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DAILY RAINFALL-RUNOFF MODELLING USING DETERMINISTIC AND STOCHASTIC APPROACHES

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Preface

For meeting the increasing requirements of water for ever growing population, it is necessary that intensive and extensive investigations and studies are carried out in a systematic manner on various aspects of hydrology of water resources projects. For a water resources project, generally, the hydrologic studies are required for (i) water availability; (ii) design flood; (iii) evaporation losses; (iv) sedimentation studies; (v) Flood forecasting; (vi) reservoir simulation studies and ; (vii) impact on hydrologic regime.

The interest of hydrologists and water resources engineers lies in the land phase of the hydrologic cycle and especially in the disposition of water received from the rainfall. A hydrologic model is a simplified description of the hydrologic cycle depicting an appropriate relationship between rainfall and runoff. Hydrologic models are required not only for deciding about water yields or design parameters, or computing forecasts but also for understanding and evaluating effects of developmental and other activities on hydrological regime of river basins.

A good hydrologic model should be capable of simulating runoff close to the observed one. The difference of historic and computed runoff from the model indicates the deviation or the error which should be minimum for a good model. This error can be analysed and an appropriate stochastic model or distribution can be fitted to it, and then it is possible to modify the computed flows and minimise the deviations.

In this report, prepared by Sh. R. Mehrotra, Scientist of the Institute, performance of a deterministic daily-rainfall runoff model of daily time step after incorporating stochastic structure is evaluated and tested on some of the catchments.

(S.M. SETH)

DIRECTOR

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ABSTRACT

The present report discusses about the application of deterministic and stochastic approaches in daily rainfall-runoff modelling. Structure of a simple hydrologic water balance type conceptual model of daily time scale is discussed and tested on three catchments of India. Further, the deviations of historic and computed runoff series obtained by using the model, which indicate the error in the fitting of model, is analysed and used to improve the predicted flows. In the first case, the average error of a day is computed and the computed runoff as obtained by the use of water balance model is modified using this error. In the second case, the error is first analysed for its serial dependence and accordingly an AR model is fitted to the series. The water balance model is run on real time mode and computed runoff is modified based on error term computed using the AR model. Study indicates that incorporation of simple error term alone can improve the performance of a water balance type model. Also, if the model is run on real time mode and computed runoff is updated using the AR model, improvement in the efficiency of the computed flows can be achieved.

INTRODUCTION

For meeting the increasing requirements of water for our growing population, it is necessary that intensive and extensive investigations and studies are carried out in a systematic manner on various aspects of hydrology of water resources projects. For a water resources development project, generally, the hydrologic studies are required for (i) water availability; (ii) design flood; (iii) evaporation losses; (iv) sedimentation studies; (v) flood forecasting; (vi) reservoir simulation studies and : (vii) impact on hydrologic regime.

The hydrologic behaviour of catchment is a very complicated phenomenon which is controlled by an unknown large number of climatic and physiographic factors that vary with both time and space. The common problem in hydrology is the establishment of relationships between rainfall and runoff. The application of system concept has led to studies in hydrology using deterministic, probabilistic and stochastic approaches to deal with problems of hydrological analysis, simulation and synthesis. A hydrologic model is a simplified description of the hydrologic cycle. These models are required not only for deciding about water yields or design parameters, but also for understanding and evaluating effects of developmental and other activities on hydrological regime of river basins. The use of physically based distributed modelling approach can provide such information and could also incorporate scenarios of proposed/ likely land use changes in the river basin for use in planning/ operation of water resources projects.

All the water balance type rainfall-runoff models try to model the behaviour of the catchment in such a way so that computed runoff match well with historical ones. In the past, many researchers have tried to improve the efficiency of the water balance type model by studying the difference of historic and computed series by the model, i.e. the error series and trying to fit some distribution or stochastic model depending upon the type of error series, to improve the efficiency or performance of the model. Specifically if the model is to be used in real time mode then predicted forecast is modified based on the observed data.

In this report, a simple water balance model of daily time step is applied on three Indian catchments. Further, the error term or the difference of modelled and historic flows is analysed and some improvement upon the computed flows is tried to achieve by using the average error for each day as such and also by fitting a simple AR model to the error series and modifying the modelled flows using this AR model.

STUDY AREA

In the present report, three catchments, out of which two are lying in Central India and one in Southern India have been considered for study. These catchments are considered because the required data was readily available. The data of these catchments are, by no means ideal to test the performance of the methodology. Details of catchments are presented in Table 1 whereas their maps and locations of raingauge stations and G&D sites are marked in Fig. 1.

Table 1 : Catchment area and other details.

Name of catchment	State	Runoff Factor (RF)	Area in Sq. Km.	Total length of record available in years	Years From - To	No. of years used for calibration	No. of years used for verification
Sher	M.P.	0.4236	1500.00	9	1978-86	6	3
Manot	- do -	0.4737	4980.00	5	1983-87	3	2
Gundlakamma	A.P.	0.2126	7831.00	9	1989-97	6	3

Following section describes in details about the characteristics of the catchments used in the study.

Manot basin

Narmada upto Manot lies between east longitude 80°24' to 81°47' and north latitude 22°26' to 23°18' in Mandla and Shadol districts of Madhya Pradesh. The river rises in Maikala range near Amarkantak in Shadol district at an elevation of 1057 meters. It flows for a total length of 239 kilometers upto Manot and drains a total area of about 4980 sq. km. The river has a number of falls in its head reaches. Flowing in a generally south-westerly direction in a narrow and deep valley, the river takes pin head turns at places. The topography of the basin is hilly with forest cover, especially in the upper reaches. Flat farmland is more evident in the lower reaches. The topographic elevations in the basin ranges from 1110 m in the upper part to 450 m near the gauging site. The basin consists of mainly black soils. The principal soil types found in Mandla district are red, yellow, shallow black and skeletal.

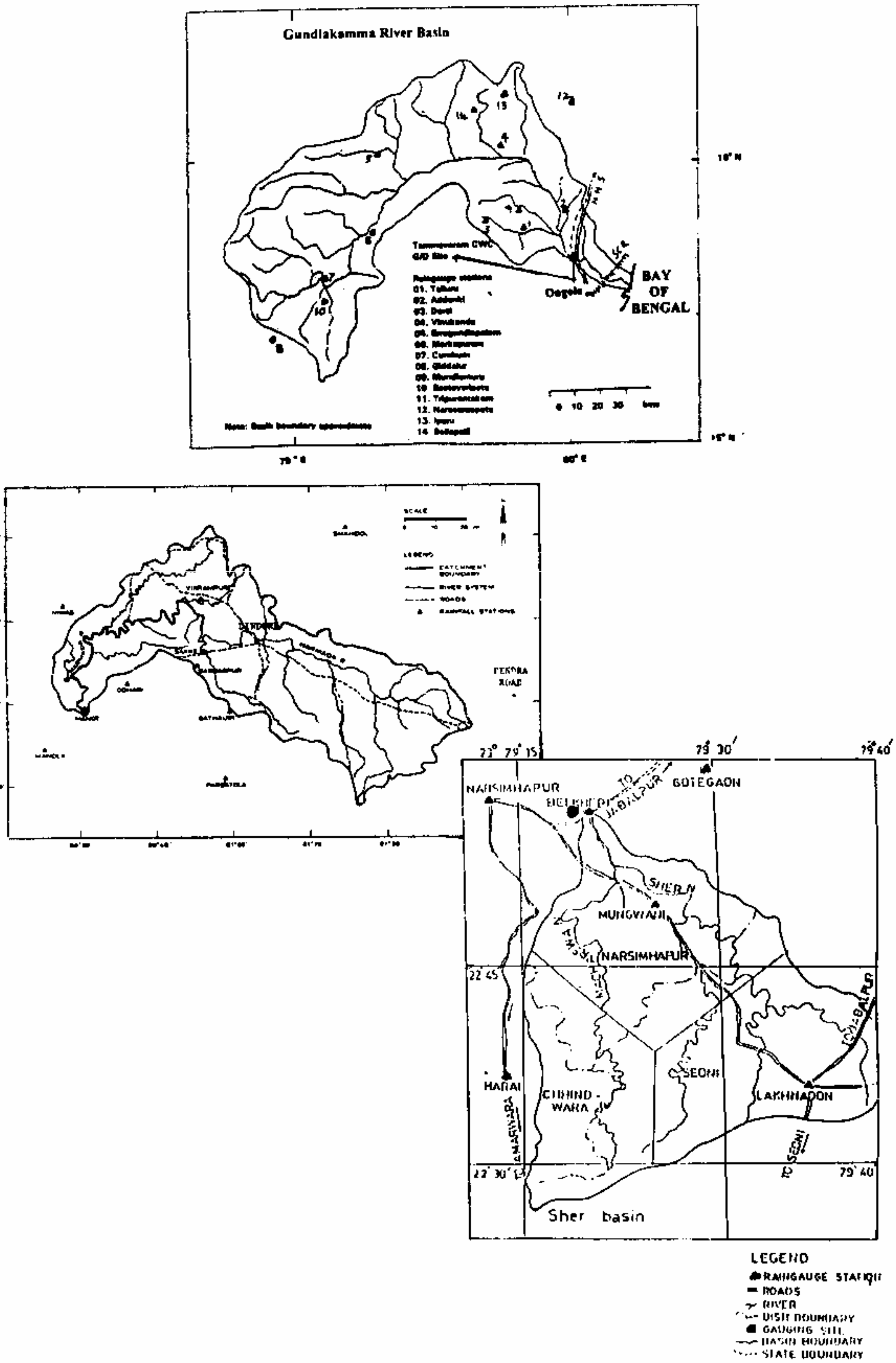

Figure 1: Index map showing locations of catchments used in the study

The climate of the basin is humid and tropical, although at places extremes of heat and cold are often encountered. in the cold weather, the mean annual temperature varies from 17.5° C to 20° C and in the hot weather from 30° C to 32.5° C. Nearly 90 percent of the total annual rainfall is received during the five monsoon months from June to October.

Sher basin

The Sher river rises in the southern Satpura range in the Durg district of M.P. at an elevation of 600 m from mean sea level. The catchment area upto the confluence point of Sher with Narmada is about 2900 sq km. However, the Central Water Commission has established a gauging site, upstream of the confluence covering about 1500 sq km of Sher basin.

The basin is characterized by hilly terrain, and is heavily intersected by streams and rivers. The vegetation of the sub-basin consists of forest of medium density, scrub land, spread pockets of cultivation on undulating land, and some denuded land. The basin lies in the districts of Narsingpur, Chhindwara and Seoni in Madhya Pradesh. The river Sher is fairly big tributary of river Narmada. About 40 km upstream of the confluence of river Sher with Narmada, the Narsingpur-Jabalpur road crosses the river Sher. At this point, the Belkheri gauging site is located at a distance of 16 km from Narsingpur.

Gundlakamma basin

The Gundlakamma river basin is a medium river of about 264 kms length taking its origin from the Nallamalai Hills in Mallamalai forest near Gundla Brahmeswaram Village in Nandyal Taluka of Kurnool district at altitude of 680 metres. It flows through deep ravines and thickly grown natural forests and hilly tracts upto Cumbum tank situated in Cumbum village in Prakasam district. The river flows generally in northeast direction upto the confluence of Konduleru river, then takes a turn towards east upto the confluence of Konkeru at Pittambanda village. It turns southeast and flows at a uniform slope till it joins Bay of Bengal near Pallipalem village. The river's total catchment area is 8195 km^2, including the area drained by its tributaries. The basin has mixed red and black soils in upper reaches, red sandy soils in the middle part and a mixture of coastal alluvium and coastal sandy soils in the lower reaches.

The climate of coastal part of the study area may be broadly classified under tropical coastal type and rest is of steppe type. The daily mean temperature is about 27.5 C. Mean maximum temperature is around 32.5 C. Mean minimum temperature is about 22.5 C. Highest maximum temperature is about 47 C and lowest minimum temperature is about 14 C. The mean diurnal range of temperature is about 10 C.

A rainfall of 25 mm between January and February, about 75 mm between March to May; about 400 mm between June to September and about 300 mm between October to December is experienced in the area. The annual runoff is about 200 mm. During monsoon season Gundlakamma occasionally swells into floods. The maximum flow recorded at CWC G/D site at Tammavaram is 3607 cumecs and minimum flow recorded is 0.10 cumecs. Also the area under study gets heavy rainfall due to cyclones forming in Bay of Bengal.

DATA USED IN THE STUDY

The use of a conceptual model requires a number of hydrometeorlogical data as input parameters. In general, rainfall, runoff, temperature and evapotranspiration data along with some catchment characteristics are needed for model calibration. Daily areal rainfall is computed by applying Thiessen polygon. Rainfall, runoff and pan evaporation data for these basins was available for the duration as mentioned in Table 1. As practically major portion of rainfall occurs during the monsoon season, stochastic analysis is performed considering monsoon (June to October) and non-monsoon periods separately.

Manot Basin

Daily rainfall records at Dindori, Gathauri, Niwas, Odhari, Sakke, Manot and Barbaspur for the year 1982-87 are considered in the study. Mean areal rainfall for the basin is computed using Theissen polygon method. Evaporation data at Pendra Road station, located outside the basin has been considered to represent the potential evapotranspiration for the basin. Discharge data at Manot gauging site was available for the monsoon period only and for non monsoon period using rating curve and measured stage, discharge values are derived.

Sher Basin

Daily rainfall records at Lakandon, Narsimhapur, Mungwani, Harai and Jabalpur for the year 1978-86 are considered in the study. Mean areal rainfall for the basin is computed using Theissen polygon method. Evaporation data at Jabalpur, located outside the basin has been considered as representative of the potential evapotranspiration for the basin. Daily discharge values at Belkheri gauging site are used. For the periods when observed discharge values are not available, these are computed using rating curve and measured stage.

Gundlakamma basin

Daily rainfall from 14 stations for the period 1989-97 are used to compute the mean areal daily rainfall for the basin. The location of raingauge stations used in the study are shown in Fig. 1. Corresponding flow records at Tammavaram site of Central Water Commission are also collected. The mean daily flow data is measured using current meter at Tammavaram site. For the periods when only gauge readings are available flow is estimated using stage discharge relationship. The catchment area upto the site is about 7831 sq.km.

Pan evaporation data at the agriculture research station, ANGRAU at Darsi is available for about 3 years period only. This data is used to estimate average daily mean monthly pan evaporation data and is utilised in the modelling study.

For all the basins, a uniform factor of 0.7 is considered to convert pan evaporation values to potential evapotranspiration values.

METHODOLOGY

In the present study, a suitable simple daily rainfall-runoff model using water balance approach is developed and the series of residuals (difference of simulated and recorded daily runoff) which shows the modelling error component are analysed. The average error for each day is computed from the series of residuals and the daily discharge of each day computed from deterministic model is modified on the basis of this average error of that day. Also, the series of residuals is analysed for its time dependence and a stochastic structure based on a time series model is formulated. As most of the rainfall occurs during monsoon period only, separate stochastic models are developed for monsoon and non-monsoon periods. Based on this model for residuals, simulated flows of deterministic model are modified by running the model on real time mode with one day lead time. Following sections describe in detail about the methodology adopted and the models used in the study.

Deterministic model

For most of the practical analysis to simulate daily rainfall runoff, simple conceptual models are being adopted because of their simplicity, less data requirement and minimal computer time. The models consist of a number of storage with model parameter controlling the storage sizes and rate of outflows. They use the conceptualization of flow processes with inputs of daily rainfall and daily evaporation to generate runoff.

A model in general comprises of a procedure to determine actual evaporation from potential evaporation, derived from pan evaporation or any other methods. The ratio of actual evaporation to potential evaporation is generally taken to be a function of the water content of one of the soil moisture storage. This function may be a linear function, i.e. a linear decline in evaporation as soil moisture content falls below some maximum, or a negative exponential function, i.e. the ratio of actual evaporation to potential evapotranspiration falls slowly at first, but more rapidly as the storage empties.

The water content of each soil moisture storage at the end of a time step is based on the content at the beginning of the step and on inflow and outflow during the step. The outflow of one storage is generally the inflow to another storage. Different models have different procedures for determining outflows and different number of storage which may be combined in different ways.

The runoff generated from the model is either a direct surface flow or a baseflow. The former is usually through a saturation excess or infiltration excess model, and the latter as a function of the soil moisture storage content. The outflow from the soil moisture storage and/or baseflow is routed to get final flow in the river. This is usually, based on a system of linear reservoirs, one from each storage.

In the present study, different model structures of daily time step are tested and compared on the basis of efficiency criteria and visual inspection of plots and, finally a five parameter model as proposed by Moore (1985) is considered for further analysis. This model is based on probability distribution technique and has a soil moisture storage with a capacity varying across the basin and a groundwater storage. Vijayakumar (NIH, 1998-99) has applied this model on Gundlakamma basin in Andhra Pradesh and found its performance satisfactory. The five parameters include, the maximum storage capacity at any point within the basin 'Cmax'; the average maximum amount of water that could 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'. The model is briefly presented here:

In the model, precipitation is added to the soil moisture and excess precipitation becomes direct runoff which is routed through two cascading reservoirs as direct runoff. Evapotranspiration and drainage from the soil moisture storage occurs at a rate proportional to storage contents. Baseflow occurs from the groundwater storage and is added to the direct runoff to get the total runoff from the basin.

Actual evapotranspiration (AE) is derived from potential evapotranspiration (PE) as:

$$AE_t = PE_t \{1-e^{(-6.68\, S_{t-1}/Smax)}\} \quad (1)$$

Drainage to the groundwater storage is:

$$Qi = Kb\ (S_{t-1}/\ Smax) \quad (2)$$

If rainfall P is less than AE and Qit there is no direct runoff. Otherwise direct runoff does occur. The critical capacity at the end of previous time step 'Cc_{t-1}' below which all the soil moisture goes to storage is calculated from the reflected power (pareto) distribution as:

$$Cc_{t-1} = Cmax\ \{1-(1-S_{t-1}/Smax)^{(1/(b+1))}\} \quad (3)$$

Hence critical capacity at the end of the present time step is:

$$Cc_t = Cc_{t-1} + (P_t - AE_t - Qi_t) \quad (4)$$

If Cct is less than Cmax, direct runoff is:

$$Qo_t = (P - AE_t - Qi_t) - Smax\ \{1-Cc_{t-1}/Cmax)^{b+1}\} \quad (5)$$

If Cct is greater than Cmax, direct runoff is:

$$Qo_t = (P_t - AE_t - Qi_t) - Smax - S_{t-1}) \quad (6)$$

and the soil moisture storage is full to Smax.

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Baseflow (Q_b) from groundwater storage g_s is:

$$Qb_t = Grout\ (S_{t-1}/100) \quad (7)$$

Direct runoff is routed through two cascading reservoir of storage Ss as:

$$Q = \text{Srout}\ (S_s) \tag{8}$$

Adding the baseflow 'Qb' and direct runoff 'Q' provides the modelled catchment runoff.

Stochastic model

The difference of modelled flow and observed flow indicate the deviation and can be attributed to the modelling deficiencies. Now, if the behaviour of the series of residuals (difference of simulated and recorded daily runoff) which shows the modelling error component is studied then it is possible to fit some time series model to these residuals. Once, a model is identified then simulated results can be modified on the basis of this model structure.

In the study, the series of residuals is analysed first for the time dependence and it is observed that for all the three basins series exhibit serial dependence. An AR model is fitted to this series for modifying the flows of the simulation model. The error estimates as computed by the AR model are added as corrections to the corresponding simulation mode discharge values to get the modified discharges.

An auto-regressive (AR) model of order p, for the simulation mode error time series, may be expressed as:

$$e_t = \bar{e} + \sum_{i=1}^{p} \phi_i (e_{t-i} - \bar{e}) + a_t \tag{9}$$

where e_t represents the error time series with mean $\bar{e}$; a_t is a sequence of uncorrelated random variables with mean zero and variance σ_a^2; ϕ_i denotes the parameters of the AR model, and p is the number of the parameters.

The parameters of the AR model are normally estimated using the Yule Walker equations (Box and Jenkins, 1976) or more simply in the case of a linear regression structure, the least squares. Having found the parameters of the AR model, the modified discharge $\hat{Q}_t$ is given by

$$\hat{Q}_t = Q_t + \hat{e}_t \tag{10}$$

where Q_t is the discharge as obtained by using the deterministic model and $\hat{e}_t = e_t - a_t$ is the estimated error.

In the study, the average error for each day is computed and the year is divided into monsoon and non monsoon periods as most of the rainfall occurs during monsoon period only. Monsoon period is considered from June to October. AR model is fitted separately for monsoon and non-monsoon periods.

Error model

The difference of modelled flow and observed flow indicate the deviation or error and can be attributed to the modelling deficiencies. Now, if the average error for each day is computed from the series of residuals then it is possible to modify the simulated discharge on the basis of this average error.

The average error of *i*th day may be expressed as:

$$e_i = \frac{1}{N} \sum_{j=1}^{N} (Q_{j,i} - \hat{Q}_{j,i}) \tag{11}$$

where $\hat{Q}_{j,i}$, $Q_{j,i}$ are the simulated and observed discharges of the *j*th year and *i*th day respectively and e_i is the average error of the *i*th day. This average error of the *i*th day so computed, is added to the simulated discharge of that day, to get modified discharge of the *i*th day.

Calibration and verification of the model

The process by which parameters of the model are determined is called calibration of a model. To calibrate a model one needs to consider a criteria of performance of the model to see how good the model is simulating the "real world".

When the first simulation models were proposed in hydrology, the main criteria for judging the model (model structure and parameters) was the graphical comparison between the observed streamflow hydrograph at specified points in the catchment versus the corresponding simulated hydrographs. In this approach the objective was to obtain the set of model parameters which produce a simulated hydrograph which best approximates the observed hydrograph. Therefore, judgement of the modeller was a very important factor determining the final set of parameters during the calibration process. A limitation in the approach was that for the same problem at hand, different answers would be obtained by different modellers because of the subjective qualitative nature of the "objective". Another limitation was that the parameter estimation had to be done by trial and error.

Objective function

In order to ameliorate these limitations some quantitative objectives in the form of "objective functions" were proposed (Lichty et al.,1968). If $QHIS_j$,$j=1$, N is the historical hydrograph and $QCOM_j$, $j=1$, N is the simulated hydrograph then the difference $QHIS_j-QCOM_j$ is the error produced by the model at time j. N is the total number of observations. An objective function to calibrate the model may be to minimize these errors for $j=1$, N.

Several numerical criteria are available and described in the literature to judge the performance of a rainfall-runoff model based on some objective functions. However, none of them can be described as fully efficient one. In the present report, following objective function is adopted.

Minimisation of the sum of squares of error, SSE which is determined as :

$$SSE = \sum_{j=1}^{N} (QHIS_j - QCOM_j)^2 \tag{12}$$

Where $QHIS_j$ and $QCOM_j$ are historical and computed runoff of the jth day respectively and, N is total number of observations during the period.

To undertake automatic optimization, Rosenbrock (1960) optimization procedure which is basically a search algorithm was invoked to calibrate the parameters of the models based on the minimisation of the objective function (SSE). The objective function may be used to compare the results from calibration and validation data sets.

Also, the performance of the models is compared on the basis of values of Nash Sutchiffe (1970) efficiently criteria to get the efficiency of the model during calibration and verification periods. The function is:

$$\text{Efficiency} = 1.0 - \sum (Q_{his} - Q_{com})^2 / \sum (Q_{his} - Q_{bar})^2 \tag{13}$$

where the numerator is the sum of the squares of difference of the observed and simulated daily flows, and the denominator is the sum of the square of differences of the daily observed and observed mean daily flows over the period of modelling. Since the objective function SSE is minimized in the optimization criteria, the above equation gives maximum efficiency. The efficiency criterion is biased towards larger discharges, but is widely used and gives an objective indication of model performance. A perfect agreement between the observed and simulated flows yields an efficiency of 1.0, whilst a negative efficiency represents a lack of agreement, worse than if the simulated flows were replaced with the observed mean daily flows. In the study efficiency based on above criteria is computed for calibration and validation periods for all the three basins and for all the approaches.

PRESENTATION OF RESULTS

In the study, the daily rainfall-runoff of the Gundalakamma basin, Manot basin and Sher basin are first simulated using the deterministic model. Data of the first 6 year period for Gundalakamma and Sher basins is used for calibration of the model and the data of later 3 year period is used for validation of the calibrated model. Similarly, for Manot basin data of first 4 years is used for calibration and remaining two years is used for validation of the model. As mentioned earlier, several runs with different initial values of storage and parameters were taken before finally accepting the values for all the catchments.

The average difference of error for each day over the years is shown in Fig. 2 to 4 for calibration period for the three basins. In first case, this average value is used as such to modify the simulated flow of each day. In the second case, an AR model is fitted to this average error for monsoon and non monsoon periods separately and the simulated flows are modified using this AR model in real time mode. The details of analysis and results are presented here.

The optimized parameter values of the deterministic model for the three basin is listed at Table 2.

Table 2: Calibrated model parameter values

Basin Name	Parameter Name				
	Smax	Cmax	Kb	Grout	Srout
Gundlakamma	281.09	440.02	1.50	2.56	0.68
Sher	228.77	315.95	0.51	2.38	0.54
Manot	180.65	469.74	0.65	1.36	0.63

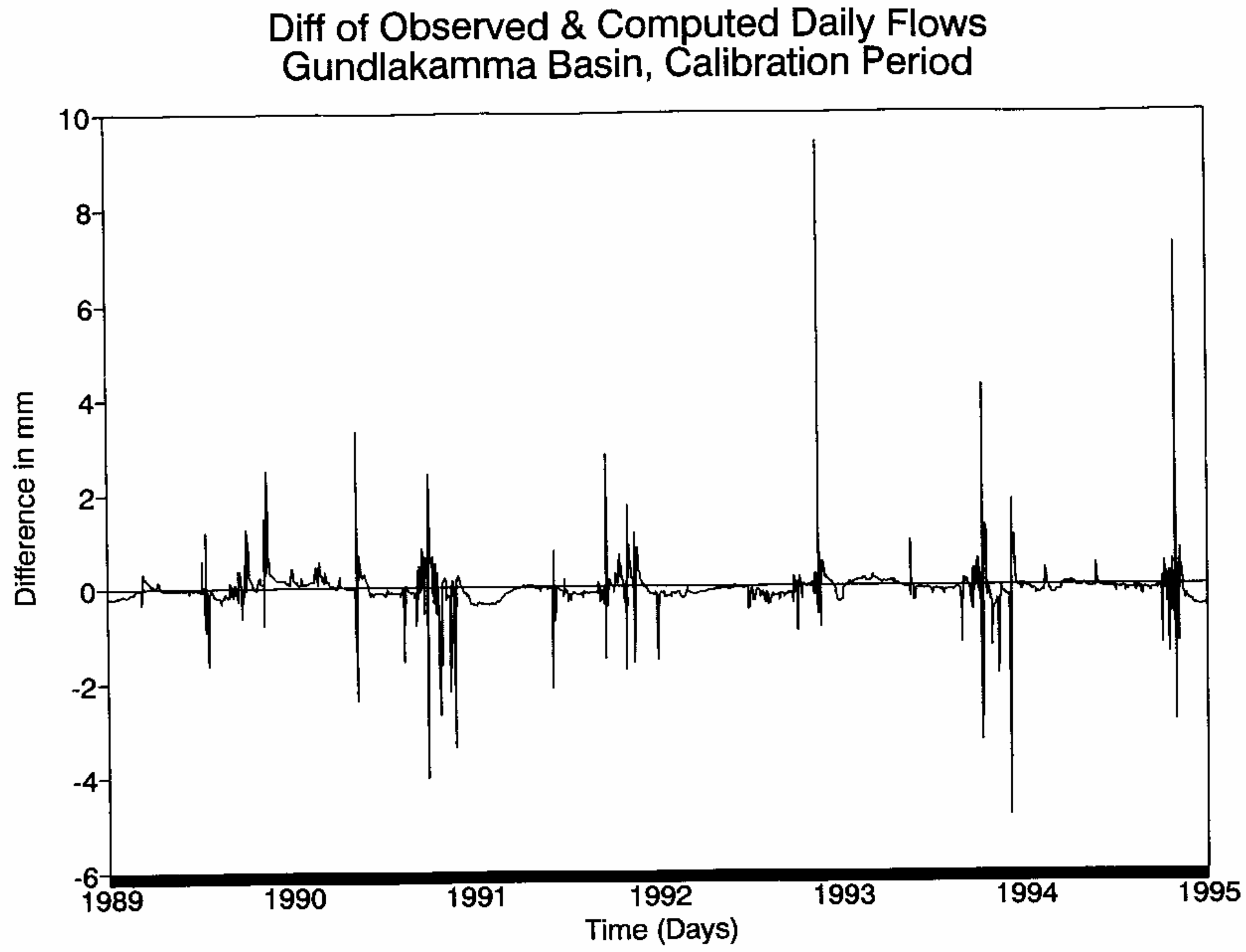

Figure 2: **Difference of observed and computed flows, Gundlakamma basin, calibration period**

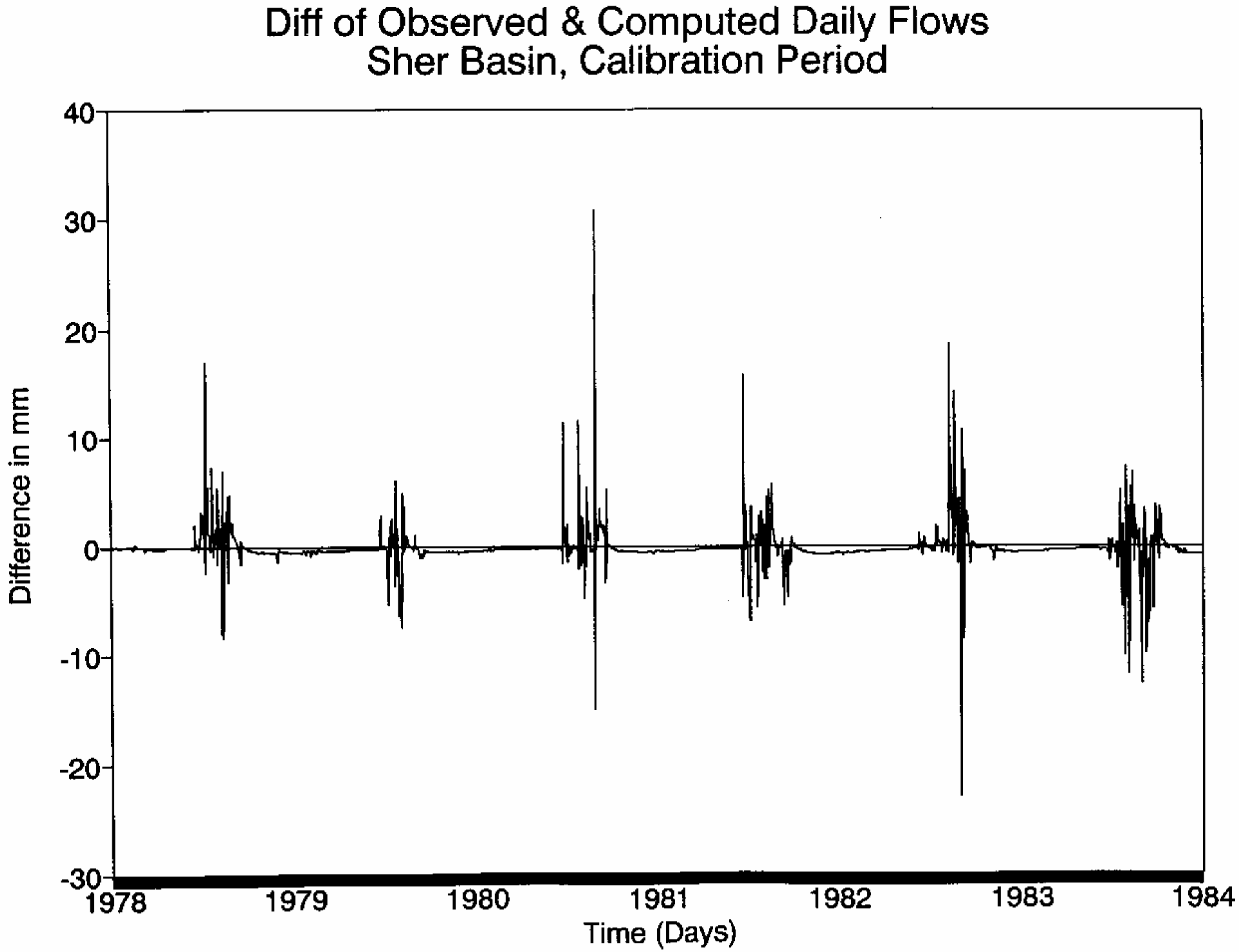

Figure 3: Difference of observed and computed flows, Sher basin, calibration period

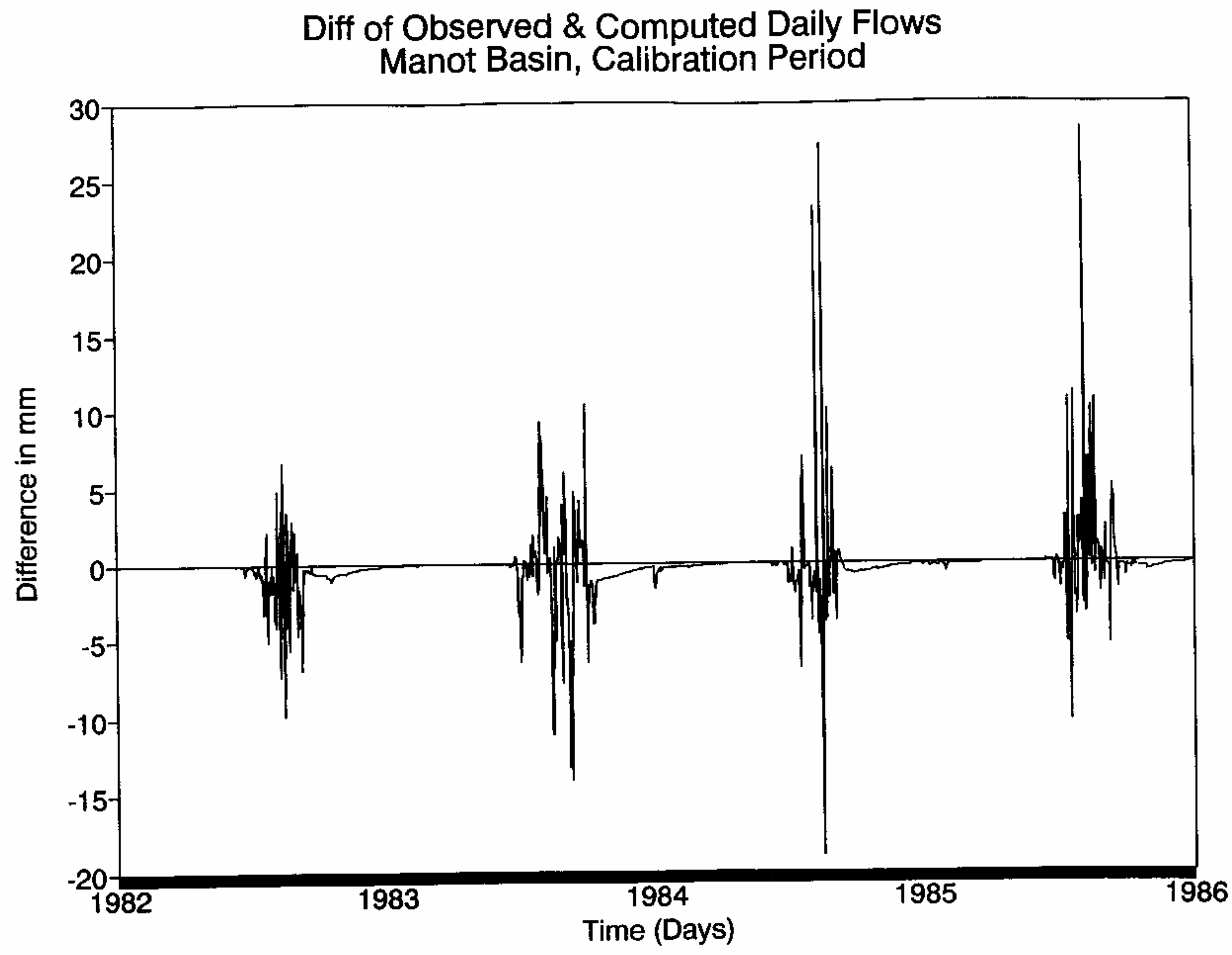

Figure 4: Difference of observed and computed flows Manot basin, calibration period

For Gundlakamma basin, for calibration period the overall efficiency is 70.07% while during verification it is 56.25%, Efficiency based on modified flows by AR model is 71.46% and 58.88%, while for flows modified by average error it is 75.42% and 58.03% for calibration and verification periods respectively. The resulting simulated daily runoff values by using all the three models along with observed runoff values for one year are plotted in Fig. 5 for calibration period and in Fig. 6 for verification periods. Similarly, the modelled and observed monthly runoff for calibration period is shown in Fig. 7 and for verification period in Fig. 8. These efficiency values are also given in Table 3.

Table : 3 Percentage overall efficiency values for daily and monthly flows during calibration and verification periods

Basin name		**Overall Efficiency Values in Percentage using**		
		Deterministic	**Det. + Stoc**	**Det. + Error**
Gundlakamma Basin				
Daily flows	Calibration	70.07	71.46	75.42
	Verification	56.25	58.88	58.03
Monthly flows	Calibration	89.04	99.65	96.67
	Verification	86.78	96.51	87.63
Sher Basin				
Daily Flows	Calibration	69.42	71.05	76.68
	Verification	64.72	68.78	67.73
Monthly Flows	Calibration	92.65	97.55	93.36
	Verification	98.39	99.01	97.43
Manot Basin				
Daily Flows	Calibration	65.38	66.71	75.02
	Verification	48.39	52.66	55.30
Monthly Flows	Calibration	97.65	97.13	96.97
	Verification	91.90	96.33	95.46

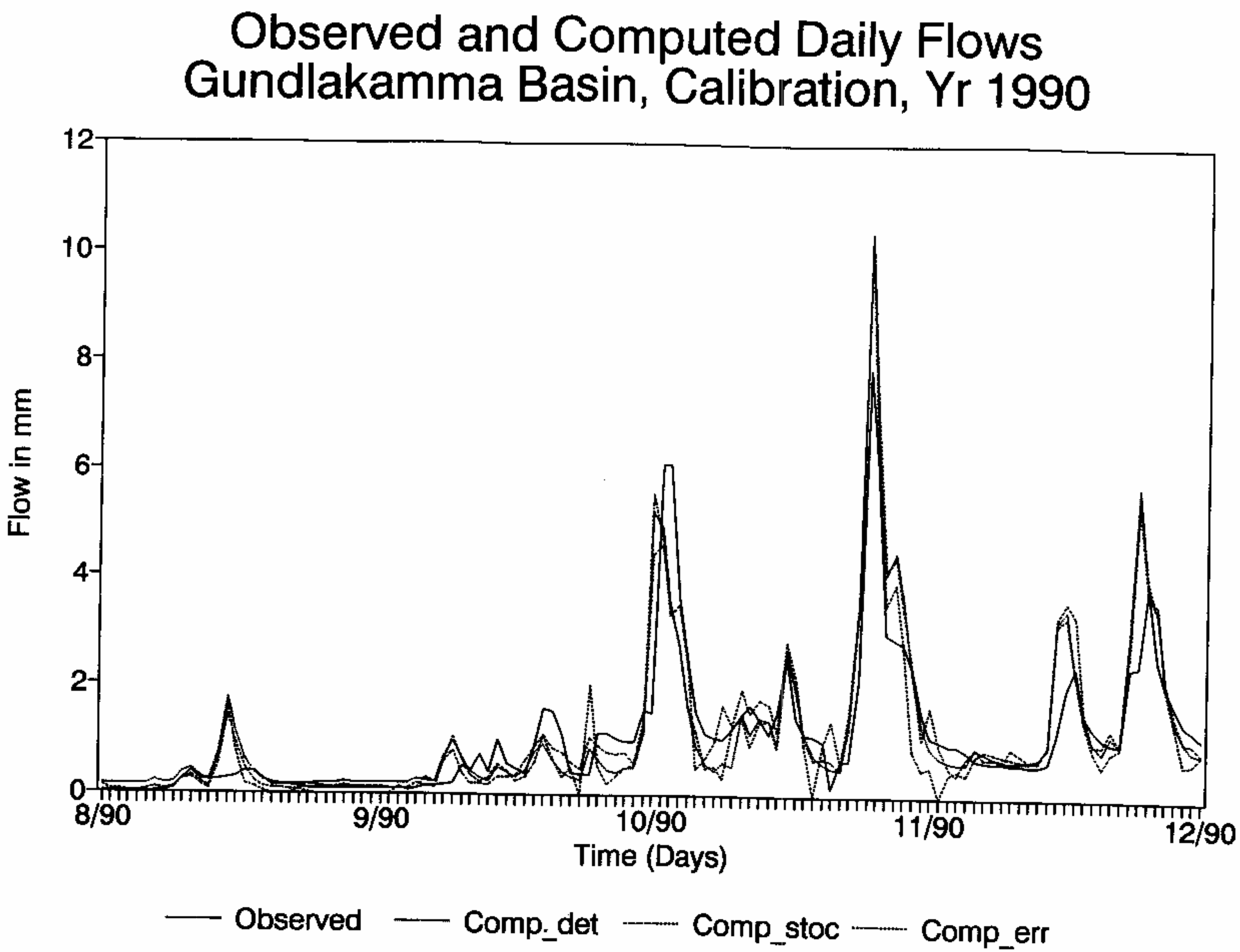

Figure 5: **Plots of observed and computed daily flows for the year 1990 for Gundlakamma basin, calibration period**

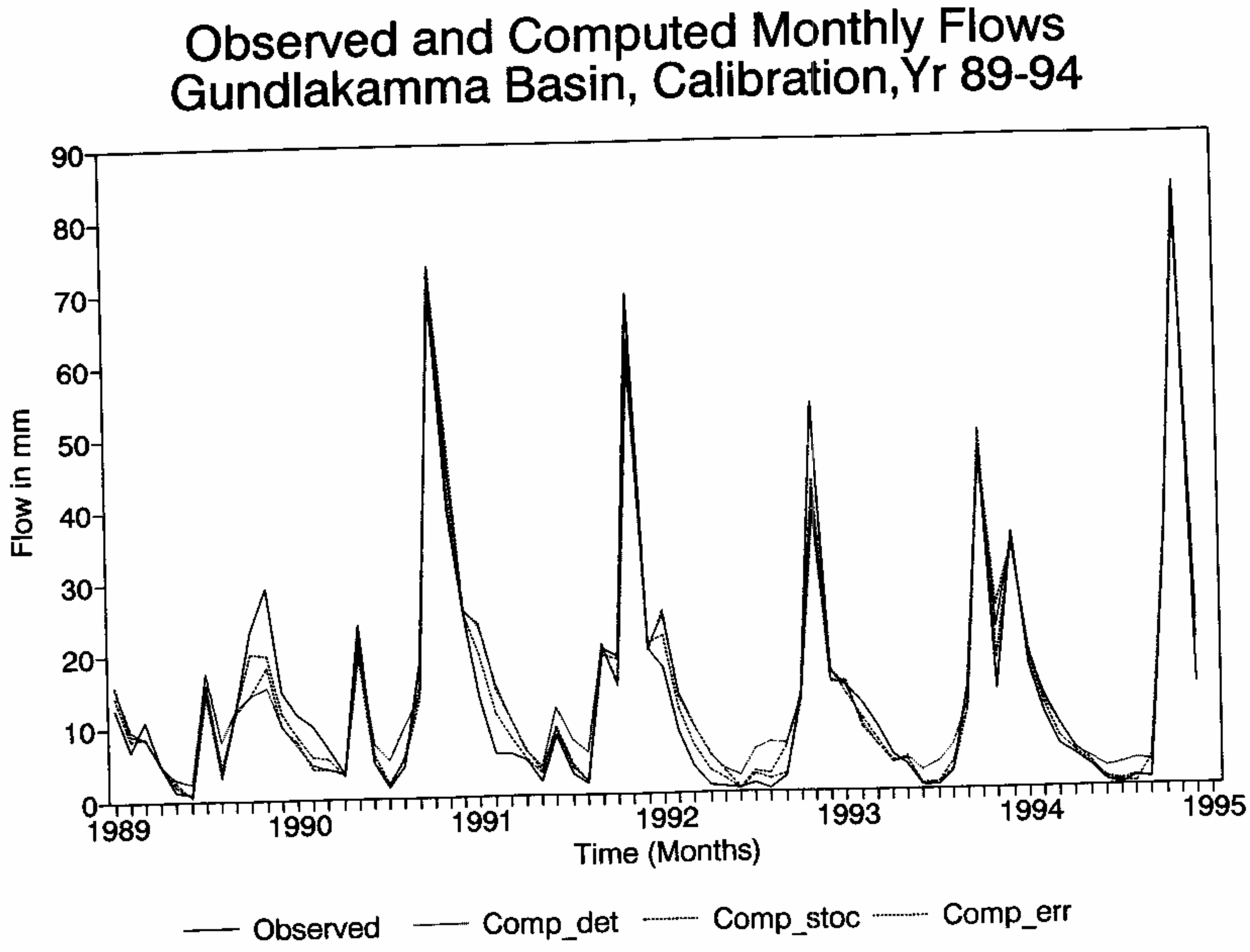

Figure 6: **Plots of observed and computed monthly flows for the years 1989-94 for Gundlakamma basin, calibration period**

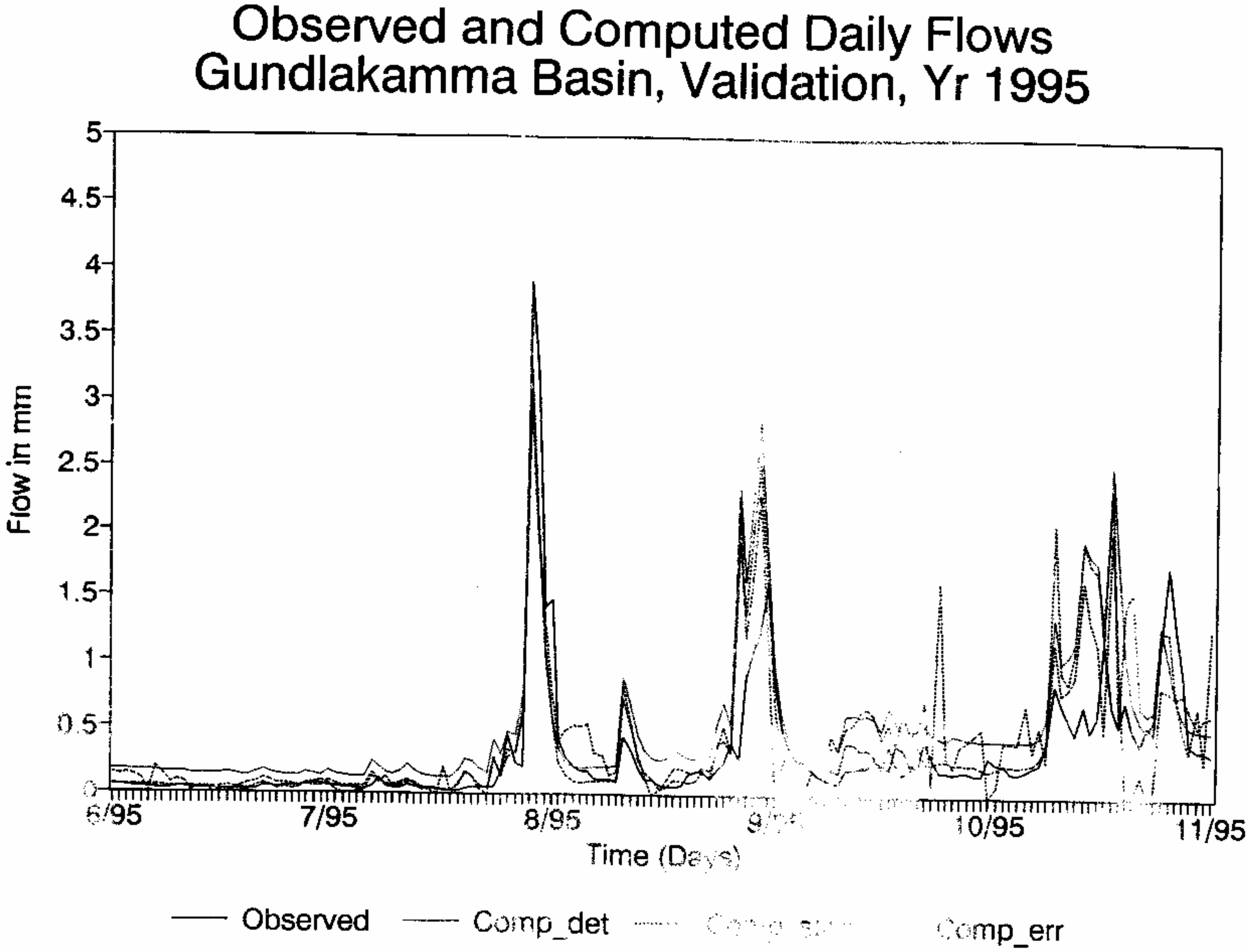

Figure 7: Plots of observed and computed daily flows for the year 1995 for Gundlakamma basin, verification period

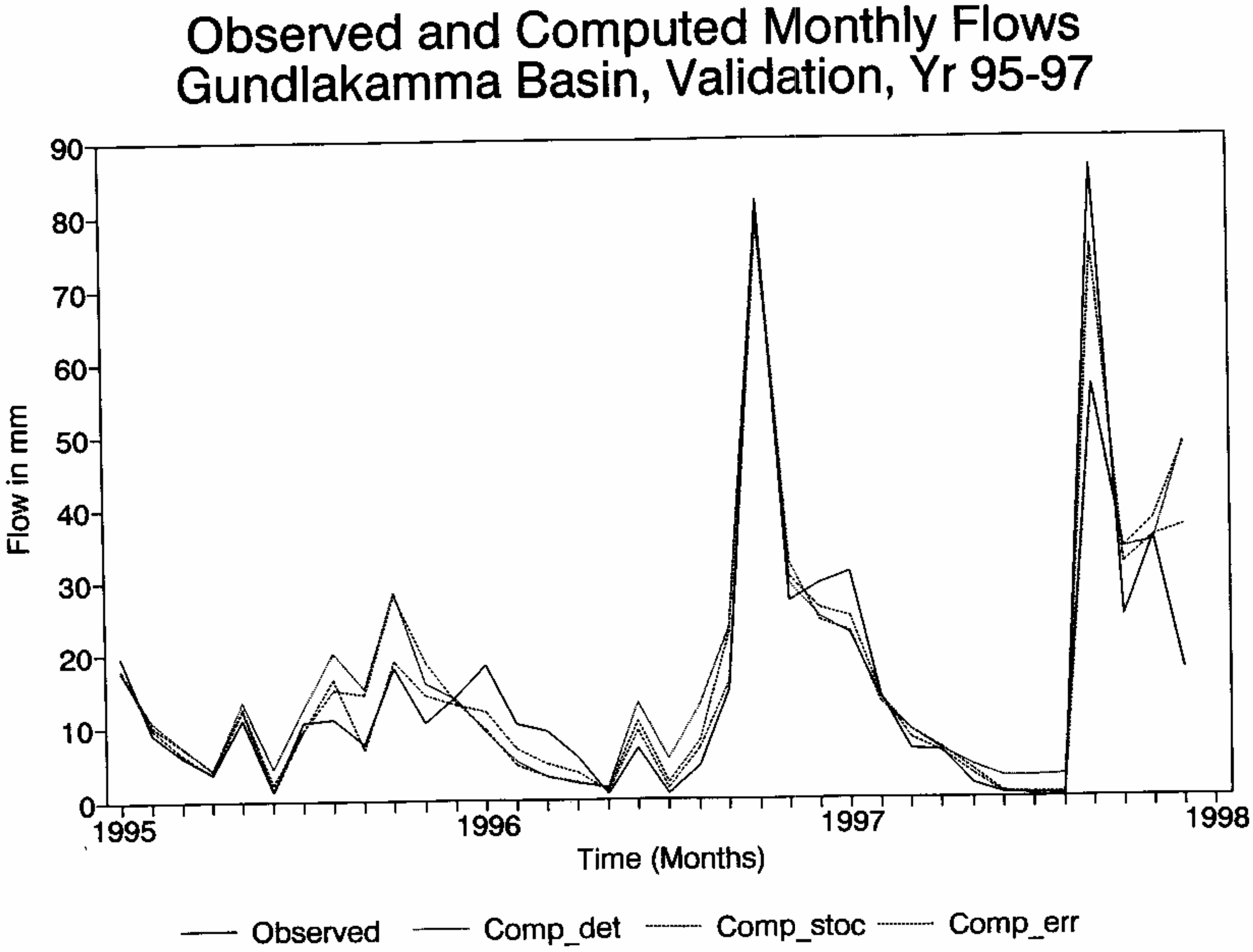

Figure 8: **Plots of observed and computed monthly flows for the years 1995-97 for Gundlakamma basin, verification period**

For Sher basin, for calibration period the overall efficiency is 69.42% while during verification it is 64.72%, Efficiency based on modified flows by AR model is 71.05% and 68.78%, while for flows modified by average error it is 76.68% and 67.73% for calibration and verification periods respectively. The resulting simulated daily runoff values by using all the three models along with observed runoff values for one year are plotted in Fig. 9 for calibration period and in Fig. 10 for verification periods. Similarly, the modelled and observed monthly runoff for calibration period is shown in Fig. 11 and for verification period in Fig. 12. These efficiency values are also given in Table 3.

Similarly, for Manot basin, for calibration period the overall efficiency is 65.38% while during verification it is 48.39%, Efficiencies based on modified flows by AR model are 66.71% and 52.66%, while for flows modified by average error these values are 75.02% and 55.30% for calibration and verification periods respectively. The resulting simulated daily runoff values by using all the three models along with observed runoff values for one year are plotted in Fig. 13 for calibration period and in Fig. 14 for verification periods. Similarly, the modelled and observed monthly runoff for calibration period is shown in Fig. 15 and for verification period in Fig. 16. Table 3 depicts these efficiency values.

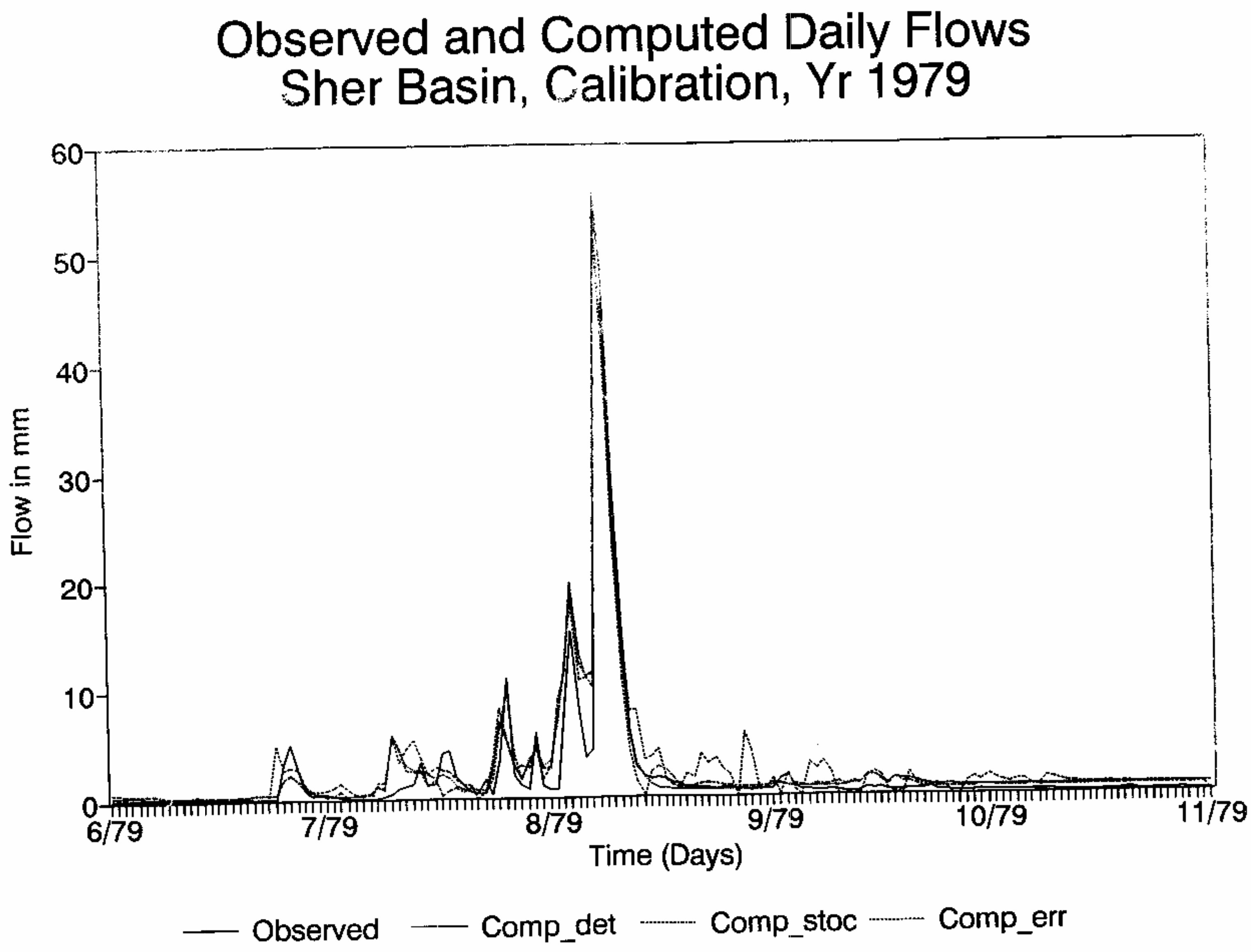

Figure 9: Plots of observed and computed daily flows for the year 1979 for Sher basin, calibration period

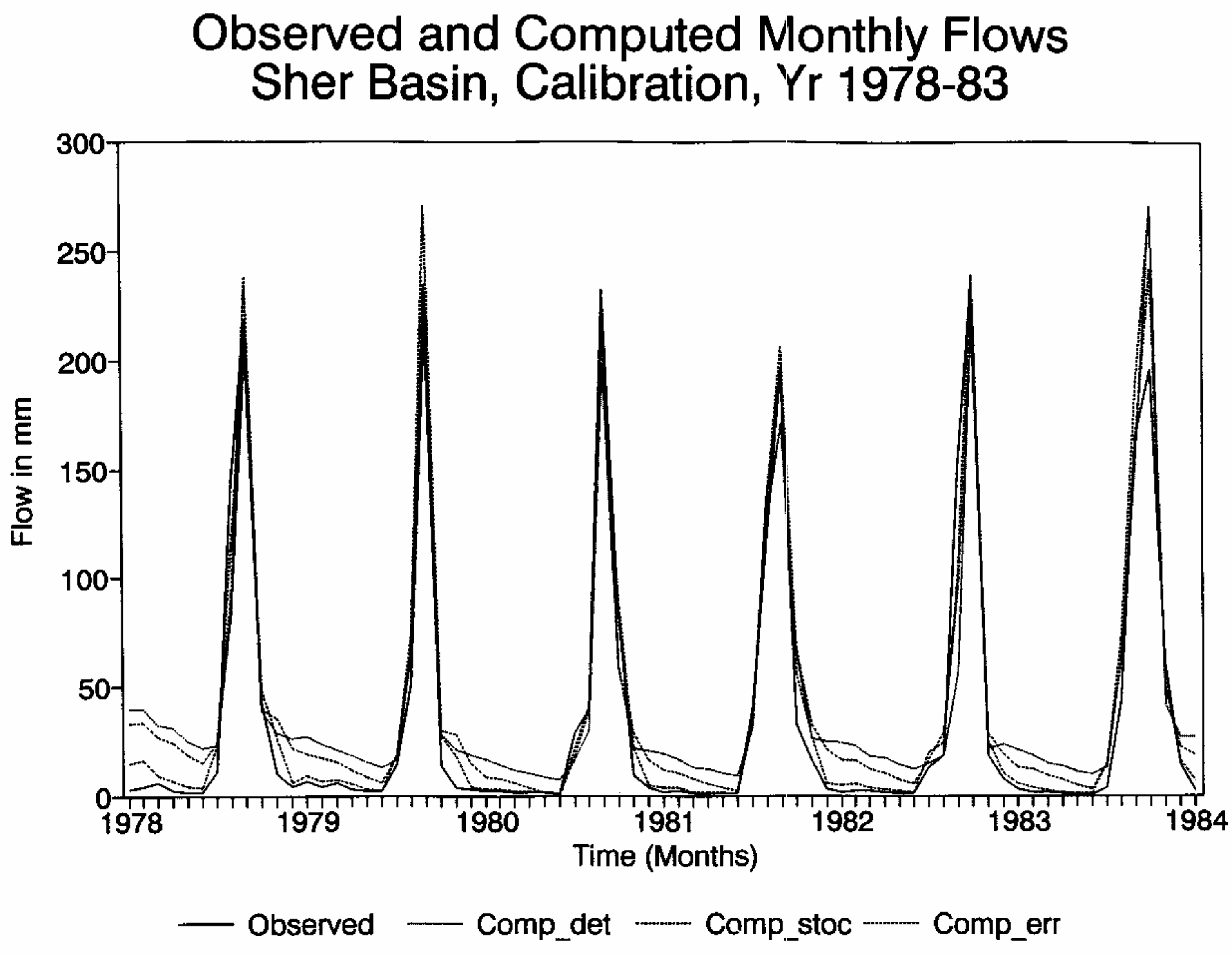

Figure 10: **Plots of observed and computed monthly flows for the years 1978-83 for Sher basin, calibration period**

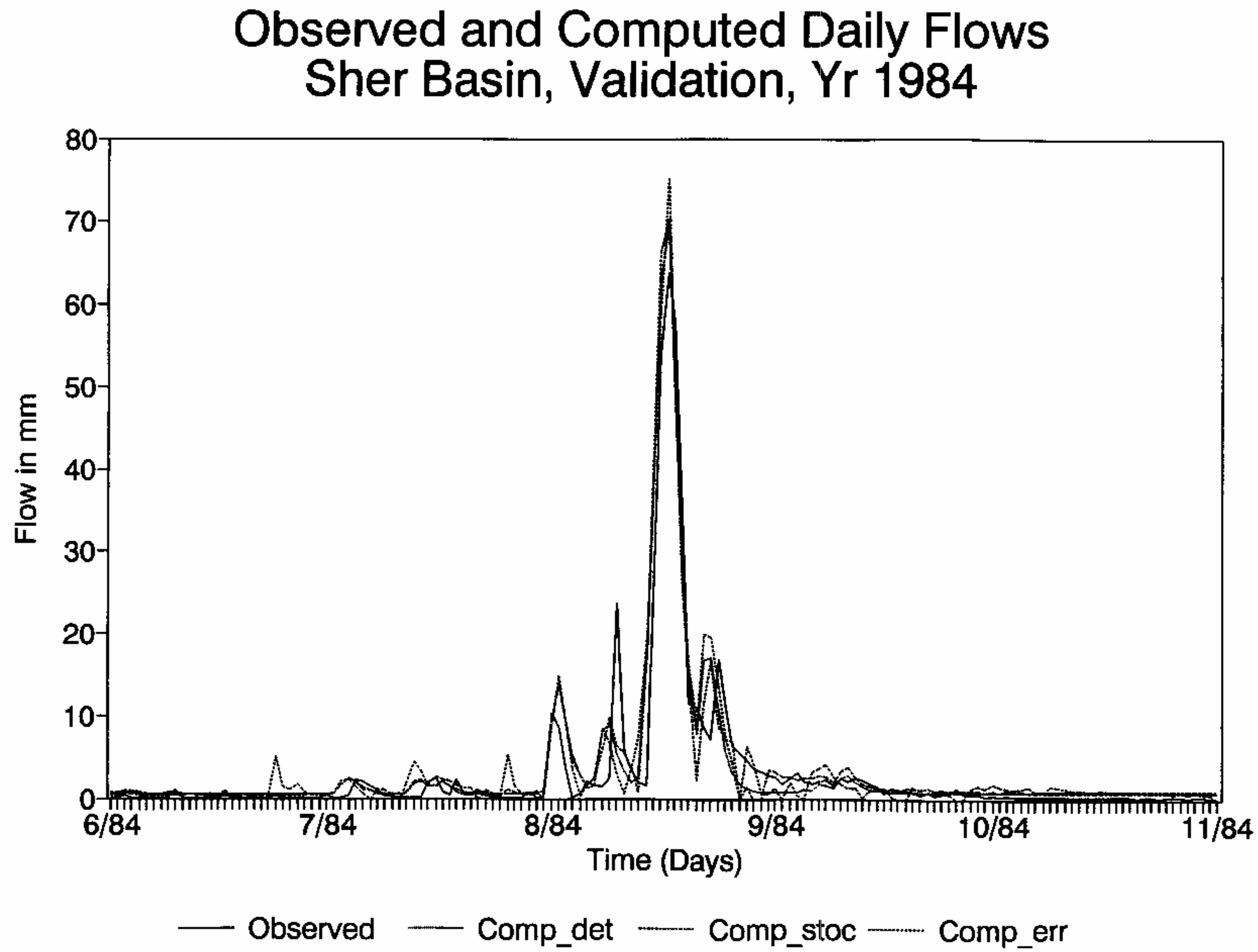

Figure 11: **Plots of observed and computed daily flows for the year 1984 for Sher basin, verification period**

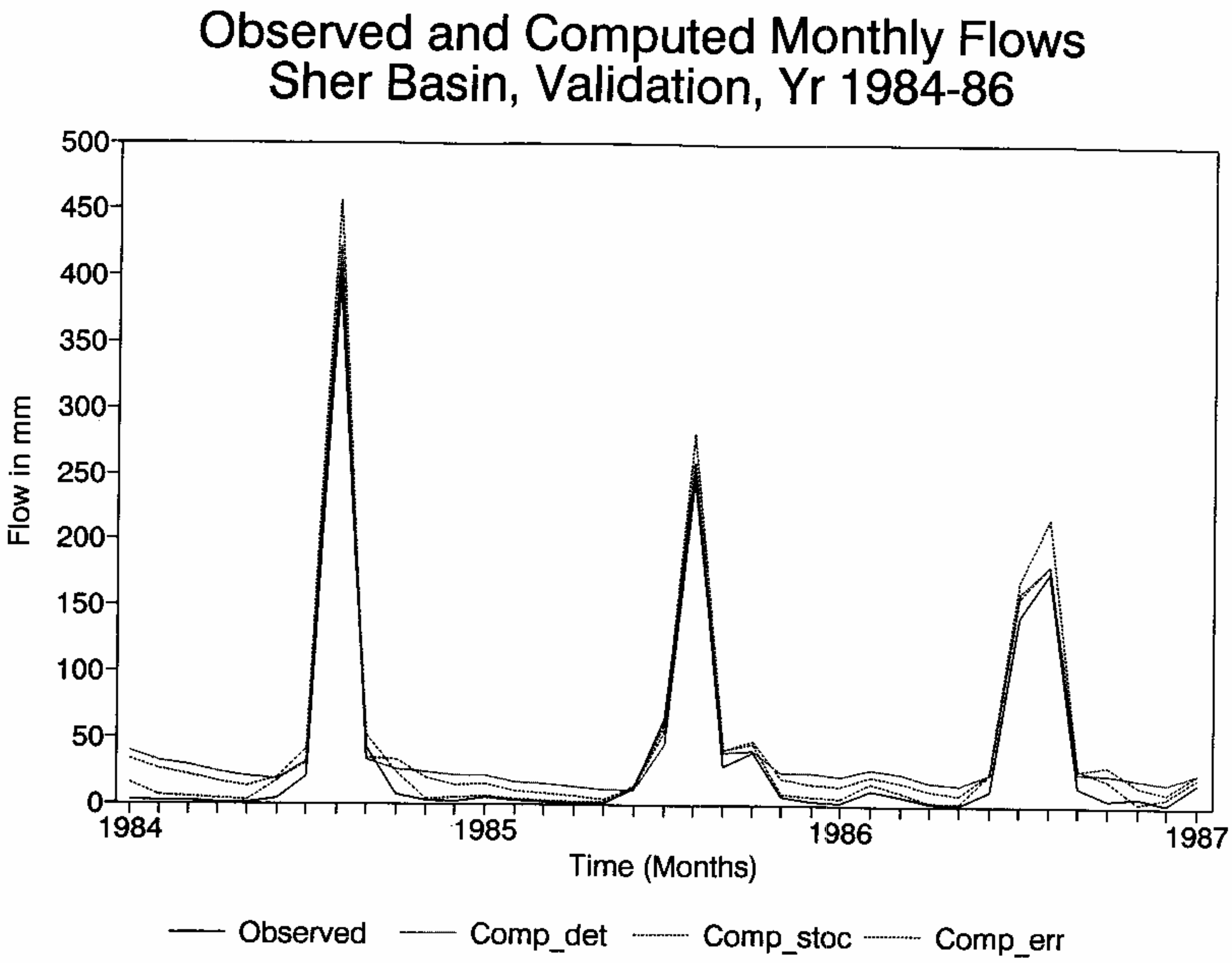

Figure 12: **Plots of observed and computed monthly flows for the years 1984-86 for Sher basin, verification period**

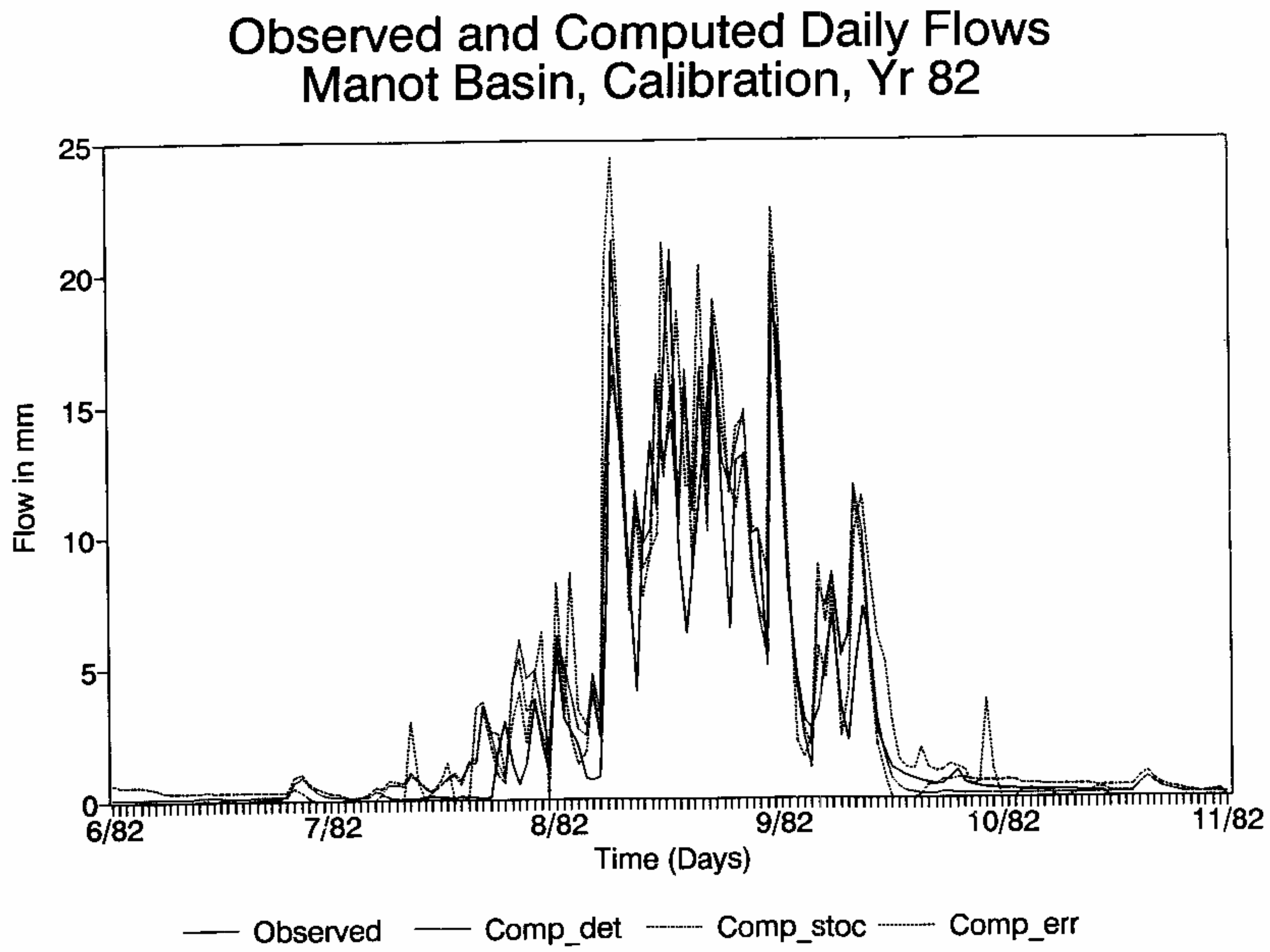

Figure 13: **Plots of observed and computed daily flows for the year 1982 for Manot basin, calibration period**

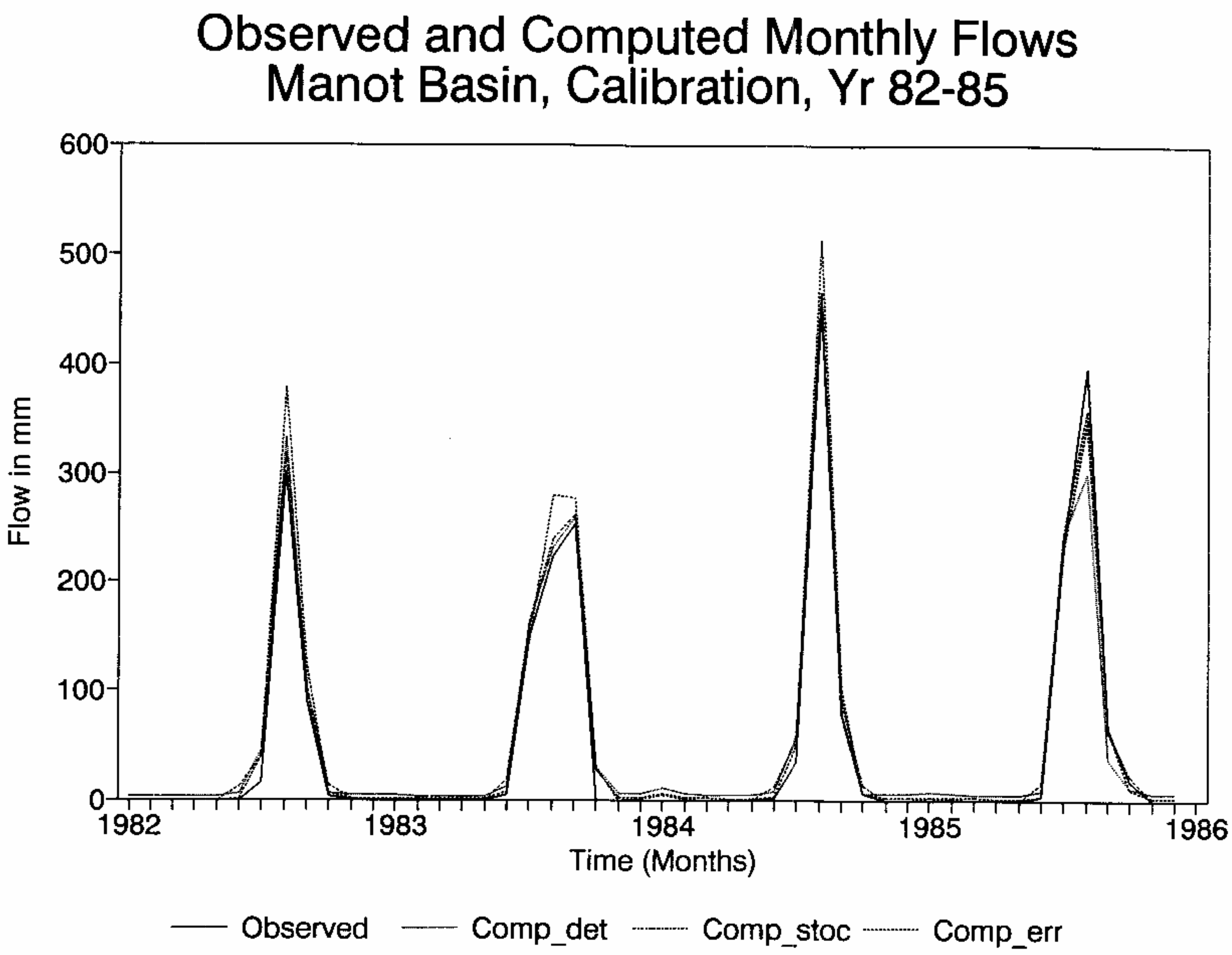

Figure 14: **Plots of observed and computed monthly flows for the years 1982-85 for Manot basin, calibration period**

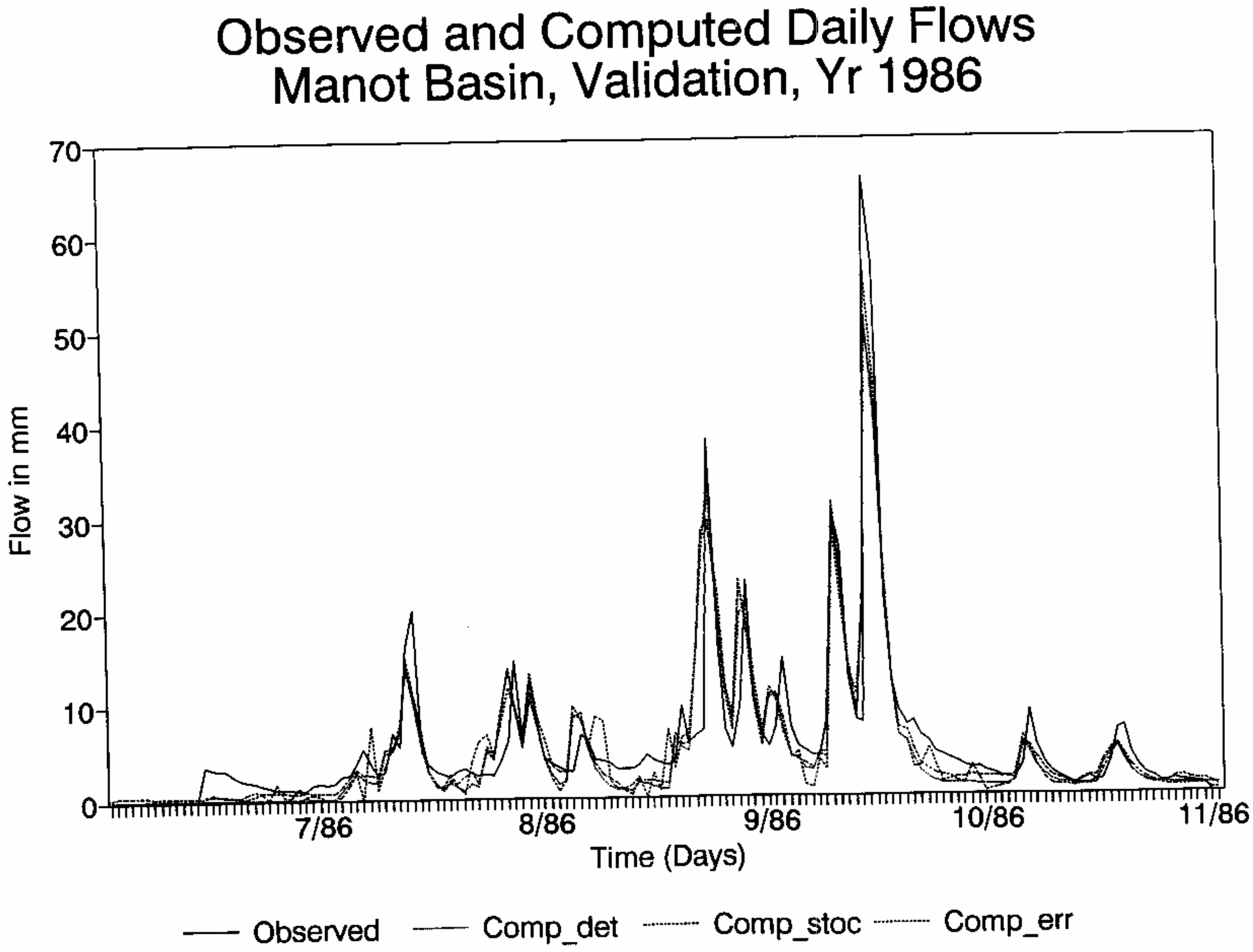

Figure 15: **Plots of observed and computed daily flows for the year 1986 for Manot basin, verification period**

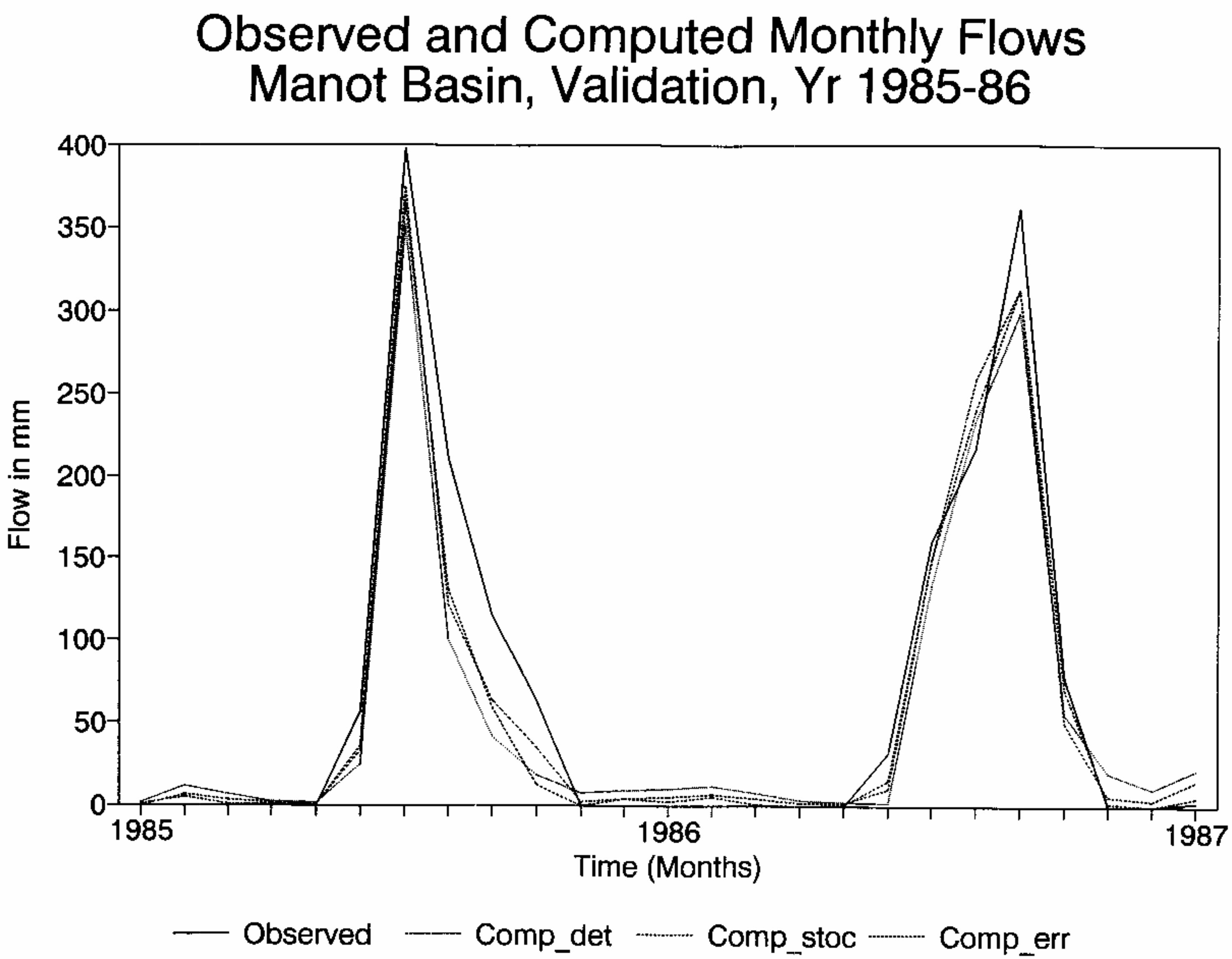

Figure 16: **Plots of observed and computed monthly flows for the years 1985-86 for Manot basin, verification period**

RESULT DISCUSSIONS

The mathematical functions or expressions or conceptual elements employed to simulate the natural hydrological processes are subject to limitations of the present state of knowledge of physical behaviour, mathematical constraints, data availability, its quality and, user requirements. In spite of rapid advances in hydrology particularly in catchment hydrology and modelling, it is not always possible to make universal use of such models because local problems predominate over other factors.

Keeping in view the above limitations and requirements, a simple structure of daily time step is tested on three basins. The daily values of flows as computed by this model are tried to refined by using average error computed for each day and also by fitting an AR model to the errors.

The efficiency and the response of the modelled runoff to the rainfall as observed visually from the figures plotted suggested that the water balance model could simulate the flows reasonably well. Also, the incorporation of AR model or error model could improve the results only marginally. As behaviour of error seemed to be event specific and erratic, it could not be modelled well and thus could not improve the computed flows. The peak flows could not be simulated properly may be due to error because of lumping the rainfall, which is common with any lumped model. Available rainfall data for stations within and near the catchments is used to derive the basin average rainfall using the Thiessen method. However, this averaging may distort the original rainfall intensity pattern if the rainfall distribution or station distribution is not uniform over the entire catchment. Thus, the spatial averaging brings in certain error into the modelled flows if storms are not uniformly distributed. Some local storm events of heavy intense rainfall on the lower reaches of catchment can result in high-observed discharges, which are difficult to be simulated properly with the lumping of data, as the storms are not uniformly distributed over the catchment. It is to be mentioned here that such events have an effect on the value of objective functions and thus on efficiency of the model. Also, the results of the study to some extent may be influenced by the quality of data as these have been used as such.

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