A MULTIPLE - INPUT SINGLE - OUTPUT MODEL FOR FLOW FORECASTING OF WARDHA RIVER

A DISSERTATION

submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
WATER RESOURCES DEVELOPMENT
(CIVIL)

By
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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"A MULTIPLE-INPUT SINGLE-OUTPUT MODEL FOR FLOW FORECASTING OF WARDHA RIVER"**, in partial fulfilment of the requirements for the award of the Degree of **Master of Engineering** in **Water Resources Development (Civil),** submitted in the Water Resources Development Training Centre, University of Roorkee, Roorkee is an authentic record of my own work carried out during the period from July 16th 2000 to January 2001 under the supervision of **Dr. U. C. Chaube**, Professor, WRDTC and **Dr. U. C. Kothyari,** Assistant Professor, Civil Engineering Department, University of Roorkee, Roorkee.

The matter embodied in this thesis has not been submitted by me for the award of any other degree.

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NOTATIONS

D	= Duration of rainfall
DRH	= Direct Runoff Hydrograph
e	= Difference between computed and observed discharge i.e. model residual
e_{OLS}	= Error in ordinary least squares estimate
E^2	= Efficiency of response function estimation i.e. model efficiency in percentage
F_d	= Initial variance of observed discharge
F_1	= Residual variance of observed discharge
G & D	= Gauge and discharge
H	= Loss of rainfall
I	= Identity matrix
J	= Total number of sub-catchments
K	= Parameter to be chosen by user in smoothed least squares estimate.
$\hat{K}$	= Ratio of Bayesian estimates
l_n	= Natural logarithm
l	= Linear portion of memory length of catchment
mm	= Sum of response function ordinates in the model
m	= Total memory length of catchment
MSE	= Mean squares error
NLP	= Non-linear programming
n	= Non-linear portion of memory length of catchment
P	= Rainfall
P^T	= Transpose of matrix by rainfall values.
Q	= Observed runoff
$\hat{Q}$	= Computed runoff.
$\overline{Q}$	= Mean of observed discharge
$Q_{d;r}$	= Observed discharge on date ‘d’ in year ‘r’.
R	= Total rainfall for a period.

RGS = Rain gauge stations

RFO = Response function ordinate

S = System

S_{err} = Standard error in response function ordinate

S^2 = Mean residual variance of observed discharge i.e. mean square error of computed and observed discharge.

t = Time at which the runoff measured

U = Response function ordinate

$\hat{U}$ = Estimated response function ordinate

U_m = Last ordinate of the response function

UH = Unit hydrograph

V = Resultant matrix from the product of $[P^T][P]$

V^{-1} = Principal diagonal terms of matrix $[P^TP]^{-1}$

X = Identity matrix or Laplacian matrix in Bayesian method.

Z = Multiplicative biasing matrix

Z_o = Objective function to be used in linear and non-linear programming model.

ε = Error term

ρ = Prior density of response function ordinate i.e. Bayesian estimate.

ξ = Positive constant i.e. Baysian estimate

ρ^2 = Noise variance

$t-\tau$ = Time-lag since the input was applied.

δ_t = Duration of time increment

τ = Time in which the rainfall occur

Σ = Summation.

ABSTRACT

A large number of methods have been proposed in the past to predict the flood discharges resulting due to a storm event in a catchment. Unit Hydrograph method described by the response functions is the most popular and widely used practical tool, among the various available methods. But, one of the basic assumptions followed in this method is that the effective rainfall is occurring simultaneously over the whole catchment uniformly, which is seldom true, in case of large catchments. The spatial variation generally becomes more and more pronounced as the size of the catchment increases. The unit hydrograph hypothesis is particularly adequate in the range of floods experienced on small catchments (size smaller about 500 km^2). For large catchments, it may even happen that some part of the catchment would not have any rain at all during the storm period. Also, these methods are derived on the concept of lumped linear response functions.

In the present thesis, a multiple-input single-output nonlinear model based on systems approach proposed by Muftuoglu (1984 & 1991) has been formulated for forecasting flows during flood events. The total rainfalls have been considered as the inputs and the total runoff as the output as against to the use of effective rainfall and direct runoff as input and output respectively used in conventional unit hydrograph method. The whole catchment area was divided into a number of sub-catchments which receive uniform rainfall, approximately. Rainfall of each sub-catchment was treated as separate lumped inputs to the model to incorporate spatial variations of rainfall as well as catchment heterogeneities. To derive composite response functions of the catchment, various data sets in calibration period were stacked together.

Rainfall and runoff data of the Wardha catchment upto Ghugus gauging site have been used for calibration and verification of the model. Results have been obtained for one, two and three rainfall inputs for the Wardha catchment with its discharge at Ghugus being the output. Both linear and nonlinear approaches have been studied. Multiple-input approach by linear and nonlinear methods was also compared with the rest of the results. Better results have been obtained when number of inputs in the nonlinear model were increased from one to three.

The search for truth is in one way hard and in another way easy. For it is evident that no one can master it fully nor miss it wholly. But each adds a little to our knowledge of Nature, and from all the facts assembled there arises a certain grandeur.

Aristotle

INTRODUCTION

1.1 GENERAL

A flood is an unusually high stage in a river normally the level at which the river overflows its banks and inundates the adjoining area, causing disruption of day to day activity. At a given location in a stream, peak flood values vary from year to year and their magnitude constitutes a hydrology series. In planning and design of water development projects peak flood values that can be expected are of primary importance as it is required to adequately proportion the structure for controlling the adverse effects of the flood.

The flood magnitude in a catchment depend upon the characteristics of the catchment, rainfall and antecedent condition, each one of these factors in turn depend upon a host of constituent parameters. This makes the prediction of the flood flows a very complex problem. Hence, the problem of flow-forecasting resulting from a known storm in a catchment has received considerable attention. The study in this direction which is essential in analyzing stream characteristics associated with floods forms the vital subject matter of applied hydrology. The computations were performed by experienced hydrometeorologists by using meteorological data in the past. Various methods ranging from highly sophisticated ones to simple empirical methods have been proposed for predicting the flood runoff. Probably the most popular and widely used method for prediction of floods is the unit hydrograph method.

This method was first suggested by Sherman in (1932). Details of background on the unit hydrograph method are discussed below.

1.2 The Unit Hydrograph Theory

A unit hydrograph represents the lumped response of the catchment to a unit rainfall excess occurring uniformly over the basin and at a uniform rate for a specified duration to produce a direct-runoff hydrograph .It relates only the direct runoff to the rainfall excess.

The basic foundation of unit hyrograph theory is supported on the assumptions / principles of (i) the linear response and (ii) the time- invariance.

These are described below (Johnstone and Cross, 1949):

1. For a given catchment, the duration of surface runoff is essentially constant for all uniform-intensity storms of the same length, regard less of differences in the total volume of surface runoff.
2. For a given catchment, if two uniform intenstiy storms of same length produce different total volumes of surface runoff, then the rates of surface runoff at corresponding times t, after beginning of two storms are in the same proportion to each other as the total volumes of surface runoff.
3. The time distribution of surfaces runoff from a given storm period is independent of concurrent runoff from antecedent storm periods.

1.2.1 Limitations of Unit Hydrograph Theory

Following are the limitations of unit hydrograph theory.

1.2.1.1 Space invariance of effective rainfall

(i) It is seldom true that the effective rainfall of a specified duration will occur uniformly over the catchment of a reasonable size. Therefore, spatial invariance of the effective rainfall is only an assumption, not a reality. The spatial variation generally becomes more and more pronounced as the size of the catchment increases.

(ii) Intense rainfall storms usually do not extend over large areas. A fair semblance of a uniform spatial distribution of rainfall may seldom be obtained on catchment exceeding 500 km^2 an upper limit conventionally observed in the application of the unit hydrograph.

(iii) The non-uniform areal distribution of rainfall can cause variation in hydrograph shape (Dickinson and Ayers, 1965).

1.2.1.2 Time – invariance of effective rainfall

The effective rainfall usually does not occur uniformly even for a short duration. However the effect of temporal variation of rainfall intensity can be accounted for by using smaller period rainfalls.

1.2.1.3 Validity of linearity hypothesis

All catchments in nature are nonlinear; some are more nonlinear and some less. They are linear only by assumption (Singh, 1988).

If the hydrographs from the storms of the same duration are compared, it is commonly found that their ordinates are not in proportion to their volumes and that their time bases are not the same. The peaks of the unit hydrographs for small rainfall events are usually lower than those for larger ones.

Also, the length of the recession depends on the hydrograph peak. Moreover, the catchment linearity requires a linear relationship between storage and discharge and that the velocity of flow at every point must be constant for all discharges. These conditions are too stringent and are almost never valid.

1.3 NEED OF THE STUDY

Runoff is the response of a catchment for a particular rainfall pattern under various hydrometeorological factors and the exact prediction of which is rather difficult but prerequisite for successful planing and design of water resources project for irrigation, water supply, hydropower, flood management/flood forecasting and other water use systems. Of the various characteristics of the flood hydrograph, the most important and widely used parameter is the flood peak the hydrograph of extreme flood and stages corresponding to flood peaks provide valuable data for purposes of hydrologic design. In the design of practically all hydraulic structures the peak flow that can be expected is of primary importance to adequately proportion the structure to accommodate its effect. T.the design of bridges, culverts, water ways and spillways for dams and estimation of scour at a hydraulic structure are some examples where in flood- peak values are required and play an important role.

It is well appreciated that a runoff series which extends back far enough to include typical long-term variations is essential for proper planning and design of various water-use systems. Very few rivers, however have runoff records which satisfy this requirement. Although statistical methods enable the designer to generate synthetic data, the success of these methods also depends on the length of the available data from which the statistical model parameters are derived. Also many of the streams in India are ungauged. Therefore, it is required to have reliable methods which can be used for the prediction of flood flow and its peak from precipitation records.

1.4 THE PHENOMENON OF CATCHMENT RUNOFF

Runoff means the draining or flowing off of precipitaion from a catchment area through a surface channel. It thus represents the output from the catchment in a given unit of time. The phenomenon of watershed runoff is complex. The watershed runoff is mainly composed of three components which may, at a given time occur separately or simultaneously with varying magnitudes. These are (i) surface runoff, (ii) subsurface runoff or inter flow and (iii) base flow or ground water runoff.

Surface runoff usually occurs when the rainfall intensity exceeds the initial demand of interception, infiltration, and surface storage. The surface runoff travels over the ground surface and through channels to the watershed outlet. So, the surface runoff may be composed of (i) over land flow and (ii) channel flow. As surface runoff flows towards the watershed outlet, a portion of it is infiltered into the soil or channel bed. The infiltration taking place in a channel is often referred to as transmission loss.

The subsurface runoff represents that portion of infiltrated rainfall that moves laterally through the upper soil horizons until it reaches the stream channel. This moves more slowly than surface runoff and may join the surface runoff during or after the storm.

The proportion of stream flow that occurs as subsurface runoff depends on geological characteristics of the watershed and space-time properties rainfall.

The base flow is that portion of infiltrated water that reaches the water table and then discharges into the stream. This type of flow moves much more slowly and has little effect on flood peaks in small watersheds. Depending upon permeability of soil, the base flow response widely varies from one ground water body to another.

The direct runoff is considered to consist of surface runoff and so-called quick inter flow, whereas base flow consists of delayed inter flow and ground water runoff. Figure 1.1 depicts different routes of runoff.

1.5 A MULTIPLE-INPUT SINGLE-OUTPUT FLOW FORECASTING MODELS- AT A GLANCE

In this approach, the continuity equation of flow is expressed is a spatially lumped form without considering the physical laws operating within the catchment and instead a general but simple relationship is assumed between rainfall amount and the discharges at the outlet of the catchment. The model in its original form with single input is sufficient for small catchments where the rainfall distribution can be assumed to be uniform. In case of larger catchments, the violation of the assumption of uniformity of rainfall is higher. Therefore, the large catchment is divided into a number of hydrologically homogeneous sub-catchments. The rainfall occurring over these sub-catchments can be considered as independent inputs. The model consists of both non-linear and linear components. Because of these reasons the model can take care of spatial variation of rainfall as well as catchment heterogeneities (which are major inabilities in the lumped models, now-a-days in the practice) while transforming daily rainfall into runoff, (Kothyari and Singh, 1999).

Muftuoglu (1984) was the first to suggest the structure of a linear – nonlinear combined model. Liang (1988) checked the validity of multiple- input single-output model in hydrological fore casting. Later, the same linear and non-linear models in the above aspect have been studied in detail covering various aspects by Liang and Nash (1988), Liang et al. (1992) and Liang et al. (1994). Kothyari and Singh (1999) applied a multiple-input single-output rainfall-runoff model for prediction of daily flows in Narmada catchment. The detailed description about these are mentioned in the Chapter-2.

1.6 PROBLEMS IN THE USE OF METHODS FOR DETERMINATION OF RESPONSE FUNCTION OF A MULTIPLE – INPUT SINGLE - OUTPUT MODEL

The Problem of the numerical instability of a unit hydrograph derived by ordinary least squares from a complex rainfall- runoff event is well known is hydrology. The same problem though perhaps less acute, arises in the identification of the pulse response of the single-input single-output linear, time invariant model applied in the process of flood routing or rainfall-runoff modeling. This problem is not due to the model itself, rather it is due to the estimation method, the sample size and the observed input and output variables, especially the input variables. Bree (1978) pointed out that the estimation of the ordinates of non-parametric unit hydrographs from sample data is very sensitive to the interrelation existing among the observed input series.

The problem has been tackled by Kutchment (1967) and Bruen and Dooge (1994) amongst others using the concept of ridge regression which produces a least squares estimate subject to a constraint expressing the preferred shape of the impulse response.

In the context of a system receiving multiple inputs in parallel, e.g. forecasting the outflow hydrograph in terms of observed inflow hydrographs further up the main stream and on tributaries with or without rainfall on the intervening catchment, the problem obviously becomes more difficult and the possibility of numerical instability is increased, because of the expectation of cross-correlation between various input functions. However, this can be overcome by addition of an uncorrelated white noise component to the inflow series (Liang and Nash, 1988). Amongst the methods available for estimation of response function in the presence of noise in the data, the method of smoothed least squares by Bruen and Dooge (1994) is probably the best suited method.

1.7 AIM OF THE PRESENT STUDY

Inspite of the fact that the unit hydrograph is a practical tool, its inability to represent the full catchment operation which is a non-linear process directed attention to non-linear models some two decades ago. The endeavor resulted in the discovery of the potentialities for catehment analysis of the functional series which was already being used in electronics (Amorocho, 1973). The functional series is a universal mathematical model for non-linear black-box systems, which produced a single output from a serial input.

The unit hydrograph is based on the assumption that the rainfall is occurring simultaneously on the whole catchment with same intensity which is practically not possible. This assumption may be true for a small catchment but the same cannot be true for large ones. Therefore, to derive a response function of a large catchment, it is divided into a number of sub-catchments having the uniform rainfall through out in those sub-areas. The aim of the present study is to derive the response function for a catchment which is divided into small sub-catchments from consideration of the rainfall inputs. Both the linear and non-linear approaches were applied.

Chapter- 2

REVIEW OF LITERATURE

2.1 GENERAL

Most hydrologic systems are extremely complex and we can not hope to understand them in all detail. Therefor abstraction is necessary if we are to understand or control some aspects of their behavior. Abstraction consists in replacing the system under consideration with a model of similar but simpler structure. The basic purpose of a model is to simulate and predict the operation of the system that is unduly complex and the effect of changes on this operation.

The hydrologic cycle can be regarded as a hydrologic system. Various components of this system might include precipitation, interception, evaporation, transpiration, infiltration, detention storage or retention storage, surface runoff, inter flow and groundwater flow. Each component is a subsystem, if it satisfies the characteristics of a system set-out in its definition.

There are many illustrations representing the hydrologic cycle. Among them, recognizing the scope of hydrology, more detailed and the simplified system representation for catchment runoff is shown in Fig.2.1.

A catchment can be stated to a hydrologic system. When unit input is applied to the hydrologic system in the form of rainfall, the response function of hydrologic system comes out in the form of runoff. Several response functions can be obtained for single catchment by applying different rainfalls. Various types of response functions are discussed below.

2.2 RESPONSE FUNCTIONS OF LINEAR SYSTEM

2.2.1 The Impulse Response Function

If a system receives an input of unit amount applied instantaneously at time 'τ' the response of the system at later time't' is described by the unit impulse response function u(t-τ).

't-τ' is the time-lag since the input was applied

2.2.2 The Step Response Function

A unit step input is an input that goes from a rate of 0 to 1 at time 'o' and continues definitely at that rate thereafter. The ouput of the system, its step response function is

$$g^{(t)} = \int_0^t u(t-\tau)d\tau \tag{2.1}$$

2.2.3 The Pulse Response Function:

A unit pulse is an input of unit amount occurring in duration δt. the rate is I(τ)= 1/δt, 0$\leq \tau \leq \delta$t and zero else where. The response of the system at time t is described by the unit pulse response function U(t).

$$U(t) = \frac{1}{\delta t}[g(t) - g(t - \delta t)] \tag{2.2}$$

2.2.4 The Standardized Unit Pulse Response

The unit hydrograph as a relationship between "effective rainfall" and "Storm runoff" is necessarily of unit volume as the volumes of the input and output are equal. However, where volume is not conserved, the sum of the ordinates multiplied by the common interval between them represents a "gain factor" which may be greater or less than unity, reflecting the ratio of the volumes of output and input.

$$J^{th} \text{ gain factor } g(j) = \sum_{j=1}^{m(j)} U_i^{(j)}, j = 1,2,\ldots\ldots, j \tag{2.3}$$

The "standardized unit pulse response" is obtained by dividing every ordinate of the least squares unit pulse response by the corresponding gain factor, thus reducing the area to unity.

2.2.5 The Gamma Function Impulse Response

For a single input-single output, linear system the model is

$$U(t) = (t/k)^{n-1} e^{-t/k} / k\Gamma(n) \qquad (2.4)$$

where,

k = a parameter of dimension time

n = a shape parameter

$\Gamma(n)$ = gamma function of n

This was suggested by Nash (1957) in the context of rainfall-runoff modeling and by Kalinin and Milyukov (1957) in the context of flood routing.

2.3 RESPONSE FUNCTION FROM MULTIPERIOD STORM

2.3.1 Linear System

It may be more representative to derive a single composite response function for a catchment from several rainfall events considered simultaneously

The relationship of the sampled various flood hydrograph ordinates Q, rainfall P and response function ordinates U can be expressed as,

$$Q_{i,n} = P_{i,n} U_1 + P_{i,n-1} U_2 + \ldots\ldots\ldots\ldots + P_{i,n-m+1} U_m \qquad (2.5)$$

$i = 1,2,\ldots..I$

$m = 1,2,\ldots M$

$n = 1,2,\ldots N,$

in which

i = number of flood event

I = total number of flood events

n = ordinate number of each observed hydrograph

N_I = total number of ordinates of the observed hydrograph

m = number of unit hydrograph ordinates

M = total number of unit hydrograph ordinates.

Matrix representation of general Eq. (2.5) is:

$$[Q] = [P]\,[U] \qquad (2.6)$$

when 'I' number of storms occur on a catchment, then the relationship among the hydrographic ordinates 'Q', rainfall 'P' and response function ordinates 'U' are represented in the matrix form as below:

$$
\begin{bmatrix} Q_{1,1} \\ Q_{1,2} \\ \cdot \\ Q_{1,N_1} \\ Q_{2,1} \\ Q_{2,2} \\ \cdot \\ Q_{2,N_2} \\ \cdot \\ \cdot \\ \cdot \\ Q_{I,1} \\ Q_{I,2} \\ \cdot \\ Q_{I,N_I} \end{bmatrix}
=
\begin{bmatrix}
P_{1,1} & 0 & 0 & \cdot & \cdot \\
P_{1,2} & P_{1,1} & 0 & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot \\
P_{1,N_1} & \cdot & \cdot & \cdot & P_{1,N_1-m+1} \\
P_{2,1} & 0 & 0 & \cdot & \cdot \\
P_{2,2} & P_{2,1} & 0 & \cdot & \cdot \\
P_{2,N_2} & \cdot & \cdot & \cdot & P_{2,N_2-m+1} \\
\cdot & \cdot & \cdot & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot \\
P_{I,1} & 0 & 0 & \cdot & \cdot \\
P_{I,2} & P_{I,1} & 0 & \cdot & \cdot \\
P_{I,N_I} & \cdot & \cdot & \cdot & P_{I,N_I-m+1}
\end{bmatrix}
*
\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ \cdot \\ \cdot \\ \cdot \\ U_m \end{bmatrix}
\qquad (2.7)
$$

Solution of Eq. (2.6) for 'U' can be obtained from the least squares solution of the above mentioned matrix equations. Details of solution procedure are discussed later. Jain (1993) used this methodology for fore casting of floods in two non-seasonal catchments namely Bird Creck in USA and Ray in UK and obtained satisfactory flood predictions, using eq. (2.5).

2.3.2 Non-Linear System

The catchment can also be considered as a variable non-linear system that operates on the rainfall continuously to transform it into the runoff.

If the catchment was a linear system, the runoff 'Q_m would be expressed in term of the rainfall 'P_I' occurring in each unit interval of the memory as.

$$Q_m = \sum_{i=0}^{m} U_{m-i} P_i \qquad (2.8)$$

where 'm' is the number of unit intervals in the duration of the memory (counting from 0) and U_{m-I} is a coefficient representing the contribution rate from the (m-i) the internal- Interception, depression, detention and soil storage are partly or fully produced by the rainfall occurring in the antecedent intervals. More over, the sheet and channel flows are non-linear functions of current rain intensities, therefore, the coefficients 'U_{m-I}' are not constant, but vary as function of antecedent and concurrent effective precipitation. Thus we have

$$U_{m-i} = \sum_{j=l}^{m} U_{m-i,m-j} P_j \qquad (2.9)$$

$$i = 0,1,2,\ldots\ldots m$$

where $U_{m-i,m-j}$ is a new coefficient representing the contribution rate from the i^{th} interval, Substituting the equivalent of U_{m-i} into Eq.(2.8) we have.

$$Q_m = \sum_{i=0}^{m} \sum_{j=l}^{m} U_{m-i,m-j} P_i P_j \qquad (2.10)$$

However, the immediate and moderately delayed responses of the catchment are highly non-linear, where as the delayed response can be assumed to be liner (Amorocho, 1963). Thus the model as given in Eq.(2.9) can be modified for immediate or moderately delayed and delayed responses of catchment simultaneously.

This can be modified as given below:

$$Q_m = \sum_{i=l}^{n} \sum_{j=l}^{n} U_{ij} P_{i+l} P_{j+l} + \sum_{i=l}^{l} U_i P_i \qquad (2.11)$$

Where 'm' is the number of unit intervals in the duration of memory. 'n' and 'l' the numbers of intervals in the non-linear and linear parts of memory respectively.

i.e. $m = n + l$ $n =$ non-linear part

$l =$ liner part

Solution of Eq. (2.11) can be obtained from the least squares solution matrix equations. Details of solution procedure are discussed later on in succeeding chapter.

Kumar (1995) had used the non-linear relationship shown in Eq. (2.11) for flood forecasting in two non-seasonal catchments namely Bird Creek in USA and Ray in UK. It was found that better flood forecasts were made by non-linear model as compared to the forecasts made by a linear model used by Jain (1993).

2.4 MULTIPLE - INPUT, SINGLE - OUTPUT SYSTEMS

2.4.1 Linear System

For a linear system, the relationship of a single input function of time p(t) to a single output function of time Q(t) may be expressed by the convolution integral:

$$Q(t) = \int_0^x U(\tau) p(t - \tau) d\tau \qquad (2.12)$$

Where U(t) is the impulse response function. A linear system may not however be restricted to a single input and a single output. A system relating a number of independent input functions of time to a single output function is linear, if the relationship of each input to its component in the output is linear and if the Principle of superposition applies to the combination of the several output components. This relationship may be written as.

$$Q(t) = \sum_{j=1}^{J} \int_0^x U^{(j)}(\tau) p^{(j)'}(t - \tau) d\tau \qquad (2.13)$$

Where, J is the total number of input functions, $p^{(j)}$ is the j^{th} input function of time and $U^{(j)}$ is the unit pulse response function corresponding to the j^{th} input function $p^{(j)}$. When the input function is expressed as a series of pulses (mean values over successive short time intervals T) and the output is similarly expressed, or expressed as a series of ordinates at the same intervals δt the unit pulse response U_1........U_k......U_m (also at intervals of δt), may provide more convenient expression of the operation of the system than the inpulse response. The multiple-input, single-output relationship may be expressed in terms of the pulse response as a series of linear algebraic equations:

$$Q(t) = \sum_{j=1}^{J} \sum_{k=1}^{m(j)} U_k^{(j)} P_{(t-k+1)}^{(j)} \qquad (2.14)$$

Where m(j) is the memory length of the system corresponding to the jth input series. Eq. (2.14) implies:

(1) Each input series p(j) is linearly related to its corresponding output component Q(j), j=1,2….J, by:

$$Q_t^{(j)} = \sum_{k=1}^{m(j)} U_k^{(j)} P_{(t-k+1)}^{(j)}$$

(2) Output components are linearly additive viz.

$$Q_t = Q_t^{(1)} + Q_t^{(2)} + Q_t^{(j)}$$

Given adequate records of input and output functions over a period generally referred to as "the calibration period", analytical solution of Eq. (2.14) for the several $U^{(j)}$ functions is possible. Even in the presence of errors of observation, nonlinearly, least square solutions may be obtained.

Equation (2.14) becomes;

$$Q_t = \sum_{j=1}^{J} \sum_{t=1}^{m(j)} U_k^{(j)} P_{(t-k+1)}^{(j)} \qquad (2.15)$$

If each $U^{(j)}$ is treated as an unrestricted series, least squares solutions may be obtained by matrix multiplication as an extension of multiple linear regression. Such solutions are referred to as "non parametric".

Where the U functions are of known form, or can be assumed to be of some specified form with sufficient generality, though varying in their parameter values, solution of Eq. (2.15) requires only the determination of these parameter values. Such "parametric" solutions are less general but also less sensitive to data errors.

Discrete non parametric solution of Eq. (2.15):

Eq. (2s.15), for a series of N values Q_1, Q_2, ...Q_n can be written in matrix form as:

$$Q = P^{(1)} U^{(1)} + P^{(2)} U^{(2)} + ... + P^{(j)} U^{(j)} \qquad (2.16)$$

Where Q is an (N,1) columns vector of the output series such that:

$$Q = \begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ \vdots \\ Q_N \end{bmatrix} \qquad (2.17)$$

$P^{(j)}$ is an $[N, m_{(j)}]$ matrix of the jth input series:

$$P^{(j)} = \begin{bmatrix} P_1^{(j)} & 0 & . & 0 \\ P_2^{(j)} & P_1^{(j)} & . & 0 \\ P_{m(j)}^{(j)} & P_{m(j)-1}^{(j)} & . & P_1^{(j)} \\ P_N^{(j)} & P_{N-1}^{(j)} & . & P_{N-m(j)+1}^{(j)} \end{bmatrix} \qquad (2.18)$$

$U^{(j)}$ is an [m(j),1] column vector of the pulse response ordinates corresponding to j^{th} input series:

$$U^{(j)} = \begin{bmatrix} U_1^{(j)} \\ U_2^{(j)} \\ \vdots \\ \vdots \\ U_m^{(j)} \end{bmatrix}$$

Eq. (2.16) can be written as:

$$Q = PU \qquad (2.19)$$

Where P is an (N,M) matrix:

$$P = [P^{(1)} P^{(2)} ....P^{(j)}]$$

And U is an (M,1) column vector of length $M = \sum_{j=1}^{J} m(j)$ obtained by writing each $U^{(j)}$ vector in sequence of j

$$U = \begin{bmatrix} U^{(1)} \\ U^{(2)} \\ \vdots \\ \vdots \\ U^{(j)} \end{bmatrix} \quad (2.20)$$

From Eq. (2.19)

$$Q = P\,U$$

$$\Rightarrow \left[P^T Q\right] = \left[P^T P\right] U$$

$$\Rightarrow U = \left[P^T P\right]^{-1} \left[P^T Q\right] \quad (2.21)$$

With the given value of observed runoff ordinates and rainfall value form each sub-catchment using Eq. (2.19) & (2.21), the response function ordinates of the large catchments can be derived. Liang and Nash (1988) had used this method for flood forecasting in Hankou catchment from the Changjiang (Yangtze) valley in China for examination. The analysis consists of four input functions. The catchment areas above each of the four input gauging sites are Yichang 1, 005, 501 km^2, Huangzhuang 142,056 km^2, Changyang 15,300 km^2 and Chenlinghj. 223,482 km^2. The hydrograph at Hankou is the corresponding output functions. The total catchment area of Hankou as shown in Fig. 2.2 is 1,488,036 km^2. Physically realistic response functions as obtained by his analysis for the above four inputs are shown in Fig. 2.3.

2.4.2 Non-linear System

Response function of a catchment may be non-linear. The multiple-input, single-output relationship may be expressed in terms of the pulse response as a series of non-linear algebraic equations:

$$Q_t = \sum_{j=1}^{J} \sum_{i=1}^{n(J)} \sum_{k=1}^{n(j)} U_{i,k}^{(j)} P_{t-i+1}^{(j)} P_{t-k+1}^{(j)} + \sum_{j=1}^{J} \sum_{i=1}^{l} U_{i+n}^{(j)} P_{t-(i+n)+1}^{(j)} \quad (2.22)$$

Where, j = 1,2,.....J (Number of subcatchment)

n = non-linear part of memory length

l = linear part of memory length

Eq. (2.22) implies

(1) Each input series $P^{(j)}$ is non-linearly related to its corresponding output component $Q^{(j)}{}_t$, j = 1,2,...J by:

$$Q_t = \sum_{t=1}^{m(j)} \sum_{i=1}^{n} \sum_{k=1}^{n} U_{i,k}^{(j)} P_{t-i+1}^{(j)} P_{t-k+1}^{(j)} + \sum_{t=1}^{m(j)} \sum_{i=1}^{1} U_{i+n}^{(j)} P_{t-(i+n)+1}^{(j)}$$

(2) Output components are linearly additive viz.

$$Q_t = Q_t^{(1)} + Q_t^{(2)} + \dots\dots\dots\dots + Q_t^{(j)}$$

Eq. (2.22) can be written in matrix form for a series of N values $Q_1, Q_2 \dots Q_N$ as

$$Q = P^1 U^1 + P^2 U^2 + \dots\dots\dots + P^J U^J \qquad (2.23)$$

Where Q is an (N,1) column vector of output series such that:

$$Q = \begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_N \end{bmatrix} \qquad (2.24)$$

$P^{(J)}$ is an [N, m(j)] matrix of the j^{th} input series:

$$P^{(j)} = \begin{bmatrix} P_1^{(j)} & P_1^{(j)} & P_{1+1}^{(j)^2} & P_{1+1}^{(j)} * P_{1+2}^{(j)} & \cdots & P_m^{(j)^2} \\ P_2^{(j)} & P_{1+1}^{(j)} & P_{1+2}^{(j)^2} & P_{1+2}^{(j)} * P_{1+3}^{(j)} & \cdots & P_{m+1}^{(j)^2} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ P_{(N-m+1)}^{(j)} & P_{(N-m+l)}^{(j)} & P_{(N-m+l+1)}^{(j)^2} & P_{(N-m+l+1)}^{(j)} * P_{(N-m+l+2)}^{(j)} & \cdots & P_N^{(j)^2} \end{bmatrix} \qquad (2.25)$$

$U^{(j)}$ is an [m(j),1] column vector of pulse response ordinates corresponding to j^{th} input series :

$$U^{(j)} = \begin{bmatrix} U_1^{(j)} \\ U_2^{(j)} \\ \vdots \\ U_m^{(j)} \end{bmatrix} \qquad (2.26)$$

Eq. (2.23) can be written as:

$$Q = P\,U \qquad (2.27)$$

Where, P is an [N, M] matrix:

$$P = [P^{(1)}\, P^{(2)} \dots\dots\dots P^{(j)}] \qquad (2.28)$$

And U is an (M,1) column vector of length $M = \sum_{j=1}^{J} m(j)$ obtaining by writing each $U^{(j)}$ vector in sequence of j

$$U = \begin{bmatrix} U^{(1)} \\ U^{(2)} \\ \vdots \\ U^{(j)} \end{bmatrix} \tag{2.29}$$

With the given values of observed runoff ordinates and rainfall value form each sub-catchment use Eq. (2.24) and (2.28) the matrix of runoff and rainfall are formed.

$$Q = P\,U$$
$$\Rightarrow [P^T P][U] = [P^T Q]$$
$$\Rightarrow U = [P^T P]^{-1}[P^T Q] \tag{2.30}$$

Where, 'U' is the response function of the large catchment.

Kothyari and Singh (1999) applied a multiple-input single-output (non-linear) rainfall-runoff model using Eqs. (2.22) and (2.30) as above for prediction of daily flows in Narmada catchment and obtained good results as shown in Fig. 2.4, 2.5 & 2.6.

2.5 METHODS FOR DETERMINATION OF RESPONSE FUNCTION

Various investigators have linked unit hydrograph characteristics of basins (Snyder, 1938; Edson, 1951; Taylor and Schwarz, 1952; Rodrigues-Iturbe and Valdes, 1979; Valdes et al, 1979; Gupta et al, 1980; Rodrigues –Iturbe et al 1982). Some of these efforts are directed towards estimating geomorphologic unit hydrographs. Others are interested in the development of topological unit hydrographs, which are based on the theory of topologically random networks (Gray, 1961, Karlinger and Troutman, 1985; Trontman and Karlinger, 1985).

Different methods have been developed to estimate response functions, Snyder (1955) used the method of least squares. Eagleson et al (1966) obtained an approximate solution of the Wiener-Hopf equations through linear programming and matrix inversion to compute optimum realizable unit hydrographs. Deininger (1969) used linear programming techniques based on minimum absolute deviations and on min-max criteria. Singh (1976) compared the linear programming and least-Squares fitting methods. Mays and Coles (1980) used linear programming. The objective function does not give special weight to the region around the unit hydrograph peak, which is an important property of unit hydrographs. Mays and Taur (1982) used two non-linear programming techniques, the large-scale generalized reduced gradient technique and the generalized reduced gradient with three different objective functions to compute unit hydrographs. Rao and Delleur (1971) compared the performances of Fourier, Laplace and Z-transform methods in estimating the unit hydrographs. Fourier transform methods were also used by Blank et al. (1971) and Sharma et al (1973). Some methods are discussed to determine the response function in the following paragraphs.

2.5.1 Linear Programming Model

Considering the following Eq. (2.31) relating rainfall-runoff process as given earlier in eq. (2.19).

$$[Q] = [P]\,[U] \qquad (2.31)$$

where 'Q' is observed runoff matrix

'P' is effective precipitation matrix

'U' is unknown response ordinate matrix

The solution of this set by "least squares method"' fields the value of unknown response function Ui, $U_{i,j}$. Owing to representation, measurement and process errors involved in the data, some of ordinates may take on negative values. In order to ensure a physically realizable set of response function, the Eq. (2.31) is to be solved under the constraint.

$$U_i, Ui_{,j} > o$$

To satisfy this additional requirement, it is necessary that the regression equations be truncated so as to form under-determined set i.e a set having more unknown than equations. There will then be a multiplicity of solutions from among which the best satisfying the above constraint can be selected. It seems logical to construct the regression equations, for a model having a memory longer than required, i.e. a model having extra response function ordinates and then to leave out the extra equations from the set of regression equations in the solution. We now need a criterion for selection of best solution of Eq. (2.31) as the extra response function ordinates will be used as slack variables in linear programming as their influence is required to be a minimum. Thus, the solution must satisfy the conditions that.

$$\sum_{i=1}^{L_1} U_i \text{ is minimum.}$$

Where, 'U_I' is the number of extra response function ordinates.

The problem can be expressed in general format of linear programming as

$$\text{Minimize} \sum_{i=1}^{L_1} U_i$$

subject to a set of linear constraints

$[P]\,[U] = [Q]$ and $[U] > 0$

This is simple linear programming problem that can be solved by using simplex algorithm. In order to make extra dummy response function ordinates having least possible effect in actual ordinates, they must be minimum in number (i.e. L_1. Must be minimum). This minimum can be found by trail and error, starting the trials with small 'L' such as '1' or '2'additional constraints can be introduced to preserve monotonically decrease in the ordinates using.

$U_I < U_{i+1}$ and $U_{i,j} < U_{i,j+1}$

2.5.2 Non- Linear Programming Method:

Mays and Taur (1982) used the non-linear programming approach for derivation of response function. The model based on non-linear programming (NLP) can be used to derive composite response function considering several multiperiod rainfall events simultaneously and does not require rainfall excess to be defined in advance. In this model rainfall losses and consequently rainfall excess is determined. Essentially this new model determines the rainfall losses for each time period of each rainfall event, considered the best composite response function by minimizing the deviation between observed and computed direct surface runoff hydrograph. The NLP codes may be used for solving the problem, which are called LSGRG [Large scale Generalized Reduced Gradient] and GRG-2 [Generalized Reduced Gradient].

In this model, rainfall excess P is defined as difference of total rainfall R for δt hour period and losses H over the same period are expressed as

$$P_{i,n} = R_{i,n} - H_{i,n} \quad (2.32)$$

Equation (2.5) can now be expressed as:

$$Q_{i,n} = [R_{i,n} - H_{i,n}]U_1 + [R_{i,n-1} - H_{i,n-1}]U_2 + ... + [R_{i,n-m+1} - H_{i,n-m+1}]U_m \quad (2.33)$$

The NLP model can be solved using either of the following two objective functions.

$$\text{Min } Z_0 = \sum_{i=1}^{I} \sum_{n=1}^{N_1} [Z_{i,n} + V_{i,n}] \quad (2.34)$$

$$\text{Min } Z_0 = \sum_{i=1}^{I} \sum_{n=1}^{N_1} [Z_{i,n^2} + V_{i,n^2}] \quad (2.35)$$

Subject to the following linear and non-linear constraints;

$$[R_{i,n-1} - H_{i,n-1}]U_1 + [R_{i,n-2} - H_{i,n-1}]U_2 + [R_{i,n-m+1} - H_{i,n-m+1}] + Z_{i,n}V_{i,n} = Q_{i,n} \quad (2.36)$$

$$\sum_{n=1}^{L_i} [R_{i,n} - H_{i,n}] = D_i \quad (2.37)$$

Where D_l = Direct runoff volume to the total rainfall excess for the i^{th} rainfall

$$\delta_t \sum_{n=1}^{m} U_m = 1 \quad (2.38)$$

and non-negativity constraints for the following decision variables

$$H_{i,n},\ V_{i,n},\ Z_{I,n} \text{ and } U_m \geq 0 \quad (2.39)$$

The direct runoff volume for the rainfall can be expressed as

$$D_i = t\sum_{n=1}^{N_i} Q_{i,n} \quad (2.40)$$

The total number of decision variables

$$=2\left[\sum_{i=1}^{I} N_i\right] + M + \sum_{i=1}^{I} L_i$$

Number of decision variable is non-linear function for objective function

$$\text{Eq.(2.34)} = M + \sum_{i=1}^{I} L_i$$

Remaining $2\sum_{i=1}^{I} N_i$, decision variables being linear in the constraints and the objective function. For Eq.(2.34) all the decision variables are non-linear either in objective function (Z,V) or in the constraints (U,H), the total number of constraints for NLP problem is

$$\sum_{i=1}^{I} N_i + I + 1$$

Procedure for NLP solution is given in Fig. 2.7 it is not expected to have the two codes specified earlier.

One con solve the problem using Kuhn Tuker conditions

$F_I = \lambda h_j = 0$

$J = 1,2,\ldots..n$

$H = 0$ (2.41)

$n>0$

$\lambda \geq 0$

f_I: differential operator

h_j: differential operator

2.5.3 Smoothed Least Squares Method:

Bruen and Dooge (1984) derived this procedure which can also be used for the estimation of composite unit hydrograph.

In cases where the rainfall pattern is such that p^Tp is ill conditioned then the pulse response will display wild variations in the estimates of adjacent ordinates (even negative estimates) which will be characterized as unrealistic by an experienced hydrologist. Kutchment (1967) has suggested that the prior expectation of smoothness in the derived unit hydrograph can be incorporated into the estimation by solving the following equations in place of the normal equations:

$$(p^Tp + KI)\, \hat{U} = p^TQ \qquad (2.42)$$

where K is a parameter chosen by the user.

This approach to regression is described variously in the literature as smoothed least squares or ridge-regression. The properties of this estimator are well known; viz. Hoerl and Kennard (1970). The estimate is biased, thus:

$$\hat{U} = Z\hat{U}_{oLS} \tag{2.43}$$

The multiplicative biasing matrix Z is given by

$$Z=I+K\,(p^Tp)^{-1} \tag{2.44}$$

Thus the degree of bias introduced into the estimate depends on the value of k. A zero value gives no bias while bias increases as k is increased. The operation of the method is best illustrated by considering the mean square error of the estimate of the parameter. This is defined as :

$$\text{MSE}(\hat{U}_S)=\sum\left\{\left[\hat{U}-U\right]^T\left[U_s-U\right]\right\} \tag{2.45}$$

This can be shown equal to

$$\text{MES} =[ZU-U]^T - [ZU-U]+\text{trace}[Ze_{oLS}\,e^T_{oLS}\,Z^T] \tag{2.46}$$

Where e_{oLS} is the error in the ordinary least squares estimates of the pulse response ordinates. The first term is the sum of the individual variance of the parameter estimates. The first increases as K increases, while the term can be shown equal to:

$$\text{trace}[Ze_{oLS}\,e^T_{oLS}\,Z^T] \quad =\sum_{i=1}^{M} \lambda/(\lambda_1+k) \tag{2.47}$$

Which decreases monotonically as K increases (Hoer / and Kenanard, 1970). It can be shown that there is a positive value of K for which the sum of the two terms is minimum. For this value, the mean square error (MSE) of estimation is least and thus offers the best basis for prediction. The coefficient matrix of equations to be solved for the case of smoothed least squares is also symmetric Teoplitz matrix $[P^T P+ KI]$.

In fact, it differs from the least squares matrix p^Tp in only its diagonal, which itself is characterized by a single number, r(1). It remains to be explained why this smoothed least square is preferable to first deriving the least squares estimate and then smoothing it. In the first place, the proposed method is a constrained least squares estimate and thus has some optimal properties, while numerically smoothing an ordinary least-squares estimate destroys its optimality. Secondly, the proposed method can be performed with a lot less computation than deriving an ordinary least-squares estimate and subsequently smoothing it.

2.5.4 Bayesian Method

The Bayesian method also gives instantaneous unit hydrogrpahs like the Ridge regression (smoothed least-squares) method with non-negative ordinates which are not oscillatory. It is the most general method and because it has not been previously used in hydrology.

The Bayesian approach was developed by Bhargava (1986) and Bhargava et al. (1987). The system equation is assumed to be as in Eq. (2.48), where 'e' is normally distributed with mean zero and co-variance matrix ρ^2 I:

$$Q = PU + e \tag{2.48}$$

The conditional probability density of Q given as p and U is given in Eq.(2.49), where ρ^2 is the noise variance:

$$\rho[Q/P, U] = \frac{1}{(2\pi\rho)^{N/2}} \exp\left[-\frac{1}{2\rho}\|Q - PU\|^2\right] \tag{2.49}$$

The prior density of U is assumed to be as in Eq. (2.50)

$$\rho(U) = \frac{1}{(2\pi\,\xi)^{N/2}\left|\det\left(x^T x\right)\right|^{1/2}} \exp\left[-\frac{1}{2\xi}\left[\|XU\|^2\right]\right] \tag{2.50}$$

Where ξ is a positive constant and X is either the Identity matrix I or the Laplacian matrix C, which is given by Eq. (2.51).

$$C=\begin{bmatrix} 1 & . & . & . & . & . & . & . \\ -2 & 1 & . & . & . & . & . & . \\ 1 & -2 & . & . & . & . & . & . \\ . & 1 & -2 & . & . & . & . & . \\ . & . & 1 & . & . & . & . & . \\ . & . & . & . & . & . & 1 & . \\ . & . & . & . & . & . & -2 & 1 \\ . & . & . & . & . & . & 1 & -2 \\ . & . & . & . & . & . & . & 1 \end{bmatrix} \tag{2.51}$$

The Laplacian matrix reduces the effects of large oscillations in the unit hydrograph and hence forces continuity from one-unit hydrograph ordinates. Assuming that the prior densities of ρ and ξ are flat and that these priors satisfy the usual conditions of probability densities, the log likelihood function is written as in Equation (2.52) where k are terms not involving U, ρ and ξ:

$$-\ln f[U,\rho,\xi/\rho,Q]=\frac{\|Q\ -PU\|^2}{2\rho}+\frac{N}{2}\ln\rho+\frac{\|XU\|^2}{2\xi}+\frac{N}{2}\ln\xi+K \tag{2.52}$$

On minimizing the log likelihood function with respect to U, ρ, ξ Eq. (2.53)-(2.55) are obtained:

$$\hat{U}=\left[\frac{P^TP}{\rho}+\frac{X^TX}{\xi}\right]^{-1}\left[\frac{P^TQ}{\rho}\right] \tag{2.53}$$

$$\hat{\rho}=\frac{1}{N}\|Q-X\hat{U}\|^2 \tag{2.54}$$

$$\hat{\xi}\overset{\Delta}{=}\frac{1}{N}\|X\hat{U}\|^2 \tag{2.55}$$

These are the Bayesian estimates because of the Gaussian assumptions above. Eqs. (2.53)-(2.55) can be written as Eqs. (2.56) and (2.57)

$$\hat{U}=\left[P^TP+\frac{\hat{\rho}}{\hat{\xi}}X^TX\right]^{-1}P^TQ \tag{2.56}$$

$$\frac{\hat{\rho}}{\hat{\xi}} = \frac{\|Q - PU\|^2}{\|P\,\hat{U}\|^2} = \hat{K} \qquad (2.57)$$

The estimate $\hat{K}$ is the ratio of the sum of squares of residuals to the sum of squares of prior information. As both the numerator and denominator in Eq. (2.57) are positive, the estimate K exists and is unique. If R is large, then the estimated unit hydrograph may not have a direct runoff volume of 1 cm. However, normalizing the unit hydrograph so that it has a unit direct runoff volume is a simple procedure. By letting

$\hat{K} = \hat{\rho} / \hat{\xi}$ Eq. (2.58) is obtained form Eqs. (2.56) and (2.57)

$$\hat{K} = \frac{\left\|Q - P\left[P^TP + \hat{K}X^TX\right]^{-1}P^TQ\right\|^2}{\left\|X\left[P^TP + \hat{K}X^TX\right]^{-1}P^TQ\right\|^2} \qquad (2.58)$$

Equivalently,

$$\hat{K} = \frac{\left\|Q - P\left[P^TP + \hat{K}X^TX\right]^{-1}P^TQ\right\|^2}{\left\|X\left[P^TP + \hat{K}X^TX\right]^{-1}P^TQ\right\|^2} = 0 \qquad (2.59)$$

After solving for $\hat{K}$ in Eq. (2.59), it is to be substituted in Eq. (2.56) to obtain the estimated response $\hat{U}$

2.6 EFFICIENCY CRITERIA FOR THE MODEL:

"Initial variance" or variance of the output Q" is the sum of squares of diviations from the mean $\overline{Q}$, the summation being taken over the period of record under consideration :

$$\text{var} (Q) = \Sigma\, (Q - \overline{Q})^2$$

We may also refer to the "residual variance" of a model as the sum of squares of difference between Observed and computed value, also taken over the period of record.

$$\text{Res. Var}\ (Q) = \sum \left(\hat{Q} - Q\right)^2$$

Neglecting the loss of few degrees of freedom, which are negligible in the context of the hundreds, or even thousands of events usually involved, we may define "the efficiency of the model as the proportion of the variance of Q accounted for by the model".

Efficiency of the model depends on the computed and observed values of the storm runoff. If the computed and observed values of storm runoff follow the same pattern, then the efficiency of the model is more. In other words-if the difference of computed and observed values of storm runoff is less, then the model is more efficient while increase in the deviation from computed value of storm runoff to the observed values indicates less efficient model.

Following criteria exists for computation exists for computation of model efficiency.

$$\text{Initial Var (Q)} = F_d = \Sigma\left[\bar{Q} - Q\right]^2 \qquad (2.60)$$

Where $\bar{Q}$ = mean of observed discharge in the calibration period.

Q = actual observed discharge

$$\text{Res var (Q)} = F_I = \Sigma\left[\hat{Q} - Q\right]^2 \qquad (2.61)$$

Where,

$\hat{Q}$ = Computed runoff hydrograph ordinate

Q =observed runoff hydrograph ordinate

Then the efficiency is given by:

$$E^2 = [(F_d - F_I)/F_d] * 100 \qquad (2.62)$$

Garrick et. al (1978) proposed that the performance of a conceptual model as a means of forecasting the discharge from a rainfall

$$R_{(t)} \ldots\ldots\ldots \Rightarrow Q_{(t)} \qquad (2.63)$$

should be judged by comparison with a basic forecast which would be the best available forecast without taking into account of rainfall. They suggested that in the absence of rainfall data, this forecast could be obtained only from the observation of previous seasonal behaviour of the discharge and they defined the seasonal forecast for given data 'd' as

$$Q_d = n^{-1}\left[Q_{d,1} + Q_{d,2} + \dots\dots\dots + Q_{d,n}\right] \tag{2.64}$$

where, $Q_{d,r}$ refers to the observed discharge on date 'd' in the year 'r' and 'n' is the number of years of data available for calibration. This Q_d replaces the $\overline{Q}$ in Eq. (2.60) and then F_d becomes:

$$F_d = \sum [Q_d - Q]^2 \tag{2.65}$$

In the present study, efficiency of the estimated response functions has been computed as above for predicting the flood magnitudes, using Eqs. (2.60), (2.61) and (2.62).

2.7 STANDARD ERROR OF RESPONSE FUNCTION ORDINATES

The standard error i.e. variance of the response function ordinates U_i may be obtained by taking the corresponding terms of the principal diagonal of $[P^T P]^{-1}$ and multiplying by S^2

$$\text{S.E.} = V^{-1} S^2 \tag{2.66}$$

$$S^2 = (n-m)^{-1} \sum_{i=1}^{n} e_i^2 \tag{2.67}$$

Where,

e_i = difference of computed and observed discharge

n = number of ordinates of observed hydrograph

m = memory length of catchment

V^{-1} = principal diagonal terms of $[P^T P]^{-1}$

The response function ordinate is considered to be significant when its standard error is smaller than its magnitude.

2.8 BRIEF SUMMARY

The system based approach has been exhaustively used for the modeling of rainfall - runoff process. Conventionally, linear relationships have been considered to exist between the rainfall and the runoff and signal-input, single-output kind of rainfall-runoff relationships have mostly been studied. The multiple-input, single-output linear rainfall-runoff relationship had been studied by Liang (1988) and Liang et al. (1994) in the context of flood routing problem. Kothyari and Singh (1999) applied a multiple - input single - output rainfall - runoff non - linear model for prediction of daily flows in the Narmada catchment. Except this, no other study has been considered so far based on nonlinear multiple - input and single - output rainfall - runoff model.

METHODOLOGY

3.1 GENERAL

The objective of present study is to use multiple - input rainfall for modeling of runoff at the catchment outlet of Wardha river of the Godavari basin having an area of 19975 km^2. The total rainfalls have been considered as inputs and the total runoff as the output as against to the use of effective rainfall and direct runoff as input and output respectively used in conventional unit hydrograph method. Both the linear as well as the non-linear relationships are constructed by stacking together the data sets of storm events those occurred at different time periods. The whole catchment of Wardha river is divided into three hydrologically homogeneous sub-areas of approximately uniform rainfall distribution. Thereby, the spatial variation of rainfall and the catchment hetrogeneities are incorporated in the model by treating rainfall as separate lumped multiple inputs.

In the present chapter, the particulars of "the multiple-input, single-output model and its description" are presented. The same model can be utilized to the single-input, single-output form by reducing the number of rainfall inputs only one.

3.2 MODEL DESCRIPTION

The output function Q_t of a lumped linear system is related to the single input function P_t as (Nash and Foley, 1981; Singh, 1988).

$$Q_t = \sum_{i=1}^{m} U_i P_{t-i+1}$$

(3.1)

Where,

U denotes the discrete series of pulse response ordinates m is the memory length of the system

t is the time expressed as an integer number of sampling intervals.

Equation (3.1) represents the classical unit hydrograph type of model.

Since, the hydraulic equations representing overland and channel flows are non-linear partial differential equations and therefore become non-linear functions of the rainfall intensities. Hence, the coefficients U_I of eq (3.1) are not constants but vary as functions of antecedent and current rainfalls (Amorocho, 1973; Muftuoglu, 1984; Singh, 1988). Therefore, the immediate and moderately delayed responses of the catchment are known to be highly non-linear, while the delayed (i.e. ground water) response can be realistically assumed to be linear (Amorocho and Orlob, 1961; Brandsteller and Orlob, 1970; Amorocho, 1973; Muftuoglu, 1984 & 1991).

With the above considerations, Eq. (3.1) was modified by Muftuoglu (1984, 1991) to simultaneously account for both the immediate and moderately delayed runoff-components and the delayed runoff components, resulting from the single lumped rainfall functions as :

$$Q_t = \sum_{i=1}^{n}\sum_{k=i}^{n} U_{i,k} P_{t-i+1} P_{t-k+1} + \sum_{i=1}^{l} U_{i+n} P_{t-(i+n)+1} \tag{3.2}$$

Where,

n = number of time intervals of rainfall contributing to the immediate and moderately delayed runoff (i.e. the non-linear part of the total memory of the catchment)

l = number of time intervals of rainfall contributing to the delayed runoff (i.e. linear part of the total memory).

m = n + l = total memory length of the model

$U_{i,k}$ = ordinates of non-linear part of the response function (also, termed as ordinates of a two-dimensional unit hydrograph)

U_i = Ordinates of linear part.

The effective number of corresponding unknowns $U_{i,k}$ are equal to n(n+1)/2 where as the number of unknowns U_i are equal to l. Thus, the total number of unknown elements i.e. ordinates which need to be identified in the calibration process of present model is the sum = mm = [n(n+1)/2+l].

The model in its original form is sufficient for small catchments where the rainfall distribution can be assumed uniform. Therefore, the catchment area of Wardha river has been divided into J (three) sub-catchments and the whole catchment was treated as assemblies of these sub-catchments which can be assumed to be an independent areas of uniformly distributed rainfall.

The memory lengths l and n for the different sub-areas of the catchment were chosen according to a subjective combination of the following criteria (Kothyari et al 1993) :

(i) The memory length values are the minimum values beyond which an increase in l (for the delayed response) and / or n (for the prompt response) does not significantly increase E^2 (efficiency).

(ii) The maximum values of n and l are such that the last ordinates of the pulse response are still above their respective standard errors;

(iii) The shapes of the desired pulse response functions are physically realistic.

3.3 MULTIPLE - INPUT, SINGLE - OUTPUT RAINFALL – RUNOFF MODEL

As explained in the preceding chapter and as above, the multiple - input, single-output non-linear relationship between rainfall and runoff can be expressed as blow :

$$Q_t = \sum_{j=1}^{J} \sum_{i=1}^{n(j)} \sum_{k=i}^{n(j)} U_{i,k}^{(j)} P_{t-i+1}^{(j)} P_{t-k+1}^{(j)} + \sum_{i=1}^{J} \sum_{i=1}^{l(j)} U_{i+n}^{(j)} P_{t-(i+n)+1}^{(j)} \qquad (3.3)$$

Where, j = 1,2, ... J (no. of independent sub-catchments)

n and l as explained in Eq. (3.2) above.

For the application of Eq. (3.3), the rainfall in each sub-catchment is lumped and treated as one of the inputs into the model Eq. (3.3) implies that ...

(1) Each input series $P^{(j)}$ is related by Eq. (3.2) to its corresponding output component $Q_t^{(j)}$, j = 1,2,, ... J. In Eq. (3.2) the current and recent rainfall values are multiplied by the non-linear response ordinates $U_{i,k}$, while the antecedent rainfall values are mutliplied by the linear response function ordinate U_i. Thus, the prompt flows (i.e. the immediate and moderately delayed flows) and the delayed flows are differently related with the corresponding rainfall values.

(2) The outflow component $Q_t^{(j)}$ in Eq. (3.3) from different sub-catchments are linearly additive (Liang and Nash, 1988) as :

$$Q_t = Q_t^{(1)} + Q_t^{(2)} + ... + Q_t^{(j)} \tag{3.4}$$

We may have to calibrate the model on a number of separate data sets of rainfall and corresponding runoff. So, Eq. (3.3) is re-written for calibrating the model by stacking together all the data-sets under consideration as :

$$Q_t^p = \sum_{j=1}^{J} \sum_{i=1}^{n(j)} \sum_{k=i}^{n(j)} U_{i,k}^{(j)} P_{t-i+1}^{(j),p} P_{t-k+1}^{(j)p} + \sum_{j=1}^{J} \sum_{i=1}^{l(j)} U_{i+n}^{(j)} P_{t-(i+n)+1}^{(j),p} \tag{3.5}$$

Where, p = the counter number of the storm – event with p = 1,2, ... NN.

The solution of Eq. (3.5) for a calibration series of N discharge values $Q_1, Q_2, ...$ Q_N can be written in vector / matrix form as

$$Q = P^{(1)}U^{(1)} + P^{(2)}U^{(2)} + ... + P^{(j)}U^{(j)} \tag{3.6}$$

In the above, N is the total number of observations from the all the storm events used for calibration, placing one immediately after the other to give a long series and Q is an [N, 1] column vector of the runoff calibration series such that .

$$
Q = \begin{bmatrix} Q_1 \\ Q_2 \\ \cdot \\ \cdot \\ Q_N \end{bmatrix} \tag{3.7}
$$

Thus, for each of the NN data sets, the set of inputs and the outputs are first arranged in the form of Eq. (3.6) and then these storm events are vertically stacked together to form the complete matrix of inputs and the corresponding complete vector of outputs. Hence $P^{(j)}$ is an [N, mm(j)] rainfall matrix of the jth input series, corresponding to the jth sub-catchment area, such that and $U^{(j)}$ is an [mm (j),1] column of the pulse response ordinates corresponding to the jth input series such that :

$$
P^{(j)} = \begin{bmatrix}
P_m^2 & P_mP_{m-1} & \cdots & P_mP_{m-(n-1)} & P_{m-1}^2 & P_{m-1}P_{m-2} & \cdots & P_{m-1}P_{m-(n-1)} & P_{m-2}^2 & \cdots & P_{m-(n-2)}^2 & P_{m-(n-2)}P_{m-(n-1)} & P_{m-(n-1)}^2 & P_{m-n} & P_{m-n-1} & \cdots & P_{m-(l+n)+1} \\
P_{m+1}^2 & P_{m+1}P_m & \cdots & P_{m+1}P_{m-n+2} & P_m^2 & P_mP_{m-1} & \cdots & P_mP_{m-n+2} & P_{m-1}^2 & \cdots & P_{m-n+3}^2 & P_{m-n+3}P_{m-n+2} & P_{m-n+2}^2 & P_{m-n+1} & P_{m-n} & \cdots & P_{m-(l+n)+1} \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
P_t^2 & P_tP_{t-1} & \cdots & P_tP_{t-(n-1)} & P_{t-1}^2 & P_{t-1}P_{t-2} & \cdots & P_{t-1}P_{t-(n-1)} & P_{t-2}^2 & \cdots & P_{t-(n-2)}^2 & P_{t-(n-2)}P_{t-(n-1)} & P_{t-(n-1)}^2 & P_{t-n} & P_{t-n-1} & \cdots & P_{t-(l+n)+1} \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
P_N^2 & P_NP_{N-1} & \cdots & P_NP_{N-(n-1)} & P_{N-1}^2 & P_{N-1}P_{N-2} & \cdots & P_{N-1}P_{N-(n-1)} & P_{N-2}^2 & \cdots & \cdots & P_{N-(n-2)}P_{N-(n-1)} & P_{N-(n-1)}^2 & P_{N-n} & P_{N-n-1} & \cdots & P_{N-(l+n)+1}
\end{bmatrix}
$$

Non - linear input [n(n+1)/2 Columns] (For the immediate and moderately delayed response)

Linear input [l - Columns] [For the delayed (ground water) response]

(3.8)

and

$$
U^{(j)} = \left[U_{1,1}^{(j)}, U_{1,2}^{(j)}, \ldots U_{1,n}^{(j)}, U_{2,2}^{(j)}, \ldots\ldots U_{n-1,n}^{(j)}, U_{n,n}^{(j)}, U_{n+1}^{(j)}, U_{n+2}^{(j)}, \ldots\ldots U_{n+l}^{(j)}\right]^T \tag{3.9}
$$

where T denotes the vector transpose.

This vector consists of n(n+1)/2 non-linear and 1 linear response function ordinates. So, U is an (M,1) column vector of

$$\text{Length } M = \sum_{j=1}^{J} mm(j)$$

Equation (3.5) can also be written as

$$Q = PU \qquad (3.10)$$

$$P = \left[P^{(1)}, P^{(2)}, \ldots\ldots\ldots P^{(J)}\right] \qquad (3.11)$$

Where, P is an (N, M) matrix such that :

and

Thus, $\{P^T P\}$ called "auto and cross covariances matrix" of the inputs is a [M x M] matrix

$$M = \sum_{j=1}^{J} mm(j) \qquad (3.12)$$

which plays very important role and U is an (M; 1) column vector obtained by writing each $U^{(j)}$ vector in the sequence of j, as :

$$U = \begin{bmatrix} U^{(1)} \\ U^{(2)} \\ . \\ . \\ . \\ U^{(J)} \end{bmatrix} \qquad \text{where, } N >> M \qquad (3.13)$$

From Eq. (3.10) we can get the vector U as :

$$Q = P\,U$$

$$\Rightarrow \left[P^T.P\right]U = P^T Q$$

$$\Rightarrow U = \left[P^T P\right]^{-1}\left[P^T Q\right] \qquad (3.14)$$

Where, U = the response function of the large catchment.

The solution in Eq. (3.14) above can be obtained from the ordinary least-squares solution, expressed in terms of auto and cross covariances of the input P and the output Q (Nash and Barsi, 1983).

If any of the ordinate values of the above derived response functions contain significant negative ordinates, the slightly more complex method of smoothed least squares also called ridge – regression (Bruen and Dooge, 1984) can be used for derivation of the response functions as positive ordinates.

In the method of smoothed least- squares, the estimate of U of Eq. (3.14) is taken as the solution U of the system of normal least – squares equations given below :

$$\left[P^{T} P + KI\right]\hat{U} = P^{T} Q \tag{3.15}$$

Where, K is a positive scalar.

I is an (M x M) unit identity matrix.

In Eq. (3.15), $\hat{U}$ is the biased estimate for U of Eq. (3.14) and the bias is proportional to K. For K equals to zero, this bias is zero and the solution obtained is the same as that of the method of ordinary least squares. This solution also yields estimates of the standard errors of the estimate of $\hat{U}$ (Nash and Barsi, 1983; Bruen and Dooge, 1984).

Standard error of estimates of the response function ordinates can be computed using Eq. (2.66).

The results obtained by different models are compared using the Nash – Sutcliffe efficiency (E^2) using Eq. (2.62) for model evaluation.

AREA OF STUDY

4.1 WARDHA SUB-BASIN

The catchment area of the river Wardha has been considered for the model study.

4.1.1 General

The Wardha is one of the right tributaries of Pranhita river. The Wardha sub-basin lies between latitudes 19° 18' N and 21° 58' N and longitudes 77° 20' E and 79° 45' E.

The Wardha river rises at an altitude of about 777 M in the southern slopes of the Dahawadhana peak in Multai Taluk of Betul district of Madhya Pradesh and traverses a total length of 528 km and joins the river Wainganga. From the source, it traverses 42 km in Madhya Pradesh, 16 km along the common boundary between Madhya Pradesh and Maharashtra, 428 km in Maharashtra and 42 km. along the common boundary of Maharashtra and Andhra Pradesh. The important left bank tributaries are the Kar, the Jam, the Wena and the Erai and the right bank tributaries are the Madu, the Bembla and the Penganga. It joins the river Pranhita near Asifabad Taluk of Adilabad district in Andhra Pradesh.

The Penganga being a major tributary of Wardha has been considered as an independent sub-basin. Thus, the Wardha sub-basin comprises of the catchment area of Wardha from its source to its confluence with Wainganga including its tributaries but excluding the catchment area of Penganga. The catchment area of Wardha sub-basin is 24087 km which is 7.7% of the area of Godavari basin. The sub-basin lies in the states of Madhya Pradesh, Maharashtra and Andhra Pradesh.

4.1.2 Topography, Physiography, Geology and Hydrogeology

The Wardha sub-basin is triangular in shape with an average width of about 90 km. The terrain is mountaneous consisting of ridges and valleys covered with forests and the country opens out lower down.

The geological formation in the sub-basin presents various types of rock formations including the older precambrian, Vindhyans, Gondwanas and sediments. Various types of rocks found in the sub-basins are classified under the Gondwanas, the Deccan trap and the Archaean.

Hydro-geological studies have been carried out by the State Ground Water Departments and the Central Ground Water Board in the sub-basin. The studies reveal that in the Vindhyans, Gondwanas, Deccan traps, laterites and alluvium groups, ground water occurrence is noticed. Ground water occurs in the soil cover, weathered mantle and in the highly jointed and fractured zones of the hard rock. In the alluvium, the ground water is found in the basal portion containing gravel and course sand under the water table. The depth of water table varies from 4.5 m to 16.0 m. The existing ground water development in the sub-basin is mainly from open wells and dug-cum-bore wells.

4.1.3 Climate

There are three seasons prevailing in the sub-basin i.e. summer from March to May, monsoon from June to October and winter from November to February. There are IMD observatories at Betul, Amaravati, Chanda, Nagpur and Yeotmal located in and adjacent to the sub-basin. There are 16 rain gauge stations in and adjacent to the sub-basin catchment. The average annual rainfall for the entire sub-basin catchment is 1000 mm (approx.).

4.1.3.1 Rainfall

The Wardha sub-basin experiences only the south-west monsoon and it is from early June to end of October. The rainfall during the non-monsoon months, i.e. November to May is not significant.

4.1.3.2 Temperature

The sub-basin is located entirely in tropical zone. The daily and seasonal variations are high. The climate in general remains dry except in the monsoon months. The sub-basin experiences uniformly high maximum temperature of 40° C and above during summer and low minimum temperature of about 10° C during December.

4.1.3.3 Humidity

Humidity in the sub-basin is more during the monsoon and comparatively less during the non-monsoon period. The minimum humidity is generally recorded during April and the maximum during August. The climate remains dry for about 7 months in the year from November to May.

4.1.3.4 Wind Speed

Winds are generally light to moderate with increasing speeds in the later part of summer and during monsoon. The sub-basin is influenced by winds from the south-east during summer and south-west during the monsoon.

4.1.3.5 Cloud Amount

Generally the sky appears clear or lightly clouded in the non-monsoon period. The intensity of cloud amounts is more during the south-west monsoon season.

4.1.4 Soils and Land Use

4.1.4.1 Soils

The soils of the Wardha sub-basin are broadly divided into three groups as shown in Table 4.1.

Table 4.1

Soils in the Wardha Sub-basin

Type of Soil	Area under each type of soil (km^2)
1. Black soil	16700
2. Red soil	289
3. Mixed black and Red soil	7098
Total	24087

4.1.4.2 Land Use

The cultivable area was maximum in the year 1991-92 at 1592964 ha. The land use figures for the year 1991-92 are given in Table 4.2.

Table 4.2

Land Use Figures for the Year 1991-92 of the Wardha Sub-Basin

Land use	Area (ha)	Percentage to sub-basin area
(i) Geographical area	2408700	100.00
(ii) Forest	507133	21.05
(iii) Barren land	76872	3.19
(iv) Land under non-agrl.use	116817	4.85
(v) Culturable waste	92641	3.85
(vi) Permanent pastures	114914	4.77
(vii) Land under misc.crops & trees	15045	0.63
(viii)Current fallows	61292	2.54
(ix) Other follows	91356	3.79
(x) Net area sown	1332630	55.33
(xi) Area sown more than once	69847	2.90
(xii) Gross sown area	1402477	58.23
(xiii)Cultivable area	1592964	66.14

HYDROLOGICAL DATA

5.1 GENERAL

The drainage area of the Wardha river of the Godavari basin has been selected for flow forecasting during monsoon periods by the present model study.

There is a G & D site located at Ghugus in Maharashtra, India being maintained by the Central Water Commission (C.W.C.), Government of India. The catchment area of the Wardha river upto Ghugus site which forms the head water catchment of the river is 19975 km^2 which covers nearly 83% of the total catchment area of the sub-basin (24087 km^2). Figure 5.1 shows the drainage pattern in the catchment.

There are 14 raingauge stations considered in and around the catchment upto Ghugus site. They are Atner, Multai, Barud (Warud) Chandur Railway, Morsi, Katol, Nagpur, Yeotmal, Arvi, Hinganghat, Kharanjha, Wardha, Chandrapur and Warora as shown in Fig. 5.1. The catchment is gauged by taking hydrological observations i.e. gauge and discharge observations on the river Wardha at Ghugus site by the Upper Godavari Division of the Central Water Commission (Southern Zone) under Godavari Circle, situated in Hyderabad, A.P. Daily rainfall and daily discharges are used in the present study. Rainfall in the catchment is observed using both the automatic recording as well as the non-recording raingauges. The rainfall data under study has been collected from the India Meteorological Department, Government of India, Additional Director General of Meteorology (Research) situated in Pune, M.S.

5.2 HYDROLOGICAL DATA

Data used in the present model study consist of daily river discharge and corresponding rainfall in the catchment which contributed flow to Ghugus G& D site. The recorded daily rainfall data for 14 RGS and the observed daily discharge data of Wardha river at Ghugus G & D site are collected from the respective organizations for the period from 1985-1996.

Since the present study is for flow forecasting during monsoon flood events, the observed rainfall, runoff data are analysed in the light of above study. Initially, nineteen flood storm events which occurred during monsoon season from 1985-1996 were identified based on observed hydrographs. Out of them, only twelve flood storm events were selected for this study for which both rainfall as well as runoff data are available concurrently. These storms occurred during the period from 1985 to 1996. The first eight of these events were used for calibration of the model and the data of the remaining four events were used for model verification. The dates of the storm events are given in Table 5.1.

The catchment representation was done in three ways. Firstly, the whole catchment was considered as a single unit of model input and the average rainfall was computed by the Thiessen Polygon method. Secondly, the catchment was divided into two and then into three sub-areas as shown in Figs. 5.2 and 5.3 respectively and taken as two inputs and three inputs scenarios of the model. For each sub-area, the Thiessen average rainfall was determined to form the input functions to the model. The sub-area demarcation as exhibited in Figs. 5.2 and 5.3 was based upon the hydro-physio-graphical homogeneity indicated by vegetation, slope, soil type and the long-term rainfall isohyetal maps for the catchment.

The rainfall-runoff data used in the present study are listed in the Appendix-1.

Table 5.1

Dates of the Selected Storm Events

Catchment	Storm No.	Period of Storm	Duration (Days)
Wardha upto Ghugus (19975 km^2)		**Calibration Period**	
	1.	19.06.85 to 03.07.85	15
	2.	01.08.85 to 20.08.85	20
	3.	02.08.86 to 27.08.86	26
	4.	01.07.88 to 11.08.88	42
	5.	15.08.88 to 28.09.88	45
	6.	11.08.89 to 14.09.89	35
	7.	08.06.90 to 30.06.90	23
	8.	12.07.90 to 31.07.90	20
		Total	226
		Verification Period	
	1.	04.08.90 to 21.09.90	49
	2.	20.07.93 to 17.08.93	28
	3.	13.07.95 to 31.07.95	19
	4.	24.08.95 to 14.09.95	22
		Total	118

Note:

Alternative Study	Scenario	Area of sub-Catchment(Km^2)	Area of Total Catchment (Km^2)
Alternative - I	One input	19975	19975
Alternative - II	Two inputs	6910 13065	19975
Alternative - III	Three inputs	6910 7534 5531	19975

RESULTS AND DISCUSSIONS

6.1 GENERAL

The daily rainfall and runoff data of the Wardha catchment are used in the present study. The total rainfalls have been considered as the inputs and the total runoff as the output as against to the use of effective rainfall and direct runoff as input and output respectively used in conventional unit hydrograph method. The catchment area upto Ghugus gauging site located on the Wardha river was considered. This catchment area falls in the Maharashtra state of India and the gauging site has been maintaining by the Central Water Commission, Government of India.

Among the identified storm events, twelve storms are selected for use in the model study of flow forecasting of Wardha river. These storms occurred in the monsoon period during 1985 to 1996. Out of these twelve storms, first eight are selected for calibration purpose and the remaining four are used for the purpose of forecasting (verification). A computer program for deriving the response functions for any number of inputs and single output based on ordinary and smoothed least squares technique has been developed and used in the present study. The Nash-Sutcliffe efficiency for the models both in calibration as well as verification period has been computed.

The study has been done by considering one, two and three rainfall inputs to the model, although any number of rainfall inputs may be used.

The study has been carried out using the following approaches viz.

(i) Linear approach : for single input and multiple inputs

(ii) Non-linear approach : for single and multiple inputs.

Results obtained are presented herein.

6.2 DISCUSSION ON RESULTS OBTAINED BY LINEAR APPROACH

The linear approach for single and multiple rainfall inputs has been studied for different memory lengths (m) varying from m = 4 to m = 10. With an increase in value of m the efficiency was increased from about 64% to 73% in linear – single input case and it increased from about 66% to 77% in case of linear – three inputs case. It indicates that when m = 10 the increase in the efficiency of linear approach from single input to three – inputs was only marginal from 73% to 77% i.e. 4%. The ordinates of the response function and the other results are presented in the Table 6.1 and 6.2 respectively. It is observed that three inputs (linear) case has given better results than lumped linear single input case for every value of m selected as above. However some of the ordinate values are negative and the same could not be smoothed by the method ridge regression.

6.3 NON - LINEAR APPROACH

6.3.1 Calibration Period

6.3.1.1 Single Rainfall Input

Average rainfall occurring on the whole catchment of the Wardha upto Ghugus is used as the model input. First eight of the selected storms have been used for calibration purpose. The Thiessen weighted averages of observed rainfall values at fourteen rain gauge stations as depicted in Fig. 5.1 are taken as one input. For different memory lengths of the catchment 'm' and for different values of Linear (l) and non-linear (n) memories, the Response Function Ordinates (R.F.O.) are derived. For these derived ordinates, the corresponding standard error (S_{err}) are also calculated. Nash-Sutchliffe efficiency (E^2) was also computed. The results obtained for single input case are presented in the Table 6.3. From the Table 6.3, it is considered that when m = 10 and n = 3, l = 7, the efficiency (E^2) is maximum. However some of the ordinate values are still negative.

From the Table 6.3, by comparing efficiency, standard error for different memory lengths of catchment, it is considered that m = 10 and n = 3, l = 7 holds good for the present catchment. Although the efficiency is still higher in case m = 10 and n = 1, l = 9, it is not considered as the appropriate response function as it contains more number of negative ordinates. The estimated discharges are computed based on these derived response functions and compared graphically with the corresponding observed discharges as shown in Figs. 6.1 to 6.12. A discussion on the graphical comparison is presented later in subsequent paragraphs.

6.3.1.2 Two rainfall inputs

In this case, the whole catchment is divided into two sub-catchments as shown in Fig. 5.2. The weighted averages of rainfall values of each sub-catchment are calculated by the Thiessen polygon method and used in the model alongwith the observed discharge at Ghugus gauging site for finding out the response functions combined for the two sub-catchments. For different values of m and for different values of n and l, R.F.O.s and S_{err} are calculated and present in Table 6.4.

As shown in Table 6.4, comparing efficiency for different memory lengths 'm' and n and l, a set of m = 10, n = 3, l = 7 was considered as the appropriate one for deriving R.F.O.s and further used for verification period. These response functions are convoluted with the rainfall values for calibration period in two sub-catchments to compute the discharges. The above computed discharges are graphically compared with the corresponding observed values as shown in Figs. 6.13 to 6.24. A discussion on the graphical comparison is presented later in subsequent paragraphs.

6.3.1.3 Three rainfall inputs

In this case, the catchment is divided into three sub-catchments as shown in Fig. 5.3. The weighted average of rainfall values over each sub-catchment are computed by the Thiessen polygen method and used individually as the inputs from their respective sub-catchments. The response functions for the three sub-catchments are computed for different 'm' values and different 'n' and 'l' values. The R.F.O. alongwith the associated efficiency are presented in the Table 6.5.Comparing the R.F.Os. and the efficiencies among various memory lengths, the values m = 10 and n = 3, l = 7 was adopted and later used for verification purpose.

Also, it was investigated that whether different value of m could be chosen for different sub-catchments, as it is expected that sub-catchment which is nearer to the catchment outlet may not contribute the flow to it for long time. These trials revealed that efficiency (E^2) is maximum when m = 10 for all the sub-catchments. It is therefore thought that the sub-catchments those are near to the river gauging site are comparatively flatter in slope, and hence it will contribute to the river flow for a longer period than as expected above.

The finally selected R.F.Os are convoluted with the corresponding rainfall values for the calibration period in the three sub-catchments and the discharges at Ghugus are estimated. The graphical comparison between the observed and computed discharges is shown in Figs. 6.25 to 6.36 and a discussion on this comparison is presented below.

6.4 DISCUSSION ON RESULTS OBTAINED FOR CALIBRATION PERIOD

The finally adopted R.F.O. values in all the three cases discussed above have the memory length m = 10 with n = 3, and l = 7, although some of the ordinates are negative. Even by using the "smoothed least squares technique", these negative ordinates could not be changed into positive values as discussed already. Comparison of E^2 values for the finally adopted R.F.Os. indicate that efficiency E^2 increases from about 76% to about 84% as the number of rainfall inputs increased from one to three with non-linear approach. However, the increase in E^2 was higher about 5% when rainfall inputs were increased from one to two. But comparatively further increase in number of inputs i.e. for three inputs, the increase in efficiency was only about 2.5%. However, the number of raingauge stations over the catchment especially over 2nd and 3rd sub-catchment areas were not considered to be sufficient and uniformly distributed for making a detailed study of this aspect.

The graphical comparison of observed and computed runoff values and that of variation of rainfall with time are shown in Fig. 6.1 to 6.36 for all the above three scenarios. From these comparative graphs, it is revealed that as the number of inputs are increased, the predictability of model with respect to the higher flows in particular is improved. Nevertheless, some of the segments of flow hydrographs are not very-well predicted by the present method. However, use of effective rainfall (i.e. total rainfall – evapotranspiration) instead of the total rainfall would result in better simulation of such data.

6.5 DISCUSSION ON COMPARATIVE STUDY OF LINEAR AND NON-LINEAR APPROACHES

The efficiency (E^2) of both linear and Nonlinear approaches as obtained above for different memory lengths (m) varying from 4 to 10 are presented in Table 6.6. From this table, it is noticed that for every value of m, linear multiple- input approach has given better results than that of lumped linear single input case. When m=10, the efficiency was increased to about 77% in linear multiple- input approach when compared with lumped linear single input case (E^2= 73%).

The efficiency of about 76% was obtained in nonlinear single input case (When m=10) which is almost equal to the efficiency as obtained in linear multiple input case.

In the case of nonlinear multiple- input case, when m=10, an efficiency (E^2) of about 84% was obtained i.e. a further improvement of about 7% in the estimation of flows from linear multiple-input to nonlinear- multiple approach. On an overall scenario, the efficiency was increased from about 73% to about 84% in case of nonlinear multiple-input approach when compared with lumped linear single rainfall input system.

Hence from the above all studies, it can be concluded that nonlinear approach of multiple-input system gives good results of estimated flows particularly in predicting peak flows.

6.6 DISCUSSION ABOUT THE NEGATIVE ORDINATES OF THE RESPONSE FUNCTIONS AND USE OF CONCEPT OF RIDGE REGRESSION (SMOOTHED LEAST SQUARES ESTIMATE)

In the present study, the memory length of catchment, m was determined by trial and error, by varying value m = 4 to m = 10 both by linear and non-linear approaches with single and multiple inputs. It is noticed from Table 6.1 to Table 6.5 that the negative ordinates were obtained almost in all data sets used in the above approaches. The range of negative ordinates varied from 12% to 40% of total number of ordinates. So, it is felt that the estimation of the ordinates of non-parametric unit-hydrographs from the sample data is very sensitive to the interrelationships existing among the observed input series. The least squares estimate is a good one if P^TP is nearly a unit matrix. If P^TP is not nearly a unit matrix, the least squares estimates are sensitive to errors which was occurred in the present study.

To tackle the above problem, the concept of ridge regression which also produces least squares estimate with some bias was used in the present case. Only in some cases, the negative ordinates could be eliminated. It was particularly possible when the number of negative ordinates are upto about 20% of the total number of ordinates or less. So, from the above, it is observed that the concept of ridge regression was helpful in eliminating the negative ordinates of the response function only for limited cases.

6.7 VERIFICATION (FORECASTING) PERIOD

Data for four storm events which were not used previously are used for flow forecasting (verification) of the present method with non-linear approach and one input, two inputs and three inputs. For each input case, the weighted average rainfall values were computed for Wardha catchment upto Ghugus.

6.7.1 Discussion on Results Obtained for Verification Period

The response function ordinates in case of one input which have $m = 10$, $n = 3$, $l = 7$ are convoluted with the corresponding rainfall values to compute the estimated flows. The efficiency (E^2) of 70% and 85% was obtained in the two storm events (i.e. storm No. 1 & 4 of verification period). However the efficiency in the other two storm events was smaller due to inaccurate and unreliable data sets. Graphical comparison of these results are shown in Figs.6.37 to 6.40.

6.8 SUMMARY

The problem of floods and their computation is one of the main and most complex problems facing by the hydrologists. The optimal development of Water Resources depends to a considerable extent on flood estimation and flood flow control.

A large number of methods have been proposed to predict magnitude of flood resulting due to a storm over a catchment based on response functions method such as unit hydrograph. But, uniformity of effective rainfall over the entire catchment is one of the assumptions followed in the derivation of response functions by unit-hydrograph theory. We know that the occurrence of uniform rainfall as expected is seldom true in case of large catchments. To account for the non-uniformity of rainfall and the catchment heterogenieties to a maximum extent, the whole catchment is divided into three sub-areas to treat the rainfall of each sub-catchment as separate lumped inputs. In the present study, the total rainfalls have been considered as the inputs and the total runoff as the output as against to the use of effective rainfall and direct runoff as input and output respectively used in conventional unit hydrograph method. A multiple-input single-output non-linear model was formulated and used in this study. This method was tested for the data from Wardha catchment upto Ghugus.

The response functions were derived for one, two and three rainfall inputs from the data used in calibration period. Then, these response functions were convoled with rainfall for forecasting the flows during storm events, which were not selected for calibration.

The results obtained herein indicated that as the number of inputs are increased, the results are improved very satisfactorily. At the same time, it is to state that accurate and reliable data for flood estimation by hydrologic analysis is very essential. It is expected that the method proposed herein would be more useful particularly when non-uniformity in spatial distribution of rainfall is significant.

Table 6.1 Results Obtained from Single Input (Linear Approach)

Memory length of the catchment (m)	R.F. value	$E^2\%$
1	2	3
4	25.4505 44.2063 21.4628 14.6001	64.01
5	24.6978 44.0204 22.2629 10.3235 6.7803	64.55
6	24.7514 42.6993 22.4098 10.9174 2.9756 6.4520	65.48
7	25.3372 42.7918 22.1058 10.8845 2.9890 5.1551 2.1126	65.48

Contd-/ Table 6.1

Contd-/ Table 6.1

Memory length of the catchment (m)	R.F. value	E^2%
1	2	3
8	26.4670 43.4147 22.4331 10.2347 2.5784 5.1603 -0.0707 3.5783	66.55
9	30.9876 45.3484 21.7319 10.2430 1.2872 5.1518 -0.4083 3.3384 -0.4597	69.90
10	31.5628 48.6979 23.3082 9.2222 0.9325 3.2491 -0.1329 3.4201 -2.5098 3.0302	73.29

Table 6.2 Results Obtained from Three - Inputs (Linear Approach)

Memory length of the catchment (m)	R.F.O	E^2%
1	2	3
4	13.7542 11.9422 -7.2568 -1.7310 ------------------ 11.1355 8.6874 5.6441 5.6559 ------------------ 0.8094 22.0769 17.2362 8.9521	66.29
7	10.7223 9.2388 -7.8182 0.3146 3.9792 4.5125 2.5538 ------------------ 16.3319 9.9966 -0.2591 1.7109 -14.5930 -4.5843 1.8753 ------------------ -3.6105 22.5271 20.9791 9.2960 14.9337 6.6743 -2.5835	69.45

Contd./ table 6.2

Contd./ table 6.2

Memory length of the catchment (m)	R.F.O	$E^2\%$
1	2	3
8	7.3513 9.7227 -8.8117 3.3661 5.4894 5.8408 0.5461 9.9980 -------------------- 23.7465 11.9407 3.7358 1.0932 -17.8711 -5.2239 2.5651 -1.1031 -------------------- -8.5267 21.4409 16.9374 8.0526 16.6427 7.4265 -3.8177 -2.0475	70.99

Contd./ Table 6.2

Contd./ Table 6.2

Memory length of the catchment (m)	R.F.O	E^2%
1	2	3
9	11.8347 6.0875 -12.5071 3.5809 6.8388 4.4121 2.0314 11.8239 11.4596 ----------------- 20.1225 21.1310 7.2287 4.8425 -16.9641 -8.0649 0.7790 -0.5694 -110750 ----------------- -5.0580 14.8934 15.9637 2.8946 14.9578 11.1535 -3.3051 -1.8217 1.6423	73.76

Contd./Table 6.2

Contd./Table 6.2

Memory length of the catchment (m)	R.F.O	E^2%
1	2	3
10	7.7341	77.02
	11.2430	
	-20.0537	
	1.9171	
	4.7488	
	4.9778	
	3.1951	
	14.0443	
	11.1076	
	13.4289	

	23.4944	
	20.3149	
	18.2787	
	9.2252	
	-12.4428	
	-8.3089	
	-3.3410	
	-1.3473	
	-11.3863	
	-2.4667	

	-4.8650	
	15.4263	
	8.8970	
	-0.0595	
	9.5258	
	11.1218	
	-0.5980	
	-0.5335	
	1.6339	
	-4.9290	

Note ------------ Demarcation line for the response function ordinates of different sub-catchments.

Table 6.3 : Results Obtained from Single Input (Non-Linear Approach)

Memory length of the catchment (m)	Non-linear part (n)	Linear part (l)	R.F.O.	Efficiency E^2%
1	2	3	4	5
4	1	3	0.4189 47.8086 20.1671 17.6580	67.18
4	2	2	0.6035 -0.2702 0.6720 31.2628 17.7385	64.57
7	1	6	0.4155 45.7900 20.1253 14.3283 1.6910 7.6017 2.2961	68.90
7	2	5	0.5788 -0.2613 0.6451 30.1028 9.7260 7.7408 6.7604 5.9773	68.06
7	3	4	0.3418 -0.1174 0.8554 0.4953 0.1964 0.2914 16.4161 5.9528 10.2522 6.6218	68.99

Contd/--Table 6.3

Memory length of the catchment (m)	Non-linear part (n)	Linear part (l)	R.F.O.	Efficiency E^2%
1	2	3	4	5
10	1	9	0.4423 53.7335 19.8818 13.7491 -0.5781 5.9427 -0.5546 3.2287 -2.2170 5.1725	75.80
10	2	8	0.5534 -0.0920 0.6327 32.4088 7.7520 6.9764 4.7014 3.6042 2.5299 -2.0839 7.4499	73.09
10	3	7	0.3291 0.2296 0.5030 0.3254 0.5524 0.2063 16.9234 3.2803 10.4213 1.4214 5.6665 -3.1757 8.6150	73.59

Table 6.4 : Results Obtained from Two Inputs (Non-Linear Approach)

Memory length of the catchment (m)	Non-linear part (n)	Linear part (l)	R.F.O.	Efficiency E^2%
1	2	3	4	5
4	1	3	0.3517 15.5108 -3.7870 2.1465 -------------- 0.1907 29.2466 20.5684 14.6145	68.30
4	2	2	0.4465 -0.3362 0.6462 8.9681 9.6019 ------------ 0.2986 -0.0925 0.2815 16.9607 10.4475	66.58
7	1	6	0.3897 16.0507 -2.7069 -1.0761 3.1957 7.1874 8.8774 ------------ 0.1821 25.6707 20.1550 12.9177 1.4672 1.5462 -3.5900	70.51

Contd/--Table 6.4

Memory length of the catchment (m)	Non-linear part (n)	Linear part (l)	R.F.O.	Efficiency E^2%
1	2	3	4	5
7	2	5	0.2716 -0.1943 0.6445 9.6677 4.9644 9.3949 14.7326 19.5830 ------------- 0.3624 -0.2312 0.3060 13.3117 9.0472 -0.5192 -1.2662 -9.6457	71.60
7	3	4	0.1757 -0.3190 1.4931 0.4605 0.2208 0.1653 9.1820 12.9697 14.3048 23.4328 ------------ 0.2793 -0.2602 0.3512 0.4214 -0.2469 0.1813 6.4655 -2.6156 -0.8284 -10.4600	73.31

Contd/--Table 6.4

Contd/--Table 6.4

Memory length of the catchment (m)	Non-linear part (n)	Linear part (l)	R.F.O.	Efficiency E^2%
1	2	3	4	5
8	1	7	0.3723 18.5801 -3.1521 0.3088 4.2268 7.1327 6.8178 7.5862 ----------- 0.1771 25.4412 20.0258 11.7138 0.4574 1.9113 -3.8631 -2.1295	71.20
8	2	6	0.2489 -0.1517 0.7998 9.8278 6.5938 11.2756 15.3223 18.6075 10.6640 ----------- 0.4137 -0.3789 0.3116 11.1392 8.2214 -2.3322 -0.7993 -10.2812 -4.6829	72.81

Contd/-- Table 6.4

Contd/-- Table 6.4

Memory length of the catchment (m)	Non-linear part (n)	Linear part (l)	R.F.O.	Efficiency E^2%
1	2	3	4	5
8	3	5	0.1893 -0.4201 1.4153 0.6484 0.1052 0.1932 10.1183 14.8752 15.2925 21.7977 14.8270 ------------- 0.3436 -0.3909 0.2607 0.4691 -0.3040 0.1837 5.0949 -4.1817 -0.7633 -10.5344 -7.3065	74.22
10	1	9	0.4884 21.7495 -5.9322 2.0862 4.1427 7.9546 8.6575 6.8922 6.2148 19.1010 ------------ 0.1786 26.9284 19.1479 10.7268 -2.0716 -0.1101 -4.5447 -0.1362 -6.2562 -8.5667	78.59

Contd/-- Table 6.4

Contd/--Table 6.4

Memory length of the catchment (m)	Non-linear part (n)	Linear part (l)	R.F.O.	Efficiency E^2%
1	2	3	4	5
10	2	8	1.4356 -2.5897 1.2244 8.3096 7.1445 10.4084 18.5809 11.4993 11.3132 7.0434 14.5450 ------------ -0.1439 0.8381 0.1796 10.3119 9.2064 -5.7256 -2.4992 -8.6364 -1.6602 -8.1539 -3.8606	80.66
10	3	7	1.3969 -2.5976 1.0241 1.3607 -0.4365 0.2952 12.2028 12.8773 19.2431 14.8072 12.7625 7.6906 15.8261 ------------ -0.2535 0.8999 0.2237 0.0215 0.3153 0.0280 6.1560 -6.5000 -2.7896 -9.4257 -2.6958 -8.6585 -4.3467	81.23

Note : ---- Demarcation line for the response function ordinates of different sub-catchments.

Table 6.5 : Results Obtained from Three Inputs (Non-Linear Approach)

Memory length of the catchment (m)	Non-linear part (n)	Linear part (l')	R.F.O.	Efficiency E^2%
1	2	3	4	5
4	1	3	0.4001 18.8690 -3.6121 2.2719 ---------- 0.1791 4.3417 10.4434 6.3415 ---------- 0.0104 23.0695 9.3007 7.6703	69.24
4	2	2	0.5292 -0.2919 0.7304 11.8417 8.9089 ---------- 0.2559 -0.5295 0.1701 0.7579 5.1884 ---------- -0.0343 0.4566 0.0753 13.3266 4.5595	68.32
7	1	6	0.3996 14.9747 -3.4845 5.2241 7.3784 9.7150 5.1405 ---------- 0.2087 5.3946 4.8721 2.4169 -19.3473 -5.3907 -0.0641 ---------- -0.0397 22.9929 11.8861 8.1980 16.5333 5.6739 -2.8380	73.06

Contd/-Table 6.5

Contd/-Table 6.5

Memory length of the catchment (m)	Non-linear part (n)	Linear part (l)	R.F.O.	Efficiency E^2%
1	2	3	4	5
7	2	5	0.2499 -0.1047 -0.5907 9.3109 7.2340 16.5036 18.3574 13.4057 ------------ 0.3279 -0.4118 0.2003 -1.5209 3.2932 -17.4266 -13.0971 -3.9469 ------------ -0.0852 0.3683 0.0867 14.0625 2.5532 13.8934 8.2446 -2.8807	74.48
7	3	4	0.4996 -0.9245 2.1694 0.8355 -0.5297 0.2338 15.1031 17.3487 22.2005 17.5439 ------------ 0.2246 -0.4567 -0.9378 0.3808 -0.8334 0.3408 1.5032 -14.4985 -10.9345 -8.0792 ------------ -0.1110 0.4349 0.3923 0.0384 0.5702 -0.1324 2.2352 7.6792 6.0647 -1.2666	77.44

Contd/-Table 6.5

Memory length of the catchment (m)	Non-linear part (n)	Linear part (l)	R.F.O.	Efficiency E^2%
1	2	3	4	5
8	1	7	0.3272 16.3181 -4.3229 8.1530 8.5152 11.1776 3.6223 7.3389 -------------- 0.2917 8.7411 8.7590 2.5434 -22.3984 -5.6352 0.6052 -0.7496 -0.1047 21.3907 7.3581 6.8239 17.9321 5.9295 -4.1014 -1.4672	74.63
8	2	6	0.0049 0.2328 0.6866 9.0999 9.6487 19.3854 20.1377 14.0934 10.1438 ------------- 0.4883 -0.6413 0.2712 1.7036 4.3045 -19.9887 -14.4071 -3.8652 -2.8170 ------------- -0.1200 0.3470 0.0496 9.1269 0.1035 14.6483 9.0293 -3.8357 -2.4347	76.59

Contd/-Table 6.5

Contd/-Table 6.5

Memory length of the catchment (m)	Non-linear part (n)	Linear part (l)	R.F.O.	Efficiency E^2%
1	2	3	4	5
8	3	5	0.3681 -0.7925 1.9219 0.8945 -0.4494 0.2476 15.6717 20.2335 23.5678 16.0704 15.8945 -------------- 0.3660 -0.6885 -0.9278 0.4558 -0.7564 0.3104 2.0646 -16.6154 -12.5095 -7.2177 -5.4839 ------------- -0.1217 0.4709 0.2940 0.0415 0.4256 -0.1058 0.1303 8.2500 7.0416 -2.1192 -2.3353	78.66

Contd/--Table 6.5

Contd/-Table 6.5

Memory length of the catchment (m)	Non-linear part (n)	Linear part (l)	R.F.O.	Efficiency E^2%
1	2	3	4	5
10	1	9	0.4577 17.1653 -14.4601 6.8443 7.9403 9.7185 5.8838 11.6817 9.1436 14.4674 ------------ 0.2382 16.4776 23.0428 11.5998 -16.6169 -9.3363 -4.0137 -2.7651 -9.2029 -5.0380 -------------- -0.0528 16.2277 -1.0224 -2.4293 11.3833 9.3292 -1.1594 0.7191 1.0777 -2.0489	80.60

Contd/-Table 6.5

Contd/-Table 6.5

Memory length of the catchment (m)	Non-linear part (n)	Linear part (l)	R.F.O.	Efficiency E^2%
1	2	3	4	5
10	2	8	0.8811 -1.8472 1.1335 -1.1769 6.7878 16.8260 24.0513 6.6420 16.8618 14.4578 12.3493 ------------ 0.2367 -0.1214 0.2574 17.7219 12.8209 -11.0722 -15.6014 -10.1263 -2.3129 -14.7614 -6.5740 ------------ -0.2473 0.6981 -0.0141 -1.1634 -5.2133 2.3252 11.7334 1.6723 -2.0802 2.5595 1.8690	83.21

Contd-/ Table 6.5

Contd/-Table 6.5

Memory length of the catchment (m)	Non-linear part (n)	Linear part (l)	R.F.O.	Efficiency E^2%
1	2	3	4	5
10	3	7	0.9729 -2.1570 1.3523 1.2246 -0.5890 0.1648 11.1535 17.8657 24.7830 12.2206 18.3807 13.4903 15.0091 ------------ 0.1434 0.0595 -0.0859 0.1833 0.1850 0.2037 12.4787 -10.4188 -13.9470 -11.2531 -4.1367 -13.0731 -7.5259 ------------- -0.2618 0.6185 0.1805 -0.0033 -0.0048 -0.0871 -5.9450 0.6555 9.4082 1.4131 -1.9194 1.3201 1.5383	83.50

Note : ------ Demarcation line for the response function ordinates of different sub-catchments.

Table 6.6 Comparative Study of Linear and Non - Linear Approaches

Memory length of the catchment (m)	Efficiency (%)				
	Linear Approach		Non-Linear Approach		
	1 Input Table 6.1	3 Inputs Table 6.2	1 Input Table 6.3	2 Inputs Table 6.4	3 Inputs Table 6.5
1	2		3		
4	64.01	66.29	67.18	68.30	69.24
7	65.48	69.45	68.99	73.31	77.44
8	66.55	70.99	-	74.22	78.66
9	69.90	73.76	-	74.96	80.22
10	73.29*	77.02	75.80	81.23	83.50**

* Efficiency of Lumped Linear Approach

** Efficiency of Nonlinear Three – inputs Approach

Note: Efficiency, E^2 (%) = $\left(\frac{F_d - F_1}{F_d}\right) x100$

F_d = sum of squares of difference between Q_{av} and Q_{obs}.

F_1 = sum of squares of difference between Q_{cst} and Q_{obs}.

CONCLUSIONS AND SUGGESTIONS

7.1 CONCLUSIONS

(1) The response function ordinates were derived by trial and error for different memory lengths of the catchment for various conditions viz. One, two and three inputs. Some of the ordinates are negative in sign.

(2) Ridge regression (smoothed least squares estimate) concept was helpful only to some extent in the process of smoothing the disappear negative values of the response functions.

(3) From comparative study among alternative approaches used the following conclusions are drawn.

 (a) Increase in efficiency with linear approach being used and rainfall varied from single input to three inputs is only marginal i.e. from 73% to 77% .

 (b) Efficiency obtained from non-linear approach by changing the rainfall from single input to three inputs is high i.e. from 76% to 84%.

 (c) Efficiency obtained through linear approach - multiple input when compared with non - linear approach single input is almost same. (i.e. E^2 = 77% and 76% respectively).

 (d) Efficiency of multiple input by non-linear approach is appreciably higher than that obtained through multiple input - linear approach (E^2 = 77% and 84% respectively).

(4) Non-linear form of the model produced better efficiency among all the methods studied.

(5) The efficiency of the model increased with an increase in number of rainfall inputs.

(6) Graphical comparison of the results indicated that capability of the model to predict the peak flows is increased when number of inputs are increased.

(7) As some of the storm events selected for present study could not be predicted satisfactorily by using any number of inputs. It is stipulated that –

  (a) Accurate and reliable data for flood estimation by hydrologic analysis is very essential.

  (b) Use of effective rainfall (total rainfall – evapotranspiration) instead of total rainfall, as input would result in better predictability.

(8) Value of 'm' for different sub-catchments ----

It is expected in general that the sub-catchment, which is nearer to the catchment outlet, may not contribute the flow for long time. But, trials revealed that it will contribute to the river-flow for a longer period than expected as above.

(9) The estimation of response function ordinates of non-parametric type from the sample data is very sensitive to the interrelationships existing among the observed input series.

7.2 SUGGESTIONS

(1) Use of Bayesian method of unit hydrograph estimation developed by Bhargava (1986) which gives non-oscillatory unit hydrographs with non-negative ordinates, can be studied instead of ridge regression method.

(2) Determination of Memory : To determine 'm', 'n' and 'l' values by trial and error, it necessiates complete calibration of the model for various values used. So, use of cross-correlation between rainfall and runoff can provide a short cut to this problem.

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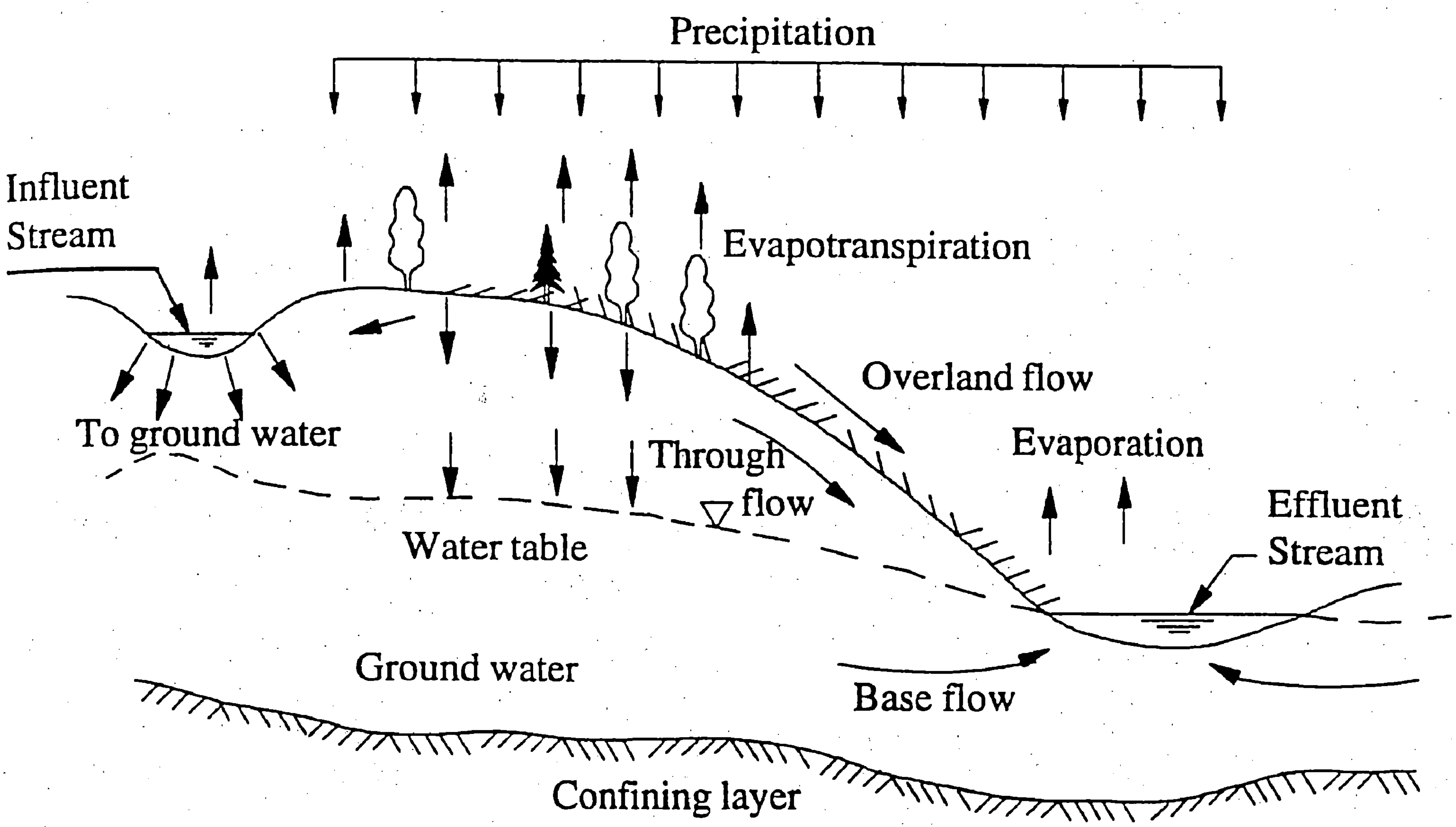

FIG 1.1 DIFFERENT ROUTES OF RUNOFF (Subramanya, 1994)

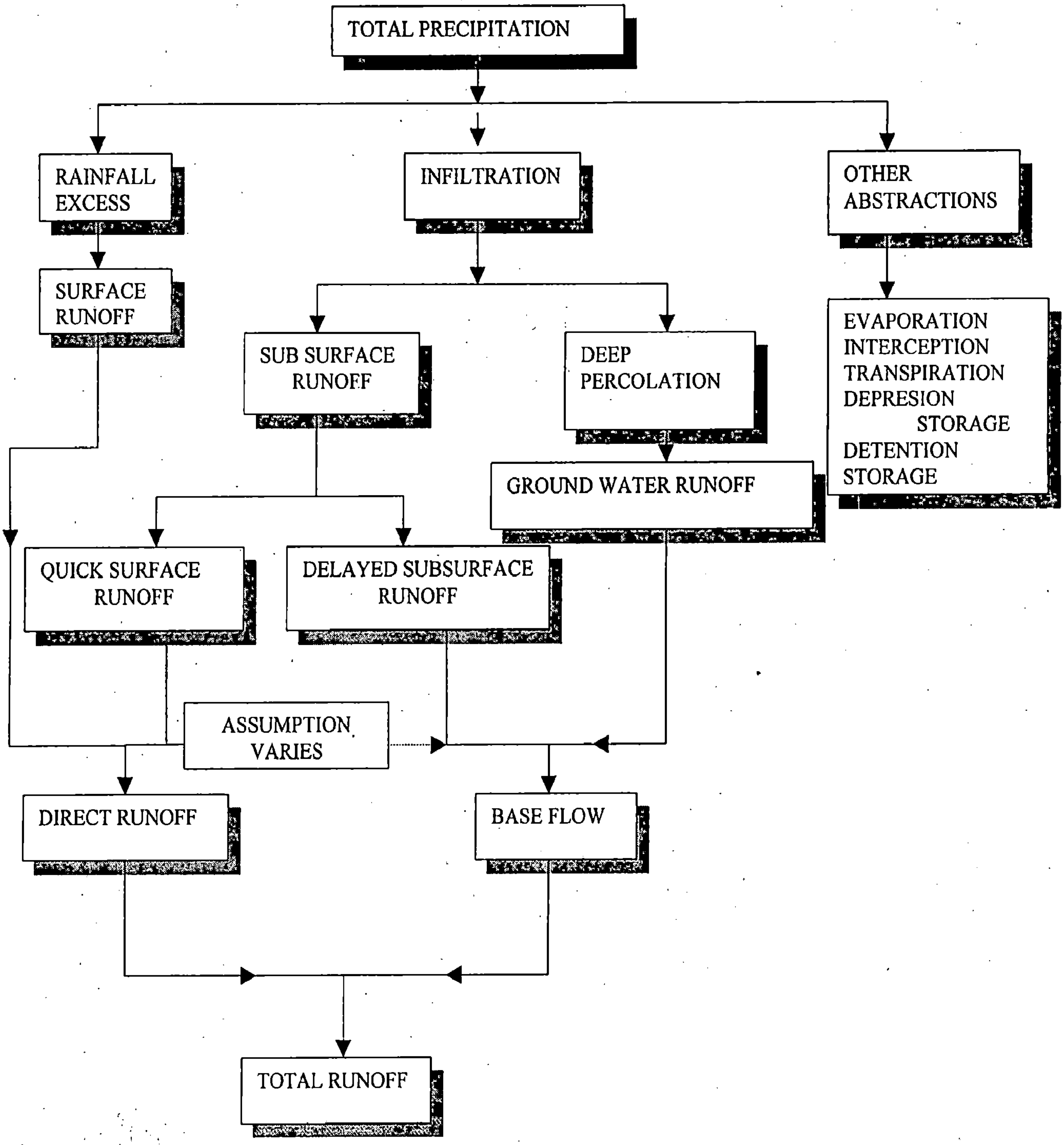

FIG. 2.1 SYSTEMS REPRESENTATION OF CATCHMENT RUNOFF (Chow, 1964).

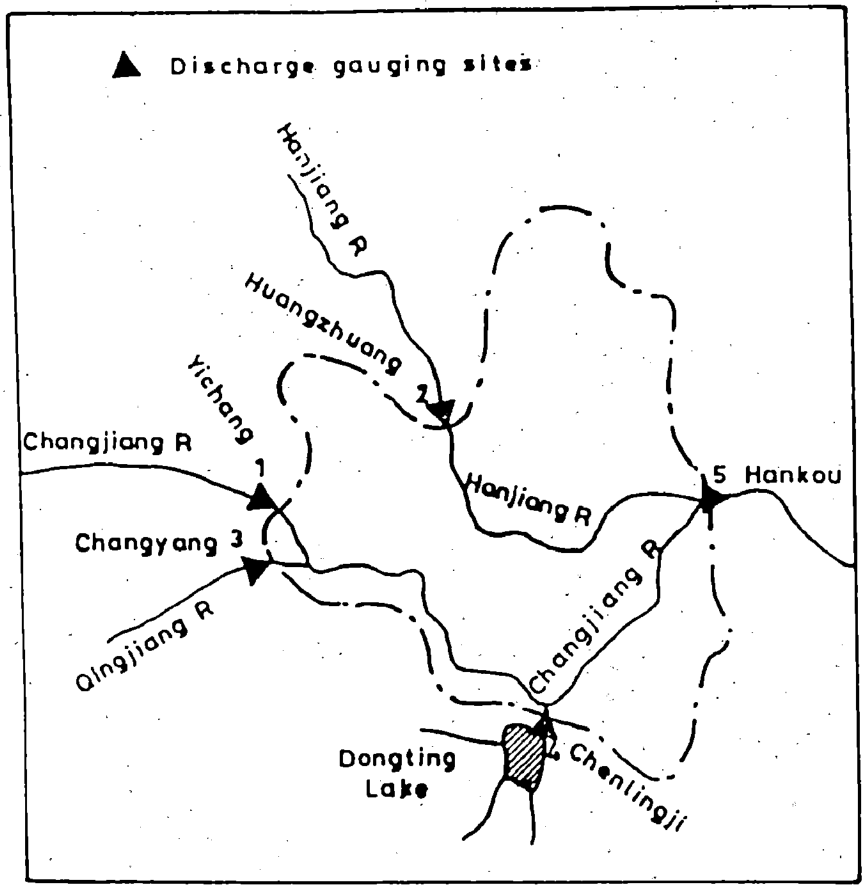

FIG. 2.2 SKETCH OF THE HANKOU CATCHMENT

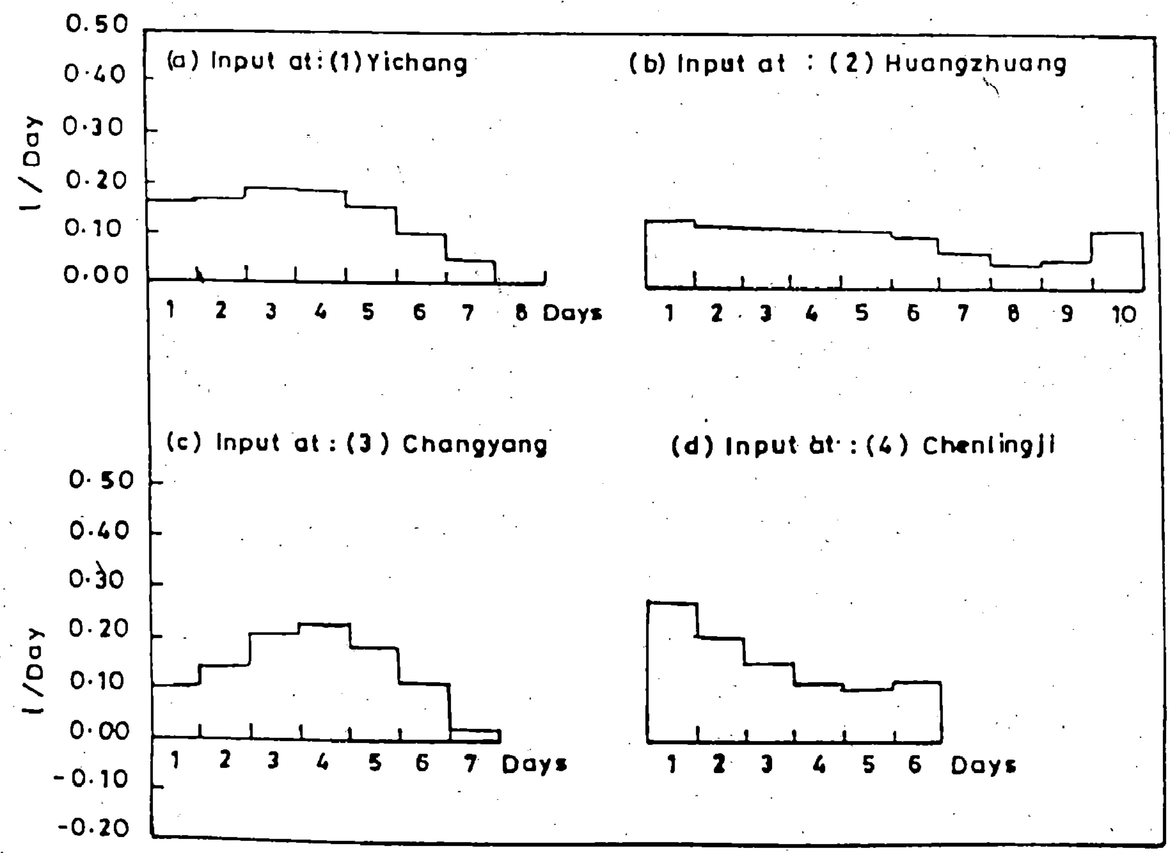

FIG. 2.3 NONPARAMETRIC RESPONSE FUNCTIONS AS OBTAINED BY LIANG (1988) FOR A LINEAR MULTIPLE – INPUT SINGLE – OUTPUT RAINFALL – RUNOFF MODEL

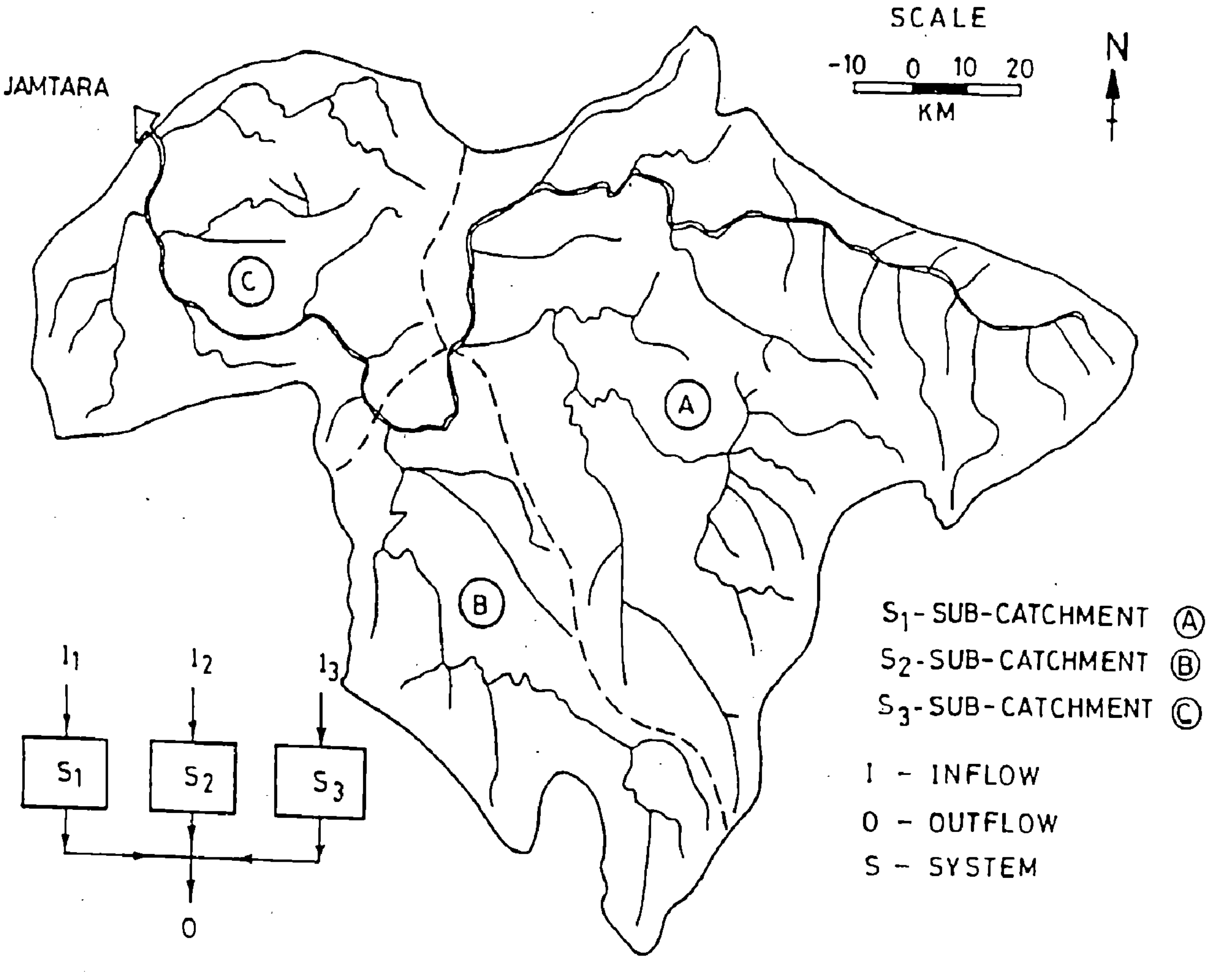

FIG. 2.4 SKETCH OF THE NARMADA CATCHMENT

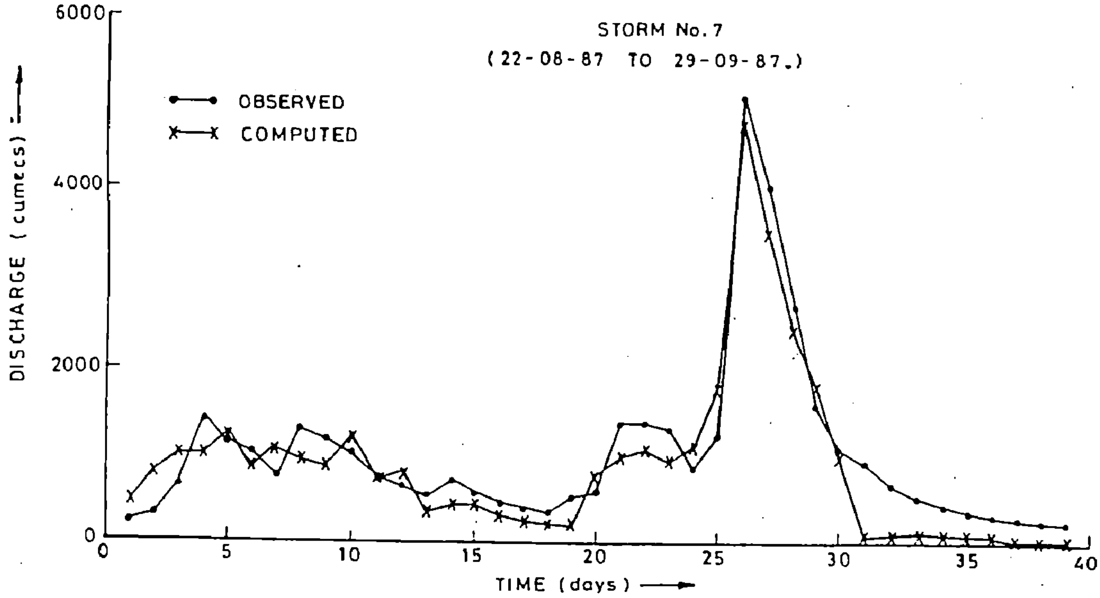

FIG. 2.5 COMPARISON OF COMPUTED AND OBSERVED RUNOFF USING THREE INPUTS AS OBTAINED BY KOTHYARI AND SINGH (1999) FOR A NON – LINEAR MULTIPLE – INPUT SINGLE – OUTPUT RAINFALL – RUNOFF MODEL

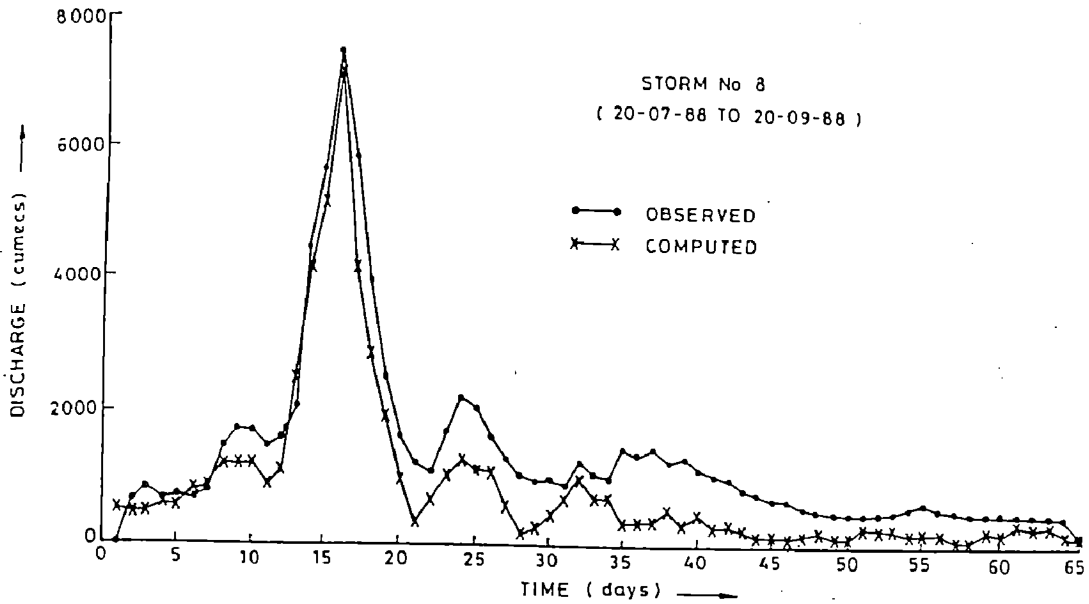

FIG. 2.6 COMPARISON OF COMPUTED AND OBSERVED RUNOFF USING THREE INPUTS AS OBTAINED BY KOTHYARI AND SINGH (1999) FOR A NON – LINEAR MULTIPLE – INPUT SINGLE – OUTPUT RAINFALL – RUNOFF MODEL

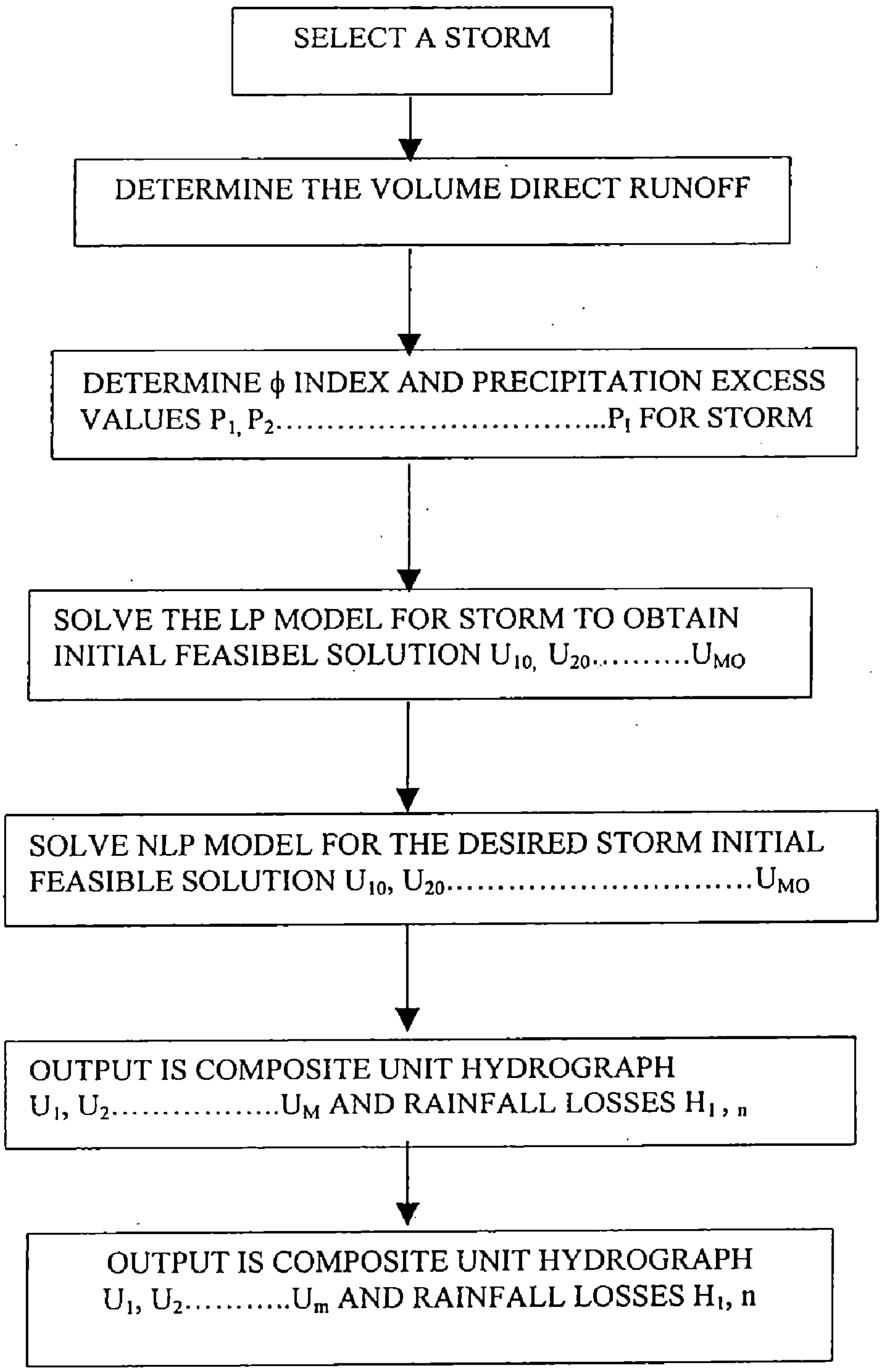

Fig. 2.7 APPLICATION STRATEGY FOR NLP

(Mays and Taur, 1982)

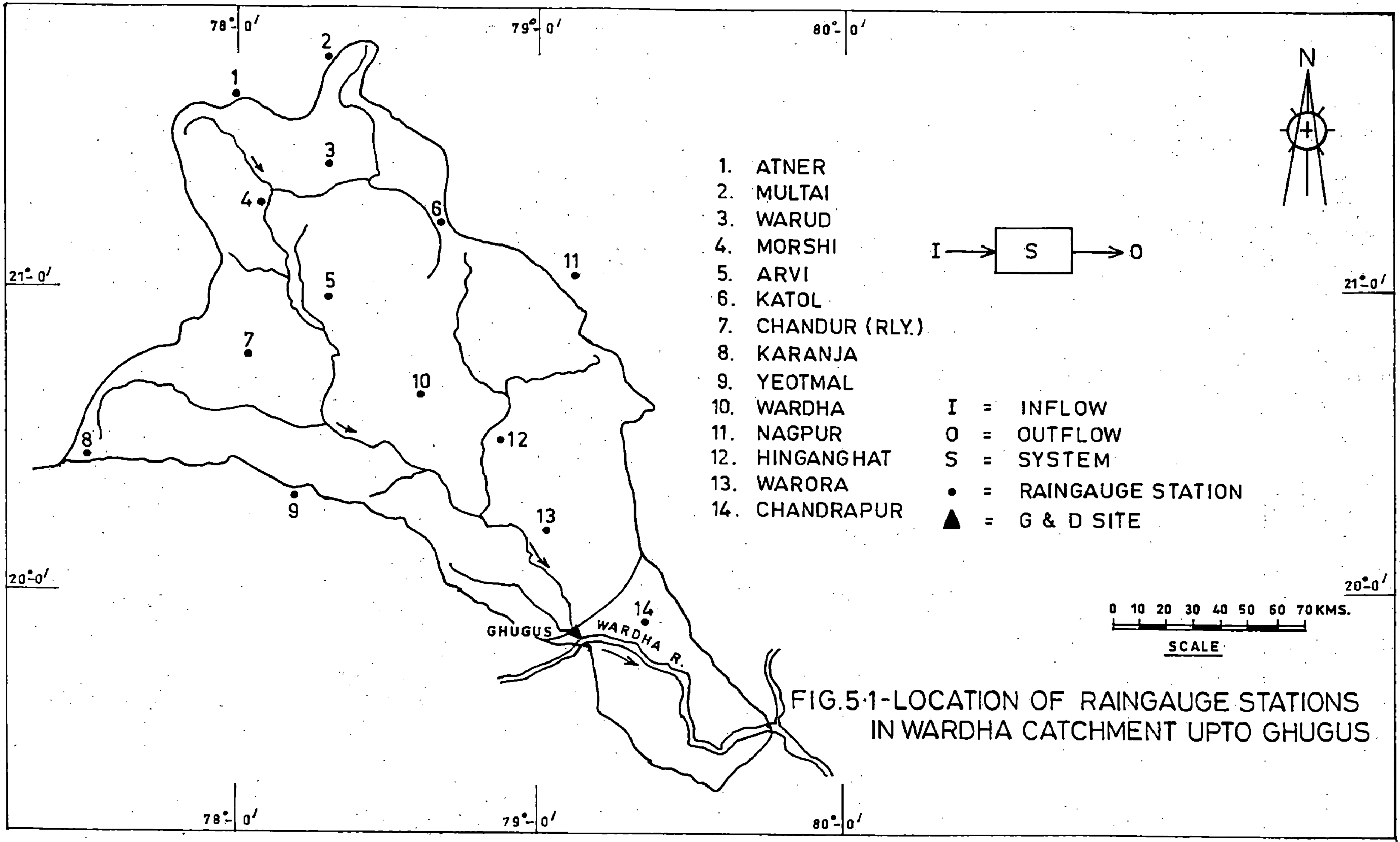

FIG.5·1-LOCATION OF RAINGAUGE STATIONS IN WARDHA CATCHMENT UPTO GHUGUS

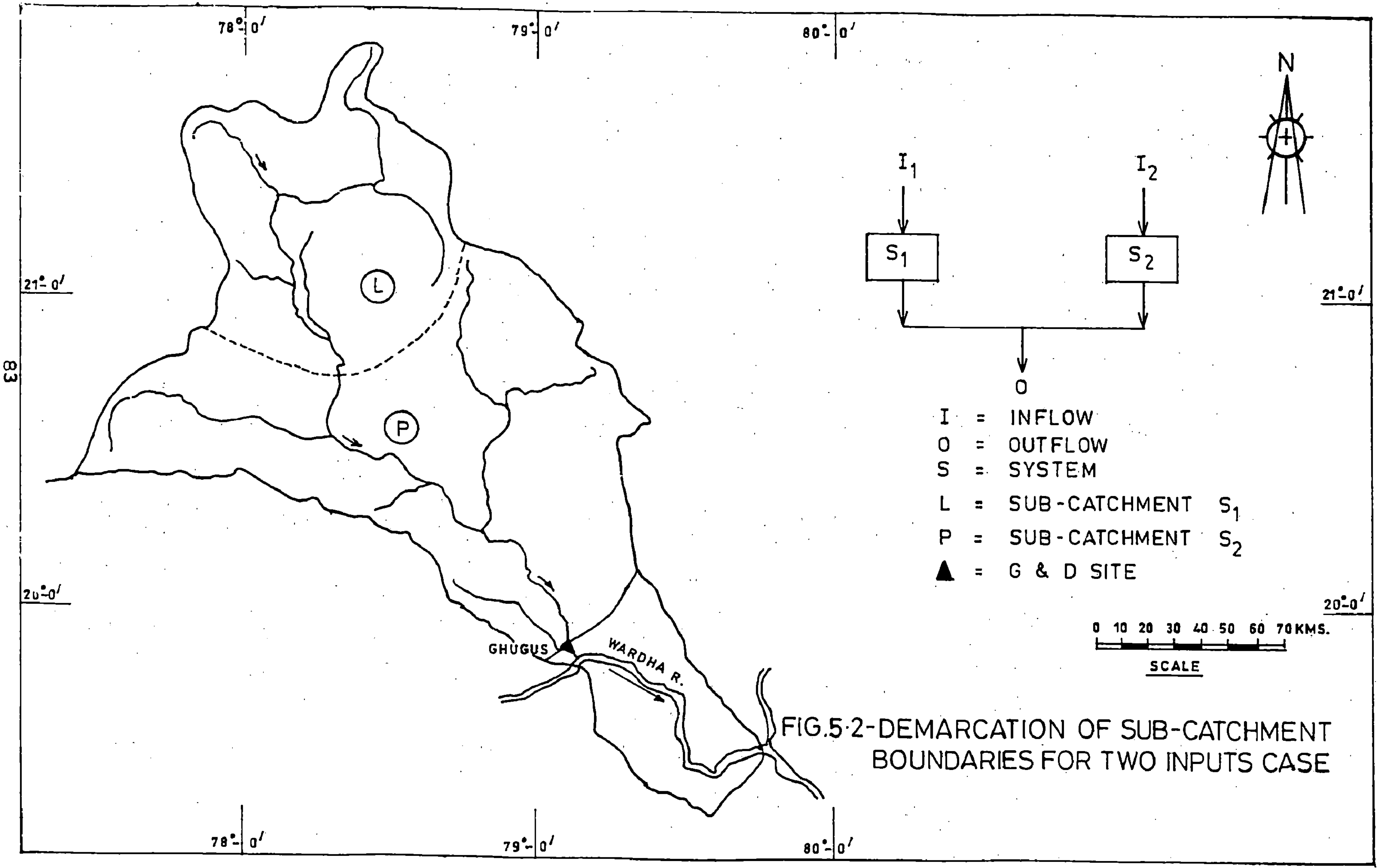

FIG.5·2-DEMARCATION OF SUB-CATCHMENT BOUNDARIES FOR TWO INPUTS CASE

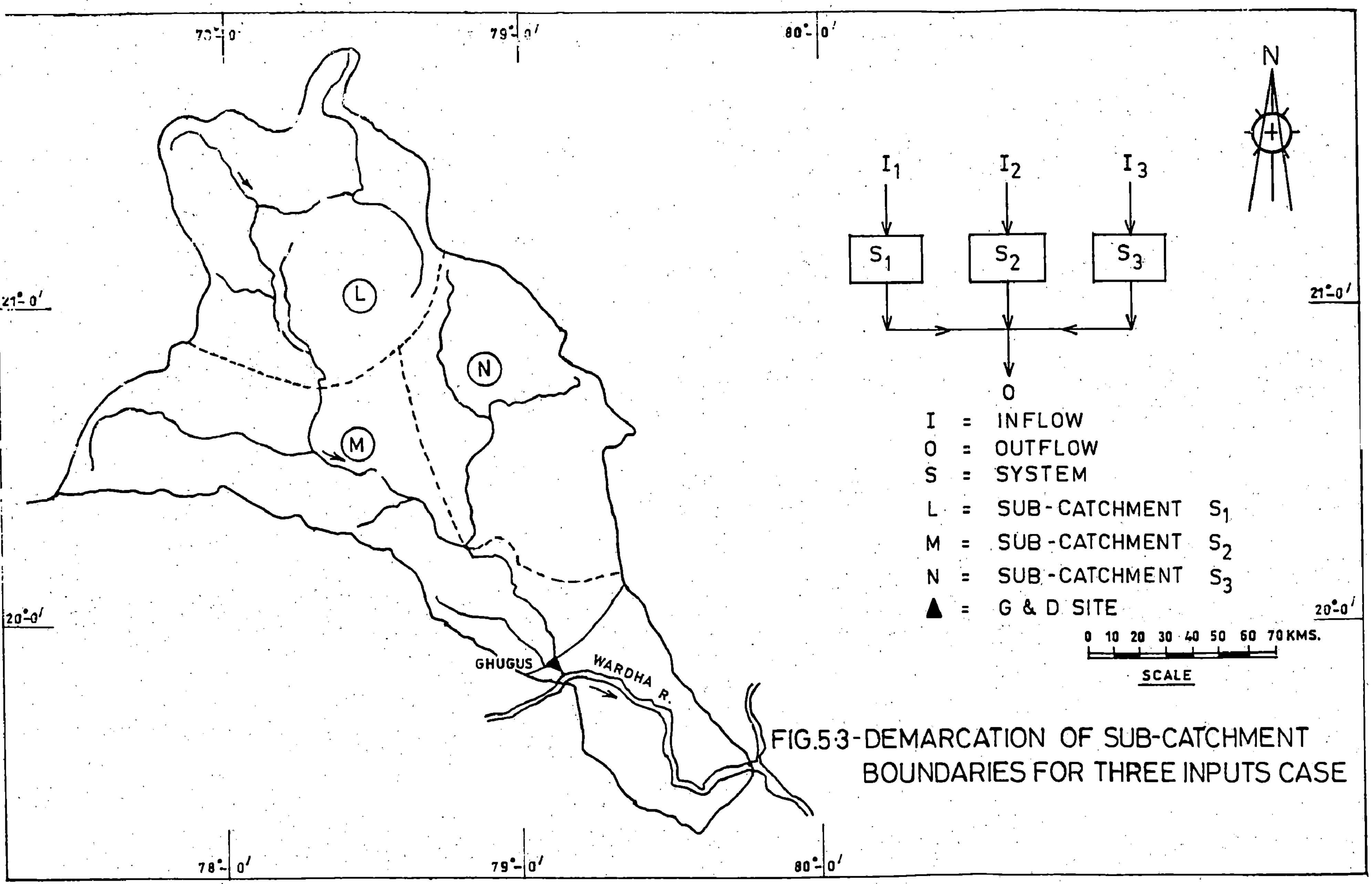

FIG.5.3-DEMARCATION OF SUB-CATCHMENT BOUNDARIES FOR THREE INPUTS CASE

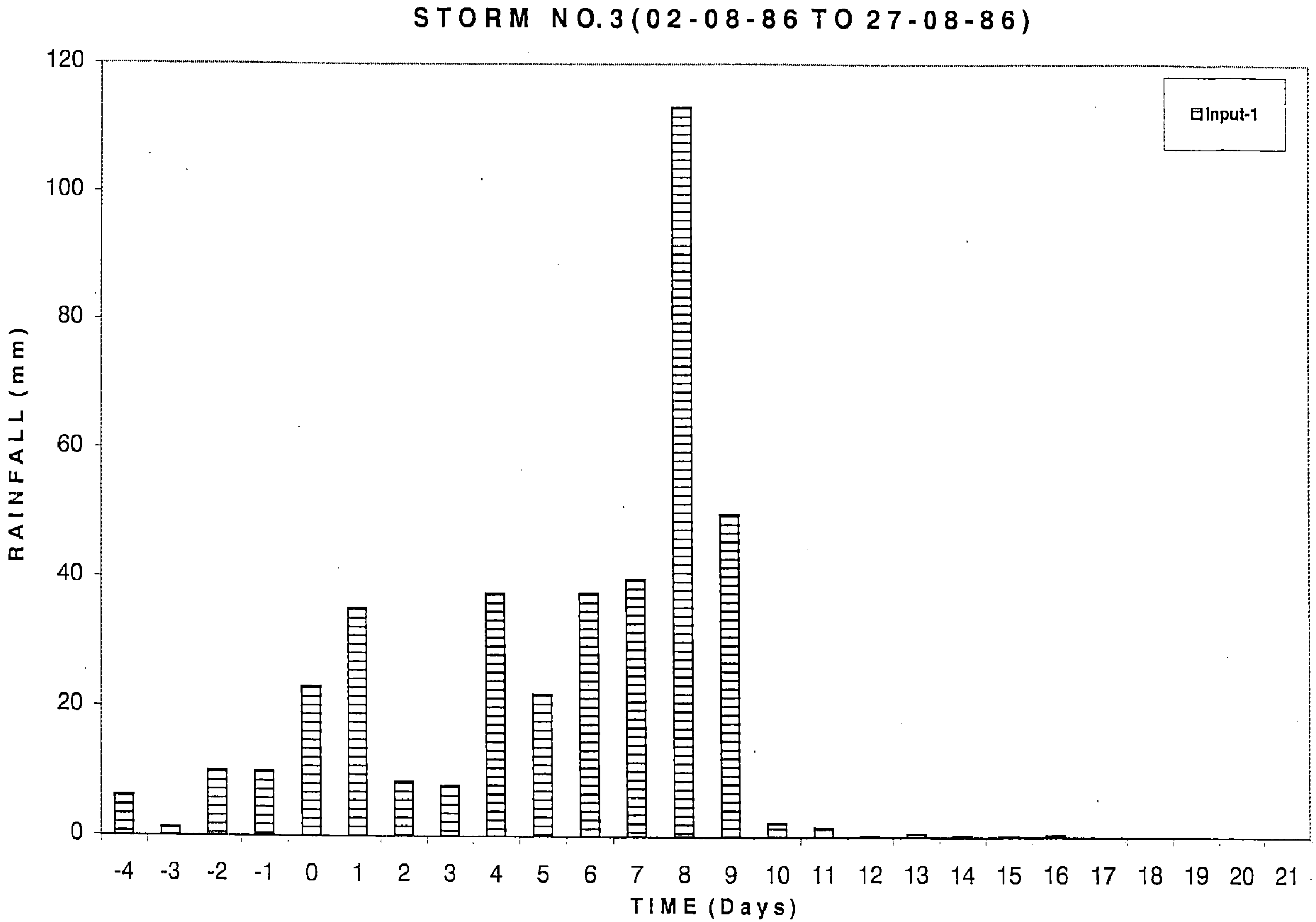

FIG. 6.1 VARIATION OF RAINFALL WITH TIME

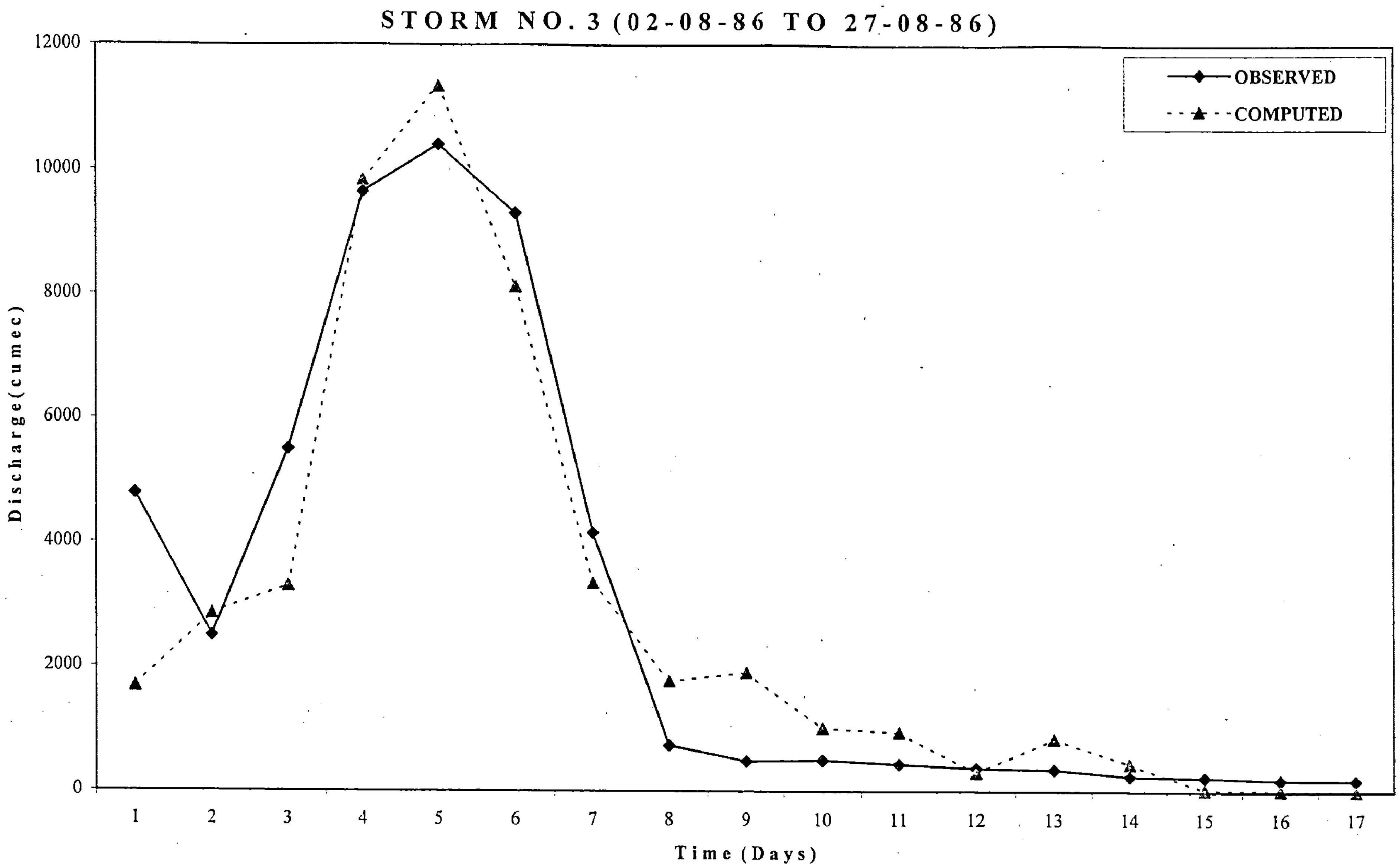

FIG. 6 . 2 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING ONE INPUT (CALIBRATION PERIOD)

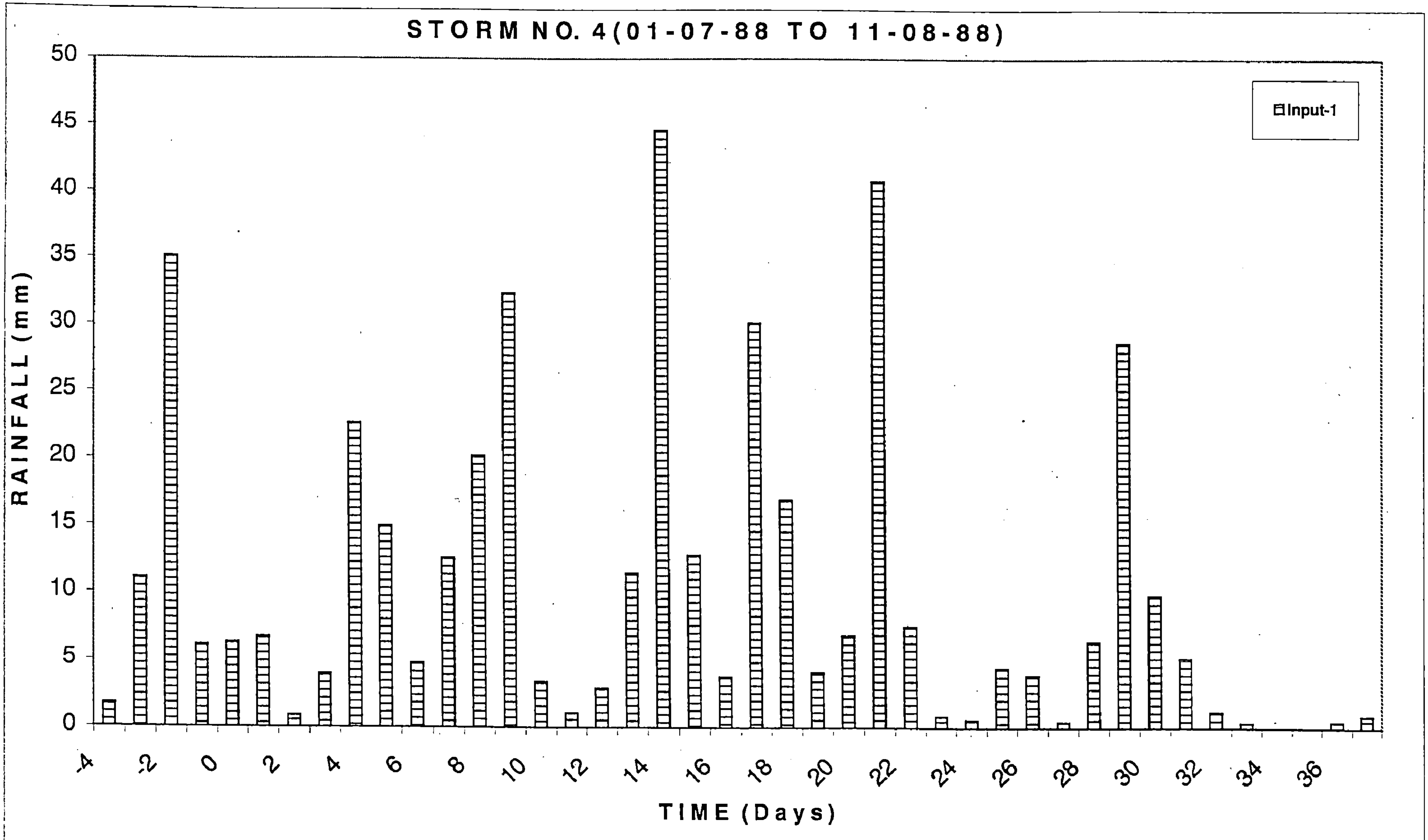

FIG. 6.3 VARIATION OF RAINFALL WITH TIME

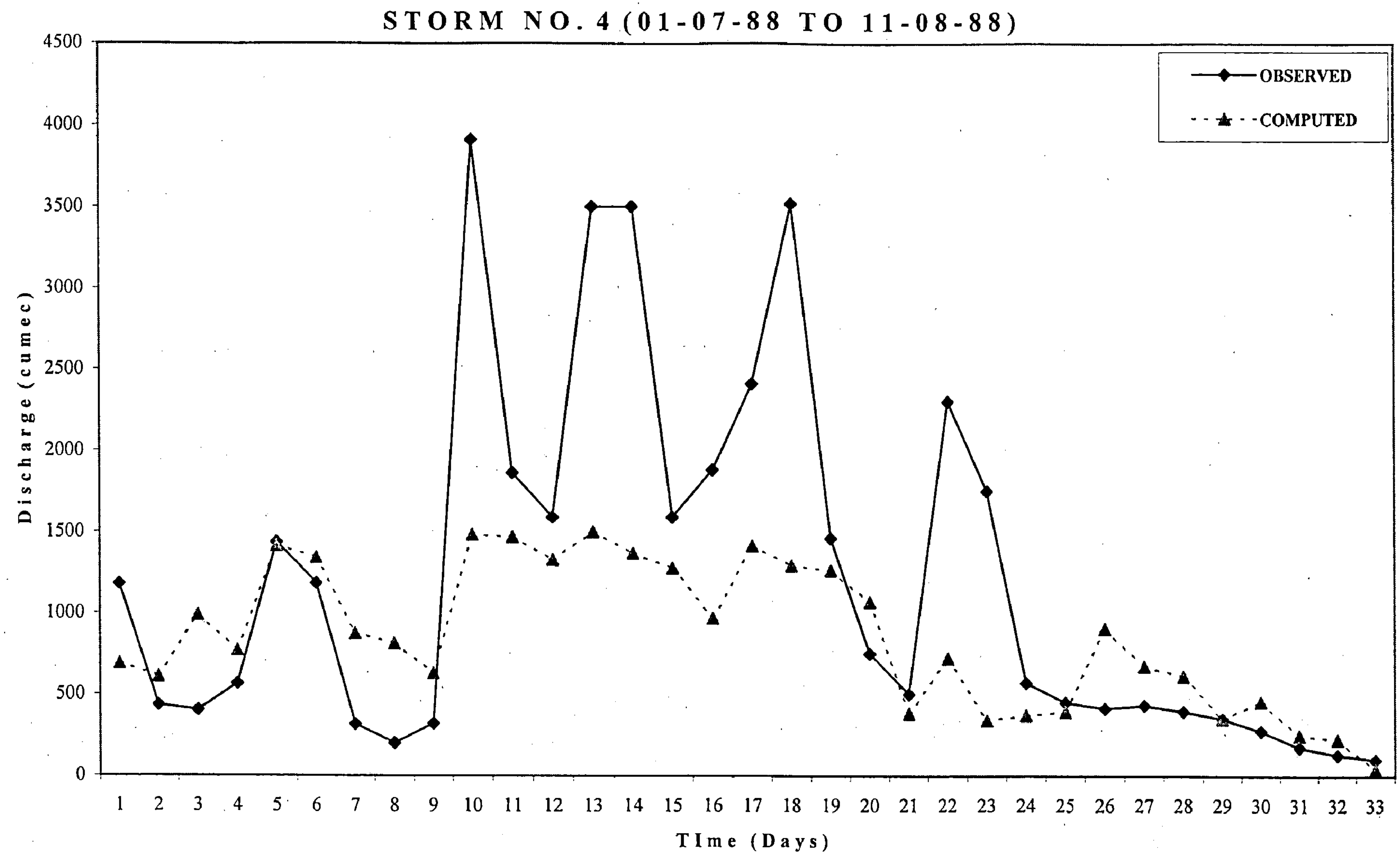

FIG. 6..4 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING ONE INPUT (CALIBRATION PERIOD)

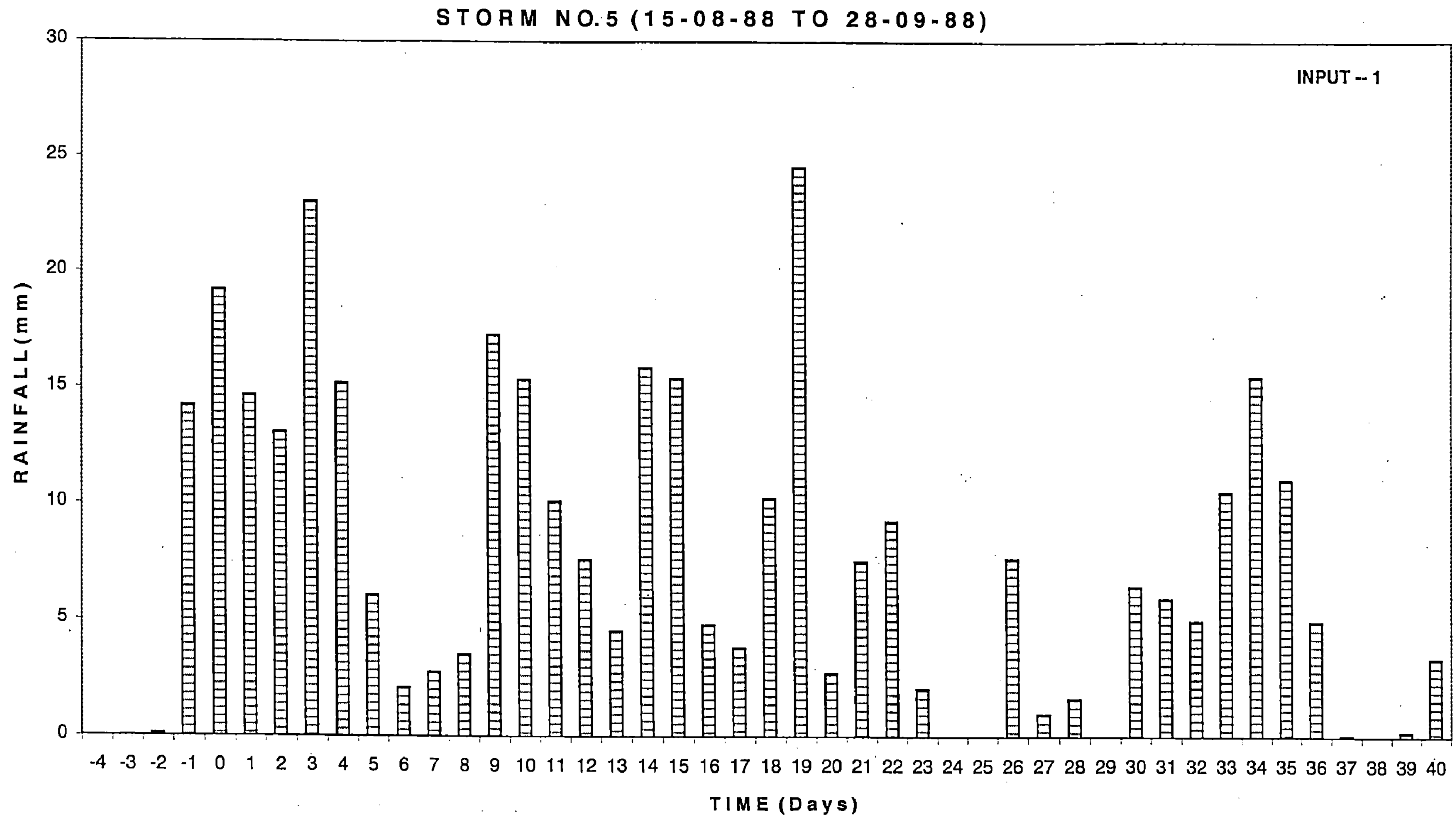

FIG.6.5 VARIATION OF RAINFALL WITH TIME

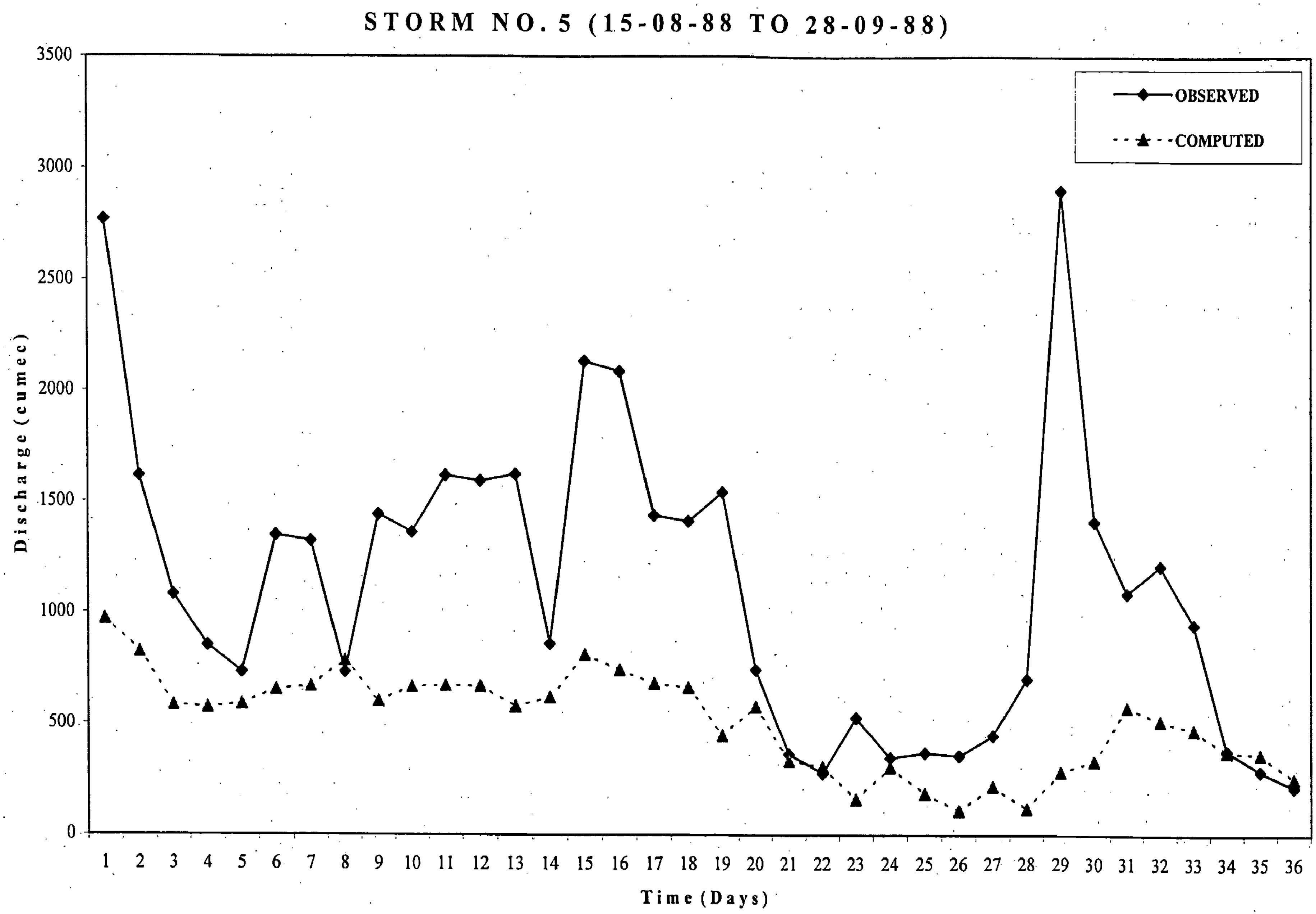

FIG. 6 . 6 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING ONE INPUT (CALIBRATION PERIOD)

STORM NO. 6 (11-08-89 TO 14-09-89)

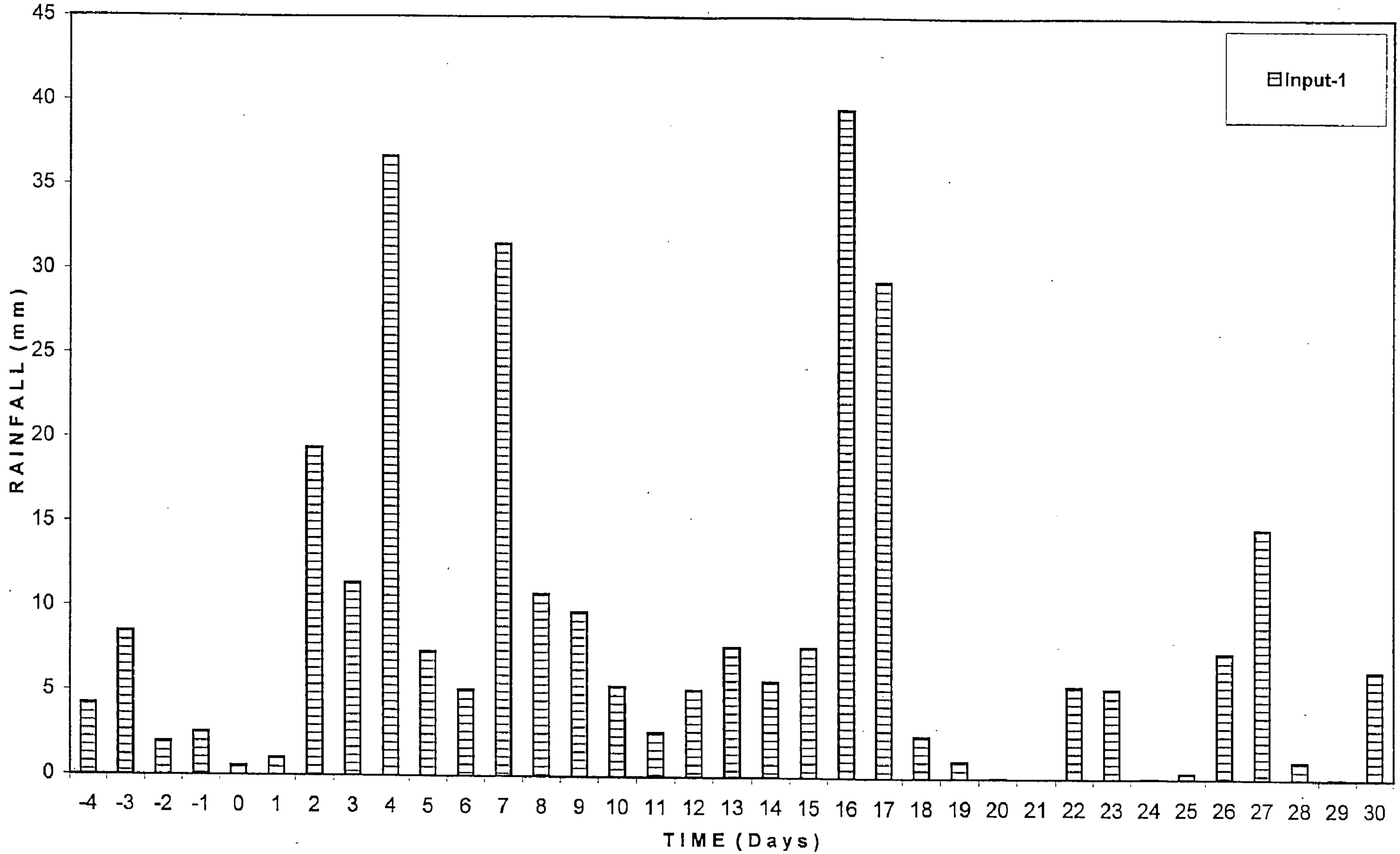

FIG.6.7 VARIATION OF RAINFALL WITH TIME

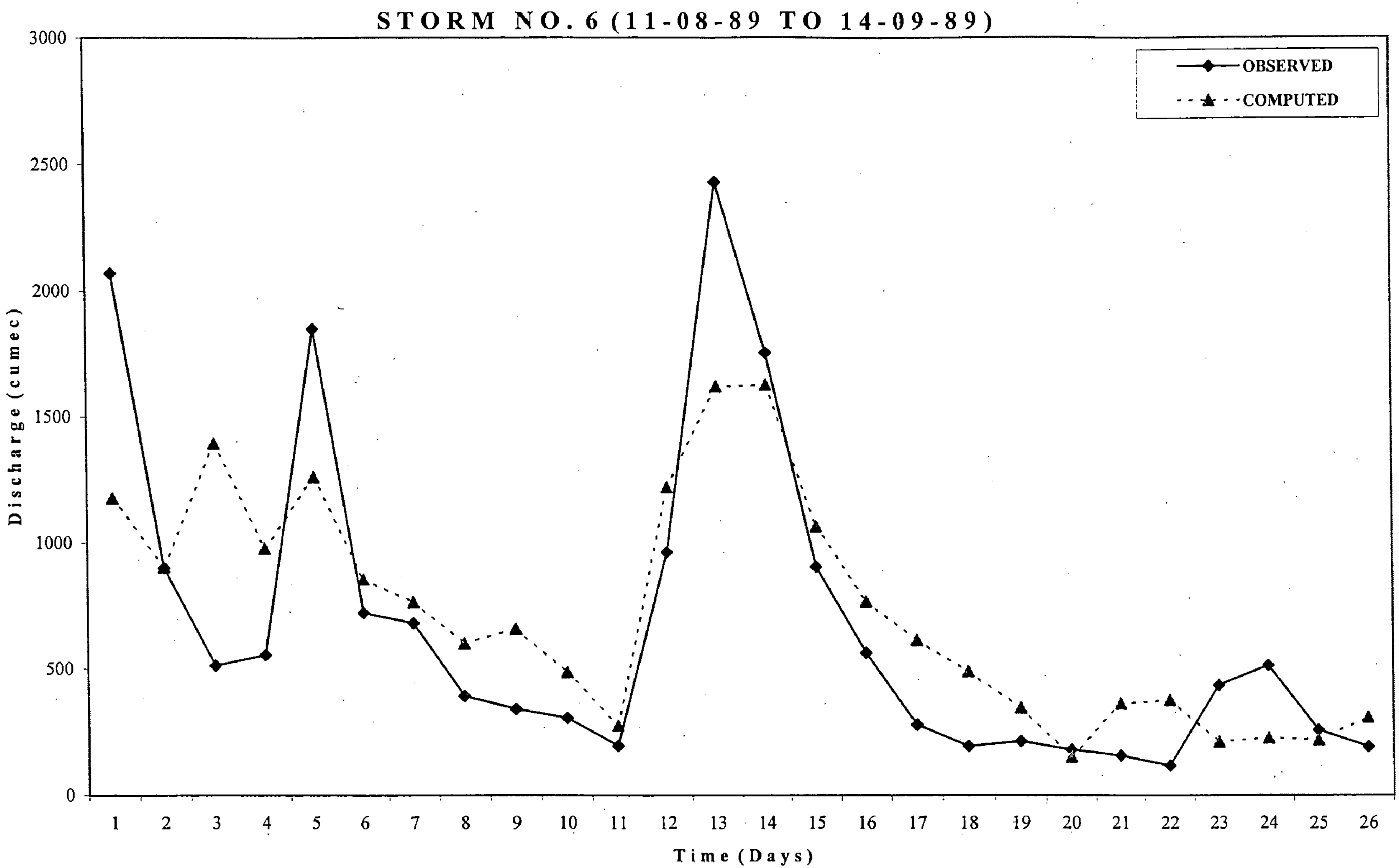

FIG. 6. 8 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING ONE INPUT (CALIBRATION PERIOD)

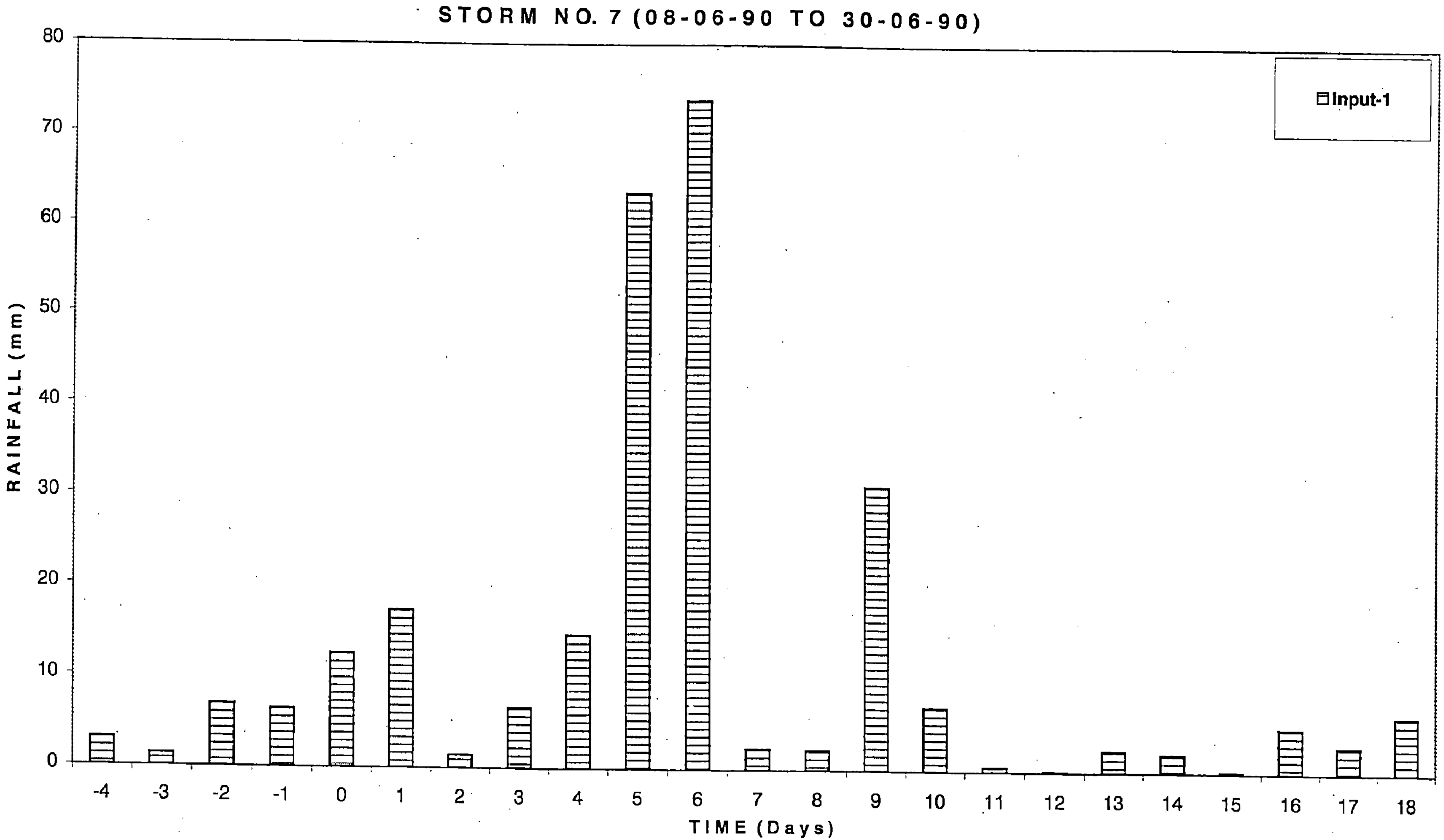

FIG.6.9 VARIATION OF RAINFALL WITH TIME

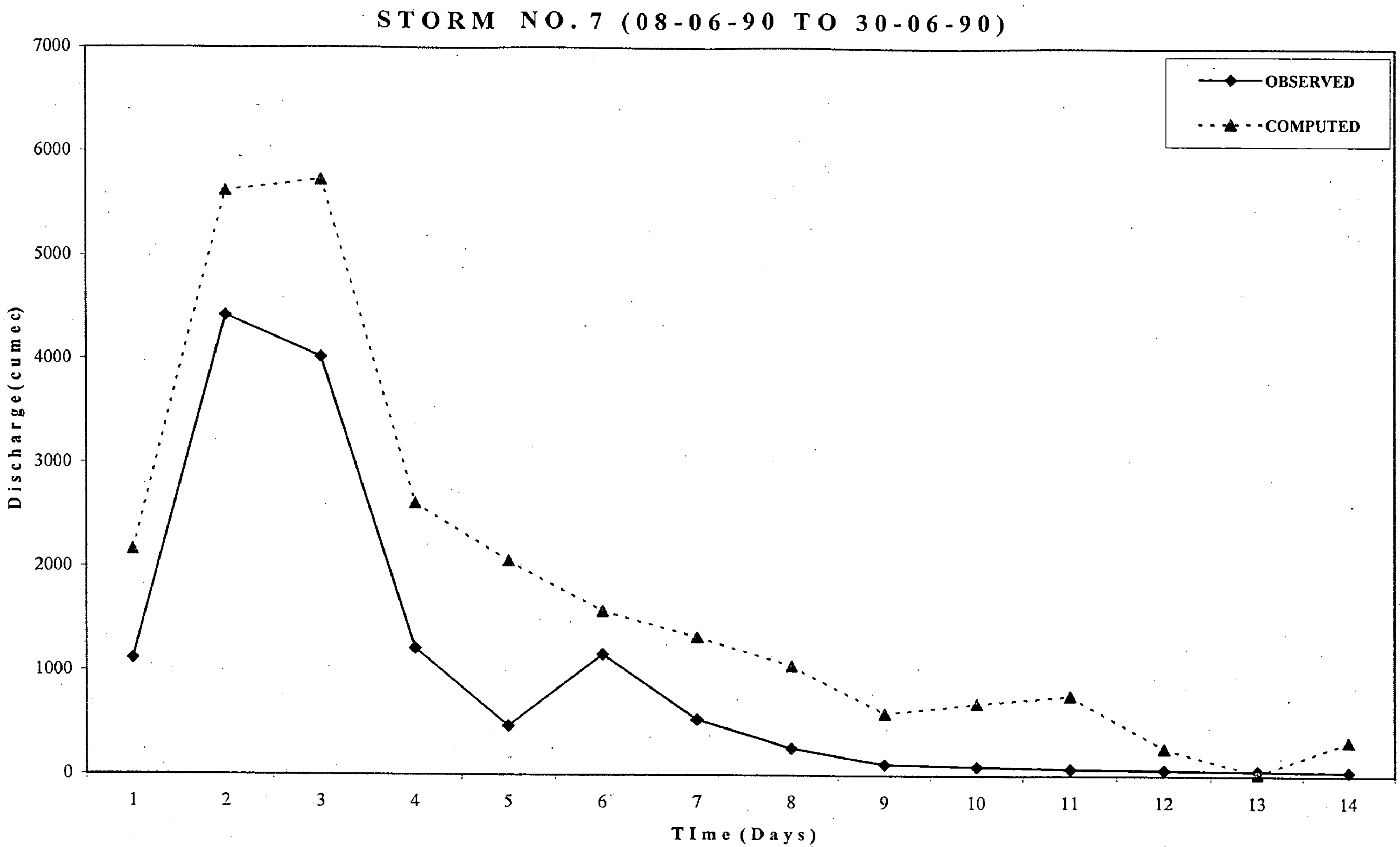

FIG. 6.10 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING ONE INPUT (CALIBRATION PERIOD)

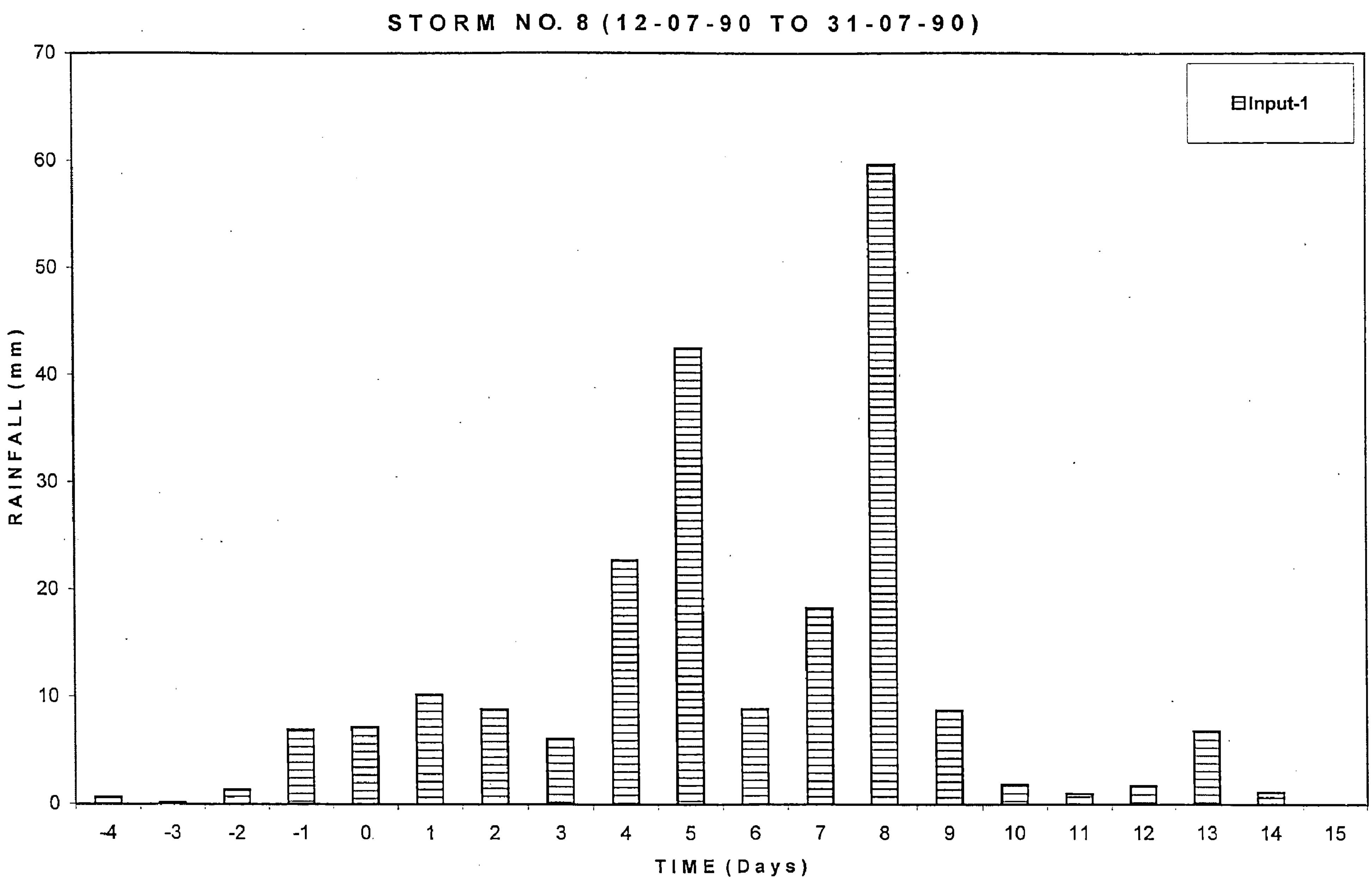

FIG.6.11 VARIATION OF RAINFALL WITH TIME

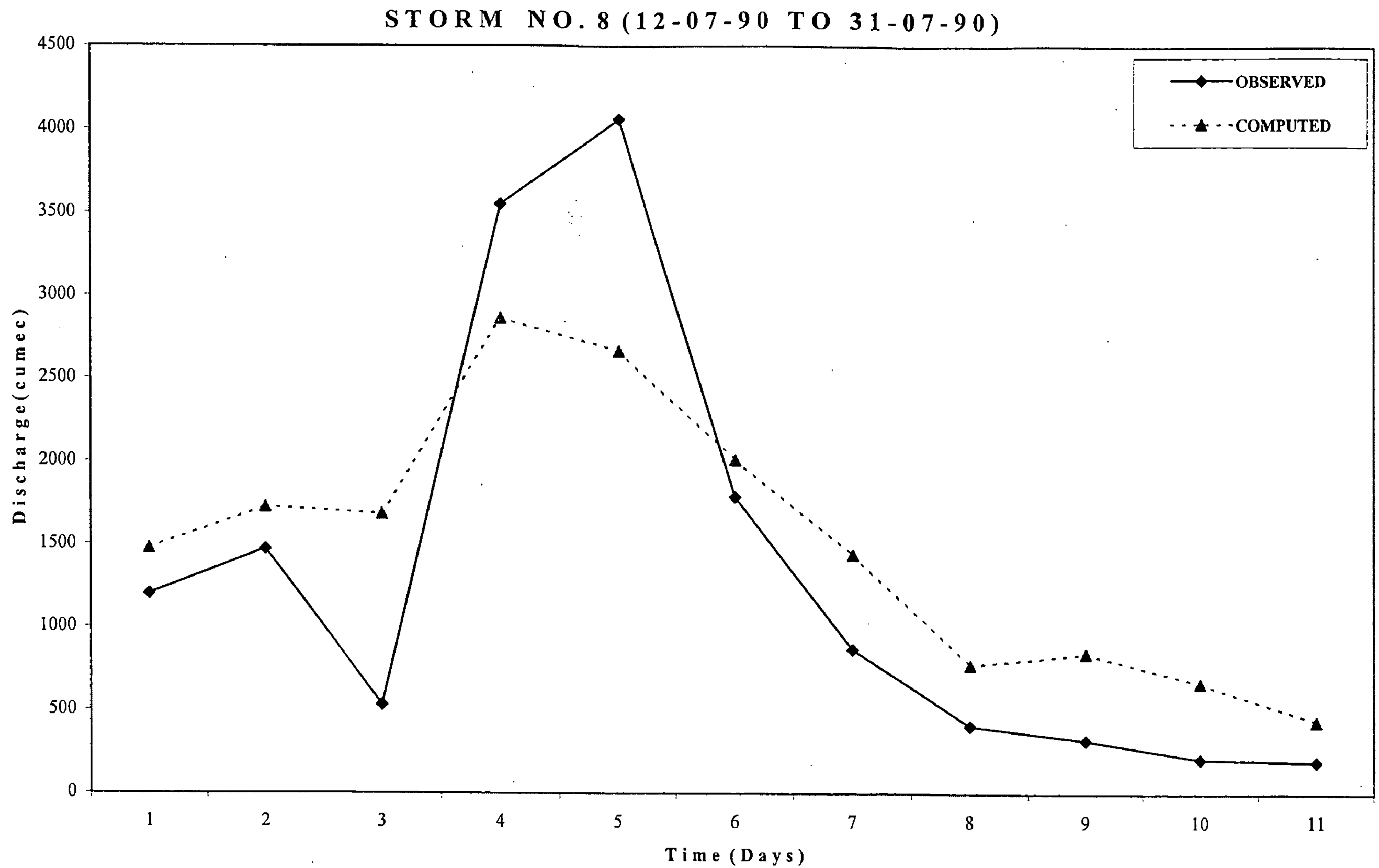

FIG. 6.12 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING ONE INPUT (CALIBRATION PERIOD)

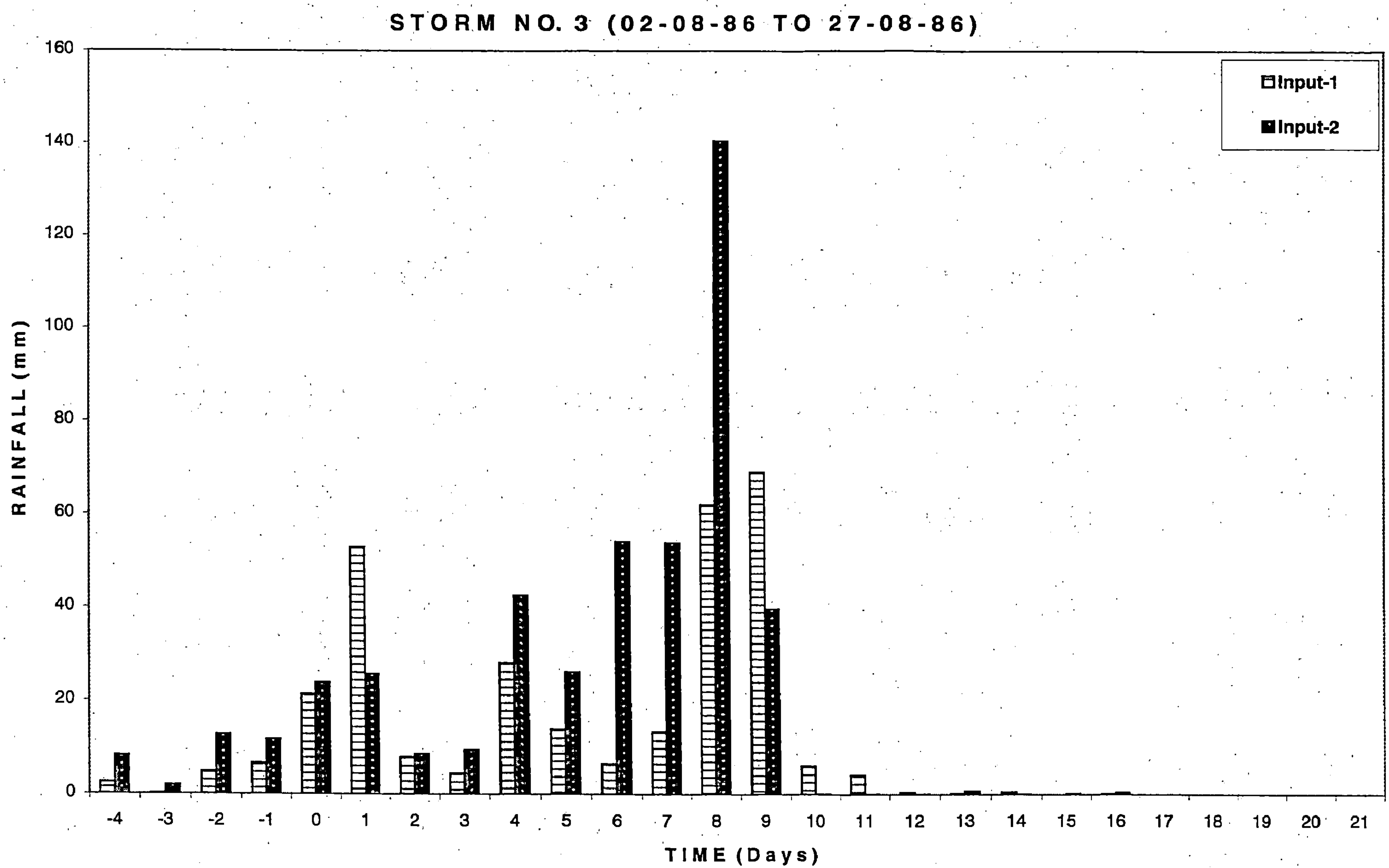

FIG.6.13 VARIATION OF RAINFALL WITH TIME

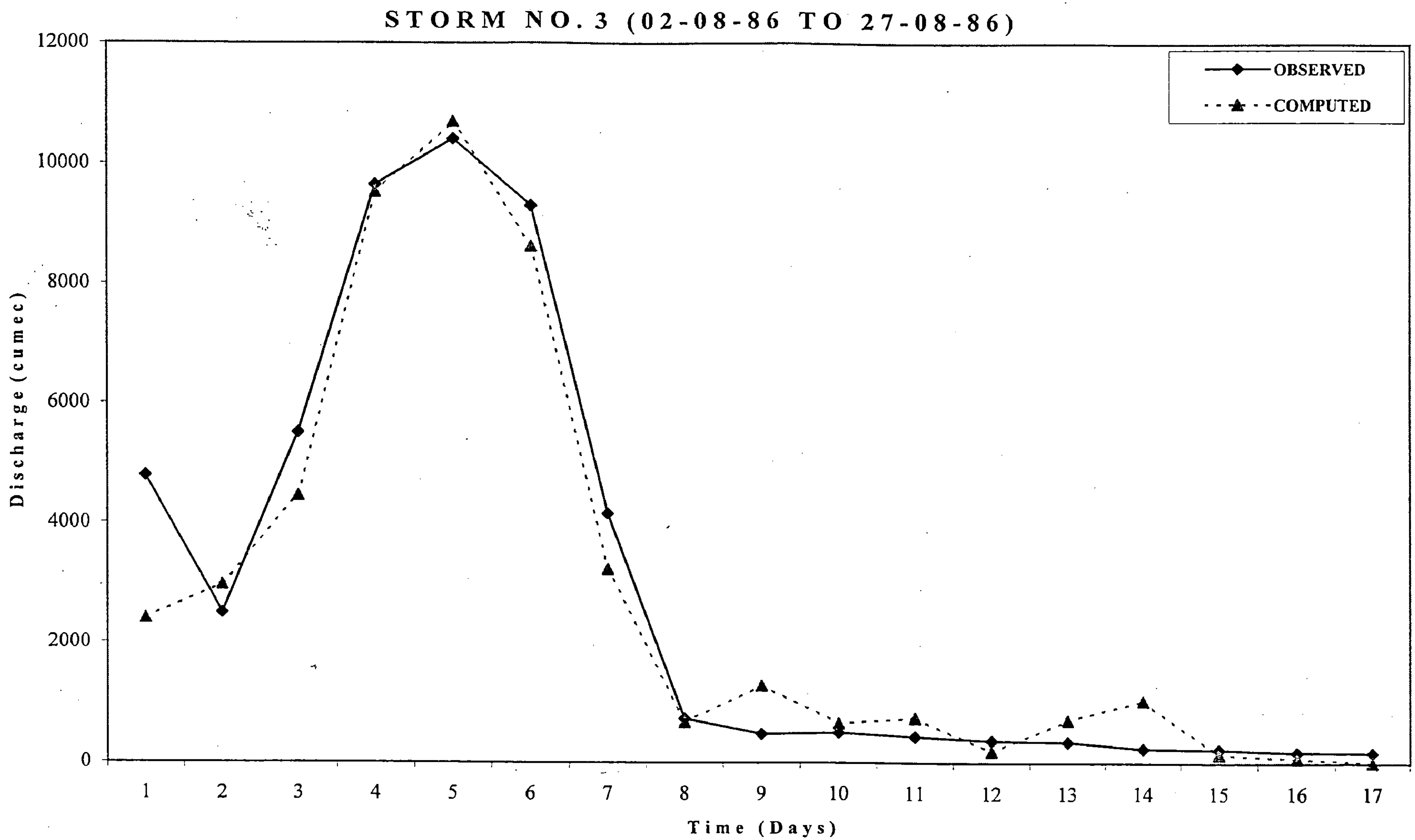

FIG.6.14 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING TWO INPUTS (CALIBRATION PERIOD)

STORM NO. 4 (01-07-88 TO 11-08-88)

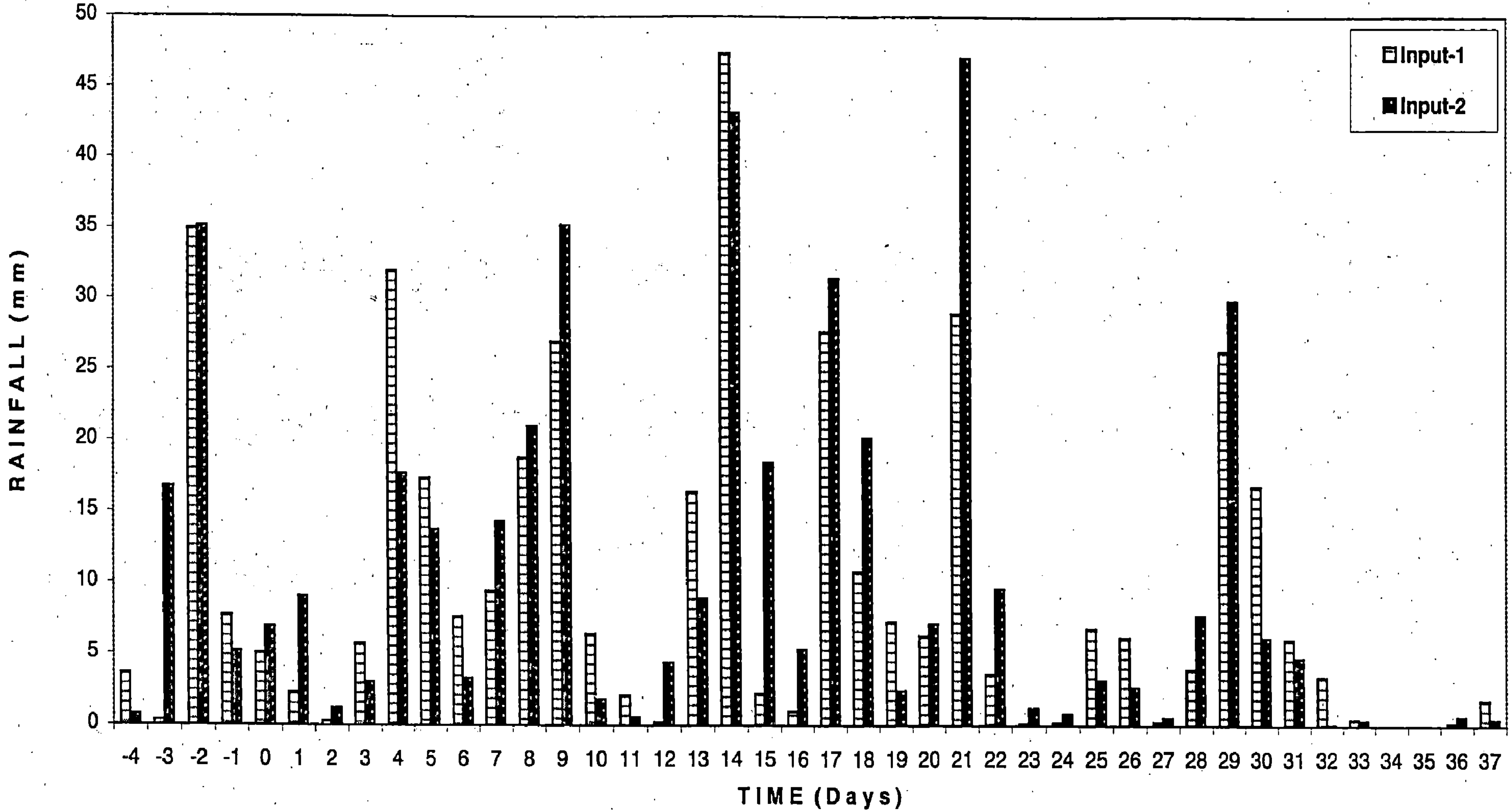

FIG. 6.15 VARIATION OF RAINFALL WITH TIME

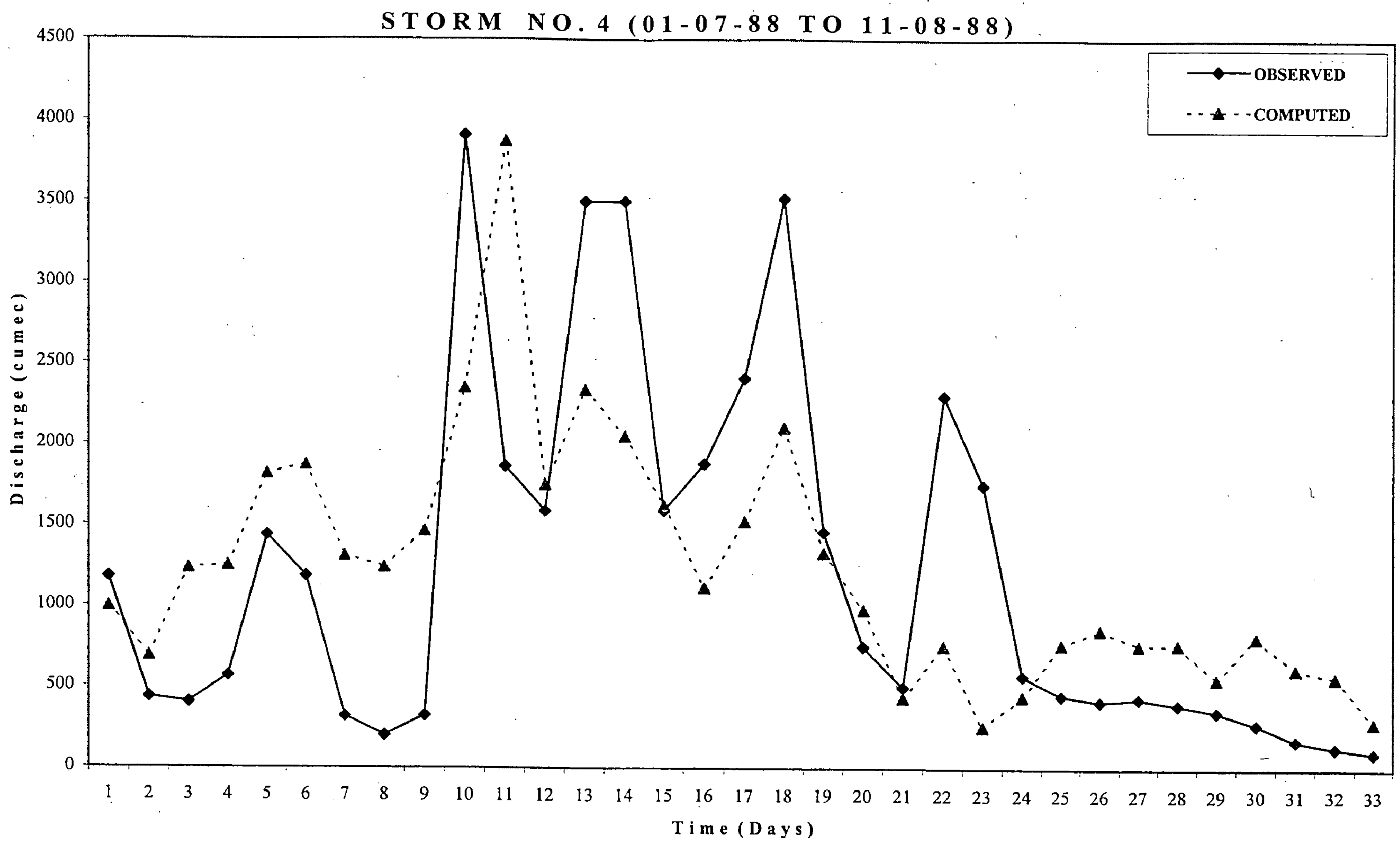

FIG.6.16 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING TWO INPUTS (CALIBRATION PERIOD)

STORM NO. 5 (15-08-88 TO 28-09-88)

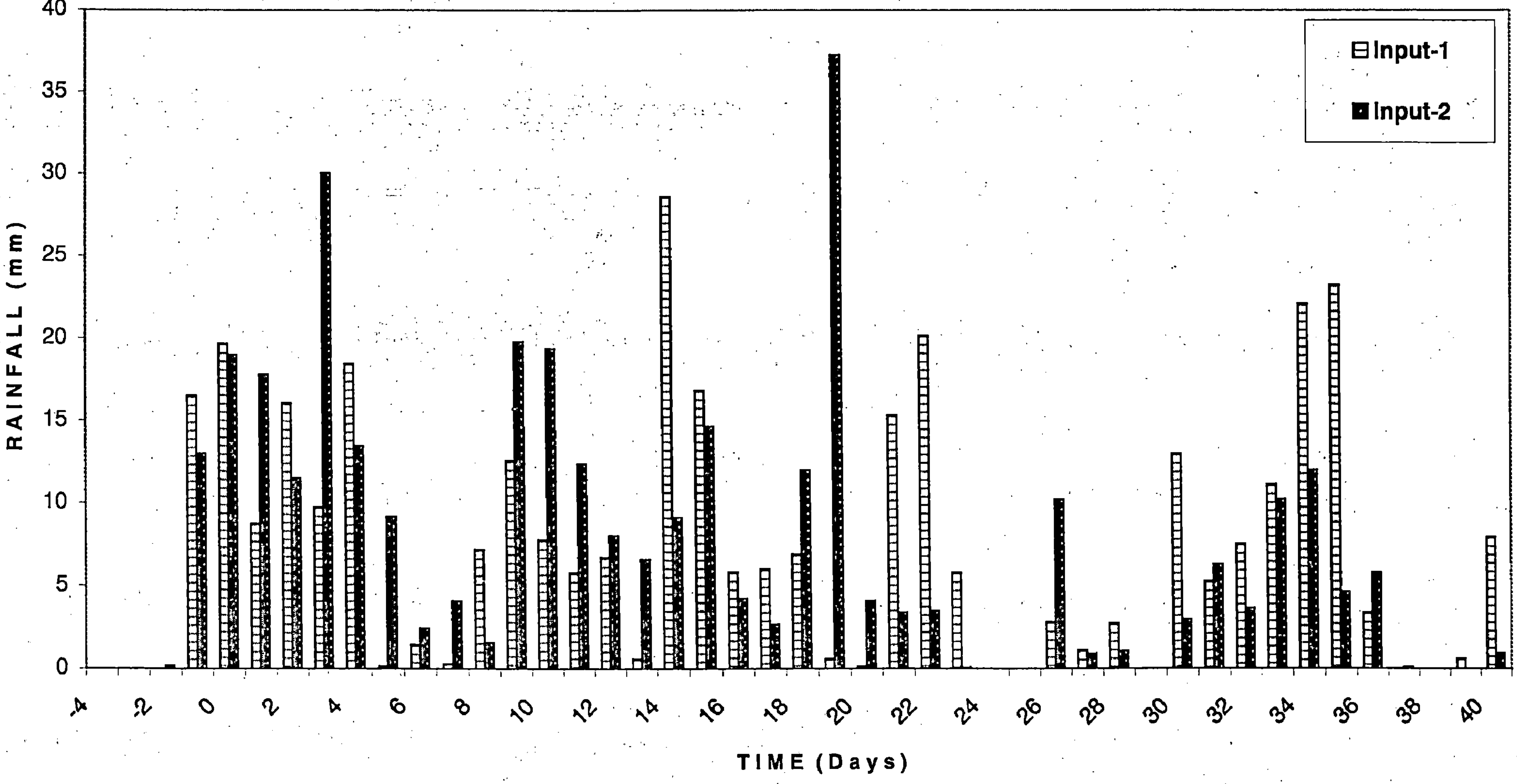

FIG.6.17 VARIATION OF RAINFALL WITH TIME

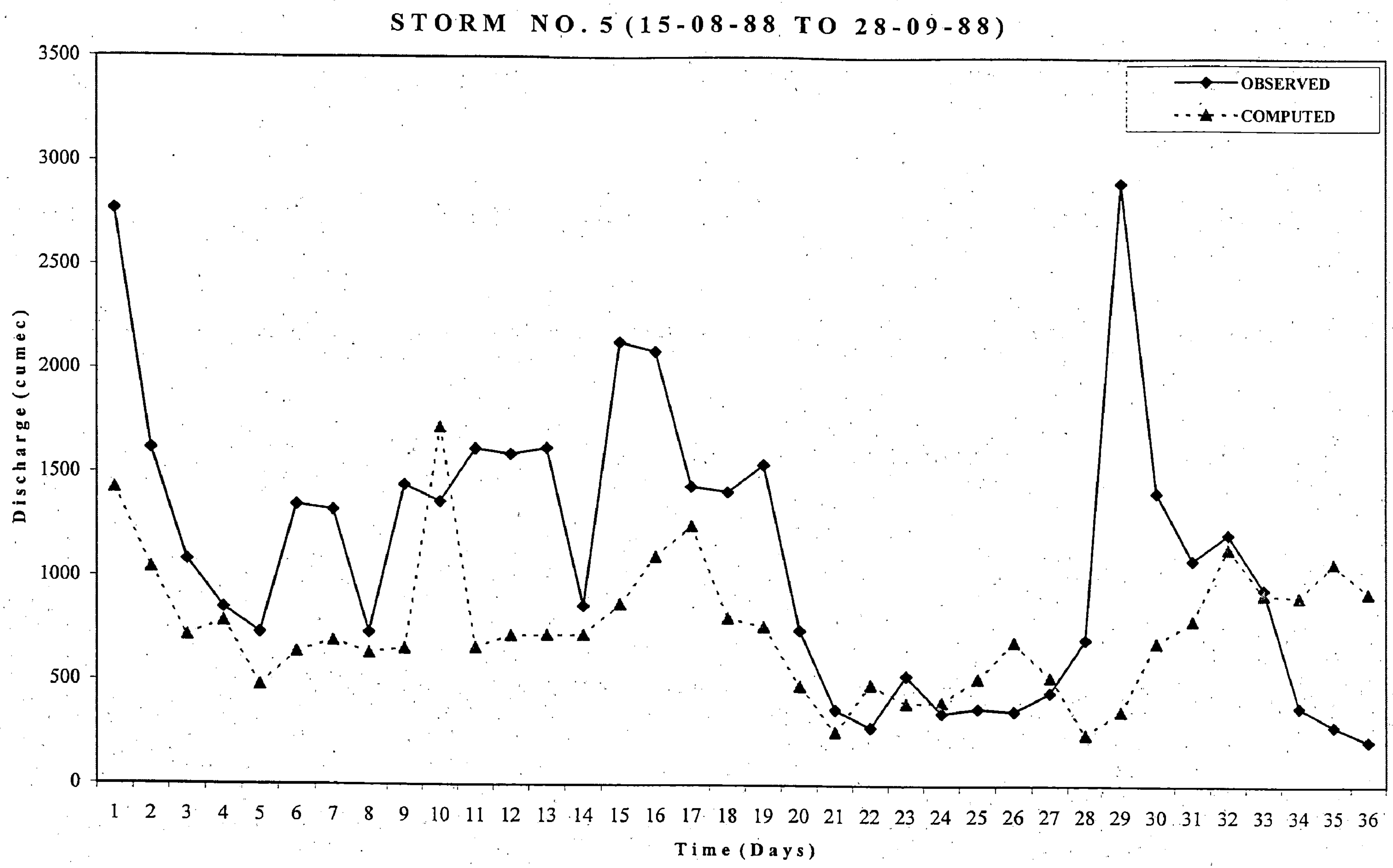

FIG. 6.18 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING TWO INPUTS (CALIBRATION PERIOD)

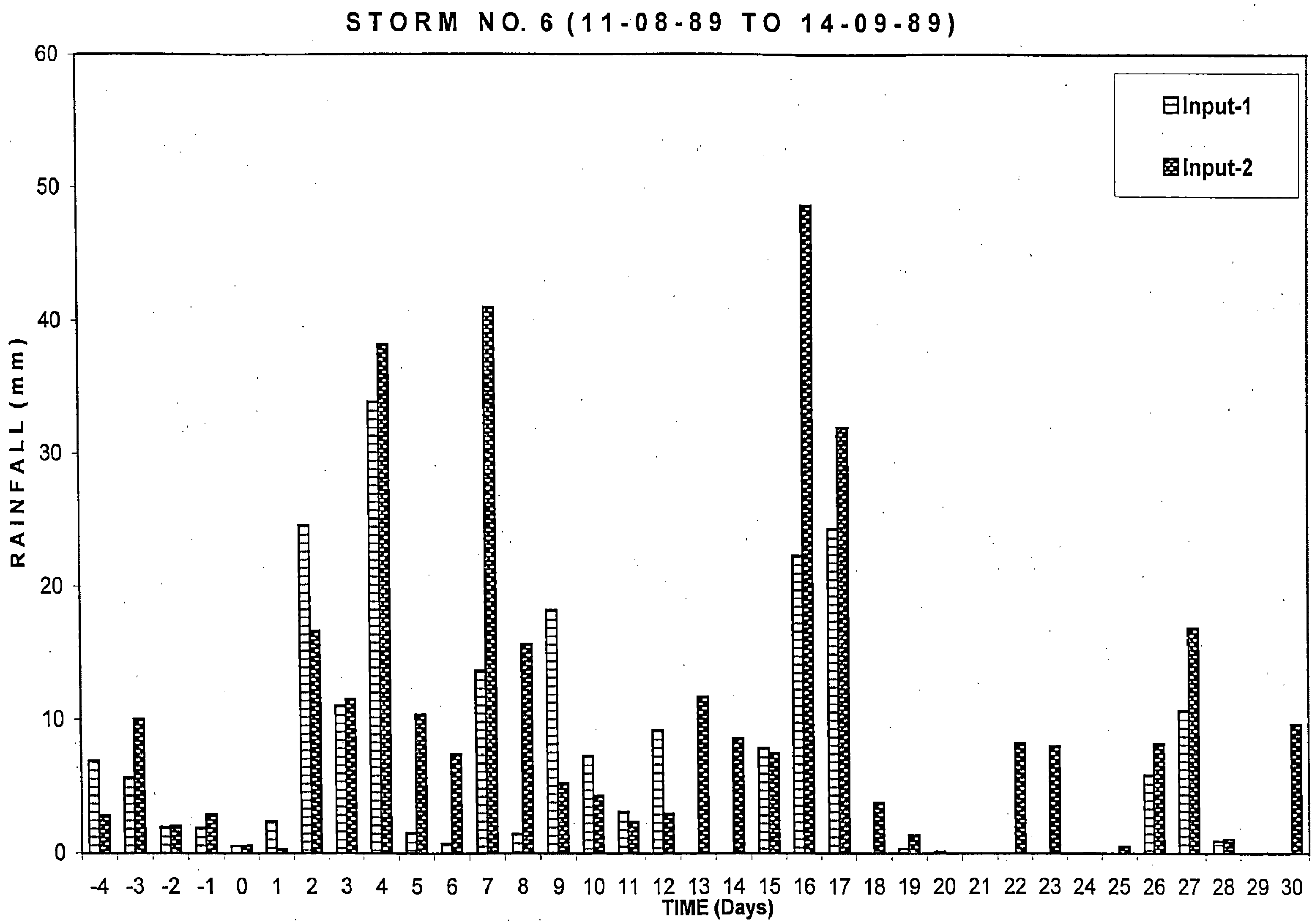

FIG.6.19 VARIATION OF RAINFALL WITH TIME

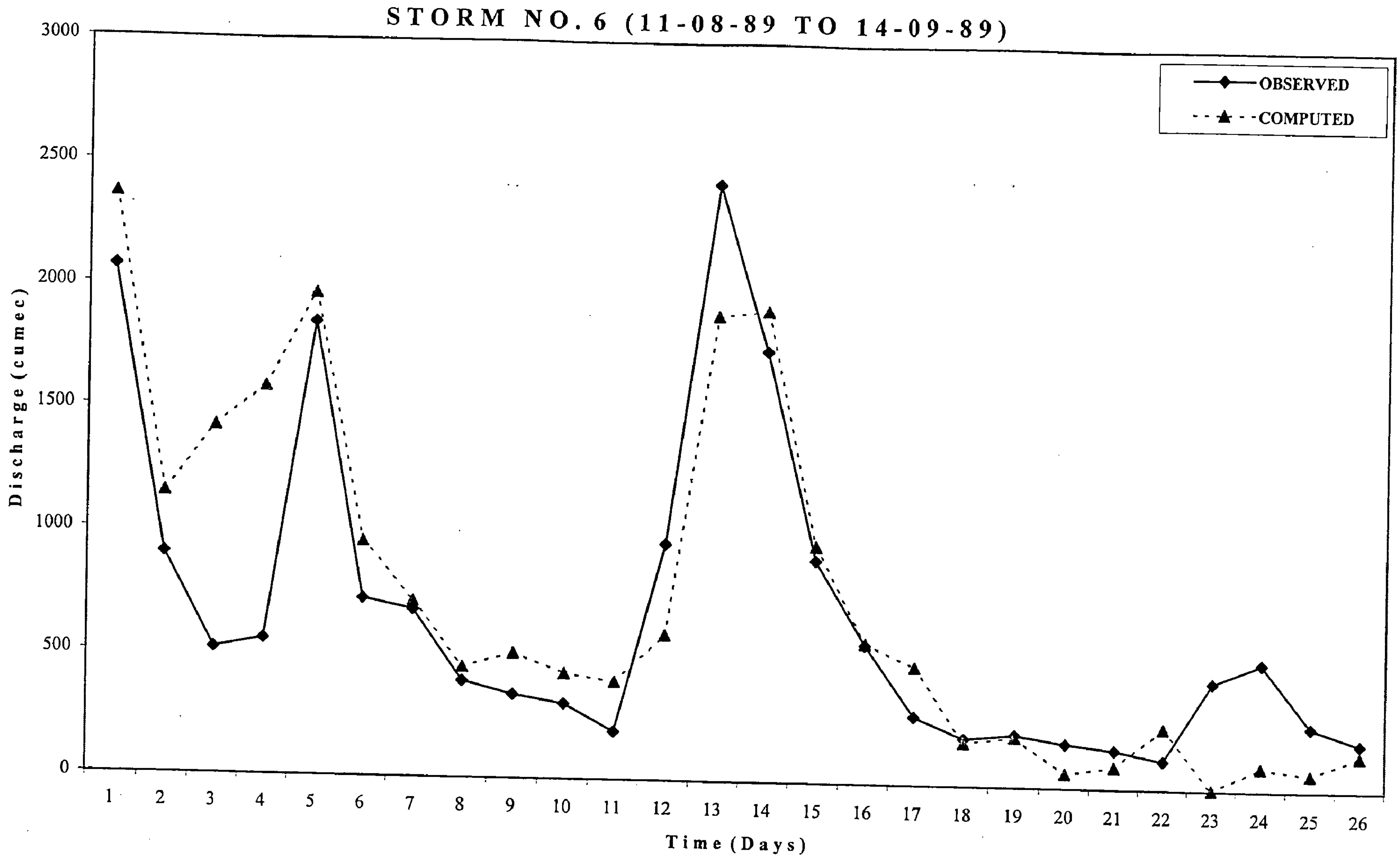

FIG. 6.20 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING TWO INPUTS (CALIBRATION PERIOD)

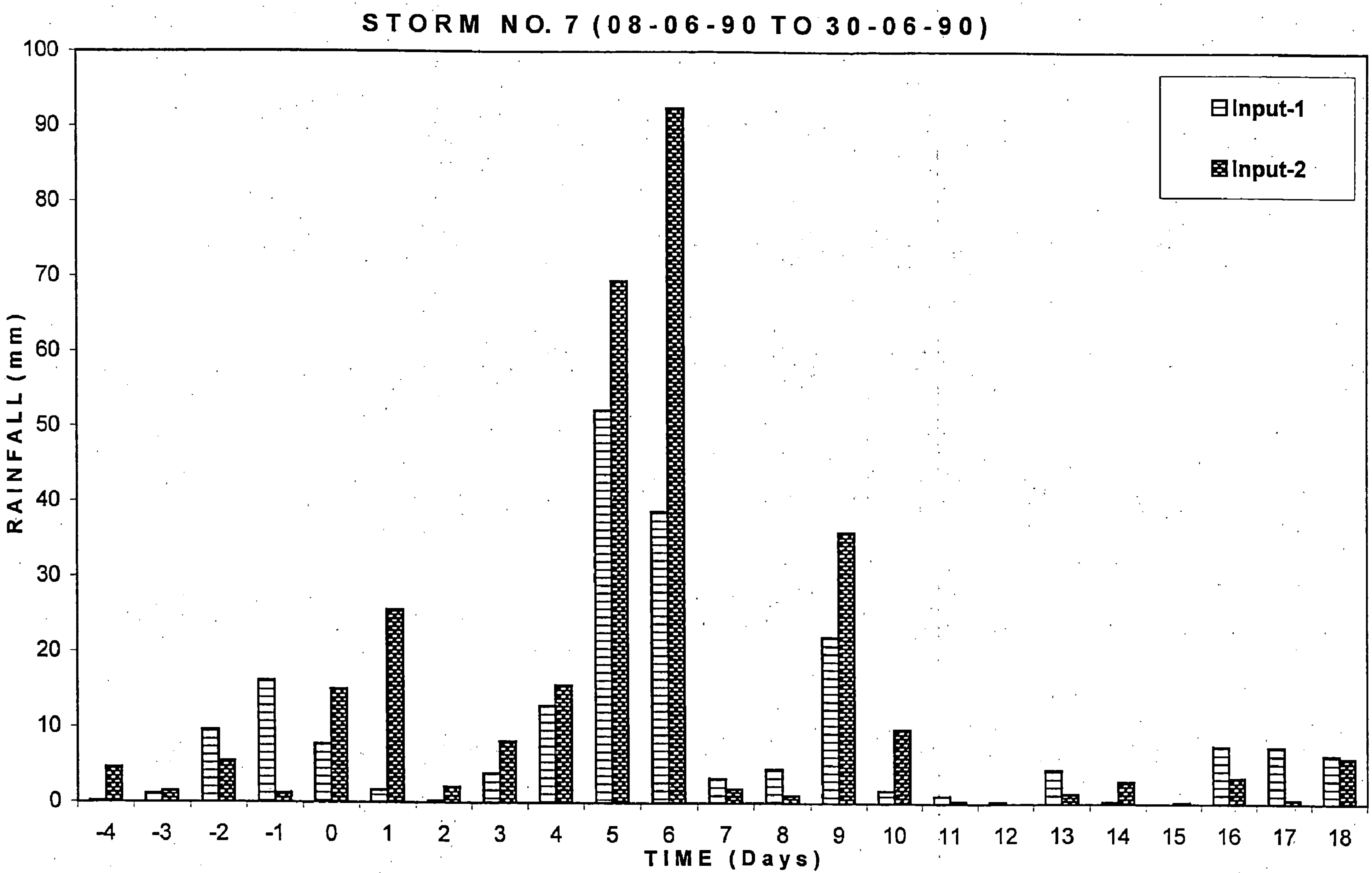

FIG.6.21 VARIATION OF RAINFALL WITH TIME

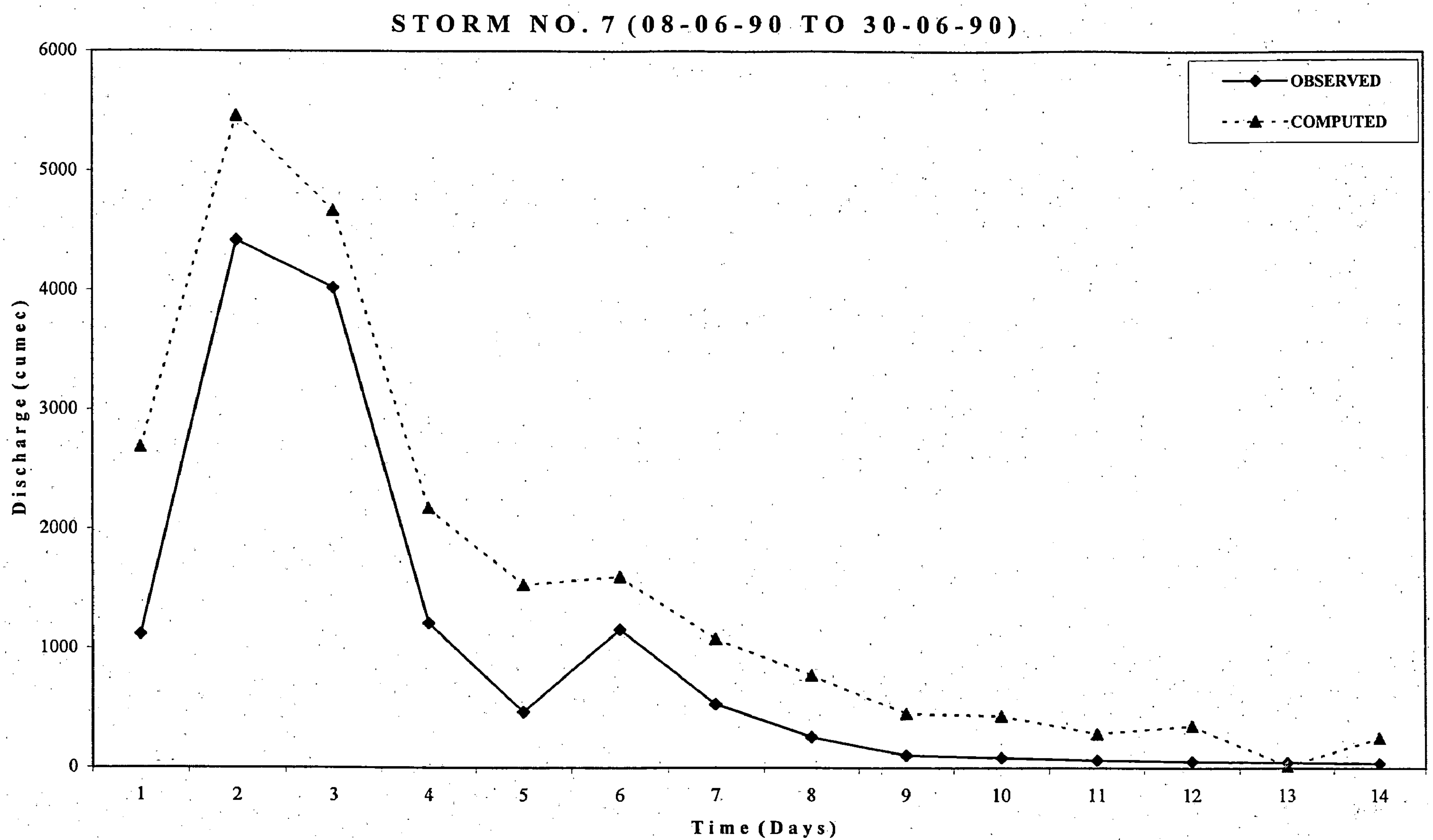

FIG. 6.22 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING TWO INPUTS (CALIBRATION PERIOD)

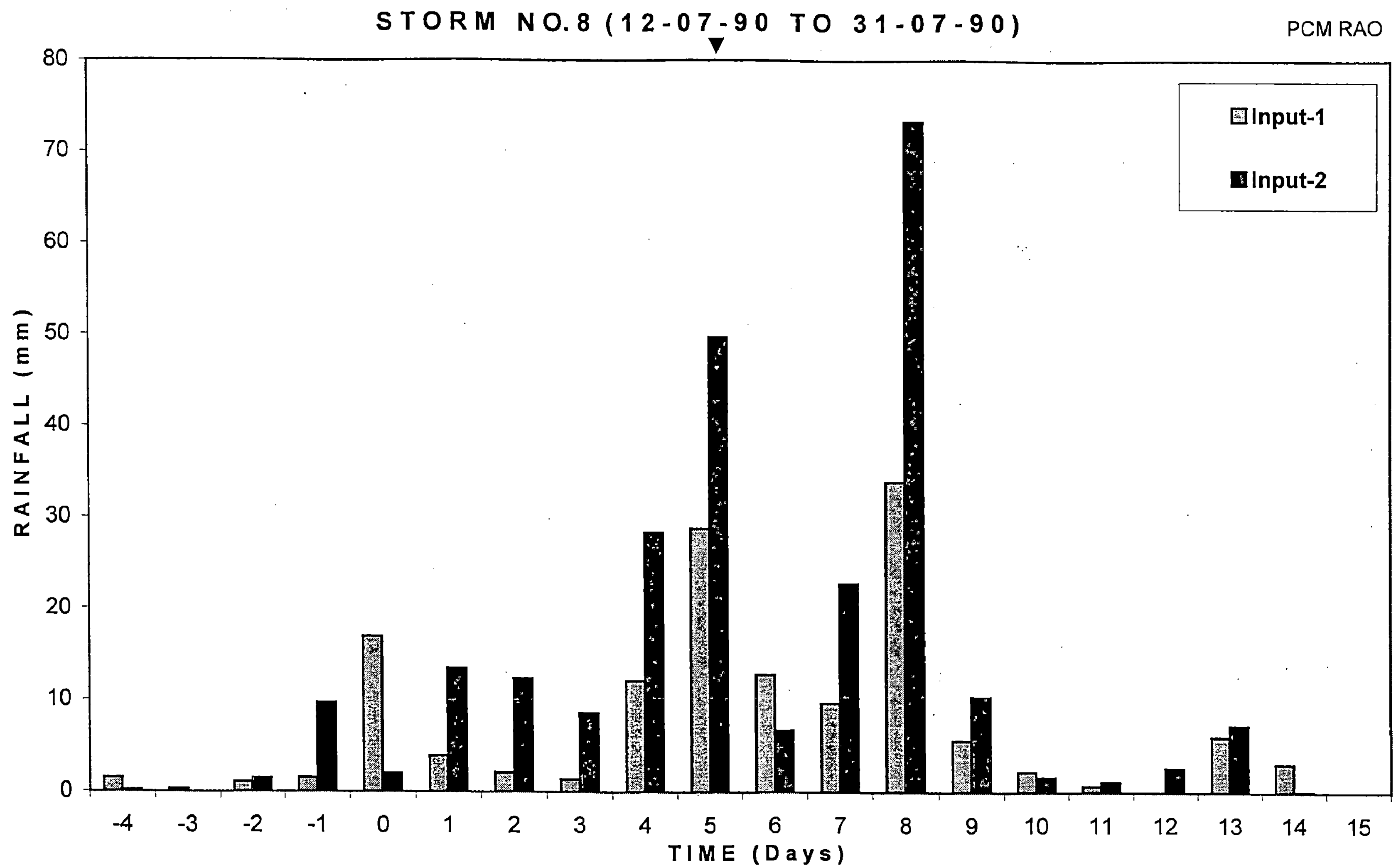

FIG.6.23 VARIATION OF RAINFALL WITH TIME

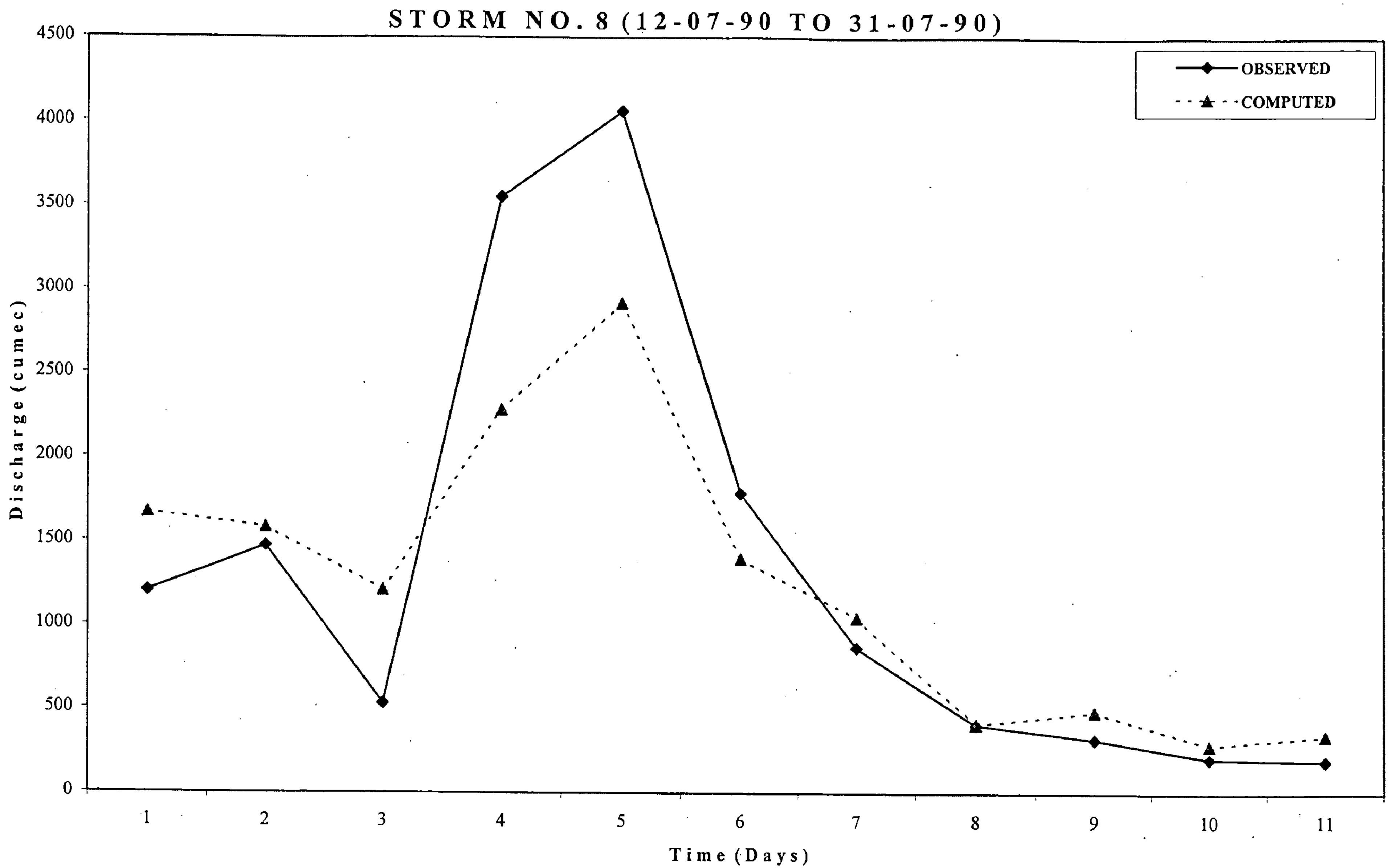

FIG.6.24 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING TWO INPUTS (CALIBRATION PERIOD)

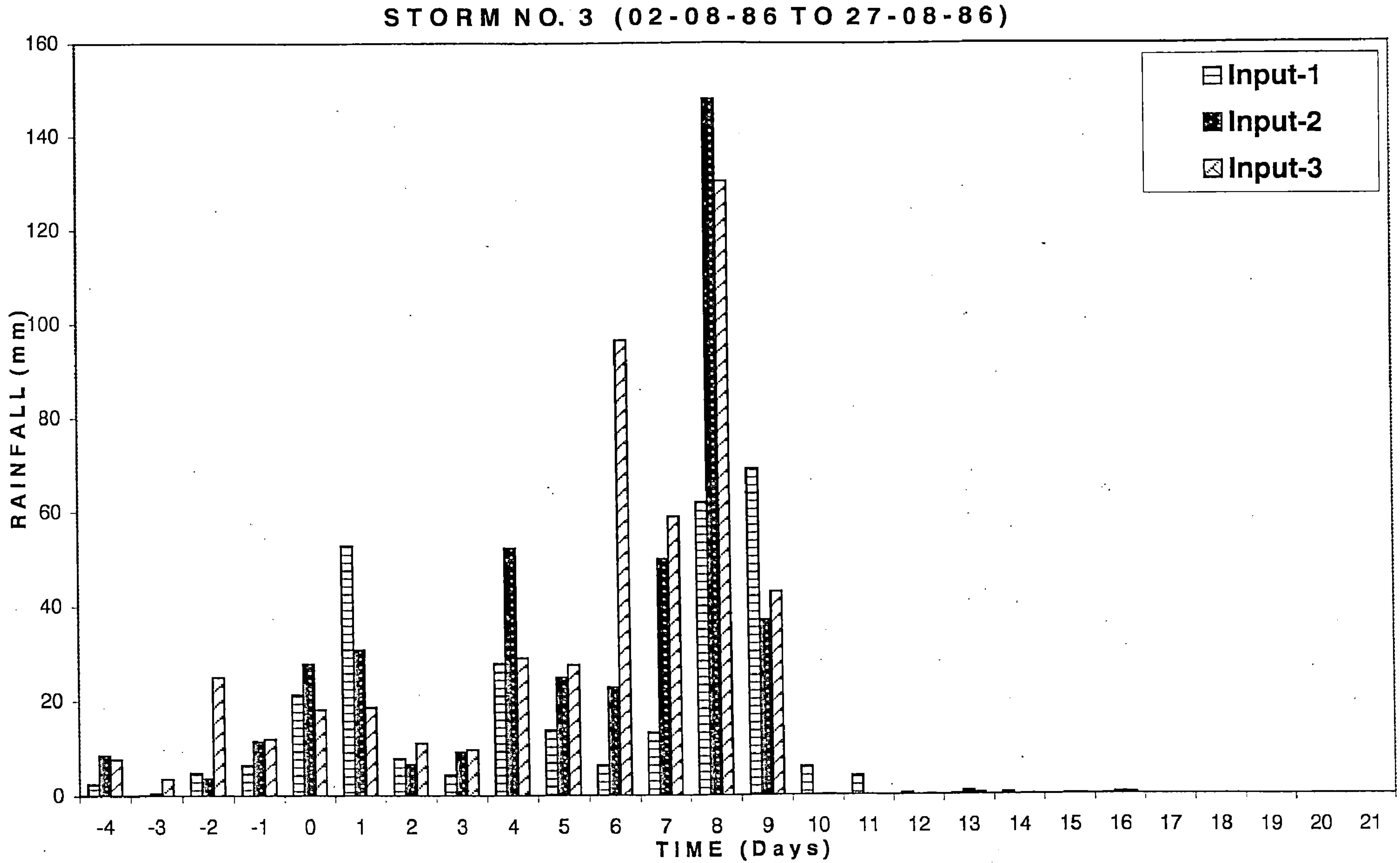

FIG. 6.2 5 VARIATION OF RAINFALL WITH TIME

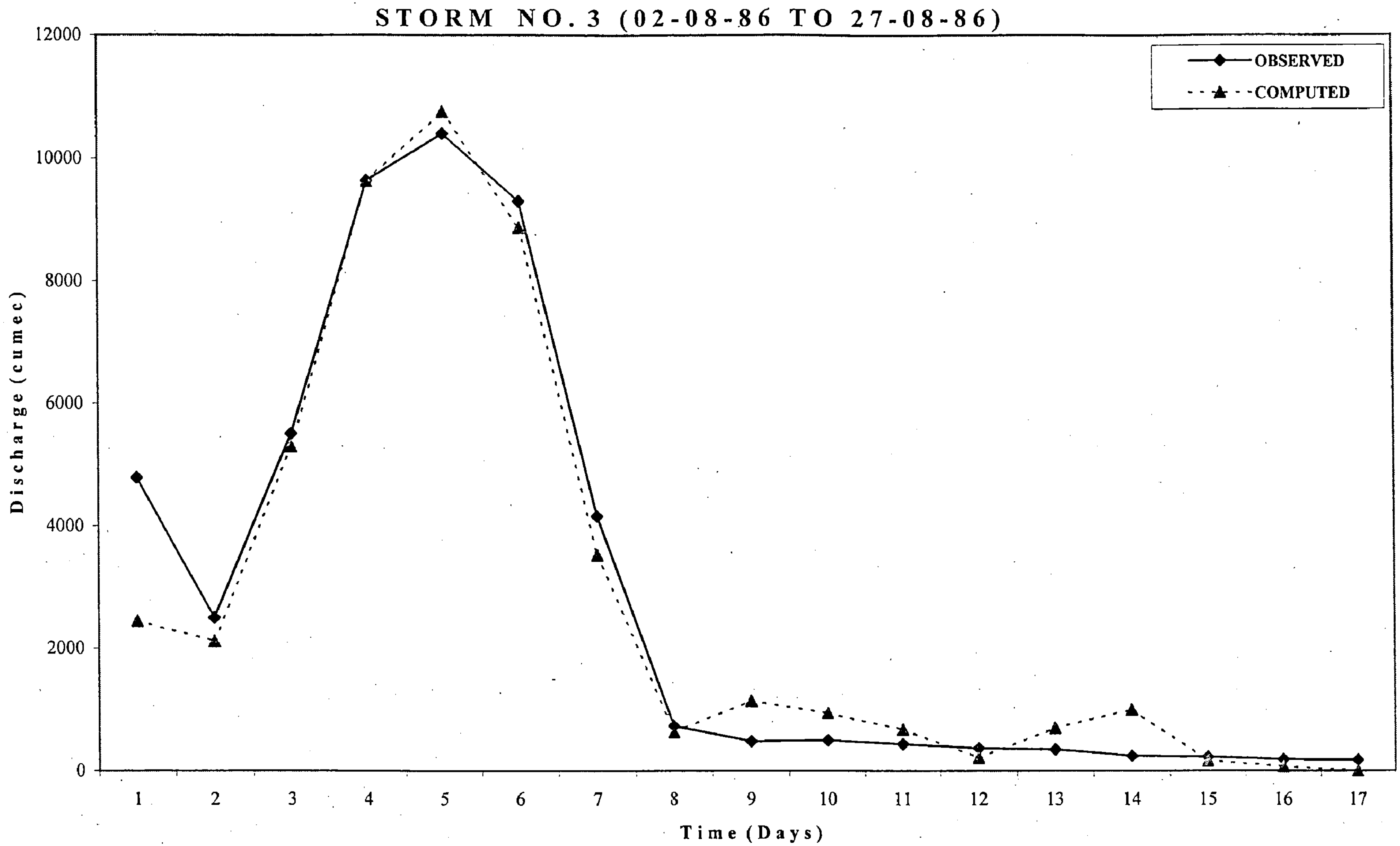

FIG. 6.26 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING THREE INPUTS (CALIBRATION PERIOD)

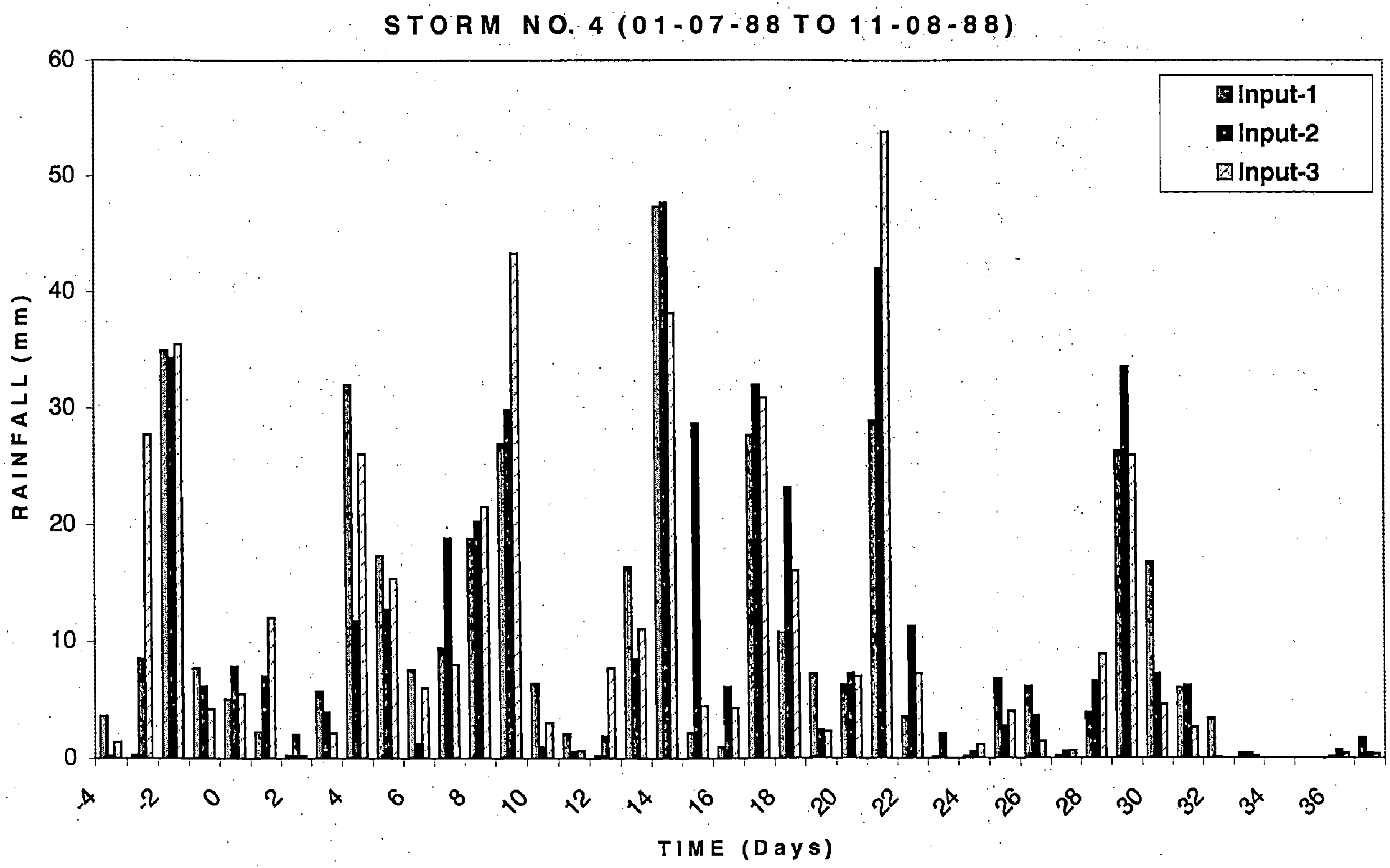

FIG.6.2 7 VARIATION OF RAINFALL WITH TIME

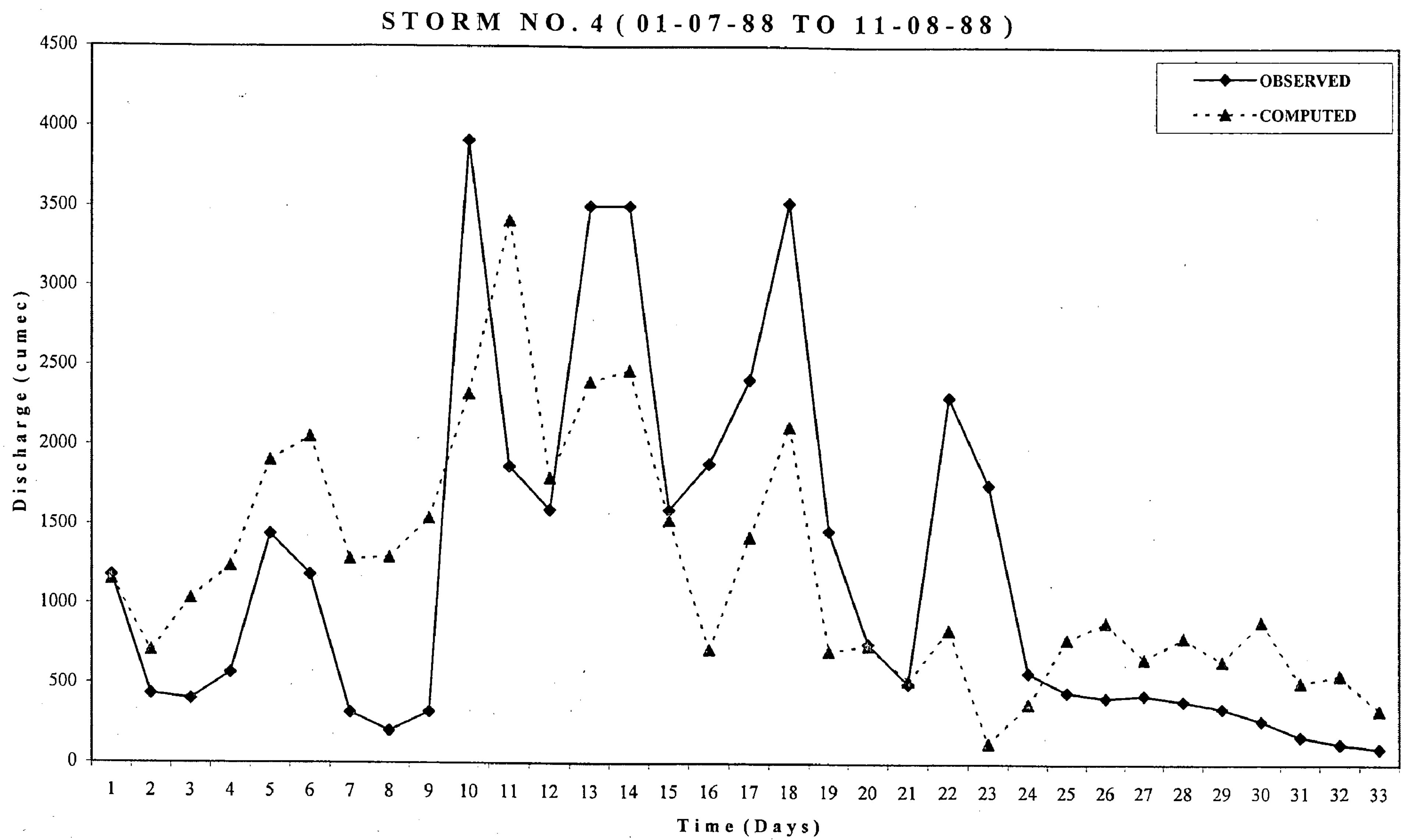

FIG.6.28 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING THREE INPUTS (CALIBRATION PERIOD)

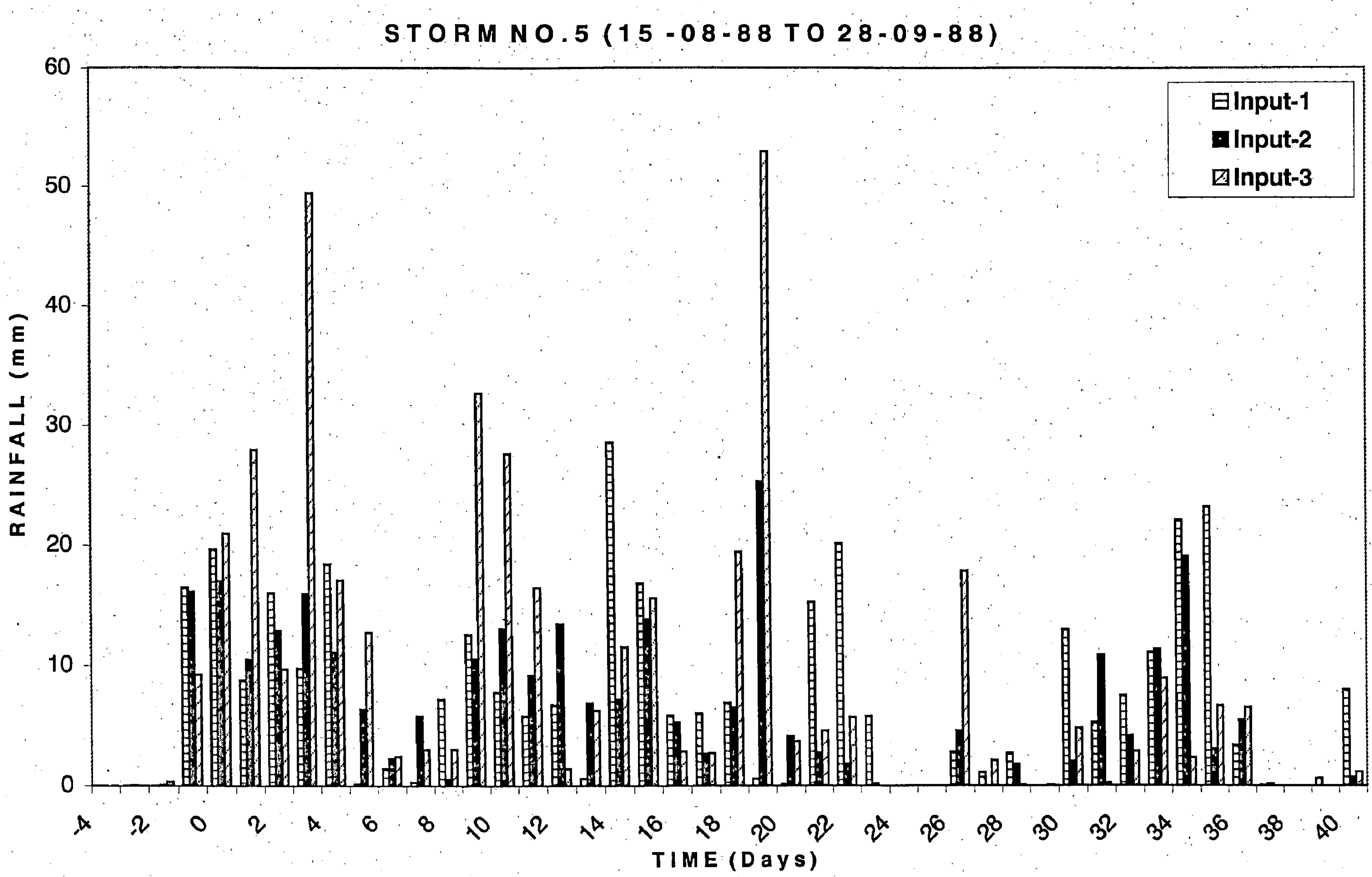

FIG.6.2 9 VARIATION OF RAINFALL WITH TIME

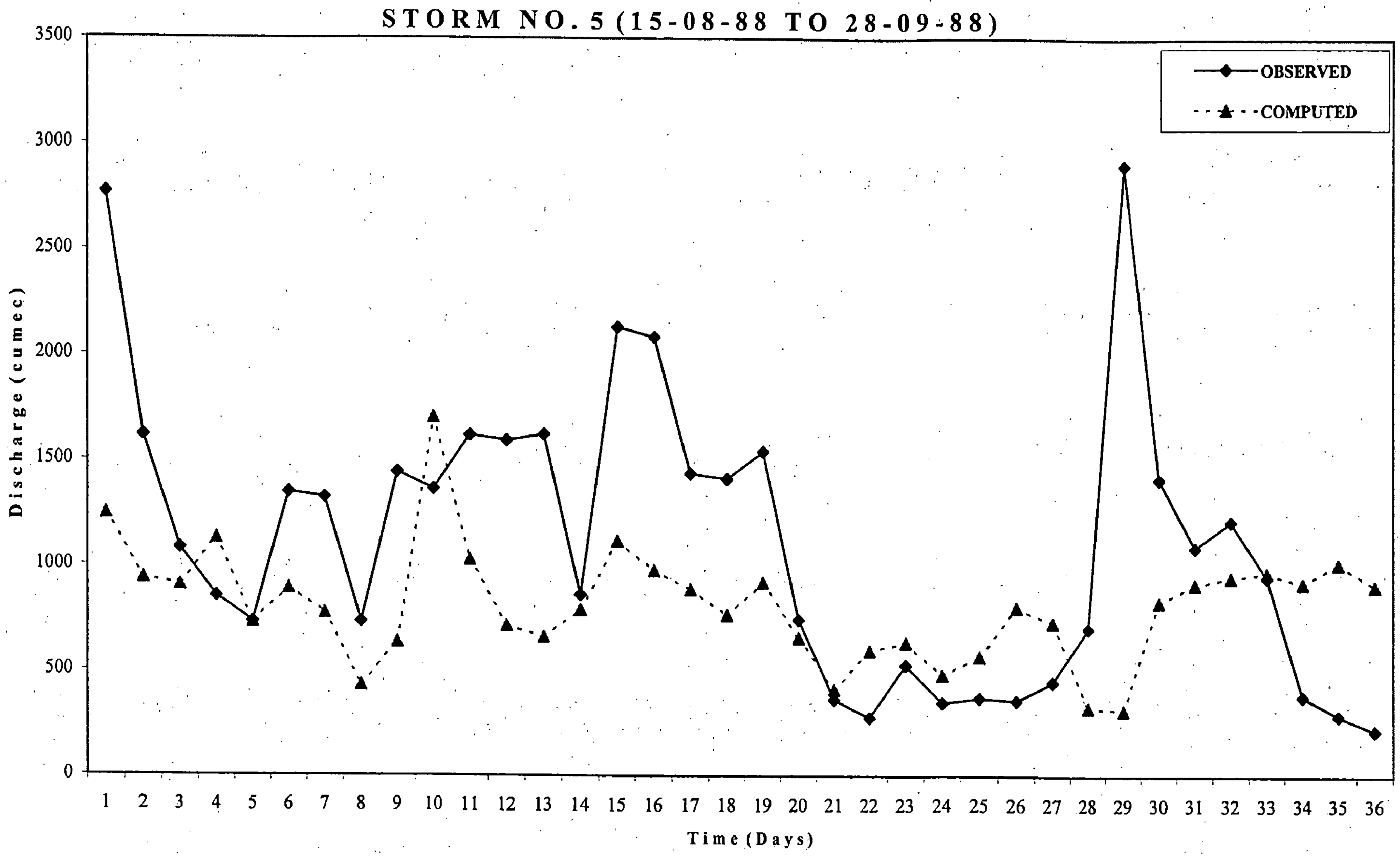

FIG.6.30 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING THREE INPUTS (CALIBRATION PERIOD)

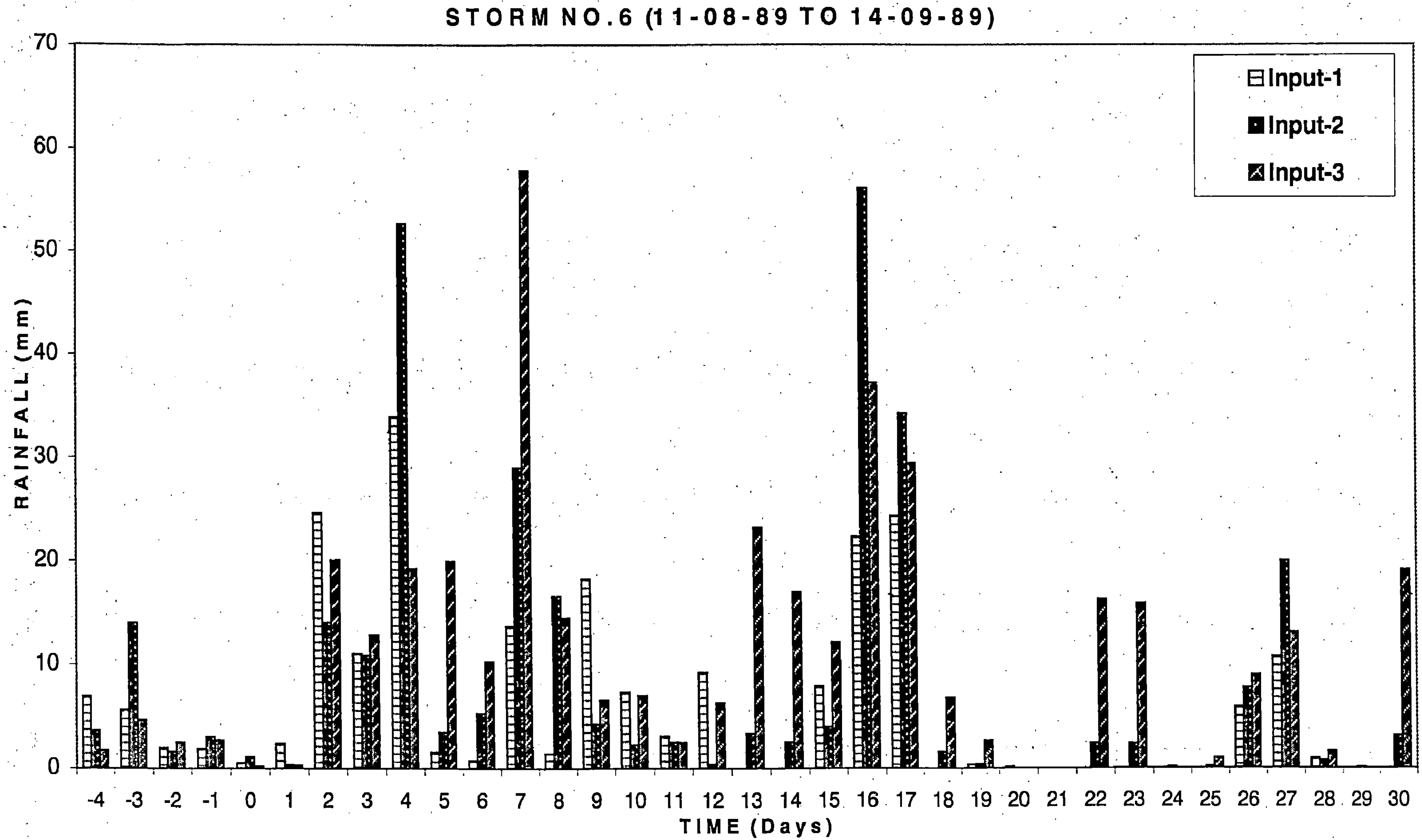

FIG.6.31 VARIATION OF RAINFALL WITH TIME

STORM NO.6 (08-06-90 TO 30-06-90)

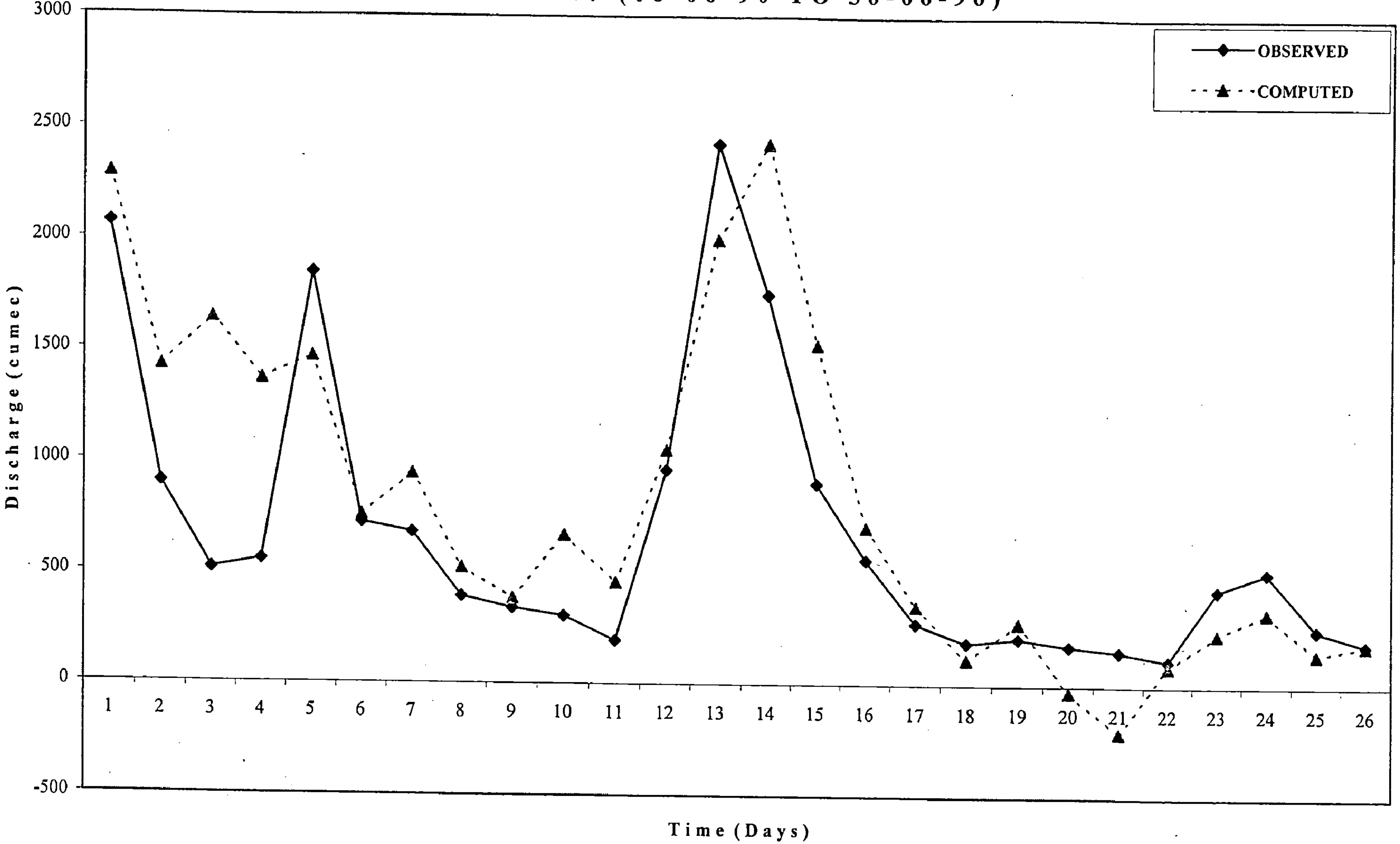

FIG.6.32 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING THREE INPUTS (CALIBRATION PERIOD)

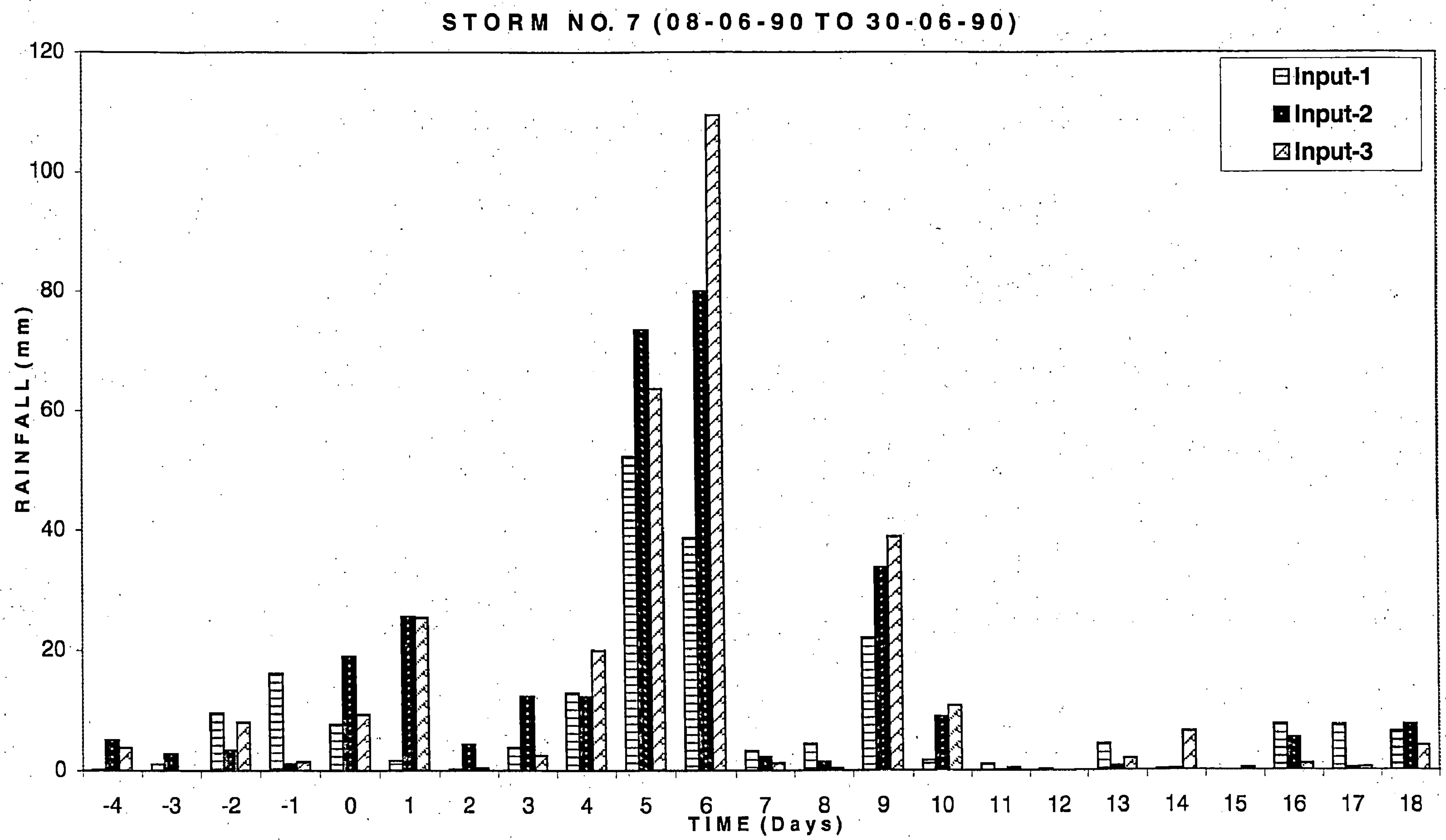

FIG.6.33 VARIATION OF RAINFALL WITH TIME

STORM NO. 7 (08-06-90 TO 30-06-90)

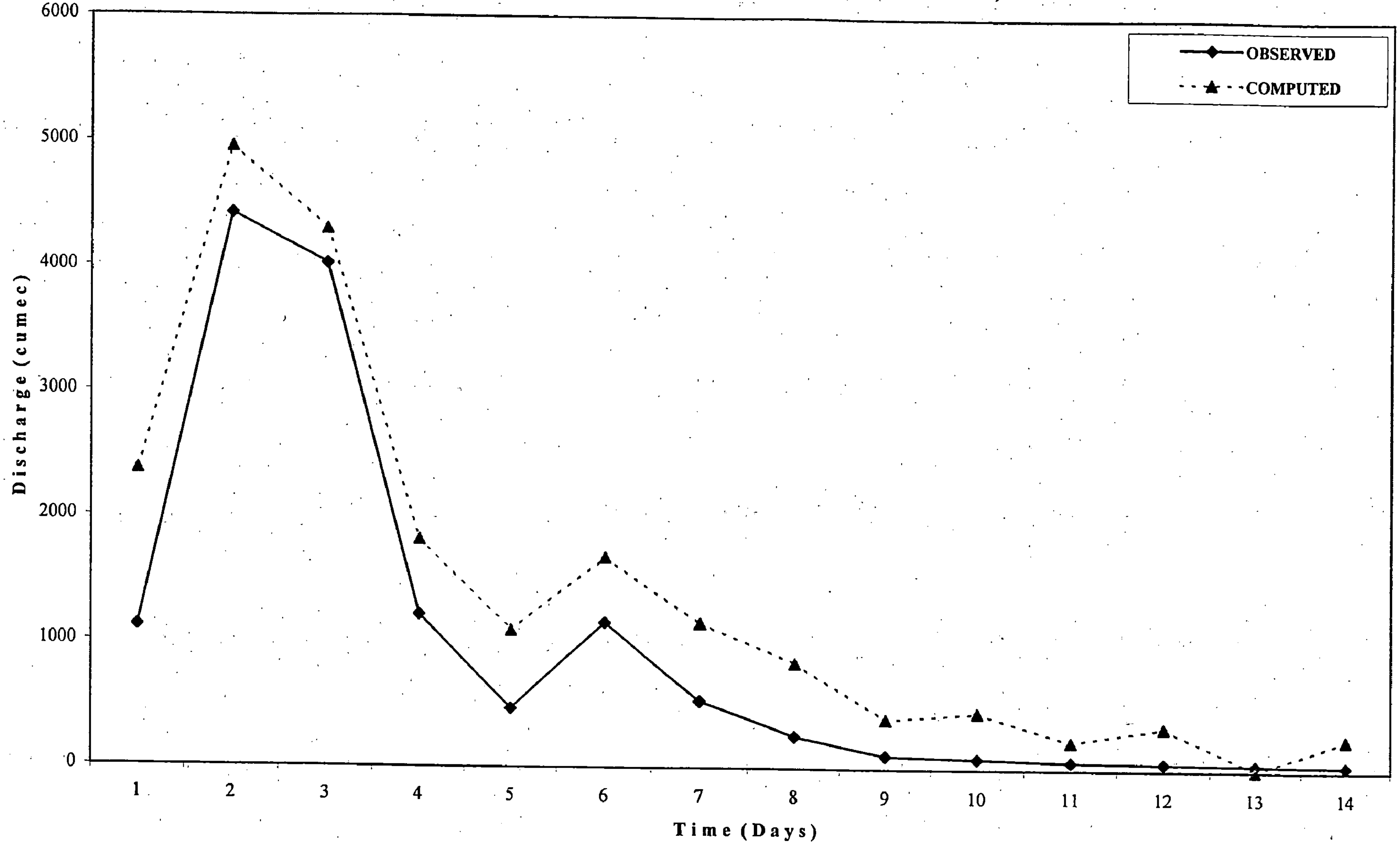

FIG.6.34 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING THREE INPUTS (CALIBRATION PERIOD)

STORM NO. 8 (12-07-90 TO 31-07-90)

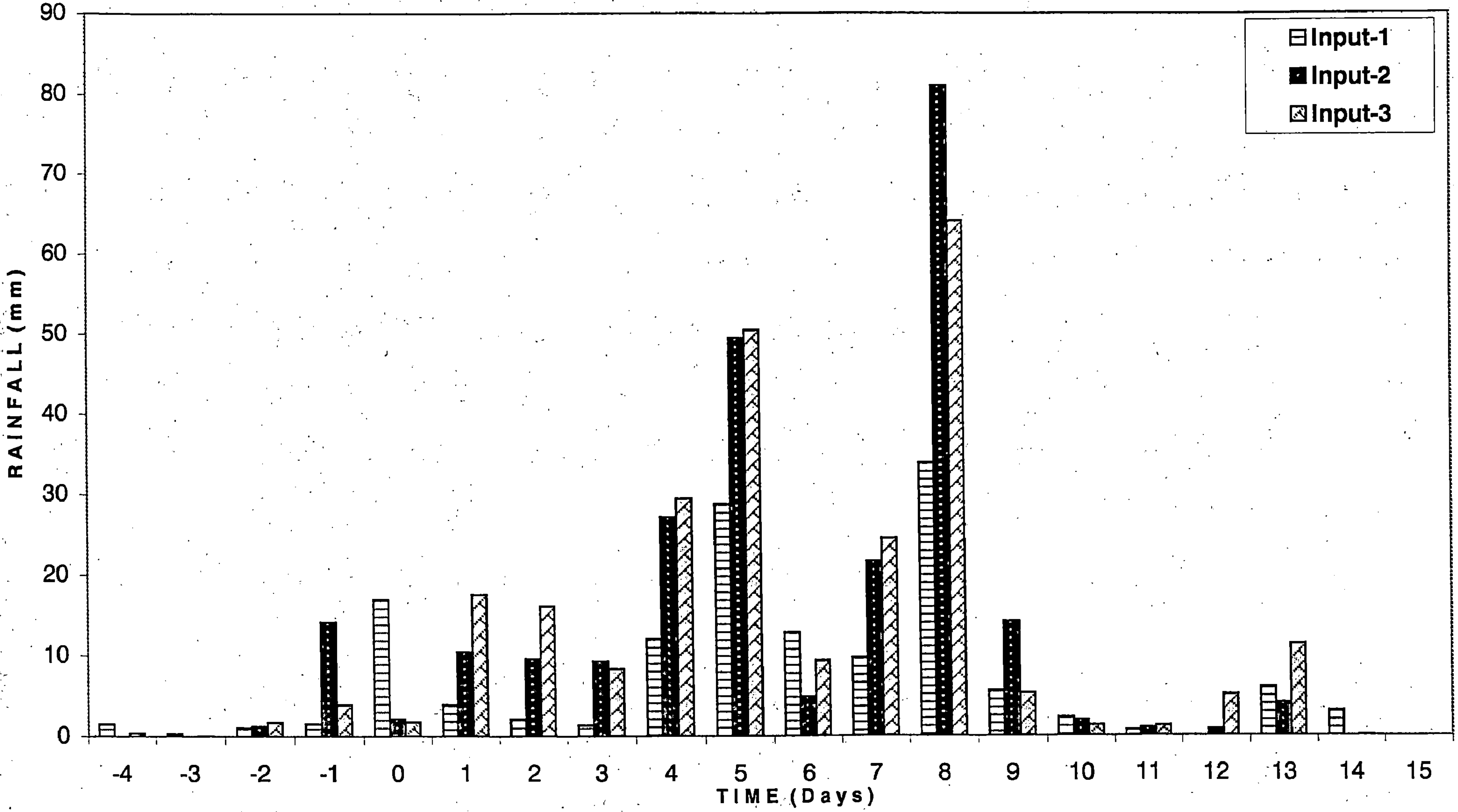

FIG.6.35 VARIATION OF RAINFALL WITH TIME

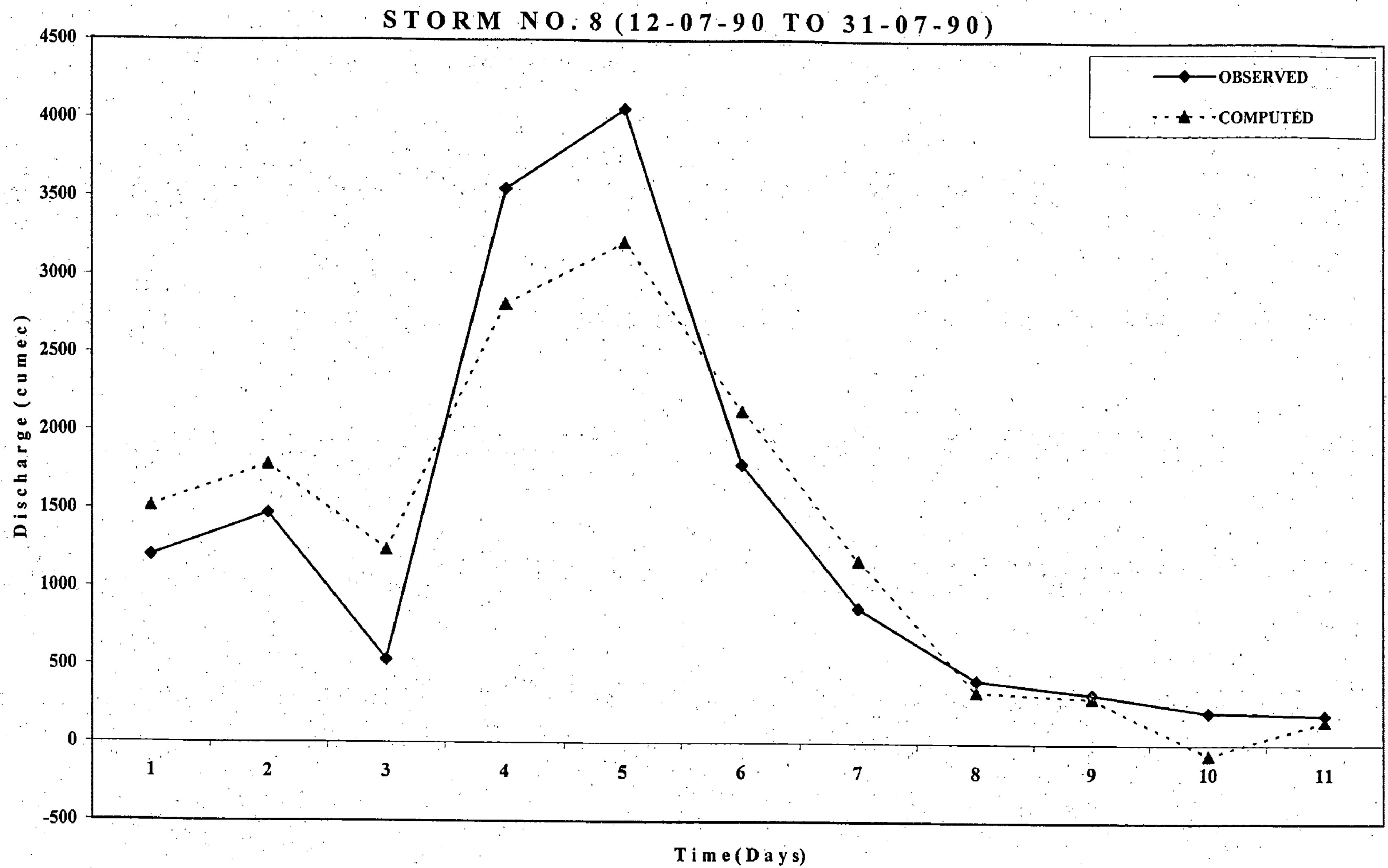

FIG.6.36 COMPARISON OF OBSERVED AND COMPUTED RUNOFF USING THREE INPUTS (CALIBRATION PERIOD)

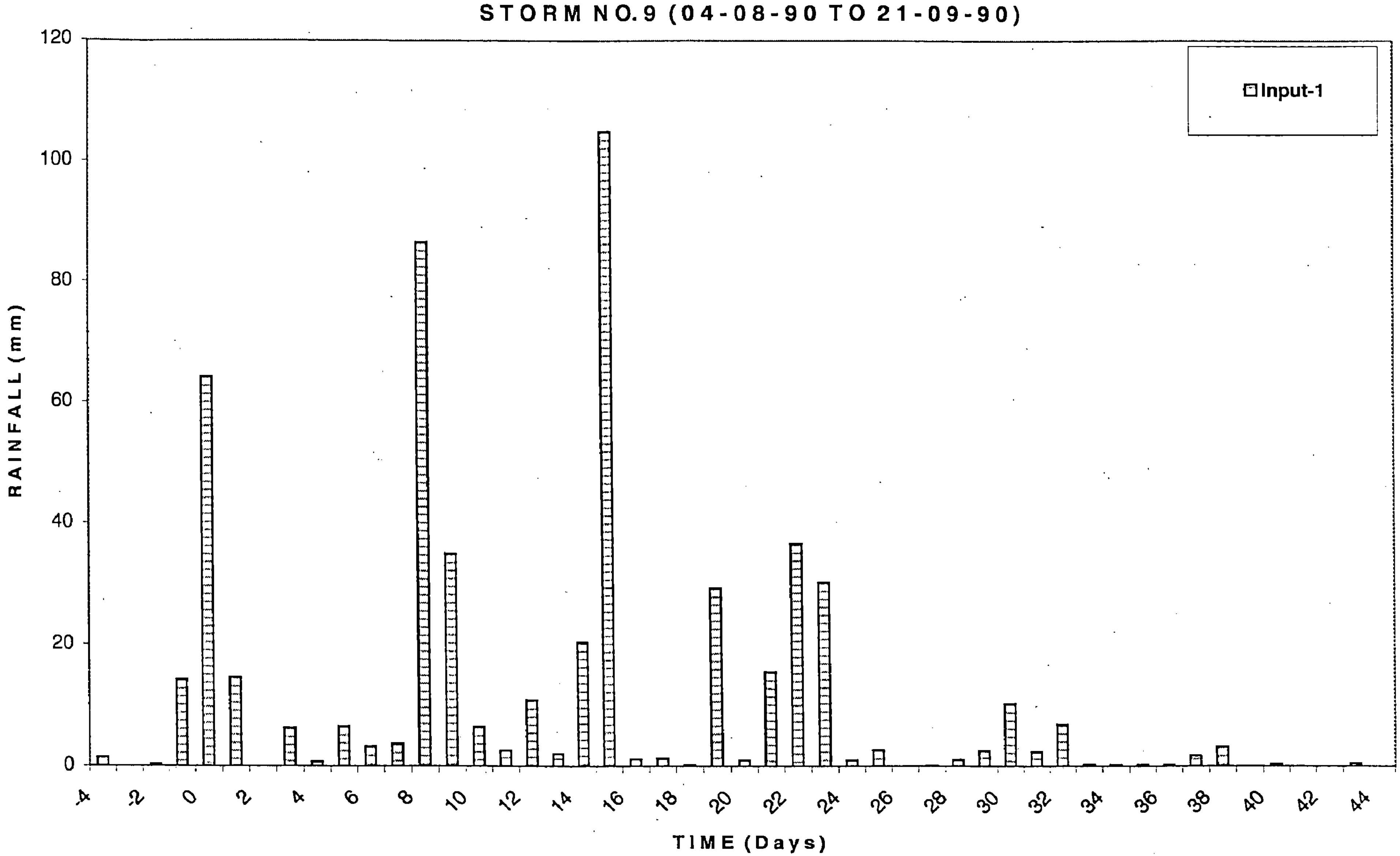

FIG.6.37 VARIATION OF RAINFALL WITH TIME

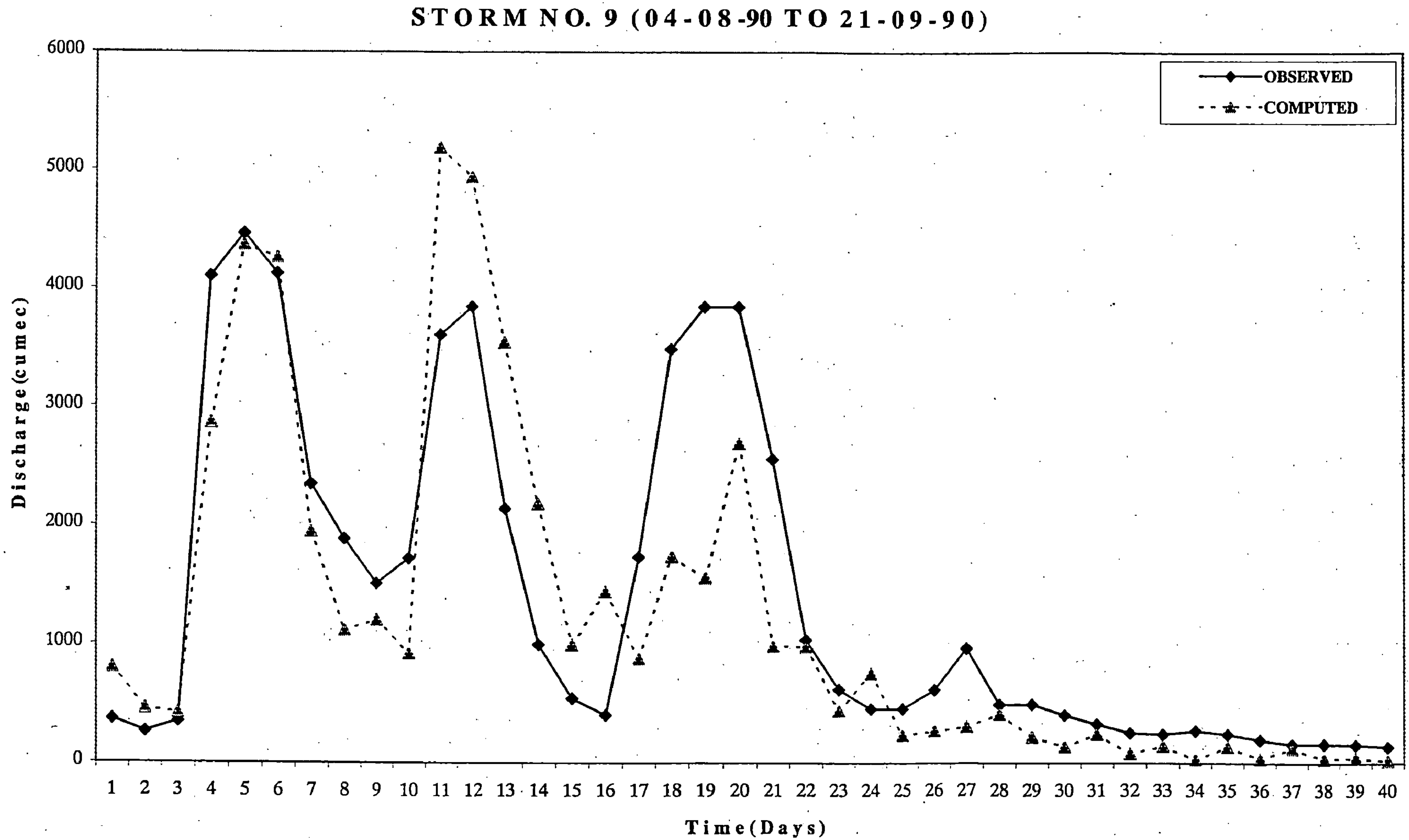

FIG.6.38 COMPARISON OF COMPUTED AND OBSERVED RUNOFF USING ONE INPUT (VERIFICATION PERIOD)

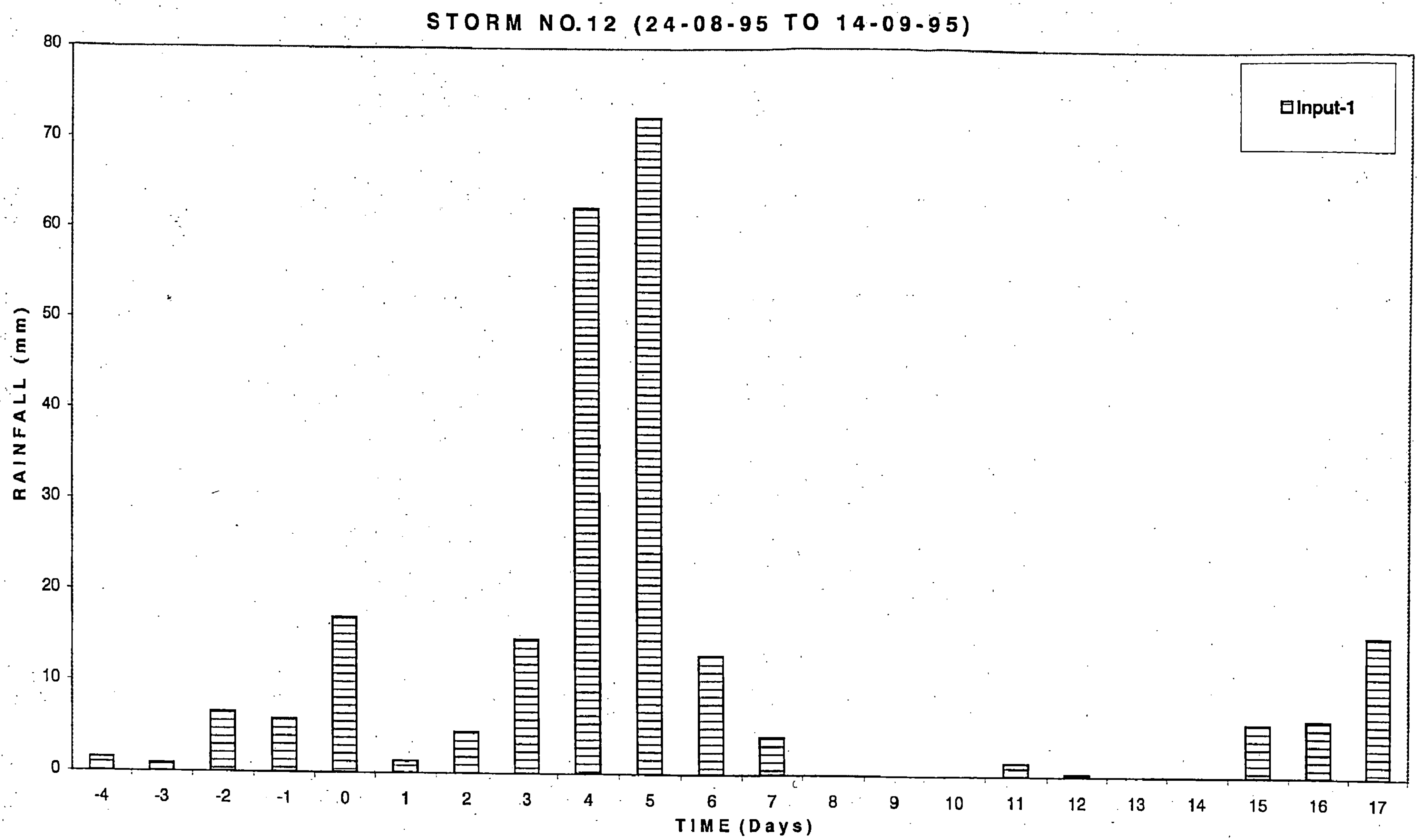

FIG.6.39 VARIATION OF RAINFALL WITH TIME

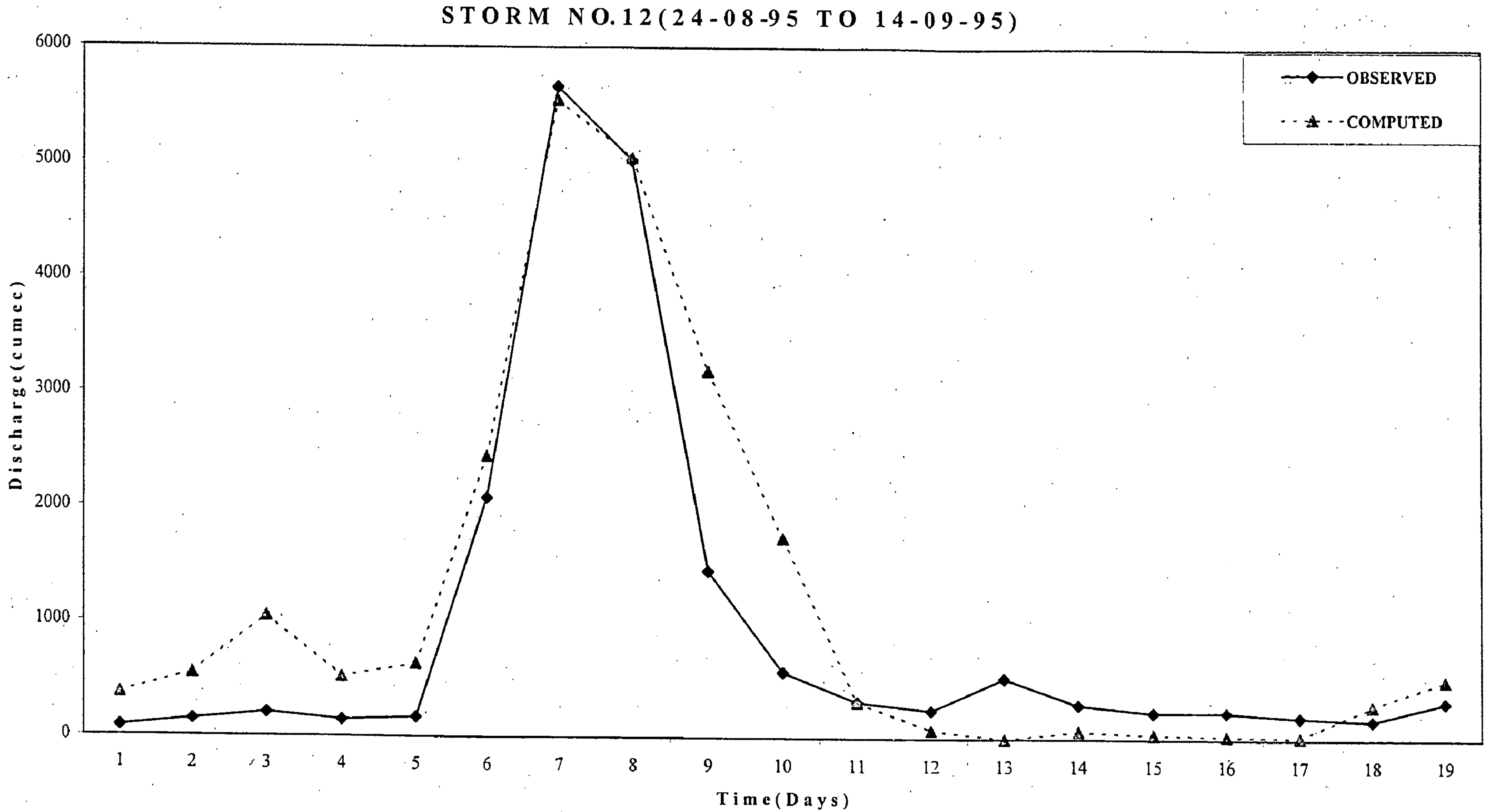

FIG. 6. 40 COMPARISON OF COMPUTED AND OBSERVED RUNOFF USING ONE INPUT (CALIBRATION PERIOD)

APPENDIX -- 1

RAINFALL -- RUNOFF DATA FOR WARDHA UPTO GHUGUS

CALIBRATION PERIOD — **Units : Rainfall in mm, Discharge in Cumec**

STORM NO. 1 (19-06-1985 TO 03-07-1985)

DATE	THREE INPUTS			TWO INPUTS		ONE INPUT	
	RAIN(1)	RAIN (2)	RAIN (3)	RAIN (1)	RAIN (2)	RAIN (1)	DISCHARGE
19.06.85	0.000	0.000	0.000	0.000	0.000	0.000	**65.2**
20.06.85	0.000	0.000	0.000	0.000	0.000	0.000	**35**
21.06.85	0.464	0.000	0.000	0.464	0.000	0.161	**12.8**
22.06.85	2.152	0.000	0.000	2.152	0.000	0.744	**8.3**
23.06.85	0.276	2.902	4.319	0.276	3.505	2.388	**10**
24.06.85	6.059	10.369	6.096	6.059	8.564	7.698	**6.7**
25.06.85	25.992	78.051	31.945	25.992	58.510	47.268	**14.9**
26.06.85	54.028	55.451	84.446	54.028	67.720	62.982	**597.2**
27.06.85	3.004	22.007	34.993	3.004	27.501	19.027	**1374.5**
28.06.85	2.452	5.129	2.372	2.452	3.961	3.440	**1848**
29.06.85	0.000	0.000	0.000	0.000	0.000	0.000	**491.7**
30.06.85	0.000	0.000	0.000	0.000	0.000	0.000	**150**
01.07.85	0.000	0.000	0.000	0.000	0.000	0.000	**70.9**
02.07.85	0.000	0.000	0.000	0.000	0.000	0.000	**47.5**
03.07.85	0.000	0.055	0.000	0.000	0.032	0.021	**22.1**

STORM NO. 2 (01-08-1985 TO 20-08-1985)

DATE	THREE INPUTS			TWO INPUTS		ONE INPUT	
	RAIN(1)	RAIN (2)	RAIN (3)	RAIN (1)	RAIN (2)	RAIN (1)	DISCHARGE
01.08.85	8.608	2.851	2.491	8.608	2.701	4.743	**74.7**
02.08.85	12.396	1.176	0.843	12.396	1.036	4.964	**61.9**
03.08.85	2.978	9.953	26.237	2.978	16.854	12.056	**113**
04.08.85	1.008	1.321	0.454	1.008	0.954	0.973	**680**
05.08.85	0.015	0.000	0.000	0.015	0.000	0.005	**192.8**
06.08.85	0.478	0.155	0.295	0.478	0.214	0.306	**131.9**
07.08.85	9.883	10.878	12.233	9.883	11.440	10.901	**121.1**
08.08.85	19.882	18.824	15.016	19.882	17.216	18.140	**384.2**
09.08.85	23.258	9.380	5.619	23.258	7.791	13.141	**319.8**
10.08.85	5.676	2.052	1.515	5.676	1.823	3.155	**147**
11.08.85	0.351	4.546	7.782	0.351	5.911	3.987	**220**
12.08.85	5.680	27.038	6.356	5.680	18.277	13.921	**564.2**
13.08.85	1.955	27.530	33.167	1.955	29.914	20.242	**1064.2**
14.08.85	2.176	4.902	8.357	2.176	6.371	4.920	**3391.4**
15.08.85	5.440	7.515	15.740	5.440	10.991	9.072	**1239.2**
16.08.85	6.825	25.537	0.750	6.825	15.044	12.201	**595.4**
17.08.85	7.497	16.815	21.800	7.497	18.941	14.984	**190.4**
18.08.85	0.424	1.301	2.325	0.424	1.732	1.279	**1075**
19.08.85	0.010	0.077	0.134	0.010	0.101	0.070	**464.5**
20.08.85	0.411	1.321	0.000	0.411	0.762	0.641	**183.5**

STORM NO.3 (02-08-1986 TO 27-08-1986)

DATE	THREE INPUTS			TWO INPUTS		ONE INPUT	DISCHARGE
	RAIN(1)	RAIN (2)	RAIN (3)	RAIN (1)	RAIN (2)	RAIN (1)	
02.08.86	2.460	8.556	7.687	2.460	8.189	6.205	**234.1**
03.08.86	0.107	0.522	3.577	0.107	1.815	1.225	**130**
04.08.86	4.780	3.635	25.070	4.780	12.706	9.970	**123.1**
05.08.86	6.551	11.483	11.977	6.551	11.691	9.915	**92.6**
06.08.86	21.292	27.888	18.253	21.292	23.810	22.937	**485.9**
07.08.86	52.838	30.840	18.698	52.838	25.702	35.085	**1891.2**
08.08.86	7.904	6.676	11.170	7.904	8.577	8.347	**1158.5**
09.08.86	4.432	9.211	9.720	4.432	9.427	7.697	**913.4**
10.08.86	28.014	52.308	29.075	28.014	42.475	37.469	**1860**
11.08.86	13.860	25.046	27.683	13.860	26.161	21.907	**4786.2**
12.08.86	6.490	22.907	96.406	6.490	54.009	37.585	**2492.2**
13.08.86	13.314	49.952	58.955	13.314	53.763	39.769	**5500**
14.08.86	61.940	147.911	130.399	61.940	140.507	113.303	**9640**
15.08.86	69.052	37.065	43.047	69.052	39.602	49.783	**10400**
16.08.86	6.055	0.000	0.087	6.055	0.037	2.120	**9300**
17.08.86	4.065	0.067	0.000	4.065	0.039	1.432	**4152.3**
18.08.86	0.400	0.000	0.123	0.400	0.052	0.172	**726.6**
19.08.86	0.194	0.869	0.424	0.194	0.681	0.512	**477.2**
20.08.86	0.518	0.032	0.116	0.518	0.068	0.224	**495.4**
21.08.86	0.009	0.227	0.158	0.009	0.198	0.133	**432.7**
22.08.86	0.119	0.456	0.441	0.119	0.450	0.335	**366.6**
23.08.86	0.000	0.000	0.000	0.000	0.000	0.000	**346.8**
24.08.86	0.000	0.000	0.000	0.000	0.000	0.000	**240**
25.08.86	0.000	0.000	0.000	0.000	0.000	0.000	**224.6**
26.08.86	0.000	0.000	0.000	0.000	0.000	0.000	**182.6**
27.08.86	0.000	0.000	0.000	0.000	0.000	0.000	**174.9**

STORM NO. 4 (01-07-1988 TO 11-08-1988)

DATE	THREE INPUTS			TWO INPUTS		ONE INPUT	DISCHARGE
	RAIN(1)	RAIN (2)	RAIN (3)	RAIN (1)	RAIN (2)	RAIN (1)	
01.07.88	3.609	0.234	1.388	3.609	0.723	1.721	**70**
02.07.88	0.317	8.502	27.737	0.317	16.735	11.057	**90**
03.07.88	34.976	34.364	35.516	34.976	35.145	35.089	**100**
04.07.88	7.701	6.164	4.202	7.701	5.205	6.070	**530**
05.07.88	5.072	7.825	5.501	5.072	6.905	6.270	**195**
06.07.88	2.262	7.028	12.015	2.262	9.013	6.679	**625**
07.07.88	0.260	2.010	0.217	0.260	1.213	0.883	**300**
08.07.88	5.716	3.953	2.156	5.716	3.019	3.952	**277.3**
09.07.88	31.998	11.752	26.033	31.998	17.680	22.636	**323.2**
10.07.88	17.331	12.740	15.372	17.331	13.705	14.961	**1179**
11.07.88	7.578	1.239	6.025	7.578	3.277	4.767	**433.5**
12.07.88	9.381	18.802	7.986	9.381	14.273	12.579	**402.2**
13.07.88	18.762	20.239	21.505	18.762	20.969	20.203	**565.7**
14.07.88	26.930	29.813	43.351	26.930	35.206	32.345	**1437**
15.07.88	6.391	0.946	3.016	6.391	1.788	3.381	**1183**
16.07.88	2.089	0.532	0.620	2.089	0.557	1.087	**315.7**
17.07.88	0.201	1.922	7.706	0.201	4.370	2.928	**200**
18.07.88	16.367	8.493	11.029	16.367	8.865	11.466	**320**

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19.07.88	47.379	47.742	38.217	47.379	43.164	44.623	**3910**
20.07.88	2.192	28.675	4.476	2.192	18.430	12.809	**1863**
21.07.88	0.957	6.085	4.285	0.957	5.279	3.784	**1590**
22.07.88	27.685	32.001	30.894	27.685	31.443	30.139	**3500**
23.07.88	10.763	23.188	16.045	10.763	20.203	16.936	**3500**
24.07.88	7.258	2.410	2.313	7.258	2.405	4.085	**1590**
25.07.88	6.279	7.288	7.030	6.279	7.105	6.820	**1880**
26.07.88	28.932	42.047	53.876	28.932	47.066	40.792	**2410**
27.07.88	3.579	11.252	7.275	3.579	9.582	7.505	**3520**
28.07.88	0.119	2.103	0.000	0.119	1.213	0.834	**1460**
29.07.88	0.190	0.587	1.178	0.190	0.810	0.596	**750**
30.07.88	6.787	2.746	4.011	6.787	3.154	4.411	**500**
31.07.88	6.124	3.651	1.457	6.124	2.672	3.866	**2300**
01.08.88	0.237	0.580	0.660	0.237	0.531	0.430	**1750**
02.08.88	3.935	6.541	8.907	3.935	7.665	6.375	**570**
03.08.88	26.318	33.564	25.971	26.318	29.905	28.664	**449.4**
04.08.88	16.773	7.240	4.607	16.773	6.120	9.805	**413.7**
05.08.88	6.011	6.193	2.593	6.011	4.696	5.150	**432**
06.08.88	3.361	0.077	0.000	3.361	0.034	1.185	**394.5**
07.08.88	0.418	0.434	0.222	0.418	0.344	0.370	**350**
08.08.88	0.000	0.011	0.000	0.000	0.005	0.003	**274.6**
09.08.88	0.000	0.000	0.019	0.000	0.008	0.005	**174.6**
10.08.88	0.175	0.727	0.443	0.175	0.607	0.457	**129.8**
11.08.88	1.771	0.440	0.396	1.771	0.424	0.890	**100.4**

STORM NO. 5 (15-08-1988 TO 28-09-1988)

DATE	THREE INPUTS			TWO INPUTS		ONE INPUT	DISCHARGE
	RAIN(1)	RAIN (2)	RAIN (3)	RAIN (1)	RAIN (2)	RAIN (1)	
15-Aug-88	0.000	0.000	0.000	0.000	0.000	0.000	**70**
16-Aug-88	0.000	0.039	0.000	0.000	0.017	0.011	**70**
17-Aug-88	0.000	0.066	0.349	0.000	0.177	0.116	**60**
18-Aug-88	16.491	16.130	9.252	16.491	12.988	14.202	**60**
19-Aug-88	19.654	17.033	20.984	19.654	18.982	19.215	**2820**
20-Aug-88	8.757	10.497	27.968	8.757	17.773	14.657	**1615**
21-Aug-88	16.039	12.893	9.656	16.039	11.499	13.070	**1390**
22-Aug-88	9.747	15.962	49.502	9.747	30.032	23.021	**1145**
23-Aug-88	18.436	11.116	17.089	18.436	13.450	15.174	**3360**
24-Aug-88	0.139	6.367	12.733	0.139	9.172	6.047	**2770**
25-Aug-88	1.433	2.291	2.456	1.433	2.431	2.086	**1615**
26-Aug-88	0.277	5.792	3.015	0.277	4.071	2.759	**1080**
27-Aug-88	7.196	0.555	3.017	7.196	1.571	3.518	**850**
28-Aug-88	12.560	10.534	32.710	12.560	19.762	17.272	**730**
29-Aug-88	7.765	13.039	27.616	7.765	19.351	15.344	**1345**
30-Aug-88	5.781	9.167	16.457	5.781	12.370	10.090	**1320**
31-Aug-88	6.707	13.415	1.395	6.707	8.041	7.578	**730**
1-Sep-88	0.599	6.857	6.220	0.599	6.586	4.514	**1440**
2-Sep-88	28.592	7.167	11.529	28.592	9.132	15.870	**1360**
3-Sep-88	16.826	13.848	15.567	16.826	14.633	15.391	**1615**
4-Sep-88	5.839	5.276	2.861	5.839	4.238	4.791	**1590**
5-Sep-88	5.993	2.629	2.709	5.993	2.649	3.806	**1619**
6-Sep-88	6.885	6.521	19.442	6.885	11.989	10.226	**857.1**
7-Sep-88	0.585	25.342	53.017	0.585	37.216	24.543	**2130**
8-Sep-88	0.129	4.119	3.689	0.129	4.070	2.706	**2083**

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9-Sep-88	15.302	2.725	4.583	15.302	3.381	7.506	**1435**
10-Sep-88	20.157	1.823	5.702	20.157	3.466	9.239	**1410**
11-Sep-88	5.784	0.160	0.000	5.784	0.070	2.047	**1540**
12-Sep-88	0.000	0.000	0.000	0.000	0.000	0.000	**740.7**
13-Sep-88	0.000	0.000	0.000	0.000	0.000	0.000	**361.6**
14-Sep-88	2.795	4.577	17.853	2.795	10.195	7.638	**276**
15-Sep-88	1.104	0.000	2.114	1.104	0.895	0.968	**525**
16-Sep-88	2.716	1.786	0.078	2.716	1.063	1.635	**345.3**
17-Sep-88	0.000	0.000	0.039	0.000	0.016	0.011	**367.8**
18-Sep-88	12.982	2.045	4.801	12.982	2.976	6.440	**355**
19-Sep-88	5.261	10.842	0.225	5.261	6.302	5.941	**445**
20-Sep-88	7.511	4.160	2.864	7.511	3.628	4.972	**700**
21-Sep-88	11.117	11.352	8.928	11.117	10.214	10.527	**2900**
22-Sep-88	22.073	19.080	2.346	22.073	11.993	15.480	**1410**
23-Sep-88	23.214	3.090	6.640	23.214	4.612	11.048	**1085**
24-Sep-88	3.366	5.473	6.529	3.366	5.785	4.949	**1211**
25-Sep-88	0.035	0.135	0.000	0.035	0.078	0.063	**945**
26-Sep-88	0.000	0.000	0.000	0.000	0.000	0.000	**377.5**
27-Sep-88	0.606	0.000	0.000	0.606	0.000	0.210	**286.8**
28-Sep-88	7.964	0.714	1.154	7.964	0.928	3.363	**215**

STORM NO. 6 (11-08-1989 TO 14-09-1989)

DATE	THREE INPUTS			TWO INPUTS		ONE INPUT	DISCHARGE
	RAIN(1)	RAIN (2)	RAIN (3)	RAIN (1)	RAIN (2)	RAIN (1)	
11-Aug-89	6.883	3.600	1.722	6.883	2.798	4.211	**29.65**
12-Aug-89	5.624	13.979	4.636	5.624	10.025	8.501	**101.5**
13-Aug-89	1.933	1.599	2.463	1.933	1.978	1.962	**103.4**
14-Aug-89	1.889	3.019	2.706	1.889	2.883	2.539	**177**
15-Aug-89	0.517	1.054	0.177	0.517	0.537	0.530	**70.37**
16-Aug-89	2.344	0.311	0.273	2.344	0.295	1.004	**31.58**
17-Aug-89	24.569	14.012	20.028	24.569	16.663	19.396	**217.4**
18-Aug-89	11.035	10.868	12.813	11.035	11.536	11.363	**310.2**
19-Aug-89	33.890	52.608	19.186	33.890	38.220	36.717	**1841**
20-Aug-89	1.519	3.464	19.930	1.519	10.390	7.325	**2070**
21-Aug-89	0.705	5.286	10.274	0.705	7.393	5.080	**900.4**
22-Aug-89	13.659	28.915	57.792	13.659	41.009	31.556	**512.7**
23-Aug-89	1.431	16.542	14.432	1.431	15.708	10.770	**553.6**
24-Aug-89	18.219	4.244	6.558	18.219	5.213	9.713	**1847**
25-Aug-89	7.293	2.232	6.995	7.293	4.282	5.323	**721.6**
26-Aug-89	3.079	2.516	2.463	3.079	2.342	2.597	**679.6**
27-Aug-89	9.208	0.389	6.293	9.208	2.959	5.120	**390.9**
28-Aug-89	0.000	3.337	23.121	0.000	11.708	7.662	**339**
29-Aug-89	0.000	2.473	16.936	0.000	8.593	5.624	**303.8**
30-Aug-89	7.886	4.007	12.091	7.886	7.492	7.630	**194.2**
31-Aug-89	22.286	56.082	37.172	22.286	48.678	39.546	**962**
1-Sep-89	24.321	34.188	29.372	24.321	31.963	29.319	**2429**
2-Sep-89	0.000	1.553	6.716	0.000	3.737	2.445	**1753**
3-Sep-89	0.320	0.373	2.633	0.320	1.329	0.980	**904.8**
4-Sep-89	0.107	0.000	0.000	0.107	0.000	0.037	**562**
5-Sep-89	0.000	0.000	0.000	0.000	0.000	0.000	**276.6**
6-Sep-89	0.000	2.367	16.206	0.000	8.223	5.381	**191.8**
7-Sep-89	0.000	2.313	15.841	0.000	8.038	5.260	**211.5**
8-Sep-89	0.000	0.066	0.000	0.000	0.029	0.019	**178.3**

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9-Sep-89	0.000	0.139	0.949	0.000	0.482	0.315	**155.7**
10-Sep-89	5.866	7.702	8.937	5.866	8.190	7.386	**116.1**
11-Sep-89	10.704	19.917	13.042	10.704	16.896	14.755	**433.6**
12-Sep-89	0.893	0.718	1.585	0.893	1.069	1.008	**512.7**
13-Sep-89	0.000	0.055	0.000	0.000	0.024	0.016	**255.8**
14-Sep-89	0.000	3.049	19.032	0.000	9.679	6.334	**190.2**

STORM NO. 7 (08-06-1990 TO 30-06-1990)

DATE	THREE INPUTS			TWO INPUTS		ONE INPUT	
	RAIN(1)	RAIN (2)	RAIN (3)	RAIN (1)	RAIN (2)	RAIN (1)	DISCHARGE
8-Jun-90	0.163	5.118	3.885	0.163	4.596	3.061	**56.51**
9-Jun-90	1.106	2.763	0.000	1:106	1.460	1.338	**43.42**
10-Jun-90	9.562	3.417	7.996	9.562	5.411	6.846	**55**
11-Jun-90	16.128	1.126	1.448	16.128	1.228	6.382	**37.66**
12-Jun-90	7.740	18.973	9.332	7.740	15.034	12.510	**33.27**
13-Jun-90	1.620	25.540	25.410	1.620	25.567	17.283	**32.78**
14-Jun-90	0.218	4.359	0.409	0.218	2.081	1.437	**85**
15-Jun-90	3.873	12.271	2.530	3.873	8.065	6.615	**148.3**
16-Jun-90	12.890	12.268	19.957	12.890	15.556	14.636	**209.6**
17-Jun-90	52.193	73.409	63.544	52.193	69.438	63.470	**1115**
18-Jun-90	38.645	79.894	109.381	38.645	92.486	73.865	**4420**
19-Jun-90	3.235	2.268	1.204	3.235	1.815	2.306	**4020**
20-Jun-90	4.441	1.415	0.365	4.441	0.963	2.168	**1210**
21-Jun-90	22.001	33.693	38.863	22.001	35.999	31.155	**465**
22-Jun-90	1.664	8.997	10.762	1.664	9.774	6.968	**1155**
23-Jun-90	1.001	0.098	0.460	1.001	0.251	0.511	**530**
24-Jun-90	0.198	0.000	0.019	0.198	0.008	0.074	**255**
25-Jun-90	4.411	0.754	2.000	4.411	1.281	2.364	**105.6**
26-Jun-90	0.218	0.294	6.467	0.218	2.901	1.973	**85.21**
27-Jun-90	0.000	0.000	0.446	0.000	0.189	0.124	**62.99**
28-Jun-90	7.600	5.363	1.080	7.600	3.412	4.861	**54.2**
29-Jun-90	7.486	0.405	0.543	7.486	0.464	2.894	**45.7**
30-Jun-90	6.395	7.553	4.090	6.395	6.078	6.187	**39.59**

STORM NO. 8 (12-07-1990 TO 31-07-1990)

DATE	THREE INPUTS			TWO INPUTS		ONE INPUT	
	RAIN(1)	RAIN (2)	RAIN (3)	RAIN (1)	RAIN (2)	RAIN (1)	DISCHARGE
12-Jul-90	1.505	0.000	0.369	1.505	0.156	0.623	**50.33**
13-Jul-90	0.296	0.011	0.019	0.296	0.013	0.111	**50.09**
14-Jul-90	1.053	1.245	1.729	1.053	1.464	1.322	**46.36**
15-Jul-90	1.538	14.151	3.906	1.538	9.698	6.874	**40**
16-Jul-90	16.922	2.159	1.756	16.922	1.985	7.157	**44.53**
17-Jul-90	3.921	10.484	17.564	3.921	13.457	10.159	**105.2**
18-Jul-90	2.116	9.587	16.115	2.116	12.337	8.802	**223.9**
19-Jul-90	1.363	9.313	8.343	1.363	8.567	6.074	**420**
20-Jul-90	12.074	27.135	29.459	12.074	28.339	22.711	**660**
21-Jul-90	28.762	49.383	50.376	28.762	49.757	42.492	**1200**
22-Jul-90	12.816	4.892	9.322	12.816	6.757	8.852	**1470**
23-Jul-90	9.661	21.653	24.475	9.661	22.734	18.209	**530**
24-Jul-90	33.835	80.951	63.962	33.835	73.282	59.634	**3550**

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25-Jul-90	5.613	14.128	5.270	5.613	10.350	8.709	**4060**
26-Jul-90	2.233	1.935	1.296	2.233	1.602	1.820	**1785**
27-Jul-90	0.691	0.945	1.226	0.691	1.080	0.945	**865**
28-Jul-90	0.000	0.756	5.096	0.000	2.597	1.699	**405**
29-Jul-90	6.014	4.059	11.326	6.014	7.207	6.794	**320**
30-Jul-90	3.063	0.011	0.073	3.063	0.037	1.084	**207.4**
31-Jul-90	0.000	0.000	0.000	0.000	0.000	0.000	**191.5**

VERIFICATION PERIOD

STORM NO. 9 (04-08-1990 TO 21-09-1990)

DATE	THREE INPUTS			TWO INPUTS		ONE INPUT	DISCHARGE
	RAIN(1)	RAIN (2)	RAIN (3)	RAIN (1)	RAIN (2)	RAIN (1)	
4-Aug-90	1.797	2.245	0.000	1.797	1.215	1.417	**108.4**
5-Aug-90	0.020	0.000	0.000	0.020	0.000	0.007	**110**
6-Aug-90	0.757	0.177	0.000	0.757	0.077	0.313	**95.15**
7-Aug-90	17.323	18.358	4.772	17.323	12.580	14.221	**91.73**
8-Aug-90	31.751	60.567	108.809	31.751	81.252	64.121	**789**
9-Aug-90	16.221	22.735	1.404	16.221	13.703	14.572	**1492**
10-Aug-90	0.020	0.000	0.000	0.020	0.000	0.007	**1374**
11-Aug-90	0.096	3.833	17.329	0.096	9.528	6.265	**866.4**
12-Aug-90	2.078	0.000	0.000	2.078	0.000	0.720	**635**
13-Aug-90	1.593	9.233	8.757	1.593	9.216	6.578	**366.9**
14-Aug-90	4.089	2.211	3.441	4.089	2.762	3.221	**260.8**
15-Aug-90	1.713	6.142	3.402	1.713	4.669	3.647	**345**
16-Aug-90	36.988	102.777	125.366	36.988	112.516	86.376	**4100**
17-Aug-90	29.150	34.287	43.177	29.150	38.023	34.951	**4460**
18-Aug-90	0.736	10.198	8.534	0.736	9.503	6.469	**4120**
19-Aug-90	4.547	1.509	1.448	4.547	1.433	2.511	**2343**
20-Aug-90	10.311	6.695	17.271	10.311	11.130	10.847	**1879**
21-Aug-90	0.673	1.029	5.215	0.673	2.769	2.044	**1502**
22-Aug-90	29.580	18.291	12.984	29.580	15.428	20.329	**1713**
23-Aug-90	45.392	117.879	162.594	45.392	136.269	104.818	**3600**
24-Aug-90	1.856	0.896	0.602	1.856	0.752	1.134	**3840**
25-Aug-90	0.491	1.978	1.125	0.491	1.617	1.227	**2133**
26-Aug-90	0.306	0.119	0.121	0.306	0.125	0.187	**990**
27-Aug-90	23.948	55.540	0.000	23.948	32.031	29.236	**538.1**
28-Aug-90	2.598	0.110	0.000	2.598	0.048	0.931	**399.7**
29-Aug-90	1.261	29.356	15.857	1.261	23.011	15.483	**1726**
30-Aug-90	42.995	35.179	30.761	42.995	33.119	36.535	**3480**
31-Aug-90	36.946	26.810	26.095	36.946	26.608	30.184	**3840**
1-Sep-90	1.294	0.897	0.649	1.294	0.778	0.957	**3837**
2-Sep-90	3.134	1.064	3.907	3.134	2.308	2.594	**2550**
3-Sep-90	0.020	0.000	0.016	0.020	0.007	0.011	**1029**
4-Sep-90	0.000	0.033	0.096	0.000	0.057	0.037	**613.5**
5-Sep-90	1.122	1.287	0.736	1.122	0.999	1.042	**452.6**
6-Sep-90	1.921	4.872	0.289	1.921	2.822	2.511	**456.1**
7-Sep-90	12.010	10.154	9.040	12.010	9.301	10.239	**614.7**
8-Sep-90	1.169	4.107	1.926	1.169	2.944	2.330	**964**
9-Sep-90	4.610	2.267	15.906	4.610	7.966	6.805	**490**
10-Sep-90	0.019	0.389	0.317	0.019	0.359	0.241	**492.2**
11-Sep-90	0.613	0.000	0.000	0.613	0.000	0.212	**400.9**
12-Sep-90	0.682	0.000	0.000	0.682	0.000	0.236	**323.9**

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13-Sep-90	0.000	0.673	0.000	0.000	0.293	0.192	**250.1**
14-Sep-90	1.186	2.542	2.024	1.186	1.994	1.715	**238.7**
15-Sep-90	3.068	3.086	3.152	3.068	3.211	3.162	**269.4**
16-Sep-90	0.059	0.000	0.000	0.059	0.000	0.021	**240**
17-Sep-90	0.262	0.608	0.000	0.262	0.351	0.320	**192.1**
18-Sep-90	0.000	0.000	0.000	0.000	0.000	0.000	**157.2**
19-Sep-90	0.000	0.000	0.000	0.000	0.000	0.000	**159.5**
20-Sep-90	1.256	0.000	0.000	1.256	0.000	0.435	**153.2**
21-Sep-90	0.000	0.000	0.000	0.000	0.000	0.000	**136.4**

STORM NO. 10 (21-07-1993 TO 17-08-1993)

DATE	THREE INPUTS			TWO INPUTS		ONE INPUT	
	RAIN(1)	RAIN (2)	RAIN (3)	RAIN (1)	RAIN (2)	RAIN (1)	DISCHARGE
21-Jul-93	0.000	0.000	0.000	0.000	0.000	0.000	**28.56**
22-Jul-93	0.000	0.000	0.000	0.000	0.000	0.000	**25.26**
23-Jul-93	0.000	0.000	0.000	0.000	0.000	0.000	**21.19**
24-Jul-93	0.000	0.000	1.340	0	0.567	0.371	**17.55**
25-Jul-93	0.000	0.358	0.336	0	0.354	0.232	**14.5**
26-Jul-93	0.316	10.066	12.405	0.316	11.181	7.423	**28.8**
27-Jul-93	0.423	7.537	12.790	0.423	9.868	6.602	**111.9**
28-Jul-93	23.944	18.704	17.666	23.944	18.273	20.236	**121.6**
29-Jul-93	7.917	15.533	21.193	7.917	18.005	14.516	**422.1**
30-Jul-93	0.547	17.306	13.359	0.547	15.749	10.490	**1274**
31-Jul-93	1.391	27.688	12.000	1.391	31.101	20.820	**2014**
1-Aug-93	4.757	5.368	17.162	4.757	10.355	8.418	**969.9**
2-Aug-93	5.985	12.915	14.613	5.985	13.625	10.983	**290.4**
3-Aug-93	0.334	15.294	13.185	0.334	14.557	9.636	**387.5**
4-Aug-93	21.467	17.385	16.052	21.467	16.864	18.457	**1247**
5-Aug-93	31.223	9.279	17.735	31.223	12.841	19.200	**636.1**
6-Aug-93	5.086	13.946	15.063	5.086	14.476	11.228	**484.4**
7-Aug-93	0.587	3.507	8.332	0.587	5.548	3.832	**253.9**
8-Aug-93	0.770	0.186	0.500	0.770	0.319	0.474	**159.7**
9-Aug-93	0.000	0.000	0.772	0.000	0.327	0.214	**111.4**
10-Aug-93	0.000	0.019	0.000	0.000	0.011	0.007	**71.47**
11-Aug-93	0.262	2.619	2.239	0.262	2.497	1.724	**49.21**
12-Aug-93	0.000	0.467	1.053	0.000	0.715	0.468	**40.09**
13-Aug-93	0.000	1.944	0.000	0.000	1.121	0.733	**31.23**
14-Aug-93	2.586	0.793	0.451	2.586	0.627	1.305	**27.06**
15-Aug-93	0.000	0.371	0.681	0.000	0.503	0.329	**23.58**
16-Aug-93	12.339	3.084	12.095	12.339	6.878	8.768	**22.62**
17-Aug-93	5.556	11.219	21.728	5.556	15.666	12.168	**27.47**

STORM NO. 11 (13-07-1995 TO 31-07-1995)

DATE	THREE INPUTS			TWO INPUTS		ONE INPUT	
	RAIN(1)	RAIN (2)	RAIN (3)	RAIN (1)	RAIN (2)	RAIN (1)	DISCHARGE
13-Jul-95	7.435	4.981	2.568	7.435	3.998	5.187	**38.1**
14-Jul-95	6.548	12.436	11.739	6.548	12.154	10.215	**144.8**
15-Jul-95	18.907	39.352	32.954	18.907	36.645	30.506	**121.7**
16-Jul-95	10.958	14.378	8.669	10.958	11.951	11.606	**604.9**
17-Jul-95	7.457	3.024	9.465	7.457	5.736	6.331	**339**

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18-Jul-95	1.331	5.463	6.174	1.331	5.796	4.253	**139.4**
19-Jul-95	7.172	18.321	13.766	7.172	16.401	13.208	**127.8**
20-Jul-95	20.547	45.364	45.227	20.547	45.442	36.830	**548.2**
21-Jul-95	8.920	12.254	6.744	8.920	9.883	9.549	**661.9**
22-Jul-95	7.182	7.949	8.795	7.182	8.297	7.910	**526.1**
23-Jul-95	1.708	3.889	6.610	1.708	5.046	3.893	**336.5**
24-Jul-95	23.982	29.610	22.255	23.982	26.487	25.619	**190.6**
25-Jul-95	49.918	37.920	29.667	49.918	34.395	39.764	**2162**
26-Jul-95	4.919	4.592	0.169	4.919	2.705	3.472	**952.3**
27-Jul-95	3.990	1.785	0.634	3.990	1.309	2.236	**687.6**
28-Jul-95	0.000	0.000	0.863	0.000	0.365	0.239	**470.5**
29-Jul-95	5.653	1.818	3.347	5.653	2.456	3.563	**317.2**
30-Jul-95	9.962	12.861	5.571	9.962	9.756	9.827	**271.6**
31-Jul-95	0.917	2.154	2.702	0.917	2.373	1.871	**456.3**

STORM NO.12 (24-08-1995 TO 14-09-1995)

DATE	THREE INPUTS			TWO INPUTS		ONE INPUT	
	RAIN(1)	RAIN (2)	RAIN (3)	RAIN (1)	RAIN (2)	RAIN (1)	DISCHARGE
24-Aug-95	1.521	0.956	2.120	1.521	1.449	1.474	**55.17**
25-Aug-95	0.041	1.541	0.910	0.041	1.273	0.847	**51.02**
26-Aug-95	0.017	8.356	12.264	0.017	9.975	6.532	**53.18**
27-Aug-95	10.712	2.178	4.615	10.712	3.194	5.796	**81.32**
28-Aug-95	1.377	26.014	24.288	1.377	25.260	16.990	**143.5**
29-Aug-95	0.065	2.026	1.827	0.065	1.937	1.289	**202.3**
30-Aug-95	1.944	8.855	1.771	1.944	5.858	4.507	**142.1**
31-Aug-95	9.934	17.163	17.336	9.934	17.186	14.681	**168.4**
1-Sep-95	11.381	82.408	98.719	11.381	89.233	62.303	**2081**
2-Sep-95	85.949	66.587	63.542	85.949	65.144	72.345	**5661**
3-Sep-95	23.442	10.168	3.739	23.442	7.458	12.987	**5024**
4-Sep-95	2.743	3.169	7.033	2.743	4.813	4.096	**1448**
5-Sep-95	0.000	0.000	0.000	0.000	0.000	0.000	**567.8**
6-Sep-95	0.000	0.000	0.000	0.000	0.000	0.000	**313.5**
7-Sep-95	0.000	0.000	0.000	0.000	0.000	0.000	**243.2**
8-Sep-95	0.000	3.674	0.000	0.000	2.117	1.386	**522.4**
9-Sep-95	0.000	0.000	0.860	0.000	0.364	0.238	**292.5**
10-Sep-95	0.000	0.000	0.000	0.000	0.000	0.000	**229.6**
11-Sep-95	0.000	0.000	0.000	0.000	0.000	0.000	**230.4**
12-Sep-95	3.783	7.545	5.748	3.783	6.797	5.756	**189.8**
13-Sep-95	0.753	8.749	9.456	0.753	9.013	6.159	**161.8**
14-Sep-95	1.803	14.996	33.054	1.803	22.541	15.371	**319.4**