TR-15

MATHEMATICAL MODELLING OF MOVING STORMS

SATISH CHANDRA

DIRECTOR

STUDY GROUP

K S RAMASASTRI

NATIONAL INSTITUTE OF HYDROLOGY

JAL VIGYAN BHAVAN, ROORKEE -247667

1986-87

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The magnitude of peak flood and the shape of a flood hydrograph depend not only on the magnitude of total storm rainfall depths but also on its distribution in space and with time. Improvements of the accuracy and timeliness of hydrological forecasting would thus largely depend on the prediction of rainfall distribution in space and with time.

It is common knowledge that in India, tropical disturbances popularly known as storms and cyclones originate in the Bay of Bengal and Arabian Sea prior to, during and after the monsoon season, and move over the mainland of India. The direction of storm movement has the greatest effect on large elongated catchments like Narmada. During a given storm period for the same amount of total storm rainfall, the magnitude of the flood peak would be greater and the rising limb steeper if the storm moves down the valley.

Modelling of moving storms has been attempted by several authors using both dynamical and statistical approaches. Some of these methods are reviewed in the report and the statistical technique of inter-station cross correlation has been applied to model the movement of four historical storms in Narmada basin which had caused critical floods in Narmada river. Hourly rainfall data recorded at a number of self recording rain gauges in the Narmada catchment has been used for the analysis. The storms considered for the analysis were, (i) 2-6 Sept 1970, (ii) 28-31 August 1973, (iii) 28-31 August 1978 and (iv) 6-10 August 1979.

The hourly rainfall data are scrutinized by visual observation for each of the storms and the storm period at each of the SRRG stations

was identified. The hourly rainfall data at each of the SRRG stations has been input to the cross correlation programme incorporating the lag observed through the visual observation. During the analysis, the inter-station correlation is computed for all pairwise combination of SRRG stations lagging the rainfall data at stations down the storm track in successive increments of 1 hour upto a maximum lag of 18 hours.

The results have indicated the usefulness of the statistical model based on cross correlation, in modelling the movement of the tropical storms inspite of the rather poor network of self recording stations in the Narmada basin.

The study further strengthened the theory regarding the size of the storm cell which has been reported in various studies to be of the order of about 5 km. The lag zero correlation obtained at any pairwise combination in all the four stations is rather poor, the maximum correlation coefficient obtained being only 0.7200.

1.0 INTRODUCTION

The principal use of meteorological forecasts in operational hydrology is as input to hydrological forecasting systems. Meteorological forecasts could be used to prolong the lead time of the forecast and enhance the accuracy and reliability of hydrological forecasts. Short term hydrological forecasts are generally based on precipitation forecasts for periods ranging from 6 to 48 hours. Considering the current trend towards using rainfall-runoff models to simulate a catchment's response from precipitation input, improvements in the timeliness of hydrological forecasting will depend largely on the progress made in rainfall prediction. Precise forecasts of short duration high intensity rainfall which is known to cause flash floods in small catchments and urban storm water drainage systems are also very essential.

In India, large parts of the country receive nearly 80 to 90 percent of the annual rainfall during the four months June to September constituting the summer monsoon or South West monsoon season. It is common knowledge that tropical disturbances, popularly known as stroms or cyclones originate in the Bay of Bengal and Arabian Sea prior to, during and after the monsoon season and move in a North-North West or Westerly direction.

Unlike the Arabian sea storms which occasionally affect the areas on the west coast and Saurashtra region, the Bay of Bengal storms cross the east coast and invariably travel long distances over the Indian main land before they become weak and unimportant. The average distance covered is of the order of 500 km per day. In their trail, these storms precipitate huge amounts of rainfall with rain centres shifting along with the movement of storm.

Unlike snow, the storm water resulting from rainstroms during monsoon season results in runoff almost instantaneously due to antecedent wet conditions. It is well known that the runoff hydrograph from a catchment due to a rainstorm depends not only on the total storm rainfall but its distribution in space and with time. The influence of rainfall movement on the magnitude of peak flood and the shape of the hydrograph has come to be recognized for some time now. The direction of storm movement has considerable effect on elongated catchments and more if they are large also. It has been seen that the same amount of rain over the same period produces a much greater peak when the storm is moving down the valley. The rainfall from a storm moving up the valley becomes runoff long before the storm reaches the top of the catchment.

Modelling of the moving storm has been attempted by several authors using both dynamical and statistical approaches. In this report, some of the methods are reviewed and the application of the statistical approach to some moving storms in the large elongated catchment of Narmada is described.

2.0 REVIEW

Individual rainstorms contribute widely differing amounts of rain. The variation of precipitation in space and time is largely determined by spatial and temporal variations in the vertical motion of air. This vertical motion results from processes within the atmosphere and interaction between the atmosphere and underlying surface of the earth. Both types of processes operate on small (mesoscale), medium (sub-synoptic) and large (synoptic scales).

Systematic observations on diverse storm types indicated the consistent occurrence of certain sub-synoptic features with similar characteristics and behaviour. Austin and Houze (1972) reported some of these sub-synoptic features.

Precipitation areas of synoptic scale (areas greater than 100 km^2) contain sub-synoptic precipitation areas (large meso scale areas). While the synoptic areas have a life span of one to several days, the life span of the large mesoscale areas was found to be within the order of several hours and their number within a synoptic area has been observed to be ranging from one to six. The larger mesoscale systems move in relation to a synoptic area. The precipitation intensity inside a large mesoscale system is always high than the region surrounding it. The small mesoscale areas build and dissipate within a large mesoscale area with an average life span of a few hours(Fig.1). These mesoscale systems contain regions of cumulus convective precipitation, commonly known as 'convective cells'. The cells build and dissipate within a few hours and generally occur in clusters, each raincell extending over 10-30 km^2.

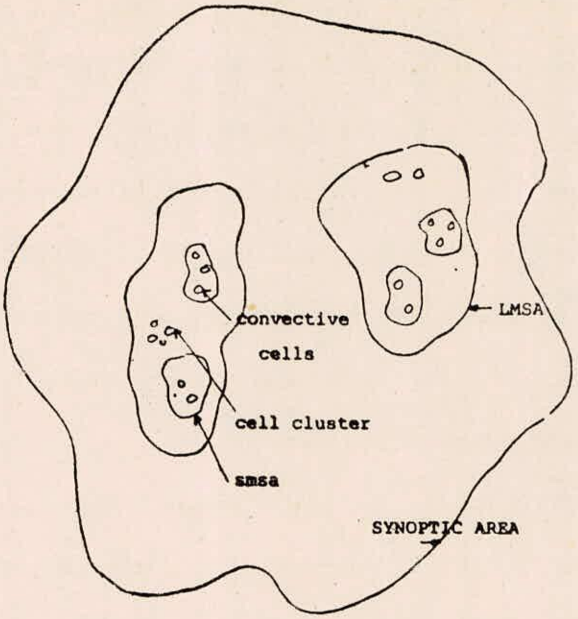

Figure 1: A Schematic Depiction of Sub-Synoptic Rainfall Features

Recent studies using Radar observation techniques and observations using densely spaced gauges, Felgate and Read(1975) and Niemczynowicz and Jonsson (1981) suggest that individual raincells are smaller than that stated by Austin and Houze.

2.1 Modelling of Rainfall in Space and Time

Models of rainfall in space and time can be grouped into three broad categories. The first category consists of the numerical modelling of space time rainfall on the basis of the principles of thermodynamics. The second category includes a numerical simulation of rainfall on the basis of regularities which rainfall has been known to exhibit in space and time. The third category includes analytical modelling of rainfall as a random field.

2.2 Dynamical Approach

Ramanathan and Bansal(1977) had used a primitive equation barotropic model to forecast the storm tracks in the Arabian Sea and Bay of Bengal during 1970.

Singh and Saha (1978) used a quasi-Lagrangian advection scheme for forecasting the movement of monsoon depressions using a primitive equation barotropic model. Using the observed wind as basic input, the monsoon depression of Aug.1968 and a tropical cyclone of October 1971 were used as case studies. The results obtained for both the cases suggested that the forecasts upto 48 hours were encouraging but deteriorated for further periods.

Saha (1983) also used a single level primitive equation barotropic model for predicting the movement of the monsoon depression over the Arabian Sea and Bay of Bengal. The initial input to the model was the subjectively analysed wind field from which geopotential field was derived. The movement of three depressions during the summer monsoon of 1979 was studied. The study has shown that a single level primitive equation barotropic model was able to predict the movement of monsoon depressions to a limited degree of accuracy.

2.3 Statistical Modelling

The general concept underlying the stochastic modelling of precipitation is not new. The most basic description of rainfall can be obtained by viewing it as a random field in the space time continum. The stochastic modelling of precipitation was motivated by the observed regularities in the evolution of space time rainfall from diverse storm types. The importance of specifying the stochastic structure of a rainfall intensity field comes from the fact that the structures of various space-time averages of rainfall intensity can then be obtained as mathematical approximations of the basic rainfall field. Given that a synoptic disturbance has originated, the main probelm in modelling rainfall is to describe the mathematical structure of the random field intensity resulting from the disturbance.

Chow and Ramaseshan (1965) represented the annual storms for the French Broad River Basin at Brent Creek, North Carolina by a first order non-stationary Markov model in log-normally distributed random components. Since the storm time distribution patterns were different, they carried out a 'Storm Shifting' procedure to obtain the best storm orientation so that the mean, standard deviation, trend and components of the hourly rainfall became regular and consistent. The storms were assumed to have the same duration which was approximately equal to the longest duration of the storm under consideration. They successfully applied a first order autoregressive model to generate sequentially the hourly rainfall depths within the annual storms having constant duration.

Ramaseshan (1971) further revised these studies that concluded that:

(i) storm precipitation could be conceived of as a finite duration, quantitized data, continuous-variable, nonstationary, stochastic process. For the river basin studied, a simple Markov model with log normally distributed random components was found to be satisfactory.

(ii) detailed steps in the mathematical modelling of the process could be standardised to yield consistent results.

(iii) shift analysis is useful in generating sequential data of storm precipitation in a basin and subsequently verifying the data.

Such data may be used in the analysis and design of water resources system by simulation.

Rodriguez Iturbe and Mejia (1974) presented a methodology for the transformation of point rainfall to areal rainfall using the spatial correlation structure of point rainfall as the commanding parameter. For this purpose, the precipitation process is assumed as stationary and isotropic and was factored as a spatial and temporal part.

Amorocho and Wu(1977) developed two mathematical models for the simulation of cyclonic storm and precipitation fields. The first, a storm sequence model uses the Monte Carlo simulation technique to generate storm sequences from the probability distributions of storm characteristics of historical storm sequences. The storm characteristics analysis included time between storms, number of bands within a storm, time between bands, band duration, band depth and band velocity. The second model which simulates a spatially distributed precipitation field, used a randomization process to generate clusters of short lived and high intensity rain cells within a storm band. The apparent sizes, life cycles and space distribution of rain cells were determined from the properties of historical data. The two models could be used either together or in succession to generate precipitation sequences for any sampling time interval and at any ground location in the path of a storm.

Creutin and Obled (1980) had proposed a hourly stochastic precipitation model which could provide some conditional distribution of the next hourly flows.

The model uses a rainfall event as split into periods of uninterrupted rain seperated by a rain free period of atleast 12 hr.,which could be described by a few simple and independent variables. The distribution functions of these variables were adjusted on a sample of 135 events and at two stations separately. The statistical dependence of these variables was tested and verified so that the model could be used for simulation with a random number generator to generate likely rainfall events.

The following characteristics needed to be defined:

(i) inter arrival time of storm events;

(ii) number of storm segments inside the event;

(iii) duration of a given storm segment;

(iv) time interval between a given storm and the previous one;

(v) total accumulation of water for the storm considered;

(vi) ratio of the hourly maximum to the hourly average of the storm;

(vii) location of the peak inside the storm period.

Most of these variables fit the simple exponential density functions or log normal distributions.

Johnson and Bras(1980) developed a stochastic model for short term (of the order of 1 hour or less) rainfall rates at multiple locations and for multiple values of lead prediction time and includes velocity and direction of storm movement as explicit parameters. Likewise, the storm arrival time at each predicted point is an explicit parameter.

Marshal (1980) described a method of estimating the speed and direction of movement of storm rainfall pattern from a network of continuously recording rain gauges. An analysis of cross correlations between all pairs of rain gauges of the network for time lags is made. Besides giving an estimate of storm motion, the method indicates the temporal and spatial structure of the storm.

Stol (1981) considered a two dimensional cross section through a gauged area, perpendicular to the direction in which storms move. This method is an improvement over the empirical inter-station correlation vs inter-station distance relationship because the correlation functions are expressed as analytically derived functions with respect to inter-station distance using storm and area characteristics as parameters.

Niemczynowicz and Jonsson (1981) working with rainfall events, in Lund, Sweden used a procedure based on the sample cross correlation between all pairwise combinations of gauges incorporating an algorithm for estimation of the velocity and direction of the drift of rain cells assuming spatial stationarity of the precipitation process. If the network is sufficiently dense, i.e.the distance between two gauges is small compared to the size of the rain cell it is reasonable to expect that the gauges within the same rain cell will have a high correlation coefficient between its hyetographs with no time lag introduced. If the time lag is introduced, the correlation factor between gauges will be higher in the direction of rain cell movement compared with other directions.

Niemczynowicz (1984) had studied the general relationship between storm movement parameters like storm duration, intensity, velocity and direction and their influence on the peak discharge from a conceptual catchment and applied the relationship to real catchments in the city of Lund.

Using hourly rainfall data of Thikri in Madhya Pradesh, Surender Kaur et al (1985) had attempted simulation of the characteristics of rainstorms for flood forecasting. Statistical distribution functions were fitted to the different rainfall segments constituting a storm event.

event.

Ramasastri and Seth (1986) had studied the implications of critical placement of the storm centres over the Narmada catchment on the peak flood magnitude and the shape of the flood hydrograph, and concluded that though the total storm depths due to two different storms may be same, the critical placement of the storm centre every day over a different part of the catchment so as to simulate the effect of moving storm has produced greater peak floods than the storm without such critical placement.

3.0 PROBLEM DEFINITION

Cyclonic storms affecting India originate either in the Bay of Bengal as low pressure systems in the pre-existing seasonal trough of low pressure or enter into Bay of Bengal from the South China Sea. Depending on the season and latitude of their formation, the low pressure areas originating in the Bay of Bengal intensify and move towards the coastal areas of the Indian sub-continent following typical tracks.

The tropical cyclone exhibits a symmetry in wind distribution around its centre. Strong surface winds are often observed to the right of the cyclonic track. Nearly 70 percent of the cyclonic storms over Indian seas are of a size whose diameter is between 600 and 1200 km. Most of these storms occur in the post-monsoon season, i.e. from October to December. The pre-monsoon storms occuring in the months of April and May are generally smaller with diameters varying between 400 and 800 km.

Before a storm attains maturity it passes through the formative stage and the immaturity stage. Prior to the full development during the immature stage, the central pressure rapidly falls and cloud bands get organised. The vertical schematic representation of mature cyclone is shown in figure 2.

During the maturity stage the life of the storm depends on the track followed by it over the sea areas. The decaying stage is very rapid varying from a few hours to a day. When the storm has decayed into a depression stage it can continue to move for a few days even over the land.

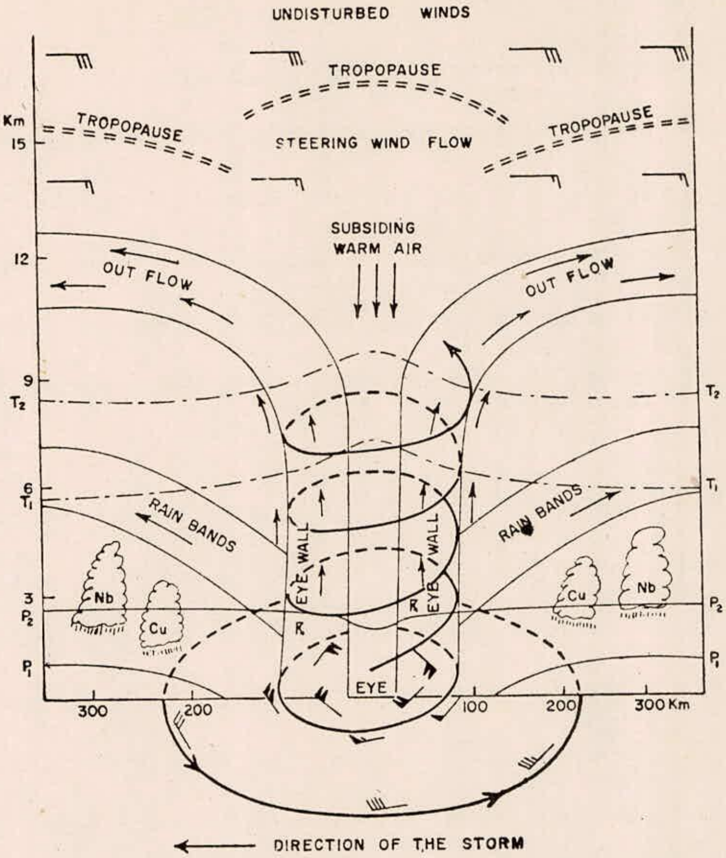

Fig. 2 : A schematic representation of vertical structure of a mature cyclonic storm

The tracks followed by cyclonic storms of the monsoon season and those in late November and December show lesser degree of variation. The May storms, however, show considerable variation in their tracks. In figures 3(a) to 3(d), the typical storm tracks in selected months are shown.

Since the amount of precipitation realised from a storm is generally associated with the severity of the system and the location of the storm, forecasting of the intensity changes and storm location would be of great help in flood forecasting. However, in view of the uncertainty associated with storm movement and other changes,

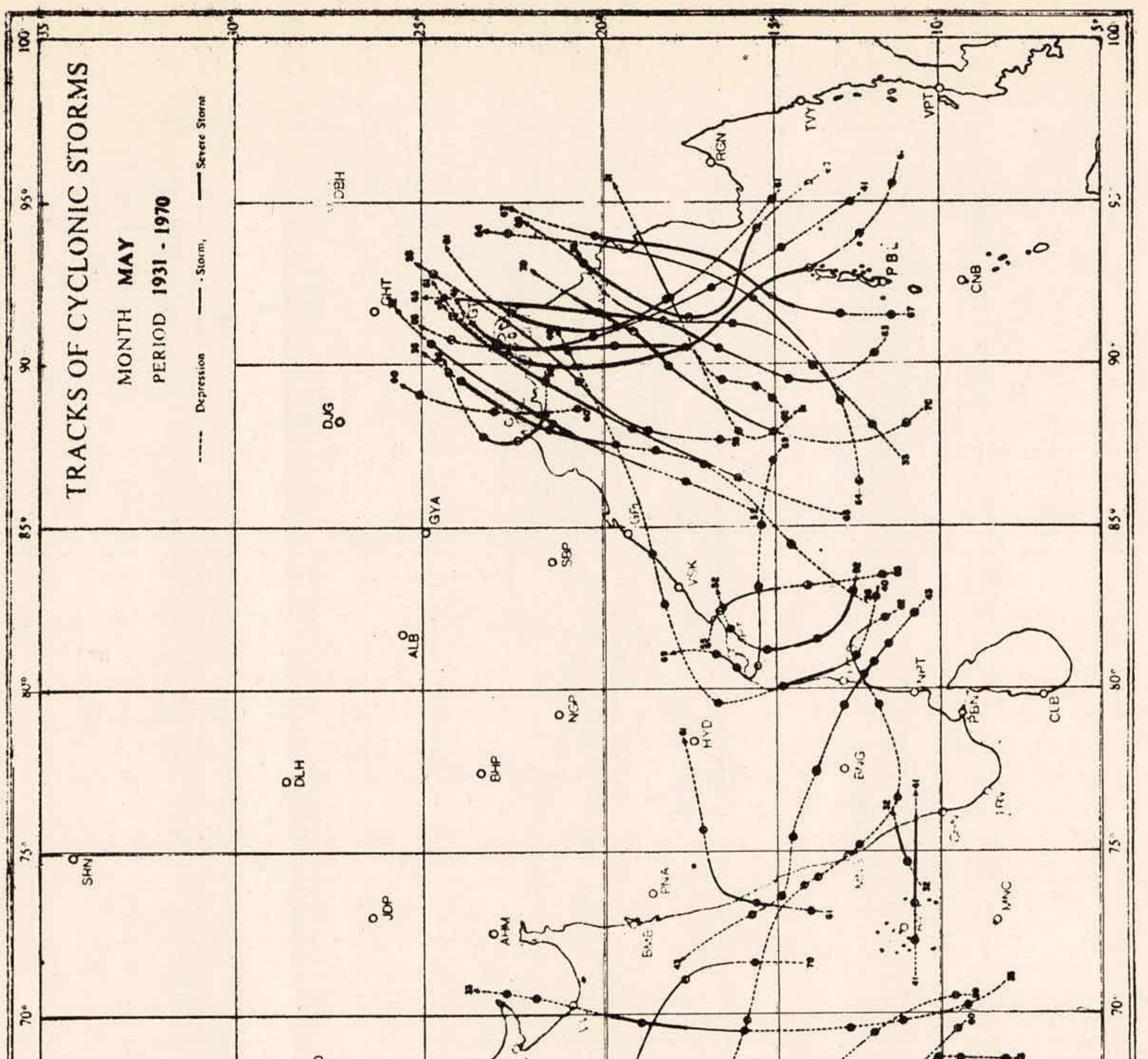
TRACKS OF CYCLONIC STORMS
MONTH MAY
PERIOD 1931 - 1970
Depression
Storm
Severe Storm
DBH
CHT
DJG
GYA
SBP
ALB
NGP
BHP
DLH
SHN
JOP
AHM
JCD
HYD
PNA
BMB
VSK
RGN
TVY
VPT
PBL
CNB
MPT
PBN
CLB
MNC
35°
30°
25°
20°
15°
10°
5°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°

Fig.3(a)

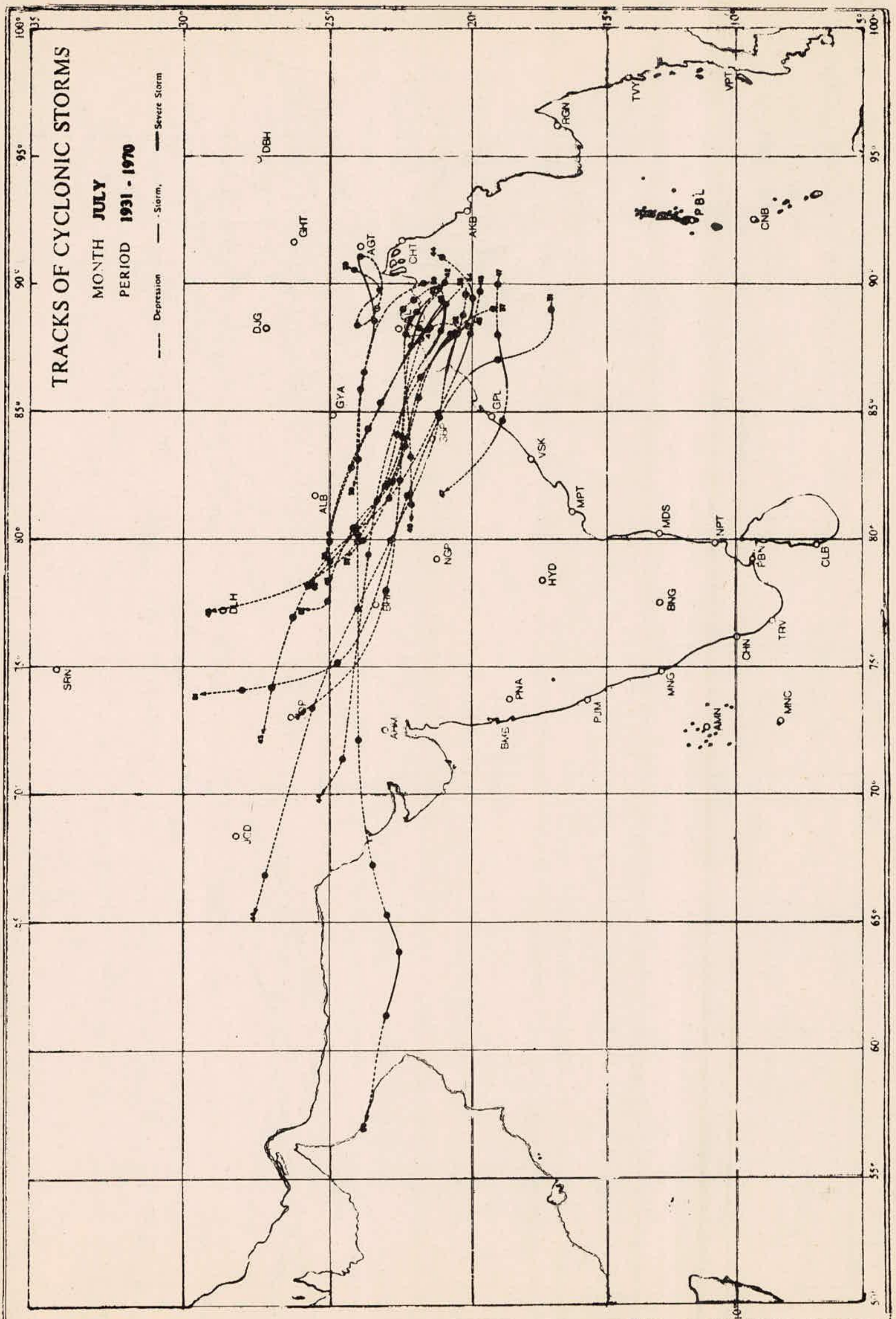
TRACKS OF CYCLONIC STORMS
MONTH JULY
PERIOD 1931 - 1970
Depression
Storm
Severe Storm
SRN
DLH
JCD
DJG
DBH
GHT
AGT
CHT
AKB
GYA
ALB
GPL
VSK
MPT
NGP
HYD
MDS
NPT
BNG
FBN
CLB
TRV
CHN
MNG
PJM
PNA
BMB
AHM
AMN
MNC
PBL
CNB
RGN
TVY
VPT
BPL
JSP
10
5°
10°
15°
20°
25°
30°
35°
50°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°

Fig.3(b)

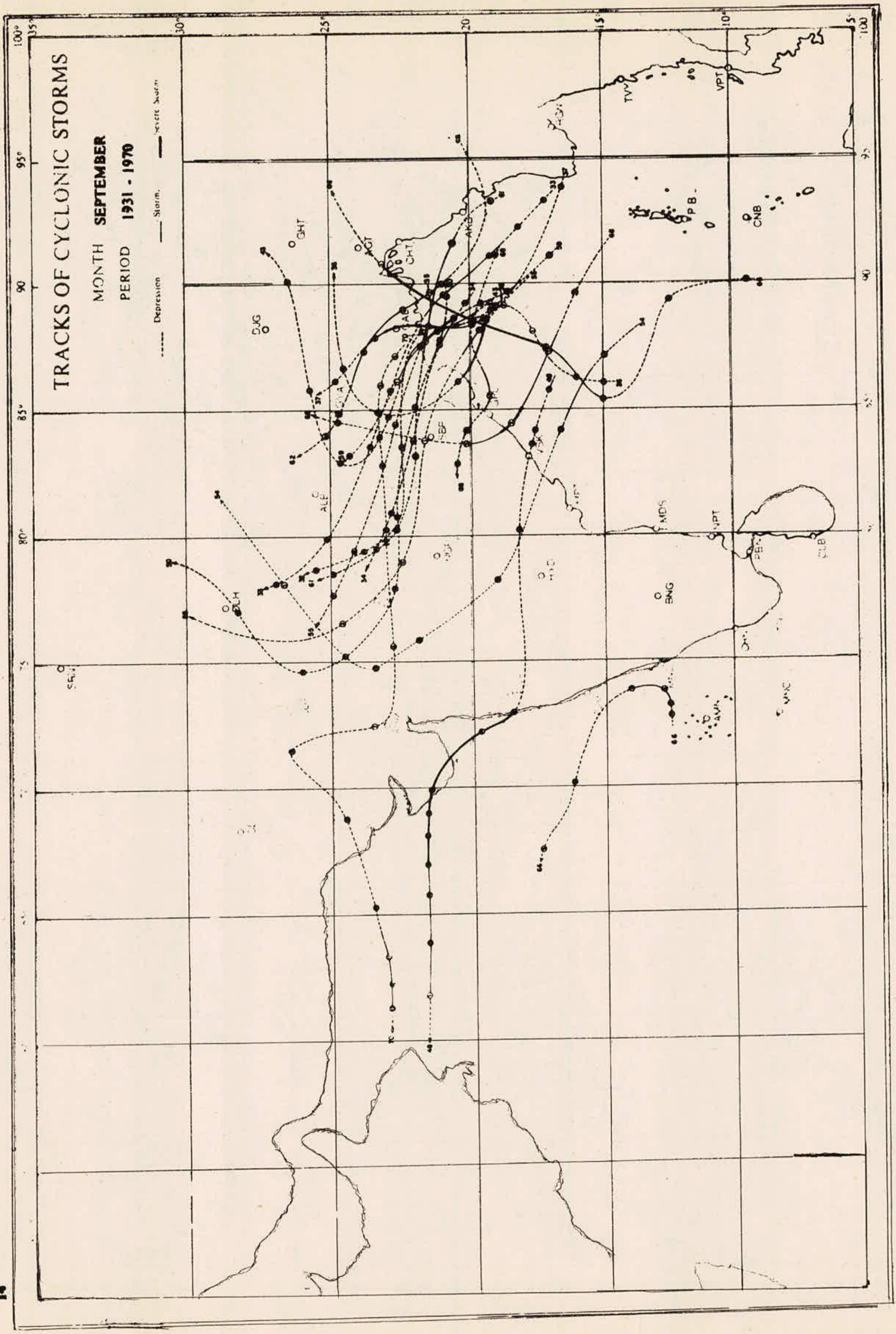
TRACKS OF CYCLONIC STORMS
MONTH SEPTEMBER
PERIOD 1931 - 1970
Depression
Storm
Severe Storm
100°
95°
90°
85°
80°
75°
35°
30°
25°
20°
15°
10°
5°
DLH
SKN
ALB
DJG
GHT
AGT
CHT
AKB
NGP
VSK
MPT
MDS
BNG
HYD
NPT
PBN
CLB
TVY
VPT
PB
CNB

Fig.3(c)

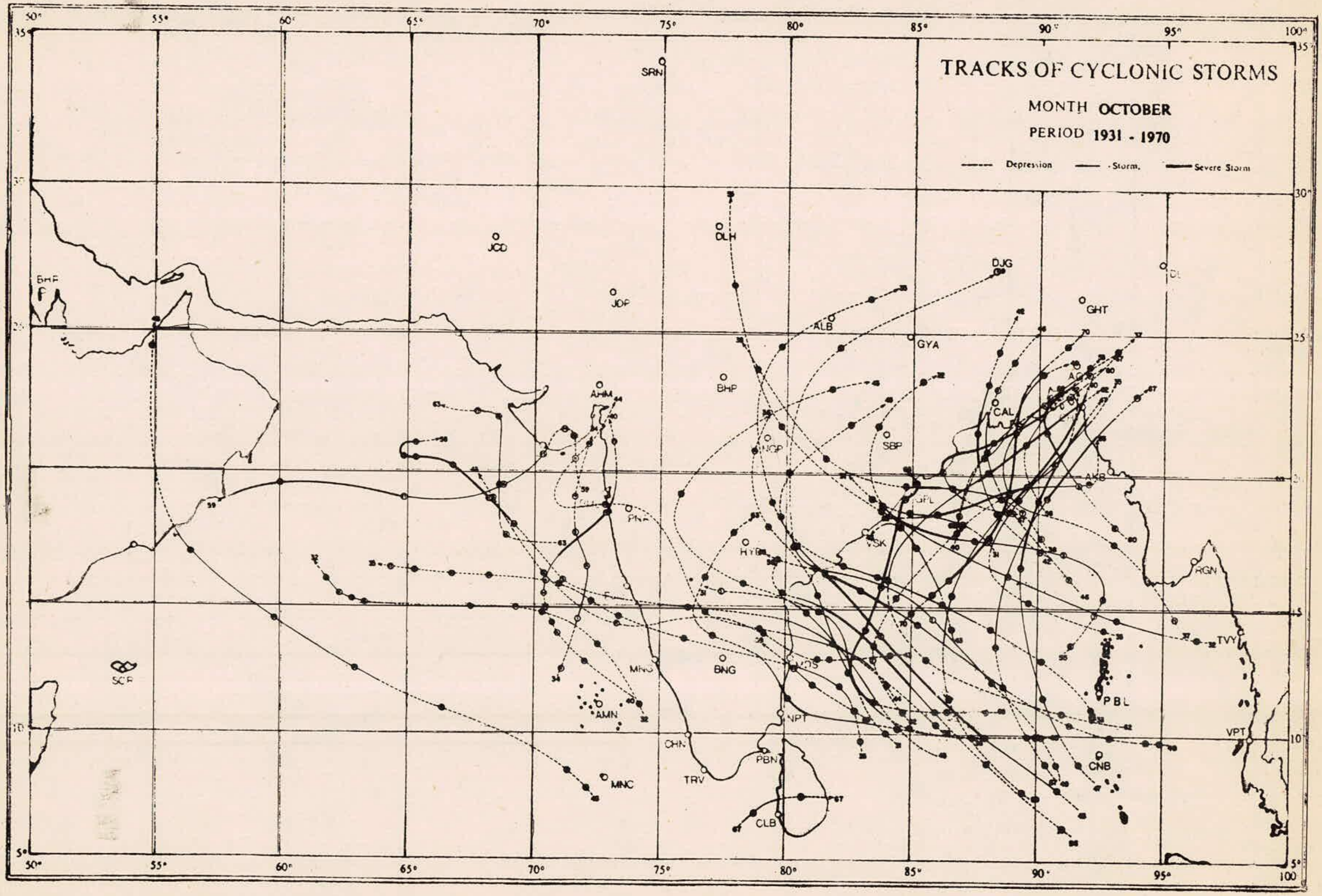
TRACKS OF CYCLONIC STORMS
MONTH OCTOBER
PERIOD 1931 - 1970
Depression
Storm.
Severe Storm
50°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°
35°
30°
25°
20°
15°
10°
5°
SRN
DLH
JCD
JOF
DJG
GHT
ALB
GYA
BHP
AHM
CAL
SBP
NGP
AKB
GPL
VSK
PNA
HYB
RGN
TVY
MNG
BNG
MDS
PBL
NPT
VPT
CHN
CNB
PBN
TRV
MNC
CLB
AMN
SCF
BHF

Fig.3(d)

it is not generally possible to forecast the storm location by mere physical and synoptic considerations alone Objective method of predicting a future storm position with its known initial position and taking into consideration the past cases and persistence of movement of the present storm or by identifying analogues have also been developed. These methods have, however, been not able to improve upon the conventional synoptic methods.

Because of the variability associated with the track of the storms, the speed of storms moving across the land and the intensity of the storm system itself, the rainfall resulting from these storms also exhibits variability not only of distribution in time and space but also in the number of rain spells at a station and the duration between the spells (bands). When the time scale considered becomes smaller and the space scale larger, the variability assumes greater prominence.

In the present study, the moving storm is modelled by inter-station correlation of hourly rainfall at self-recording raingauge stations in Narmada basin. By shifting the hourly rainfall data at the downstream stations in comparison to the upstream stations, the time lag in precipitation occurrence at two stations,in other words, the time taken by the storm to travel from one station to another is estimated.

3.1 Description of the Study Area

The river Narmada rises in the Amarkantak plateau of the Maikal range in Madhya Pradesh at an elevation of 1057 m a.s.l. The river travels a distance of 1312 km before it enters the Arabian Sea. The total area of the basin upto Bharuch in Gujarat is 98,796 sq.km.

85% of this area is in Madhya Pradesh, 11.5% in Gujarat and rest in Maharashtra.

The climate of the basin ranges from sub-humid in the east to semi-arid in the west with pockets of humid and per-humid climates in the higher hill reaches. The Southwest monsoon season from June-September is the principal rainy season contributing nearly 90% of the annual rainfall. During this period a series of tropical storms originating from Bay of Bengal move west northwestwards over or along the basin. Figure 4a to 4d show the frequency of storms and depressions over the Narmada basin in a $2\frac{1}{2}^{\circ} \times 2\frac{1}{2}^{\circ}$ grid covering the region from 20° to 25°N and $72^{\circ}30'$ to $82^{\circ}30'$ E during the period from 1891 -1970. As may be seen from the figures, the storms and depressions are more frequent and intense during August and September.

There are about 150 non-recording and 50 recording raingauge stations in and around Narmada basin. Most of the self recording raingauge stations are maintained by the India Meteorological Department many of which have started after 1970. Besides, some self recording raingauges are also known to be under the operation of the state irrigation departments of Madhya Pradesh and Gujarat. A list of all such raingauges whose details are known is given in Table 1. The locations of some of these gauges are shown in the index map of the Narmada basin given in the figure 5.

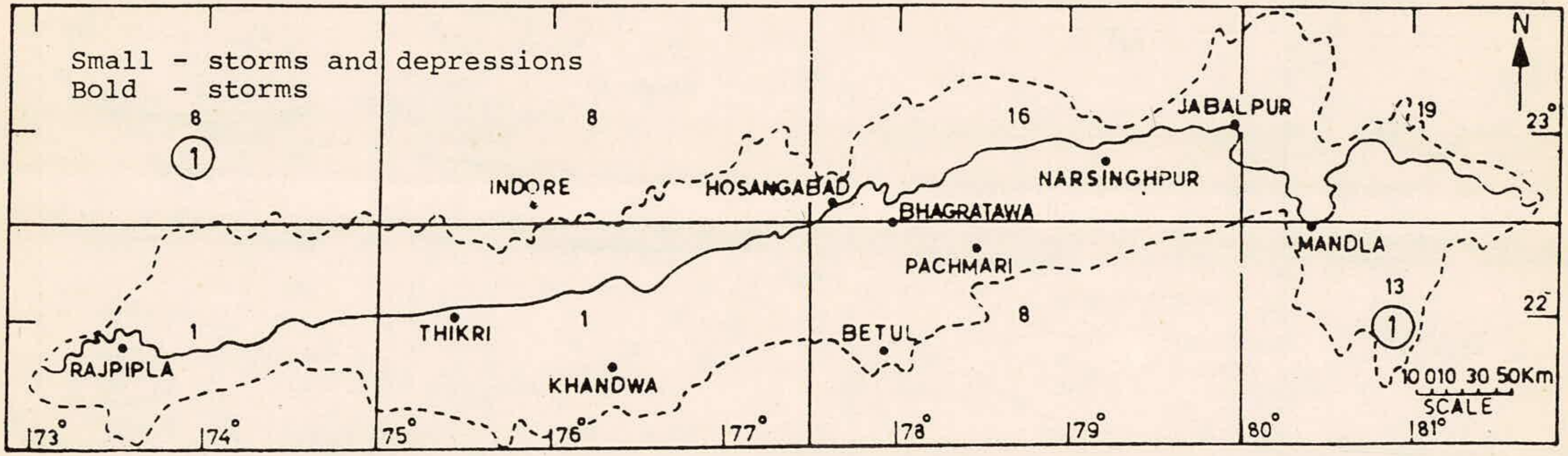

FIGURE 4 (a) - FREQUENCY OF STORMS AND DEPRESSIONS - JUNE

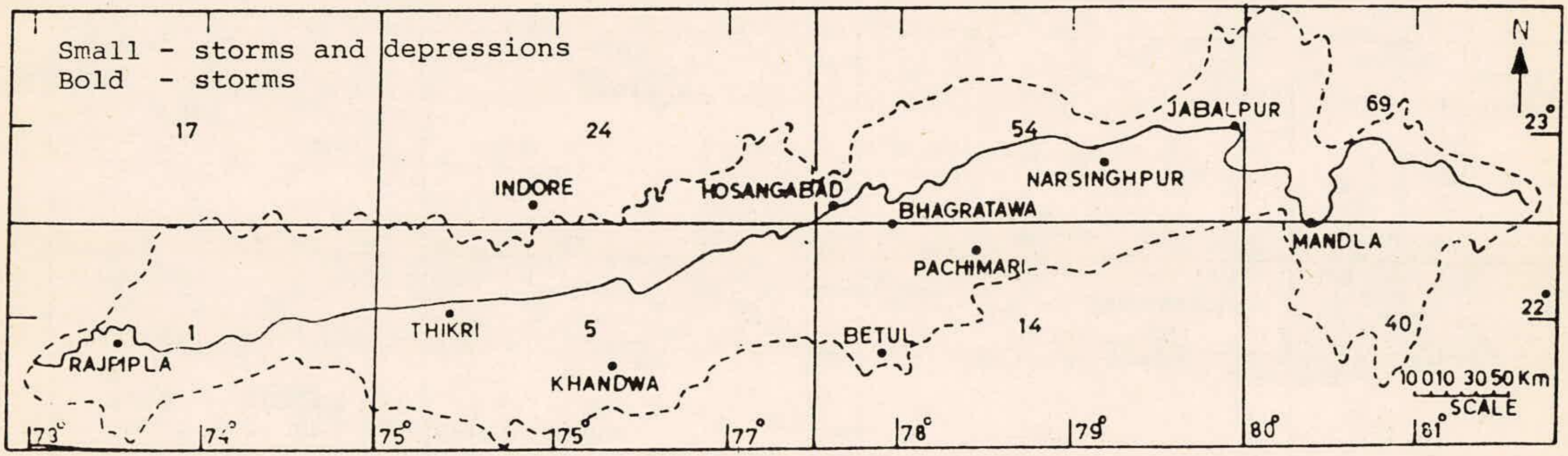

FIGURE 4 (b) - FREQUENCY OF STORMS AND DEPRESSIONS - JULY

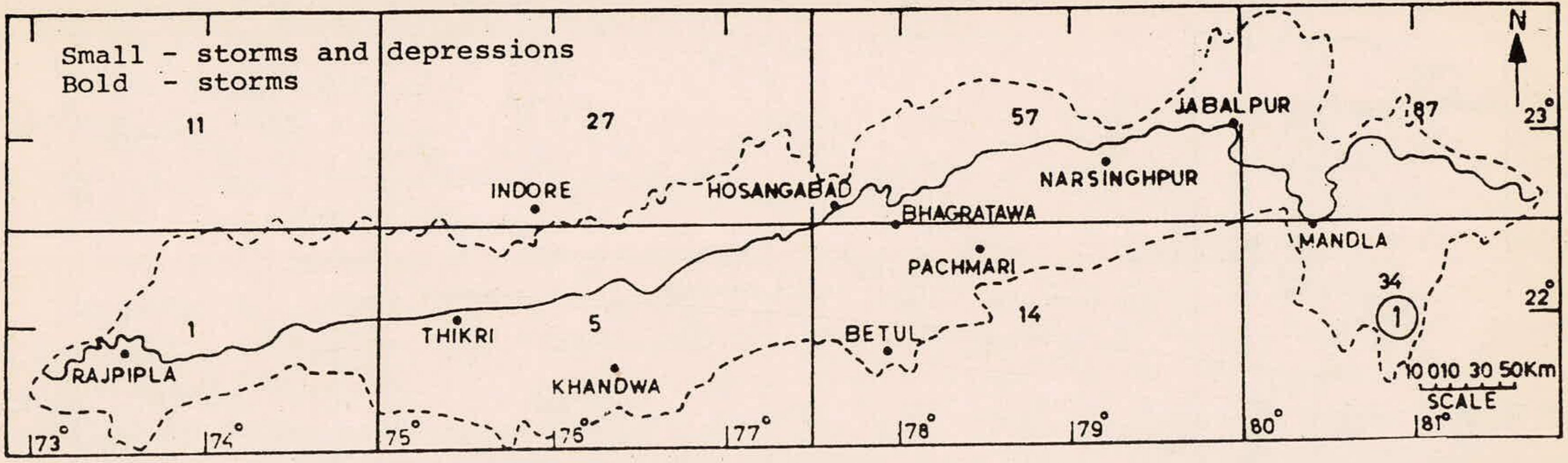

FIGURE 4(c)- FREQUENCY OF STORMS AND DEPRESSIONS - AUGUST

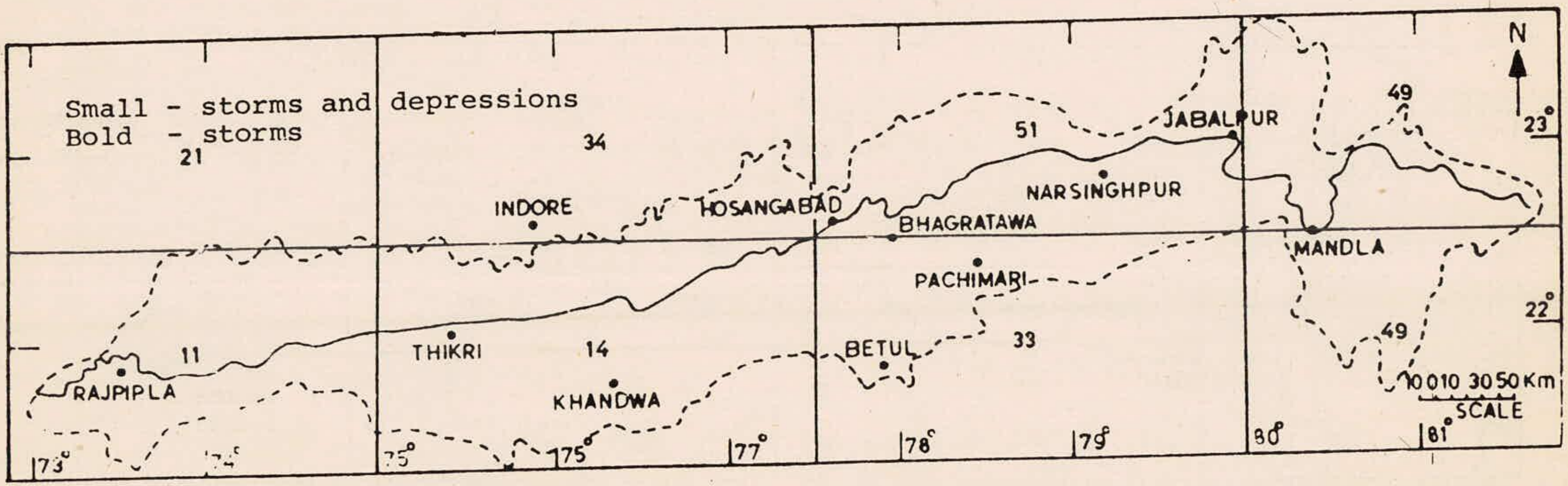

FIGURE 4(d)- FREQUENCY OF STORMS AND DEPRESSIONS- SEPTEMBER

TABLE 1: List of Self recording raingauge stations in and around Narmada basin.

State	District	S.R.R.G.	Date of Starting
Madhya Pradesh	Rajnandgaon	Kawardha	
	Bilaspur	Pendra Road	1968
	Champa	Champa	12.8.68
	Mandla	Mandla	13.12.67
	Shahdol	Umaria	16.8.68
	Balaghat	Malanjkhand	21.7.78
	Jabalpur	Jabalpur	25.8.51
		Jamtara	19.6.75
	Seoni	Lakhandon	26.4.77
		Seoni	11.9.74
	Jabalpur	Sihora	
	Damoh	Damoh	1970
	Narasimhapur	Narsimhapur	25.9.69
		Gadarwara	4.8.79
		Mohapani	
		Bermanghat	17.6.75
		Bamhori	
	Chindwara	Harai	13.6.78
		Chindwara	1.8.68
	Hoshangabad	Hoshangabad	30.7.75
		Bagratawa	1.8.70
		Tawa Dam	16.4.77
		Pachmarhi	19.10.67
		Chhidgaon	
	Bhopal	Bairgarh	2.4.52
	Raisen	Barna Dam	1.12.77
		Silvani	20.7.70
	Betul	Betul	8.12.67
		Sarni Dam	13.4.77
	Nimar	Khandwa	22.7.68
		Burhanpur	23.4.70
		Punasa	1.6.50
		Mandhata	
		Mortakka	12.6.75
	Dewas	Kannode	14.7.70
	Indore	Indore	1963
	Khargone	Mandleshwar	14.6.48
		Thikri	14.6.48
		Barwani	8.6.75
	Ujjain	Ujjain	1.2.72
	Jhabua	Alirajpur	
Gujarat	Broach	Rajpipla	23.6.78
		Kewadia Colony	1966
Maharashtra	Amrawati	Dharni	25.11.77
	Jalgaon	Jalgaon	1976
	Dhule	Dhadgaon	

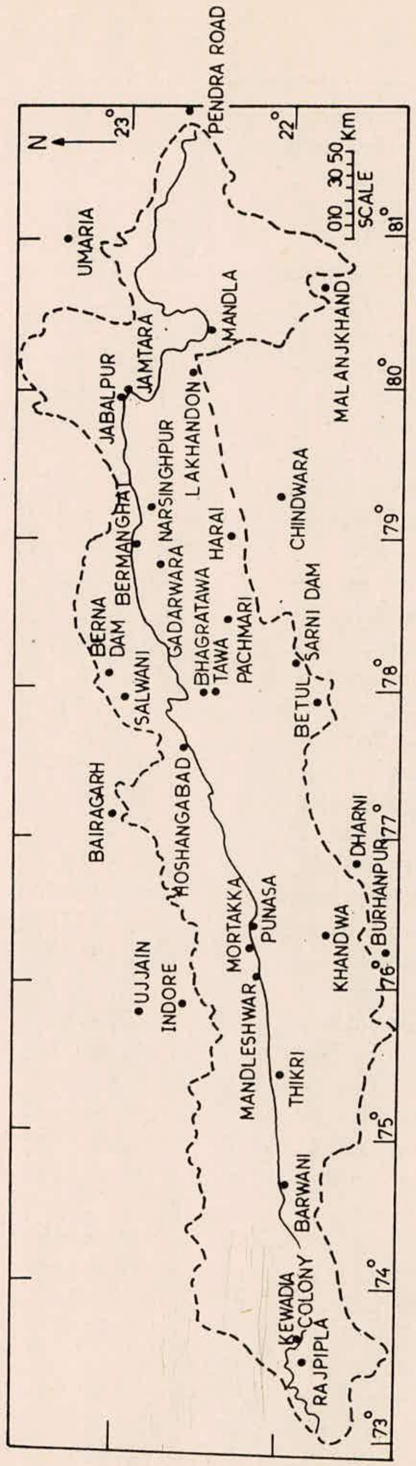

Fig.5 Index Map of Narmada Basin

4.0 METHODOLOGY

In the proposed methodology, the moving storm is modelled based on the correlation between stations and assuming non-stationarity in time and stationarity in space. The inter-station distance between neighbouring stations being large (the average distance being 100 km) in size as compared to the size of the rain cell (with diameter of 5 to 10 km) correlation function as related to inter-station distance at lag zero was found not suitable and as such, the movement of storm across the river basin is modelled by correlation analysis with time lag introduced.

The cross correlation between gauges i and j is a function of the lag and the relative distance between the gauges i and j:

$$r_{ij} = \frac{\mathrm{Cov}(X_{i,t} ; X_{j,\, t+r})}{\sigma(x_i)\ \sigma(x_j)} \qquad \ldots(1)$$

where, $X_{i,t}$ is rainfall at gauge i at time t,

$X_{j,\, t+r}$ is rainfall at gauge j at time t+r,

r is the lag or shift in hours,

and $\sigma(x)$ and $\sigma(x_j)$ are the standard deviations at gauges i and j respectively.

A computer programme which computes correlation coefficient between pairs of stations lagging data at the later station in successive increments has been used for this purpose.

4.1 Analysis by shifting

Preliminary scrutiny of the rainfall data is carried out by visual observation of the rainfall hyetographs at each of the SRRG station to identify the rainstorm duration. The scrutiny would also reveal the storm movement as indicated by the lag of the storm duration from one station to another.

Subsequent to the scrutiny, the hourly rainfall data are input to the computer program by introducing the appropriate lag noticed during the scrutiny. As indicated earlier, the program further lags the hourly rainfall at the later station by one time increment (1 hour in this case) upto a prespecified maximum lag.

5.0 DATA

The Narmada basin had experienced very high floods in the years 1970 and 1973 at Garudeshwar and Mortakka respectively. The data availability of self recording raingauges in these years, however, is very limited, about 12 to 15 stations' data in these years. Availability of hourly rainfall data has improved after 1977 with the installation of SR raingauges at more locations in Narmada basin. Moderate to high floods had occurred in 1978 and 1979 in Narmada. For the purpose of the present analysis one storm each associated with the 1970, 1973, 1978 and 1979 floods have been considered. Their storm tracks are shown in figure 6. A brief description of each of the storms and the details of the SRRG stations whose data has been considered in the analysis is given below.

5.1 Storm of 2-6 Sept.1970

A land depression which originated in West Bengal on 2nd has intensified into a deep depression by 3rd morning and was lying near Ranchi. It moved practically westwards across Madhya Pradesh and lay about 50 km. southwest of Jabalpur on 5th morning and was centred 50 km.west of Indore on 6th morning. Under its influence, wide-spread rain with isolated heavy falls occurred on 3rd and 4th and heavy to very heavy rain on 5th and 6th over west Madhya Pradesh.

Hourly rainfall data of 13 hourly rainfall stations was considered for the purpose of analysis of the above storm. They are, in the order from east to west- Pendra Road Mandla, Jabalpur, Chindwara, Pachhmarhi, Bagra Tawa, Betul, Bairagarh, Punasa, Khandwa, Indore,

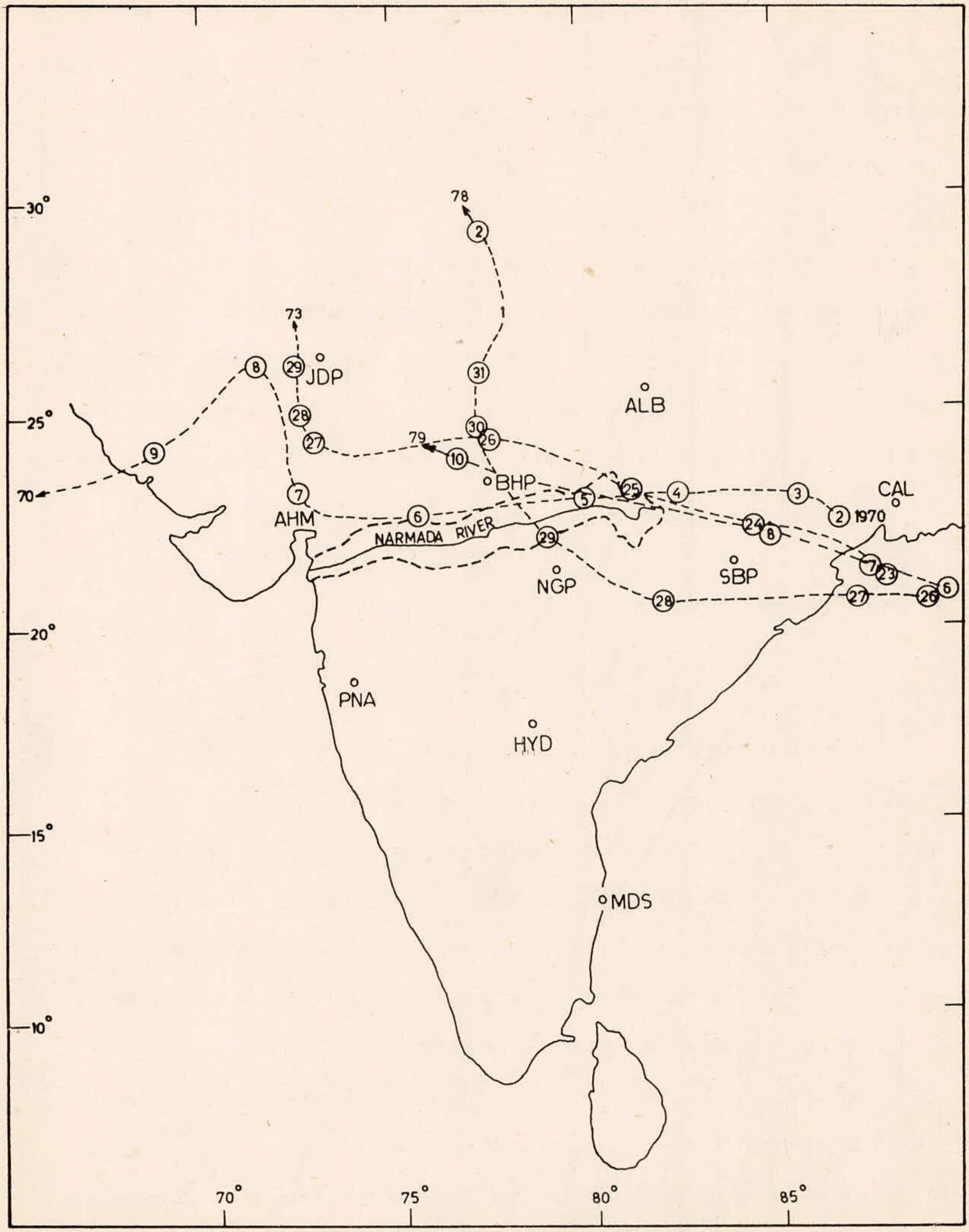

FIG.6- STORM TRACKS OF THE STORMS UNDER STUDY

Thikri and Kewadia Colony. Their locations are shown in index map.

5.2 Storm of 28-31 August, 1973

Under the influence of a low pressure wave from the Tropical depression ' Joan' over Thailand a low pressure area formed in the head Bay on 24th . It concentrated into a depression on 26th. Before crossing the coast it intensified into a deep depression and moved west north westwards and reached Pendra by 28th evening as a deep depression. On 29th, it was situated 50 km. to the northwest of Jabalpur. Probably, due to feeding from Arabian Sea it intensified into a deep depression and moved towards Guna on 30th. It moved further westwards to Rajasthan, on 31st August.

Hourly rainfall data of 12 self recording raingauge stations was considered for analysis of the August 1973 storm. They are from east to west- Pendra Road, Mandla, Umaria, Jabalpur, Pachmarhi, Betul, Bairagarh, Punasa, Khandwa, Thikri, Indore and Ujjain.

5.3 Storm of 28-31 August, 1978

A low pressure area formed over north Bay on 25th and concentrated into a deep depression by 26th morning. It intensified into a cyclonic storm by mid night of 26th and crossed the Orissa coast by the noon of 27th and was lying as a deep depression over Orissa. Subsequently it moved west northwest across Madhya Pradesh and weakened into a depression on 30th morning over northwest Madhya Pradesh. Later it recurved northeastwards.

Hourly rainfall data at 27 S.R.R.G.stations was available for the above storm. They are listed in order of east to west below: Pendra Road, Umaria, Malanjkhand, Mandla, Jamtara, Jabalpur, Lakhandon, Narsimhapur, Harai, Bermanghat, Chindwara,

Pachmarhi, Sarni Dam, Tawa Dam, Bagra Tawa, Hoshangabad,

Salwani, Barna Dam, Betul, Khandwa, Dharni, Burhanpur, Indore,

Mortakka, Thikri, Barwani and Rajpipla .

5.4 Severe cyclonic storm of 6-10 August 1979

A low formed over north Bay and adjoining parts of Bangladesh on the morning of 5th August. Under the influence of a low pressure wave, the low over north Bay concentrated into a deep depression on the morning of 6th with its centre at 0300 GMT near $21.0^{\circ}N, 90^{\circ}E$. Moving slowly in a westerly direction, and progressively intensifying, it became a cyclonic storm by the morning of the 7th and a severe cyclonic storm the same afternoon. The severe storm crossed Orissa coast early that night near Balasore. Later moving west north-west across east Madhya Pradesh as a deep depression and west Madhya Pradesh as a depression the system weakened into a well marked low over south-west Rajasthan by the evening of 10th.

Though a number of SRRG stations were in operation in 1979, the availability of data at the time of analysis was rather poor. SRRG data of sixteen stations had been used in the analysis. They are given in the order from east to west as below:

Mandla, Malanjkhand, Umaria, Jabalpur, Jamtara, Narasimhapur,

Harai, Chindwara, Bermanghat, Gadarwara, Barna Dam,

Bagra Tawa, Tawa, Bairagarh, Mandleshwar and Indore.

6.0 APPLICATION

The interstation correlation of pair wise hourly rainfall at the SRRG stations for the different storms has been determined using the inter-station correlation programme described in section 4.0. Before using the data as input to the programme preliminary scrutiny of the data has been carried out by preparing the hourly rainfall hyetograph of the hourly rainfall recorded at each of the recording raingauge stations during the storm period concerned. This scrutiny has helped in identifying the time lag or shift in rainfall occurrence from station to station in the Narmada basin. The preliminary inferences from the scrutiny are described for each of the storm considered.

2-6 Sept.1970 Storm

Initial scrutiny of hourly rainfall data and the rainfall hyetograph in Fig.7 has indicated the following pattern of time lag in rainfall occurrence at the stations in the down track with reference to the station Pendra Road in up track.

S.N.	Station(s)	Lag in Hrs.	Storm Period(48hrs) considered
1.	Pendra Road	0	13 hrs of 3rd-12 hrs of 5th Sept.
2.	Mandla,Jabalpur, Chindwara, Pachmarhi	6	19 hrs of 3rd-18 hrs of 5th Sept.
3.	Bagra Tawa, Betul, Bairgarh	12	1 hr. of 4th-24hrs of 5th Sept.
4.	Khandwa, Punasa, Indore, Thikri	24	13 hrs of 4th-12 hrs of 6th Sept.
5.	Kewadia Colony	36	1hr.of 5th-24 hrs of 6th Sept.

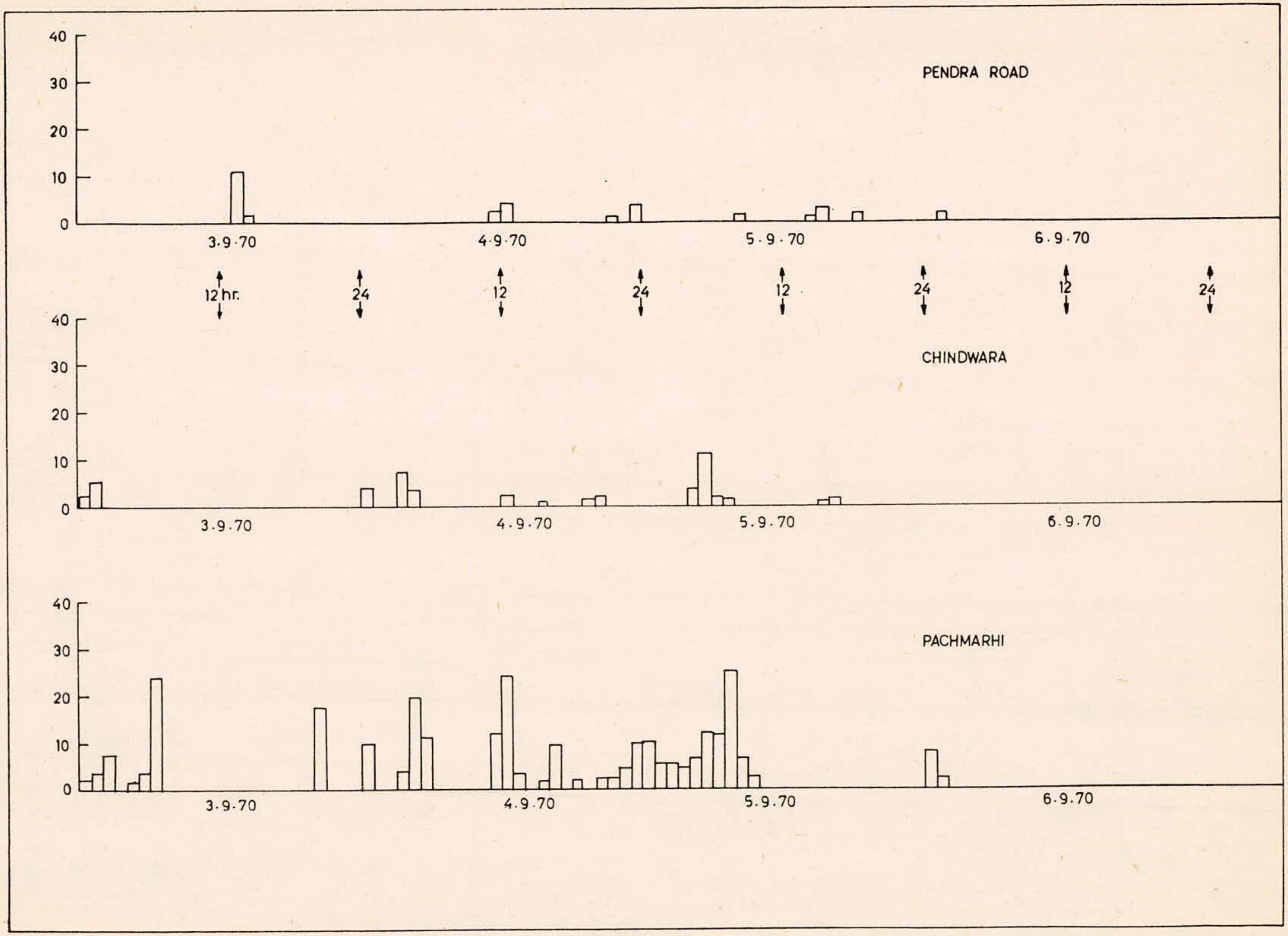

Fig.7(a) Storm Hyetograph- September 1970

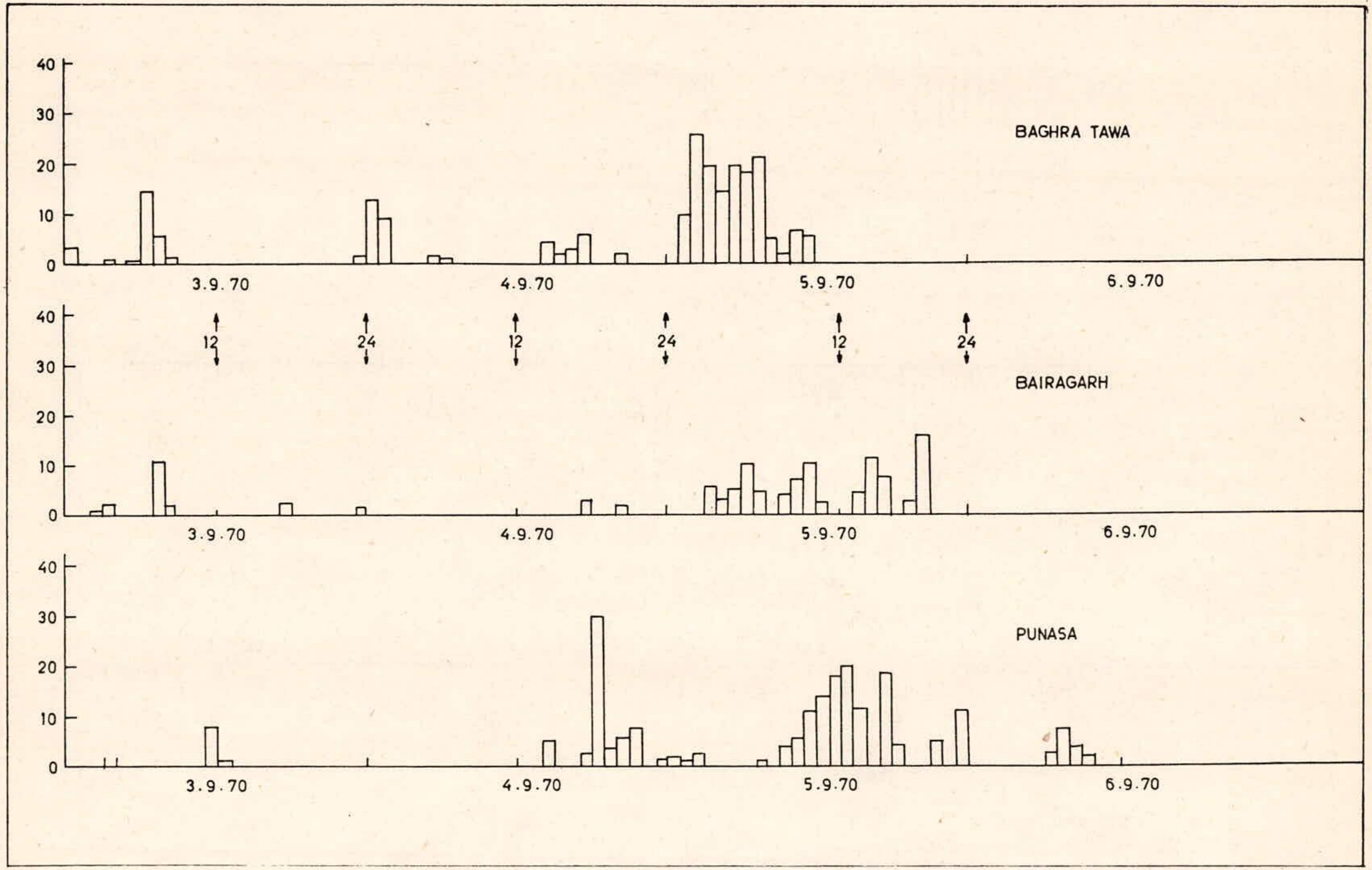

Fig.7(b) Storm Hyetograph - September 1970

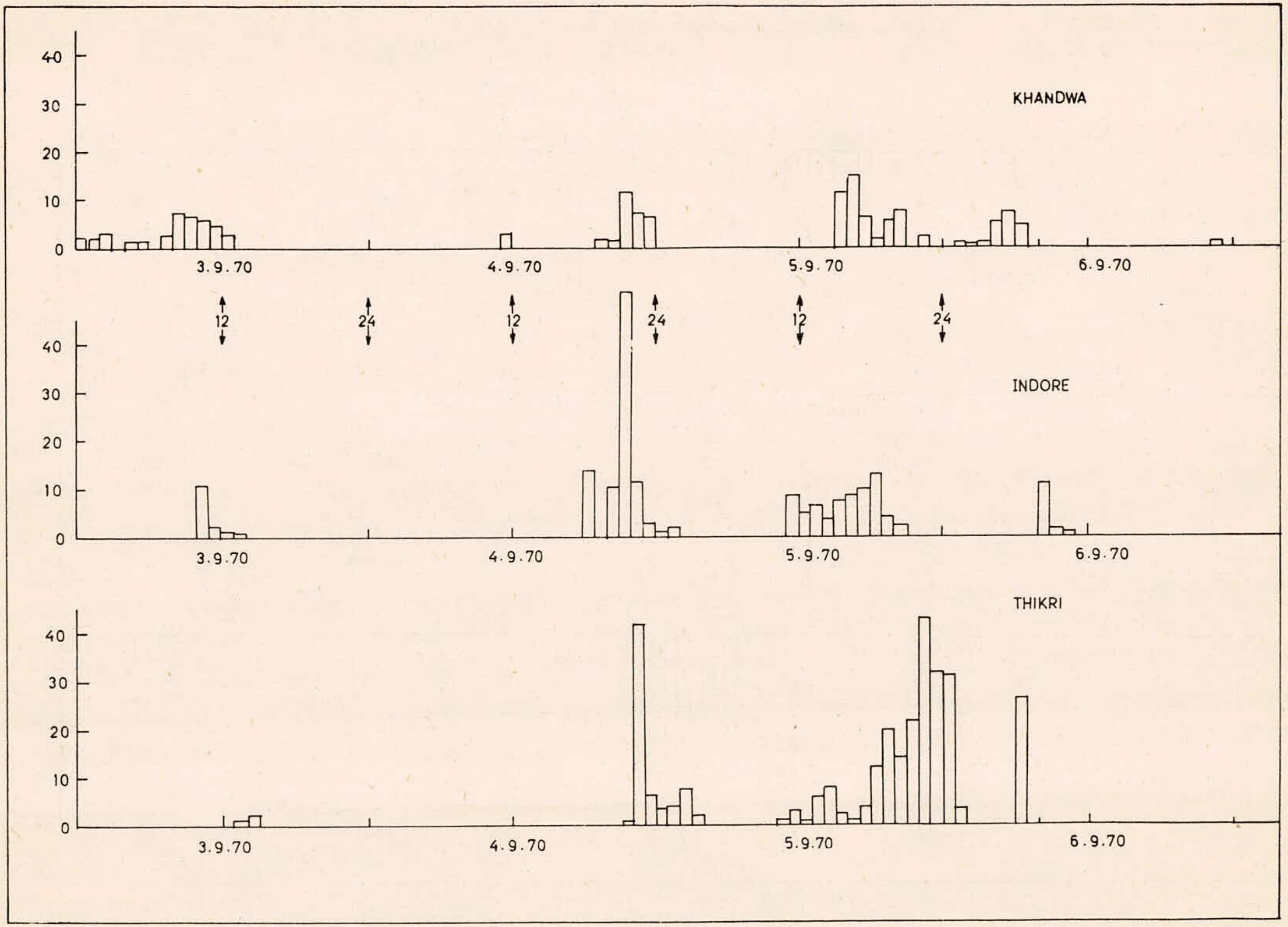

Fig.7(c) Storm Hyetograph - September 1970

28-31 August 1973 Storm:

Preliminary scrutiny of hourly rainfall data and hyetograph has indicated a lag pattern as indicated below:

S.No.	Station(s)	Lag in hrs.	Storm Period(48 hrs) considered
1.	Pendra Road	0	1 hr.of 28-24 hrs.of 29 Aug.
2.	Umaria, Mandla, Jabalpur, Pachmarhi	6	7hrs.of 28-6 hrs of 30 Aug.
3.	Betul, Bairgarh	12	13 hrs of 28-12 hrs of 30 Aug.
4.	Punasa, Khandwa, Thikri, Indore, Ujjain	24	1 hr of 29-24 hrs.of 30 Aug.

28-31 August 1978 Storm:

On initial examination of the hourly rainfall data and the hyetograph lag as indicated below has been noticed from group of stations to group.

Stations	Lag.in hrs.	Storm period (48 hrs) considered
Pendra Road, Umaria, Malanjkhand, Mandla, Jabalpur, Jamtara, Lakhandon, Narsimhapur, Harai and Bermanghat.	0 hrs.	1 hr of 28-24 hrs of 29 Aug.
Chindwara, Panchmarhi, Sarni Dam Tawa Dam, Bagra Tawa, Hoshangabad, Salwani, Barna Dam, Betul, Khandwa and Dharni.	12 hrs.	13 hrs of 28-12 hrs of 30 Aug.
Burhanpur, Mortakka, Indore Thikri, Barwani and Rajpipla.	18 hrs.	19 hrs of 28-18 hrs.of 30 Aug.

6-10 August 1979 Storm:

The preliminary scrutiny of hourly rainfall and hyetograph has indicated the following lag pattern with respect to Mandla and its neighbours.

S.N.	Station(s)	Lag in Hrs. considered.	Storm Period(48 hrs)
1.	Mandla, Malanjkhand, Umaria	0 hrs	1 hr of 8-24 hrs.of 9Aug.
2.	Jabalpur, Jamtara Narasimhapur	4 hrs	5 hrs of 8- 4 hrs of 10th Aug.
3.	Harai, Chindwara, Bermanghat, Gadarwara, Barna Dam, Bagra Tawa, Tawa	8 hrs	9 hrs of 8- 8 hrs of 10 Aug.
4.	Bairagarh, Mandleshwar, Indore	24 hrs	1 hr of 9-24 hrs of 10 Aug.

6.1 Inter-station Correlation with lag:

For the storm period (48 hrs) shown against each station, inter-station correlation analysis were carried out using a maximum lag of 18 hrs for each of the four storms.

In table 2, the inter-station distance between pair-wise combination of self recording raingauges is given.

To study the behaviour of rainfall distribution in space the inter-station correlation at lag zero has been studied in relation to the distance between neighbouring stations in case of each of the storms. A plot of inter-station correlation versus inter-station distance has been made for each of the storms considered.

Sept.1970 storm

The highest lag zero correlation obtained at any pair of neighbouring gauges is 0.50 indicating that the network is not close enough anywhere to be covered under a single rain cell. The minimum distance between any pair of neighbouring gauges is 55 km., that of Pachmarhi and Bagra Tawa.

The relation between inter station distance and inter station correlation coefficient at lag zero could be seen in Fig.8(a). While a decreasing trend of correlation coefficient with increasing distance

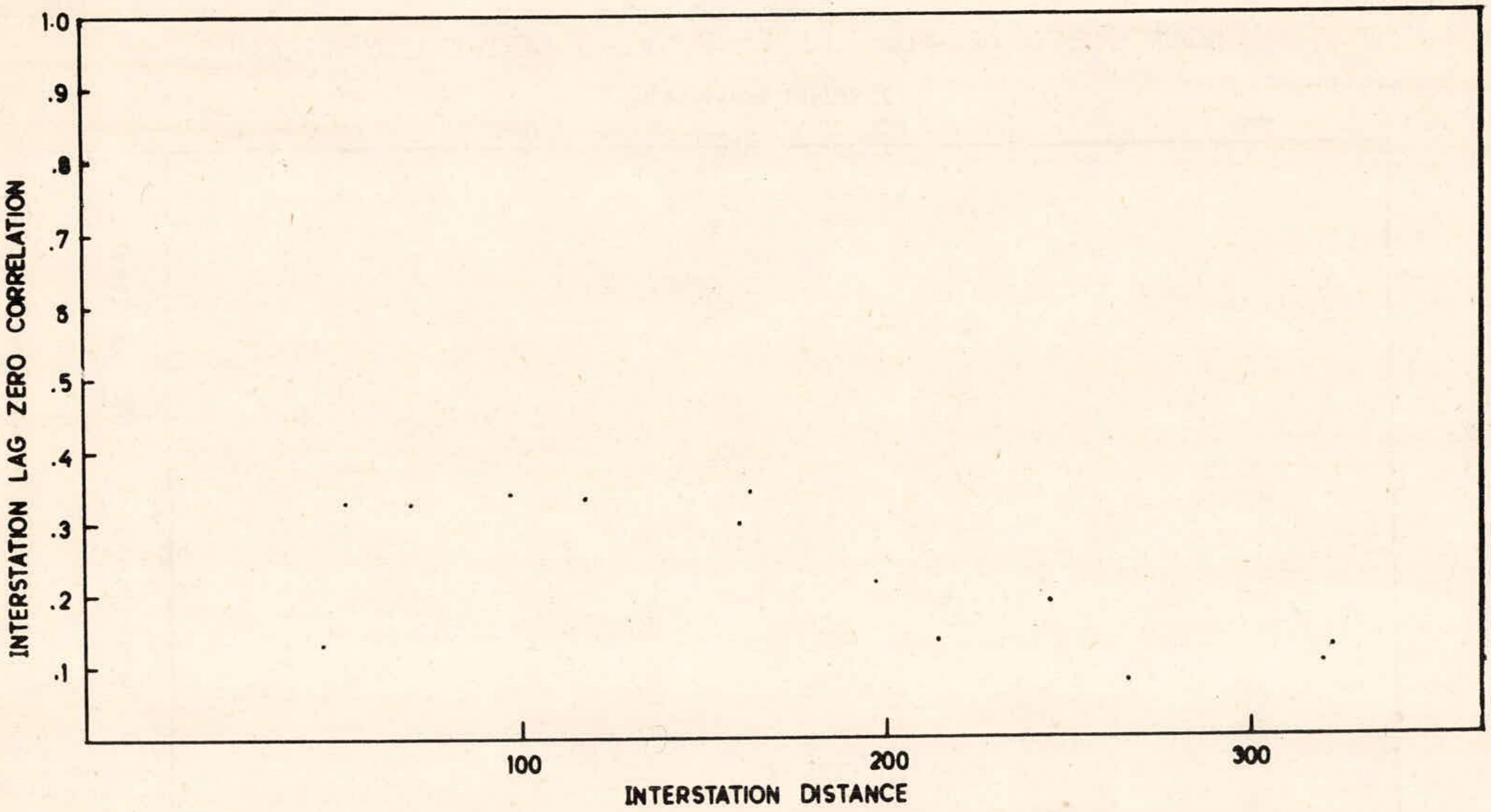

FIG.8(b) INTERSTATION DISTANCE Vs INTERSTATION CORRELATION-SEPT. 1970

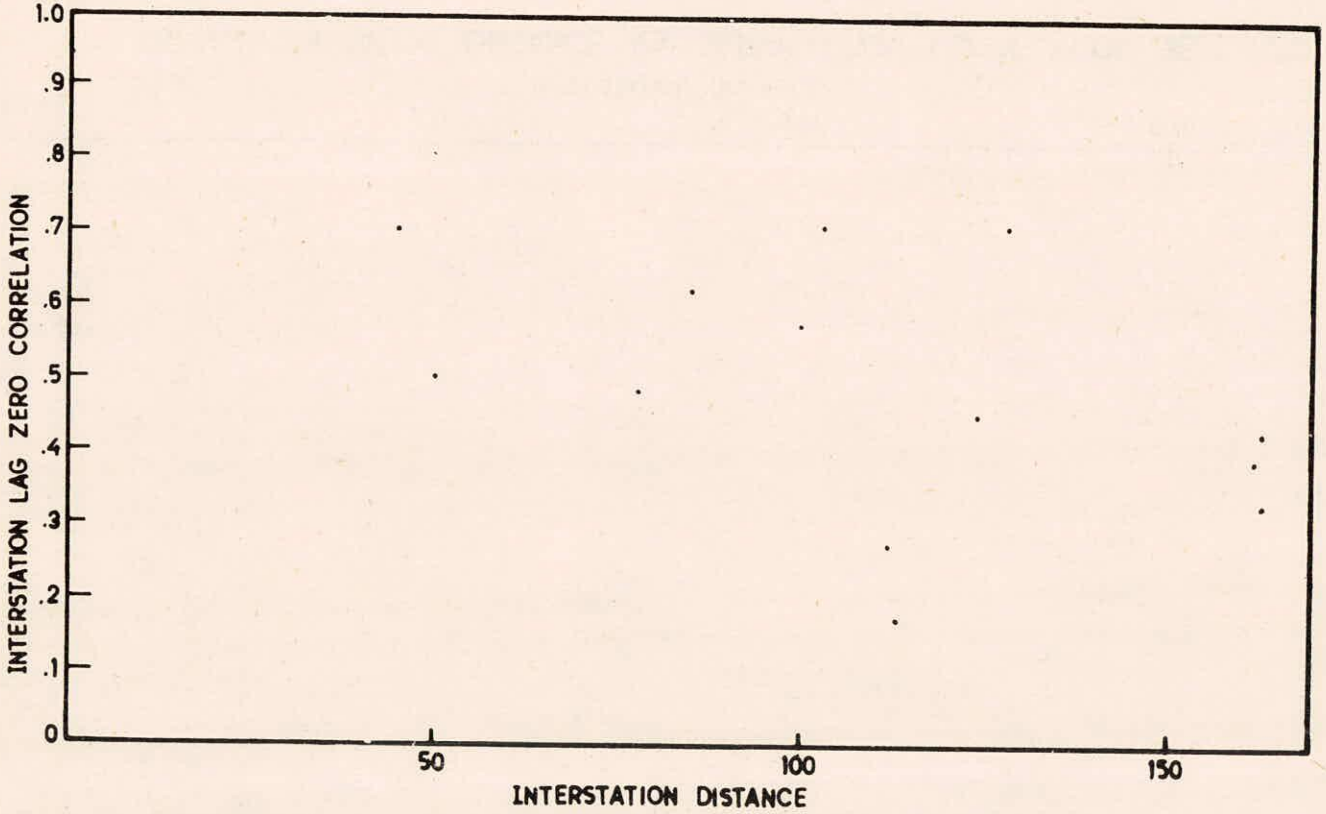

FIG.8(b)-INTERSTATION DISTANCE Vs INTERSTATION CORRELATION
(AUGUST 1973)

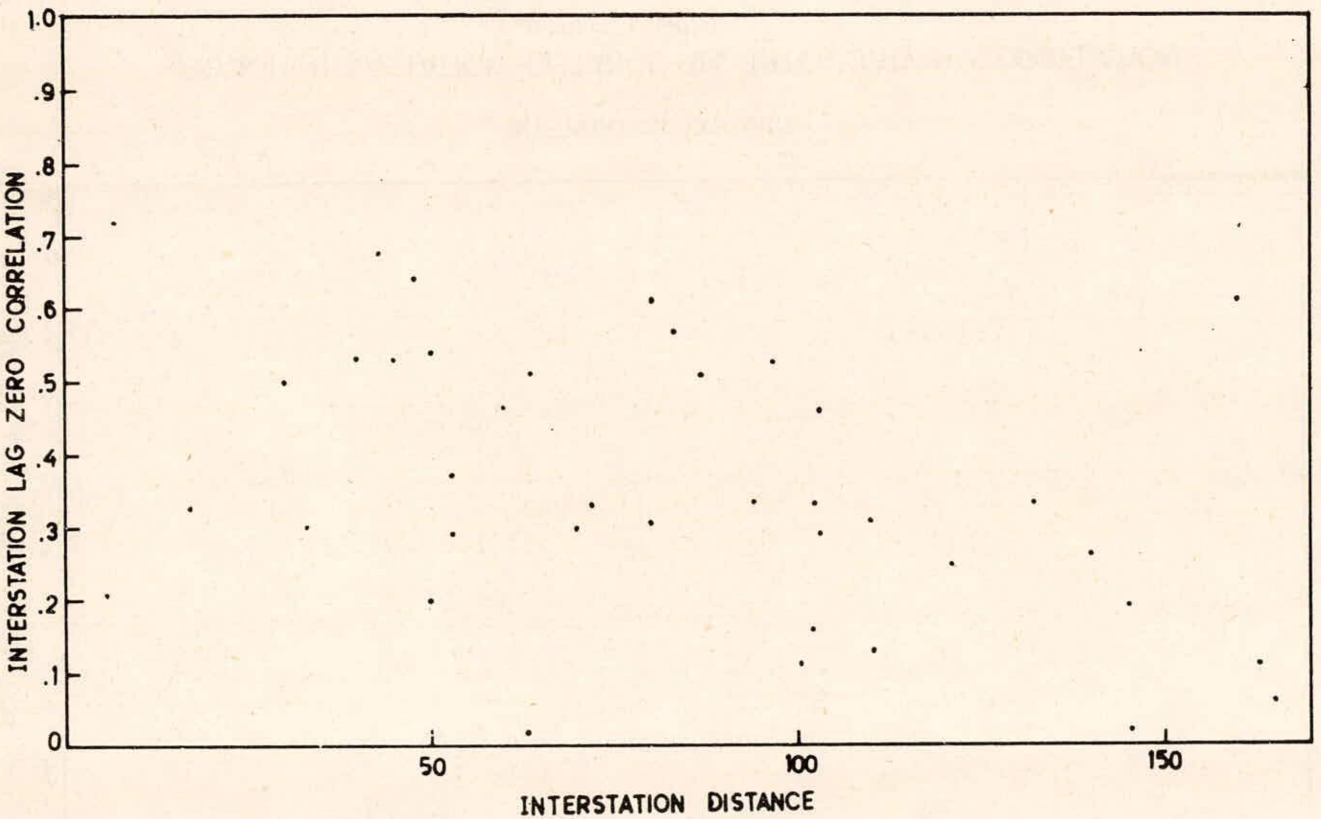

FIG. 8(c) INTERSTATION DISTANCE Vs INTERSTATION CORRELATION
(AUGUST 1978)

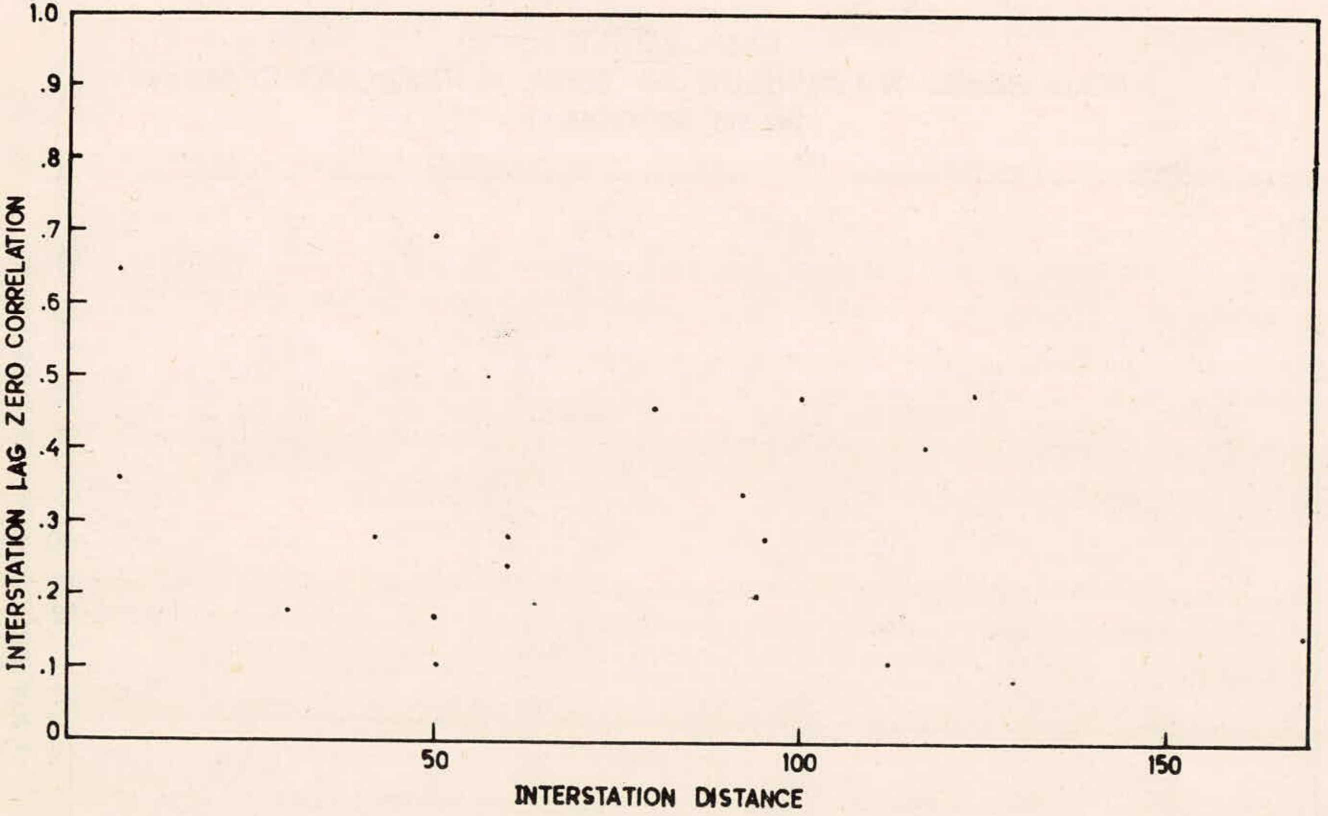

FIG.8(d)-INTERSTATION DISTANCE Vs INTERSTATION CORRELATION
(AUGUST 1979)

is discernible, the randomness at smaller distances is obvious.

August 1973 storm

The highest lag zero correlation obtained at any pair of neighbouring gauges is 0.708 at Punasa- Khandwa and Punasa-Thikri. The network is not adequate in case of this storm also. The inter-station distance versus the inter-station correlation coefficient of lag zero is shown in Fig.8(b) for the August 1973 storm. The plot is quite scattered.

August 1978 storm

The highest lag zero correlation obtained at any pair of neighbouring gauges is .72 between Tawa and Bagra Tawa. Though the network in the 1978 storm is not adequate as per standards, It is certainly a vast improvement over the earlier two storms being nearly double the number. The lag zero inter-station correlation coefficient plotted against the inter-station distance is shown in Fig.8(c). The inter station correlation does not reveal any visible relationship with the inter distancein spite of the better network and large sample of pairwise correlation.

August 1979 storm

The highest lag zero correlation observed is .6970 at Barna Dam and Tawa. The plot of inter-station correlation vs inter-station distance is shown in Fig.8(d). The plot is as random as in case of 1973 and 1978 storms.

		UMARIA	MANDLA	MALANJKHAND	JAMTARA	JABALPUR	LAKHANDON	NARASIMHAPUR	CHINDWARA	HARAI	BERMANGHAT	GADARWARA	PACHMARHI	TAWA	BAGRA TAWA	HOSHANGABAD	SALWANI	BARNA DAM	BETUL	SARNI DAM	BAIRAGARH	PUNASA	KHANDWA	DHARNI	MORTAKKA	MANDLESHWAR	BURHANPUR	INDORE	UJJAIN	THIKRI	BARWANI	KEWADIA COLONY	RAJPIPLA
1	PENDRA ROAD	145	163	160	208	210	243	283	320	280	297	323	360	408	407	434	463	405	427	390	477	572	584	535	606	636	610	623	632	675	728	865	880
2	UMARIA		113	175	102	100	165	180	255	193	188	220	270	312	303	331	245	285	351	310	360	477	497	459	510	543	532	517	519	578	633	763	778
3	MANDLA			80	67	74	80	126	160	117	142	165	198	247	245	274	212	240	265	229	322	410	422	374	444	475	449	464	475	513	567	703	718
4	MALANJKHAND				147	155	135	190	183	170	208	225	240	290	290	320	277	291	288	257	377	443	447	393	478	505	463	504	523	455	597	730	745
5	JAMTARA					7	65	80	155	92	91	122	169	212	210	233	158	190	252	208	270	377	396	357	411	450	435	425	430	484	537	670	685
6	JABALPUR						70	80	160	95	92	121	172	212	210	234	155	191	248	210	271	377	397	359	411	450	435	425	430	484	537	670	685
7	LAKHANDON							57	92	40	74	91	129	167	167	196	143	163	191	153	246	331	344	300	365	400	377	388	400	440	491	625	640
8	NARASIMHAPUR								103	38	17	42	94	133	129	155	83	115	201	135	197	297	317	282	332	368	355	346	353	404	455	590	605
9	CHHINDWARA									68	110	100	70	115	118	148	148	142	110	76	215	261	267	216	295	330	292	330	350	367	415	545	560
10	HARAI										50	60	82	129	128	157	110	128	158	117	210	293	308	265	327	360	340	347	363	400	452	585	600
11	BERMANGHAT											30	90	124	120	143	70	100	173	133	181	288	309	277	321	357	350	333	340	394	445	578	590
12	GADARWARA												62	94	89	113	55	175	145	106	156	257	278	246	290	335	324	314	322	370	422	555	570
13	PACHMARHI													50	52	82	93	75	83	43	147	213	228	188	246	280	262	269	290	317	370	503	515
14	TAWA														7	33	93	50	72	53	103	165	186	157	200	234	230	220	237	272	325	460	475
15	BAGRA TAWA															30	87	45	80	60	98	169	190	164	202	235	234	220	235	273	327	462	477
16	HOSHANGABAD																97	50	94	184	71	146	172	155	178	210	220	190	204	248	300	435	450
17	SALWANI																	48	165	132	115	242	270	250	272	300	318	273	274	340	390	520	535
18	BARNA DAM																		130	103	82	197	225	207	228	253	270	225	230	293	340	476	490
19	BETUL																			40	162	157	158	108	190	220	183	230	260	258	310	440	455
20	SARNI DAM																				155	185	193	149	220	253	222	253	273	292	345	475	490
21	BAIRAGARH																					150	190	196	177	200	245	162	158	238	286	413	425
22	PUNASA																						45	90	35	60	103	78	124	103	155	293	305
23	KHANDWA																							64	52	60	58	112	163	100	152	285	300
24	DHARNI																								113	130	73	169	214	164	212	340	355
25	MORTAKKA																									25	102	60	112	69	120	258	270
26	MANDLESHWAR																										105	60	112	40	95	235	247
27	BURHANPUR																											163	213	121	160	278	290
28	INDORE																												50	85	128	255	270
29	UJJAIN																													128	160	272	285
30	THIKRI																														53	190	203
31	BARWANI																															135	147
32	KEWADIA COLONY																																15

TABLE 2 - INTERSTATION DISTANCE

7.0 RESULTS

After inter-station correlation of hourly rainfall data of Sept., 1970 storm, the following time lag in rainfall occurrence were noticed with respect to the reference station, Pendra Road.

Pendra Road	... 0 hr,	Mandla	...6hrs.
Jabalpur	...8hrs	Chindwara	...14hrs.
Pachmarhi	15 hrs.,	Bagra Tawa	...15 hrs.
Betul	...18 hrs,	Bairagarh	...19 hrs.
Punasa	29 hrs.,	Khandwa	32 hrs.
Indore	...32 hrs,	Thikri	33 hrs.
Kewadia Colony	...56 hrs.		

Theinitial analysis of the hourly rainfall data of August 1973 storm has indicated the possibility of rainfall having occured at Mandla and Umaria earlier than what is indicated by preliminary scrutiny which is 6 hrs. The revised analysis has indicated the following lag pattern with reference to the station, Pendra Road.

Pendra Road.	...0 hrs,	Mandla	..1hr before
Umaria	...4 hrs,	Jabalpur	. 11 hrs
Pachmarhi	...19 hrs,	Betul	..31 hrs.
Bairagarh	...32 hrs,	Punasa	...40 hrs.
Khandwa	41 hrs.,	Thikri	...48 hrs.
Indore	44 or 48 hrs,	Ujjain	...49 hrs.

The inter-station correlation analysis for the August 1978 storm has revealed some interesting features. They are (i) the poor correlation at lag zero between Jamtara and Jabalpur separated by only 7 km., (ii) the indication of rainfall at Umaria as having occured later than Mandla,

(iii) the poor correlation of Pendra Road with all other stations, (iv) the large lag at Indore and (v) the indication that rainfall at Mortakka has occurred later than Thikri, Barwani and Rajpipla. While it is difficult to explain the poor lag zero correlation at Jamtara-Jabalpur, some explanation could be offered for the anomalies in the other four cases.

Rainfall occurrence at Umaria later than Mandla:

As may be seen from the storm track in Fig6, the storm has entered the basin from near Balaghat and Seoni. The rainfall would, therefore, be around this place and could not be expected to the north east as per the popular theory that rainfall always occurs in the S W Quadrant of storm track.

Poor correlation of Pendra Road with other Stations:

This could again be explained as due to the track of the storm with respct to Pendra Road which is far east of the track.

Large Lag at Indore:

The lag at Indore with respect to Mandla is around 36 hrs and during the recurving phase of the storm (Fig.6) the storm was very slow in movement and Indore might have received the rainfall while the storm was in the recurving phase thus making the lag 36 hrs.

Indication of rainfall occurrence at Mortakka:

The late occurrence of rainfall at Mortakka as compared to Thikri, Barwani and Rajpipla in other words rather the early occurrence of rainfall at the later stations could possibly be due to the stations being in line of the moisture feed from Arabian Sea while the storm was passing from Balaghat to Bairagarh (Bhopal).

The revised analysis indicated the following lag pattern at the different SRRG stations. The lag is shown with respect to Mandla because of the rather poor correlation Pendra Road had with the other Stations.

1.	Pendra Road	2 or 3 hours earlier	2.Mandla	0hr.
3.	Umaria	8 hrs	4.Malanjkhand	1hrs.
5.	Jamtara	5 hrs	6.Jabalpur	13 hrs
7.	Lakhandon	6 hrs	8. Chindwara	7 hrs.
9.	Narasimhapur	12 hrs	10.Harai	7 hrs.
11.	Bermanghat	7 hrs.	12.Tawa Dam	9 hrs.
13.	Bagra Tawa	9 hrs	14.Pachmarhi	15 hrs
15.	Sarani Dam	15 hrs	16. Barna Dam	17 hrs
17.	Salwani	9 hrs	18.Hoshangabad	9 hrs.
19.	Betul	15 hrs	20.Khandwa	18 hrs
21.	Dharni	23 hrs.	22.Burhanpur	25 hrs
23.	Mortakka	28 hrs.	24. Thikri	24 hrs.
25.	Barwani	25 hrs	26.Rajpipla	27 hrs.
27.	Indore	36 hrs.		

In the incase of the September 1979 storm, the initial inter station correlation analysis had suggested the slightly earlier occurrence of rain at Jabalpur as compared to Mandla, Malanjkhand and Jamtara. Since the storm was moving north east to the catchment (Fig.6) it is possible that the stations which are far from the track would receive rainfall later than those nearer. But this does not explain the 1 hr. lag at Jamtara, though, the lag zero correlation (.644) is also fairly close to the lag 1 correlation which is .646.

The revised inter-station correlation analysis indicated the following lag patterns taking Jabalpur as the reference station.

Jabalpur	0 hrs	Mandla	1hrs.
Jamtara	1 hr	Malanjkhand	2 hrs
Harai	4 hrs.	Chindwara	15 hrs
Gadarwara	6 hrs	Bermanghat	9 hrs.
Barna Dam	10 hrs.	Bagra Tawa	6 hrs.
Tawa	6 hrs.	Bairagarh	8 hrs.
Mandleshwar	27 hrs.	Indore	28 hrs.

7.1 Comparison with storm Isohyetal Pattern:

The lag corresponding to the optimum correlation as indicated by the correlation analysis is compared with the physical movement of the storm as reported by the India Meteorological Department and as revealed by the daily storm isohyetal pattern.

September 1970 Storm

As indicated in the Storm description in section 5.1, the storm was centered 50 km south-west of Jabalpur on 5th and was centered 50 km southwest of Indore on 6th which means the storm has taken 24 hrs to travel from Jabalpur to Indore. As could be seen from the results, the travel time at Jabalpur is 8 hours while it is 32 hrs. at Indore thus indicating a 24 hrs inter station duration of storm movement between Jabalpur and Indore which is in exact confirmity with the above finding.

Figs.9a to 9b show the rainfall pattern on 5th and 6th (observational day) Sept.1970 respectively which are drawn on the basis of totaling rain gauges. The rainfall on 4th was very little except for small pockets over upstream Narmada and west of Pachmarhi and Betul. On 5th there are well established centres over Pachmarhi and Thikri. The further movement of these two rain centres to the west on 6th

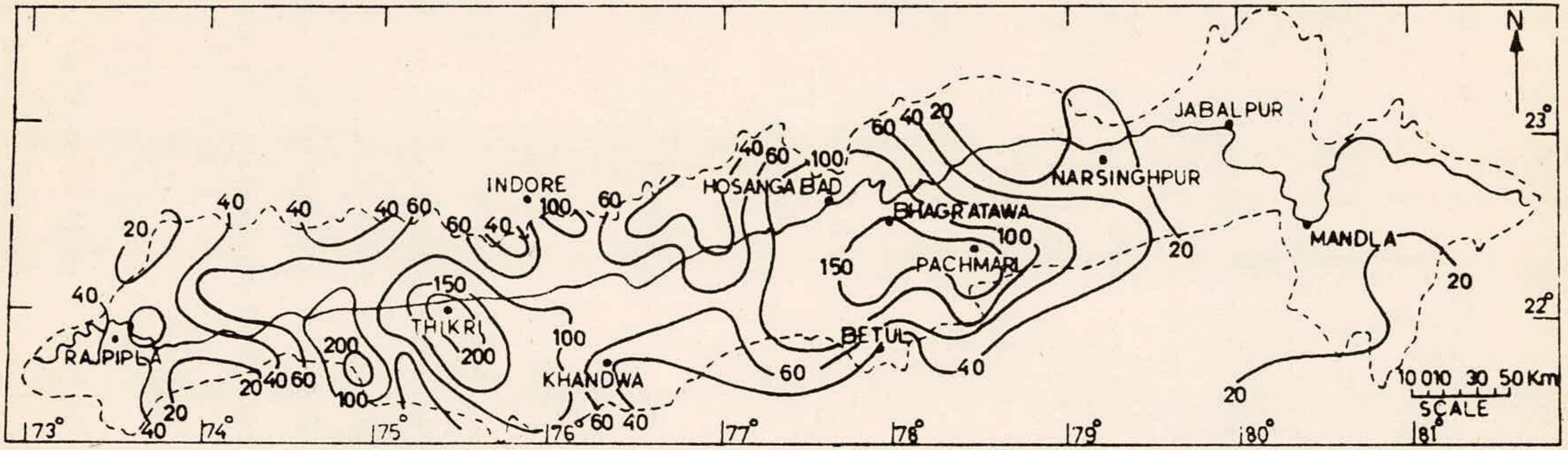

Fig.9 (a) Isohyetal Map - 5 Sept.1970

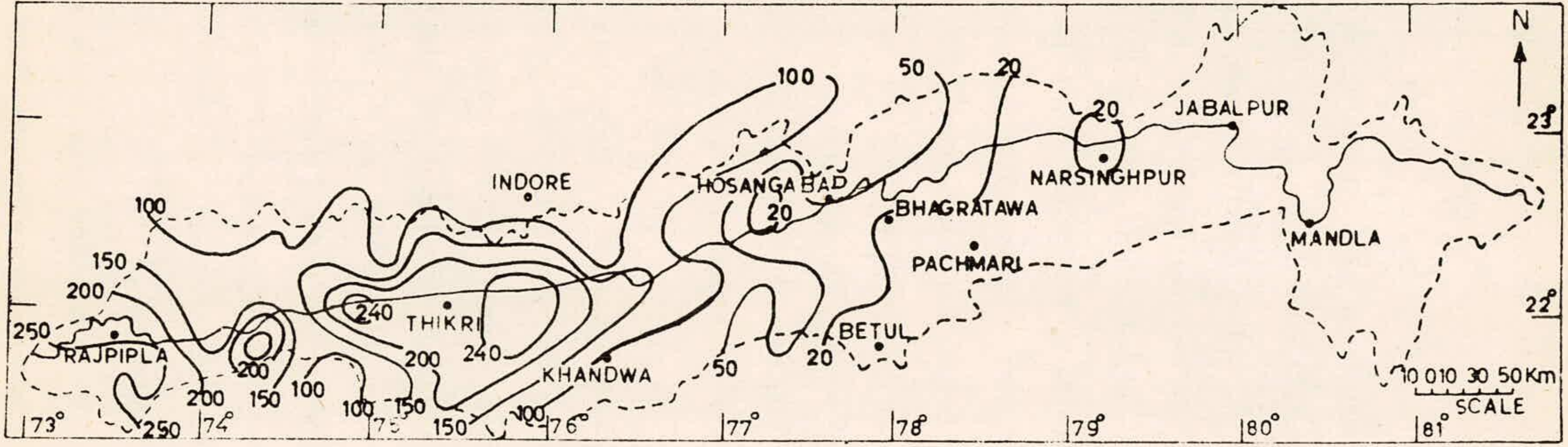

Fig.9(b) Isohyetal Map-6 Sept 1970

could be observed in the form of heavy rain centres east of Thikri and nearer to Garudeshwar i.e, Kewadia Colony.

This had indicated an approximate movement of 20 hrs. to Pachmarhi, 36 hrs to Thikri and 60 hrs to Kewadia Colony which is in rough agreement with that indicated by inter station correlation analysis.

August 1973 Storm:

According to the storm description given in section 5.2 the storm has reached Pendra Road on the evening of 28th August and moved to Jabalpur on 29th morning which is 12 hrs travel time from Pendra Road to Jabalpur. The storm moved further to Guna which is northwest of Bhopal and northeast of Ujjain on 30th. This would mean a travel time of 30 hrs to Bairagarh (Bhopal) and 48 hrs to Ujjain. The inter-station duration of storm movement as obtained from the inter station correlation is around the same order.

The daily isohyetal pattern of 29 and 30 August 1973 based on ORG data is shown in Fig.10(a) to 10(b). On 29th the rain centre is around Narayanganj to the east of Jabalpur. The centre shifted to south of Hoshangabad on 30th. This accounts for about 36 hrs. The timing of 31 hrs at Betul and 32 hrs at Bairagarh is, therefore, in order. The storm centre on 31 st August lay at Mhow/Manpur south of Indore. This accounts for another 12 hrs from Hoshangabad considering the fact that there was no rain on the evening of 30th and the morning of 31st. This makes the travel time at Thikri and Indore around 48 hrs which is what has been obtained by the inter-station correlation analysis at Thikri and Indore.

August 1978 storm:

The comparison with storm movement had been discussed earlier. The isohyetal patern on 29th and 30th is shown in Fig.11 a and 11b.

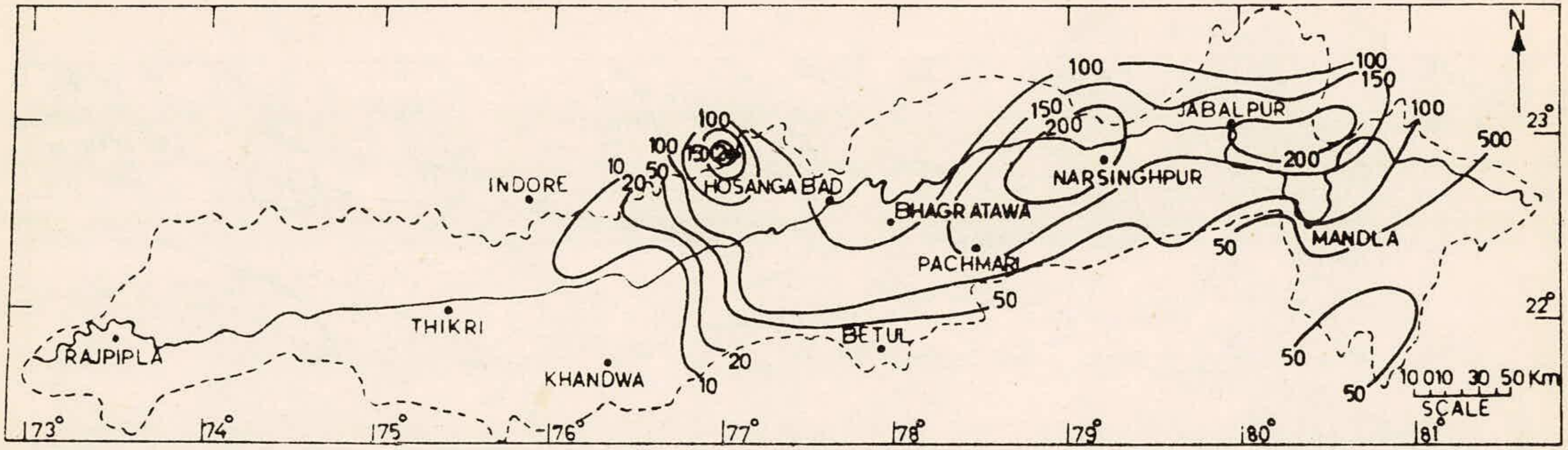

Fig.10(a) Isohyetal Map -29 Aug.1973

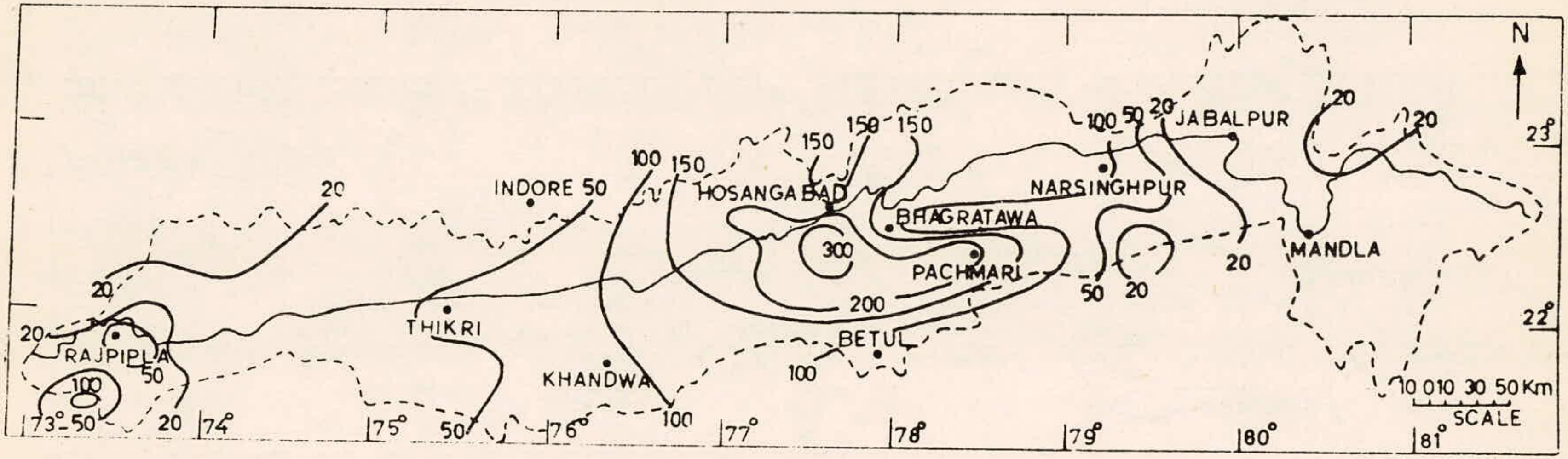

Fig.10(b) Isohyetal Map-30 Aug.1973

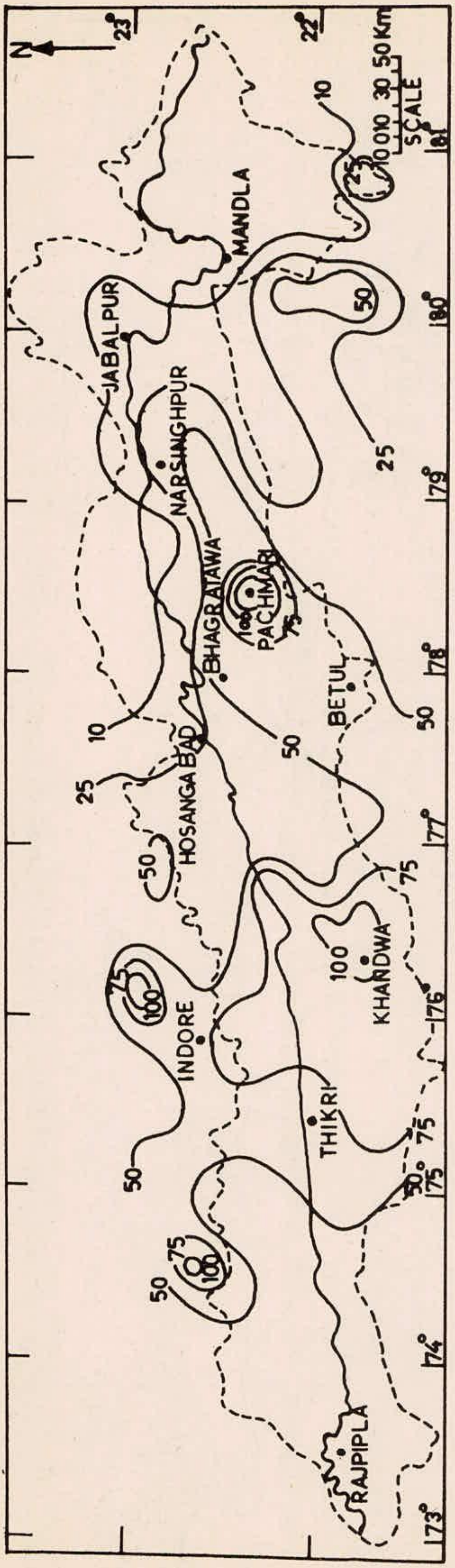

Fig.11(a) Isohyetal Map-29 Aug.1978

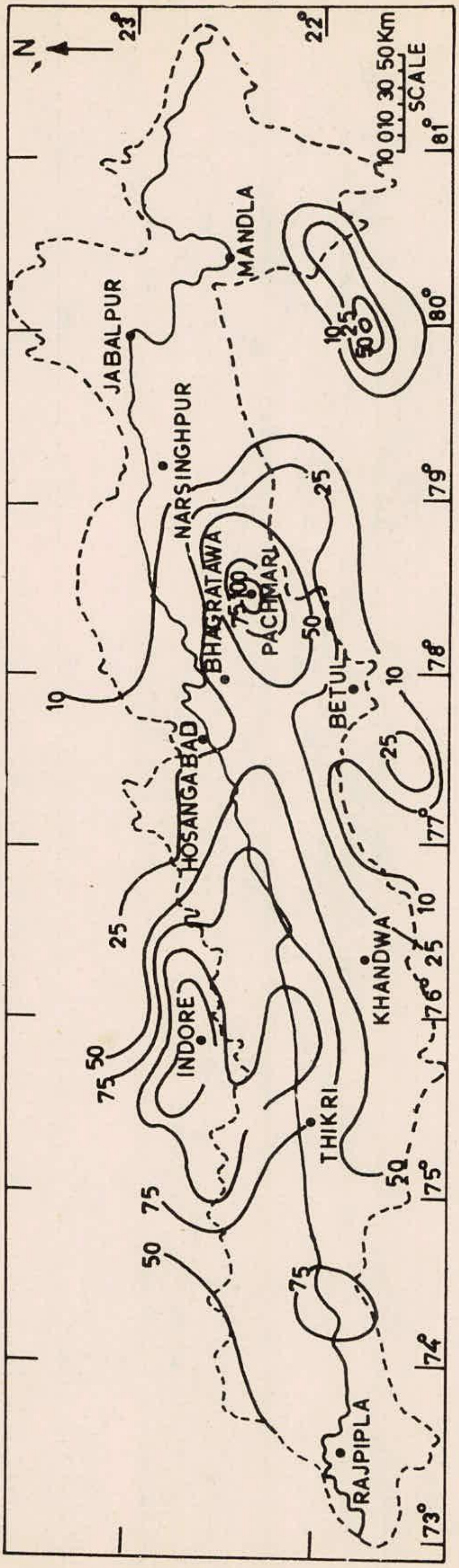

Fig.11(b) Isohyetal Map-30 Aug. 1978

On 29th, the centre with 50 mm was around Balaghat. The centre at Pachmarhi is due to orographic effect. On 30th besides the centre at Pachmarhi, the main rain centre is around Indore thus giving a lag time of about 36 hours from the time the system has entered the basin at Balaghat.

August 1979 Storm

The storm track in Fig.6 and the description in section 5.4 indicates that the storm has arrived east of the catchment towards evening of 8th and was north west of Jabalpur on 9th and north west of Bhopal on 10th. The storm has thus taken around 12 hrs from Jabalpur to reach Bairagarh and another 12 hrs to reach Indore. The lag time indicated by the inter-station correlation is of the same order.

The isohyetal pattern on 9th and 10th is shown in Figs.12a to 12b. On 9th, the rain centre was around Seoni, Bori in Seoni district. It has moved to Depalpur and Sardarpur in the Districts of Indore and Dhar respectively on 10th. The centre was around Garudeshwar on 11th August.

The isohyetal pattern thus indicates a travel time of around 24 hrs from Jamtara-Jabalpur to Indore-Dhar. This also confirms the lag time observed by inter-station correlation at Indore/Mandleshwar with respect to Jabalpur.

7.2 Summary

A summary of the inter-station lag of rainfall event occurrence or the time taken by the storm to move from one station to another is indicated in table 3 for each of the storms whose data has been considered for analysis. As the number of SRRG stations and the reference station vary from storm to storm it may not be readily possible

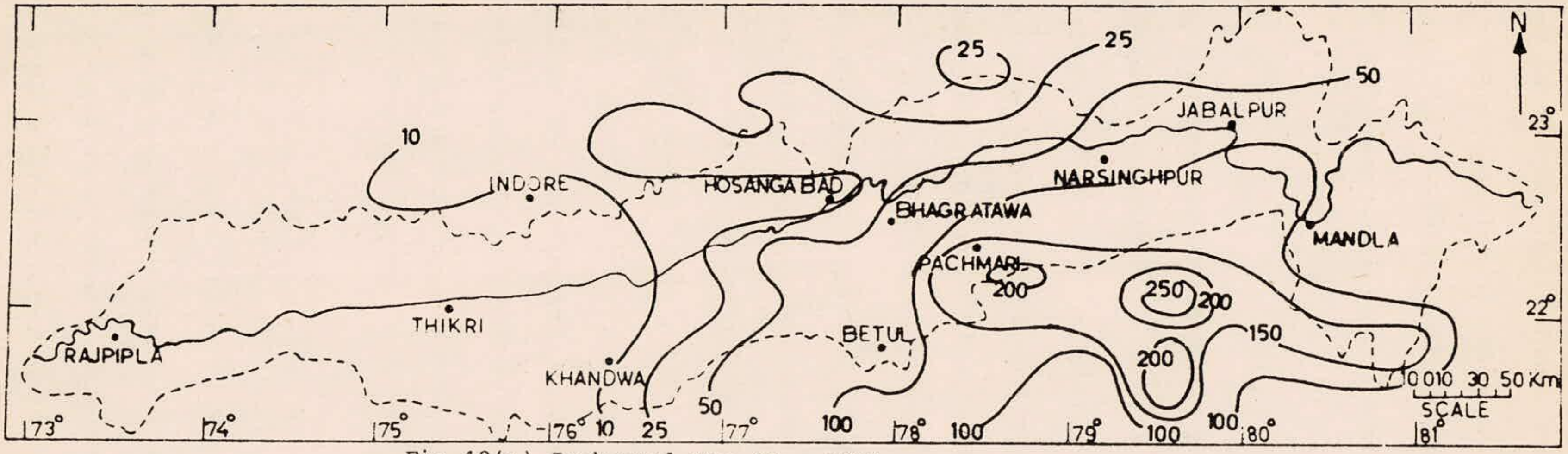

Fig.12(a) Isohyetal Map-9Aug.1979

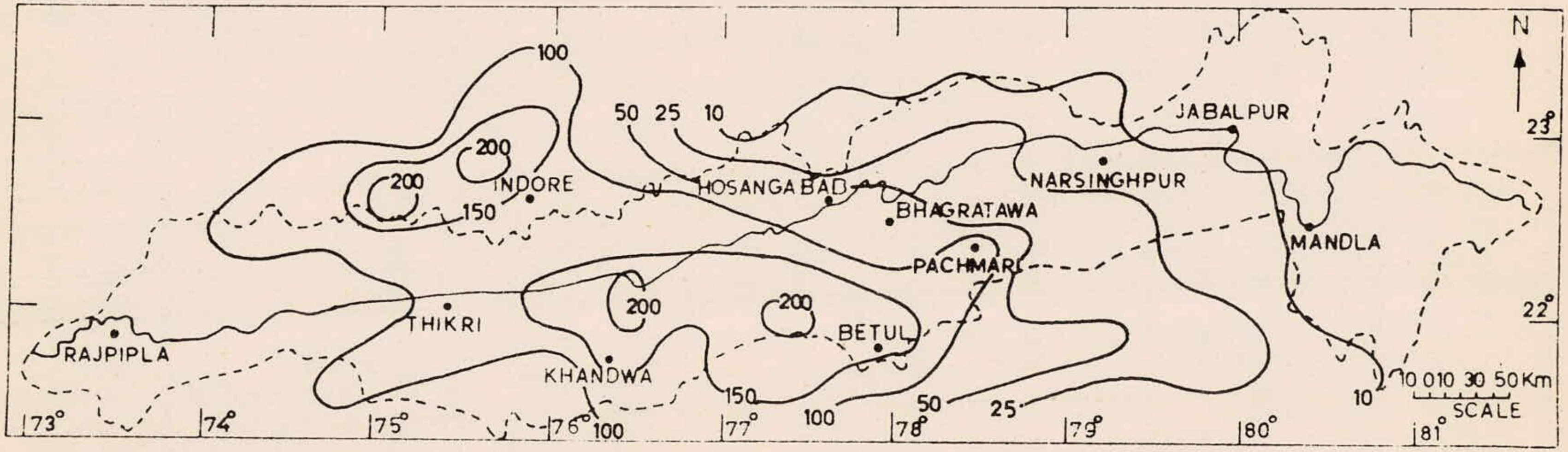

Fig.12(b) Isohyetal Map-10 Aug.1979

Table 3: SUMMARY TABLE OF LAG TIME OBSERVED IN HOURS AT VARIOUS SRRG IN DIFFERENT STORMS

Station	3-6 Sept. 1970	28-31 Aug. 1973	28-31 Aug. 1978	7-10 Aug. 1979
Pendra Road	0	0	2 or 3 hrs earlier	
Umaria		4	8	
Mandla	6	1hr before	0	1 hr later
Malanjkhand			1	2 hrs later
Jamtara			5	1 hr later
Jabalpur	8	11	13	0
Lakhandon			6	
Narasimhapur			12	
Harai			7	4
Chindwara	14		7	
Bermanghat			7	9
Gadarwara			-	6
Pach-marhi	15	19	15	
Tawa			9	6
Bagratawa	15		9	6
Hoshangabad			9	
Banna Dam			17	10
Sanni Dam			15	
Betul	18	31	15	
Salwani			9	
Bairagarh	19	32	-	8
Punasa	29	40	-	
Mortakka	-	-	28	
Khandwa	32	41	18	
Mandleshwar			-	27
Dharni	-	-	23	-
Thikri	33	48	24	
Burhanpur	-	-	25	
Barwani			25	
Indore	32	48	36	28
Ujjain		49	-	
Khewadia Colony	56		-	
Rajpipla			27 hrs.	

to draw conclusions regarding the movement of the storm. To facilitate comparison of the relative movement of each of the storms with one another, a matrix of inter-station distance between the different SRRG stations is given in table 2. By studying the results summarised in table 3 in conjunction with the interstation distance given in table 2 it would be possible to compare the relative speeds of the movement of the different storms.

It is seen from the summary that the storms of Aug.1979, August 1978 and September 1970 are relatively fast moving storms in comparison to the August 1973 storm. The storm of August 1978 was fast until it reached Bairagarh. During the recurving phase it became slow.

8.0 CONCLUSIONS

The runoff hydrograph from a catchment due to a rain storm depends not only on the total storm rainfall but also its distribution with time and in area. The direction of storm movement has the greatest effect on elongated catchments such as Narmada. The amount of rain over the same period prodnces a much greater peak when the storm is moving down the valley. Storms moving down the valley have much larger flood potential than storms moving up the valley.

Studies have shown that besides the direction of the movement of the storm, the relative movement of the storm with respect to the catchment and the speed of movement of the storm determine to a large extent the magnitude of flood peak and the shape of the flood hydrograph.

In spite of the limitations of the rather poor network of self recording raingauges in the Narmada catchment, the present study has indicated the usefulness of the statistical model based on the cross correlation of hourly rainfall data at pairwise combination of recording raingauge stations for modelling the movement of storms in India and studying their hydrological responses especially in large elongated catchments like Narmada.

When sufficient information becomes available after the analysis of a number of storms over a given area, it should be possible to subject the data of duration between storm spells and inter-station duration of the movement of storm cell to further statistical analysis to identify the presence of any persistence or pattern in the occurrence of the storm event and its movement. If such a persistence is established it could well be used as a prognostic tool.

REFERENCES

1. Amorocho, J and B.Wu (1977)"Mathematical models for the simulation of cyclonic storm sequences and precipitation fields" Journal of Hydrol.Vol32, pp.329-345.

2. Austin, P.M. and R.A.Houze (1972)"Analysis of the structure of precipitation patterns in New England". Journ.Appl.Meteorol. Vol.11, pp.926-934.

3. Chow, V.T. and S.Ramaseshan (1965),"Sequential generation of rainfall and runoff data" Journ. of Hydraulic Divn.American Society of Civil Engineer (Hy.4) pp.205-223.

4. Creutin, J.D. and C.Obled (1980) "Modelling of spatial and temporal characteristics of rainfall as input to a flood forecasting model " Proc. of Symp on Hydrological forecasting (IASH), Oxford (U K) pp 41-50.

5. Felgate, D G and D.G.Read (1975) "Correlation analysis of the cellular structure of storms observed by raingauges" Journ. of Hydrol. Vol.24, pp.191-300.

6. Johnson, F.R. and Rafael L Bras (1980)"Multivariate short term rainfall prediction". Water Resources Research Vol.16, No.1 pp.173-185.

7. Marshal, R.J.(1980)"The estimation and distribution of storm movement and storm structure using a correlation analysis technique and raingauge data". Journ. of Hydrol.Vol.48, pp.19-39.

8. Niemczynowicz, J & O.Jonsson (1981),"Extreme rainfall events in Lund 1979-80". Nordic Hydrology, Vol.12, pp.129-142.

9. Niemczynowicz, J.(1984),'Investigation of the Influence of Rainfall movement on runoff hydrograph, Parts I & II", Nordic Hydrology Vol.15, No.2, pp.57-84.

10. Ramanathan Y & R.K.Bansal (1977),"On the application of a primitive equation barotropic model for the prediction of storm tracks in the Indian region". Indian Journ.Meteorology, Hydrology and Geophysics, Vol.26, No.2, pp.169-176.

11. Ramasastri, K.S. and S.M.Seth (1986)",Sensitivity of estimated flood to changes in parameters of HEC 1 Model" Proc. of 53rd R & D Session, CBIP, Bhubaneshwar.

12. Rodriguez Iturbe, I and J.M.Mejia (1974),"On the transformation of point rainfall to areal rainfall", Water Resources Research Vol.10, No.4, pp.729-735.

13. Saha, S.(1983),"Behaviour of monsoon depressions in a Primitive equation barotropic model" Mausam, Vol34, No.1, pp.27-32.

14. Singh, S.S. and K.R.Saha, (1978),"Numerical experiment with primitive equation barotropic model using quasi-Lagrangian advection scheme to predict the movement of monsoon depression and tropical cyclone", Indian Journ. of Meteor.,Hydrol. and Geophy.,Vol.29 No.1 and 2, pp.367-374.

15. Stol, Ph.Th.(1981),"Rainfall interstation correlation functions. Part I and II, Journ. of Hydrol.Vol.50 No.1 and 3, pp.45-104.

16. Surendar Kaur, S.N.Kathuria and Rohini Bala (1985),"On simulating characteristics of rainstorms for flood forecasting" Vayu Mandal Vol.15, Nos.1 and 2 pp.65-67.