

INFORME FINAL

HYDROLOGIC MODELING SYSTEM

(CSU - HMS)

USERS MANUAL 1/

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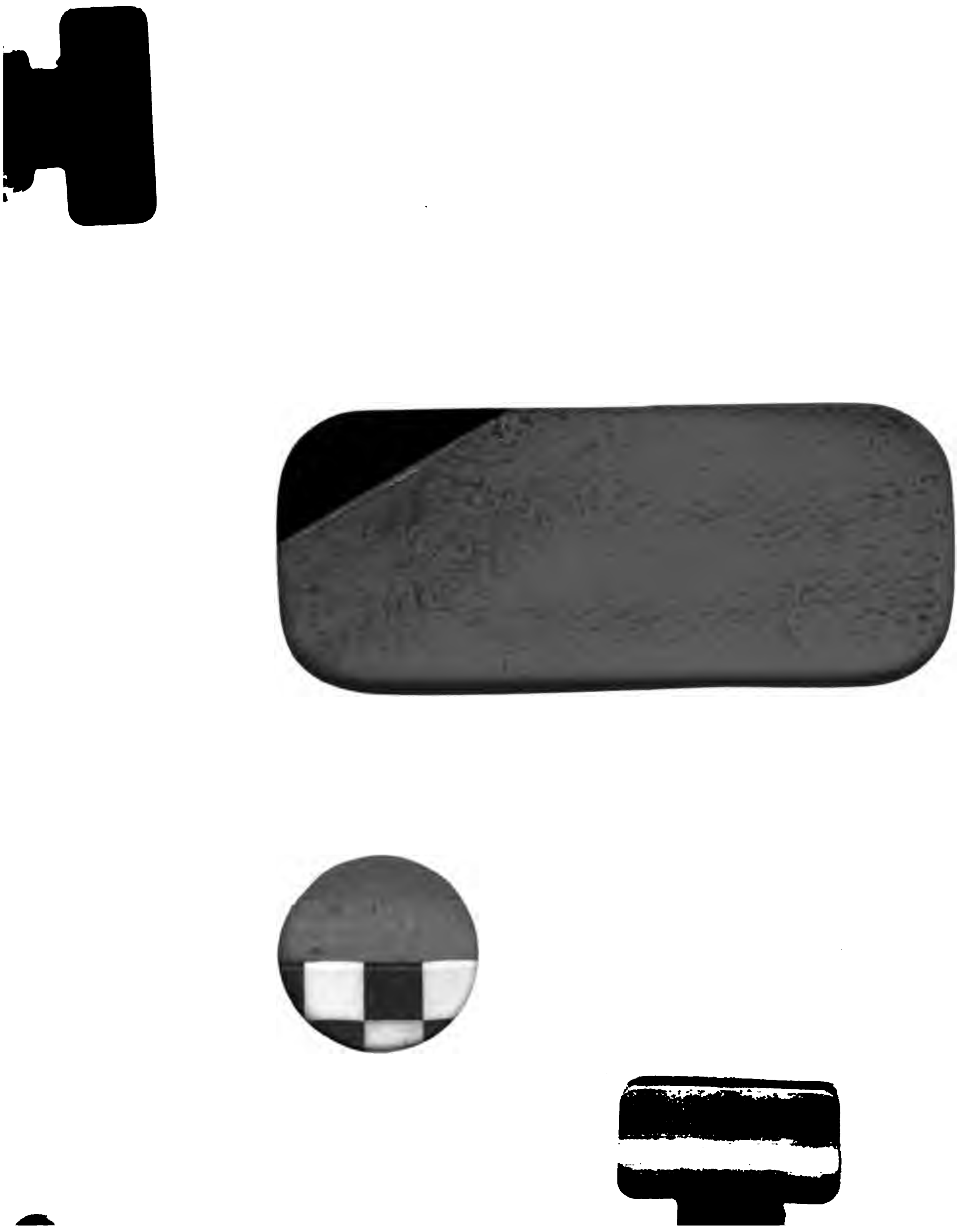

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PRESENTACION

Los estudios de Operación y Seguridad del Sistema de Embalses de Valdesia fueron ejecutados conjuntamente por el Instituto Nacional de Recursos Hidráulicos (INDRHI) de la República Dominicana, la Universidad del Estado de Colorado (CSU) y el Instituto Interamericano de Cooperación para la Agricultura (IICA a través del Contrato IICA/INDRHI/CSU firmado el 6 de abril de 1984. Los estudios se iniciaron el 6 de agosto de 1984 y finalizaron el 31 de agosto de 1986.

Los estudios fueron financiados por el INDRHI a través del préstamo 1655-DO del Banco Mundial.

La ejecución de los estudios se desarrolló en seis áreas:

a) Estudios Hidrológicos
b) Operación Normal
c) Operación de Emergencia
d) Inspección, Mantenimiento y Seguridad de Presas
e) Organización para la Operación del Sistema de Embalses
f) Entrenamiento y Transferencia de Tecnología

En este documento se incluye parte del material técnico del Informe Final, el cual consta de los siguientes volúmenes:

-Resumen
-Estudios Hidrológicos
-Operación Normal
-Estudios de Operación de Crecidas
-Estudios de Inspección, Mantenimiento y Seguridad de Presas
-Organización y Funciones para la Operación del Sistema de Embalses de Valdesia.

-Transferencia de Tecnología y Capacitación.

-Plan de Operación de Emergencia para el Sistema de Embalses de Valdesia.

-Plan de Operación Normal para el Sistema de Embalses de Valdesia: (1) Riego y Energía, (2) Control de Crecidas.

-Manuales de Operación de Modelos Computarizados para la Operación Normal del Sistema de Embalses.

-Manual de Usuario de Modelos de Sistemas Hidrológicos.

Santo Domingo, República Dominicana
31 de agosto de 1986

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Table of Contents

COLORADO STATE UNIVERSITY HYDROLOGIC MODELING SYSTEM (CSU-HMS)

1. INTRODUCTION

1.1 Purpose

Colorado State University Hydrologic Modeling System(CSU-HMS) is a collection of software useful for hydrologic studies and short term operation of a reservoir system. This system has been specifically designed for the Valdesia - Las Barias reservoir system in the Nizao basin located in the Dominican Republic. However, it can be adopted to any other system with little modification. The system includes software for mapping, interpolation, and averaging of precipitation, rainfall-runoff modeling, real-time flood forecasting and reservoir routing. Since, this particular basin experiences tropical cyclones originating in Atlantic ocean, additional software has been included to forecast the track of such storms. The system is specifically designed for microcomputers and comes with software for graphical display of results which is useful particularly in real time operation of the reservoir system.

1.2 Available Options

The system currently can be installed in an IBM-PC with the MS-DOS operating system. The hardware requirements are specified in Section 1.3. The system may be initiated by entering CSU-HMS to bring up the main menu which outlines the options available. The main menu is shown below:

HYDROLOGY AND WATER RESOURCES PROGRAM
COLORADO STATE UNIVERSITY
HYDROLOGIC MODELING SYSTEM
Prepared for
Operation of Valdesia - Las Barias Reservoir System
in Nizao basin of the Dominican Republic
under
CSU/IICA/INDRHI Agreement

1. Precipitation Data Analysis
2. Flood Event Simulation
3. Flood Forecasting
4. Reservoir Routing
5. Hurricane Track Forecasting
6. Streamflow Forecasting

Enter Your Selection at the prompt:
(Enter FINISH to exit)

Precipitation Data Analysis

This system currently consists of two programs:(a).PCMAPS; and (b).OPTIM. The PCMAPS is an easy to use software for precipitation data analysis which has many capabilities. They include:(a) Interpolation of a precipitation field using data available at gaging stations in and around a basin;(b) Computation of areal precipitation over a given given area defined by a set of coordinate using one of several techniques:(c) Printer display of isohyetal maps of areal precipitation;and (d) Derivation of depth-area data which is used in computing Depth-Area-duration curves. The program is designed in modular form such that different options may be combined according to the needs of the user.

The OPTIM is a simple program to compute the weights for different combinations of a set of nine precipitation stations located in and around Nizao basin. These optimal weights are used in computing areal precipitation over a given subarea. Currently, this program is specifically designed for Nizao and needs to be modified if user wishes to adopt it to another basin.

The complete description of these software are given in Section 2.

Flood Event Simulation

Currently this option includes only the PC-version of HEC-1 model of the U.S. Army Corps of Engineers. It is an event type rainfall-runoff model which has many capabilities. These include computations of basin precipitation, unit hydrograph derivation with or without optimization, runoff simulation using unit hydrograph or kinematic wave routing, reservoir and channel routing by different methods and flow through breached dams. The economic analysis available in the main-frame version of HEC-1 is not available in the PC- version.

Flood Forecasting

Currently, this includes software for continuous simulation of rainfall- runoff process in a given basin consisting of several subbasins. The model uses the soil moisture accounting procedure of the National Weather Service River Forecast System and the kinematic wave routing of HEC-1. It is designed in modular form so that user may combine different operations according to his/her needs. An optimization capability is included to supplement the manual calibration. The primary use of the model is for real time flood forecasting using precipitation measurements obtained in real time or forecasted at the time of forecast. Convenient graphical displays of average precipitation over each subbasin and the corresponding runoff at the outlet of each subbasin are included.

The complete description of this software is given in Section 4.

Reservoir Routing

The software in this option simulates a flood through the spillways and other outlets of the Valdesia-Las Barias system. It is used for reservoir routing studies including the routing of design floods and to

determine the spillway gate operation schedule for forecast floods at Valdesia. This is a convenient tool for operation of the system under flood emergency conditions. Graphical display of routing results are also available. This software needs to be modified if the user wishes to adopt it to another system.

The description of this option is given in Section 5.

Hurricane Track Forecasting

This option includes an interactive version of the CLIPER regression model of National Hurricane Center in Miami for forecasting of hurricane tracks. Graphical display of forecast and /or actual tracks is available for the Caribbean region.

The description of the different options available and the programs available are given in Section 6.

Streamflow Forecasting

This option consists of software for forecasting weekly or monthly streamflow at Paso del Ermitano gaging station in the Nizao basin. The so-called Kalman Filter approach is used for forecasting streamflow in a sequential manner with parameter updating. This is a convenient tool for making real time decisions in the operation of Valdesia system using normal operating rules.

The complete description of this software and a sample application is given in Section 7.

1.3 Hardware Requirements

The current version of the Hydrologic Modeling System with example data sets can be stored in five 360k diskettes. It can be installed in an IBM-PC/XT/AT or a compatible with (a) at least 512 k memory; (b) a hard disk , and (c) the MS-DOS operating system. It requires a graphics card compatible with the monitor. The software requires very minor modification to run on a system installed with a Hercules graphics card and a monochrome monitor.

2. PRECIPITATION DATA ANALYSIS

Precipitation analysis is based on the Programs PCMAPS and OPTIM.

2.1 General Description

The computer program PCMAPS is for mapping, interpolation and areal averaging of hydrologic processes having areal or spatial characteristics. The techniques utilized consist of two general types, namely: proximal mapping and contour mapping.

Proximal mapping employs primarily the Theissen polygon method using different distance formula options. Mapping based on proximity has found wide applications for data with discontinuous surface characteristics. Contour mapping which is for data with relatively continuous spatial characteristic includes the inverse distance method, polynomial interpolation, (Lagrange or least-squares method), multiquadric interpolation, optimal interpolation and Kriging interpolation. In addition to the interpolated values, the error of interpolation may be optionally computed. Program outputs include basic system statistics of the area of interest and graphic displays of the interpolated values and error of interpolation. The graphic displays are made using a standard line printer.

For ease in running the program, the input called programs statements are designed to be user oriented. The use of the program statements attempt to provide versatility in using the different options available. The program statements are divided into two types, namely: INPUT statements and PROCEDURE statements. The INPUT statements are used to initially input basic data requirements before any PROCEDURE statement can be executed. Each INPUT statement is contained in one card and generally followed by the input data requirements. On the other hand, the PROCEDURE statements are some sort of executable statements for invoking the available mapping or interpolation procedures. The PROCEDURE statement is likewise contained in one card except that the procedure options for each mapping or interpolation technique is contained in the same card.

The program is designed to process different jobsteps in one jobstream. A jobstep is defined herein as one problem consisting of fixed physical boundaries and station locations. A jobstream is one program run which may consist of one or more jobsteps.

The ensuing sections present the following: section 2.2 describes the INPUT statements; section 2.3 describes the PROCEDURE statements; section 2.4 presents a sample program application; and section 2.5 presents a subset program of PCMAPS called OPTIM for optimal areal weighting.

2.2 Input Statements

(1) TITLE. For each jobstep, this statement is the first statement. Thus, this statement separates different jobsteps within one program run. The TITLE statement is followed by

one card containing the title (alphanumeric data), punched between columns 1 to 80.

Example: TITLE
SPATIAL MODELING IN HYDROLOGY
C_1

where C_1 denotes column 1.

(2) RANGE. This INPUT statement is succeeded by one card containing the code defining the type of coordinate system used and the coordinate points of the extent of the boundary system. The card after the input statement RANGE the following specifications.

No. of Card	Input Data	Columns
1	a. type of coordinate system	15
	0 - rectangular coordinates	
	1 - spherical coordinates (longitude east of Greenwich)	
	2 - spherical coordinates (longitude west of Greenwich)	
	b. horizontal axis	
	maximum	20-29
	minimum	30-39
	c. vertical axis	
	maximum	40-49
	minimum	50-59

When using rectangular coordinates, the points must be inputted as floating-point values. When the coordinates are in terms of spherical coordinates, the values of the degrees, minutes and seconds should be expressed as single whole number ended by a period. The example below exemplifies this point.

Example: Using spherical coordinates

RANGE
C_1
1 (C_{15}) 1225930. (C_{20}) 1201038. (C_{30}) 130508. (C_{40}) 115631. (C_{50})

In this example, the type of coordinate system used is spherical coordinates with the longitude east of Greenwich. The maximum coordinate of the vertical axis is 122°59'30" while the minimum is 120°10'38". For the horizontal axis, the maximum is 13°05'08" and the minimum is 11°56'31".

NOTE: Without the TITLE and RANGE statement, a particular jobstep is terminated.

(3) BOUNDARY. This INPUT statement is followed by cards containing the boundary points of the study area of interest.

Each of these cards contains one boundary point defined by the horizontal point punched anywhere between columns 20-29 and the vertical point punched between columns 30-39, where each value is a floating-point value as in RANGE statement. The cards must be arranged sequentially in a counterclockwise manner as the boundary system are lines formed by connecting these points. In effect, the last boundary point is connected to the first boundary point inputted. The last boundary point must be succeeded by an END statement (see next statement). The computer program can handle a maximum of 100 boundary points.

When the BOUNDARY input statement and the boundary points are not inputted, the input data of the RANGE statement will be considered as the boundary points.

Example:

```
BOUNDARY
C1
                  1205932.     113218.
                  C20          C30
                  1205855.     110612.
                  C20          C30
                    ..           ..
                    ..           ..

                  1205760.     112513.
                  C20          C30

END
C1
```

(4) END. This statement is not considered as an input statement but rather, an end-of-input statement for the input statements, BOUNDARY, STATION, DATA and other input statements to be described later.

(5) STATION. To input the coordinates of the station or sampling points, this statement is used. The STATION statement is followed by the station names if desired, and their coordinate points. For each station contained in one card, the station name is punched between columns 1 to 10, and the coordinates defined by the vertical and horizontal axes are punched in columns 20-29 and columns 30-39 respectively. As in RANGE and BOUNDARY statements the coordinates are inputted as floating-point values. Also, the last station point should be followed the END statement.

Example:

```
STATION
C1
```

```
STAONE              1213950.        111632.
C1                  C20             C30
STATNO              1235318.        131728.
C1                  C20             C30
                       .               .
                       .               .
                       .               .
STALST              1226310.        121850.
C1                  C20             C30
END
C1
```

NOTE: The type of coordinate system specified in the RANGE input statement must be consistent with the type of coordinate points inputted in the BOUNDARY and STATION statements.

(6) DATA. The DATA statement is used followed by the observed data from the available stations or sampling points. The observed value of each station must be inputted in the same sequence as the station coordinate points in the STATION statement. Following the DATA statement are data cards containing the station name if desired, punched from columns 1 to 10 and the corresponding observed values in columns 20-29 as floating point values. An END statement should follow the last input data.

Example:

```
DATA
C1
STAONE              8.56
C1                  C20
STATNO              7.08
C1                  C20
   .                   .
   .                   .
   .                   .
STALAST             8.05
C1                  C20
END
C1
```

(7) STATISTICS. This INPUT statement must be followed by a card containing three basic statistics, namely; the global mean of the observed data, its global standard deviation and the global standard error of measurement punched anywhere between columns 20-29, 30-39, and 40-49, respectively. If these two cards are omitted, the mean and standard deviation are computed based on the input data in the DATA statement and the standard error of measurement is assumed zero.

(8) SPACOR. This INPUT statement allows inputting the type of spatial correlation model to be used and its single model parameter. The card following SPACOR statement has the following specifications:

No. of Card	Input Data	Column
1	a. Type of Spatial Correlation Model	15
	1. Exponential model	
	$\rho(d) = \exp(-d/do)$	
	2. Inverse model	
	$\rho(d) = (1 + d/do)^{-1}$	
	b. Model parameter, d_o	20-29

The SPACOR statement is required only when the error of spatial interpolation is desired. However, if the technique of optimal interpolation is used, the SPACOR statement must be included.

(9) VARIOGRAM. This INPUT statement is required when the technique of Kriging interpolation is used. Following this statement contains the type of variogram model to be used and the model parameters. The input specifications are as follows:

No. of Card	Input Data	Columns
1	a. Type of Variogram Model	15
	1. Linear model	
	$\gamma = \omega d$	
	2. Polynomial model	
	$\gamma = \omega d^{\sigma}$	
	3. Exponential model	
	$\gamma = \omega\ (1-\exp\ (\alpha d))$	
	4. Gaussian model	
	$\gamma = \omega\ (1-\exp\ (\alpha d^2))$	
	5. Spherical model	
	$\gamma = \omega\ (3d/\alpha - (d/\alpha)^3)/2 \quad d \leq \alpha$	
	$\gamma = 2 \quad d > \alpha$	
	b. Model Parameters	
	ω	20-29
	α	30-39

(10) STAMEANS. This INPUT statement is required when Kriging interpolation option 1 is used. This specific Kriging technique requires the stations means since the weights of the interpolation function are additionally computed based on these means. This statement is followed by cards containing the station means ended by an END statement inputted in the

same sequence as those input values of statements STATION or DATA. Similar to STATION or DATA statements, the station names may be punched in columns 1-10 and their corresponding stations means in columns 20-29 as floating-point values. It should be noted that STAMEANS should be given prior to invoking the kriging interpolation option 1.

NOTE: The input data for the INPUT statements RANGE, BOUNDARY and STATION are considered fixed data, thus they cannot be changed within one jobstep. However, the input data for input statements DATA, STATISTICS, SPACOR, VARIOGRAM and STAMEANS may be changed within one jobstep thus the program allows multiple entry of these statements. But prior to an execution of any procedure statement, the DATA statement should be inputted and some of their specific data requirements.

(11) STADEPTH. In the procedure statement DEPTH, one can compute the weights of specified recording stations using the Thiessen polygon method (straight-distance option) for each subarea in the basin defined within the range of the so-called extended class (see DEPTH statement, item 3.9). The recording stations are specified by inputting their coordinates in statement STADEPTH. The coordinates are inputted following the same syntax as statement STATION. The statement STADEPTH can be used several times as desired within a jobstep.

(12) RETITLE. If the user desires to change the title within a jobstep, this INPUT statement is used followed by a card containing the new title. This statement may be used for example to distinguish one or more data sets in the DATA statement.

(13) STOP. This statement should be given at the end of each jobstep when running the program for several jobsteps. Thus, in addition to the TITLE statement, the STOP statement separates different jobsteps. The STOP statement however is not required for the last jobstep in one jobstream or one program run.

2.3 Procedure Statements

Basically, the PROCEDURE statements are used to call the different mapping or interpolation techniques available in the program. However, there are other PROCEDURE statements that are available such as PTDATA, MASK and DEPTH which can be used and also described herein. The following are the PROCEDURE statements and brief descriptions of each.

(1) THIESSEN. This statement calls the Thiessen polygon mapping technique. This technique is based on proximal mapping or nearest-distance neighbor mapping. The statement THIESSEN is punched starting in column 1 and its options are punched in column 15. The mapping technique and its options are described below.

Let h_o be an estimate of the process at any point with coordinates x_o and y_o be represented by the linear interpolation function

$$h_o = \sum_{j=1}^{n} w_j h_j \qquad (1)$$

where h_j denotes the observed values at station j with coordinates x_j and y_j, w_j is the weight of station j and n in the total number of sampling points or stations. In the Thiessen method, the estimate of the process h_i is equal to the observed value of the nearest sampling point to point (x_o, y_o). In terms of the interpolation function (1), the nearest sampling point, say i with coordinates x_i and y_i has weight

$$w_j = 1.0 \quad \text{for} \quad j = 1 \qquad (2a)$$

and the rest of the stations has weights

$$w_j = 0.0 \quad \text{for} \quad j \neq i \qquad (2b)$$

in which j=1,...,n stations.

In this program, six different optional distance formulas are used to search for the "nearest neighbor" denoted by i in Eqs. (2a) and (2b). Essentially the search is such that

$$d_{oi} = \min (d_{o1},\ldots,d_{oj},\ldots,d_{on}) \qquad (3)$$

where d_{oi} is the minimum point-station distance between point (x_o,y_o) and station (x_i,y_i) out of all point-station distances d_{oj}, j=1,...,n. Given below are the different distance formulas.

a) Straight Distance: (option code = 1)

In this case the point-station distance is computed by

$$d_{oj} = \sqrt{(x_o - x_j)^2 + (y_o - y_j)^2} \qquad (4)$$

for all j=1,...,n stations. Note that this distance formula is the one commonly used when constructing Thiessen polygons.

An example in using this option is:

THIESSEN	1
C_1	C_{15}

b) Orthogonal Distance: (Option Code = 2)

$$d_{oj} = |x_o - x_j| + |y_o - y_j| \qquad (5)$$

where |.| denotes absolute values.

c) Maximum Leg Distance: (Option Code = 3)

$$d_{oj} = \max\left(|x_o - x_j|, |y_o - y_j|\right) \tag{6}$$

d) Data Weighted Straight Distance: (Option Code = 4)

This method may be referred to as "bubble analogy" method where arcs are formed ~~at midpoints~~ between stations.

$$d_{oj} = |h_j| \times \sqrt{(x_o - x_j)^2 + (y_o - y_j)^2} \tag{7}$$

where h_j is the observed value at station j. The computed distance d_j in this case may be called weighted or moment-distance.

e) Correlation-Residual Distance: (Option Code = 5)

$$d_{oj} = \rho(d)\,|h_j - \mu| \tag{8}$$

where $\rho(d)$ is the spatial correlation coefficient given the distance d of point (x_o, y_o) and (x_i, y_i) by Eq. ( ). Note that to be able to use this option, the SPACOR statement must be used beforehand.

(2) INVERSE. This PROCEDURE statement invokes the mapping technique called inverse distance or distance weighting method. The interpolated value h_o at any point (x_o, y_o) is likewise obtained as in Eq. (1). The weights in this case are obtained as follows:

$$w_j = \frac{1/d_{oj}^a}{\sum_{i=1}^{n} 1/d_{oi}^a} \tag{9}$$

where a is an exponent and d_{oj} is computed using the straight distance formula Eq. (4). When the exponent a=1.0, the technique is called reciprocal distance method; and if a=2.0, it is called inverse square distance method. The exponent a can be any specified real number.

The statement INVERSE is punched starting in column 1 and the exponent a is punched between columns 20-29 as a floating-point value.

(3) POLYNOMIAL. This procedure statement calls the technique of polynomial interpolation. In this technique, a global equation is fitted using algebraic polynomial to represent the study area of interest. Two approaches of fitting the polynomial function are available in this procedure. These are the least-squares method and the Lagrange method. The method to be used is defined by a code number punched in column 15. In addition to this, the degree of the polynomial

function must be specified an punched between columns 20-29 as a floating-point value.

The general form of the algebraic polynomial function is

$$h_o = \sum_{k=1}^{m} a_k \phi_k(x_o, y_o) \tag{10}$$

where m = number of monomials as a function of the degree of the polynomials, D; h_o = interpolated value; a_k = polynomial coefficient; and $\phi_k(x_o, y_o)$ = monomials in terms of x_o and y_o coordinates.

The degree of the polynomial D and their corresponding monomials for D = 1,...,5 degrees are given in the table below.

D	k	$\phi_k(x,y)$	m
0	1	1	1
1	2-3	$x\ y$	3
2	4-6	$x^2\ xy\ y^2$	
3	7-10	$x^3\ x^2y\ xy^2\ y^3$	10
4	11-15	$x^4\ x^3y\ x^2y^2\ xy^3\ y^4$	15
5	16-21	$x^5\ x^4y\ x^3y^2\ x^2y^3\ xy^4\ y^5$	21

In the interpolation, Eq. (10) is expressed in terms of Eq. (1). The two sections below describe how the weights are obtained.

a) Least-Squares Method: (Option Code = 1)

The primary requirement in this method is that the number of sampling points must be greater than the number of monomials specified in Eq. (10).

Let h_j be the observed value at station j and let $\hat{h}_j$ be the estimate of the same value based on Eq. (10) so that

$$\hat{h}_j = \sum_{k=1}^{m} a_k \phi_k(x_j, y_j) \quad \text{for} \quad j=1,\ldots,n \tag{11}$$

To obtain the parameter set a_k, k=1,...,m monomials, we minimize the function

$$F = \sum_{j=1}^{n} (h_j - \hat{h}_j)^2$$

Taking derivatives with respect to α_{kj}, it can be shown that

$$a_k = \sum_{j=1}^{n} \alpha_{kj} h_j \quad \text{for} \quad k=1,\ldots,m \tag{12}$$

where

$$\alpha_{kj} = \sum_{i=1}^{m} \psi_{ki}\phi_i(x_j,y_j) \tag{13}$$

with $k=1,\ldots,m$; $i=1,\ldots,m$ in which ψ_{ki} is the kth row and ith column element of the inverse of an $m \times m$ matrix $\underline{\theta}$ with elements

$$\theta_{ki} = \sum_{j=1}^{n} \phi_k(x_j,y_j)\phi_i(x_j,y_j) \tag{14}$$

with $k=1,\ldots,m$ rows and $i=1,\ldots,m$ columns.

Combing Eqs. (12) and (10) results in

$$h_o = \sum_{j=1}^{n} \left[\sum_{k=1}^{m} \alpha_{kj} \phi_k (x_o,y_o) \right] h_j \tag{15}$$

Upon comparing the resulting equation to Eq. (1), the weights can be shown to be

$$w_j = \sum_{k=1}^{m} \alpha_{kj} \phi_k (x_o,y_o) \tag{16}$$

When interpolating over an area the matrix with elements α_{kj} is evaluated only once since it is only a function of the fixed sampling points. The monomials $\phi_k(x_o,y_o)$ must be evaluated however for each point to be interpolated.

b) Lagrange Approach: (Option Code = 2)

This approach requires that the number of stations, n is equal to the number of monomials, m. Since n=m, Eq. (11) becomes

$$\hat{h}_j = \sum_{k=1}^{n} a_k\phi_k(x_j,y_k) \quad \text{for} \quad j=1,\ldots,n \tag{17}$$

Such that

$$a_k = \sum_{j=1}^{n} \beta_{kj} h_j \quad \text{for} \quad k=1,\ldots,n \tag{18}$$

where β_{kj} is an element of inverse of the $n \times n$ matrix with elements $\phi_k(x_j,y_j)$, $k=1,\ldots,n$ monomials (rows) and $j=1,\ldots,n$ stations (columns). In terms of the interpolation function (1), and following the development of Eq. (15), the weights are given by

$$w_j = \sum_{k=1}^{n} \beta_{kj}\phi_k(x_o,y_o) \tag{19}$$

(4) QUADRIC. This statement invokes the multiquadric interpolation technique. The technique is based on representing the influence of each station as cones of quadric surfaces. Then the interpolated value at any point (x_o,y_o) is obtained by the sum of contributions from all such cones. In equation form

$$h_o = \sum_{j=1}^{n} c_j d_{oj} \tag{20}$$

where c_j = multiquadric coefficient for station j.

In terms of Eq. (1) it can be shown that Eq. (20) can be written as

$$h_o = \sum_{j=1}^{n} \left[\sum_{i=1}^{n} \delta_{ij} d_{oi} \right] h_j$$

The term in the square bracket is essentially the weight w_j written as

$$w_j = \sum_{i=1}^{n} \delta_{ij} d_{oi} \ ; \quad j=1,\ldots,n \tag{21}$$

where δ_{ij} is an element of the inverse of the n x n interstation distance matrix with elements d_{ji}, j=1,...,n (rows) and i=1,...,n (columns).

This procedure has four optional distance formulas. For each option, the distances d_{oi} or d_{ii} are obtained using Eq. (4), square of straight-distance, Eq. (5) and Eq. (6) which corresponds to the option code numbers 1, 2, 3 and 4, respectively. The code number is punched in column 15 in the procedure statement QUADRIC.

(5) OPTIMAL. The use of this procedure statement calls the optimal interpolation technique. The technique is based on minimizing the mean-square error of the interpolation function (Eq.) with respect to the weights. Two methods of arriving at the optimal weights are provided in this procedure.

a) Constrained Optimal Interpolation: (Option Code = 1)

Under the assumption of homogeneity in the means and variances over the study area, the weights of each station are obtained by solving the linear of system of equations below

$$\sum_{i=1}^{n} w_i \rho(d_{ij}) + w_j \frac{\sigma_\epsilon^2}{\sigma^2} + \lambda = \rho(d_{oj}) \qquad j=1,2,\ldots,n$$

$$\sum_{i=1}^{n} w_i = 1 \qquad (22)$$

where σ_e^2 = measurement error variance; σ^2 = homogeneous point variance; $\rho(d_{ij})$, $\rho(d_{oj})$ = spatial correlation coefficients, between stations i and j and between point o and station j, respectively; and λ = Lagrange multiplier to render the sum of the weights equal to one.

b) Unconstrained Optimal Interpolation: (Option Code = 2)

In this case, the sum of weights is not constrained to one.. The weights are evaluated by simultaneous solution of the equation below.

$$\sum_{i=1}^{n} w_i \rho(d_{ij}) + w_j \frac{\sigma_e^2}{\sigma^2} = \rho(d_{oj}) \qquad j=1,2,\ldots,n \qquad (23)$$

where the same notations are used as in Eq. (22).

It will be noted that a spatial correlation function to evaluate ρ_{oj} is to be defined a priori which is done using the input statement SPACOR.

NOTE: The difference between constrained and unconstrained optimal interpolation is that the former gives unbiased estimates while the latter does not. The unbiasness condition is met by constraining the sum of the weights equal to one. Both options however provide minimum error-variance estimates.

(6) <u>KRIGING</u>. The technique of Kriging interpolation can be invoked by using this procedure statement. This technique is similar to optimal interpolation except that the correlation function is replaced by the variogram (see input statement VARIOGRAM). In the same manner, Eq. (7) is used to interpolate the values. Four procedure options are available to evaluate the weights.

a) Unconstrained Kriging: (Option Code = -1)

In this option the weights are obtained by solving the system below

$$\sum_{i=1}^{n} w_i[\gamma(d_{ij}) - \sigma^2] = \gamma(d_{oj}) - \sigma^2 \quad \text{for } j=1,2,\ldots,n \qquad (24)$$

where $\gamma(d)$ is the variogram as a function of distance d.

b) Constrained Kriging: (Option code = 0)

In this case, the sum of the weights are constrained to one. The weights are obtained by solving

$$\sum_{i=1}^{n} w_i \gamma(d_{ij}) + \lambda = \gamma(d_{oj}) \quad j=1,2,\ldots,n$$

$$\sum_{i=1}^{n} w_i = 1 \tag{25}$$

c) Constrained Kriging with Station Mean Parameterization (Option Code = 1)

An additional constraint is imposed on the weights based on the estimated means. The equations below yield the desired weights

$$\sum_{i=1}^{n} w_i \gamma(d_{ij}) + \lambda_o + \lambda_1 N_j = \gamma(d_{oj}) \quad j=1,2,\ldots,n$$

$$\sum_{i=1}^{n} w_i = 1 \tag{26}$$

$$\sum_{i=1}^{n} w_i M_i = M_o$$

where M_o is time averaged overall station means and M_i = time-averaged station means.

d) Universal Kriging: (Option Code = 2)

The constraint on the weights is assumed to follow a polynomial trend. Thus,

$$\sum_{i=1}^{n} w_i \gamma(d_{ij}) + \sum_{k=1}^{m} \lambda_k \phi_k(x_j, y_j) = \gamma(d_{oj}) \quad j=1,2,\ldots,n$$

$$\sum_{i=1}^{n} w_i \phi_k(x_i, y_i) = \phi_k(x_o, y_o) \quad k=1,2,\ldots,m \tag{27}$$

where m is the number of monomials and $\phi_k(x,y)$ are monomials in terms of x and y coordinates defined in Table 1. Note that the second equation above includes the constraint that the sum of the weights is equal to one.

(7) PTDATA. This procedure is used to print interpolated values at some specified points in the area. There are two ways to use this statement: a) statement PTDATA with 1 in column 15, and 2) statement PTDATA with blank or 0 in column 15. In the first case, this statement must be followed by the coordinates of the points where the interpolated values are to be printed. The horizontal coordinate is punched in columns 20-29 and vertical coordinate in columns 30-39 using the same coordinate system as in RANGE, BOUNDARY or STATION statements. The last

coordinate point should be followed by END statement. Using the PTDATA statement with 0 or blank in column 15 also prints the interpolated values at some specified points in the area, with the same coordinates as those given by statement PTDATA in the first case. Note that the statement PTDATA with 0 or blank can only be used after having inputted the desired points in statement PTDATA with 1 in column 15.

(8) MASK. In printing the interpolated values as a contour map using a line printer display, the contour intervals are based on the computed minimum and maximum interpolated values. Using the MASK statement allows specifying these maximum and minimum values to base the contour intervals. Also, the line printer display has a so-called tolerance where between contour intervals, the character "." are printed instead of characters corresponding to interpolated values when they are outside this tolerance. The tolerance in the program is specified as ±0.25 which means that if character "A" is for values between 10 and 20 and character "B" is for values between 20 and 30; the line printer displays A's for values between 7.5 to 12.5, character "." for values between 12.5 and 17.5, and B's for values between 17.5 and 22.5. The MASK statement also allows the user to change this tolerance which is between 0.0 and 1.0. The MASK statement has the following specification: the statement MASK is punched starting in column 1; number 1 is punched in column 15 if masking is to be done to the map of interpolated values or otherwise number 2 is punched in column 15 if masking is to be done to the map of the errors of interpolation; the "minimum" is punched between columns 20-29; the "maximum" in columns 30-39; and the desired tolerance in columns 40-49. These latter three values must be punched as floating-point numbers. Note that MASK statement can only be used after invoking an interpolation scheme.

(9) DEPTH. This PROCEDURE statement is used to derive the depth-area curve based on the latest contour map of interpolated values. The cumulative areas and corresponding average depths are computed based on so-called "extended" classes specified by the user. The DEPTH statement has the following specification: the statement DEPTH is punched starting column 1; the number of classes desired (NC) in columns 14-15 (integer and right justified); the lower most class limit (LMCL) in columns 20-29; and the uppermost class limit (UMCL) in columns 30-39. The program computes the extended classes with class width (UMCL-LMCL)/NC.

The DEPTH procedure has also an option for computing weights of specified recording stations for each subarea in the basin defined within the range of each extended class. The stations points are specified using input statement STADEPTH (see item 11, section 2.2). If STADEPTH is not used prior to involing DEPTH, no weights are computed. Once STADEPTH is used, all succeeding DEPTH computations are the same recording stations unless a different set of recording stations are respecified by using STADEPTH again.

2.4 Sample Program Application

This section presents a sample program application of PCMAPS. The purpose here is to simply illustrate the manner of inputting data as well as to show the output and graphic display capabilities of the program. Given in Figure 2.1 is the printout of the input data file for precipitation analysis of the Nizao Basin, Dominican Republic. This specific program run illustrates the use of multiquadric interpolation, depth-area curve computations, and optimal interpolation. The output for this sample application is given in Figure 2.2.

2.5 Optimal Areal Weights Program

A subset of the PCMAPS program which is designed specifically for obtaining areal weights using optimal interpolation for different combinations of a set of nine precipitation stations in the Nizao Basin has also been developed. This program is called OPTIM and can be run interactively. The input data required are station indicators (1 if available, 0 otherwise) for which the weights are desired and are inputted interactively. The output consists of weights of stations for which rainfall data is available for each of the three sub-basins, namely La Estrechura, Palo de Caja and Paso del Ermitano of Nizao Basin. A sample run of this program is shown in Figure 2.3. The current program set-up is specific for the Nizao Basin but may be modified for appication to other basins.

```
TITLE
   PRECIPITATION STATIONS AT NIZAO BASIN - DOMINICAN REPUBLIC
RANGE
            0     75.00     25.00     85.00     30.00
BOUNDARY
     1              65.70     34.20
     2              68.50     32.90
     3              68.80     34.00
     4              70.00     35.10
     5              71.00     35.20
     6              72.50     35.00
     7              73.00     36.00
     8              72.50     37.00
     9              71.50     38.00
    10              70.80     39.00
    11              70.00     40.00
    12              69.30     41.80
    13              69.70     42.50
    14              69.50     43.30
    15              69.70     44.20
    16              69.00     44.30
    17              65.30     48.00
    18              65.00     49.80
    19              64.20     51.60
    20              65.00     52.00
    21              65.20     53.00
    22              65.00     54.00
    23              64.00     55.00
    24              63.30     56.00
    25              63.20     58.00
    26              63.90     59.00
    27              65.20     61.00
    28              62.50     63.00
    29              62.30     64.60
    30              60.80     65.80
    31              60.20     67.00
    32              60.00     69.80
    33              58.30     70.90
    34              55.20     71.60
    35              53.60     72.00
    36              53.00     73.90
    37              51.50     74.20
    38              51.30     75.00
    39              49.30     74.00
    40              48.20     74.50
    41              47.60     74.50
    42              46.60     73.50
    43              46.30     72.80
    44              45.00     72.90
    45              43.70     73.80
    46              41.80     76.00
    47              40.00     78.80
    48              37.20     79.50
    49              35.50     82.10
    50              33.00     80.60
```

Figure 2.1. Sample PCMAPS application input data listing.

```
        51            29.00     82.20
        52            28.50     80.70
        53            27.50     80.40
        54            27.70     77.70
        55            26.60     75.70
        56            27.20     74.80
        57            29.00     74.40
        58            31.00     72.70
        59            31.20     71.00
        60            30.90     69.80
        61            31.00     68.70
        62            32.20     67.50
        63            33.00     66.80
        64            33.80     67.10
        65            35.20     67.40
        66            37.10     65.70
        67            39.30     64.10
        68            40.40     60.20
        69            43.10     59.70
        70            43.20     58.60
        71            43.80     58.50
        72            44.80     56.00
        73            44.30     54.70
        74            45.40     54.00
        75            45.80     53.00
        76            47.30     52.80
        77            47.70     51.20
        78            47.00     50.20
        79            46.80     49.00
        80            47.70     45.80
        81            49.70     44.60
        82            49.80     43.80
        83            51.20     42.60
        84            54.30     42.50
        85            54.30     41.50
        86            55.00     40.80
        87            57.60     41.20
        88            58.80     40.80
        89            59.80     39.80
        90            61.20     38.70
        91            60.70     36.80
        92            61.20     34.80
        93            62.50     34.90
        94            64.70     34.30
END
STATION
VALDESIA              64.90     35.60
LAESTREC              43.70     71.20
PALODECA              52.30     49.20
END
DATA
VALDESIA               8.90
LAESTREC               3.70
PALODECA               5.30
END
STADEPTH
VALDESIA              64.90     35.60
LAESTREC              43.70     71.20
```

Figure 2.1 (continuation)

```
PALODECA            52.30    49.20
END
QUADRIC
DEPTH          6
SPACOR
               2    14.21313
OPTIMAL
STOP
```

Figure 2.1 (continuation)

```
+----------------------------------------------------------------------+
!   HYDROLOGIC MAPPING, INTERPOLATION AND AREAL AVERAGING SYSTEM       !
+----------------------------------------------------------------------+

S.001        INPUT TITLE
S.002              PRECIPITATION STATIONS AT NIZAO BASIN - DOMINICAN REPUBLIC

S.003        INPUT RANGE
S.004                       0     75.00     25.00     85.00     30.00

S.005        INPUT BOUNDARY
S.006                1             65.70     34.20
S.007                2             68.50     32.90
S.008                3             68.80     34.00
S.009                4             70.00     35.10
S.010                5             71.00     35.20
S.011                6             72.50     35.00
S.012                7             73.00     36.00
S.013                8             72.50     37.00
S.014                9             71.50     38.00
S.015               10             70.80     39.00
S.016               11             70.00     40.00
S.017               12             69.30     41.80
S.018               13             69.70     42.50
S.019               14             69.50     43.30
S.020               15             69.70     44.20
S.021               16             69.00     44.30
S.022               17             65.30     48.00
S.023               18             65.00     49.80
S.024               19             64.20     51.60
S.025               20             65.00     52.00
S.026               21             65.20     53.00
S.027               22             65.00     54.00
S.028               23             64.00     55.00
S.029               24             63.30     56.00
S.030               25             63.20     58.00
S.031               26             63.90     59.00
S.032               27             65.20     61.00
S.033               28             62.50     63.00
S.034               29             62.30     64.60
S.035               30             60.80     65.80
S.036               31             60.20     67.00
S.037               32             60.00     69.80
S.038               33             58.30     70.90
S.039               34             55.20     71.60
S.040               35             53.60     72.00
S.041               36             53.00     73.90
S.042               37             51.50     74.20
S.043               38             51.30     75.00
S.044               39             49.30     74.00
S.045               40             48.20     74.50
S.046               41             47.60     74.50
S.047               42             46.60     73.50
S.048               43             46.30     72.00
S.049               44             45.00     72.90
S.050               45             43.70     73.80
```

Figure 2.2. Sample PCMAPS application output listing.

S.051	46	41.80	76.00
S.052	47	40.00	78.80
S.053	48	37.20	79.50
S.054	49	35.50	82.10
S.055	50	33.00	80.60
S.056	51	29.00	82.20
S.057	52	28.50	80.70
S.058	53	27.50	80.40
S.059	54	27.70	77.70
S.060	55	26.60	75.70
S.061	56	27.20	74.80
S.062	57	29.00	74.40
S.063	58	31.00	72.70
S.064	59	31.20	71.00
S.065	60	30.90	69.80
S.066	61	31.80	68.70
S.067	62	32.20	67.50
S.068	63	33.00	66.80
S.069	64	33.80	67.10
S.070	65	35.20	67.40
S.071	66	37.10	65.70
S.072	67	39.30	64.10
S.073	68	40.40	60.20
S.074	69	43.10	59.70
S.075	70	43.20	58.60
S.076	71	43.80	58.50
S.077	72	44.80	56.00
S.078	73	44.30	54.70
S.079	74	45.40	54.00
S.080	75	45.80	53.00
S.081	76	47.30	52.80
S.082	77	47.70	51.20
S.083	78	47.00	50.20
S.084	79	46.80	49.00
S.085	80	47.70	45.80
S.086	81	49.70	44.60
S.087	82	49.80	43.80
S.088	83	51.20	42.60
S.089	84	54.30	42.50
S.090	85	54.30	41.50
S.091	86	55.00	40.80
S.092	87	57.60	41.20
S.093	88	58.80	40.80
S.094	89	59.80	39.80
S.095	90	61.20	38.70
S.096	91	60.70	36.80
S.097	92	61.20	34.80
S.098	93	62.50	34.90
S.099	94	64.70	34.30
S.100	END		
S.101	INPUT STATION		
S.102	VALDESIA	64.90	35.60
S.103	LAESTREC	43.70	71.20
S.104	PALODECA	52.30	49.20
S.105	END		

Figure 2.2 (continuation)

```
S.106        INPUT DATA
S.107             VALDESIA             8.90
S.108             LAESTREC             3.70
S.109             PALODECA             5.30
S.110             END

S.111         PROC STADEPTH
S.112             VALDESIA            64.90     35.60
S.113             LAESTREC            43.70     71.20
S.114             PALODECA            52.30     49.20
S.115             END

S.116         PROC QUADRIC

S.117         PROC DEPTH        6

S.118        INPUT SPACOR
S.119                           2    14.21313

S.120         PROC OPTIMAL

S.121         STOP
```

Figure 2.2 (continuation)

DIAGNOSTIC CHECK OF COORDINATE SYSTEM : PRECIPITATION STATIONS AT NIZAO BASIN - DOMINICAN REPUBLIC

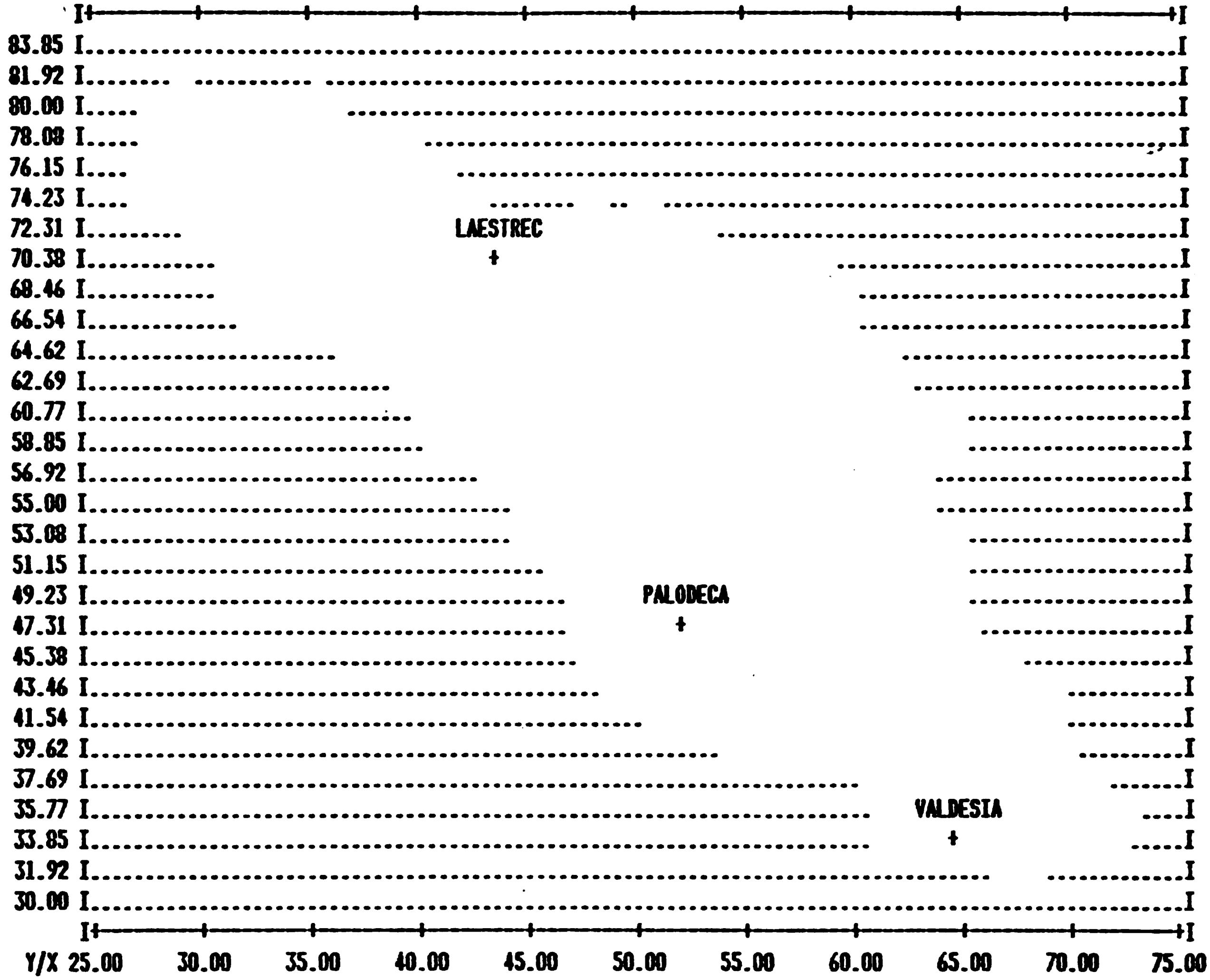
CONTROL POINTS	SPHERICAL DEG.MIN.SEC LONGITUDE	SPHERICAL DEG.MIN.SEC LATITUDE	RECTANGULAR X-COORDINATE	RECTANGULAR Y-COORDINATE	Z-ELEVATION	DIAGNOSTICS
MINIMUM			25.000	30.000		
MAXIMUM			75.000	85.000		
STA 1 VALDESIA			64.900	35.600	0.000	INSIDE OF RANGE
STA 2 LAESTREC			43.700	71.200	0.000	INSIDE OF RANGE
STA 3 PALODECA			52.300	49.200	0.000	INSIDE OF RANGE
BOUNDARY POINT 1			65.700	34.200		INSIDE OF RANGE
BOUNDARY POINT 2			68.500	32.900		INSIDE OF RANGE
BOUNDARY POINT 3			68.800	34.000		INSIDE OF RANGE
BOUNDARY POINT 4			70.000	35.100		INSIDE OF RANGE
BOUNDARY POINT 5			71.000	35.200		INSIDE OF RANGE
BOUNDARY POINT 6			72.500	35.000		INSIDE OF RANGE
BOUNDARY POINT 7			73.000	36.000		INSIDE OF RANGE
BOUNDARY POINT 8			72.500	37.000		INSIDE OF RANGE
BOUNDARY POINT 9			71.500	38.000		INSIDE OF RANGE
BOUNDARY POINT 10			70.800	39.000		INSIDE OF RANGE
BOUNDARY POINT 11			70.000	40.000		INSIDE OF RANGE
BOUNDARY POINT 12			69.300	41.800		INSIDE OF RANGE
BOUNDARY POINT 13			69.700	42.500		INSIDE OF RANGE
BOUNDARY POINT 14			69.500	43.300		INSIDE OF RANGE
BOUNDARY POINT 15			69.700	44.200		INSIDE OF RANGE
BOUNDARY POINT 16			69.000	44.300		INSIDE OF RANGE
BOUNDARY POINT 17			65.300	48.000		INSIDE OF RANGE
BOUNDARY POINT 18			65.000	49.300		INSIDE OF RANGE
BOUNDARY POINT 19			64.200	51.600		INSIDE OF RANGE
BOUNDARY POINT 20			65.000	52.000		INSIDE OF RANGE
BOUNDARY POINT 21			65.200	53.000		INSIDE OF RANGE
BOUNDARY POINT 22			65.000	54.000		INSIDE OF RANGE
BOUNDARY POINT 23			64.000	55.000		INSIDE OF RANGE
BOUNDARY POINT 24			63.300	56.000		INSIDE OF RANGE
BOUNDARY POINT 25			63.200	58.000		INSIDE OF RANGE
BOUNDARY POINT 26			63.900	59.000		INSIDE OF RANGE
BOUNDARY POINT 27			65.200	61.000		INSIDE OF RANGE
BOUNDARY POINT 28			62.500	63.000		INSIDE OF RANGE
BOUNDARY POINT 29			62.300	64.600		INSIDE OF RANGE
BOUNDARY POINT 30			60.800	65.800		INSIDE OF RANGE
BOUNDARY POINT 31			60.200	67.000		INSIDE OF RANGE
BOUNDARY POINT 32			60.000	69.800		INSIDE OF RANGE
BOUNDARY POINT 33			58.300	70.900		INSIDE OF RANGE
BOUNDARY POINT 34			55.200	71.600		INSIDE OF RANGE
BOUNDARY POINT 35			53.600	72.000		INSIDE OF RANGE
BOUNDARY POINT 36			53.000	73.900		INSIDE OF RANGE
BOUNDARY POINT 37			51.500	74.200		INSIDE OF RANGE
BOUNDARY POINT 38			51.300	75.000		INSIDE OF RANGE
BOUNDARY POINT 39			49.300	74.000		INSIDE OF RANGE
BOUNDARY POINT 40			48.200	74.500		INSIDE OF RANGE

Figure 2.2 (continuation)

BOUNDARY POINT 41	47.600	74.500	INSIDE OF RANGE
BOUNDARY POINT 42	46.600	73.500	INSIDE OF RANGE
BOUNDARY POINT 43	46.300	72.800	INSIDE OF RANGE
BOUNDARY POINT 44	45.000	72.900	INSIDE OF RANGE
BOUNDARY POINT 45	43.700	73.800	INSIDE OF RANGE
BOUNDARY POINT 46	41.800	76.000	INSIDE OF RANGE
BOUNDARY POINT 47	40.000	78.800	INSIDE OF RANGE
BOUNDARY POINT 48	37.200	79.500	INSIDE OF RANGE
BOUNDARY POINT 49	35.500	82.100	INSIDE OF RANGE
BOUNDARY POINT 50	33.000	80.600	INSIDE OF RANGE
BOUNDARY POINT 51	29.000	82.200	INSIDE OF RANGE
BOUNDARY POINT 52	28.500	80.700	INSIDE OF RANGE
BOUNDARY POINT 53	27.500	80.400	INSIDE OF RANGE
BOUNDARY POINT 54	27.700	77.700	INSIDE OF RANGE
BOUNDARY POINT 55	26.600	75.700	INSIDE OF RANGE
BOUNDARY POINT 56	27.200	74.800	INSIDE OF RANGE
BOUNDARY POINT 57	29.000	74.400	INSIDE OF RANGE
BOUNDARY POINT 58	31.000	72.700	INSIDE OF RANGE
BOUNDARY POINT 59	31.200	71.000	INSIDE OF RANGE
BOUNDARY POINT 60	30.900	69.800	INSIDE OF RANGE
BOUNDARY POINT 61	31.800	68.700	INSIDE OF RANGE
BOUNDARY POINT 62	32.200	67.500	INSIDE OF RANGE
BOUNDARY POINT 63	33.000	66.800	INSIDE OF RANGE
BOUNDARY POINT 64	33.800	67.100	INSIDE OF RANGE
BOUNDARY POINT 65	35.200	67.400	INSIDE OF RANGE
BOUNDARY POINT 66	37.100	65.700	INSIDE OF RANGE
BOUNDARY POINT 67	39.300	64.100	INSIDE OF RANGE
BOUNDARY POINT 68	40.400	60.200	INSIDE OF RANGE
BOUNDARY POINT 69	43.100	59.700	INSIDE OF RANGE
BOUNDARY POINT 70	43.200	58.600	INSIDE OF RANGE
BOUNDARY POINT 71	43.800	58.500	INSIDE OF RANGE
BOUNDARY POINT 72	44.800	56.000	INSIDE OF RANGE
BOUNDARY POINT 73	44.300	54.700	INSIDE OF RANGE
BOUNDARY POINT 74	45.400	54.000	INSIDE OF RANGE
BOUNDARY POINT 75	45.800	53.000	INSIDE OF RANGE
BOUNDARY POINT 76	47.300	52.800	INSIDE OF RANGE
BOUNDARY POINT 77	47.700	51.200	INSIDE OF RANGE
BOUNDARY POINT 78	47.000	50.200	INSIDE OF RANGE
BOUNDARY POINT 79	46.800	49.000	INSIDE OF RANGE
BOUNDARY POINT 80	47.700	45.800	INSIDE OF RANGE
BOUNDARY POINT 81	49.700	44.600	INSIDE OF RANGE
BOUNDARY POINT 82	49.800	43.800	INSIDE OF RANGE
BOUNDARY POINT 83	51.200	42.600	INSIDE OF RANGE
BOUNDARY POINT 84	54.300	42.500	INSIDE OF RANGE
BOUNDARY POINT 85	54.300	41.500	INSIDE OF RANGE
BOUNDARY POINT 86	55.000	40.800	INSIDE OF RANGE
BOUNDARY POINT 87	57.600	41.200	INSIDE OF RANGE
BOUNDARY POINT 88	58.800	40.100	INSIDE OF RANGE
BOUNDARY POINT 89	59.800	39.800	INSIDE OF RANGE
BOUNDARY POINT 90	61.200	38.700	INSIDE OF RANGE
BOUNDARY POINT 91	60.700	36.800	INSIDE OF RANGE
BOUNDARY POINT 92	61.200	34.100	INSIDE OF RANGE
BOUNDARY POINT 93	62.500	34.900	INSIDE OF RANGE
BOUNDARY POINT 94	64.700	34.500	INSIDE OF RANGE

Figure 2.2 (continuation)

DELINEATION OF BASIN BOUNDARY: PRECIPITATION STATIONS AT NIZAO BASIN - DOMINICAN REPUBLIC



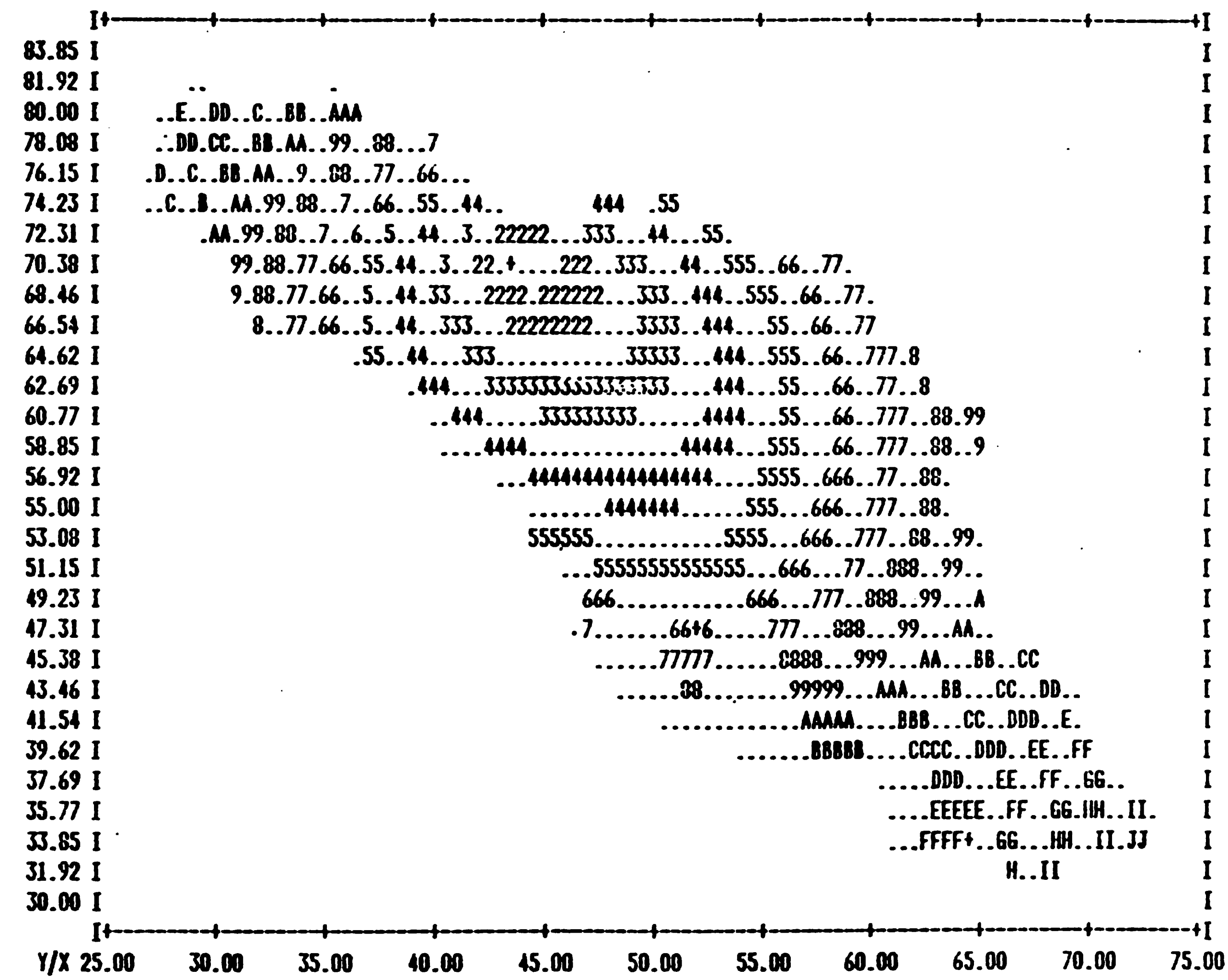
TOTAL AREA = 971.154
UNIT AREA = 0.962

DELTA X = 0.500
DELTA Y = 1.923

LEGEND:
I.I OUTSIDE OF BASIN
I I INSIDE OF BASIN
I+I STATION

Figure 2.2 (continuation)

MULTIQUADRIC INTERPOLATION : PRECIPITATION STATIONS AT NIZAO BASIN - DOMINICAN REPUBLIC



LEGEND :

SYMBOLS	CONTOURS	TOLERANCE
0	3.200	+/- 0.100
1	3.600	+/- 0.100
2	4.000	+/- 0.100
3	4.400	+/- 0.100
4	4.800	+/- 0.100
5	5.200	+/- 0.100
6	5.600	+/- 0.100
7	6.000	+/- 0.100
8	6.400	+/- 0.100
9	6.800	+/- 0.100
A	7.200	+/- 0.100
B	7.600	+/- 0.100
C	8.000	+/- 0.100
D	8.400	+/- 0.100
E	8.800	+/- 0.100

Figure 2.2 (continuation)

F	9.200	+/-	0.100
G	9.600	+/-	0.100
H	10.000	+/-	0.100
I	10.400	+/-	0.100
J	10.800	+/-	0.100
K	11.200	+/-	0.100

MULTIQUADRIC OPTION CODE = 1

```
1  SQRT((X-XS)**2+(Y-YS)**2)
2  (X-XS)**2 + (Y-YS)**2
3  ABS(X-XS) + ABS(Y-YS)
4  MAX(ABS(X-XS),ABS(Y-YS))
```

AREAL MEAN OF INTERPOLATED VALUES = 6.08452

DEPTH-AREA CURVE COMPUTATIONS: PRECIPITATION STATIONS AT NIZAO BASIN - DOMINICAN REPUBLIC

NUMBER	LOWER LIMIT	UPPER LIMIT	CUM.AREA	AVE.DEPTH
6	9.640	10.816	27.88	10.163
5	8.463	10.816	92.31	9.313
4	7.287	10.816	200.96	8.512
3	6.111	10.816	400.96	7.573
2	4.935	10.816	714.42	6.654
1	3.758	10.816	971.15	6.085

STATION WEIGHTS USING THIESSEN POLYGON METHOD (STRAIGHT DISTANCE FORMULA)

NUMBER	LOWER LIMIT	UPPER LIMIT	VALDESIA	LAESTREC	PALODECA
6	9.640	10.816	1.0000	0.0000	0.0000
5	8.463	10.816	0.8958	0.1042	0.0000
4	7.287	10.816	0.7368	0.2440	0.0191
3	6.111	10.816	0.3981	0.2686	0.3333
2	4.935	10.816	0.2234	0.3190	0.4576
1	3.758	10.816	0.1644	0.4396	0.3960

Figure 2.2 (continuation)

SYSTEM STATISTICS:

SPATIAL MEAN	5.967
SPATIAL STANDARD DEVIATION	2.663
STANDARD MEASUREMENT ERROR	0.000
AREAL AUTOCORRELATION COEFFICIENT	0.66193
UPPER LIMIT	0.83541
HIGH LOWER LIMIT	0.48846
LOW LOWER LIMIT	0.27606
CENTROID-AREA CROSS CORRELATION COEFFICIENT	0.52541
BASIN AREA	971.154
BASIN PERIMETER	167.819
BASIN EQUIVALENT RADIUS	11.574
BASIN CENTROID	
X - AXIS	51.192
Y - AXIS	57.963

SYSTEM CORRELATION COEFFICIENTS:
(STATION CORRELATION COEFFICIENTS)

SPATIAL CORRELATION FUNCTION:
RHO = EXP(-RADIUS/RC)
==) RHO = 1.0/(1.0+RADIUS/RC)
CHARACTERISTIC RADIUS, RC = 14.213

STATION NAME	AREAL CROSS CORR.COEFF.	STATION-STATION CROSS CORRELATION COEFFICIENTS AND DISTANCES		
		VALDESIA	LAESTREC	PALODECA
VALDESIA	0.39967	1.00000	0.25541	0.43395
(DISTANCES)		0.000	41.434	18.540
LAESTREC	0.47480	0.25541	1.00000	0.37567
(DISTANCES)		41.434	0.000	23.621
PALODECA	0.50228	0.43395	0.37567	1.00000
(DISTANCES)		18.540	23.621	0.000

Figure 2.2 (continuation)

OPTIMAL INTERPOLATION BASED ON STRAIGHT DATA: PRECIPITATION STATIONS AT NIZAO BASIN - DOMINICAN REPUBLIC

```
      I+---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+I
83.85 I                                                                                                      I
81.92 I     .6      .                                                                                        I
80.00 I   ..666666666........                                                                                I
78.08 I   666666666......5555555....                                                                         I
76.15 I  66666666......55555......44444                                                                      I
74.23 I  6666666......55555....444....3333        .44  ..5                                                   I
72.31 I      66.....55555....444...33...2222..333..444...5555.                                               I
70.38 I         ....55555....444...33..22+22..333..444...555....66666....                                    I
68.46 I         .....55555....444....333333333...4444...5555....6666.....77                                  I
66.54 I           .....55555.....444444.....444444....5555....66666.....777                                  I
64.62 I                    55555..................55555.....66666.....777777...                               I
62.69 I                         5555555555555555555......666666.....777777......                             I
60.77 I                           ..................6666666......77777......888888..                         I
58.85 I                            6666666666666666666666......777777.....888888.....                        I
56.92 I                                 666666666666.........777777.....88888.....                           I
55.00 I                                    ...............777777....88888.....999                            I
53.08 I                                    ..............77777....8888....99999.....                         I
51.15 I                                       77777777....77777...888...9999.....AAAA                        I
49.23 I                                         7777777777.777..88...999....AAAA.....                        I
47.31 I                                         ..........+.888...999...AAA....BBBBB..                       I
45.38 I                                          888888......999...AAA...BBBB....CCCCCCCCC                   I
43.46 I                                            .9999999....AAA...BBB...CCC....DDDDDDDDDDDDD              I
41.54 I                                                ..AAAA...BBB...CCC..DDD....EEEEEEEEEE..               I
39.62 I                                                      BB..CCC..DDD..EE...FFFFFFFFFF....               I
37.69 I                                                                  .FF..GG......GG...FF...             I
35.77 I                                                                   ..G.H..I.I..H..G..FFF..EE          I
33.85 I                                                                   ..GG.HH+HHHH..GG..FFF..E           I
31.92 I                                                                              GG...                   I
30.00 I                                                                                                      I
      I+---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+I
Y/X 25.00     30.00     35.00     40.00     45.00     50.00     55.00     60.00     65.00     70.00     75.00
```

LEGEND :

SYMBOLS	CONTOURS	TOLERANCE
0	3.300	+/- 0.075
1	3.600	+/- 0.075
2	3.900	+/- 0.075
3	4.200	+/- 0.075
4	4.500	+/- 0.075
5	4.800	+/- 0.075
6	5.100	+/- 0.075
7	5.400	+/- 0.075
8	5.700	+/- 0.075
9	6.000	+/- 0.075
A	6.300	+/- 0.075
B	6.600	+/- 0.075
C	6.900	+/- 0.075
D	7.200	+/- 0.075
E	7.500	+/- 0.075
F	7.800	+/- 0.075
G	8.100	+/- 0.075
H	8.400	+/- 0.075
I	8.700	+/- 0.075

AREAL MEAN OF INTERPOLATED VALUES =   5.6085

Figure 2.2 (continuation)

OPTIMAL STANDARD ERROR OF INTERPOLATION: PRECIPITATION STATIONS AT NIZAO BASIN - DOMINICAN REPUBLIC

```
      I+---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+I
83.85 I                                                                                                       I
81.92 I        ..           B                                                                                 I
80.00 I     C........BBBBBBB...                                                                               I
78.08 I     ......BBBBBBB.....AAAAA...                                                                        I
76.15 I    .....BBBBBB.....AAAA...9999...                                                                     I
74.23 I    ....BBBBBB....AAAA...99..888..77.        88.  99.                                                  I
72.31 I         BBBB....AAAA..999..8..7.6.5.44.5.6.7..88..999...A                                             I
70.38 I            .....AAA...99..88.77.6..4+.4..6.77.88..999....AAAAA......                                  I
68.46 I            .....AAAA...99..88..77...66...77..88...999.....AAAAA.......                                I
66.54 I              ...AAAAA...999...8888......88888....9999.....AAAAAAA.....                                I
64.62 I                       .....99999.............9999999......AAAAAAAA........                            I
62.69 I                            ....99999999999999999999.........AAAAAAAA.......                           I
60.77 I                              ........999999999999999...........AAAAAAAA.........                      I
58.85 I                               A..........99999999999999999........AAAAAAAA......                      I
56.92 I                                    .....9999999999.....999999999......AAAAAAA                         I
55.00 I                                       .99999......88888888.....99999.....AAAA                         I
53.08 I                                       9999...888...777777...888...9999......AAAA                      I
51.15 I                                          ..88..77.66.....6..7..888...9999.....AA                      I
49.23 I                                            88.7...5...1345.6.77.888...9999......                      I
47.31 I                                            88..77.6..+5..66.77..888....999999....                     I
45.38 I                                             ..88...7777777....8888.......99999999....                 I
43.46 I                                               .....8888888888888.................999999...            I
41.54 I                                                   999.................88888888888....999              I
39.62 I                                                          9999......88888....77777...888...            I
37.69 I                                                                       ..77.66....66.77.88..99         I
35.77 I                                                                        7..65..21345.6.7.88..99..      I
33.85 I                                                                        .77.6..+5..6..7.88..99..       I
31.92 I                                                                                   ..888               I
30.00 I                                                                                                       I
      I+---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+I
  Y/X 25.00     30.00     35.00     40.00     45.00     50.00     55.00     60.00     65.00     70.00     75.00
```

LEGEND :

SYMBOLS	CONTOURS	TOLERANCE
0	0.200	+/- 0.050
1	0.400	+/- 0.050
2	0.600	+/- 0.050
3	0.800	+/- 0.050
4	1.000	+/- 0.050
5	1.200	+/- 0.050
6	1.400	+/- 0.050
7	1.600	+/- 0.050
8	1.800	+/- 0.050
9	2.000	+/- 0.050
A	2.200	+/- 0.050
B	2.400	+/- 0.050
C	2.600	+/- 0.050
D	2.800	+/- 0.050
E	3.000	+/- 0.050

Figure 2.2 (continuation)

OPTIMAL AREAL AVERAGING

STA.NO.	STA. NAME	INPUT DATA	OPTIMAL WEIGHT
1	VALDESIA	8.900	0.2573
2	LAESTREC	3.700	0.3861
3	PALODECA	5.300	0.3566

SUM OF OPTIMAL WEIGHT = 1.00000
OPTIMAL AREAL MEAN = 5.609
STD. ERROR OF AREAL MEAN = 1.4773

Figure 2.2 (continuation)

```
**************************************
OPTIMAL AREAL WEIGHTING FOR NIZAO BASIN
**************************************

ENTER FILENAME OF SPATIAL STATISTICS
   (FOR NIZAO BASIN, ENTER SPNIZAO)?_ spnizao


STATION INDICATORS, NONZERO IF AVAILABLE, ZERO IF NOT AVAILABLE.
INPUT STATION INDICATORS IN FOLLOWING SEQUENCE:
1 EL RIO,2 ENGOMBE,3 JUMA BONAO,4 LALAGUNA,5 QUEMADOS
6 NIZAO,7 PALO DE CAJA,8 VALDESIA AND 9 VALLENUEVO.
? 0 1 1 0 1 0 1 1 0

                    LA ESTRECHURA PALO DE CAJA PASO DEL ERMITANO

STATION   1  WEIGHT =     0.00000      0.00000      0.00000
STATION   2  WEIGHT =     0.12052      0.10446      0.09818
STATION   3  WEIGHT =     0.16340      0.15624      0.06159
STATION   4  WEIGHT =     0.00000      0.00000      0.00000
STATION   5  WEIGHT =     0.34667      0.18104      0.05317
STATION   6  WEIGHT =     0.00000      0.00000      0.00000
STATION   7  WEIGHT =     0.25596      0.44834      0.42595
STATION   8  WEIGHT =     0.11345      0.10992      0.36112
STATION   9  WEIGHT =     0.00000      0.00000      0.00000

 MORE STATION COMBINATIONS ( 1=YES, 0=NO) ? 1


STATION INDICATORS, NONZERO IF AVAILABLE, ZERO IF NOT AVAILABLE.
INPUT STATION INDICATORS IN FOLLOWING SEQUENCE:
1 EL RIO,2 ENGOMBE,3 JUMA BONAO,4 LALAGUNA,5 QUEMADOS
6 NIZAO,7 PALO DE CAJA,8 VALDESIA AND 9 VALLENUEVO.
? 1 0 0 1 0 1 0 0 1

                    LA ESTRECHURA PALO DE CAJA PASO DEL ERMITANO

STATION   1  WEIGHT =     0.18139      0.10746      0.13286
STATION   2  WEIGHT =     0.00000      0.00000      0.00000
STATION   3  WEIGHT =     0.00000      0.00000      0.00000
STATION   4  WEIGHT =     0.12048      0.27007      0.53886
STATION   5  WEIGHT =     0.00000      0.00000      0.00000
STATION   6  WEIGHT =     0.31064      0.50322      0.20663
STATION   7  WEIGHT =     0.00000      0.00000      0.00000
STATION   8  WEIGHT =     0.00000      0.00000      0.00000
STATION   9  WEIGHT =     0.38750      0.11925      0.12165

 MORE STATION COMBINATIONS ( 1=YES, 0=NO) ? 0

Execution terminated : 0
```

Figure 2.3. Sample OPTIM program interactive run.

3. FLOOD EVENT SIMULATION

This option of CSU-HMS currently includes the PC version of the HEC-1 model of U.S.Army Corps of Engineers. It is basically a single storm event simulation model which has many capabilities to use many different techniques of loss computation and routing. Two capabilities of interest are : (a) the optimization of parameters of the loss function, unit hydrograph and the channel ~~routing~~; and (b) the simulation of a flood event over a large basin divided into different subbasins, channel segments, and artificial and/or natural storage facilities such as reservoirs. These capabilities are well documented in publications of Corps of Engineers and therefore will not be repeated here. The interested user may want to refer to the HEC-1, Flood Hydrograph Package, Users Manual, January 1985 published by the Hydrologic Enginering Ceneter, U.S. Army Corps of Engineers, Davis, Cailfornia.

4. FLOOD FORECASTING

4.1 Introduction

The program SACKW is a conceptual-hydraulic model of watershed which simulates the various elements of the hydrologic cycle. Basically, the model starts with simulating the basin hydrology through the conceptual based Sacramento soil moisture accouting (SAC) model (Burnash et al., 1979) to derive the different runoff components in the basin accruiing from input precipitation. Then, the pertinent runoff components are hydraulically routed through overland-flow planes and channels to arrive at the streamflows at the basin outlet using the kinematic wave (KW) routing methodology (U.S. Army Corps of Engineers, 1985). The model has two operational modes: the calibration mode for model parameter estimation, and the forecasting mode for simulating basin hydrology under some specified or known set of model parameters. In the calibration mode, the parameters of the SAC model may be calibrated manually or automatically using the constrained Rosenbrock optimization technique. The time scale of model simulation is at the least on an hourly basis and can be at longer time intervals but as multiples of one hour.

The ensuing sections present the description of Program SACKW, input requirements, output information, some guidelines for model usage and parameter calibration, and sample model application.

4.2 Program Description

Program SACKW is written in FORTRAN 77 which can be ran in mainframe computers or desktop computers. It is composed of 14 subprograms and a main program. A descriptive flowchart of the program operation and sequence is given in Figure 4.1. Included in the flowchart are the pertinent program and subprograms used in the various operations. Given below are brief descriptions of the main program and subprograms.

MAIN PROGRAM

The MAIN program reads all input data and controls the overall sequence of program operations.

Subroutine SETPAR

This subprogram checks and sets up default values of model parameters for the Sacramento soil moisture accounting model.

Subroutine SACROUT

Subroutine SACROUT resets model parameters, sequences the soil moisture accounting and routing operations, and output some execution results.

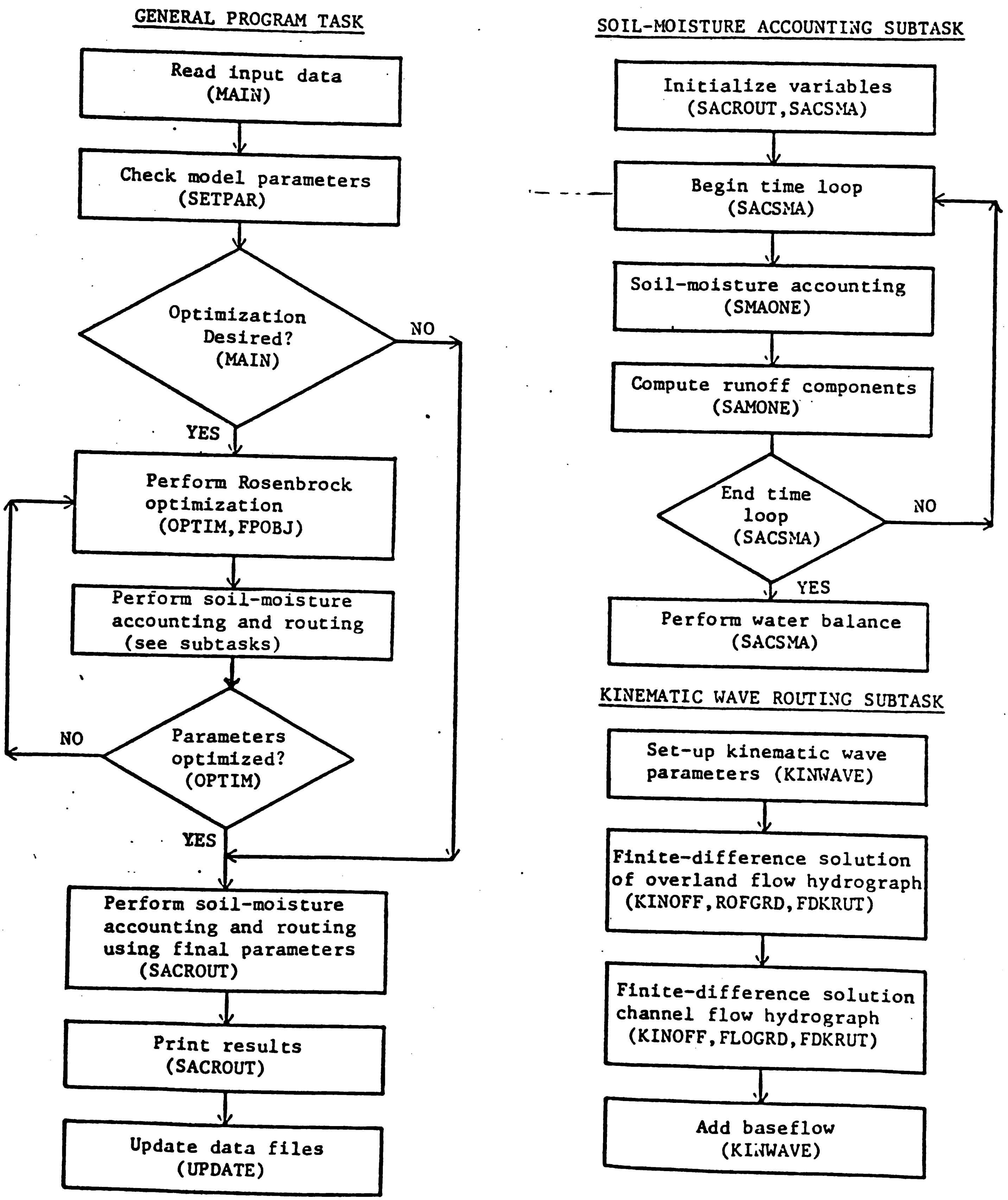


Figure 4.1. Descriptive flow chart of PROGRAM SACKW.

Subroutine SACSMA

Subroutine SACSMA specifically controls the time loop of the Sacramento soil moisture accounting, performs water balance and prints results of soil moisture accounting.

Subroutine SMAONE

This subroutine performs all soil moisture accounting computations for one time step.

Subroutine KINWAVE

This subroutine controls the timing and sequencing of kinematic wave routing operations. Additionally, the routed streamflows and computed baseflows from different flow planes and subbasins are combined in this subroutine.

Subroutine KINOFF

This subroutine determines the runoff hydrograph for each flow plane using the kinematic wave method.

Subroutine FDKRUT

Subroutine FDKRUT generates overland flow runoff hydrograph or stream discharge hydrographs.

Subroutine ROFGRD

Subroutine ROFGRD computes the incremental length and time required in finite-difference grid computations for overland flow.

Subroutine FLOGRO

This subroutine computes the size and number incremental lengths required in finite-difference solution in the stream discharge routing computation.

Subroutine FRMMTC

Converts input data from metric units to English units in the kinematic wave routing computations.

Subroutine TOMTRC

Converts computed results in English units to metric system in the kinematic wave routing computation.

Subroutine OPTIM

Subroutine OPTIM performs the constrained Rosenrock optimization algorithm for the SAC model parameters.

Function FPOBS

This subprogram computes the value of the objective function for the optimization routine based on observed and computed streamflows.

Subroutine UPDATE

This subprogram generates an updated model input data file if derived to incorporate adjusted model parameters when optimized and sending volumes of soil-moisture contents for eventual use in the future.

4.3 Input and Output Information

Generally, the program input can be summarized in the following sequence:

1. Model run information
2. Control parameters for input, output and optimization options
3. Soil-moisture accounting model parameters
4. Kinematic wave model parameters
5. Hydrologic input data control parameters

A detailed description and sequence of the program input is given in Appendix 4.A. To facilitate in model inputting some data or parameter input (data sets) require a five-letter word identifier as a leading record or contained in the beginning of an input record. For further clarification on the input requirements, Section 4.5. presents a sample program application.

The program output is primarily in the form of tabular and graphical displays on a line printer. The tabular outputs include summaries of soil-moisture contents, runoff components, evapotranspiration and rainfall. Tabular and graphical outputs of observed and simulated streamflows at subbasin outlets are also given. There are printing frequency control options provided in the program. A sample program output is given in Section 4.5.

4.4 Some Guidelines For Model Usage and Parameter Calibration

For details of setting-up the parameter values of the SAC model and kinematic wave routing model, the manuals prepared by Burnash, et al., 1979 and the U.S. Corps of Engineers (1985), respectively can be consulted. The ensuing text presents only some guidelines on model parameter calibration with emphasis on the SAC model parameters.

For the SAC model, Burnash (1985) have shown that from several tests conducted on the sensitivity of the model, the rainfall input data practically accounts for all variations in the computed streamflows as opposed to the rest of the model parameters. This result is shown in Figure 4.2. in which a particular runoff hydrograph is ten times as sensitive to a shift in the rainfall input as it is to a similar change in the most sensitive parameters. In view of this, an important aspect in using the model is to resolve the question of handling the rainfall data. As done in the model calibration for Nizao basin, the rainfall

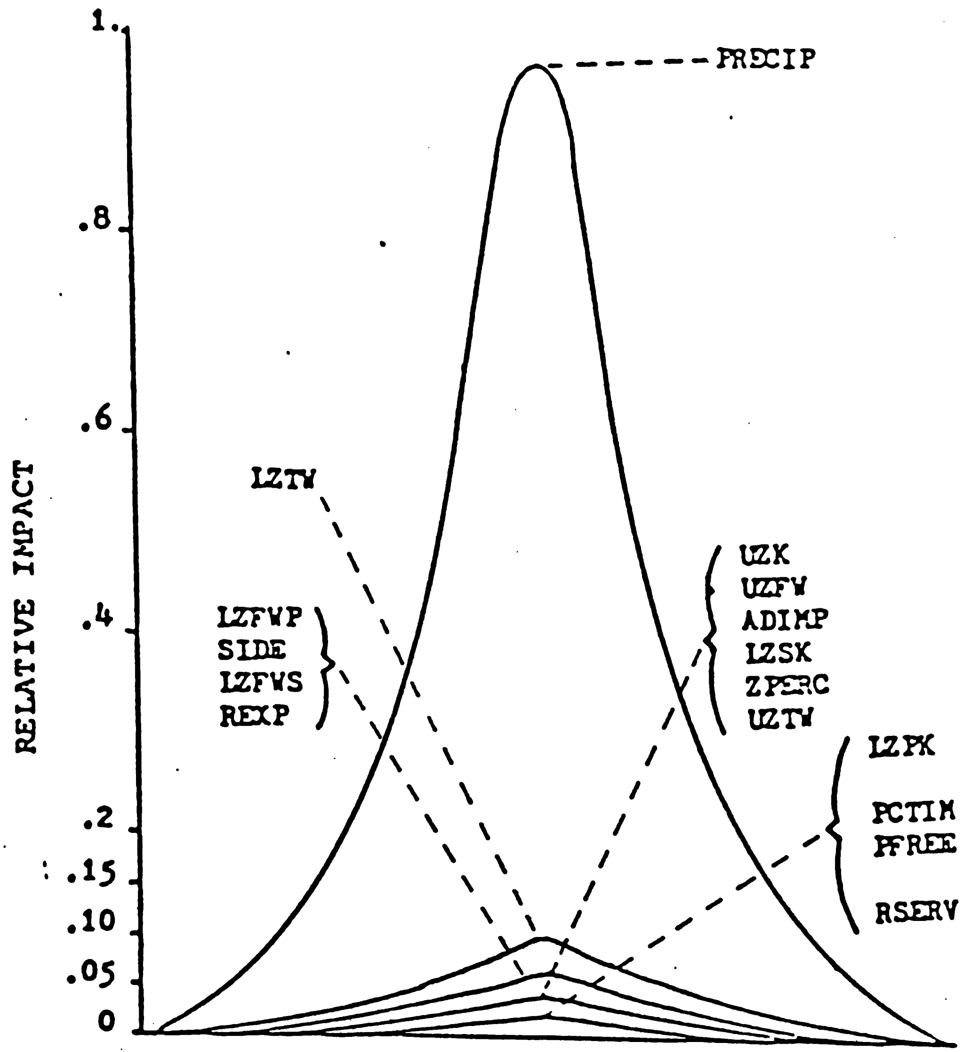


Figure 4.2. Incremental effect of 10% changes in basic input or parameter values as evaluated with the Sacramento model. After Burnash (1985).

input data has been defined for each subwatershed based on areally averaging point rainfall time series data from several stations. An areal averaging technique such as Thiessen method or optimal interpolation technique can be used for this purpose.

As mentioned earlier, the initial model parameters of SAC model may be obtained from guidelines given by Burnash, et al., (1979). Once this is set-up, some parameters may be refined by manual calibration or automatically through the optimization algorithm. Generally, the SAC model parameters to be calibrated are: UZK, REXP, ZPERC, SIDE, UZTWM, UZFWM, LZTWM, LZFSM and LZFPM. In the case of manually calibrating the model parameters, the following guidelines may be useful.

1. If surface runoff is excessive and baseflow is too low, the percolation could be inadequate. A possible action is to increase LZFSM and LZFPM which increases percolation and potential baseflow.

2. If initial runoff is inadequate, decreasing UZTWM allows runoff to take place sooner.

3. If surface runoff is generally excessive, the following action may be taken: i) raise ZPERC and thus increase percolation, ii) enlarge LZFSM and LZFPM which results in higher potential baseflow, and iii) lower REXP to increase continuing percolation and also alter shape of percolation curve.

4. If streamflow rising limbs are underforecast, too much water may be required to fill LZTWM. Action: reduce LZTWM by as much as water balance residual.

5. If streamflow rising limbs are overforecast but recession limbs underforecast, interflow could be inadequate which can be corrected by increasing UZFWM.

6. If the streamflow hydrograph baseflow time is too wide and rising peaks are flat the impervious area parameter ADIMP may be small. Decreasing ADIMP sharpens rising peaks and diminishes baseflow area.

7. To increase the general level of surface runoff and slightly decrease the trailing baseflow, ZPERC may be reduced.

For the kinematic wave model, most of the parameters can be obtained from basin topographic maps, such as basin areas and overland-flow and channel slopes, widths and lengths. The channel geometry may be obtained from actual photographs with scales or river cross-sectional data. The parameter that may require some calibration is the roughness coefficient since flow-plane or channel heterogeneity effects may be difficult to fully parameterize into some lumped or average values.

4.5 <u>Sample Model Application</u>

This section presents a sample model application for illustration purposes. One watershed is used in the example with three overland-flow

elements as shown in Figure 4.3. The input hydrologic data are rainfall, streamflow and evapotranspiration demand which are on an hourly basis. Given in Figure 4.4, is the input data file for the model. In this case, the hydrologic data are read as part of the overall model input file.

It is worthwhile to mention the manner in which the kinematic wave routing parameters are inputted with respect to the river basin configuration. Referring to Figures 4.3 and 4.4, the overland-flow element 1 runoff hydrograph is computed first which corresponds to the first "ROUTE" operation in the data file. Then the hydrograph of overland-flow element 2 is computed in the second "ROUTE" operation. In both cases, the "ROUTE" operation are followed by "BASEF" operations so that baseflow components are added at their outlet. At point A, the two hydrographs are combined using the "ADD" operation. The hydrograph for overland-flow element 3 is computed in the third "ROUTE" operation plus the contribution of baseflow upon issuing the last "BASEF" operation. Note that in this third "ROUTE" operation, the variable ARUPF(.) is set equal to 1.0 which indicates that the upstream hydrograph (at point A) is also routed together with the flows in subbasin 3.

The program output for this run is given in Figure 4.5. In this output all soil-moisture accouting results are printed on an hourly basis. This sample run is made where 5 SAC model parameters are optimized. In the printout, for the optimization results, the X(.) variable correspond to the model parameters optimized in the order they are inputted.

4.6 References

Burnash, R.J.C., 1985. Real-time forecasting with the Sacramento watershed model. In Proc. 14th Annual Hydrology Day, Colorado State University, Ft. Collins, CO, pp. 103-113.

Burnash, R.J.C., R.L. Ferral and R.A. McGuire, 1979. A generalized streamflow simulation system conceptual modeling for digital computers. National Weather Service, California Dept. of Water Resources, March, 1979 (second printing).

Kuester, J.L. and J.H. Mize, 1973. Optimization techniques with FORTRAN. McGraw-Hill Book Co., New York.

National Weather Service, 1984. NWS-river forecast system manual calibration version 3.0. National Weather Service, Silver Spring, Md.

U.S. Army Corps of Engineers, 1985. HEC-1 flood hydrograph package user's manual. The Hydrologic Engineering Center, Dan's, CA, January, 1985 (revised edition).

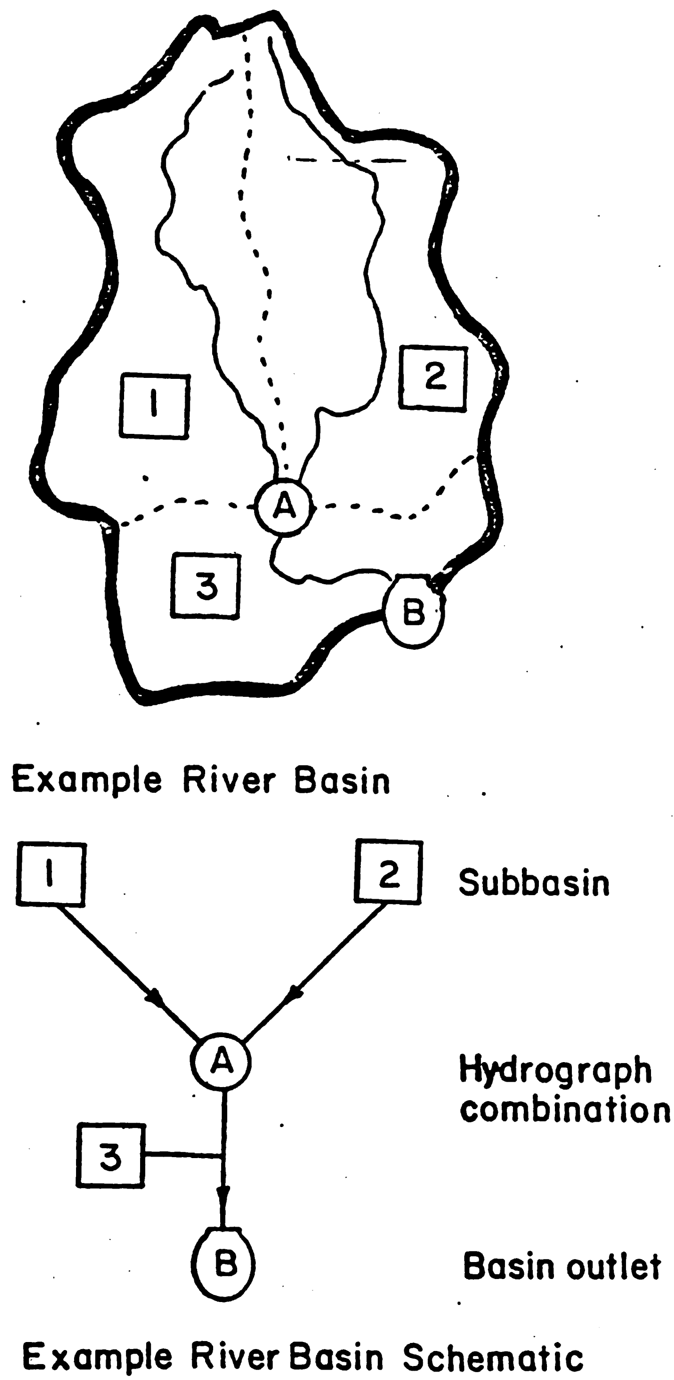


Figure 4.3. Sample river basin and schematic representation.

```
SAMPLE MODEL APPLICATION
    5     0   72    1    1
0.01        1   25    1    1
ZPERC     147.0     15.0      160.      5.0
REXP      0.507     0.4       5.0       0.1
SIDE      0.183     0.0001    10.0      0.001
UZK       0.0096    0.001     0.90       0.001
ADIMP     0.1175    0.001     0.5       0.001
RSERV     0.42      0.01      .50       0.01
RIVA      0.84      0.25      0.90       0.01
PCTIM     0.089     0.05      .80       0.01
LZPK      0.010     0.005     .80       0.001
LZSK      0.0055    0.003     .50       0.001
PFREE     0.790     0.01      .999      0.0001
UZTWC     89.0      50.0      150.0     2.0
UZFWC     33.0      30.0      80.0      2.0
LZTWC     120.0     40.0      250.0     5.0
LZFSC     33.00     30.0      150.0     2.0
LZFPC     405.0     400.0     800.0     5.0
ADIMC     102.0      90.0     400.0     10.0
UZTWM     150.0
UZFWM     100.0
LZTWM     300.0
LZFSM     200.0
LZFPM     800.0
PXADJ     1.0
PEADJ     0.7
END
ROUTE
70.0
2500.0    0.6       0.4       100.0
16000.    0.105     0.06      0.0
5.0       15.0      1.0       4.92      0.0
BASEF    2
ROUTE
70.0
2500.     0.6       0.4       100.
20000.    0.0837    0.06      70.0
5.0       15.0      1.0       4.92      0.0
BASEF    2
ADD      2
ROUTE
45.0
4500.0    0.5       0.3       100.0
8500.0    0.0133    0.040     45.0
5.0       85.0      1.0       4.92      1.0
BASEF    2
END
RAIN
    1   72    0    1    0
(8F10.0)
0.6       0.2       0.2       2.70      0.7       1.10      0.5       0.0
2.50      57.6      15.1      0.90      0.4       0.0       0.0       0.0
0.00      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       0.0       0.0
0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
```

Figure 4.4. Input data file for sample model application.

```
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       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       0.0       0.0       0.0       0.0       0.0       0.0
ETDATA
   1    0    1    0
(8F10.0)
0.438     0.438     0.438     0.438     0.438     0.438     0.438     0.438
0.438     0.438     0.438     0.438     0.179     0.179     0.179     0.179
0.179     0.179     0.179     0.179     0.179     0.179     0.179     0.179
0.179     0.179     0.179     0.179     0.179     0.179     0.179     0.179
0.179     0.179     0.179     0.179     0.217     0.217     0.217     0.217
0.271     0.271     0.271     0.271     0.271     0.271     0.271     0.271
0.271     0.271     0.271     0.271     0.271     0.271     0.271     0.271
0.271     0.271     0.271     0.271     0.271     0.271     0.271     0.271
0.271     0.271     0.271     0.271     0.271     0.271     0.271     0.271
FLOW
   1    1    0    1    0
(8F10.0)
4.92      4.92      5.57      5.57      5.57      5.57      5.57      5.57
6.27      6.27      6.64      7.84      17.4      39.46     50.1      39.46
30.44     24.64     20.41     17.40     15.34     10.65     12.86     12.28
11.72     11.18     10.65     10.14     9.65      9.65      9.18      8.71
8.71      8.27      7.84      7.84      7.84      7.84      7.84      7.42
7.42      7.02      7.02      7.02      7.02      7.02      7.02      7.02
7.02      6.64      6.27      6.27      6.27      6.27      6.27      6.27
6.57      6.27      6.27      6.27      6.27      6.27      6.27      6.27
7.02      6.64      6.27      6.27      6.27      6.27      6.27      6.27
END
```

Figure 4.4 (continuation)

```
BASIN 1 RUN: SAMPLE MODEL APPLICATION

LIST OF PARAMETERS TO BE OPTIMIZED

  NAME          VALUE      MINIMUM    MAXIMUM   STEP SIZES

 ZPERC       147.00000    15.00000  160.00000    5.00000
 REXP          0.50700     0.40000    5.00000    0.10000
 SIDE          0.18300     0.00010   10.00000    0.00100
 UZK           0.00960     0.00100    0.90000    0.00100
 ADIMP         0.11750     0.00100    0.50000    0.00100

LIST OF PARAMETERS MANUALLY CALIBRATED

  NAME          VALUE

 RSERV         0.42000
 RIVA          0.84000
 PCTIM         0.08900
 LZPK          0.01000
 LZSK          0.00550
 PFREE         0.79000
 UZTWC        89.00000
 UZFWC        33.00000
 LZTWC       120.00000
 LZFSC        33.00000
 LZFPC       405.00000
 ADIMC       102.00000
 UZTWM       150.00000
 UZFWM       100.00000
 LZTWM       300.00000
 LZFSM       200.00000
 LZFPM       800.00000
 PXADJ         1.00000
 PEADJ         0.70000

OPTIMIZATION PARAMETERS :
  OBJECTIVE FUNCTION TYPE               1
  MAXIMUM NUMBER OF ITERATIONS         25
  CONVERGENCE CRITERION       0.10000E-01
  STEP SIZE UPDATE OPTION               1
  PRINTING FREQUENCY                    1

NUMBER OF PARAMETERS TO BE OPTIMIZED =   5
NUMBER OF PARAMETERS MANUALLY CALIBRATED = 19

PARAMETERS TO BE OPTIMIZED AFTER CHECKING

   ITEM NAME      VALUE      MINIMUM    MAXIMUM   STEP SIZES

   1  ZPERC    147.00000    15.00000  160.00000    5.00000
   2  REXP       0.50700     0.40000    5.00000    0.10000
   3  SIDE       0.18300     0.00010   10.00000    0.00100
   4  UZK        0.00960     0.00100    0.90000    0.00100
   5  ADIMP      0.11750     0.00100    0.50000    0.00100

PARAMETERS MANUALLY CALIBRATED AFTER CHECKING

  ITEM NAME       VALUE

   6  RSERV      0.42000
   7  RIVA       0.84000
   8  PCTIM      0.08900
```

Figure 4.5. Program output of sample model application.

9	LZPK	0.01000
10	LZSK	0.00550
11	PFREE	0.79000
12	UZTWC	89.00000
13	UZFWC	33.00000
14	LZTWC	120.00000
15	LZFSC	33.00000
16	LZFPC	405.00000
17	ADIMC	102.00000
18	UZTWM	150.00000
19	UZFWM	100.00000
20	LZTWM	300.00000
21	LZFSM	200.00000
22	LZFPM	800.00000
23	PXADJ	1.00000
24	PEADJ	0.70000

Figure 4.5 (continuation)

```
OPTIMIZATION BY ROSENBROCK HILLCLIMB PROCEDURE

11
STAGE        FUNCTION            PROGRESS          LATERAL PROGRESS
  1      -0.90737742E+01      0.16250006E+02      0.24414062E-06

NUMBER OF FUNCTION EVALUATIONS =        70

VALUES OF X(.) AT THIS STAGE
  X( 1) =      0.158250E+03    X( 2) =      0.492937E+00    X( 3) =      0.183000E+00
  X( 4) =      0.959805E-02    X( 5) =      0.117500E+00    X(

STAGE        FUNCTION            PROGRESS          LATERAL PROGRESS
  1      -0.90737672E+01      0.16250006E+02      0.24414062E-06

NUMBER OF FUNCTION EVALUATIONS =        76

VALUES OF X(.) AT THIS STAGE
  X( 1) =      0.158260E+03    X( 2) =      0.492831E+00    X( 3) =      0.183000E+00
  X( 4) =      0.959803E-02    X( 5) =      0.117500E+00    X(

FINAL DIRECTION VECTOR MATRIX
  V( 1, 1) = 0.99999963    V( 1, 2) = -.00086538    V( 1, 3) = 0.00000002
  V( 1, 4) = -.00000012    V( 1, 5) = 0.00000002    V(
  V( 2, 1) = -.00086538    V( 2, 2) = -.99999962    V( 2, 3) = 0.00001736
  V( 2, 4) = -.00013889    V( 2, 5) = 0.00001736    V(
  V( 3, 1) = -.00000012    V( 3, 2) = 0.00000000    V( 3, 3) = 0.12309149
  V( 3, 4) = -.99473193    V( 3, 5) = 0.12309149    V(
  V( 4, 1) = -.00000012    V( 4, 2) = 0.00000000    V( 4, 3) = 0.00000000
  V( 4, 4) = -.99227788    V( 4, 5) = 0.12403473    V(
  V( 5, 1) = -.00000002    V( 5, 2) = 0.00000000    V( 5, 3) = 0.00000000
  V( 5, 4) = 0.00000000    V( 5, 5) = 1.00000000    V(

FINAL STEP SIZES
  S( 1) =      0.976563E-02    S( 2) =      0.195312E-03    S( 3) =      0.122070E-06
  S( 4) =      0.122070E-06    S( 5) =      0.122070E-06    S(
```

Figure 4.5 (continuation)

SACRAMENTO SOIL-MOISTURE ACCOUNTING OPERATION

PARAMETER VALUES - CAPACITIES ARE IN MM.

PX-ADJ	PE-ADJ	UZTWM	UZFWM	UZK	PCTIM	ADIMP	RIVA
1.000	0.700	150.000	100.000	0.010	0.089	0.118	0.840

DAILY ET DIST. ASSUMED UNIFORM

PBASE	ZPERC	REXP	LZTWM	LZFSM	LZFPM	LZSK	LZPK	PFREE	RSERV	SIDE
9.100	158.260	0.493	300.000	200.000	800.000	0.006	0.010	0.790	0.420	0.183

SOIL-MOISTURE CONTENTS (MM)

UZTWC	UZFWC	LZTWC	LZFSC	LZFPC	ADIMC
89.000	33.000	120.000	33.000	405.000	102.000

DETAILED SOIL-MOISTURE ACCOUNTING OUTPUT   UNITS ARE IN MM.

DAY	HR	UZTWC	UZFWC	LZTWC	LZFSC	LZFPC	ADIMC	PERC	IMP	DIR	SUR	INT	SUP	PRI	TOT-RO	ET-DMD	ACT-ET	RAIN
1	1	89.4	20.511	122.59	36.974	410.71	102.41	12.479	0.053	0.000	0.000	0.008	0.005	0.115	0.105	0.307	0.269	0.60
1	2	89.4	12.705	124.19	39.436	414.22	102.43	7.800	0.018	0.000	0.000	0.005	0.006	0.116	0.069	0.307	0.269	0.20
1	3	89.5	7.758	125.20	40.985	416.40	102.44	4.943	0.018	0.000	0.000	0.003	0.006	0.117	0.068	0.307	0.269	0.20
1	4	92.0	4.637	125.82	41.955	417.71	104.96	3.118	0.240	0.000	0.000	0.002	0.006	0.117	0.290	0.307	0.269	2.70
1	5	92.5	2.537	126.22	42.604	418.53	105.46	2.099	0.062	0.000	0.000	0.001	0.006	0.117	0.115	0.307	0.270	0.70
1	6	93.4	1.389	126.43	42.953	418.90	106.37	1.147	0.098	0.000	0.000	0.000	0.007	0.118	0.151	0.307	0.270	1.10
1	7	93.7	0.761	126.53	43.140	419.03	106.68	0.628	0.045	0.000	0.000	0.000	0.007	0.118	0.099	0.307	0.270	0.50
1	8	93.5	0.417	126.57	43.237	419.02	106.48	0.344	0.000	0.000	0.000	0.000	0.007	0.118	0.055	0.307	0.270	0.00
1	9	95.8	0.229	126.58	43.286	418.93	108.79	0.188	0.223	0.000	0.000	0.000	0.007	0.118	0.277	0.307	0.270	2.50
1	10	150.0	3.349	126.57	43.308	418.81	166.18	0.103	5.126	0.001	0.000	0.000	0.007	0.118	5.185	0.307	0.270	57.60
1	11	150.0	14.545	127.32	44.418	420.35	180.90	3.595	1.344	0.009	0.000	0.002	0.007	0.118	1.480	0.307	0.279	15.10
1	12	150.0	9.521	128.50	46.151	422.86	181.48	5.613	0.080	0.001	0.000	0.004	0.007	0.118	0.210	0.307	0.279	0.90
1	13	150.0	5.970	129.30	47.323	424.52	181.75	3.823	0.036	0.000	0.000	0.002	0.007	0.119	0.164	0.125	0.114	0.40
1	14	149.9	3.595	129.80	48.044	425.49	181.63	2.373	0.000	0.000	0.000	0.001	0.007	0.119	0.128	0.125	0.114	0.00
1	15	149.7	1.987	130.14	48.528	426.09	181.50	1.608	0.000	0.000	0.000	0.001	0.007	0.119	0.127	0.125	0.114	0.00
1	16	149.6	1.099	130.33	48.790	426.34	181.38	0.888	0.000	0.000	0.000	0.000	0.007	0.120	0.127	0.125	0.114	0.00
1	17	149.5	0.608	130.43	48.930	426.39	181.25	0.491	0.000	0.000	0.000	0.000	0.008	0.120	0.127	0.125	0.114	0.00
1	18	149.4	0.337	130.49	49.002	426.35	181.13	0.271	0.000	0.000	0.000	0.000	0.008	0.120	0.127	0.125	0.114	0.00
1	19	149.2	0.186	130.52	49.037	426.24	181.00	0.150	0.000	0.000	0.000	0.000	0.008	0.120	0.127	0.125	0.114	0.00
1	20	149.1	0.103	130.54	49.051	426.10	180.88	0.083	0.000	0.000	0.000	0.000	0.008	0.120	0.127	0.125	0.114	0.00
1	21	149.0	0.057	130.54	49.054	425.95	180.76	0.046	0.000	0.000	0.000	0.000	0.008	0.120	0.127	0.125	0.114	0.00
1	22	148.9	0.032	130.55	49.050	425.78	180.63	0.025	0.000	0.000	0.000	0.000	0.008	0.120	0.127	0.125	0.114	0.00
1	23	148.8	0.017	130.55	49.043	425.61	180.51	0.014	0.000	0.000	0.000	0.000	0.008	0.120	0.127	0.125	0.114	0.00
1	24	148.6	0.010	130.55	49.034	425.43	180.38	0.008	0.000	0.000	0.000	0.000	0.008	0.120	0.126	0.125	0.114	0.00
2	25	148.5	0.010	130.55	49.023	425.26	180.26	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.126	0.125	0.114	0.00
2	26	148.4	0.010	130.55	49.012	425.08	180.13	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.126	0.125	0.114	0.00
2	27	148.3	0.010	130.55	49.001	424.90	180.01	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.126	0.125	0.114	0.00
2	28	148.1	0.010	130.55	48.989	424.72	179.89	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.126	0.125	0.114	0.00
2	29	148.0	0.010	130.55	48.978	424.54	179.76	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.126	0.125	0.114	0.00
2	30	147.9	0.010	130.55	48.967	424.37	179.64	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.126	0.125	0.114	0.00
2	31	147.8	0.010	130.55	48.956	424.19	179.51	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.126	0.125	0.114	0.00
2	32	147.6	0.010	130.55	48.944	424.01	179.39	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.126	0.125	0.114	0.00
2	33	147.5	0.010	130.55	48.933	423.83	179.27	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.125	0.125	0.114	0.00
2	34	147.4	0.010	130.55	48.922	423.66	179.14	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.125	0.125	0.114	0.00
2	35	147.3	0.010	130.55	48.911	423.48	179.02	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.125	0.125	0.114	0.00
2	36	147.1	0.010	130.55	48.899	423.30	178.90	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.125	0.125	0.114	0.00
2	37	147.0	0.010	130.55	48.888	423.12	178.75	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.125	0.152	0.138	0.00
2	38	146.8	0.010	130.55	48.877	422.95	178.60	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.125	0.152	0.138	0.00
2	39	146.7	0.010	130.55	48.866	422.77	178.45	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.124	0.152	0.138	0.00
2	40	146.5	0.010	130.54	48.854	422.59	178.30	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.124	0.152	0.138	0.00
2	41	146.4	0.010	130.54	48.843	422.42	178.12	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.124	0.190	0.172	0.00

Figure 4.5 (continuation)

2	42	146.2	0.010	130.54	48.832	422.24	177.93	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.123	0.190	0.172	0.00
2	43	146.0	0.010	130.54	48.821	422.06	177.75	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.123	0.190	0.172	0.00
2	44	145.8	0.010	130.54	48.809	421.89	177.56	0.000	0.000	0.000	0.000	0.000	0.008	0.119	0.123	0.190	0.172	0.00
2	45	145.6	0.010	130.54	48.798	421.71	177.38	0.000	0.000	0.000	0.000	0.000	0.008	0.118	0.123	0.190	0.172	0.00
2	46	145.4	0.010	130.54	48.787	421.53	177.19	0.000	0.000	0.000	0.000	0.000	0.008	0.118	0.123	0.190	0.172	0.00
2	47	145.3	0.010	130.53	48.776	421.36	177.01	0.000	0.000	0.000	0.000	0.000	0.008	0.118	0.122	0.190	0.172	0.00
2	48	145.1	0.010	130.53	48.765	421.18	176.82	0.000	0.000	0.000	0.000	0.000	0.008	0.118	0.122	0.190	0.172	0.00
3	49	144.9	0.010	130.53	48.753	421.00	176.64	0.000	0.000	0.000	0.000	0.000	0.008	0.118	0.122	0.190	0.172	0.00
3	50	144.7	0.010	130.53	48.742	420.83	176.45	0.000	0.000	0.000	0.000	0.000	0.008	0.118	0.122	0.190	0.172	0.00
3	51	144.5	0.010	130.53	48.731	420.65	176.27	0.000	0.000	0.000	0.000	0.000	0.008	0.118	0.122	0.190	0.172	0.00
3	52	144.3	0.010	130.52	48.720	420.47	176.09	0.000	0.000	0.000	0.000	0.000	0.008	0.118	0.122	0.190	0.172	0.00
3	53	144.2	0.010	130.52	48.709	420.30	175.90	0.000	0.000	0.000	0.000	0.000	0.008	0.118	0.121	0.190	0.172	0.00
3	54	144.0	0.010	130.52	48.697	420.12	175.72	0.000	0.000	0.000	0.000	0.000	0.008	0.118	0.121	0.190	0.172	0.00
3	55	143.8	0.010	130.52	48.686	419.95	175.54	0.000	0.000	0.000	0.000	0.000	0.008	0.118	0.121	0.190	0.172	0.00
3	56	143.6	0.010	130.52	48.675	419.77	175.36	0.000	0.000	0.000	0.000	0.000	0.008	0.118	0.121	0.190	0.172	0.00
3	57	143.4	0.010	130.51	48.664	419.60	175.17	0.000	0.000	0.000	0.000	0.000	0.008	0.118	0.121	0.190	0.172	0.00
3	58	143.2	0.010	130.51	48.653	419.42	174.99	0.000	0.000	0.000	0.000	0.000	0.008	0.118	0.120	0.190	0.172	0.00
3	59	143.1	0.010	130.51	48.642	419.24	174.81	0.000	0.000	0.000	0.000	0.000	0.007	0.118	0.120	0.190	0.172	0.00
3	60	142.9	0.010	130.51	48.630	419.07	174.63	0.000	0.000	0.000	0.000	0.000	0.007	0.118	0.120	0.190	0.172	0.00
3	61	142.7	0.010	130.50	48.619	418.89	174.45	0.000	0.000	0.000	0.000	0.000	0.007	0.118	0.120	0.190	0.172	0.00
3	62	142.5	0.010	130.50	48.608	418.72	174.27	0.000	0.000	0.000	0.000	0.000	0.007	0.118	0.120	0.190	0.172	0.00
3	63	142.3	0.010	130.50	48.597	418.54	174.09	0.000	0.000	0.000	0.000	0.000	0.007	0.118	0.119	0.190	0.172	0.00
3	64	142.2	0.010	130.50	48.586	418.37	173.91	0.000	0.000	0.000	0.000	0.000	0.007	0.118	0.119	0.190	0.172	0.00
3	65	142.0	0.010	130.49	48.575	418.19	173.72	0.000	0.000	0.000	0.000	0.000	0.007	0.117	0.119	0.190	0.172	0.00
3	66	141.8	0.010	130.49	48.563	418.02	173.54	0.000	0.000	0.000	0.000	0.000	0.007	0.117	0.119	0.190	0.172	0.00
3	67	141.6	0.010	130.49	48.552	417.84	173.36	0.000	0.000	0.000	0.000	0.000	0.007	0.117	0.119	0.190	0.172	0.00
3	68	141.4	0.010	130.48	48.541	417.67	173.18	0.000	0.000	0.000	0.000	0.000	0.007	0.117	0.119	0.190	0.172	0.00
3	69	141.3	0.010	130.48	48.530	417.49	173.01	0.000	0.000	0.000	0.000	0.000	0.007	0.117	0.118	0.190	0.172	0.00
3	70	141.1	0.010	130.48	48.519	417.32	172.83	0.000	0.000	0.000	0.000	0.000	0.007	0.117	0.118	0.190	0.172	0.00
3	71	140.9	0.010	130.47	48.508	417.14	172.65	0.000	0.000	0.000	0.000	0.000	0.007	0.117	0.118	0.190	0.172	0.00
3	72	140.7	0.010	130.47	48.496	416.97	172.47	0.000	0.000	0.000	0.000	0.000	0.007	0.117	0.118	0.190	0.172	0.00

```
TOTAL CHANNEL INFLOW =      15.5338
COMPONENTS OF TOTAL CHANNEL INFLOWS
 RUNOFF FROM PERMANENT IMPERVIOUS AREA =        7.3425
 RUNOFF FROM TEMPORARY IMPERVIOUS AREA =        0.0112
 SURFACE RUNOFF WHEN UZFWS IS FULL =      0.0000
 INTERFLOW FROM LATERAL DRAINAGE OF UZFWS =        0.0300
 SUPPLEMENTARY BASEFLOW =        0.5277
 PRIMARY BASEFLOW =        8.5188
WATER BALANCE RESIDUAL (IDEALLY EQ 0.0) =    0.00000
```

Figure 4.5 (continuation)

```
KINEMATIC WAVE ROUTING FOR SUBBASIN  1

 TOTAL AREA =       70.00

OVERLAND FLOW ELEMENT 1

 CHLNG =    2500.00
 SLOPE =    0.60000
 RCMAN =    0.40000
 PAREA =    100.000


MAIN CHANNEL

 CHLNG =  16000.00
 SLOPE =   0.10500
 RCMAN =   0.06000
 SAREA =    70.000

 ISHAPE=         5
 CHWDT =    15.000
 ZLNG  =     1.000

 FLOIC =     4.920

COMPUTED KINEMATIC PARAMETERS

 ELEMENT       ALPHA        M        DT (MIN)   DX (MT)
    1          2.8854     1.667        60.00      833.55
    2          0.7189     1.604        60.00     8002.05

ADD BASEFLOW TO SUBBASIN  1 USING A LINEAR DECAY FUNCTION OF THE FORM:

 ADDED BF AT TIME T = SUM OF W(L) * BF(T-L) FOR L = 0 TO  2 ; WHERE

 W(L):  0.3000      0.5000      0.2000


KINEMATIC WAVE ROUTING FOR SUBBASIN  2

 TOTAL AREA =       70.00

OVERLAND FLOW ELEMENT 1

 CHLNG =    2500.00
 SLOPE =    0.60000
 RCMAN =    0.40000
 PAREA =    100.000


MAIN CHANNEL

 CHLNG =  20000.00
 SLOPE =    0.08370
 RCMAN =    0.06000
 SAREA =     70.000

 ISHAPE=          5
 CHWDT =     15.000
 ZLNG  =      1.000

 FLOIC =      4.920
```

Figure 4.5 (continuation)

```
COMPUTED KINEMATIC PARAMETERS

 ELEMENT      ALPHA       M        DT (MIN)   DX (MT)
    1        2.8854     1.667       60.00      833.55
    2        0.6419     1.604       60.00    10002.56

ADD BASEFLOW TO SUBBASIN  2 USING A LINEAR DECAY FUNCTION OF THE FORM:

 ADDED BF AT TIME T = SUM OF W(L) * BF(T-L) FOR L = 0 TO  2 ; WHERE

 W(L):  0.3000      0.5000      0.2000

ADD FLOWS OF SUBBASINS   1,  2,


KINEMATIC WAVE ROUTING FOR SUBBASIN  3

 TOTAL AREA =      45.00

OVERLAND FLOW ELEMENT 1

 CHLNG =    4500.00
 SLOPE =    0.50000
 RCMAN =    0.30000
 PAREA =    100.000


MAIN CHANNEL

 CHLNG =    8500.00
 SLOPE =    0.01330
 RCMAN =    0.04000
 SAREA =     45.000

 ISHAPE=          5
 CHWDT =     85.000
 ZLNG  =      1.000

 FLOIC =      4.920

ROUTE UPSTREAM FLOW


COMPUTED KINEMATIC PARAMETERS

 ELEMENT      ALPHA       M        DT (MIN)   DX (MT)
    1        3.5120     1.667       60.00     1125.29
    2        0.1068     1.654       60.00     4251.09

ADD BASEFLOW TO SUBBASIN  3 USING A LINEAR DECAY FUNCTION OF THE FORM:

 ADDED BF AT TIME T = SUM OF W(L) * BF(T-L) FOR L = 0 TO  2 ; WHERE

 W(L):  0.3000      0.5000      0.2000

   VALUE OF OBJECTIVE FUNCTION (1) =        9.07377

  DAY  HOUR  OBSERVED  COMPUTED  I-------------------------------------------------------------------I
   1     1     4.920     0.589   IC     O                                                             I
   1     2     4.920     1.453   I C    O                                                             I
   1     3     5.570     2.542   I   C    O                                                           I
   1     4     5.570     4.419   I      C O                                                           I
   1     5     5.570     5.923   I        E                                                           I
```

Figure 4.5 (continuation)

1	6	5.570	6.478
1	7	5.570	6.635
1	8	5.570	6.709
1	9	6.270	6.761
1	10	6.270	6.833
1	11	6.640	9.047
1	12	7.840	15.515
1	13	17.400	31.163
1	14	39.460	40.797
1	15	50.100	41.219
1	16	39.460	37.902
1	17	30.440	33.717
1	18	24.640	29.636
1	19	20.410	26.058
1	20	17.400	23.007
1	21	15.340	20.485
1	22	10.650	18.537
1	23	12.860	16.932
1	24	12.280	15.578
2	25	11.720	14.404
2	26	11.180	13.478
2	27	10.650	12.707
2	28	10.140	12.048
2	29	9.650	11.482
2	30	9.650	10.992
2	31	9.180	10.566
2	32	8.710	10.193
2	33	8.710	9.865
2	34	8.270	9.576
2	35	7.840	9.319
2	36	7.840	9.091
2	37	7.840	8.883
2	38	7.840	8.583
2	39	7.840	8.427
2	40	7.420	8.290
2	41	7.420	8.166
2	42	7.020	8.053
2	43	7.020	7.950
2	44	7.020	7.856
2	45	7.020	7.769
2	46	7.020	7.690
2	47	7.020	7.616
2	48	7.020	7.549
3	49	7.020	7.486
3	50	6.640	7.428
3	51	6.270	7.374
3	52	6.270	7.324
3	53	6.270	7.277
3	54	6.270	7.233
3	55	6.270	7.192
3	56	6.270	7.154
3	57	6.570	7.118
3	58	6.270	7.084
3	59	6.270	7.053
3	60	6.270	7.023
3	61	6.270	6.994
3	62	6.270	6.968
3	63	6.270	6.942
3	64	6.270	6.918
3	65	7.020	6.896
3	66	6.640	6.874
3	67	6.270	6.854
3	68	6.270	6.834
3	69	6.270	6.815

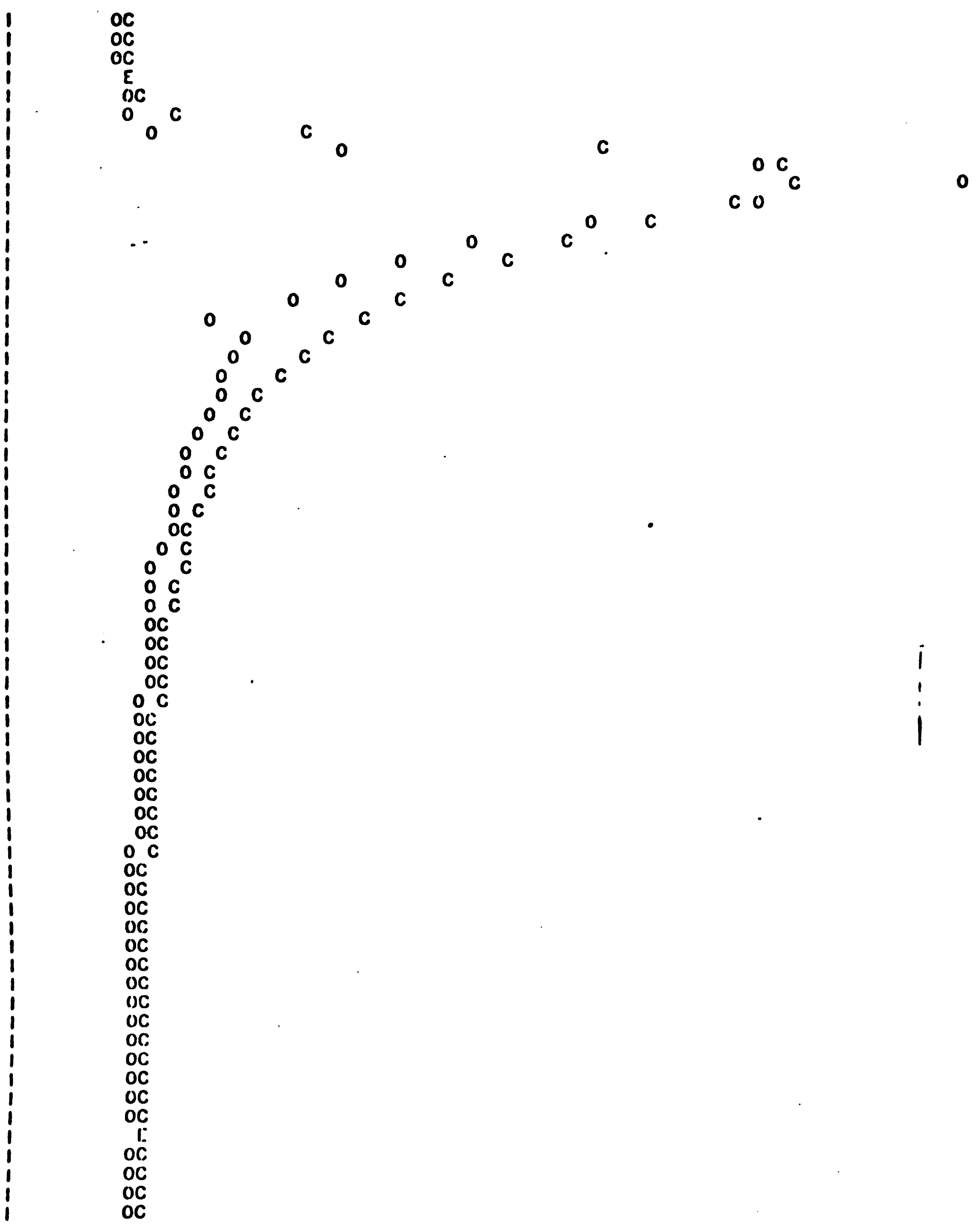


Figure 4.5 (continuation)

```
    3    70      6.270      6.798  I        OC                                                    I
    3    71      6.270      6.781  I        OC                                                    I
 11 3    72      6.270      6.765  I        E                                                     I
                                   I--------------------------------------------------------------I

   MINIMUM ORDINATE =      0.59
   MAXIMUM ORDINATE =     50.10

   SYMBOLS USED:
    COMPUTED - C
    OBSERVED - O
    IF EQUAL - E


NORMAL TERMINATION
```

Figure 4.5 (continuation)

APPENDIX 4.A

PROGRAM INPUT REQUIREMENTS AND DESCRIPTION

Data Set 1. Model run information

This data set is contained in one record and read in variable TITLE(.) usign Fortran FORMAT(10A8). No data set identifier is specified.

Data Set 2. Control parameters

This data set is also contained in one record to read the following variables using FORMAT(5I5):

NPOP - number of SAC model parameters to be optimized
IROUTE - 0 if kinematic wave routing, otherwise lag routing
IWBLNC - number of time steps water balance are made
IPFRQR - printing frequency of SAC results
IPFRQQ - printing frequency of streamflow

This data set has no record identifier.

Data Set 3. Optimization parameters

This data set is needed if optimization is desired by specifying NPOP not equal to zero. The values of the variables below are read using FORMAT (F10.0,4I5) with no record identifier.

ERROR - error criterion of relative difference of old and new objective function value

IOBF - type of objective function

MXITER - maximum number of iterations

NSTEP - step size update option, equals 1 if updated, otherwise equal to 0

IPROP - printing frequency of results at each stage evaluation

Note: For the option and types of objective functions available, see comment statement in program listing.

Data Set 4. Soil-moisture accounting model parameters

In this data set, the 24 SAC model parameters are read which could be any order. The value of each parameter is contained in one record with a record identifier. If a parameter is to be optimized, the record string should include some specified minimum and maximum values as well as the step size since these latter three values are required in the optimization routine. For each record, the following variables are read using FORMAT (2A5,4F10.0)

PNAME(.) - variable name of model parameter which is also the record identifier

DUM - dummy variable which is not used in the program but simply read for "echo" printing purposes

XMP(.) - value of parameter

XMIN(.) - lower found of parameter

XMAX(.) - upper bound of parameter

ESS(.) - parameter step size

A record containing the word "END" should be placed at the bottom of this data set.

The variable name of the 24 model parameters are listed below with brief descriptions of each. These variable names are also used as identifiers and read in PNAME(.).

1. PXADJ - precipitation adjustment factor

2. PEADJ - evapotranspiration demand adjustment factor

3. PCTIM - fraction of permanent inpervious area

4. ADIMP - fraction of impervious area when all tension storage water are met

5. RIVA - fraction of basin covered by streams, lakes and riparian vegetation

6. UZK - upper zone for water storage depletion coefficient

7. LZSK - lower zone supplementary storage depletion coefficient

8. LZPK - lower zone primary storage depletion coefficient

9. PFREE - fraction of percolated water transmitted directly to the lower zone free water

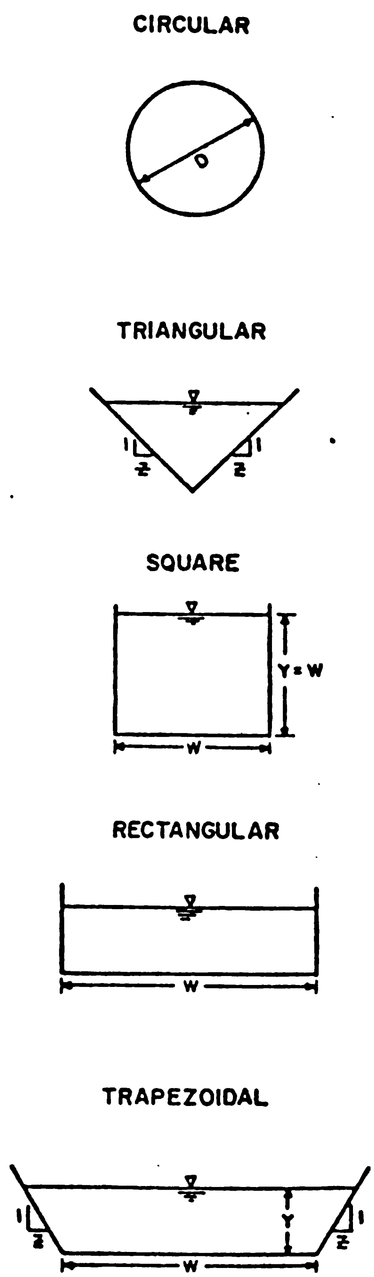
10. RSERV - fraction of lower zone free water unavailable for transpiration purposes

11. ZPERC - proportionality constant in increasing percolation from saturated to dry condition

12. REXP - exponent defining curvature in percolation curve with changes in the lower zone soil moisture deficiency

13. SIDE - portion of baseflow not observed in the channel

14. UZTWM - upper zone tension water storage content



Circular:

$$\alpha = \frac{.804}{n} S^{1/2} D^{1/6}$$

$$m = 5/4$$

Triangular:

$$\alpha = \frac{0.94}{n} S^{1/2} \left(\frac{z}{1+z^2}\right)^{1/3}$$

$$m = 4/3$$

Square:

$$\alpha = \frac{.72}{n} S^{1/2}$$

$$m = 4/3$$

Rectangular:

$$\alpha = \frac{1.49}{n} S^{1/2} W^{-2/3}$$

$$m = 5/3$$

Trapezoidal:

$$Q = \frac{1.49}{n} S^{1/2} A^{5/3} \left(\frac{1}{W+2Y\sqrt{1+z^2}}\right)^{2/3}$$

Figure 4.A.1. Kinematic wave parameters for various channel shapes. After U.S. Army Corps of Engineers (1985).

15. UZFWM - upper zone free water storage content

16. LZTWM - lower zone tension water storage content

17. LZTSM - lower zone supplementary water storage content

18. LZFPM - lower zone primary water storage content

19. UZTWC - upper zone tension water storage capacity

20. UZFWC - upper zone free water storage capacity

21. LZTWC - lower zone tension water storage capacity

22. LZFSC - lower zone supplementary water storage capacity

23. LZFPC - lower zone primary water storage capacity

24. ADIMC - additional impervious area storage capacity usually taken as UZTWM + LZTWM

There are two rules to be followed in inputting the above data set.

1. If some model parameters are to be optimized, they must be placed on top of the others.

2. The model parameters containing the initial soil-moisture contents should be placed after those containing the soil-moisture capacities. This is done when the soil-moisture content parameters are not optimized since otherwise the maximum values are specified.

Data Set 5. Kinematic wave routing parameters

The manner in which the kinematic wave model parameters are inputted is based on the physical configuration of the basin. For this purpose, three types of operations have been designated which accommodates practically any basin configuration. These three operations are "ROUTE", "ADD" and "BASEF" which are also used as record identifiers. In inputting a parameter set corresponding to an operation, the first record contains either one of the three operations with an integer variable which are read into ROPER and IOPER using FORMAT (A5, I5). This record may be followed by some input parameters depending on the type of operation as described below.

ROUTE Operation. This operation computes the flow hydrograph from overland plane to channel outlet. As many as two, overland flow planes and collector channels plus a main channel are used to represent a subbasin (second-level). The input parameter sets and sequence are as follow:

Parameter Set 1: Basin Area
TAREA - total subbasin area which is read as (F10.0)
Parameter Set 2: Overland flow element (one record and read as 4F10.0)

CHLNG(.) - overland flow length
SLOPE(.) - slope
RCMAN(.) - roughness coefficient
PAREA(.) - percent of subbasin area

If PAREA(1) is less than 99.5% a second overland-flow element is expected and the same parameters above are required for this second one.

Parameter Set 3: Collector and Main Channel (two records using 5F10.0)

Record 1: CHLNG(.) - channel length
SLOPE(.) - slope
RCMAN(.) - roughness coefficient
SAREA(.) - contributing area

Record 2: ASHAPE(.) - shape of channel used
CHWDT(.) - channel width
ZLNG(.) - side slope
FLOIC(.) - initial flows at outlet
ARUPF(.) - indicator if upstream flow from another subbasin is routed (applicable only in the main channel)

At least one collector channel and the main channel must be specified in a subbasin. A second collector channel is specified if SAREA(.) of the first collector channel is less than the total area TAREA(.). However, the program assumes that there is only one collector channel if SAREA(1) is inputted as zero.

Variable ASHAPE(.) specifies the shape of collector or main channel. These are shown in Figure 4.A.1. The variable ASHAPE(.) is set equal to: 1.0 for circular, 2.0 for triangular, 3.0 for square, 4.0 for rectangular, and 5.0 for trapezoidal. Depending on channel shape specified, either ZLNG(.) or CHWDT(.) may be left blank. In the case of a circular channel, the diameter D is specified in CHWDT(.). Only in the case of triangular and trapezoidal channel shapes where ZLNG(.) is required. However, CHWDT(.) is not required for triangular channels.

Depending on the storage space (array dimension) fixed in the program, several ROUTE operations can be issued for a subwatershed (first-level partitioning). For example, if there are three subbasins (at second-level partitioning) that are separated from each other three ROUTE operations have to be made and possibly "ADD" the three routed flows after.

<u>ADD operation.</u> This operation adds the previous IOPER flow hydrograph processed in the "ROUTE" operation. The "ADD" operation can only be used after two or more flow hydrographs have already been computed.

<u>BASE operation.</u> This operation adds the baseflow component to the surface flow hydrograph at a subbasin outlet. Usually this operation is done after a "ROUTE" operation. The baseflow hydrograph component is computed using a linear weighted function of current and previous IOPER

baseflow runoff components (obtained in SAC). One or more records should follow the "BASEF" record which contains the weights WBF(I), for I = 1,...,IOPER + 1 which is read using FORMAT (5G10.0).

The usage, sequencing and combinations of ROUTE, ADD and BASEF to represent a certain basin or subbasin configuration will be further explained in the sample model application.

As in data set 4, a record with "END" should be placed at the bottom of this data set 5.

Data Set 6. <u>Hydrologic input data</u>

Three types of hydrologic data that may be required in the model are rainfall, evapotranspiration (ET) demand, and streamflow. Rainfall data is always required in running the model. The ET data when not inputted is assumed to be zero. The streamflow data may not be inputted unless model parameter optimization is desired. Any hydrologic input data is read by issuing an identification record with identifiers "RAIN", "ETDAT" or "FLOW". Each record is followed by some input control parameters as follow.

<u>RAIN input.</u> This is followed by a record with control parameters (read as 5I5):

NHOUR - time interval in hours

NDATA - number of data points

KFMT - read format option, if KFMT = 0, read format in (8F10.0), otherwise it is read in the next record

IREW - data file rewind option, if IREW is not = 0, the data file is rewound

If KFMT is not equal to 0 another record is expected containing the read format FMT(.) which is read as (10A8).

<u>ETDAT input</u>. To read the ET demand data, the following control parameters are read in the next record (read as 4I5):

NHRP - time interval in hours
KFMT - read format option
IREW - data file rewind option

As in "RAIN" input, if KFMT is not equal to 0, a record containing the read format follows.

<u>FLOW input.</u> Inputting the streamflow requires the following parameters:

NHRQ - time interval in hours
INPQ - indicates if streamflow is available (if not available INPQ = 0, otherwise, INPQ is nonzero)

KFMT - read format option
IREW - data file rewind option

If a FLOW record is not issued, the streamflows are computed with the same time interval as rainfall. If one is interested in a different time interval (specified in NHRQ), and no streamflow data is available, the FLOW record can be issued with INPQ nonzero.

Some items above need further clarification as follows:

1. Given the number of data points NDATA for rainfall, the number of data points required for ET demand or flow, if inputted are: NDATA/NHRP and NDATA/NHRQ, respectively.

2. The data file rewind option specified in IREW is desirable when two or more subwatersheds (first-level partitioning) with different hydrologic time series are stored in a file where values for the different subwatersheds at each time period (sampling time) are contained in one record. For example, an areally averaged rainfall for the first subwatershed can be read first with say, FORMAT (F10.0). Then the rainfall for the second subwatershed can be read, say as FORMAT (10X,F10.0) after rewinding the same file.

At the bottom of this data set 6, an "END" record should be placed.

5. RESERVOIR ROUTING MODEL

5.1 Introduction

This component of the CSU-HMS is a computer model called ROUTS for simulating the hydraulic characteristics of the spillways and outlets of the Valdesia Las Barias dams(in the Dominican Republic) for flood routing through the reservoirs. This reservoir system consists of a main reservoir, dam and spillway, a power plant and outflow regulating works, together with an afterbay, a diversion and spillway system short distance downstream of the main dam. The model is useful for routing studies of design floods and for real time flood operation of the reservoir system. Three modes of operation of the spillway gates at Valdesia is included for use under different flood conditions. The output of the model includes a convenient listing of gate regulation schedules at both Valdesia and Las Barias dams.

Currently, the routing results can be displayed on the monitor screen. Specifically, the inflow and outflow hydrographs and reservoir elevations are displayed.

It must be noted that program ROUTS is system specific and considerable modifications may be necessary to adopt it to another system.

5.2 Computer Model

Routing a flood inflow hydrograph through a reservoir system and determining the gate regulation schedules during the controllable phase of spillway operation is a tedious excercise. The graphs and charts developed in the earlier sections can be of tremendous help in real-time operation, but they have to updated from time to time with the accumulation of experience or as new or better quality data becomes available. Considerable effort has therefore been expended to develop a comprehensive computer model for carrying out the flood routing operation described in this chapter.

The computer model is basically a set of interacting mathematical algorithms that attempt to simulate the working and interaction of the component works that constitue the physical system for known sets of inputs, boundary conditions and system constraints. It is basically a simulation model which provides a 'what if' type of results/response for use by the operator in decision making. When used in real-time, the model can also advise on the gate regulation schedule for direct implementation (see Figure 5.1).

The computer model that has been developed to carry out the emergency operation comprises a main program and sixteen subroutines. A brief description of each of the program components is given below:

(i) Main Program - the driving program that reads input data organizes and controls the routing operations by calling the various subroutines and prints out the results of the operation study.

(ii) Subroutine OUTFLW - computes the required reservoir release by the induced surcharge method given the current reservoir elevation and inflow

(iii) Subroutine STORA - contains the stage-storage curve for Valdesia. It computes the reservoir elevation given the storage, or vice versa using a linear interpolation techniques

(iv) Subroutine STORB - contains the stage-storage curve for Las Barias. It computes the reservoir elevation given the storage or vice versa using linear interpolation technique.

(v) Subroutine FREEA - computes the uncontrolled release over the Valdesia Spillway

(vi) Subroutine FREEB - computes the uncontrolled release over Las Barias Spillway accouting for tail water submergence effect

(vii) Subroutine GATEA - computes the release through Valdesia gates given the reservoir elevation, the number of gates which are opened and the size of the opening

(viii) Subroutine GATEB - computes the release through Las Barias gates given the reservoir elvation, the number of gates which are opened and the size of the opening

(ix) Subroutine OPENA - determines the gate regulation schedule for Valdesia given the required outflow release and the reservoir elevation

(x) Subroutine OPENB - determines the gate regulation schedule for Las Barias given the required outflow release and the reservoir elevation

(xi) Subroutine SPILLA - carries out a storage routing throught Valdesia Reservoir in the uncontrollable phase of spillway operation. It computes the outflow and resulting reservoir level given the inglows, initial outflow and reservoir storage (see Appendix 5.A)

(xii) Subroutine SPILLB - carries out a storage routing through Las Barias Reservoir in the uncontrollable phase of spillway operation. It computes the outflow and resulting reservoir level in Las Barias given the inflows, initial outflow and reservoir storage (see Appendix 5.A)

(xiii) Subroutine HYDRO - determines the hydro-release required for generating a specified power output given the reservoir elevation

(xiv) Subroutine SLUICE - determines the discharge through the sluice valves given the reservoir elevation and the sluice valves given the reservoir elevation and the sluice opening. It can also compute the sluice opening required given the discharge and reservoir elevation.

(xv) Subroutine INTDL - a mathematical procedure to carry out linear interpolation

(xvi) Subroutine NEWTON - a Newton Raphson iterative procedure for use in solving for the coordinates of the Ogee Crest Spillway (called by subroutine GATEA

A simplified flowchart of the main program is given in Figure 5.1.

A brief outline of the routine computations undertaken at each step of routing is as follows:

(i) Check whether hydrograph is rising or recessing

(ii) Determine the magnitude of release (including the hydro-release) depending on outcome of (i) and the mode of routing. determine whether spillway is in the controllable phase of operation or otherwise

(iii) If spillway release is controllable, determine the gate regulation schedule (i.e. number of gates to be opened and size of openings)

(iv) If spillway release is uncontrollable, carry out storage routing to determine the end of time step outflow and reservoir elevations (see Appendix 5.A)

(v) The outflows of Valdesia are used as inflows (without logging) to Las Barias and the above step (i) to (iv) repeated

(vi) Results of routing are printed and running variables reset for the next time step.

The printout contains a brief echo print of the routing control parameters followed by a tabulation of the results of routing at each time step. The following details are provided:

Q_1 - the inflow at the beginning of time step

H_1 - the reservoir elevation at the beginning of time step

V_1 - the reservoir storage at the beginning of time step

O_1 - the initial outflow at the beginning of time step

O_2 - the final outflow at the end of time step

H_2 - the final reservoir elevation at end of time step

The gate regulation schedule which tells the operator how many and which combination of gates to be opened.

Y_L - the amount of gate opening for the gates being operated

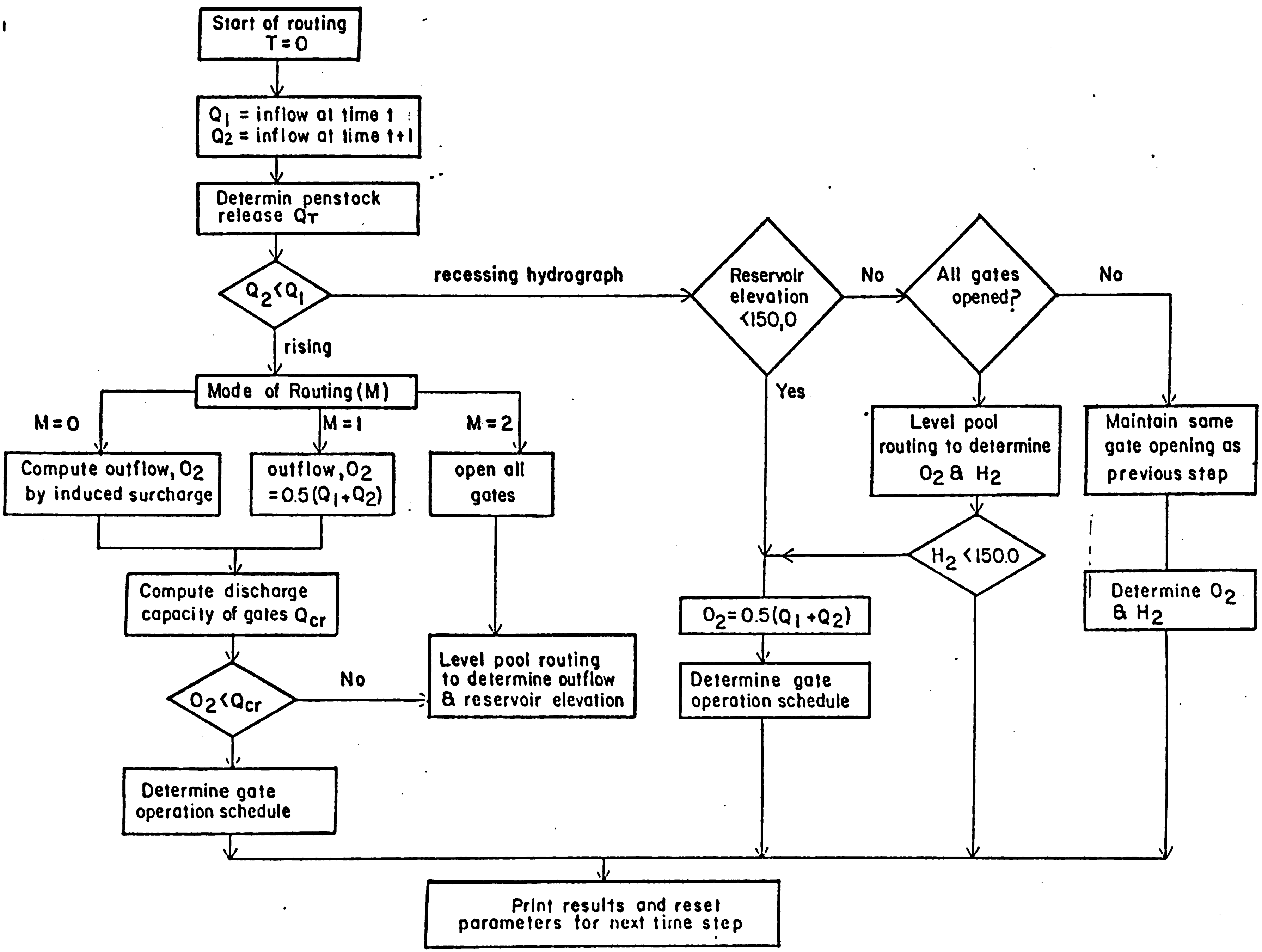


Figure 5.1 . Simplified flow chart for routing flood flows through Valdesia (also applicable to Las Barias with appropriate changes).

5.3 Graphic Display

The inflow and outflow hydrographs and the reservoir elevations for the entire period of routing are stored in two files with names RESF1 and RESF2 for Valdesia and Las Barias respectively. A plotting routine written in basic language is available to plot these results on the screen once the execution is completed. This feature enables one to have quick glance at the routing results. Once the plotting is completed, pressing any key can transfer the execution to the main menu.

5.4 Instructions to the User

The routing model is interactive except that the inflow hydrograph must be input from a file. The following is a description of questions displayed and some guidelines as to what answers should be entered.

1. ENTER THE CURRENT MONTH,DATE,YR,HR,MIN ?
   (##/##/## ##:##)
   This information is used for plotting hydrographs and reservoir elevations as a function of time. In real time operation they correspond to the current date and time.

2. ENTER FILE CONTAINING INFLOW HYDROGRAPH ?
   This is the name of the file which contains inflow values. The data may be stored in free format and the number of inflow values may be more than the actual number used for routing. The file name must be valid according to the specifications of DOS operating system. It may be created by using the editor EDIX available with HMS.

3. FACTOR TO MULTIPLY THE INFLOW ?
   This factor is used to multiply the entire inflow hydrograph before routing. This facility is useful for routing studies when different ratios of the same design inflow hydrograph needs to be routed under various initial conditions. If the inflow hydrograph is to be routed as it is then a factor of 1 must be entered.

4. ENTER THE NAME OF THE OUTPUT FILE ?
   This must be a valid DOS file which will contain all the results of routing. In particular it will contain the gate regulation schedules for both Valdesia and Las-Barias. After execution it may be viewed by using the editor EDIX. It is noted that the output file has a width of 132 columns.

5. NO. OF POINTS IN INFLOW HYDROGRAPH ?
   This is the number of routing periods desired. It can be less than the number of routing periods for which inflow hydrograph is defined in the input file mentioned above.

6. TIME STEP FOR ROUTING IN HOURS ?
   This is the time interval of routing and it may be less than or equal to the time interval in inflow hydrograph as given in the input file mentioned above.

7. TIME INCREMENT IN INFLOW HYDROGRAPH ,HOURS ?
This define the time interval for which the inflow hydrograph is provided in the input file. As mentioned above it can be greater than the time step used for routing.

8. TIME CONSTANT,TS, FOR INDUCED SURCHARGE ROUTING ,HRS ?
This is the time constant of the recession side of the inflow hydrograph. For details of its definition reference is made to Reservoir Regulation Manual EM 1110-2-3600 dated 25 May 59 of U.S.Army Corps of Engineers. It is used in induced surcharge mode of routing. Typical values for Nizao basin lie between 6 to 15 hours. If the inflow hydrograph recedes fast a smaller value (such as 6 hrs) should be used. If the recession is slow a higher TS may be used.

9. MODE OF ROUTING IN VALDESIA, 0,1 OR 2 ?
Mode 0 corresponds to the induced surcharge routing. Mode 1 is similar to the existing operation rule of inflow-outflow but with slight modification. The details are given in the final report written on the project on Valdesia system. Mode 2 is "Hurricane mode" which corresponds to immediate opening of all gates at the beginning of the flood.

10. MODE OF ROUTING IN LAS BARIAS, 1 OR 2 ?
These modes of operation are similar to the modes available for Valdesia. Note that induced surcharge mode(i.e. mode 0) is not available for Las-Barias.

11. CURRENT WATER LEVEL IN VALDESIA ,METERS ?
This is the initial elevation of the Valdesia reservoir in meters above sea level. It must lie between 130.75 (power intake level) and 150.0 meters (top of the gates when they are closed).

12. HYDRO POWER GENERATION IN MW ?
This is the current output of the turbines in the power house. It is assumed to be constant during the passage of a flood.

13. GATE REGULATION SCHEDULE IN VALDESIA, 0,1,2,3,OR 4 ?
This is the entry which specifies the initial gate opening. The current opening may belong to one of five schedules:

Schedule	Description
0	All gates closed
1	Only Gate #3 in operation
2	Gate #3 fully opened Gates 2 & 4 in operation
3	Gates 2, 3, & 4 fully opened Gates 1 & 5 in operation
4	All gates fully opened

14. VALDESIA GATE/SLUICE OPENINGS IN METERS OR PERCENT ?
If all gates are closed this specifies the sluice opening in percent. Otherwise the initial opening of the gate(s) corresponding to the above schedule must be specified.

15. CURRENT WATER LEVEL IN LAS BARIAS ,METERS ?
Enter the initial water level in Las-Barias afterbay.

16. GATE REGULATION SCHEDULE IN LAS BARIAS, 0,1,2,3,4,5 ?
The initial gate opening in Las Barias may belong to one of six schedules:

Schedule	Description
0	All gates fully closed
1	Gates 4 & 5 in operation
2	Gates 4 & 5 fully opened Gates 3 & 6 in operation
3	Gates 3, 4, 5, and 6 fully opened. Gates 2 & 7 in operation
4	Gates 2, 3, 4, 5, 6 and 7 fully opened. Gates 1 & 8 in operation
5	All gates fully opened

17. GATE OPENING IN LAS BARIAS ,METERS ?
Current gate opening in Las-Barias for gates specified in the initial schedule as given above.

Once all of the above data are entered the program begins execution. Upon completion, a new set of data are requested beginning with the question:

NO. OF POINTS IN THE INFLOW HYDROGRAPH ?

At this point if the user does not wish to run another data set he/she must enter 0. Then the execution automatically transfers to plotting routine. The inflow and outflow hydrographs and the reservoir elevations are stored in files RESF1 and RESF2 for Valdesia and Las Barias respectively. The desired file name must be entered upon request from the plotting routine. Once the first plot is completed pressing any key will bring up the question "Would you like to plot?" and the user must enter "yes" if the results of the second file are to be plotted. After plotting the execution is transferred to the main menu. It is cautioned that before plotting the hydrographs the program takes some time reading the results from the disk and the user must be patient.

5.5 Sample Application

The use of the reservoir routing component of HMS is illustrated with the routing of the largest historic flood of record at Valdesia dam site which occurred on May 20, 1972. The file which contains this inflow hydrograph is named "inflow". It is listed below:

18.5 35.4 52.3 391.48 785.08 1517.27 1457.72 1493.39 1577.28 1589.34
1601.42 1760.06 1698.69 1517.27 1760.06 1224.52 1111.09 1033.03 945.26
891.21 837.81 785.08 722.74 651.36 581.51 532.62 484.62 456.26 428.25
400.61 373.34 359.85 337.60 320.01 302.61 285.40 272.63 264.19 251.62
247.46 239.18 235.06 230.95 222.79 218.73 218.73 222.79 230.95 239.18
239.18 218.73 202.64 182.88 171.23 163.54 155.93 148.40 137.23 129.89
122.63 115.46 111.90 104.86 101.38 97.92 94.48 97.92 94.48 91.07 91.07

The listing of the interactive input sequence necessary to run the model is presented Table 5.1. The plot of results for Valdesia reservoir is shown in Figure 5.2. The fist page of the listing of the output file "outfile" is shown in Table 5.2. Note that the maximum elevation reached is 150.7 m.a.s.l and that the water level is maintained at 150 m.a.s.l when the flood is receding.

Table 5.1. The sample run of the reservoir routing model

```
 ************************************************
 FLOOD ROUTING THROUGH VALDESIA LAS BARIAS SYSTEM
 ************************************************

 ENTER THE CURRENT MONTH,DATE,YR,HR,MIN ?
(##/##/## ##:##) 05/20/72 08:00

 ENTER FILE CONTAINING INFLOW HYDROGRAPH ? inflow

 FACTOR TO MULTIPLY THE INFLOW ? 1.0

 ENTER THE NAME OF OUTPUT FILE ? outfile

 NO. OF POINTS IN INFLOW HYDROGRAPH ? 40

 TIME STEP FOR ROUTING IN HOURS ? 0.5

 TIME INCREMENT IN INFLOW HYDROGRAPH ,HOURS ? 1.0

 TIME CONSTANT,TS, FOR INDUCED SURCHARGE ROUTING ,HRS ? 6.0

 MODE OF ROUTING IN VALDESIA, 0,1 OR 2 ? 0

 MODE OF ROUTING IN LAS BARIAS, 1 OR 2 ? 1

 CURRENT WATER LEVEL IN VALDESIA ,METERS ? 145.0

 HYDRO-POWER GENERATION IN MW ? 22.5

 GATE REGULATION SCHEDULE IN VALDESIA, 0,1,2,3,OR 4 ? 0

 VALDESIA  GATE/SLUICE OPENINGS IN METRES OR PERCENT ? 0

 CURRENT WATER LEVEL IN LAS BARIAS ,METRES ? 77.0

 GATE REGULATION SCHEDULE IN LAS-BARIAS, 0,1,2,3,4,5 ? 0

 GATE OPENING IN LAS BARIAS ,METRES ? 0

 NO. OF POINTS IN INFLOW HYDROGRAPH ? 0

Execution terminated : 0
```

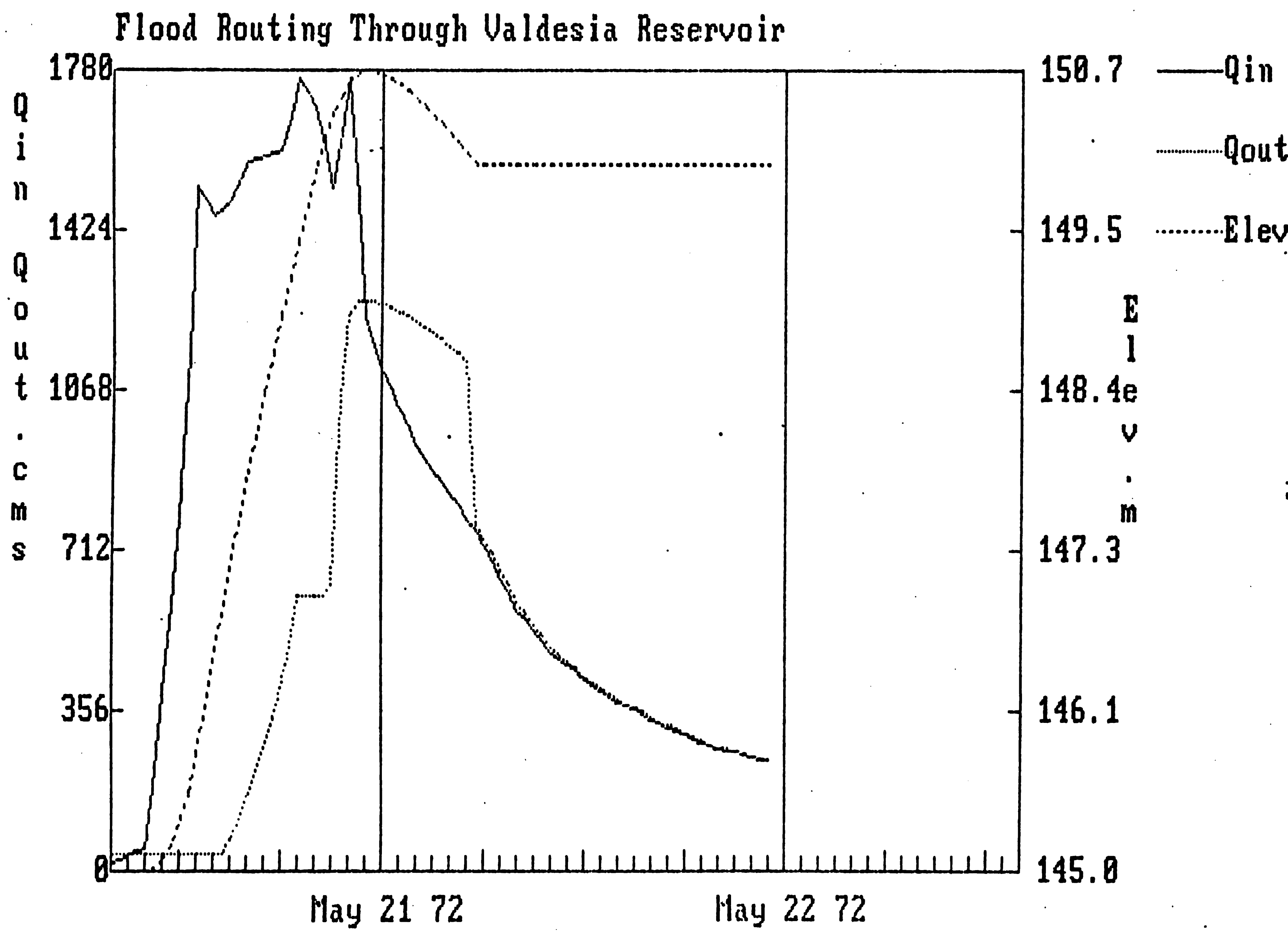


Figure 5.2. A sample plot of the reservoir routing results produced by CSU-IMS

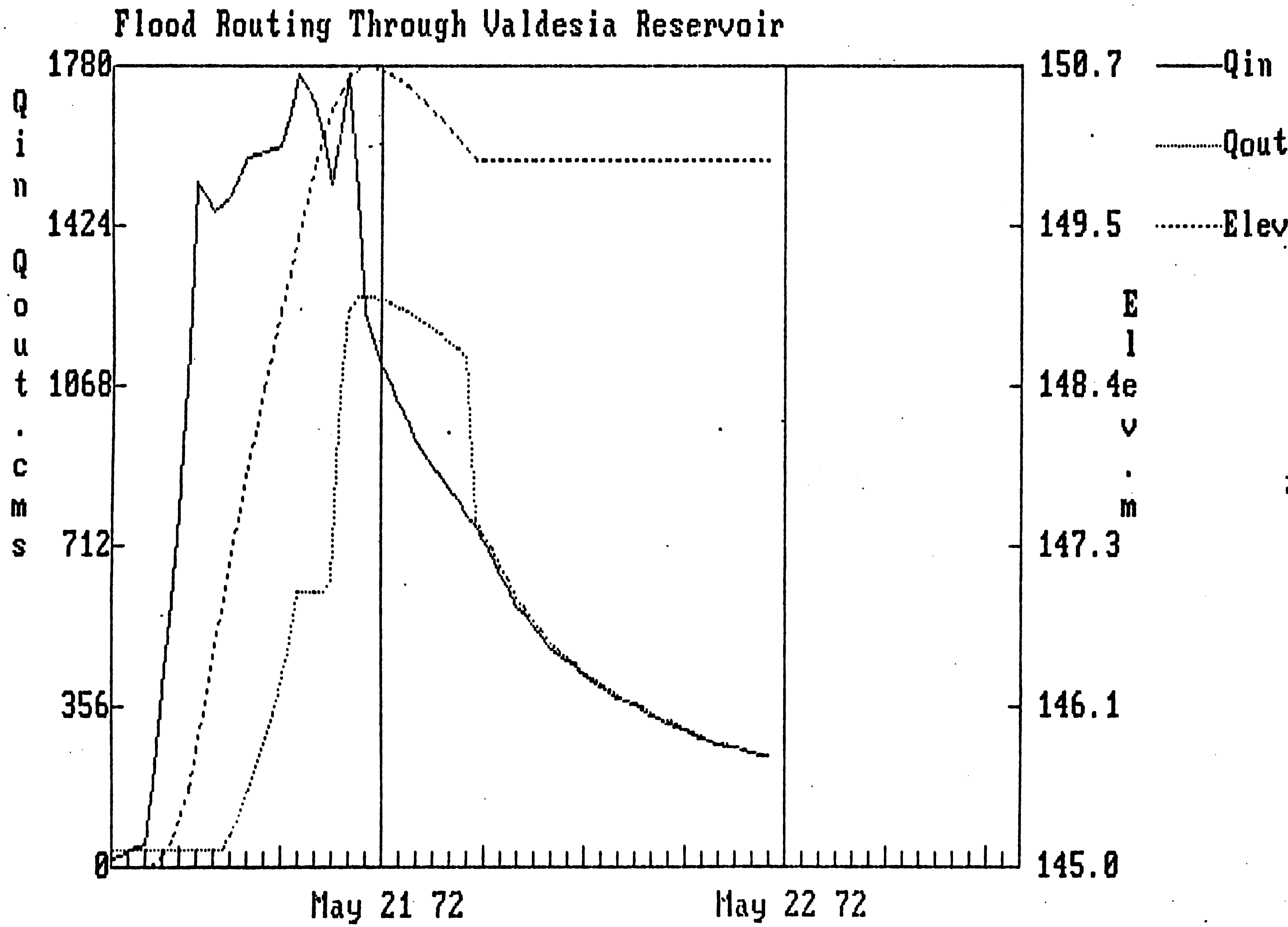


Figure 5.2. A sample plot of the reservoir routing results produced by CSU-IHMS

Table 5.2. A typical output of the reservoir routing model

FLOOD ROUTING THROUGH VALDESIA AND LAS BARIAS RESERVOIRS

INPUT PARAMETERS AS FOLLOWS :-

TIME STEP IN ROUTING	0.50
TIME CONSTANT IN INDUCED SURCHARGE METHOD	6.00
MODE OF ROUTING IN VALDESIA	0
MODE OF ROUTING IN LAS BARIAS	1

TIME	01	H1	V1	01	02	H2	GATE OPERATION INSTR	YL
0.00 VALDESIA	18.50	145.00	113.46	39.50	39.50	145.00	SLUICE OPENED BY (%)	0.00
0.00 LAS-BARIAS	39.50	77.00	3.00	0.00	39.50	77.00	GATES 4 + 5 UP BY	0.16
0.50 VALDESIA	26.95	145.00	113.43	39.50	39.50	144.99	SLUICE OPENED BY (%)	0.00
0.50 LAS-BARIAS	39.50	77.00	3.00	39.50	39.50	77.00	GATES 4 + 5 UP BY	0.16
1.00 VALDESIA	35.40	144.99	113.42	39.50	39.50	144.99	SLUICE OPENED BY (%)	0.00
1.00 LAS-BARIAS	39.50	77.00	3.00	39.50	39.50	77.00	GATES 4 + 5 UP BY	0.16
1.50 VALDESIA	43.85	144.99	113.42	39.50	39.50	145.00	SLUICE OPENED BY (%)	0.00
1.50 LAS-BARIAS	39.50	77.00	3.00	39.50	39.50	77.00	GATES 4 + 5 UP BY	0.16
2.00 VALDESIA	52.30	145.00	113.44	39.50	39.50	145.02	SLUICE OPENED BY (%)	0.00
2.00 LAS-BARIAS	39.50	77.00	3.00	39.50	39.50	77.00	GATES 4 + 5 UP BY	0.16
2.50 VALDESIA	221.89	145.02	113.61	39.50	39.49	145.08	SLUICE OPENED BY (%)	0.00
2.50 LAS-BARIAS	39.50	77.00	3.00	39.50	39.50	77.00	GATES 4 + 5 UP BY	0.16
3.00 VALDESIA	391.48	145.08	114.09	39.49	39.44	145.18	SLUICE OPENED BY (%)	0.00
3.00 LAS-BARIAS	39.49	77.00	3.00	39.50	39.47	77.00	GATES 4 + 5 UP BY	0.16
3.50 VALDESIA	588.28	145.18	114.90	39.44	39.37	145.33	SLUICE OPENED BY (%)	0.00
3.50 LAS-BARIAS	39.44	77.00	3.00	39.47	39.41	77.00	GATES 4 + 5 UP BY	0.16
4.00 VALDESIA	785.08	145.33	116.07	39.37	39.27	145.54	SLUICE OPENED BY (%)	0.00
4.00 LAS-BARIAS	39.37	77.00	3.00	39.41	39.32	77.00	GATES 4 + 5 UP BY	0.16
4.50 VALDESIA	1151.18	145.54	117.74	39.27	39.12	145.83	SLUICE OPENED BY (%)	0.00
4.50 LAS-BARIAS	39.27	77.00	3.00	39.32	39.20	77.00	GATES 4 + 5 UP BY	0.16
5.00 VALDESIA	1517.27	145.83	120.07	39.12	39.12	146.17	SLUICE OPENED BY (%)	0.00
5.00 LAS-BARIAS	39.12	77.00	3.00	39.20	39.12	77.00	GATES 4 + 5 UP BY	0.16
5.50 VALDESIA	1407.49	146.17	122.70	39.12	39.12	146.49	SLUICE OPENED BY (%)	0.00
5.50 LAS-BARIAS	39.12	77.00	3.00	39.12	39.12	77.00	GATES 4 + 5 UP BY	0.16
6.00 VALDESIA	1457.72	146.49	125.29	39.12	38.41	146.82	SLUICE OPENED BY (%)	0.00
6.00 LAS-BARIAS	39.12	77.00	3.00	39.12	38.76	77.00	GATES 4 + 5 UP BY	0.16
6.50 VALDESIA	1475.55	146.82	127.86	38.41	69.66	147.14	SLUICE OPENED BY (%)	0.33
6.50 LAS-BARIAS	38.41	77.00	3.00	38.76	54.03	77.00	GATES 4 + 5 UP BY	0.22
7.00 VALDESIA	1493.39	147.14	[illegible]	69.66	114.09	147.46	GATE NO.3 UP BY	0.07
[illegible] LAS-BARIAS	69.66	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	GATES 4 + 5 UP BY	0.37

APPENDIX 5.A

Storage Routing by Newton Raphson Iterative Procedure

The continuity equation for storage-routing is given by

$$S_1 - S_2 = \frac{\Delta t}{2} [I_1 + I_2] - \frac{\Delta t}{2} [O_1 + O_2] \qquad (1)$$

where S = storage

I = inflow

O = outflow

Δt = time interval

(subscript 1 and 2 refer to beginning and end of time step)

The unknowns in the above equation are S_2 and O_2, both of which are functions of reservoir storage

$$S_2 = S_2(H) \qquad (2)$$

$$O_2 = O_2(H) \qquad (3)$$

Rewriting Equation (1) as follows:

$$S_2 = [0.5\Delta t(I_1 + I_2) + S_1 - 0.5\Delta t O_1] - 0.5\Delta t O_2 = K - 0.5\Delta t O_2 \qquad (4)$$

where K is a routing constant which can be evaluated using the known values of I_1, I_2, S_1, and O_1. Using Equation (4), a new function F can be defined as follows

$$F = S_2 - K + 0.5\Delta t O_2 \qquad (5)$$

The solution for S_2 and O_2 is obtained when F = 0.

There are two unknowns in Equation (5), but both are functions of reservoir stage, H. Hence, it is more convenient to solve for H first and then recompute S_2 and O_2. The most convenient approach is the Newton Raphson method which is described as follows:

(i) Assume a value for H (can use the initial reservoir elevation H_1)

(ii) Evaluate F from Equation (5)

(iii) Evaluate $\frac{\partial F}{\partial H}$ from the following expression

$$\frac{\partial F}{\partial H} = \frac{\partial (S_2(H))}{\partial H} + 0.5\Delta t \frac{\partial (O_2(H))}{\partial H}$$

(iv) if F is not equal to zero, a correction to H can be computed as

$$\Delta H = -\frac{F}{\partial F/\partial H}$$

(v) Using the improved estimate of H, repeat the steps (ii) to (iv) until covergence

The above procedure is highly efficient for storage routing in the Valdesia and Las Barias System because:

(i) The stage-storage curve can be represented as a piece-wise linear relationship which greatly simplifies the evaluation of $\frac{\partial S}{\partial H}$

(ii) The stage discharge relationship $O_2(H)$ is a simple polynomial equation, the derivative of which can be easily evaluated by an exact analytical expression

6. HURRICANE TRACK FORECASTING

6.1 Introduction

For emergency operation of reservoir systems affected by hurricanes or tropical cyclones the forecasting of both track and precipitation amount is important. This component of HMS describes the interactive version of the CLIPER model developed by National Hurricane Center in Miami for hurricane track forecasting. Three options for graphical display of the actual or forecast tracks are available. It is noted these software may be used to forecast hurricane tracks in any part of the Caribbean region.

The option no. 5 in the main menu displays the following menu specifically for hurricane track forecasting:

COLORADO STATE UNIVERSITY

HYDROLOGIC MODELING SYSTEM

HURRICANE TRACK FORECASTING SOFTWARE

5A. Clipper Model

5B. Plot the Forecast Track in the Dominican Republic

5C. Plot the Forecast Track in the Caribbean Region

5D. Compare Forecast Track and Actual Track

5E. Return to main menu

Enter your selection at the prompt:

The option 5A is described in Section 6.2 whereas the options 5B through 5D are described in Sections 6.3. Instructions to use the software is provided in Section 6.4. Section 6.5 provides a sample application.

6.2 CLIPER Model

CLIPER Stands for CLImatology and PERsistence. It is a system of regression equations fitted to several predictors available from past observations on the motions of tropical cyclones in the North Atlantic. Eight basic predictors are used and they as follows:

1. Initial longitude
2. Initial latitude
3. Initial E-W component of speed
4. E-W component 12-hrs ago
5. Initial S-N component of speed
6. S-N component 12-hrs ago
7. Maximum wind
8. Day number

Twelve regression equations provide predictions for following variables.

1. 12-hr N/S displacement
2. 24-hr N/S displacement
3. 36-hr N/S displacement
4. 48-hr N/S displacement
5. 60-hr N/S displacement
6. 72-hr N/S displacement
7. 12-hr E/W displacement
8. 24-hr E/W displacement
9. 36-hr E/W displacement
10. 48-hr E/W displacement
11. 60-hr E/W displacement
12. 72-hr E/W displacement

The software consists of an interactive program for using the CLIPER subroutine provided by the National Hurricane Center in Miami. Options are available for: (a). creating or updating a file which contains input parameters necessary for making track forecasts; and (b). computing track forecasts every 12-hours up to 72 hours lead time from the current position. It is suggested that once a tropical cyclone begins to develop in the Atlantic pertinent data for initial positions of the cyclone be entered into a file using the update facility so that a record containing a minimum number of track positions is available at the time of first forecast. The current version requires that the actual positions correspond to equal time steps(eg. 6 hrs or 3 hrs). The minimum information required are the position(longitude and latitude) and the maximum sustained wind speed. The other required information will be computed using the actual track positions if they are not available. The past track positions and the forecast tracks are stored in a file named "fdata" for purpose of plotting.

6.3 Graphic Displays

Options 5B and 5C in the menu(see Section 6.1) consists of two programs written in basic language for displaying track forecasts on the screen. The input to these programs are obtained from the file "fdata" mentioned above. The option 5B displays the actual/forecast track on the map of Dominican Republic. Also shown in this map is the boundary of the Nizao basin and regions around Valdesia dam site defined by circles drawn at 50 km intervals. These are provided for a quick glance at the current/forecast tracks of the hurricane which is useful for operation under emergency conditions. The option 5C displays the same tracks but on a much larger(but low resolution) map covering the Caribbean region between 50 deg. West-100 deg. West longitude and 5 deg.North - 35 deg. North latitude.

Option 5C can be used to compare forecast and actual tracks in the Caribbean region.

6.4 Instructions to the User

The interactive program is called MCLIPER. It has two modes: (a) updating mode ; and (b) forecasting mode. The following is a set of guidelines to input necessary data in the updating mode.

Updating mode

In this mode the information pertaining to the motion of the storm at regular intervals(say 6 hrs. or 3 hrs.) is entered into a file. Specifically, the information requested include current date and time, longitude and latitude of current position, current speed of motion if available, and maximum sustained wind speed in the current position. The following is a list of questions displayed and the instructions to answer them:

1. Enter 0 if this run is for updating
   Enter 1 if this run is for forecasting
   Enter 0 or 1 according to the desired mode. Before forecasting tracks it is recommended that a file be created with the updating mode.

2. Is this a new hurricane
   This facility allows creation of separate files for each hurricane
   Answer yes or no.

3. Enter the name of the hurricane
   The name of the hurricane entered here is used for displaying it in the output and the plots.

4. Enter the name of the track file
   This is the name of the file which contains past track information. If this is a new hurricane a name has to be selected to store the track information. The name may be same as the one entered in no. 3 above.

At this point the date,time and other information corresponding to the last record in the file if it exists. The new track information to be entered include:

1. The letter A or F to indicate the track information entered is for actual or forecast positions.
2. Date eg. 08/31/79
3. Time eg. 18:00
4. Longitude
5. Latitude
6. Current speed. Enter -1 if this information is not available.
7. Maximum sustained wind speed

Once all records(corresponding to each position) then entering letter e or E will exit the updating mode. The file stored may be subsequently used for forecasting.

Forecasting Mode

In the forecast mode, the necessary data are obtained in two ways. First, they may be read from an existing file which contains current information created by using the updating mode. Second, the current information may be entered interactively at the time of the forecasting. It is assumed that the existing track file contains the information corresponding to the previous time step. The option to use one of the above two ways is displayed with the following:

Enter 0 if current information is in file
Enter 1 if you want to enter the current information

Once the current information is available, the program computes and displays the following information:

(1) Current latitude
(2) Current longitude
(3) Current direction
(4) Current speed
(5) Direction 12hrs earlier
(6) Speed 12hrs earlier
(7) Max. sustained wind

At this point the user has the option to modify any of the above information. This may be accomplished by answering "no" to the question:

Ok to run(enter no if changes to be made)?

Otherwise, the forecasts are computed and displayed.

The past track and the forecast track are stored in a file named "fdata" for purpose of plotting. The user has the option to update the forecast file once new forecasts are computed.

6.5 Sample Application

The actual data of hurricane DAVID which occurred in late August of 1979 will be used illustrate the options available for hurricane track forecasting. The sample run to create the file in the updating mode is shown in Table 6.1. In this run four records of the track position are created in the file named DAVID6hr. Table 6.2 shows how this file is updated to add three more records. This table also shows the listing of the file created. The subsequent forecast run is illustrated in Table 6.3. The plots of forecast tracks made using the forecast file is shown in Figures 6.1 and 6.2 for options 5B and 5C (see menu in section 6.1) respectively. A comparison of forecast track and the actual track made using option 5D is shown in Figure 6.3.

Table 6.1. A sample run to create a track file using MCLIPER in updating mode.

```
Enter 0 if this run is for updating
Enter 1 if this run is for forecasting
0

Is this a new hurricane
yes

Enter the name of the hurricane
DAVID

Enter the name of the track file
DAVID6hr


Enter following information for each new position of the hurricane
actual or forecast position,enter A or F
date,time,longitude,latitude,current speed,maximum sustained wind speed
Eg:A,08/31/79,18:00,70.00,17.00,15.0,100.0
When you finish enter E
#,##/##/##,##:##,##.##,##.##,##.#,###.#
A,08/27/79,00:00,47.00,11.70,-1.0, 55.0

#,##/##/##,##:##,##.##,##.##,##.#,###.#
A,08/27/79,06:00,48.50,11.80,-1.0, 65.0

#,##/##/##,##:##,##.##,##.##,##.#,###.#
A,08/27/79,12:00,50.00,11.80,-1.0, 80.0

#,##/##/##,##:##,##.##,##.##,##.#,###.#
A,08/27/79,18:00,51.50,11.90,-1.0, 95.0

#,##/##/##,##:##,##.##,##.##,##.#,###.#
e

Execution terminated : 0
```

The listing of file DAVID6hr

```
A  8 27 79  0  0 47.00 11.70 -1.0  55.0
A  8 27 79  6  0 48.50 11.80 -1.0  65.0
A  8 27 79 12  0 50.00 11.80 -1.0  80.0
A  8 27 79 18  0 51.50 11.90 -1.0  95.0
```

Table 6.2. A sample run to update the track file

```
Enter 0 if this run is for updating
Enter 1 if this run is for forecasting
0

Is this a new hurricane
no

Enter the name of the hurricane
DAVID

Enter the name of the track file
DAVID6hr

Note: Last information in the file is for following date and time
 8/27/79 18:
Last position(long.,lat.):51.50,11.90
                    Speed:-1.0
   Maximum Sustained Wind: 95.0

Enter following information for each new position of the hurricane
actual or forecast position,enter A or F
date,time,longitude,latitude,current speed,maximum sustained wind speed
Eg:A,08/31/79,18:00,70.00,17.00,15.0,100.0
When you finish enter E
#,##/##/##,##:##,##.##,##.##,##.#,###.#
A,08/27/79,24:00,52.90,12.20,-1.0,115.0

#,##/##/##,##:##,##.##,##.##,##.#,###.#
A,08/28/79,06:00,54.40,12.50,-1.0,125.0

#,##/##/##,##:##,##.##,##.##,##.#,###.#
A,08/28/79,12:00,55.70,12.80,-1.0,130.0

#,##/##/##,##:##,##.##,##.##,##.#,###.#
e

Execution terminated : 0
```

Updated file DAVID6hr

A	8	27	79	0	0	47.00	11.70	-1.0	55.0
A	8	27	79	6	0	48.50	11.80	-1.0	65.0
A	8	27	79	12	0	50.00	11.80	-1.0	80.0
A	8	27	79	18	0	51.50	11.90	-1.0	95.0
A	8	27	79	24	0	52.90	12.20	-1.0	115.0
A	8	28	79	6	0	54.40	12.50	-1.0	125.0
A	8	28	79	12	0	55.70	12.80	-1.0	130.0

Table 6.3. A sample run of MCLIPER in forecast mode.

```
Enter 0 if this run is for updating
Enter 1 if this run is for forecasting
1

Enter the name of the hurricane
DAVID

Enter the name of the track file
DAVID6hr

Enter 0 if current information is in the file
Enter 1 if you want to enter the current information
0

Following is a list of current conditions
(1)  Current latitude =  12.800
(2)  Current longitude=  55.700
(3)  Current direction= 283.299
(4)  Current speed    =  13.035
(5)  Direction 12hrs earlier = 282.352
(6)  Speed 12hrs earlier     =  14.017
(7)  Max. sustained wind     = 130.000

Ok to run(enter no if changes to be made)?
yes



 Track forecast for hurricane DAVID

Time of forecast =  8/28/79 at 12hrs 0 mins
Current position(longitude,latitude) =55.70,12.80

               Forecast
         Longitude            Latitude

  12-hr    58.27                13.48
  24-hr    60.88                14.35
  36-hr    63.41                15.35
  48-hr    65.83                16.48
  60-hr    68.03                17.72
  72-hr    69.97                19.04
Would you like to update the forecast file?
yes

Execution terminated : 0
```

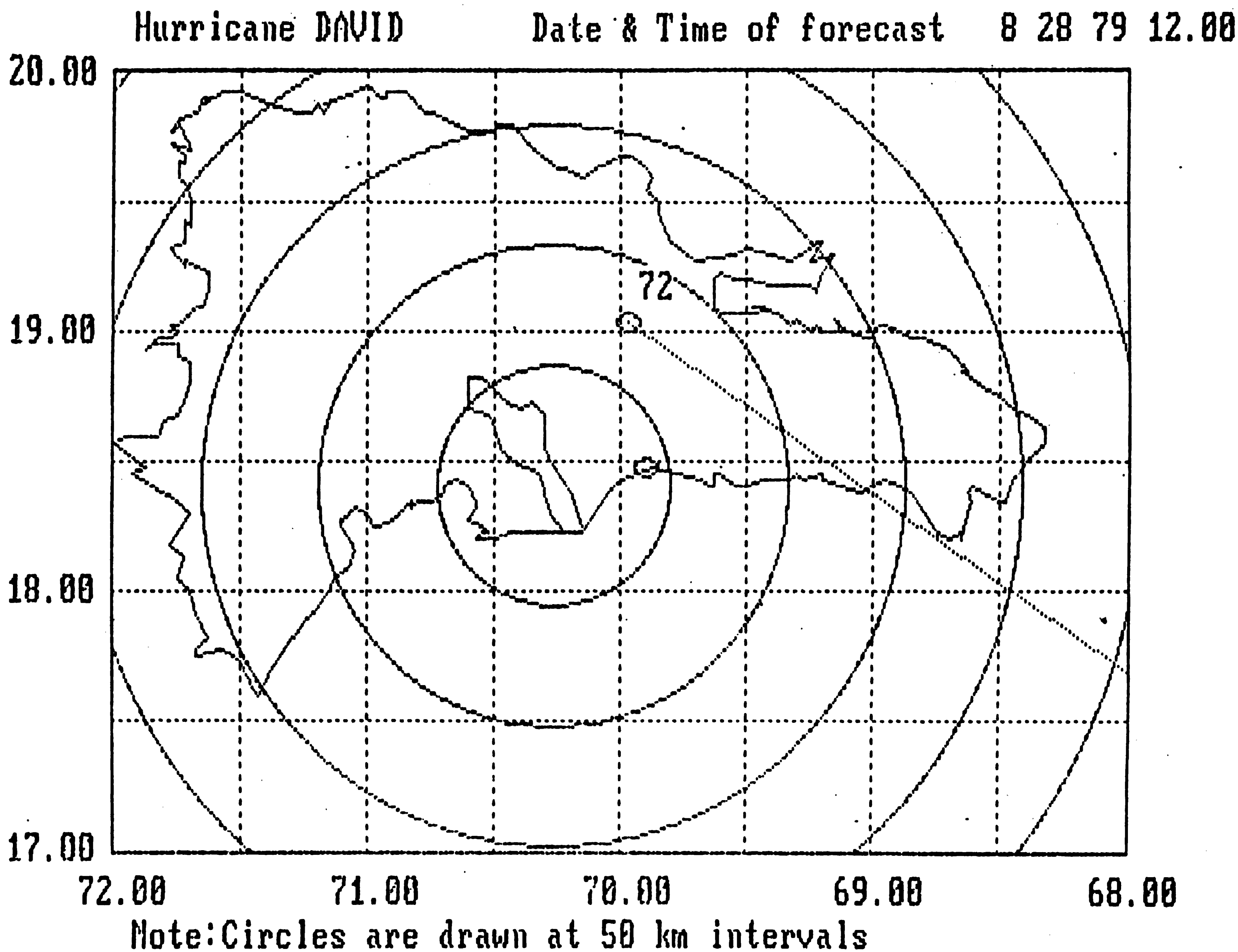


Figure 6.1. Plot of forecast track around Dominican Republic provided by MCLIPER.

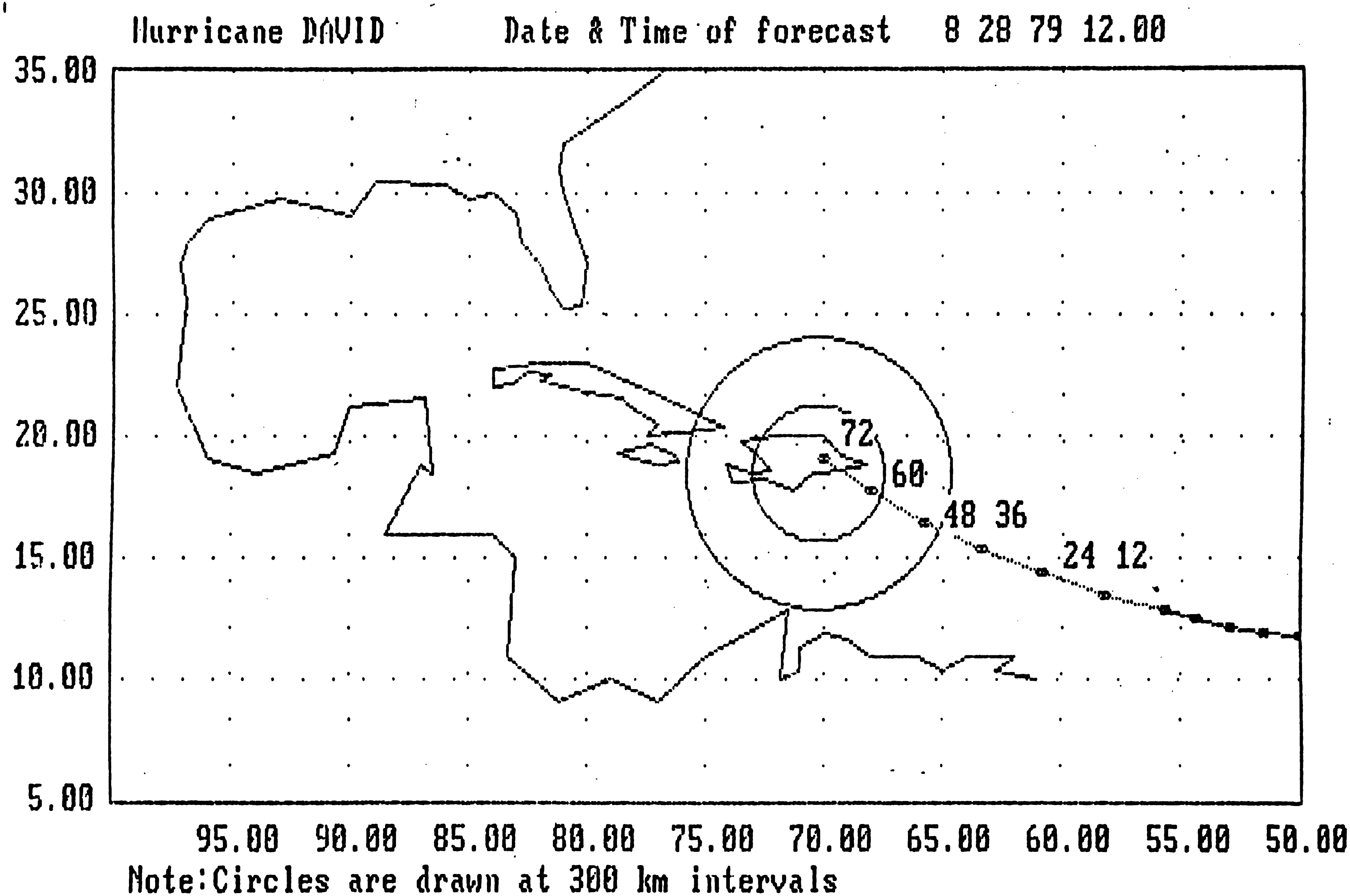


Figure 6.2. Plot of forecast track in the Caribbean region provided by MCLIPER.

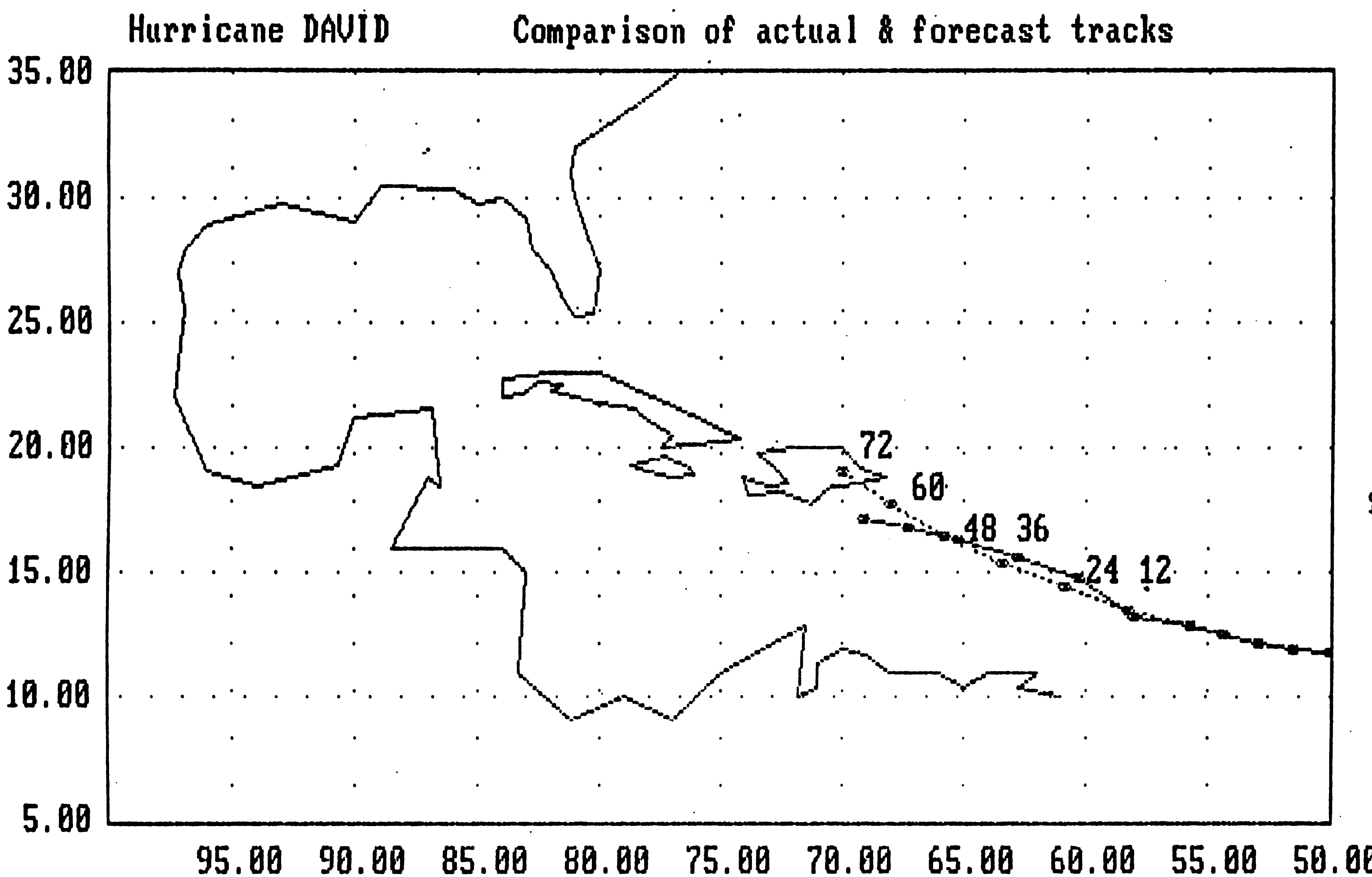


Figure 6.3. A comparison of actual track and the forecast track computed by MCLIPER (made by option 5D in the menu).

7. STREAMFLOW FORECASTING

7.1 Introduction

For purposes of streamflow forecasting on a weekly or monthly basis, the so-called Kalman filter approach can be used which computes forecast values and errors in an efficient and sequential manner. This section briefly describes the Kalman filter algorithm and its accompanying computer program. A sample application is also given below for monthly and weekly streamflow forecasting for Paso del Ermitano, Nizao Basin, Dominican Republic.

In the CSU-HMS, the Kalman filter forecasting algorithm is included in the main menu as option number 6.

7.2 Kalman-Bucy Filter

The linear filter as originally proposed by Kalman (1960) and Kalman and Bucy (1961) is referred to here as the standard Kalman filter. The filter requires that the system model parameters and the noise statistics are accurately specified and that the system model is precisely designed.

Let the respective system (state) and measurement equations be described by discrete, linear, stochastic process as

$$X_t = \Phi X_{t-1} + W_t \tag{1}$$

and

$$Z_t = H_t X_t + V_t \tag{2}$$

where X_t = n-dimensional state vector, Φ = (n x n) state transition matrix, W_t = (n x 1) system noise vector, Z_t = m-dimensional observation vector, H_t = (m x n) measurement matrix, and V_t = (m x 1) measurement noise vector.

The system noise W_t and measurement noise V_t above are assumed to be independent Gaussian processes with zero means and known variance-covariance such that

$$E(W_t) = 0 \qquad E(V_t = 0 \qquad E(W_t V_t) = 0$$

$$E(W_t W_t^T) = Q \qquad E(V_t V_t^T) = R$$

in which E(.) is the expectation operator. The covariances Q and R are matrices of sizes (n x n) and (m x m), respectively.

With the above assumptions, the standard Kalman filter algorithm is summarized as follows:

Initial data:

$$\hat{X}_{0/0}, \hat{P}_{0/0}, \Phi, Q, R$$

State propagation:

$$\bar{X}_{t/t-1} = \Phi \hat{X}_{t-1/t-1}$$

Associated error covariance:

$$\bar{P}_{t/t-1} = \Phi \hat{P}_{t-1/t-1} \Phi^T + Q$$

Measurement noise:

$$V_t = Z_t - H_t \bar{X}_{t/t-1}$$

Kalman gain:

$$K_t = \bar{P}_{t/t-1} H_t^T [H_t \bar{P}_{t/t-1} H_t^T + R]^{-1}$$

State estimation:

$$\hat{X}_{t/t} = \bar{X}_{t/t-1} + K_t V_t$$

Associated error covariance:

$$\hat{P}_{t/t} = (I - K_t H_t) \bar{P}_{t/t-1}$$

where K_t = (n x m) Kalman gain matrix and I = (n x n) identity matrix.

It will be noted that the matrices Φ, Q and R are not subscripted since they are constant in time. The matrix H_t is assumed constant in time but may be time-varying in some applications (e.g. in parameter estimation problems).

7.3 Program PCKFA

This program contains the Kalman filter as described above. The program is written in FORTRAN 77. The main program reads the input data and controls the timing and sequencing of the overall forecating algorithm. Subroutine KALBUC specifically performs the Kalman filter computations. The subroutine MATINV is a matrix inversion routine employing Guassian elimination with pivotal condensation. Subroutines PRINT1 and PRINT2 prints the results as the user desires. A so-called user-supplied subroutine USERSUB is also included in this program which is specifically designed for purposes of the sample application given later. A listing and descriptions of variables used in Program PCKFA is given in Table 7.1.

7.4 Program Input and Output Information

The input to Program PCKFA is contained in one file. This includes the control parameters, initial filter states and streamflow data. Details of preparing the input data file is given in Table 7.2.

Table 7.1. List of variables used in Program PCKFA.

Variable Name	Description
NSTR	BEGINNING TIME
NFIN	ENDING TIME
NS	NUMBER OF STATES
MS	NUMBER OF MEASUREMENTS
NT	TIME INDEX
IWR1 = 1	PRINT CONTENTS OF LABELLED COMMON /RVAR/
IWR2 = 1	PRINT CONTENTS OF LABELLED COMMON /KALBUC/
IF IWR1 = 0 AND/OR IWR2 = 0	PRINTS ONLY WHEN NT.EQ.NFIN
IDTP = 1	PRINTS THE MEASURED TIME SERIES THROUGH CALL PRINT2
XP(NS)	PROPAGATED STATES
XF(NS)	FILTERED STATES
PP(NS,NS)	PROPAGATED STATE ERROR COVARIANCE
PF(NS,NS)	FILTERED STATE ERROR COVARIANCE
PHI(NS,NS)	STATE TRANSITION MATRIX
ZT(MS)	MEASUREMENTS
VT(MS)	INNOVATIONS
HT(MS,NS)	MEASURMENT MATRIX
AK(NS,MS)	KALMAN GAIN
RT(MS,MS)	MEASUREMENT NOISE COVARIANCE
QT(NS,NS)	MODEL NOISE COVARIANCE
NSX	NUMBER OF SEASONS
NFC	NUMBER OF FORECAST TIME STEPS DESIRED
ZM(.)	INITIAL SEASONAL MEANS
ZV(.)	INITIAL SEASONAL VARIANCES
ZDT(MS,NFIN-NSTR+1)	STORAGE VARIABLE OF MEASUREMENTS
VDT(MS,NFIN-NSTR+1)	STORAGE VARIABLE OF INNOVATIONS
RFM(20)	READ FORMAT FOR ALL REAL NUMBER INPUT DATA

The program output consists of printing the input control parameters, initial filter data and filter results. The input streamflow data can also be printed which is optional. Printout for the filter results includes, the propagated and filter states and associated error variance-covariances, measured values, innovations and computed Kalman gain which is done for every time step. These filter results can be printed either at ending time only or every time step. When forecasting is done (i.e., NFC is not equal to zero), the forecast values are stored in a file with filename specified by the user when running the program. A sample printer output of the program is shown in Figure 7.1.

Table 7.2. Program PCKFA input description.

Variable Name	Input Description	Remarks	Format
NSTR NFIN	Beginning time Ending time		(2I5)
NS MS IWR1 IWR2 IDTP	Number of states Number of measurements If 1, print contents of labeled COMMON/RVAR/ If 1, print contents of labeled COMMON 1-1 specific to each Kalman filter subroutine If 1, prints the vector of observed time series		(5I5)
RFM(20)	Read format for all succeeding real number input data, e.g. (4F10.2)		(20A4)
PHI(I,J)	State transition matrix for J = 1, NS	Read in a DO-loop for I = 1, NS	RFM(20)
HT(I,J)	Measurement matrix for J = 1, NS	Read in a DO-loop for I = 1, MS	RPM(20)
XF(I)	Initial filtered states for I = 1, NS		RFM(20)
PF(I,J)	Initial error variance-covariance of filtered states for J = 1, NS	Read in a DO-loop for I = 1, NM	RFM(20)
RT(I,J)	Measurement noise variance-covariance matrix for J = 1, MS	Read in a DO-loop for I = 1, MS	RFM(20)
QT(I,J)	Model noise variance-covariance matrix for J = 1, NS	Read in a DO-loop for I = 1, NS	RFM(20)
NSX NFC	Number of seasons Number of forecast time steps desired		(2I5)
ZM(I) ZV(I)	Initial seasonal means for I = 1,...,NSX Initial seasonal variances I = 1,...,NSX	Read only if NSX is not equal to zero	RFM(20)

Table 7.2. continued.

Variable Name	Input Description	Remarks	Format
ZDT(I,J)	Observed time series vector for J = 1, MS	Read in a loop for I = 1,..., NFIN-NSTR+1	RFM(20)

7.5 Sample Application

Described herein is a sample application of the Kalman filter program for monthly and weekly streamflow forecasting of Paso del Ermitano, Nizao Basin. For this example, the filter equations are based on a first-order autoregressive model written as follows: In terms of the state-equation given by Eq. (1); $X_t = \alpha_t$, $\Phi = 1.0$, $W_t = 0.0$ and that $Q = 0.0$; and the measurement equation (2) is such that, Z_t is the observed streamflow, $H_t = Z_{t-1}$, and V_t is some finite residual noise with variance R.

For this example, two cases are considered. First is that the streamflow Z_t are seasonally standardized such that

$$Z_t = \frac{Y_{v,\tau} - \bar{Y}_\tau}{S_\tau}$$

where $Y_{v,\tau}$ is the streamflow at year v and season τ; $\bar{Y}_\tau$ and S^2_τ are the seasonal mean and variance, respectively; and Z_t is the standardized flow at time $t = (v-1)\ \omega + \tau$, where ω is the number of seasons ($\omega = 12$ for monthly and $\omega = 52$ for weekly). For purposes of forecasting, the mean $\bar{Y}_\tau$ and variance S^2_τ has to be updated as an observation arrives. The updating equations are:

$$\bar{Y}_\tau^{(v)} = \frac{v-1}{v}\ \bar{Y}_\tau^{(v-1)} + \frac{Y_{v,\tau}}{v}$$

and

$$S_\tau^{2(v)} = \frac{v}{v-1}\ S_\tau^{2(v-1)} + \frac{v}{(v-1)^2}\ (\bar{Y}_\tau^{(v)} - Y_{v,\tau})^2$$

where the superscript (v) or (v-1) qualifies for the estimate at year v of the pertinent statistics.

The second case cosidered is that the streamflows Z_t are taken as the straight data.

In the computer program, the first case requires inputting seasonal means and variances based on first few years of data. The input variable NSX which stands for the number of seasons is set equal to ω for the case seasonally standardized the data (case 1) and NSX is set equal to zero for the case of using straight data (case 2).

Note that the specific problem formulation and update equations for this example practically evolves only in the user-supplied subroutine USERSUB. Thus, should a different problem formulation is needed for specific applications of the Kalman filter, the current version of the program may be used by writing one's own USERSUB subroutine.

For this example, the monthly and weekly flows of Paso del Ermitano for the period of 1968 to 1971 were used to derive the initial statistics and state estimate α_t. Then the streamflows for the period of 1973 to 1975 were used for forecasting and evaluating the performance of the filter. Table 7.3 presents the forecast error evaluations for the two problem cases tried on monthly and weekly levels. From the results herein, it is found that the problem case 2 (using straight data) gives better forecasts for one-step, up to five-step ahead forecasts. Figures 7.2 to 7.5 give the plots of the observed and forecast values for monthly and weekly levels for the case 2 formulation. For purposes of illustration, the input data listing for case 2 program run is given in Figure 7.6.

7.6 References

Kalman, R.E., 1960. A new approach to linear filtering and prediction problems. Jour. of Basic Engineering, Vol. 82D, pp. 35-45.

Kalman, R.E. and R.S. Bucy, 1961. New results in linear filtering and prediction theory. Jour. of Basic Engineering, Vol. 83, pp. 85-108.

Table 7.3. Results of forecast error evaluation.

	Monthly		Weekly	
	Case 1	Case 2	Case 1	Case 2
One-step				
MB	3.996	1.261	1.883	1.158
RE	0.295	0.130	0.044	0.112
RMSE	10.874	3.745	20.610	5.527
Two-step				
MB	8.652	3.802	5.095	2.906
RE	0.720	0.425	0.453	0.345
RMSE	15.290	7.129	11.718	6.523
Three-step				
MB	9.576	4.888	6.769	3.645
RE	0.865	0.538	0.636	0.431
RMSE	13.570	8.026	15.626	7.727
Four-step				
MB	10.999	6.021	8.397	4.285
RE	0.995	0.645	0.756	0.491
RMSE	15.004	8.839	21.378	8.823
Five-step				
MB	12.341	7.284	8.023	4.475
RE	1.111	0.748	0.762	0.526
RMSE	16.431	10.391	15.927	8.381

Note: MB (mean bias) = $1/n \, \Sigma(F_i - O_i)$;

RF (relative error) = $1/n \, \Sigma \, (F_i - O_i)/O_i$; and

RMSE (root mean-square error) = $\sqrt{1/n \, \Sigma \, (F_i - O_i)^2}$; where F_i and O_i are the precast and observed values, respectively, and n is the total number of forecasts made.

```
STANDARD KALMAN FILTER (KALMAN-BUCY)

CONTROL PARAMETERS:

     BEGINNING TIME          = 49
     ENDING TIME             = 82
     NO. OF STATES           =  1
     NO. OF MEASUREMENTS     =  1
     PRINT OPTION CODE 1     =  0
     PRINT OPTION CODE 2     =  0
     PRINT DATA OPTION       =  0

FILTER INITIAL VALUES:

     STATE TRANSITION MATRIX:
          1.000
     MEASUREMENT MATRIX:
          -.2570
     FILTERED STATES:
          .8550
     ASSOCIATED ERROR COVARIANCE:
          100.0
     MEASUREMENT NOISE VARIANCE:
          9.430
     MODEL NOISE VARIANCE:
          0.

TIME STEP:     82

     PROPAGATED STATES:
          .8215
     ASSOCIATED ERROR COVARIANCE:
          1.208
     MEASUREMENTS:
          1.204
     INNOVATIONS:
          .5582e-02
     KALMAN GAIN:
          -.4983E-01
     FILTERED STATES:
          .8212
     ASSOCIATED ERROR COVARIANCE:
          1.184
```

Figure 7.1. Sample output of Program PCKFA for illustrative purposes.

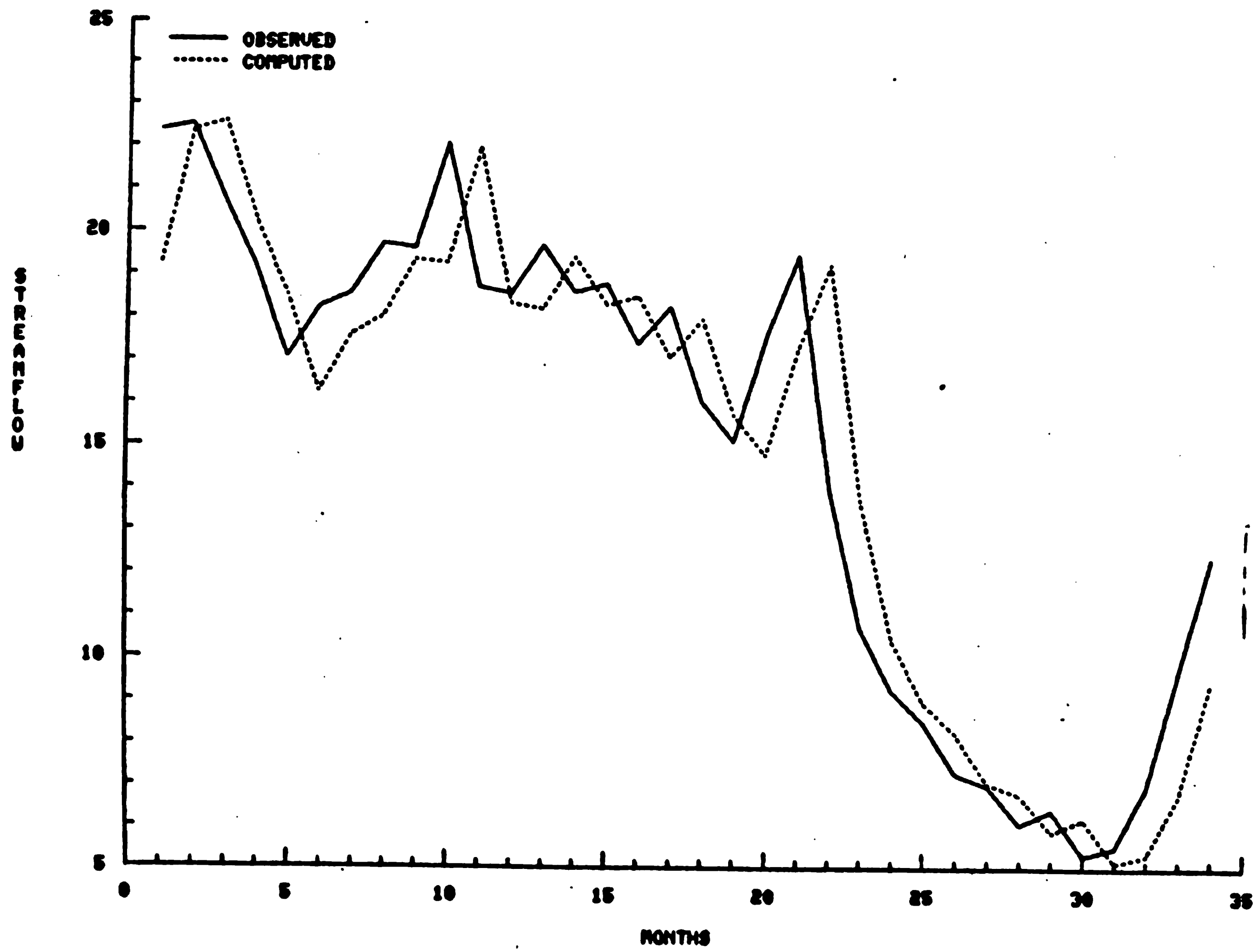


Figure 7.2. Observed and one-step ahead forecasts of monthly streamflows for case 2.

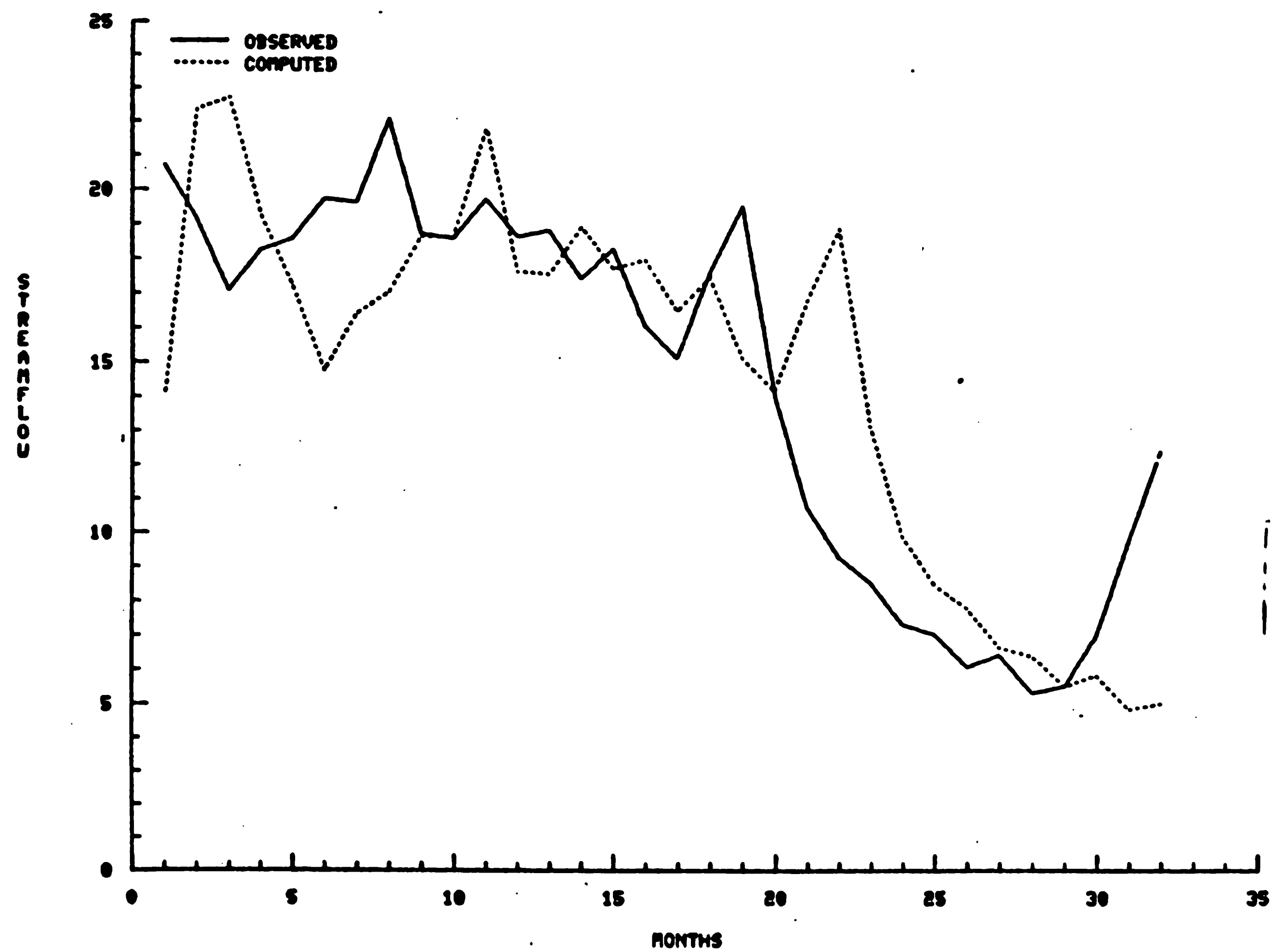


Figure 7.3. Observed and three-step ahead forecasts of monthly streamflows for case 2.

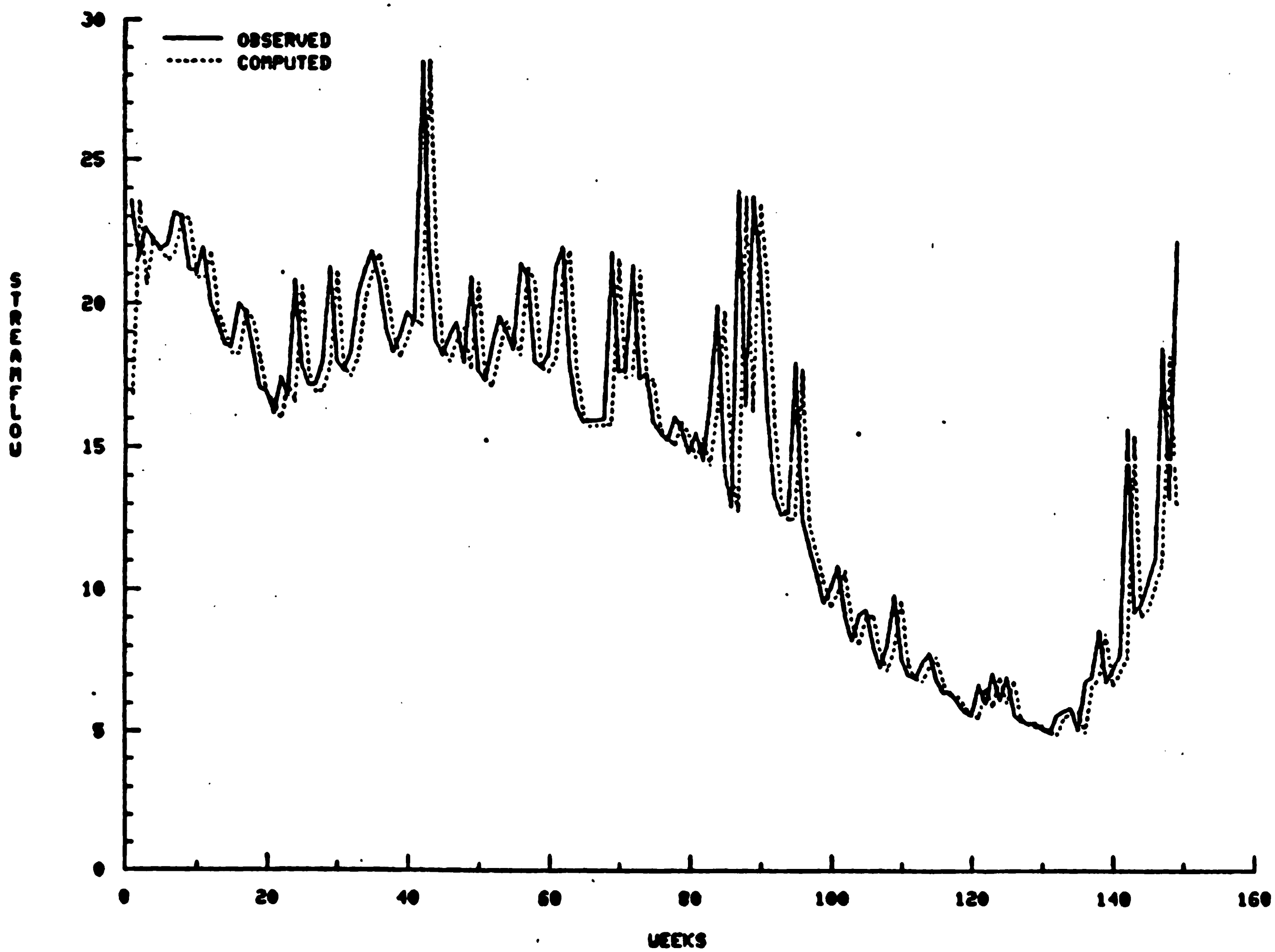


Figure 7.4. Observed and one-step ahead forecasts of weekly streamflows for case 2.

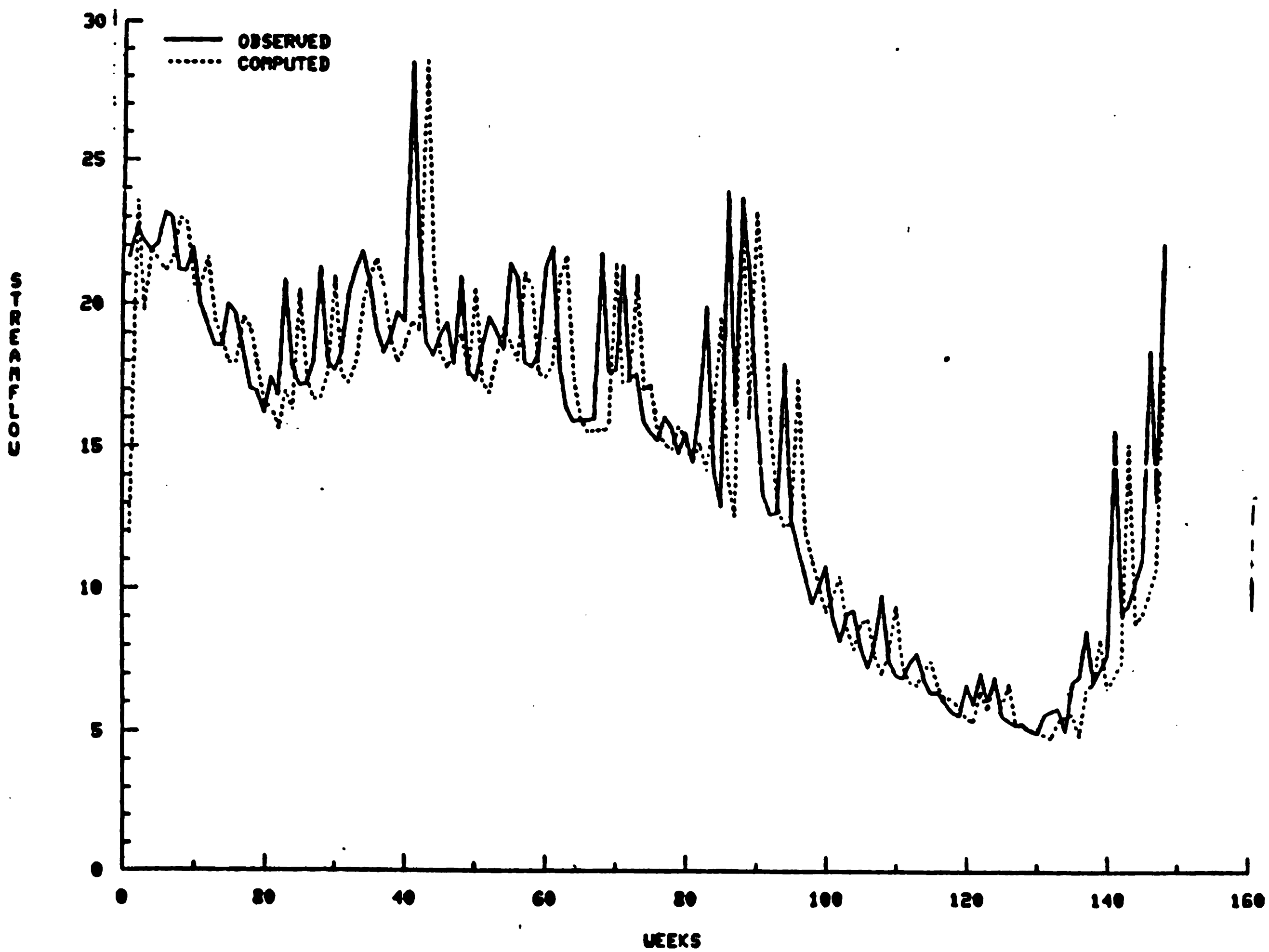


Figure 7.5. Observed and three-step ahead forecast of weekly streamflows for case 2.

```
   49   82
    1    1    0    0    0
(8F10.0)
1.0
-0.257
0.855
100.0
9.430
0.0
    0    5
(20X,F8.0)
 1973    1             22.368 31
 1973    2             22.504 28
 1973    3             20.732 31
 1973    4             19.173 30
 1973    5             17.074 31
 1973    6             18.233 30
 1973    7             18.561 31
 1973    8             19.719 31
 1973    9             19.613 30
 1973   10             22.058 31
 1973   11             18.697 30
 1973   12             18.561 31
 1974    1             19.684 31
 1974    2             18.600 28
 1974    3             18.771 31
 1974    4             17.400 30
 1974    5             18.255 31
 1974    6             16.057 30
 1974    7             15.116 31
 1974    8             17.581 31
 1974    9             19.473 30
 1974   10             14.081 31
 1974   11             10.753 30
 1974   12              9.261 31
 1975    1              8.519 31
 1975    2              7.300 28
 1975    3              7.013 31
 1975    4              6.073 30
 1975    5              6.413 31
 1975    6              5.317 30
 1975    7              5.516 31
 1975    8              6.984 31
 1975    9              9.740 30
 1975   10             12.406 31
```

Figure 7.6. Input data listing for case 2 formulation for monthly level.