RAINFALL RUNOFF MODELLING USING A CONCEPTUAL MODEL

1.0 INTRODUCTION

The conceptual model approach to rainfall runoff modelling lies intermediate between physically based models and black box models. Generally the term 'conceptual' is used to describe models which rely on simple arrangement of a relatively small number (say 3 to 6) of interlinked conceptual elements, each representing a segment of land phase of hydrologic cycle. The most commonly used element in a conceptual model is a storage. Each of these unequal sized storage usually has one input and several outputs and is used to represent various catchment storages like detention, soil moisture etc. Linear reservoirs and channels are used for routing purposes. The modelling basically consists of a set of rules which govern moisture flow from one element to another. Since this is a non-iterative accounting procedure, these models are computationally very efficient and pose very small computational requirements in terms of CPU time and memory. Many of these type of models can be easily run on a personal computer.

The conceptual models were initially developed to model small homogeneous areas. However, they have been successfully applied to basins having wide variations in topography and vegetations and catchment area of the order of thousands of sq. km. The input data requirements for these models are also quite modest and can be easily met with, particularly in the Indian context. The Stanford Watershed model and the Tank model are two well known conceptual models. Ciriani et al (1977) and Blackie & Eeles (1985) provide excellent discussion on philosophy and applications of conceptual models.

2.0 DESCRIPTION OF PROPOSED MODEL

In the proposed model the catchment is represented with the help of three storages. The first storage, termed as surface storage, represents the water stored on the surface and top few cms of soil of the catchment. It has a maximum storage capacity given by S_{max}. The second storage represents the catchment soil moisture storage and has a maximum water holding capacity given by C_{max}. The third storage represents the ground water zone.

The rainfall is input to the surface storage. The water leaves this storage through evaporation, infiltration or overland flow. The moisture content of this storage at any time is denoted by SURF. So long as SURF > E_p*dt (E_p is potential evaporation in mm/hr), the actual evapotranspiration (ET) is at the potential rate else ET takes place from the lower storage at some lesser rate. If SURF = 0, the ET takes place from the soil storage at a rate E_a(mm/hr) given by

$$E_a = C_{soil}/C_{max} * E_p \qquad ...(1)$$

and $$C_{soil} = C_{soil} - E_p*dt$$

If SURF < E_p*dt, the actual ET is SURF+E_a*dt where E_a is calculated using eq. (1) and dt is length of computation interval in hour. The maximum value of E_a is E_p. The approach similar to eq. (1) has been used in some other conceptual rainfall runoff models and is also given in texts such as Haan (1982).

The infiltration of water from the surface storage to the soil storage takes place at the rate INF :

$$\begin{aligned} INF &= (1 - C_{soil}/C_{max}) * F_{inf} \qquad \text{if SURF} > 0 \\ &= 0 \qquad \text{otherwise} \end{aligned} \qquad ...(2)$$

and $C_{soil} = C_{soil} + INF*dt$

where F_{inf} is a factor(mm/hr) controlling the infiltration rate. It may be noted that when $C_{soil}=C_{max}$, INF will be zero. One may visualize that in this event the surface and the soil moisture storages have merged and the downward movement of moisture is computed using eq. (5) given below.

If at any instant SURF > S_{max}, the excess water over S_{max} flows as overland flow (OF). The OF is routed through a linear reservoir LR1 with time constant K_1.

The water which infiltrates from the surface storage enters the soil storage. The outflow from this storage can take place through evapotranspiration losses, interflow or recharge to the ground water zone.

If the contents of soil storage are greater than a threshold denoted by FC, moisture flows out of it as interflow and recharge to groundwater. The excess moisture available for these two is :

$$Exw = (C_{soil}/C_{max} - FC)*Ewf \quad \text{if } C_{soil}/C_{max} > FC \qquad ...(3)$$

and $C_{soil} = C_{soil} - Exw*dt$

where Ewf is a factor(mm/hr) controlling the volume of excess water. The interflow rate is given as :

$$IntF = Exw * C_{int} \qquad ...(4)$$

and rate of recharge to groundwater is

$$RECH = Exw * (1 - Cint) \qquad ...(5)$$

where Cint is a dimensionless coefficient which controls how much of the excess moisture goes as recharge and how much as interflow. The interflow is routed through a linear reservoir LR2 with time constant Ki.

The ground water zone behaves as a linear reservoir whose time constant is KG. The moisture comes out of it as the baseflow (BF).

The flow coming out of the reservoirs LR1, LR2 and LR3 is combined and then routed through a linear reservoir, LR4, to yield the discharge from the catchment, denoted by TF. The box diagram of the model structure is given in Fig. 1.

3.0 INPUT REQUIREMENTS

The input to the model consists of the values of various model parameters, the period of simulation, and the time step size. Initial contents of various storages are also specified. The rainfall and potential evaporation data for the period of simulation are also given as input.

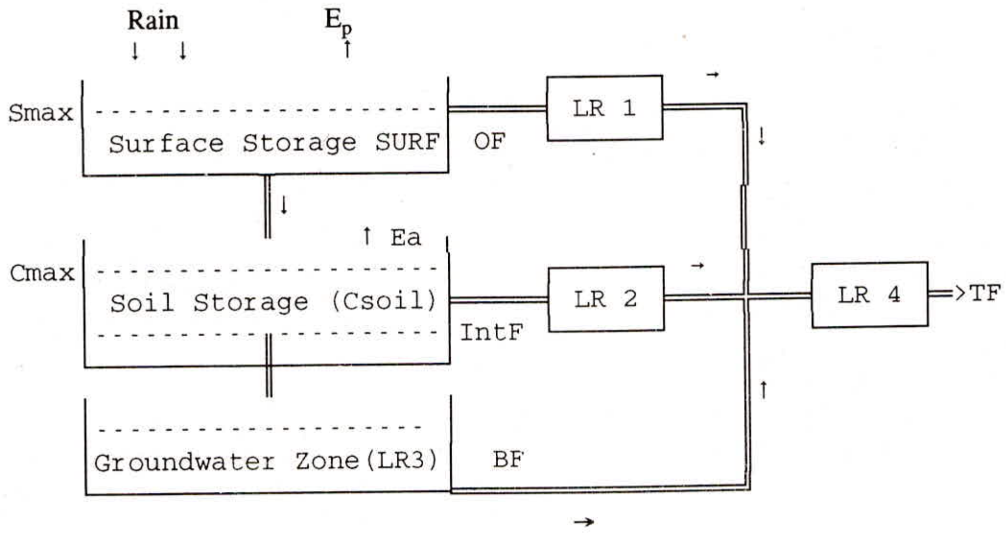

Fig. 1 Structure of the Model

4.0 PARAMETER ESTIMATION

The most important step in application of a conceptual model to a catchment is model calibration. The objective of a calibration is to determine the model parameters such that the best match is obtained between the observed behaviour of the variable of interest, say discharge, and the computed behaviour. The calibration process requires a procedure of comparison of the simulated behaviour and the observed behaviour and then to further adjust the parameters, if required. For this model, either the trial and error procedure or automatic calibration using an optimization technique can be used. The parameters obtained from automatic calibration may be further fine tuned manually to achieve an improved match from the point of view of interest. A good understanding of the basin response mechanism is very much essential in choosing the first guess of the various parameters and subsequent alterations. The criterion of success may be a subjective judgment on adequacy, some statistic selected as measurement of goodness of fit or some user defined objective function, James and Burges (1982). Ibbitt and O'Donnell(1971) and Johnston and Pilgrim(1976) have given a comprehensive discussion on the various aspects of calibration of conceptual models.

Out of ten parameters, four are time constants of various reservoirs and hence only other six parameters are to be calibrated in the beginning. This small number of parameters makes the calibration process quite simple. A two stage process is recommended for calibration of this model. The first stage involves matching the volumes of observed and simulated hydrographs on monthly basis. The main parameters affecting it are S_{max}, C_{max}, FC and FINF. In the second stage, the shape of the simulated hydrograph is matched with the shape of the observed hydrograph by fine tuning of various parameters and time constants of linear reservoirs. This approach gives flexibility to the modeller to adjust the model parameters in light of the objectives of his study, e.g., whether peak flow modelling is more important or low flow modelling. If the user has access to a plotter, it will be very helpful in model calibration.

5.0 MODEL APPLICATIONS

This model was used to simulate rainfall-runoff process in several Indian basins. The results for a basin lying in central India are being presented in the following. This basin is, by no means, ideal to test the performance of a model; standard data sets are available and have been used in the past, e.g. in intercomparison of conceptual models, WMO(1975). However, the data availability in this basin is representative of a typical Indian catchment.

5.1 Kolar Basin Up To Satrana

The Kolar basin is located in the latitude range of 22 40' to 23 08' and longitude 77 01' to 77 29'. The catchment has elevation varying from 600m to 300m. The catchment area of 820 sq. km. up to Satrana gauge & discharge measurement site has been modeled. The index map of the basin showing the locations of gauge - discharge and raingauge stations is given in Fig. 2.

The Kolar basin has two distinct topographic zones. The upper four-fifth part is predominantly covered by deciduous forest. The soils are skeleton to shallow in depth except near channels where they are relatively deep. The outcrops of weathered rocks are visible at many places. Crops are grown in large pockets in the north western part and in small pockets elsewhere. The general response of this part of basin appears to be quick. The lower part of the basin consisting of flat bottomed narrowing valley is predominantly cultivated area. Here soils are deep and ground slopes are flat. The response of this part appears to be slow, Jain(1990).

5.2 Data Availability

The hourly rainfall data at four stations - Rehti, Jholiapur, Birpur and Brijeshnagar was used to get weighted average hourly rainfall for the basin. As seen from the Fig. 2, the coverage of the rainfall stations is not uniform; there is no station in the northern part of the basin. The hourly gauge data for monsoon season only was available at Satrana. Rating curves were developed for this site to obtain hourly discharge values from hourly stages. The pan evaporation data for a station located near the basin in agricultural area was used.

5.3 Model Calibration And Validation

The data for the period 1983-85 was chosen for model calibration. The length of computational time step was one hour. The automatic calibration approach using the Rosenbrock method, which is a search technique, was used in the present study. The objective function was

$$\text{Min } Z = \sum (VO - VS) \qquad \ldots(6)$$

where VO = Volume of observed hydrograph in mm for month t, and VS = Volume of simulated hydrograph in mm for month t.

A comparison of volumes of observed and simulated hydrographs for this period on monthly basis for the final calibration run is given in Table 1. The observed and simulated hydrographs for this period are plotted in Fig. 3. The final values of various model parameters are listed in Table 2.

The data for the period 1986-87 was used for validation purposes. The parameter values arrived at after calibration were used to simulate basin response. The comparison of volumes of observed

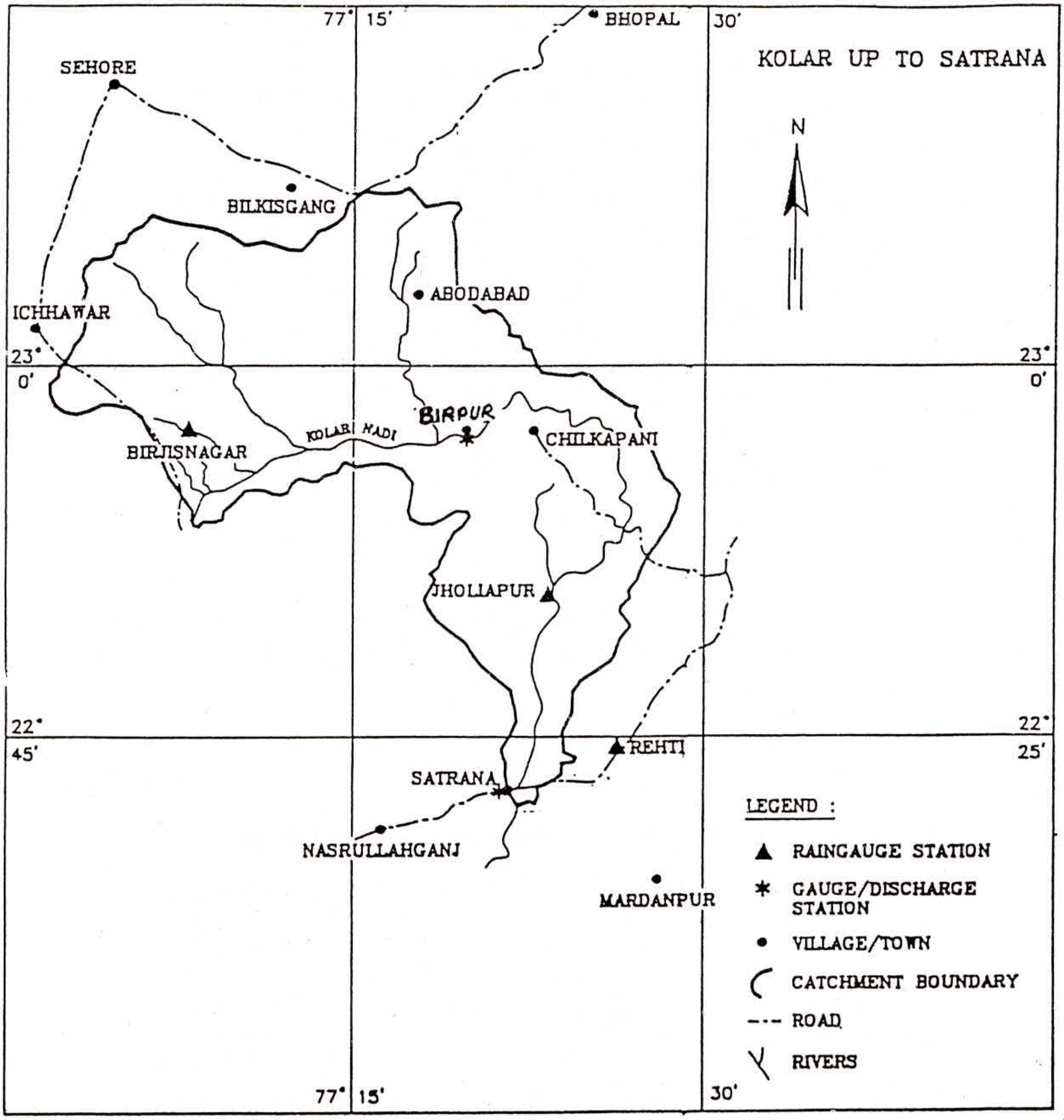

Fig. 2 : The Kolar basin upstream of the Satrana gauging station

Table 1

Comparison of Volumes of Observed and Simulated Discharges for Calibration Period - Kolar Basin

Year	Mon	RF mm	Obs_Q mm	Sim_Q mm
1983	6	7	0	0
1983	7	270	29	0
1983	8	548	361	336
1983	9	382	248	289
1983	10	10	37	53
Sum		1217	675	678
1984	6	141	10	0
1984	7	141	20	0
1984	8	851	592	649
1984	9	27	53	38
1984	10	4	23	38
Sum		1164	698	715
1985	6	139	0	0
1985	7	293	76	94
1985	8	386	218	251
1985	9	181	60	98
1985	10	118	40	40
Sum		1117	394	483

Table 2

Values of Various Parameters for Kolar Basin

Parameter	Value	Parameter	Value
C	283.76mm	S	63.78mm
FC	0.69	Ewf	0.70mm/hr
F	0.72mm/hr	C	0.0025
K	4hr	K	3hr
K	4hr	K	1000hr

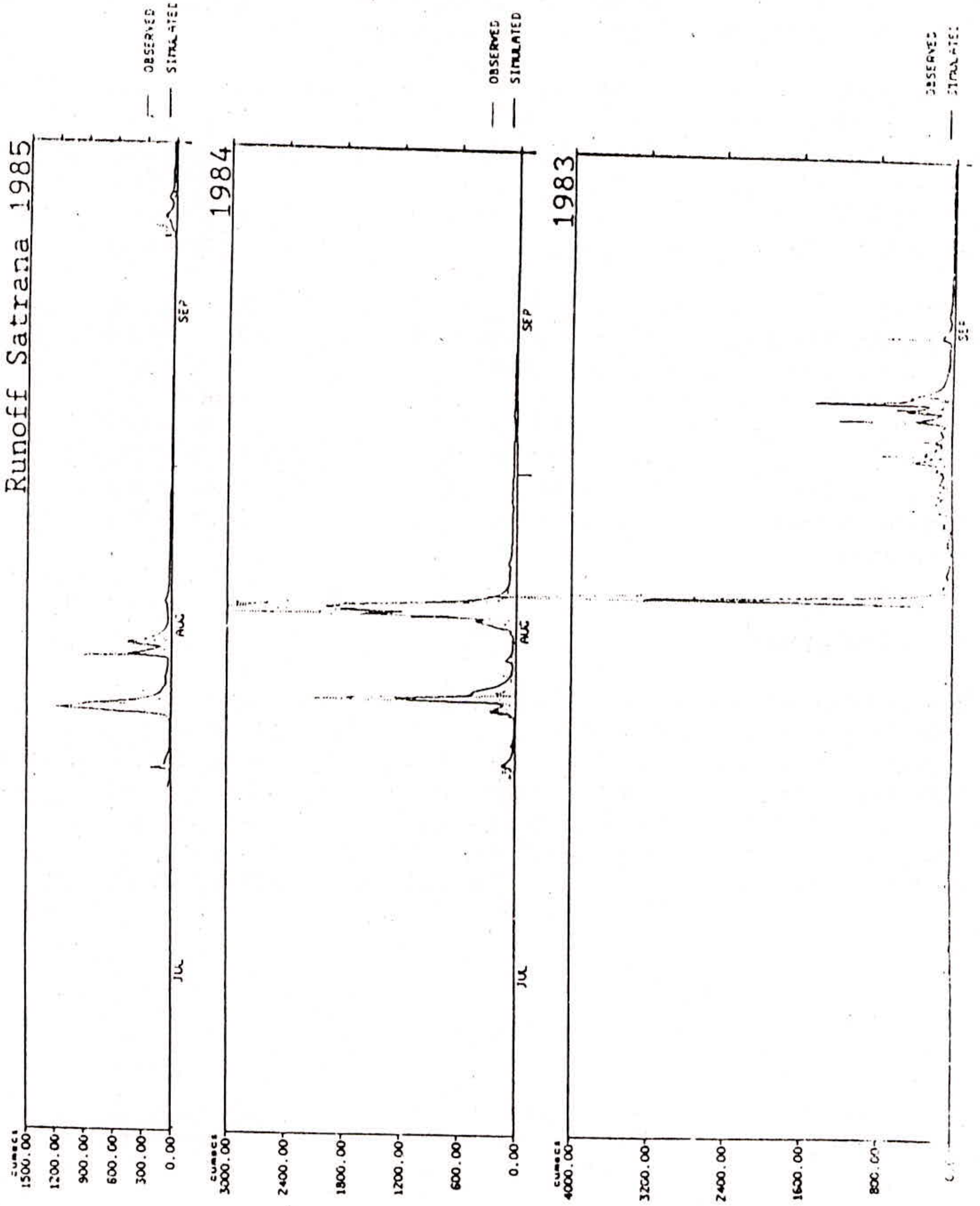

Fig. 3 : Simulated and observed hydrograph for the calibration period 1983-85.

and simulated hydrographs on monthly basis for this period is given in Table 3. The observed and simulated hydrographs for the validation period are plotted in Fig. 4.

Several criteria are available in the literature to test the efficiency of a rainfall-runoff model, ref. Nash & Sutcliffe(1970) and Garrick et al (1978). However, most of these suffer from one or other deficiency. Hence in this study, the volume of the simulated discharge was compared with the volume of the observed discharge on monthly basis followed by visual comparison of observed and simulated hydrographs. This criteria also allows the modeller to view the results in light of the objectives of his study, e.g., whether peak flow modelling is more important or low flow modelling.

The results of final calibration given in Table 1 show a good match between the volumes of observed and simulated hydrographs except for one month in 1985. It is seen from Fig. 3 that the hydrograph peaks, recession and base flow are also simulated reasonably well. The peaks are moderately over simulated in some cases and under simulated in some others. It is not possible to further improve the match for one year without deteriorating it for others. The discharge volumes for the validation period also show a reasonably good match for 1987 and about 14% over-estimation in 1986. The match in shapes is acceptable. It may be pointed out that the input data is subject to uncertainties in view of inadequate coverage. The results of the simulation are therefore acceptable particularly in view of spatial lumping.

6.0 CONCLUSIONS

A conceptual model for rainfall -runoff simulation has been presented. The main features of the model are simple structure and small number of parameters. The model has been applied to Indian catchments whose size varies form about one thousand to five thousand sq. km. The available input data for these catchments was inadequate. There was no raingauge station in the upper part of either of the catchments. The time distribution of the rainfall for the second station was quite uncertain. Probably the potential evaporation data for the catchments was also not representative. The performance of the model is encouraging even with the above constraints on data availability.

Table 3
Comparison of Volumes of Observed and Simulated Discharges for Validation Period - Kolar Basin

Year	Mon	RF mm	Obs_Q mm	Sim_Q mm
1986	6	201	0	6
1986	7	958	625	733
1986	8	302	218	221
1986	9	60	36	37
1986	10	0	22	19
Sum		1521	901	1015
1987	6	105	21	0
1987	7	160	30	0
1987	8	509	201	275
1987	9	58	61	50
1987	10	58	18	32
Sum		890	331	357

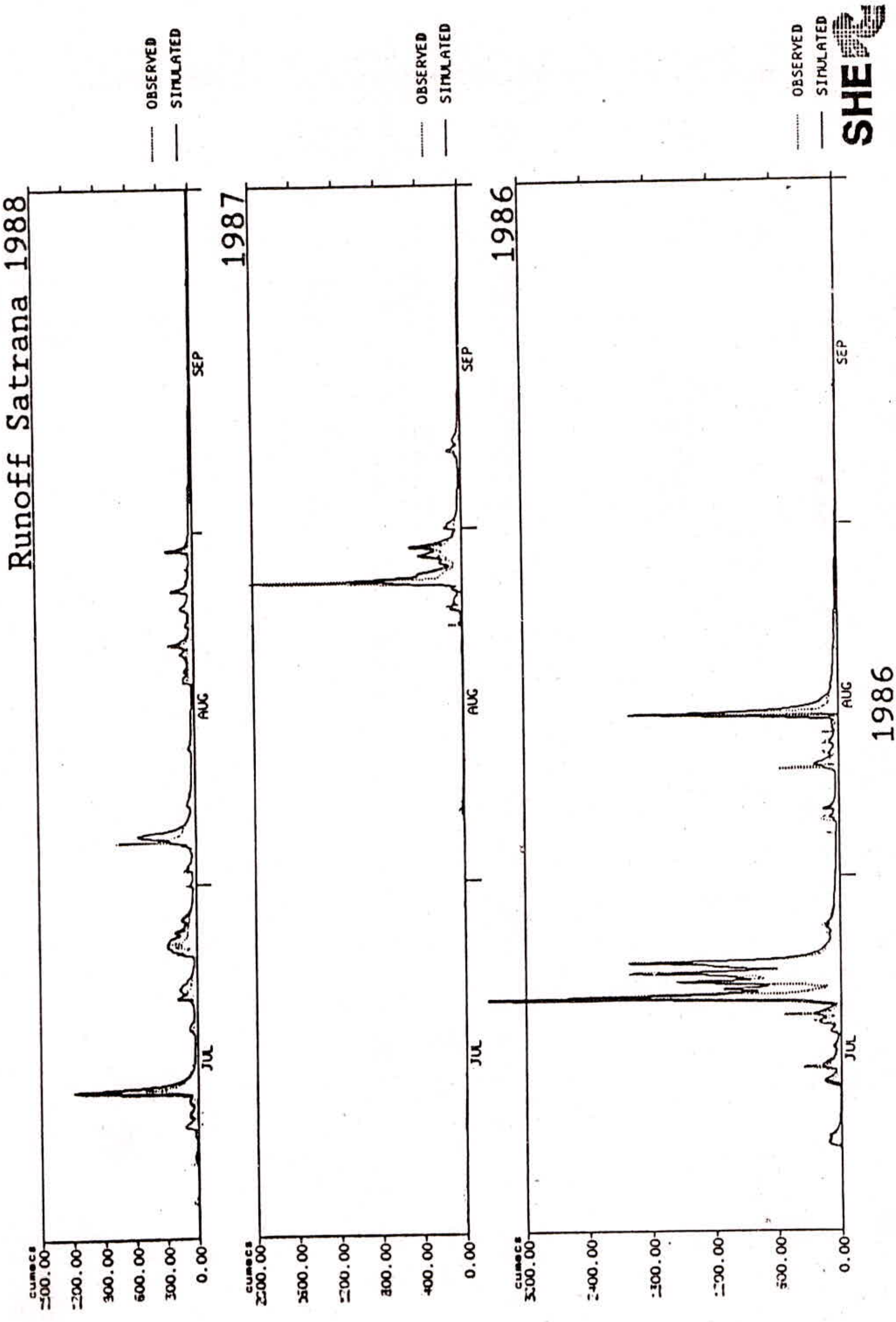

Fig. : Simulated and observed hydrograph for the validation period 1986-88.

REFERENCES

Blackie, J.R, and C.W.O. Eeles, 1985. *Lumped catchment models. in Hydrological Forecasting.* M.G. Anderson and T.P. Burt (ed). John Wiley and Sons. New York.

Ciriani, T.A., Maione, U., and J.R. Wallis, 1977. *Mathematical Models for Surface Water Hydrology.* John Wiley & Sons. London.

Garrick, M., C. Cunnae, and J.E. Nash, 1978. *A criterion of efficiency for rainfall-runoff model.* Journal of Hydrology. Vol. 36. 375-381.

Haan, C.T., H.P. Johnson, and D.L. Brakensiek, 1982. *Hydrologic Modelling of Small Watersheds.* Monograph No. 5. ASAE.

Ibbitt, R.P., and T. O'Donnell, 1971. *Fitting methods for conceptual catchment models.* Journal of Hydraulic Division, ASCE, 97(HY9), 1331-1342.

Jain, S.K. 1990. *Application of SHE Model to Kolar Subbasin of Narmada.* Report No. CS - 33, National Institute of Hydrology, Roorkee.

James, L.D., and S.J. Burges, 1982. *Selection, calibration and testing of hydrologic models in Hydrologic Modelling of Small Watersheds.* edited by C.T. Haan, H.P. Johnson, and D.L. Brakensiek. Monograph No. 5. ASAE.

Johnston, P.R., and D.H. Pilgrim, 1976. *Parameter optimization for watershed models.* Water Resources Research, 12(3), 477-486.

Nash, J.E., and J.V. Sutcliffe 1970). River flow forecasting through conceptual models, Part 1: A discussion of principles. Journal of Hydrology. Vol. 10, 282-290.

WMO, 1975. *Intercomparison of Conceptual Models Used in Operational Hydrological Forecasting.* Operational Hydrology Report No. 7. WMO No. 429.

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