CASE STUDY

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RAINFALL RUNOFF MODELLING OF NAGAVALI RIVER UPTO NARAYANAPURAM

DELTAIC REGIONAL CENTRE
NATIONAL INSTITUTE OF HYDROLOGY
KAKINADA (INDIA)

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PREFACE

Rainfall runoff modelling of stream flow is very important to ascertain, to forecast and to distribute the river flows properly, optimally and judiciously. It has become an inevitable tool in water resources engineer's hand ever since water attained the distinction of scarce commodity. Also to warn about flood disasters any forecasting or warning system is to be linked to a good rainfall runoff model.

This report is second in series of hydrological modelling studies of Eastern Ghat rivers taken up by Institute following an earlier study of 'hydrological modelling of river Sarada using the Tank model'. Daily flow modelling using HYRROM a PC based version for rainfall-runoff modelling developed at Institute of Hydrology, Wallingford, U.K., is undertaken for Eastern ghat river of Nagavali upto Narayanapuram Anicut (8526 km^2). The results are then compared with those obtained using five other simple conceptual models having 3 to 5 parameters. The utilities of GIMIC, a software being developed as a graphical interface for developing models at Institute of Hydrology, Wallingford, as a tool in calibrating and testing these models for data sets of above catchment is demonstrated. The software of Institute of Hydrology, Wallingford, U.K., is applied for an Eastern Ghat river for the first time in this study.

This report entitled 'Rainfall runoff modelling of Nagavali river upto Narayanapuram' is part of the work programme of Deltaic Regional Centre, Kakinada. This study is carried out with the facilities provided by Institute of Hydrology, U.K., by Mr. S.V.Vijaya Kumar, Sc'B' who is assisted by Mr. S.M.Saheb, SRA and Mr. U.V.N.Rao, RA under the guidance of Dr. P.V.Seethapathi, Sc'F', Head and Coordinator.

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ABSTRACT

As part of the work programme of the regional centre it is planned to undertake the rainfall - runoff modelling for the rivers of the east coastal region of India. Some simple lumped conceptual models are applied to Nagavali river catchment and a comparison among them is made in the study.

Daily flow modelling using HYRROM a PC based version for rainfall-runoff modelling developed at Institute of Hydrology, Wallingford, U.K., is undertaken for Eastern ghat river of Nagavali upto Narayanapuram Anicut (8526 km^2).The results are then compared with those obtained using five other simple conceptual models having 3 to 5 parameters. The utilities of GIMIC, a software being developed as a graphical interface for developing models at Institute of Hydrology, Wallingford, as a tool in calibrating and testing these models for data sets of above catchment is demonstrated.

The performance of HYRROM for Indian river catchment is undertaken for the first time and it could model the process acceptably well. Since HYRROM can be installed on a PC and analysis can be easily carried out with various menu screens it will be a good tool for field engineers involved in water resources projects. The performance of Model 4 based on Probability distributed method with its five model parameters in modelling the flows properly for the catchment suggests that even simple conceptual models can be relied upon.

1.0 INTRODUCTION:

With the increase in demand for water to meet the necessities like Water supply, Irrigation, Power generation, there is increasing need to asses the available flows in rivers more accurately to plan, operate and manage the scarce water resource. The conventional means and methods to estimate the availability of water using empirical models at a place from the available rainfall estimates are frequently misleading the planners and managers. It is time to realise and apply some of the simple conceptual rainfall river flow techniques to asses the flows more realistically. The practicing Civil Engineer at field level should try to update their know how of estimating river flows for proper justification of their designs to meet the set goals. The use of empirical formulas should be avoided for the deterministic conceptual models, based on the understanding of the physics of the rainfall runoff processes. In the beginning, some simple models may be attempted before going into the more advanced, rigorous, complex distributed, physical modelling of the various processes of hydrologic cycle. The purpose of developing better conceptual models for the individual components was to improve the overall modelling of the system but most of the times it brought in more complexities which limited the applicability of such models, at field level.

As part of the work programme of the regional centre it is planned to undertake the rainfall - runoff modelling for the rivers of the east coastal region of India. Some simple lumped conceptual models are applied to Nagavali river catchment and a comparison among them is made in the study.

The east flowing rivers between Mahanadi and Godavari Rivers are typical in their flow regime that they all originate in the high grounds of Eastern Ghats descend down to the east coastal plain and empty into the Bay of Bengal none of them forming any deltaic or estuarian conditions. Some of them form catchment areas of about 15000 km^2 others about 1500 km^2 only, sizes which can be considered medium to small from Indian river sizes. Flows in most of these rivers are seasonal, very flashy in nature and in the lower reaches owing to their restricted flood plain inundate many urban built up lands and rural crop lands on their banks very often and cause lot of disruption to communication network, like railways, roads ,telecom etc.,

The daily river flow modelling is undertaken in this study to model the rainfall-runoff in Nagavali river basin of the region using some simple conceptual models linked to GIMIC, a software interface to develop and test simple models along with HYRROM, a rainfall runoff model of Institute of Hydrology, Wallingford, U.K., which has 9 parameters. Other models have 3 to 5 parameters. Nagavali river up to Narayanapuram Anicut (8526 Km^2) just upstream of Srikakulam town is considered in this study. Performance of the models used is analysed to decide on which of the models used can model the flows in the catchment in a better way.

The following sections describe the details of software used, the formulation of the models, and the data used. Discussion of the results and analysis and the relative performance of the models used in the study is also presented.

2.0 DATA & INFORMATION:

The description of the River Nagavali the data used for the daily rainfall - runoff modelling is presented in this section.

The Nagavali river basin is surrounded by the Mahanadhi on north, Godavari basin on west, Champavathi basin, Peddagedda, Kandivalasa river basins and Bay of Bengal in south and Vamsadhara river basin in the east.

The total catchment area of the basin is about 8845 sq km. The catchment area of the river in Orissa state is 4040 sq km and in Andhra Pradesh state is 4805 sq km. The maximum length of the basin from north to south is about 210 km lying between latitudes $18^{\circ}11$ to 19° 45 . The maximum width of the river basin is about 110 kms. in between longitudes 82° 53' to 84° 2.

The Nagavali river rises in the Eastern ghats (fig 1) in the Orissa state and flows, in south Eastern direction for about 40 km and takes a turn towards southerly direction and flows in this direction for 25 km where the river crosses the visakhapatnam-Raipur railway line between miles 203 and 204 and continues to flow in the same direction and parallel to the railway line for another 22 km where it passes one and half km east of Rayagada. The level of the river here is about +164 m . The river continues to flow for another 20 km in the same direction and almost parallel to the railway line

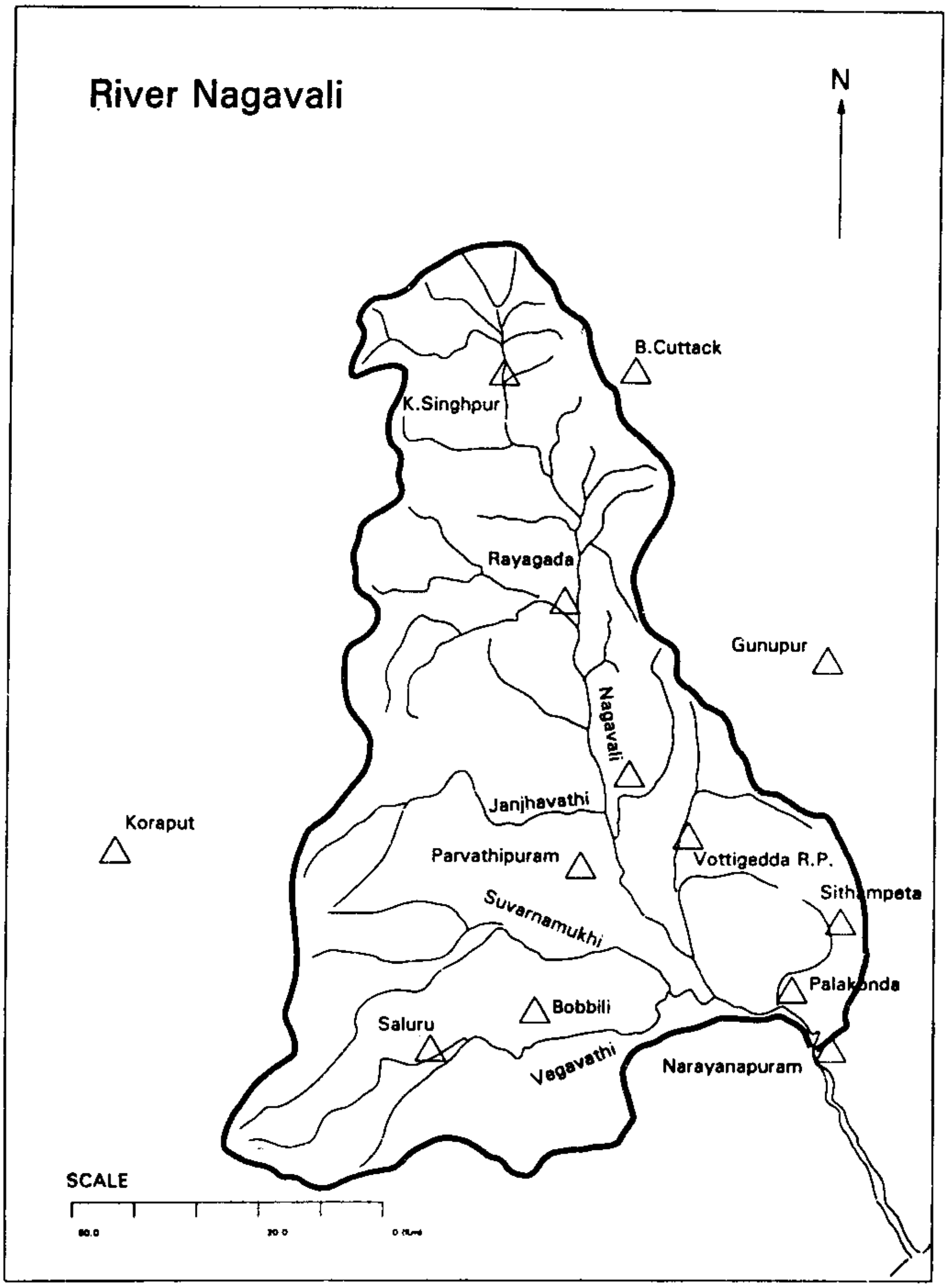

River Nagavali
N
B.Cuttack
K.Singhpur
Rayagada
Gunupur
Nagavali
Janjhavathi
Koraput
Parvathipuram
Vottigedda R.P.
Suvarnamukhi
Bobbili
Saluru
Vegavathi
Narayanapuram
SCALE

Fig. 1

and parvathipuram - Rayagada road, Where it enters Andhra Pradesh State limits at a point 6 km south of Jimidepeta R.S. A number of minor hill streams fall in to the main river in the orissa state limits.

After entering Andhra Pradesh state the Nagavali river takes a south easterly direction and continues to flow in this direction till it falls in to Bay of Bengal about 10 km south east of Srikakulam town near Dibbala palem village. The bed level of the river where it crosses the Orissa --Andhra Pradesh state border is +152 m . After flowing for about 30 km in Andhra Pradesh state limits, the river passes 8 km east of parvathipuram town. The river flows in the same direction, for the rest of its course and passes through Srikakulam town and crosses G.N.T. Road between 550/2 and 550/3 and finally enters into the sea. The main tributaries and their description is given in the following section.

1. JANJAVATHI RIVER: The Janjavathi river takes its origin in Koraput district of Orissa state and flows for about 60 km in easterly direction. It joins the Nagavali river on the right side near Devara Gumpa in Komarada Mandal of Vizianagaram district.

2. VOTTIGEDDA: The Vottigedda takes its origin near the Andhra Pradesh - Orissa state border near Addapi at an altitude of +1060 MSL and flows in southerly direction for about 50 km and joins the Nagavali river on the left side near Chidimi(V) in Veeraghattam Mandal in Srikakulam District. The bed level of the river at the confluence is about +60 MSL.

3. VEGAVATHI RIVER: Vegavathi river is the major tributary of the Nagavali river which takes its origin in Arakuvalley Mandalam in Visakhapatnam district at an altitude of +1600 MSL. The river flows almost in easterly direction for about 80 km and is joined by the Suvarnamukhi river on the left side at a place called Kottisa. The bed level of the river at the confluence is +58 MSL.

4. SUVARNAMUKHI RIVER: There is one sub tributary to Vegavathi called Suvarnamukhi river which takes its origin in Koraput district of Orissa state at +1474. After flowing for 40 km in north easterly direction the river takes turn and flows easterly direction. After flowing for 67 km, in easterly direction, the river joins the Vegavathi river near Kottisa in Vangara

Mandal in Srikakulam District. After joining with the Vegavathi, the river flows in easterly direction for 11 km and joins the Nagavali river one mile down stream of Sangam village where the bed level is +47 MSL.

Data:

The following data are used in the modelling:

i. Daily rainfall data for a period of six years from 1987 to 1992 for about 12 stations in and around the basin namely Rayagada, Bissam Cuttack, Kalyana Singhpur, Gunupur, Koraput, in the state of Orrissa and Parvathipuram, Bobbili, Saluru, Palakonda, Sithampeta, Vottigedda Reservoir Project and Narayanapuram Anicut in Andhra pradesh.

ii. Daily weighted discharges at Narayanapuram Anicut for the corresponding period are used.The catchment area of Nagavali at the Anicut is 8526.28 sq km.

iii. Average of Mean monthly evaporation from 1989 to 1992 observed at Visakhapatnam IMD station, the nearest place at which evaporation data is available, is used in the modelling.

The initial period of 1987 to 1989 is considered for the calibration of the rainfall runoff model and the last three years period of 1990 to 1992 is used for the validation of the model Average daily rainfall values of the basin are calculated using Thiessen weights for the 12 raingauge stations.

3.0 CRITERIA AND METHODOLOGY:

The criteria adopted and the related methodology of the analysis undertaken in this study are explained below.

3.1 Description of HYRROM :

HYRROM is a nine parameter conceptual rainfall runoff model developed at the Institute of Hydrology, Wallingford, U.K., for use on personal computers. It is designed in such a way that it is easy to operate with the help of on screen menus for data preparation and parameter modification. Output is in the form of graphs and tables and can be directed to printers or plotters. Catchment rainfall runoff modelling can be carried out on daily basis with minimal data requirement of daily rainfall, evaporation and observed flows with an inbuilt automatic optimisation procedure to be carried out in three steps, with a consideration of 4 parameters in each step because of computational limitations. If desired instead of automatic optimisation one can conduct optimisation by trial and error. Once the optimisation analysis is satisfactory prediction analysis part of the model is very useful in estimating flows over periods of non-available flows provided rainfall estimates are available for that period.

The main stages in carrying out the rainfall runoff analysis using HYRROM are as listed below:

*Preparation of input data using HYLINK

*Calibration and Validation using Optimisation Analysis

*Estimating flows using Prediction Analysis

The Schematic diagram describing the formulation of HYRROM is shown in Figure 2. The model uses the concept of stores to keep account of movement of water with in the basin and different phases of transfer of moisture are expressed by a set of mathematical equations. These stores can fill or empty during simulation and effect the runoff in time and magnitude. In this model four stores, namely surface or routing store; interception store; soil store; groundwater store are used. Blackie and Eeles (1985) describe the technical formulation of the model in detail. About nine numbers of parameters are made variable in the model, the ranges of which are given in Table 1, and are explained below.

SS is a parameter showing the size of the interception store in millimeters and causes proportional time delay of flow of water in to subsequent stores.

RC is a parameter controlling the proportion of rainfall which enters the routing store and hence affects the runoff resulting from surface store.

FC is a parameter affecting the amount of water that is proportinally lost by evaporation and transpiration from the catchment.

RK, RX, are parameters defining the contribution of routing store to runoff.

$$\text{Runoff} = \text{RK (routing store)}^{\text{RX}}$$

RDEL is the time delay, in days, between water leaving the routing store and resulting runoff.

GSU and GSP are parameters defining the contribution of the groundwater

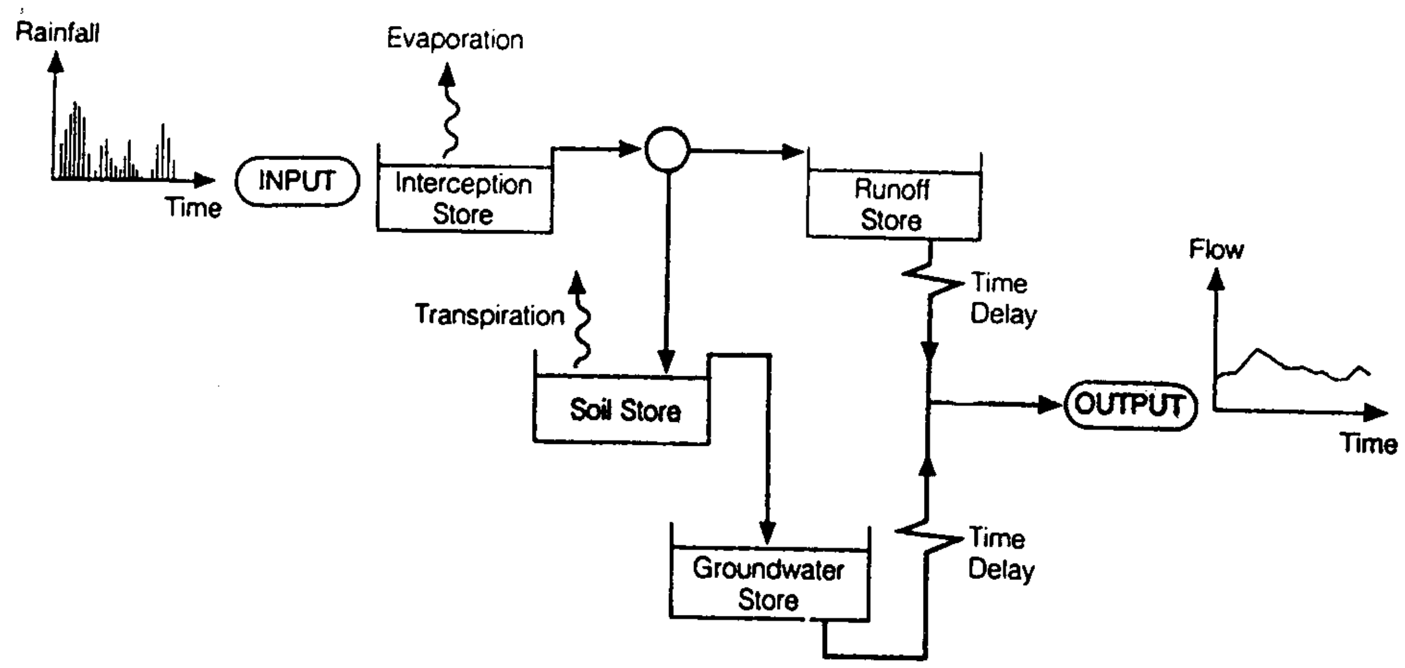


Fig. 2 Schematic diagram describing HYRROM

TABLE I

LIST OF PARAMETERS AND THEIR RANGES IN HYRROM

Parameter	Name	Range
SS	Size of the vegetation interception and surface detention store (mm)	0 < x < 5
RC	Surface runoff partitioning factor	0 < x < 1
RDEL	Routing store delay (days)	x > 0
RX	Routing store index	x > 1
RK	Routing store factor	0 < x < 1
FC	Penman open water evaporation factor	0.3 < x < 1
GDEL	Groundwater store delay (days)	x > 0
GSP	Groundwater store index	x > 1
GSU	Groundwater store factor	x > 30

store to runoff.

$$\text{Runoff} = (\text{groundwater store/GSU})^{GSP}$$

GDEL is the time delay, in days, between water leaving groundwater store and resulting runoff.

By adjusting the values of these nine parameters, an experienced hydrologist should be able to obtain a satisfactory catchment model. Alternatively, an automatic optimisation can also be performed to achieve the desired objective of modelling. The data requirement and the procedure for conducting calibration are discussed in following section.

3.2 METHODOLOGY:

The procedure for calibration and necessary data required are explained in this section.

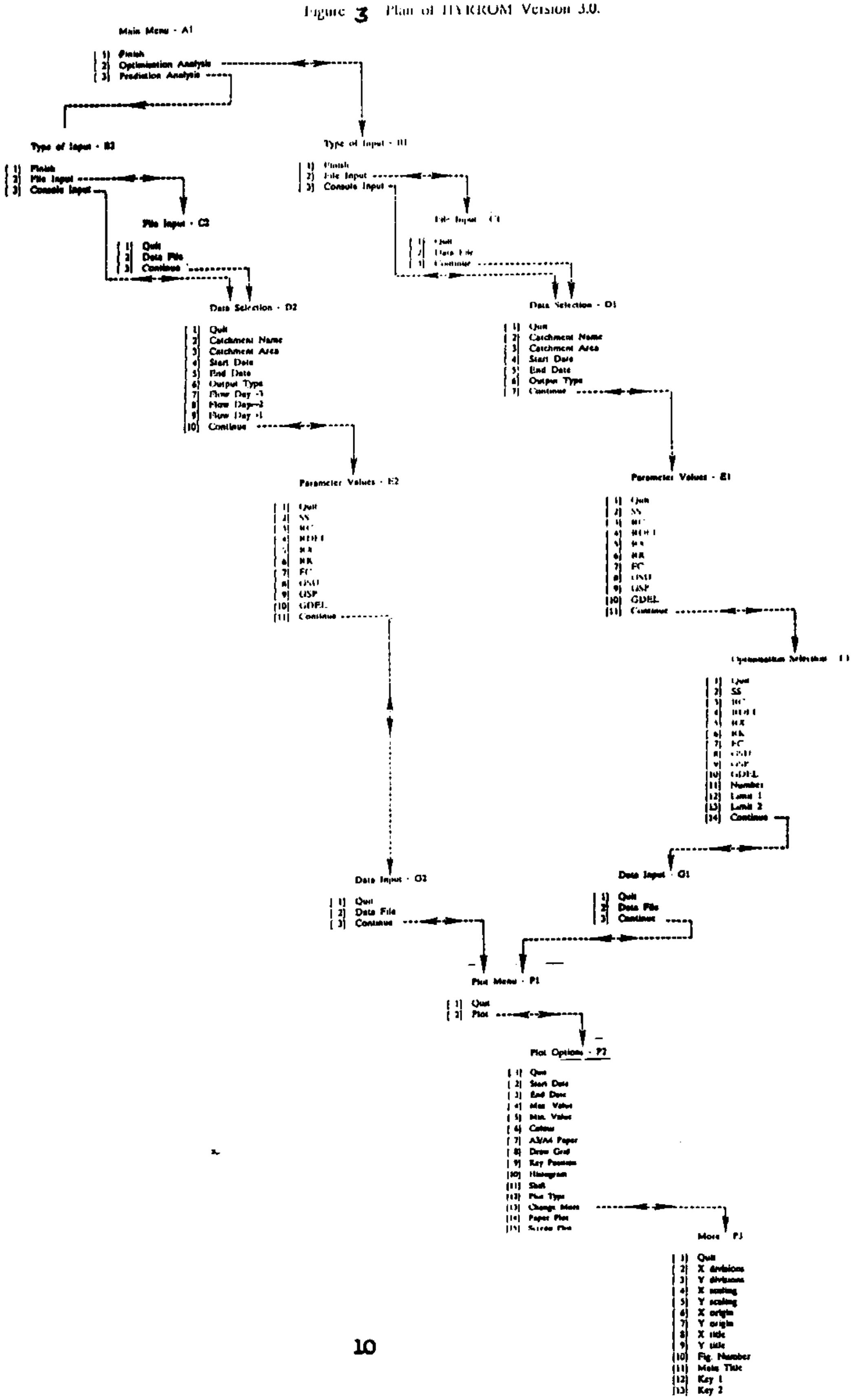
3.2.1 Data Requirement:

A sequence of daily rainfall over the basin and the consequent runoff at the basin outlet for the period of calibration are necessary in the optimisation analysis with other details of open water evaporation and catchment area. It should be noted that the saying of garbage in garbage out very much applies to this model too. The data should be of good quality with no unrealistically high or low values. When the pattern of runoff mismatches with that of rainfall the optimisation can't be carried out. Data for at least one year is needed for calibration. A maximum of ten years of data is allowed for optimisation. A data preparation utility HYLINK is supplied with the model software, and required data is to be supplied in ASCII files with one value per record. HYLINK is menu driven and can also read input data directly from Institute of Hydrology's hydrological data base system (HYDATA) for preparing data file for HYRROM. HYLINK provides two features which avoid the need to supply daily values of evaporation. The daily evaporation values instead be calculated either by supplying mean monthly values or by specifying an assumed sinusoidal variation in evaporation rate. The first alternative is used in the present study.

3.2.2 Optimisation Analysis:

The step wise procedure and different menu screens that appear while working with the HYRROM are shown in Figure 3. The aim of optimisation

Figure 3 Plan of HYRROM Version 3.0.



analysis is to find optimum parameter values to minimize the objective function. The objective function considered in HYRROM is as below:

$$Obj = \sqrt{\sum_{1}^{N}(Qo-Qp)^2/N}$$

where

Qo is Observed daily flow in cumecs
Qp is predicted daily flow in cumecs
N is number of days of flows used for optimisation.

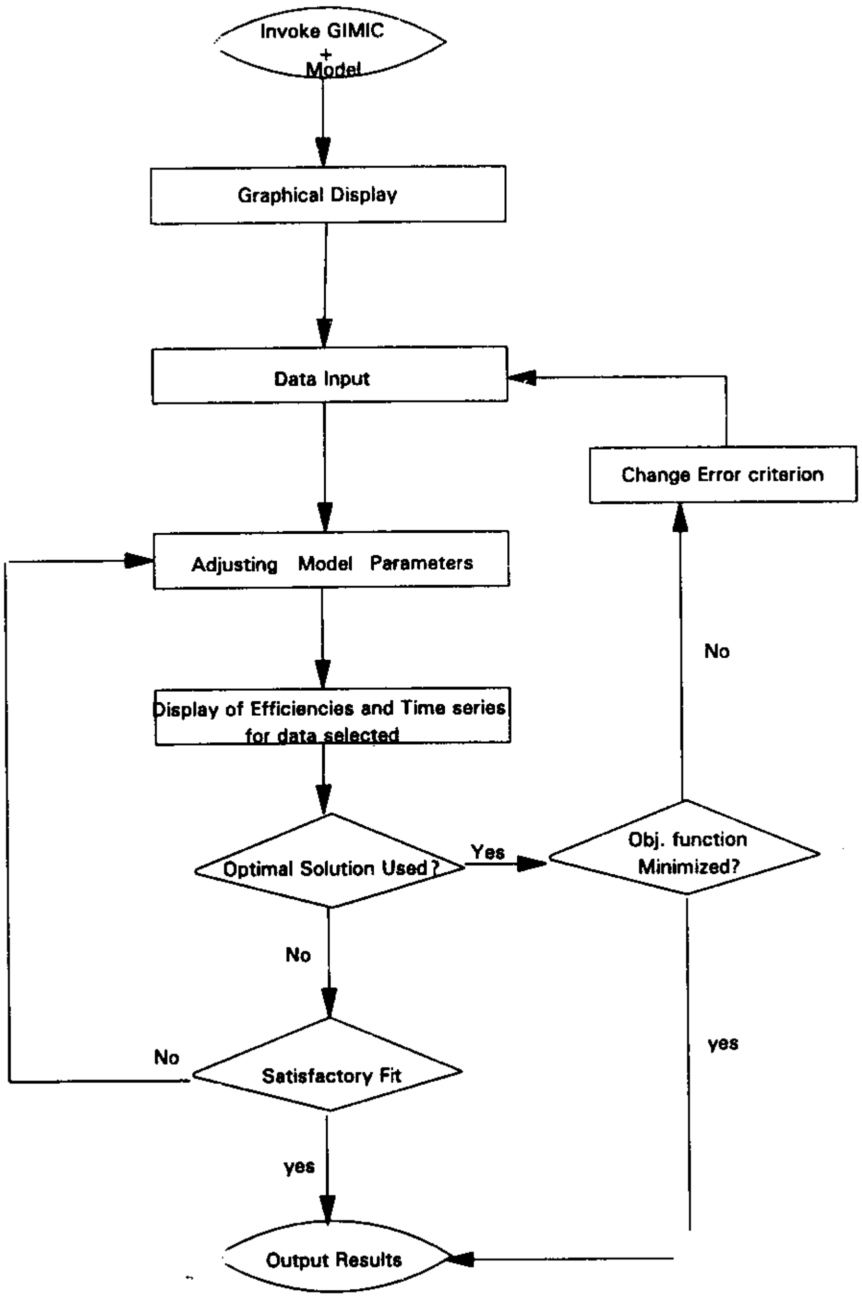
The objective function can be regarded as a measure of typical error in the predicted daily flows. However since much of the error may come from errors in timing or magnitude of peak flows, a large value of the objective function does not necessarily imply an unsatisfactory catchment model. Since the function is standardised it enables comparison of results from the calibration and validation analysis of flows at a particular g/d site of any basin for which modelling study is being carried out.

The optimisation must be performed for a period over which daily flow records are available. The analysis is performed by first assuming an initial set of parameter values, and continuing with different menu screens, then adjusting the parameter values. This may be continued till a satisfactory agreement between the observed and predicted flows is arrived at. This can be done either manually by trial and error by selecting the number of parameters to be optimised as zero and continuing or can be carried out through the inbuilt automatic optimisation utility. TO perform optimisation analysis HYRROM uses the Rosenbrock optimisation technique, which is one of the most reliable methods available (Rosenbrock, 1960). It should be noted that an automatic optimisation searches for a set of parameter values that achieve the optimisation criterion irrespective of their physical meaning. It may therefore be necessary to exclude some parameters from automatic optimisation or to limit the range over which they can vary. Most of the problems associated with automatic optimisation are in locating the global minimum in a parameter space that contains numerous local minima. An experienced hydrologist may be able to produce a more satisfactory catchment model than that given by the automatic optimisation routine.

In HYRROM the automatic optimisation procedure performs the optimisation on each of the selected parameters in turn. The order in which parameters are to be optimised is defined by the user by giving a rank against each parameter. A default set of FC, GSP, RC, SS is available. It is recommended that a maximum of four parameters are optimised at one time. Otherwise, the computing time will greatly increase and it is possible that the analysis may fail. To perform an automatic optimisation it is advised to repeat the analysis several times, by selecting different parameters each time. Three sequences suggested for HYRROM are FC-GSP-RC-SS; RX-RK-RDEL-GSU; and GDEL-FC-GSP-RC with parameter rankings in the order. This sequence optimises the most sensitive parameters first and fine tunes them in the final analysis. The limits with in which the parameters can vary during the analysis may be supplied as fractions or multiples of the initial parameter values subjected to model defined limits given in Table 1. Once the analysis has started the screen display gives details of the optimised parameter values and the objective function and the results are written to a file called RRMLOG.DAT. Also results can be seen in graphical output which can be redirected to printer or plotter. The optimised parameter values are written to a file called RRMAIN.DAT which can be directly used in further analysis of the sane basin. Observed and predicted flows are written to a file called RRMFLW.DAT. Also there is a facility to have results of monthly or annual periods.

3.3 Description of GIMIC:

Graphical Interface for Model Identification and Calibration (GIMIC) is a software package under development at IH for testing and developing a rainfall runoff model for a catchment. By linking a rainfall runoff model to GIMIC and using different forms of fitting criteria and visual plots one can compare the performance of the model for different parameter values and design a model to their satisfaction. When presented with a host of models one can decide very quickly on the best one by subjecting them to GIMIC. It is further development of PC based software called MIMIC, i.e., Microcomputer based Interactive package for Model Identification and Calibration which was developed to allow models to be investigated both objectively and subjectively. The structure of GIMIC is given at Fig. 4. The important



Structure of GIMIC

Fig. 4

features of GIMIC are graphical and statistical screen displays showing various hydrological measures as listed below.

- time series plots of observed and simulated flows
- time series plots of rainfall
- time series plots of potential and estimated evaporation
- time series plots of for all other processes like base flow, storage etc.,
- volumes of observed and simulated flows modelled
- values of error function and efficiency measures
- duration curve plot for simulated and observed flows
- seasonal plot of the flooding events
- double mass curve for simulated and observed flows
- scatter plot for simulated and observed flows

Modeler can feel the effects of changes in parameter values he is making on the screen and tune the model to his satisfaction or can go for automatic optimisation by selecting the objective function criterion. Output facilities available include hard copies of selected plots. The list of options available while working GIMIC are listed at Annexure-I. In the present study GIMIC is run with Fortran 77 compiler on Sun's UNIX system with UNIRAS and OPENWIN utilities.

3.3.1 Optimisation criteria:

The classical approach to fitting a conceptual model to observed data to obtain an optimum parameter set involves minimizing an objective function, generally by automatic optimisation technique. As in HYRROM Rosenbrock's technique is used for automatic optimisation in GIMIC. As suggested by Gan and Burges (1990) least squares and least squares of logarithms are used as objective functions in GIMIC. What ever might be the objective function as mentioned elsewhere the main problem of locating the global optimum in a parameter space of numerous local optima still exists. The advantage of daily rainfall runoff modelling within the GIMIC framework is that the objective function is regarded as a tool to aid fitting and asses the model rather than the criterion by which fit is judged.

Objective function-I in GIMIC is

$$Obj_1 = \Sigma\,(Q_{obs} - Q_{sim})^2$$

where, Q_{obs} is observed flow and Q_{sim} is simulated flow over an interval over which flows are being modelled and Σ indicates that the squares of differences are summed for the period of modelling.This objective function may give good fit to long periods of low flows.

Objective function-II is

$$Obj_2 = \Sigma\,(\log Q_{obs} - \log Q_{sim})^2$$

where, $\log$ indicates that it is logarithm of the respective flows. This objective function prevents the optimisation becoming biased towards larger flows. This function may not be useful when there are no flows during most part of the year.

Objective function-III as defined by Nash-Sutcliffe (1970) is

$$Obj_3 = \text{Efficiency} = 1.0 - Obj_1/\Sigma(Q_{obs} - Q_{bar})^2$$

where, Q_{bar} is the observed mean flow during the interval and the function is evaluated for the period of modelling. The efficiency criterion is biased towards large discharges, but gives an objective indication of model performance.

Standardising the objective function enables comparison of the results from calibration and validation data sets for each catchment; however those results are not comparable across catchments. By normalising the objective function one can go for comparison of performance of a model over different catchments. For this reason Objective function III is very handy. A perfect agreement between observed and simulated flows yields an efficiency of 1.0.

The criteria which may be examined for a definitive assessment of model performance vary with the ultimate purpose of the model but a high efficiency and a well simulated daily flow should indicate a generally good performance of the model According to Houghton-Carr & Arnell (1994) it is also almost always necessary to be able to quantify the fit through a criteria such as efficiency in order to compare models.

3.4 Description of Models Linked to GIMIC :

A number of conceptual rainfall-runoff models have been developed based on different priorities to flow processes for various hydro-climatic conditions and are reviewed from time to time. Fleming (1975) presented a review on the models which are considered and short listed by Bonvoisin & Boorman (1992a) based on their simplicity i.e. minimum number of parameters to account for the flow processes satisfactorily. For undertaking such an exercise they developed a PC based software, to assist in model fitting and development, called MIMIC (Bonvoisin & Boorman, 1992b). It is concluded that most of the existing models were too complex to model successfully. Since some of the simpler models gave acceptable simulations there is no justification for using such complex models. Among the simple models those with 4 or 5 parameters gave acceptable results on the catchments of U.K. which are modelled in their work. Houghton-Carr & Arnell (1994) compared the performance of a number of simple conceptual models on about 25 catchments of U.K., and ranked their performance. In the present study the best four models suggested by them are considered (M 2 to M 5) along with another model with 5 parameters (M 1) to test their performance on the two test catchments of this study.

These models represent the catchment as a set of interconnected stores. Flows into, out of and between stores represent the water movement in the modelled catchment and are often labelled accordingly, although this is often misleading. Most of the processes are determined by equations; frequently the flow out of a store is determined by the volume of water currently in store. The stores may have limited or unlimited capacities. The store's capacities and constants of the equations are called as model parameters. The summary of parameters of different models considered in this study are presented in Table 2.

TABLE 2: Summary of Model Parameters

Model	NO. of Parameters	Parameter 1	2	3	4	5
1	6	S_{max}	D_{soil}	$K_{channel}$	B_{soil}	K_{ground}
2	3	S	K1	K2		
3	5	C_a	C_b	C_c	C_{r1}	C_{r2}
4	5	C_{max}	S_{max}	K_b	g_{rout}	s_{rout}
5	3	S	K1	K2		

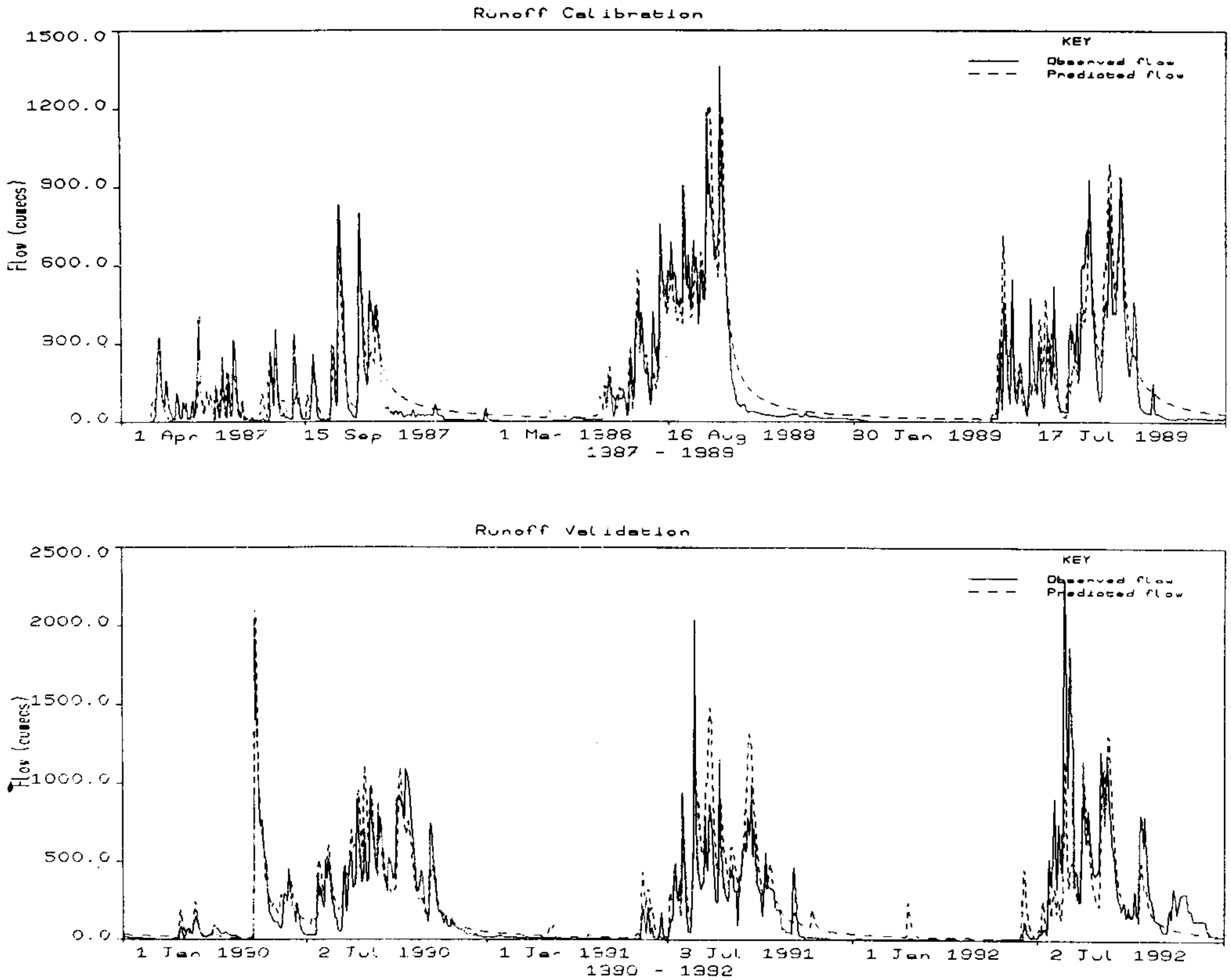
Detailed description of these models is available in Bonvoisin & Boorman (1992a) and Houghton-Carr & Arnell (1994) and is briefly presented in Annexure-II.

4.0 ANALYSIS & RESULTS:

Initially HYRROM is used to conduct rainfall-runoff modelling for the Nagavali up to Narayanpuram Anicut. The inbuilt automatic optimisation option is considered to decide on the model parameters. As mentioned in the description of the HYRROM the three sequences of parameter sets FC-GSP-RC-SS; RX-RK-RDEL-GSU and GDEL-FC-GSP-RC is used and optimisation repeated. It is observed that the objective function is improving with each step and is continued till it stabilized at a value of 80.3. The % error in estimated flows for the calibration period was 13.9%. The same set of parameters are used for the validation period and resulted in an error of 9.7% with an objective function of 166.6. The monthly estimated and observed flows for both calibration and validation periods are presented in Table 3. The estimated and observed hydrographs for calibration period of 1987 - 1989 and validation period of 1990 - 1992 is shown in Fig. 5. During 1992 predicted flows are less than observed flows. In all other years they are more. The flows recorded during 1992 are definitely not consistent with the rainfall distribution.

Since there is a doubt on the consistency of the observed flow data which is actually not measured by current meter but is based on flow over a weir, it is proposed to undertake an exercise to see how other models perform on the same data sets. For this purpose the GIMIC software developed at IH is used to study the performance of other selected rainfall-runoff models on the data sets. The description of GIMIC and the five simple models used with it are discussed in an earlier section. For easy comparison of the results the objective function value of HYRROM is converted to that of GIMIC and relevant efficiencies are also worked out to find out which of the models is performing better.

The relative performance of all the models studied for Nagavali data set is presented in Table 4. Among the models used with GIMIC, M-1, M-4, M-5, M-3 and M-2 is the order of best performance based on efficiency as well as objective function criteria during the calibration period. For the validation period all the models gave lower efficiencies indicating higher differences between modelled and observed flows. Since the observed flows are on higher



Runoff Calibration
KEY
Observed flow
Predicted flow
Flow (cumecs)
1500.0
1200.0
900.0
600.0
300.0
0.0
1 Apr 1987
15 Sep 1987
1 Mar 1988
16 Aug 1988
30 Jan 1989
17 Jul 1989
1987 - 1989
Runoff Validation
KEY
Observed flow
Predicted flow
Flow (cumecs)
2500.0
2000.0
1500.0
1000.0
500.0
0.0
1 Jan 1990
2 Jul 1990
1 Jan 1991
3 Jul 1991
1 Jan 1992
2 Jul 1992
1990 - 1992

Figure No. 5

TABLE NO. 3 **HYRROM**

Observed and Estimated Monthly Flows (mm) for Nagavali upto Narayanapuram

Month	1987	1988	1989	1990	1991	1992
JAN	-	14.8	9.0	3.9	12.3	9.8
	(30.1)	(6.5)	(4.1)	(3.4)	(5.4)	(2.5)
FEB	-	9.2	6.2	8.5	7.8	14.5
	(5.3)	(2.2)	(0.8)	(4.0)	(3.3)	(1.9)
MAR	-	7.3	5.5	18.1	12.9	6.5
	(4.9)	(0.9)	(0.0)	(17.3)	(2.7)	(2.0)
APR	2.0	6.4	4.4	3.9	5.8	4.6
	(0.1)	(0.0)	(0.0)	(10.8)	(1.7)	(1.3)
MAY	15.4	7.5	3.9	195.3	4.6	4.0
	(27.3)	(2.5)	(0.0)	(141.9)	(1.1)	(1.3)
JUN	13.5	22.1	64.9	78.2	41.7	26.0
	(26.4)	(13.9)	(45.3)	(52.0)	(19.7)	(7.7)
JUL	20.7	66.4	62.6	95.3	116.5	91.0
	(23.1)	(58.3)	(64.2)	(63.4)	(113.7)	(176.7)
AUG	28.6	134.6	71.9	172.8	238.0	146.9
	(20.3)	(161.3)	(96.8)	(118.1)	(150.1)	(214.3)
SEP	21.9	201.3	176.5	164.0	207.8	186.5
	(22.2)	(194.6)	(142.3)	(164.7)	(149.4)	(164.3)
OCT	52.2	119.1	69.6	171.4	87.4	65.7
	(58.9)	(90.4)	(49.6)	(206.6)	(67.5)	(100.9)
NOV	87.0	23.1	20.9	65.1	32.9	22.4
	(85.4)	(8.1)	(5.4)	(69.4)	(21.9)	(62.1)
DEC	29.5	13.3	12.5	21.3	15.0	13.0
	(9.3)	(7.5)	(4.8)	(12.0)	(2.6)	(24.2)
ANNUAL	270.6	625.1	507.9	997.8	782.7	590.9
	(273.0)	(546.2)	(413.3)	(863.6)	(539.1)	(759.2)
% ERROR	0.8	14.5	22.9	15.5	45.2	-22.2

Note: Observed flows are shown within ( )

TABLE 4
PERFORMANCE OF DIFFERENT MODELS ON NAGAVALI UPTO NARAYANAPURAM ANICUT

Performance Criterion	HYRROM*	Model 1	Model 2	Model 3	Model 4	Model 5
Objective function	666.7	885.0	1200.0	1190.0	942.0	1020.0
	3125.9	*2810.0*	*3390.0*	*2770.0*	*3810.0*	*3370.0*
Efficiency	0.845	0.813	0.747	0.749	0.801	0.784
	0.692	*0.724*	*0.666*	*0.728*	*0.625*	*0.668*
% Error	13.9	0.9	-14.4	-7.1	-8.2	8.5
	9.7	*-16.8*	*-23.9*	*-17.6*	*-23.6*	*-12.1*

* Note: Modelling starts on 1st April 1987 for others on 1st January 1987
Calibration: 1987 to 1989 *Validation: 1990 to 1992*

side compared to estimated flows for all the models it may give an indication that there is some problem with the flow observations; especially all the 3 years experiencing high rainfall and resulting in heavy floods. It should be remembered that M-1 and M-4 have 5 parameters and M-5 has 3 parameters. That M-3 which is 5 parametered and M-2 with 3 parameters could not model the flows properly may be because of poor modelling of moisture stores and their releases such that the hydrologic processes are badly simulated. HYRROM performed very efficiently compared to all the five models used with GIMIC during calibration phase and performed rather poorly during validation stage. The 9 parameters available with HYRROM might have resulted in a better fit during calibration. But during both the phases predicted flows are on higher side compared to observed flows which is totally different compared with the performance of the other 5 models used with GIMIC. The flow hydrograph for the modelling period along with the rainfall histogram are shown in Fig 6 to 15 for all the models. The predicted and observed monthly flows from all the models are presented in Table 5 to Table 9.

GIMIC

Rainfall-runoff model

TIME SERIES PLOT

Model No. 1

D 'Nagavali'

Modelled from 2/ 1/1987 to 1/ 1/1990
Displayed from 1/ 1/1987 to 1/ 1/1990

Smax/100	Dsoil*100.	Kchannel	Bsoil	Kground
1.723	1.437	0.232	100.000	1.000

Obs Flow	Sim flow	Rainfall	Pot Evap	Act evap	Storage	Baseflow
1273	1285	3344	5001	2216	152	861

Count	529
First error	0.885E+03
Second error	Inf
Efficiency	0.813E+00

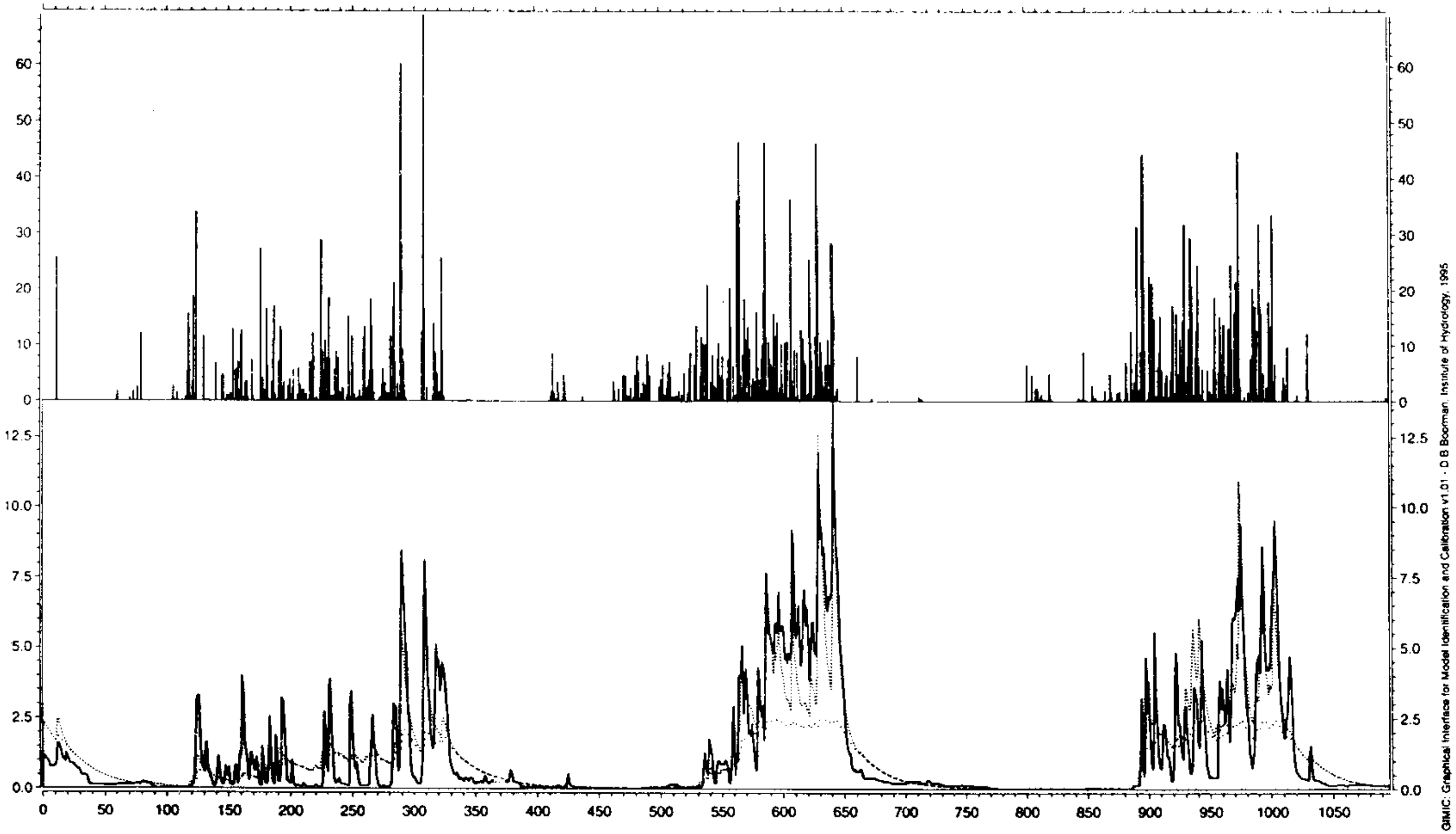


Fig. No. 6

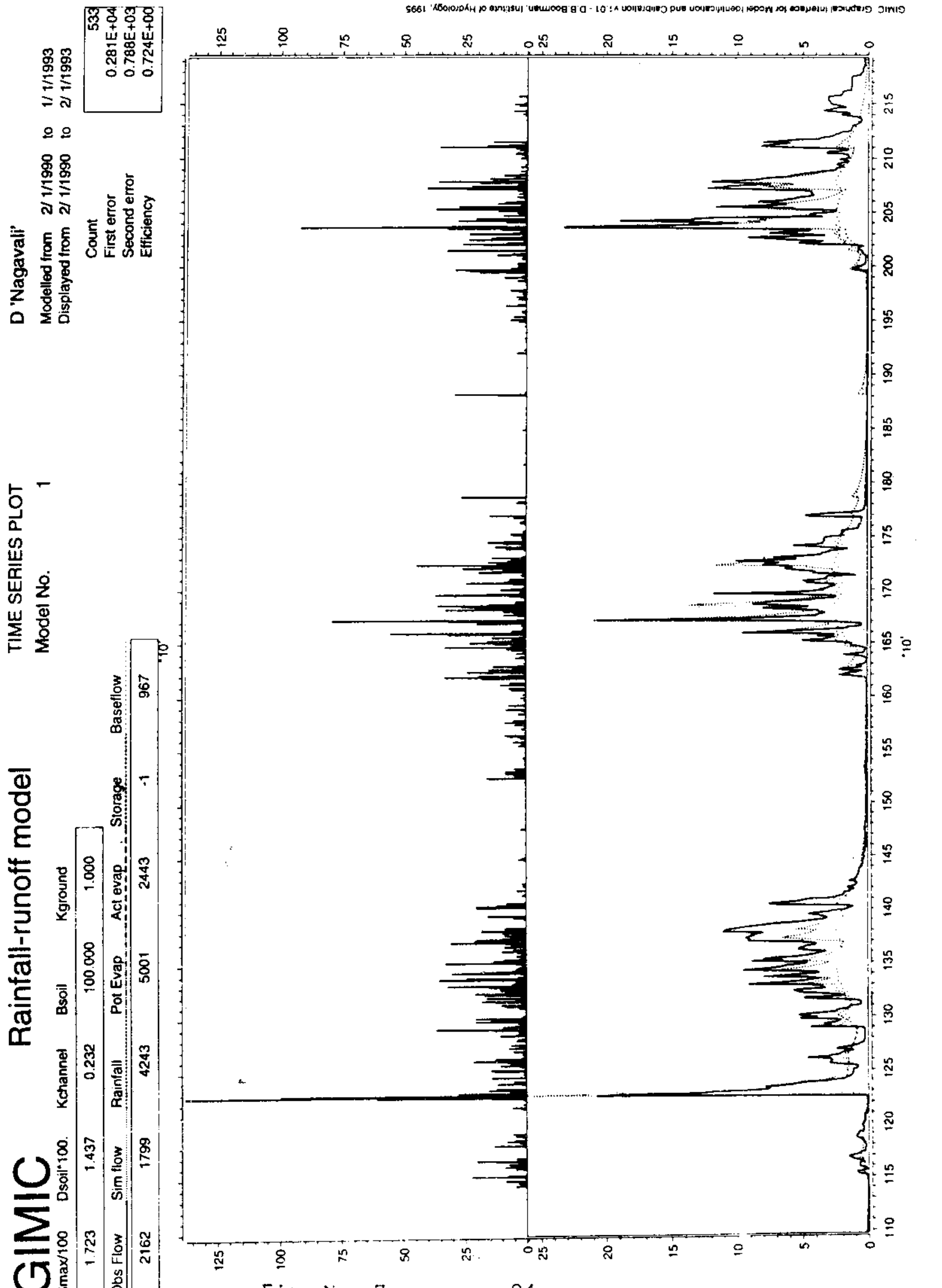

GIMIC
Rainfall-runoff model
TIME SERIES PLOT
Model No. 1
D 'Nagavali'
Modelled from 2/1/1990 to 1/1/1993
Displayed from 2/1/1990 to 2/1/1993
Smax/100 1.723
Dsoil*100. 1.437
Kchannel 0.232
Bsoil 100.000
Kground 1.000
Obs Flow 2162
Sim flow 1799
Rainfall 4243
Pot Evap 5001
Act evap 2443
Storage -1
Baseflow 967
Count 533
First error 0.281E+04
Second error 0.788E+03
Efficiency 0.724E+00
*10'
GIMIC Graphical Interface for Model Identification and Calibration v1.01 - D.B.Boorman, Institute of Hydrology, 1995

Fig. No. 7

GIMIC

Rainfall-runoff model

TIME SERIES PLOT

Model No. 2

D 'Nagavali'

S/100	K1*100	K2
1.699	0.000	0.086

Obs Flow	Sim flow	Rainfall	Pot Evap	Act evap	Storage	Baseflow
1273	1090	3344	5001	2347	75	2

Modelled from 2/ 1/1987 to 1/ 1/1990

Displayed from 1/ 1/1987 to 1/ 1/1990

Count	423
First error	0.120E+04
Second error	Inf
Efficiency	0.747E+00

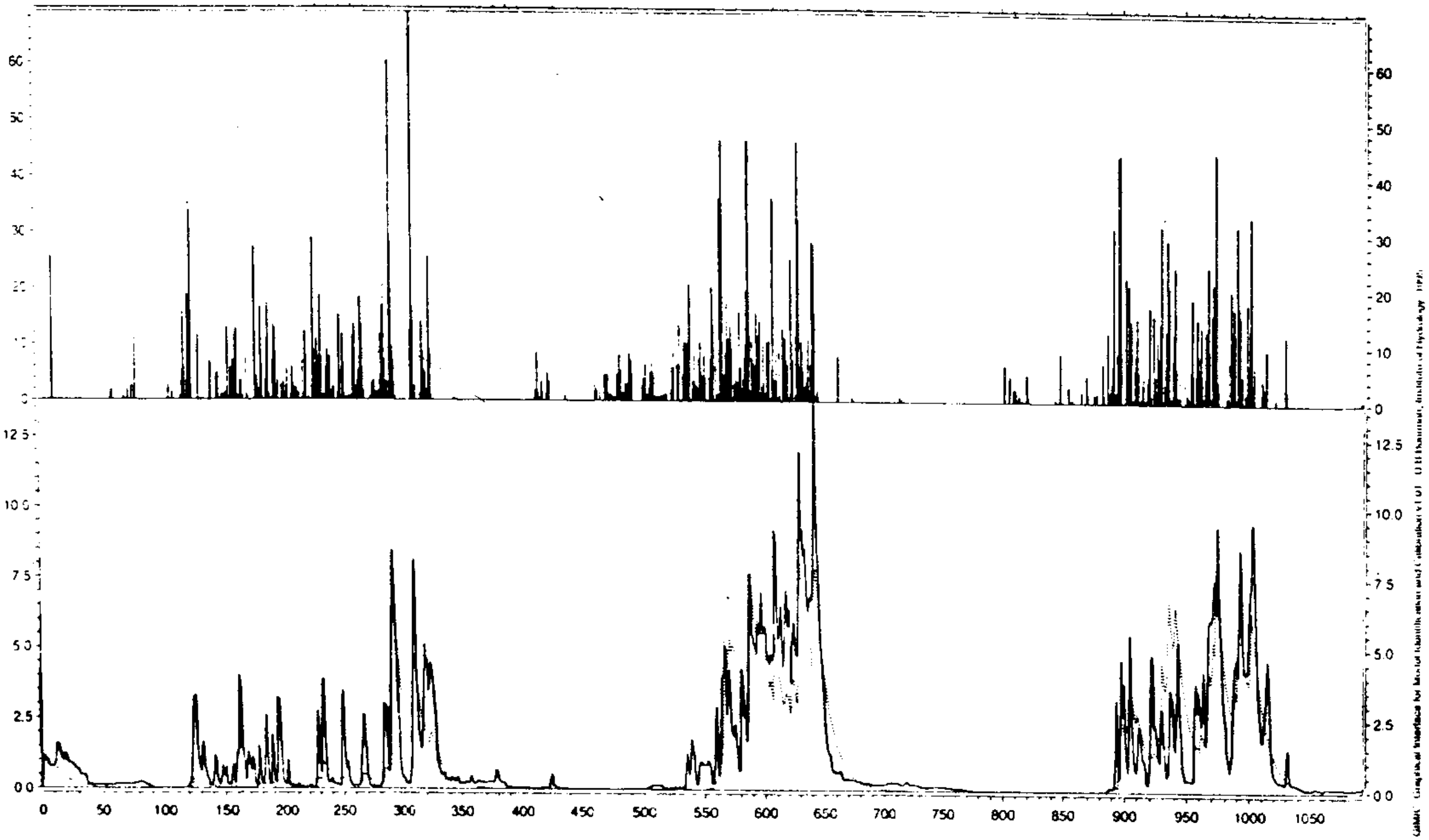
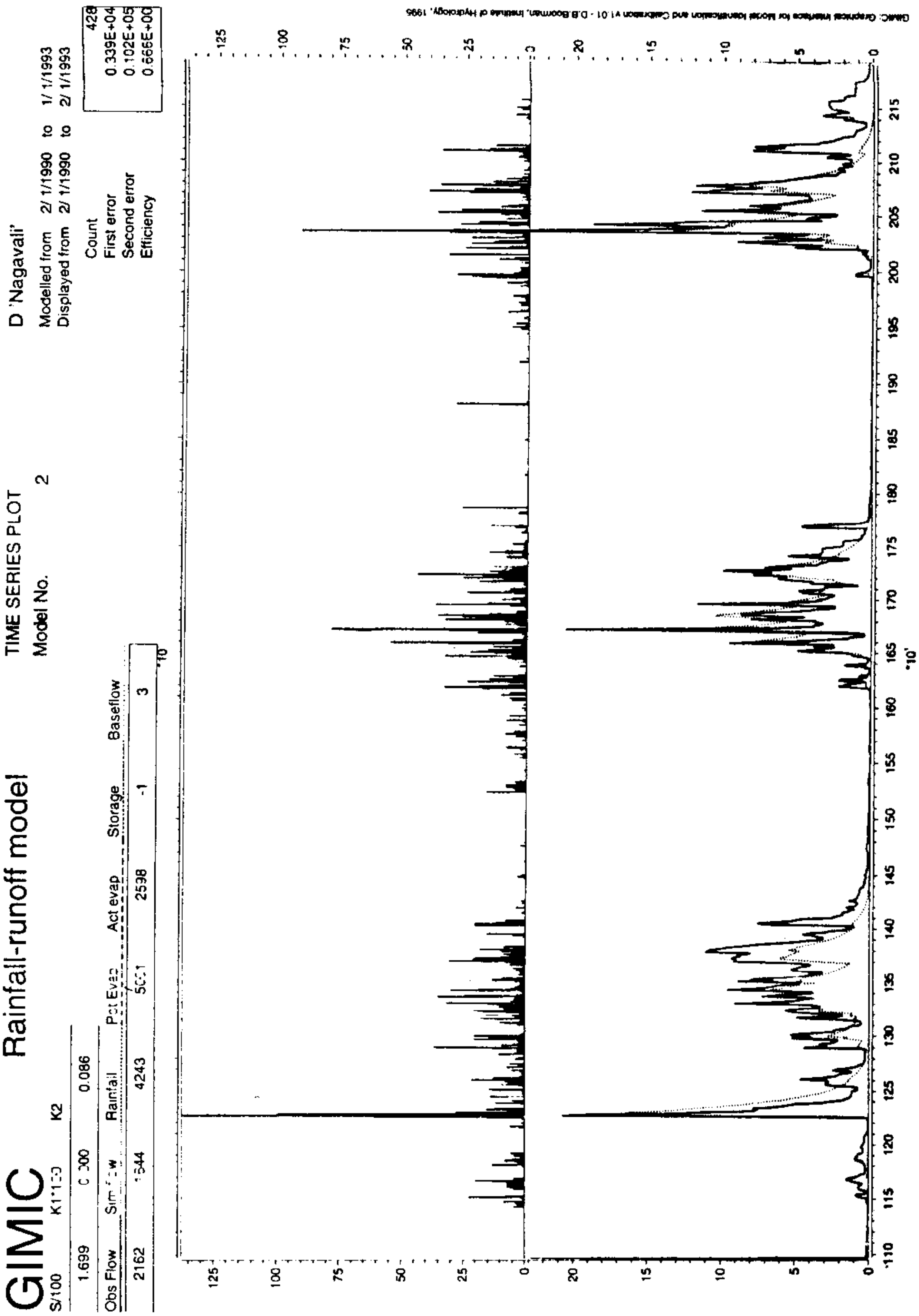


Fig. No. 8

25



GIMIC
Rainfall-runoff model
TIME SERIES PLOT
Model No. 2
D 'Nagavali'
Modelled from 2/1/1990 to 1/1/1993
Displayed from 2/1/1990 to 2/1/1993
Count 428
First error 0.339E+04
Second error 0.102E+05
Efficiency 0.666E+00
S/100 1.699
K2 0.086
Obs Flow 2162
Rainfall 4243
Act evap 2598
Storage -1
Baseflow 3

Fig. No. 9

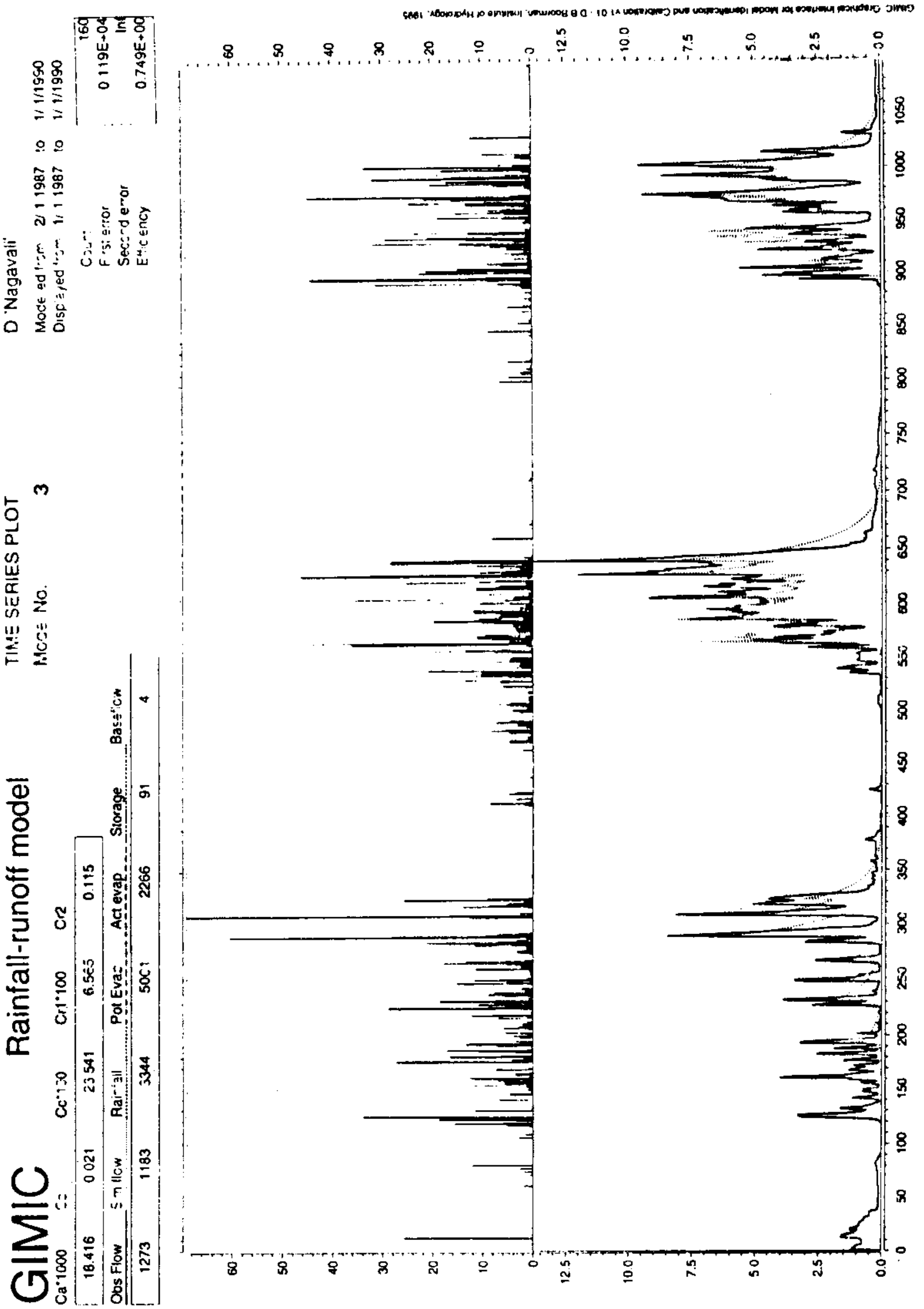

GIMIC
Rainfall-runoff model
TIME SERIES PLOT
Mode No. 3
D Nagavali
Modelled from 2/1/1987 to 1/1/1990
Displayed from 1/1/1987 to 1/1/1990
Count 160
First error 0.119E+04
Second error Inf
Efficiency 0.749E+00
Ca*1000 18.416
Cs 0.021
Cc*100 23.541
Cr1*100 6.565
Cr2 0.115
Obs Flow 1273
Sim flow 1183
Rainfall 3344
Pot Evap 5001
Act evap 2266
Storage 91
Baseflow 4
GIMIC Graphical Interface for Model Identification and Calibration v1.01 - D B Boorman, Institute of Hydrology, 1995

Fig. No. 10

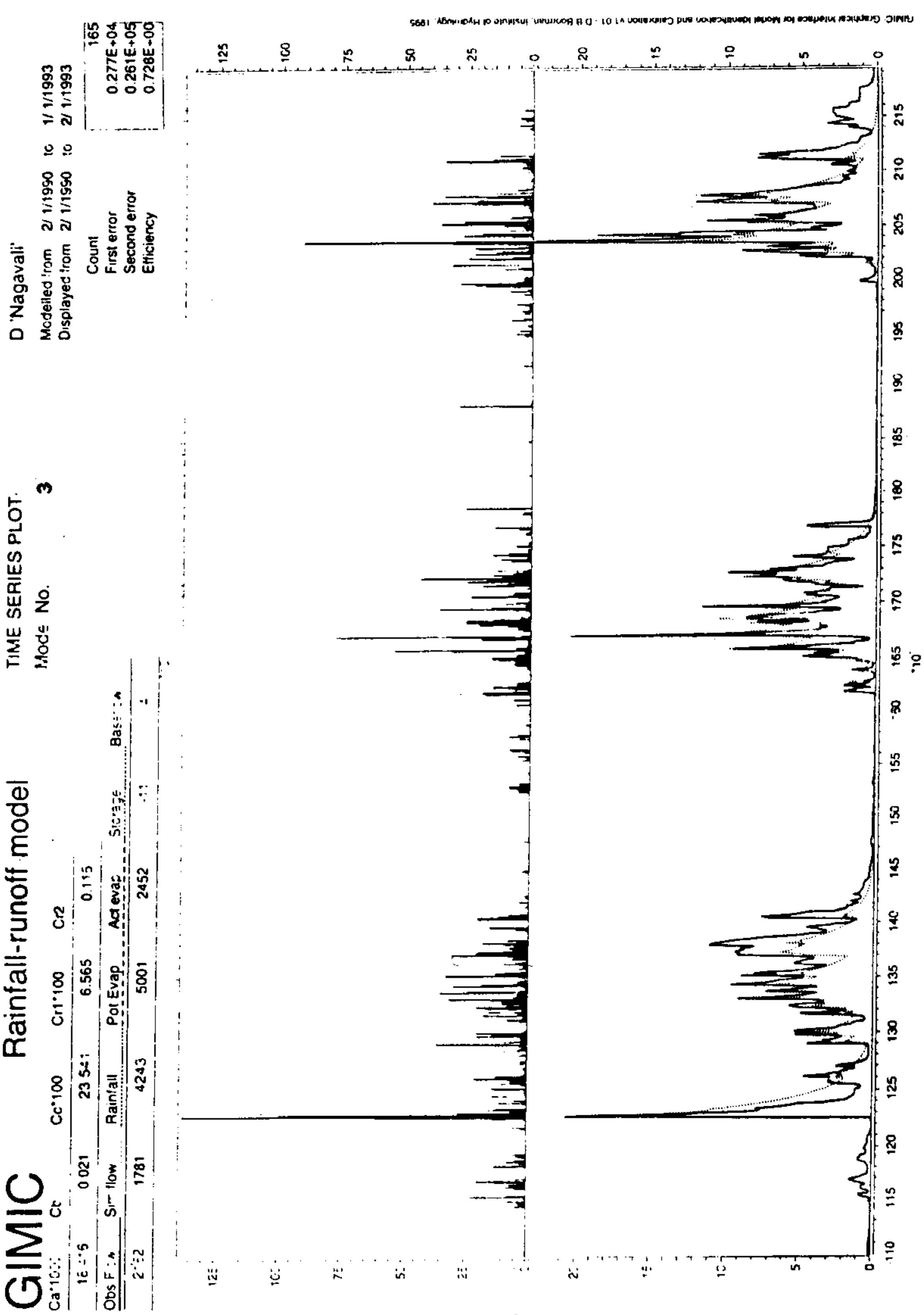

GIMIC
Rainfall-runoff model
TIME SERIES PLOT
Mode No. 3
D 'Nagavali'
Modelled from 2/1/1990 to 1/1/1993
Displayed from 2/1/1990 to 2/1/1993
Count 165
First error 0.277E+04
Second error 0.261E+05
Efficiency 0.728E+00
Ct 0.021
Cc*100 23.541
Cr1*100 6.565
Cr2 0.115
Rainfall 4243
Pot Evap 5001
Act evap 2452
Sim flow 1781

Fig. No. 11

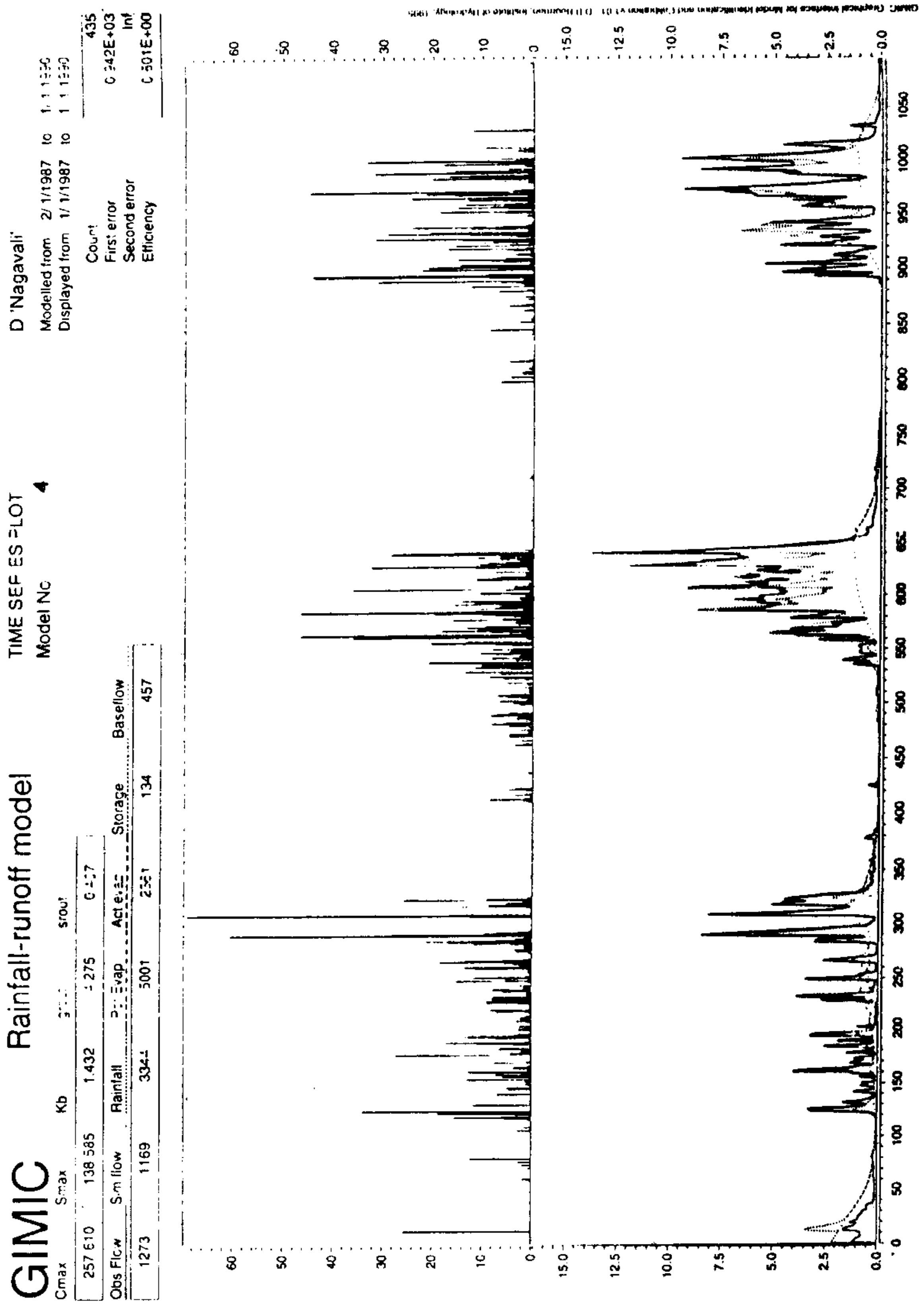

GIMIC
Rainfall-runoff model
Model No 4
D 'Nagavali'
Modelled from 2/1/1987
Displayed from 1/1/1987
Count 435
First error
Second error Inf
Efficiency
Cmax 257 610
Smax 138 585
Kb 1.432
Obs Flow 1273
Sim flow 1169
Rainfall 3344
Pot Evap 5001
Storage 134
Baseflow 457

Fig. No. 12

GIMIC

Rainfall-runoff model

TIME SERIES PLOT
Mode No 4

D 'Nagavali'
Modelled from 2/ 1/1990 to 1/ 1/1993
Displayed from 2/ 1/1990 to 2/ 1/1993

Cmax	Smax	Kb	grout	srout
257.610	138.585	1.432	4.275	0.407

Obs Flow	Sim flow	Rainfall	Pot Evap	Act evap	Storage	Baseflow
2162	1652	4243	5001	2592	0	467

Count	440
First error	0.381E+04
Second error	0.851E+03
Efficiency	0.625E+00

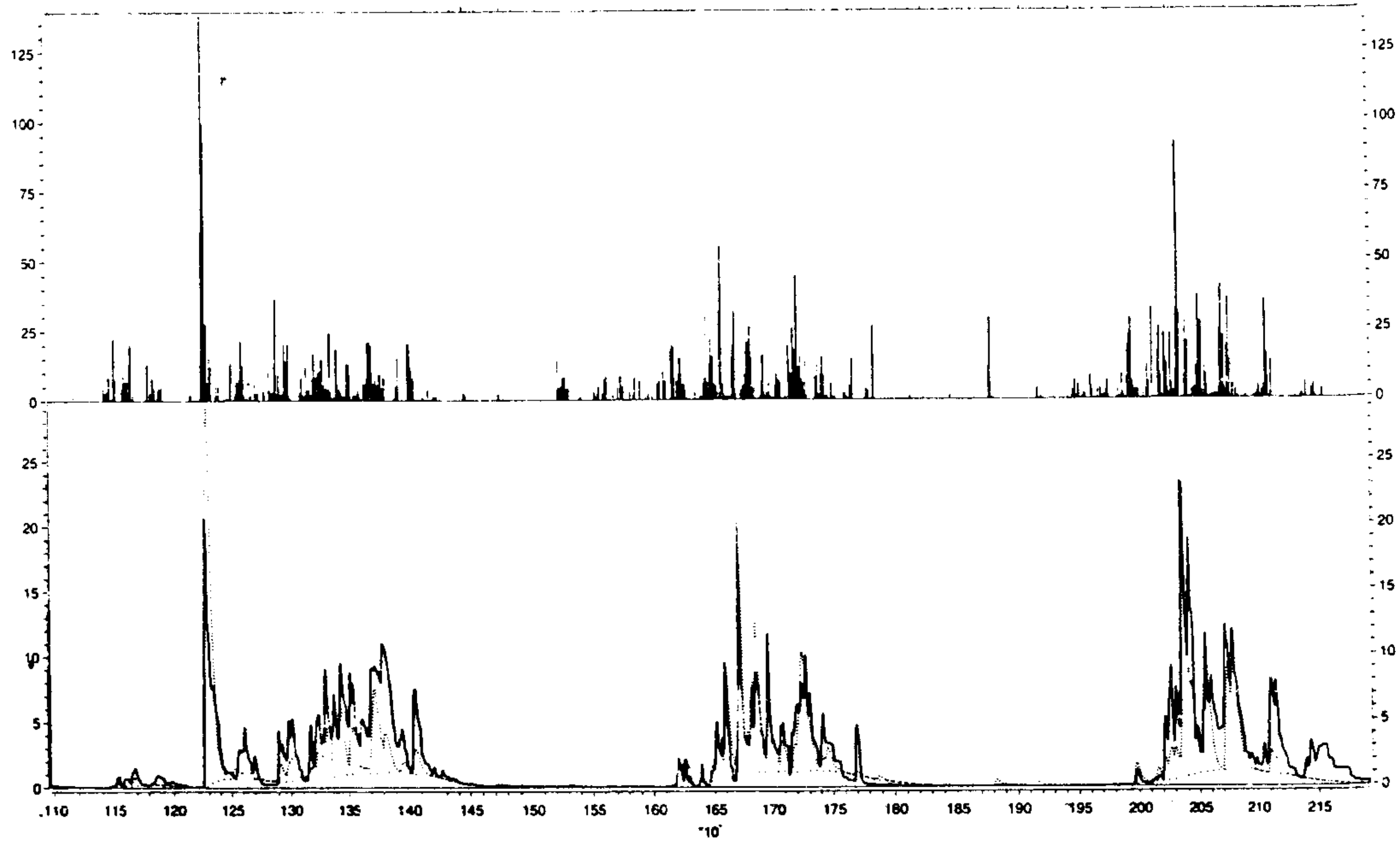
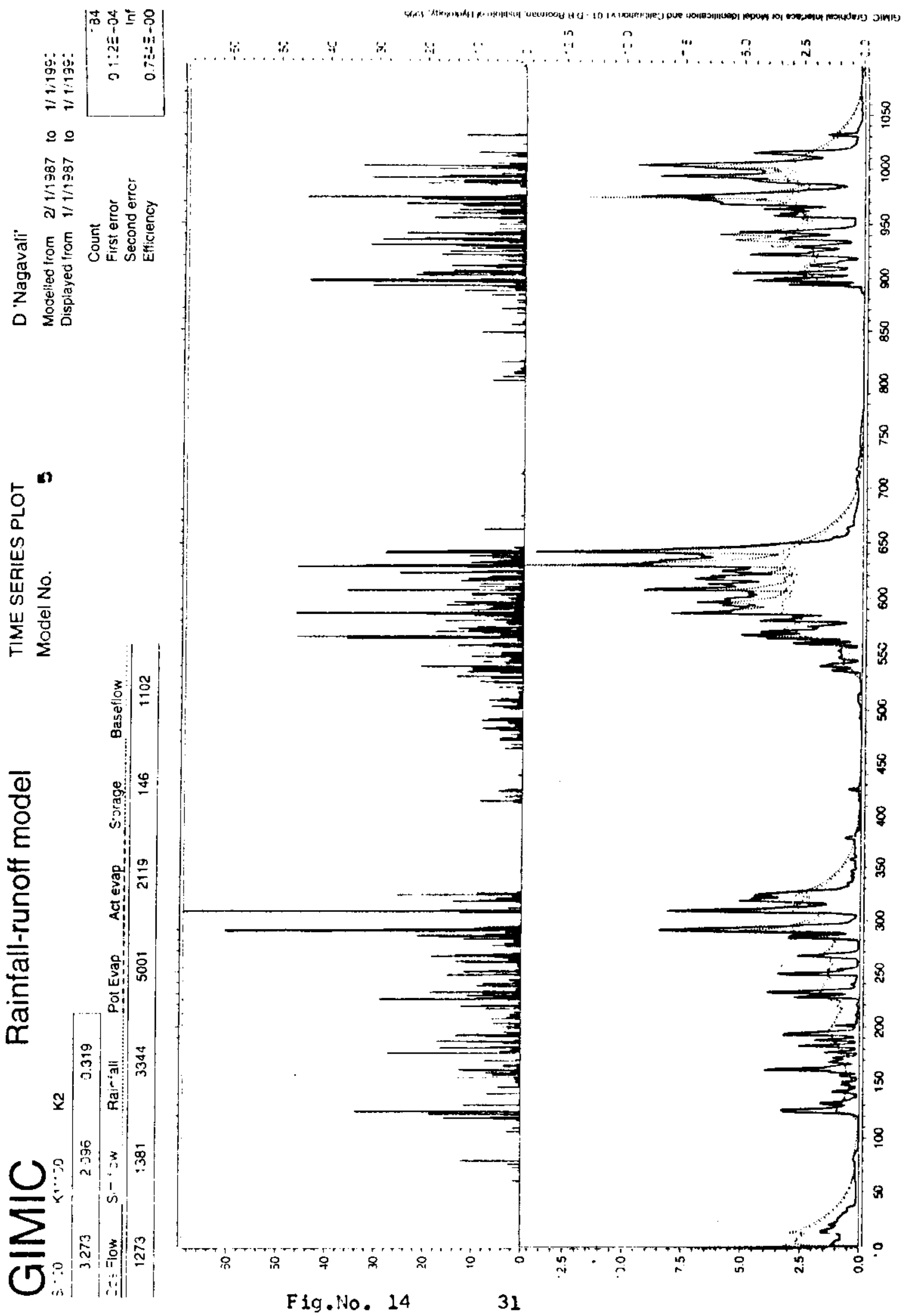


Fig.No. 13



GIMIC
Rainfall-runoff model
TIME SERIES PLOT
Model No. 5
D 'Nagavali'
Modelled from 2/1/1987 to 1/1/1991
Displayed from 1/1/1987 to 1/1/1991
K2
3.273
2.096
0.319
1273
1381
Rainfall
3344
Pot Evap
5001
Act evap
2119
Storage
146
Baseflow
1102
Count
First error
Second error
Efficiency
Inf

Fig.No. 14

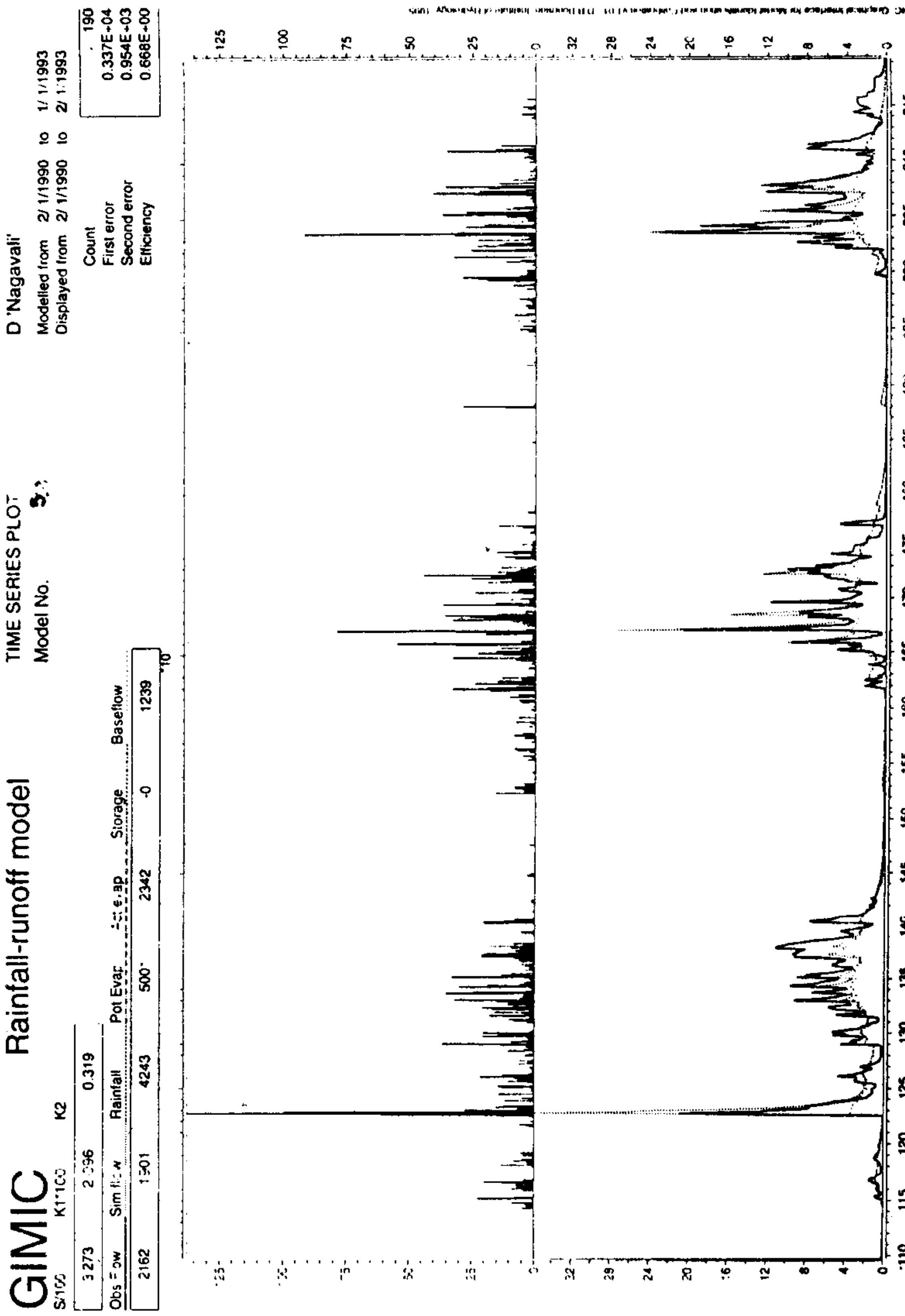

GIMIC
Rainfall-runoff model
TIME SERIES PLOT
Model No.
D 'Nagavali'
Modelled from 2/1/1990 to 1/1/1993
Displayed from 2/1/1990 to 2/1/1993
Count 190
First error 0.337E+04
Second error 0.954E+03
Efficiency 0.668E+00
S/100
K2
0.319
Rainfall
4243
Pot Evap
500
2342
Storage
-0
Baseflow
1239
2162
1501

Fig. No. 15

TABLE NO. 5 **MODEL 1**

Observed and Estimated Monthly Flows (mm) for Nagavali upto Narayanapuram

Month	1987	1988	1989	1990	1991	1992
JAN	52.9 (30.1)	7.9 (6.5)	1.7 (4.1)	1.7 (3.4)	5.0 (5.4)	4.0 (2.5)
FEB	16.2 (5.3)	3.1 (2.2)	0.5 (0.8)	2.4 (4.0)	1.5 (3.3)	4.9 (1.9)
MAR	6.3 (4.9)	1.7 (0.9)	0.5 (0.0)	14.5 (17.3)	4.9 (2.7)	6.8 (2.0)
APR	2.8 (0.1)	0.6 (0.0)	0.4 (0.0)	7.8 (10.8)	2.7 (1.7)	1.5 (1.3)
MAY	15.7 (27.3)	1.6 (2.5)	0.6 (0.0)	186.6 (141.9)	2.1 (1.1)	0.9 (1.3)
JUN	13.5 (26.4)	9.1 (13.9)	46.5 (45.3)	45.3 (52.0)	30.1 (19.7)	13.9 (7.7)
JUL	27.7 (23.1)	59.3 (58.3)	91.5 (64.2)	46.7 (63.4)	142.8 (113.7)	120.1 (176.7)
AUG	32.9 (20.3)	130.2 (161.3)	99.4 (96.8)	88.1 (118.1)	190.3 (150.1)	163.3 (214.3)
SEP	34.0 (22.2)	142.0 (194.6)	131.6 (142.3)	105.5 (164.7)	137.9 (149.4)	135.8 (164.3)
OCT	64.9 (58.9)	95.4 (90.4)	55.6 (49.6)	109.9 (206.6)	59.9 (67.5)	44.3 (100.9)
NOV	74.1 (85.4)	15.9 (8.1)	15.8 (5.4)	43.6 (69.4)	27.6 (21.9)	15.3 (62.1)
DEC	23.5 (9.3)	5.0 (7.5)	5.0 (4.8)	14.4 (12.0)	12.0 (2.6)	5.3 (24.2)
ANNUAL	364.5 (313.3)	471.8 (546.2)	449.1 (413.3)	666.5 (863.6)	616.8 (539.1)	516.1 (759.2)
% ERROR	16.3	-13.6	8.7	-22.8	14.4	-32.0

Note: Observed flows are shown within ( )

TABLE NO. 6

MODEL 2

Observed and Estimated Monthly Flows (mm) for Nagavali upto Narayanapuram

Month	1987	1988	1989	1990	1991	1992
JAN	15.8 (30.1)	0.5 (6.5)	0.0 (4.1)	0.0 (3.4)	0.1 (5.4)	0.1 (2.5)
FEB	1.4 (5.3)	0.1 (2.2)	0.0 (0.8)	0.3 (4.0)	0.0 (3.3)	0.9 (1.9)
MAR	0.2 (4.9)	0.0 (0.9)	0.0 (0.0)	1.9 (17.3)	0.4 (2.7)	1.2 (2.0)
APR	0.1 (0.1)	0.0 (0.0)	0.0 (0.0)	0.4 (10.8)	0.1 (1.7)	0.1 (1.3)
MAY	3.5 (27.3)	0.0 (2.5)	0.0 (0.0)	200.9 (141.9)	0.0 (1.1)	0.0 (1.3)
JUN	1.6 (26.4)	1.1 (13.9)	46.4 (45.3)	41.5 (52.0)	11.3 (19.7)	3.5 (7.7)
JUL	4.3 (23.1)	69.3 (58.3)	103.9 (64.2)	29.0 (63.4)	143.0 (113.7)	103.4 (176.7)
AUG	10.9 (20.3)	149.0 (161.3)	98.7 (96.8)	95.2 (118.1)	211.6 (150.1)	198.7 (214.3)
SEP	9.4 (22.2)	135.8 (194.6)	135.5 (142.3)	112.7 (164.7)	136.5 (149.4)	137.9 (164.3)
OCT	70.4 (58.9)	98.1 (90.4)	49.9 (49.6)	115.2 (206.6)	51.6 (67.5)	20.0 (100.9)
NOV	65.3 (85.4)	6.3 (8.1)	3.3 (5.4)	17.3 (69.4)	5.4 (21.9)	1.9 (62.1)
DEC	8.0 (9.3)	0.4 (7.5)	0.2 (4.8)	1.3 (12.0)	1.0 (2.6)	0.1 (24.2)
ANNUAL	190.9 (313.3)	460.6 (546.2)	437.9 (413.3)	615.7 (863.6)	561.0 (539.1)	467.8 (759.2)
% ERROR	-39.1	-15.7	6.0	-28.7	4.1	-38.4

NOTE: Observed flows are shown within

TABLE NO. 7 MODEL 3

Observed and Estimated Monthly Flows (mm) for Nagavali upto Narayanapuram

Month	1987	1988	1989	1990	1991	1992
JAN	0.1 (30.1)	2.0 (6.5)	0.2 (4.1)	0.1 (3.4)	0.6 (5.4)	0.2 (2.5)
FEB	0.0 (5.3)	0.2 (2.2)	0.0 (0.8)	0.0 (4.0)	0.1 (3.3)	0.0 (1.9)
MAR	0.0 (4.9)	0.0 (0.9)	0.0 (0.0)	0.0 (17.3)	0.0 (2.7)	0.0 (2.0)
APR	0.0 (0.1)	0.0 (0.0)	0.0 (0.0)	0.0 (10.8)	0.0 (1.7)	0.0 (1.3)
MAY	0.0 (27.3)	0.0 (2.5)	0.0 (0.0)	189.2 (141.9)	0.0 (1.1)	0.0 (1.3)
JUN	0.0 (26.4)	0.0 (13.9)	38.1 (45.3)	60.0 (52.0)	21.8 (19.7)	0.0 (7.7)
JUL	10.8 (23.1)	85.5 (58.3)	101.8 (64.2)	48.1 (63.4)	147.2 (113.7)	105.7 (176.7)
AUG	24.5 (20.3)	153.9 (161.3)	107.1 (96.8)	102.9 (118.1)	213.4 (150.1)	199.7 (214.3)
SEP	18.7 (22.2)	138.0 (194.6)	139.5 (142.3)	117.6 (164.7)	145.7 (149.4)	148.6 (164.3)
OCT	78.0 (58.9)	105.7 (90.4)	60.3 (49.6)	120.8 (206.6)	67.6 (67.5)	37.8 (100.9)
NOV	79.3 (85.4)	12.8 (8.1)	7.3 (5.4)	30.9 (69.4)	9.3 (21.9)	6.6 (62.1)
DEC	16.4 (9.3)	1.7 (7.5)	1.0 (4.8)	4.6 (12.0)	1.2 (2.6)	0.9 (24.2)
ANNUAL	227.8 (313.3)	499.8 (546.2)	455.3 (413.3)	674.2 (863.6)	606.9 (539.1)	499.5 (759.2)
% ERROR	-27.3	-8.5	10.2	-21.9	12.6	-34.2

Note: Observed flows are shown within

TABLE NO. 8 **MODEL 4**

Observed and Estimated Monthly Flows (mm) for Nagavali upto Narayanapuram

Month	1987	1988	1989	1990	1991	1992
JAN	59.5 (30.1)	3.9 (6.5)	1.1 (4.1)	1.0 (3.4)	3.0 (5.4)	1.9 (2.5)
FEB	19.1 (5.3)	1.5 (2.2)	0.3 (0.8)	2.1 (4.0)	0.8 (3.3)	2.8 (1.9)
MAR	6.7 (4.9)	1.3 (0.9)	0.6 (0.0)	10.0 (17.3)	3.2 (2.7)	2.3 (2.0)
APR	2.5 (0.1)	1.5 (0.0)	0.8 (0.0)	4.5 (10.8)	2.7 (1.7)	0.7 (1.3)
MAY	10.7 (27.3)	3.9 (2.5)	0.8 (0.0)	203.4 (141.9)	2.5 (1.1)	1.5 (1.3)
JUN	8.1 (26.4)	9.7 (13.9)	54.1 (45.3)	32.6 (52.0)	27.0 (19.7)	12.8 (7.7)
JUL	16.8 (23.1)	65.3 (58.3)	94.6 (64.2)	35.4 (63.4)	139.5 (113.7)	120.5 (176.7)
AUG	22.8 (20.3)	125.7 (161.3)	91.1 (96.8)	79.9 (118.1)	181.3 (150.1)	145.7 (214.3)
SEP	22.0 (22.2)	136.1 (194.6)	125.2 (142.3)	89.9 (164.7)	131.4 (149.4)	129.0 (164.3)
OCT	49.7 (58.9)	85.9 (90.4)	42.3 (49.6)	101.4 (206.6)	51.8 (67.5)	38.3 (100.9)
NOV	55.8 (85.4)	15.3 (8.1)	12.9 (5.4)	39.0 (69.4)	21.9 (21.9)	11.2 (62.1)
DEC	13.7 (9.3)	4.3 (7.5)	3.6 (4.8)	10.6 (12.0)	6.9 (2.6)	3.5 (24.2)
ANNUAL	287.4 (313.3)	454.4 (546.2)	427.4 (413.3)	609.8 (863.6)	572.0 (539.1)	470.2 (759.2)
% ERROR	-8.3	-16.8	3.4	-29.4	6.1	-38.1

Note: Observed flows are shown within ( )

TABLE NO. 9 **MODEL 5**

Observed and Estimated Monthly Flows (mm) for Nagavali upto Narayanapuram

Month	1987	1988	1989	1990	1991	1992
JAN	65.4 (30.1)	7.4 (6.5)	1.2 (4.1)	1.1 (3.4)	4.1 (5.4)	3.4 (2.5)
FEB	18.4 (5.3)	2.6 (2.2)	0.3 (0.8)	2.1 (4.0)	1.0 (3.3)	4.3 (1.9)
MAR	6.0 (4.9)	1.6 (0.9)	0.4 (0.0)	18.0 (17.3)	5.8 (2.7)	8.7 (2.0)
APR	2.8 (0.1)	0.5 (0.0)	0.4 (0.0)	9.7 (10.8)	3.2 (1.7)	1.7 (1.3)
MAY	18.5 (27.3)	2.1 (2.5)	0.9 (0.0)	200.8 (141.9)	2.5 (1.1)	0.9 (1.3)
JUN	15.6 (26.4)	10.8 (13.9)	49.7 (45.3)	53.0 (52.0)	35.6 (19.7)	15.7 (7.7)
JUL	33.7 (23.1)	65.0 (58.3)	98.7 (64.2)	49.8 (63.4)	157.2 (113.7)	137.6 (176.7)
AUG	37.8 (20.3)	135.5 (161.3)	106.9 (96.8)	89.2 (118.1)	185.2 (150.1)	160.9 (214.3)
SEP	39.7 (22.2)	144.7 (194.6)	129.8 (142.3)	110.0 (164.7)	139.6 (149.4)	139.3 (164.3)
OCT	67.5 (58.9)	102.1 (90.4)	64.7 (49.6)	111.2 (206.6)	70.4 (67.5)	49.7 (100.9)
NOV	79.4 (85.4)	17.6 (8.1)	17.3 (5.4)	51.0 (69.4)	29.9 (21.9)	16.4 (62.1)
DEC	27.7 (9.3)	4.4 (7.5)	4.3 (4.8)	14.8 (12.0)	12.5 (2.6)	4.6 (24.2)
ANNUAL	412.5 (313.3)	494.3 (546.2)	474.6 (413.3)	710.7 (863.6)	647.0 (539.1)	543.2 (759.2)
% ERROR	31.7	-9.5	14.8	-17.7	20.0	-28.5

NOTE: Observed flows are shown within ( )

5.0 Conclusions & Recommendations:

Performance of Institute of Hydrology's rainfall runoff model HYRROM for modelling the daily flow of the rivers of India namely Nagavali is assessed for the first time in the study. HYRROM is PC based requiring minimal data, easy to run and performs reasonably well in modeling daily runoff provided the data supplied is consistent. Being a 9 parameter model it has certain limitations in accounting for certain processes of hydrologic cycle properly. Higher efficiencies resulted from the study indicate that even simple models like HYRROM can simulate the flows reasonably well.

The utility of the Graphical Interface for Model Identification and Calibration GIMIC's role as a tool in model testing and development is utilised for the first time in the study in evaluating the performance of five simple conceptual models in modelling the daily flows in river Nagavali. Different objective and subjective criteria that are available with GIMIC to give on screen graphical displays suggest how the model under testing is performing. This is the assistance a modeller is definitely in need of while testing or developing a model and to fine tune it. Out of the five models that are tested the performance of M-4 based on Bob Moore's Probability distributed method and having 5 parameters is very satisifactory in simulating the daily flows of both the basin. It performed equally well with HYRROM. M-5 with 3 parameters also did well in modelling the flows.

It is to be remembered that efforts are to be made to improve the quality of the data like rainfall and flow that is basic requirement in conducting such studies so that they are consistent. Priorities are to be given for proper data collection, processing and analysis at the preliminary stage of recording the data.

It is recommended that some more catchments are to be modelled for daily runoff in order to further assess the performance of HYRROM in modelling daily rainfall runoff process before making a general conclusion on it's applicability to model flows in Indian rivers.

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ANNEXURE : I

LIST OF COMMANDS AVAILABLE WITH GIMIC

Bn	Swap to best set of Parameters
C n xx.xx	Change parameter n to xx.xx
D	Distribution display mode
E n xx.xx	Excedence threshold for nth display
F 1	Plot display from point (day) 1
G	Double mass curve display mode
H	Produce hardcopy of the plot (a file POST is written)
I a 1	Ignore 1 points (days) at start (if a=s) or at end (if a=e) in medelling calculations
j dd mm yyyy	To get day number for date dd/mm/yyyy
J 1	To get for a day number 1
K	Scatter graph display mode
L 1	Plot display upto 1 points (days)
M	List maximum and minimum parameter values
N	Read new data sets
O	Optimise error function e in m iterations
P a n	Play (fix if a=f or vary if a=v) parameter n
QQ	quit GIMIC
R	Rescale or refresh plot
S n xx.xx yy.yy m	Step parameter n from xx.xx to yy.yy in m steps
T	Time series display mode (Default mode)
U f 1 p	Output monthly totals from day f to day 1 for p hydrological processes (written to file mon.out)
W a	Write period of graph display if a=D period modelled if a=M
X n 1 1...	No. of graph plots n for time display mode followed by plot in which a process is to be shown (Default is four plots)
Y	Seasonal (Year) display mode
Z	Zero the counter
?	Display the list of commands of GIMIC

Description of Models used with GIMIC

MODEL 1:

This is one version of the probability-distributed model with the non-linear store like model 4 and is devised at IH as part of testing GIMIC. It is a combination of model 4 and 5. It has two separate stores; one is a channel store S1 for excess rainfall and another groundwater store S2 for the drainage but both have the same time constant and are routed separately unlike model 4.

The model has five parameters: the average maximum amount of water that can be held in storage over the whole basin 'smax '; a soil drainage coefficient 'Dsoil '; a groundwater routing coefficient 'Kground '; a channel routing coefficient 'Kchannel '; the degree of spatial heterogeneity 'Bsoil ' the model works through the accounting procedure in a much similar way as model 4 except for that in model 4 evaporation is a Willmot's non-linear function. In this model, like in model 5 actual evaporation is considered equal to potential evaporation if rainfall is more than potential evaporation or else it is equal to rain fall and residual evaporation is fulfilled from soil store by arriving at an evaporation factor which is a fraction of current store to the maximum store with limits of zero and one. The model works through the accounting procedure in the following stages:

i. Rainfall r is first subjected to evaporation pe at potential rate.

   a. If r > pe, actual evaporation ae is equal to pe and residual evaporation will be zero.

   b. If r < pe, actual evaporation ae is equal to r and residual evaporation is

$$re = pe - r$$

$$r = 0.0$$

ii. There will be drainage dr from soil store st, which is

$$st = 0.95 * smax$$

$$dr = kl * st$$

iii. Residual evaporation is at reduced rate from soil store as described above and depends on evaporation factor ef which limits between zero and one.

$$ef = st / smax$$

$$re = re * ef$$

iv. Changes in soil store are accounted for excess ex.

$$st = st - dr - re$$

$$ex = 0.0$$

$$csmax = (smax - st) * (b+1)$$

If r > 0.0, then

$$css = r$$

If css < csmax then $\Delta s = (smax - st)*(1-(1-css/csmax)^{(b+1)}$

or else, $\Delta s = smax-st$

$$ex = r - \Delta s$$

$$st = st + \Delta s$$

If store is full it will be added to excess

v. Actual evaporation gets updated by residual evportion and excess water from soil is added to channel store s1. Drainage from soil is added to groundwater store s2 and both the stores are routed for q1 and q2, and outflow q is arrived at as below:

$$q1 = k1 * s1$$

$$q2 = k2 * s2$$

$$q = q1 + q2$$

Model 2 is described along with Model 5.

Model 3:

Model 3 uses a soil moisture deficit with only a lower bound, rather than with two bounds. Precipitation is added to the soil decreasing the deficit. Evaporation and subsurface flow occur from the soil increasing the deficit. If the soil becomes saturated the excess precipitation becomes overland flow. The subsurface flow and overland flow are summed and routed through a linear reservoir to become the runoff at the outlet. The model has five parameters: an evaporation coefficient 'Ca '; Subsurface flow coefficients 'Cb ' and 'Cc ' and routing coefficients 'Cr1 ' and 'Cr2 '. The model works through the accounting procedure in the following stages:

i. Determine the soil moisture deficit, smd (>0.0) after the precipitation p.

$$smd_t = smd_{t-1} - p_t$$

where t and t-1 refer to the present and previous days respectively.

ii. Determine the overland flow, Qo. If the soil moisture deficit is satisfied, the excess rainfall becomes overland flow and soil moisture deficit is reset to zero.

$$Qo_t = -smd_t$$

$$smd_t = 0.0$$

iii. Determine the subsurface flow from the soil, Qi. Subsurface flow depends on the soil moisture deficit and also modifies it.

$$Qi_t = Cb * e^{(-Cc * smd_t)}$$

$$smd_t = smd_t + Qi_t$$

iv. Determine the evapotranspiration from the soil, AE. The proportion of PE that is satisfied depends on the soil moisture deficit and again modifies the deficit.

$$AE_t = PE_t * e^{(-Ca * smd_t)}$$

$$smd_t = smd_t + AE_t$$

v. Finally, add the subsurface flow and overland flow and route through a linear reservoir to calculate the runoff at outlet.

$$Q_t = Q_{t-1} + Cr1 * (Qo_{t-1} + Qi_{t-1} - Q_{t-1}) + Cr2 * (Qo_t - Qo_{t-1} + Qi_t - Qi_{t-1})$$

Model 4:

Model 4 is one form of a probability-distributed model developed by Moore (1985) with a soil moisture store of a capacity varying across the basin and a groundwater store. The model is being widely used in flood-forecasting. The distribution of the soil moisture capacity, c, is represented by the reflected power (or pareto) distribution.

$$F(c) = 1-(1- c / cmax)^b \qquad \text{for } 0 \leq c \leq cmax$$

where cmax is the maximum storage capacity at any point within the basin and b is a dimensionless parameter which defines the degree of spatial heterogeneity. The maximum amount of water that can be held in storage in the basin, smax, for the reflected power distribution is

$$smax = \int_0^{cmax} (1 - F(c)) dc = cmax / (b+1)$$

In the model precipitation is added to the soil moisture store, and excess precipitation becomes direct runoff which is routed through two cascading linear reservoirs. Evapotranspiration from the soil moisture store occurs at a rate proportional to store content, as does drainage from the soil moisture store to the groundwater store. Baseflow occurs from the groundwater store and is added to the direct runoff to become discharge.

The model has five parameters: the maximum storage capacity at any point with in the basin 'cmax '; the average maximum amount of water that can be held in storage over the whole basin 'smax '; a soil drainage coefficient 'Kb '; a groundwater discharge coefficient 'Grout ' and a channel routing coefficient 'Srout '. cmax and smax together determine the degree of spatial heterogeneity b. The model works through the accounting procedure in the following stages:

i. Determine the evapotranspiration from the soil moisture store, AE. AE is a function of the potential evapotranspiration, PE, and the soil moisture content, s, at the end of previous time step:

$$AE_t = (1 - e^{(-6.68 * s_{t-1} / smax)}) * PE_t$$

where t and t-1 refer to the present and previous days respectively. This particular actual evaporation function is taken from Wilmott et.al. (1985) and assumes that the rate of decline of actual evapotranspiration increases as soil moisture deficit increases (the coefficient of 6.68 is there to ensure that AE $\simeq$ PE when s = smax, though the actual value of the coefficient is not that important in practice).

ii. Determine the drainage from the soil moisture store to the groundwater store, Qi. Qi is also a function of the soil moisture content at the end of the previous time step:

$$Qi_t = Kb * s_{t-1} / smax$$

iii. Determine the direct runoff, Qo.

(a) If the precipitation p is less than that going to AE and Qi, there is no direct runoff.

$$Qo_t = 0.0$$

$$s_t = s_{t-1} + (p_t - AE_t - Qi_t)$$

(b) If the precipitation is greater than that going to AE and Qi direct runoff does occur. The critical capacity , Cc, at the end of the previous time step, below which all the soil moisture goes to storage is calculated from the reflected power distribution.

$$s_{t-1} = \int_0^{Cc_{t-1}} \{1 - F(c)\}\, dc = \int_0^{Cc_{t-1}} \{ (1-c/cmax)^b \}\, dc$$

$$= smax\ \{1-(1-Cc_{t-1} / cmax)^{b+1}\}$$

which yields

$$Cc_{t-1} = cmax * \{1-(1-s_{t-1} / smax)^{1/b+1}\}$$

therefore the critical capacity at the end of the present time step is

$$Cc_{t-1} = Cc_{t-1} + (p_t - AE_t - Qi_t)$$

(i) If Cc is less than cmax i.e., the basin is unsaturated the direct runoff is given by

$$Qo_t = (p_t - AE_t - Qi_t) - smax * \{(1-Cc_{t-1}/cmax)^{b+1} - (1- Cc_t/cmax)^{b+1}\}$$

$$s_t = s_{t-1} + p_t - AE_t - Qi_t - Qo_t$$

(ii) If Cc is greater than cmax i.e., the entire basin has become saturated during day, the direct runoff is given by

$$Qo_t = (p_t - AE_t - Qi_t) - (smax - s_{t-1})$$

$$s_t = smax$$

iv. Determine the baseflow from the groundwater store, Qb. Qb is a function of the groundwater store content, gs, at the end of previous time step.

$$Qb_t = Grout * gs_{t-1}/1000.0$$

$$gs_t = gs_{t-1} + Qi_t - Qb_t$$

v. Route the direct runoff through two cascading linear reservoirs. The reservoirs have the same routing coefficient, Srout.

For the 1st reservoir:

$$Q1_t = Srout * (s1_{t-1} + Qo_t)$$
$$s1_t = s1_{t-1} + Qo_t - Q1_t$$

where s1 is the content of 1st reservoir and Q1 the outflow from the 1st reservoir.

For the 2nd reservoir:

$$Q2_t = Srout * (s2_{t-1} + Q1_t)$$
$$s2_t = s2_{t-1} + Q1_t - Q2_t$$

where s2 is the content of 2nd reservoir and Q2 is the outflow from the 2nd reservoir.

vi. Finally the outflow from the second linear reservoir is combined with the baseflow to give the catchment outflow, Q:

$$Q_t = Q2_t + Qb_t$$

MODEL 2 & 5:

These models use the concept of contributing areas with a range of soil moisture store capacities from zero to some maximum. The total contents of all these stores translate to a level in the largest store. Precipitation is immediately subjected to evapotranspiration at he potential rate, and the remaining rainfall is added to the soil moisture stores. Remaining rainfall is also added to a linear channel storage at a rate proportional to the content of the soil moisture stores. Unsatisfied potential evaporation and subsurface flow from the soil moisture stores again are proportional to store content. The subsurface flow is added to the channel storage. The catchment outflow from the channel storage is also proportional to the store content.

The models have three parameters like the capacity of the largest soil moisture store 'smax '; a subsurface flow coefficient 'K1 '; and a routing coefficient 'K2'. The difference between the two models lies in the way the subsurface flow from the soil moisture stores is determined. Model 2 has a non-linear dependence on soil moisture, whilst in model 5 the relationship is assumed to be linear. The models work through the accounting procedure in the following stages:

i. Translate the total contents of all the soil moisture stores, scap, to a level, sl, in the largest store.

$$sl_t = smax - 2 * scap_{t-1}$$

where t and t-1 refer to the present and previous days respectively.

ii. Determine the evapotranspiration, AE, from the rainfall, p

(a) If the rainfall is greater than PE:

$$AE_t = PE_t$$
$$RE_t = 0.0$$
$$p_t = p_t - PE_t$$

(b) If the rainfall is less than PE, then

$$AE_t = p_t$$
$$RE_t = PE_t - p_t$$
$$p_t = 0.0$$

where RE is the residual evapotranspiration.

iii. Add the remaining rainfall to the soil moisture stores and determine the excess, Qo.

(a) If the soil is saturated all the rainfall is excess.

$$Qo_t = p_t$$

(b) If the soil is unsaturated and the the rainfall is greater than the deficit the soil will become saturated reducing the excess.

$$Qo_t = p_t - 0.5 * sl_t$$

(c) If the soil is unsaturated but rainfall is less than the deficit, the soil will remain unsaturated, reducing the excess further.

$$Qo_t = 0.5 * p_t^2 / sl_t$$

iv. Add the excess to the channel storage, cs.

$$cs_t = cs_{t-1} + Qo_t$$

v. Determine the total content of all the soil moisture stores.

$$scap_t = scap_{t-1} + (p_t - Qo_t)$$

vi. Satisfy the residual evapotranspiration from the soil moisture stores. Evapotranspiration from the soil moisture stores occurs at a rate proportional to the content.

$$RE_t = RE_t * (smax - sl_t) / smax$$

$$AE_t = AE_t + RE_t$$

$$scap_t = scap_t - RE_t$$

vii. Determine the subsurface flow, Qi, from the soil moisture stores. Subsurface flow from the soil moisture stores occurs at a rate proportional to content. In model 2 it is proportional to the square of the contents.

$$Qi_t = K1 * scap_t^2$$

But in model 5 it is linear.

$$Qi_t = K1 * scap_t$$

(a) If the soil moisture store capacity is greater than the subsurface flow, then

$$scap_t = scap_t - Qi_t$$

(b) If the soil moisture store capacity is less than the subsurface flow, then

$$Qi_t = scap_t$$
$$scap_t = 0.0$$

viii. Add the subsurface flow to the channel storage.

$$cs_t = cs_t + Qi_t$$

ix. Finally, route the channel storage to calculate the catchment outflow, Q. The outflow from the channel storage occurs at a rate proportional to the content.

$$Q_t = K2 * cs_t$$

(a) If the channel storage is greater than the out flow then

$$cs_t = cs_t - Q_t$$

(b) If the channel storage is less than the outflow, then

$$Q_t = cs_t$$

$$cs_t = 0.0$$

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