SPACE TIME CHARACTERISTICS OF RAINFALL IN EAST RAJASTHAN

A THESIS

submitted in fulfilment of the
requirements for the award of the degree
of
DOCTOR OF PHILOSOPHY
in
HYDROLOGY

By

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December 1993

Gratis

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled SPACE TIME CHARACTERISTICS OF RAINFALL IN EAST RAJASTHAN in fulfilment of the requirement for the award of the Degree of Doctor of Philosophy of the University of Roorkee is an authentic record of my own work carried out during a period from 19th March 1986 to December 1993 under the supervision of Dr Satish Chandra and Dr S M Seth

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

Signature of the Candidate

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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Date 29-12-93 Signature of Supervisor Signature of Supervisor

The Ph.D Viva-Voce examination of Shri K S Ramasastri, Research Scholar has been held on 7th Nov. 1994.

7/11/94 7.11.'94

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ABSTRACT

Rainfall in semi arid regions is low and uncertain. For long term planning of water resources development and short term planning for agricultural operations it is essential to understand the mechanisms and behaviour of rainfall process and analyse its space and time characteristics.

In India, semi arid regions in the north have a distinct wet season restricted to about 80 to 90 days during the summer monsoon season June to September. Rajasthan in northwest India has semi arid climate in the east and arid in the west. The region is characterised by low to moderate rainfall with high degree of variability. The region is not only prone to frequent droughts but occasional heavy rain storms. The mean annual rainfall varies from about 100 cm in the south east to 15 cm in the west and 40 cm in the north. The coefficient of variability of annual rainfall varies from 35% in the southeast to more than 80 % in the west and 40 % in the north.

Literature review has indicated that no systematic studies have been carried out for this region to understand the behaviour of rainfall occurrence in space and time. The review has further indicated the possibility of the application of Thomas Fiering model for monthly rainfall data generation and the transition probability matrix and alternating renewal process methods for daily rainfall data generation for semi arid regions.

The objective of the study was to analyse systematically the space and time characteristics of monthly, monsoon and annual rainfall and rainy days over east Rajasthan. General spatial

variability of annual rainfall over whole of Rajasthan was studied using data of 521 long term and short term raingauge stations in the state. The adequacy of the existing raingauge network in east east Rajasthan was examined and based on the study, catchmentwise raingauge network has been recommended.

The study was done broadly on the following lines :

(i) Time series analysis of monthly, monsoon and annual rainfall and rainy days has been carried out to identify

- (a) persistence in the series
- (b) dependance of rainfall of a month or season on the rainfall of the previous month or season and
- (c) presence of any rising or falling trend and the type (linear or curvilinear) trend

(ii) Thomas Fiering model has been used for generation of monthly rainfall data with appropriate transformations of historical monthly rainfall data,

(iii) Two daily rainfall models described above have been used for generation of daily rainfall data,

(iv) Structure of spatial correlation over the region has been analysed and

(v) Covariance model has been used for simulation of rainfall field within homogeneous rainfall groups .

Data of monthly rainfall for the period 1901 - 1985 for 20 stations located in the twenty districts in east Rajasthan has been used for the anlayses. The homogeneity of the rainfall and rainy days series has been tested. The series in general were found to be stationary. The randomness of the monsoon and annual rainfall and rainy days series has been tested using turning point test and through serial correlation. The analysis did not indicate any persistence or non-randomness in the series.

Cross correlation among the rainfall of four monsoon months June to September was computed which was found to be low and not significant. Also, no relation was found between the rainfall series of non-monsoon season and the rainfall of the previous monsoon season. This has indicated the independance of rainfall of any month or season from the rainfall of any previous month or season.

Analysis for presence of trend has been done by fitting linear and polynomial (2nd order) regression to monthly, monsoon and annual series of rainfall and monsoon and annual series of rainy days. Four stations Banswara, Dausa, Pratapgarh and Sirohi have shown trend in the series which was tested to be significant. Two other stations Ajmer, Jalore and Khanpur (Jhalawar District) have also indicated some trend, positive in the case of the earlier two and negative in the case of the later. These were, however, statistically not significant.

Rainy days series of Bharatpur and Dholpur both representing the northeastern part of Rajasthan have indicated a negative trend which was statistically significant.

Correlation between rainfall and rainy days at some stations indicated that the number of rainy days influence to some extent the total rainfall amounts received in a month or season. Correlation between rainfall amount and intensity (amount of rainfall per rainy day) is comparatively less and there is no relation between rainy days and intensity.

Thomas Fiering model has been used for generation of monthly rainfall data by incorporating modifications and transformation of the historical series. The use of square root transformation and power transformation gave better results than log transformation.

Transition Probability Matrix (TPM) method and the Alternating Renewal Process (ARP) method have been used for simulation and generation of daily rainfall data. In the TPM method, the rainfall is modeled to occur in seven classes. Daily rainfall data for 90 years is generated from 30 years of historical series (1961-1990) normalised using the Box-Cox transformation.

In the ARP method, the run length of a dry or wet spell is modeled by a two parameter truncated binomial distribution, and the rainfall amounts above a given rainfall threshold are generated by the two parameter Gamma distribution. Daily rainfall data of 30 years has been generated using 30 years of historical data as above.

The performance of the two methods was evaluated by comparing the statistics of the generated series with the statistics of the historical series . The TPM method was found to have performed well in comparison to the ARP method based on the reproduction of the statistical parameters like mean, standard deviation, average number of wet days and highest daily rainfall which were used as criterion for comparison of generated and historical series.

Cluster analysis has been used for sub-dividing the study area and grouping the different raingauge stations. The clusters identified by this way have been used for selecting the representative stations from each cluster for studying the space time characteristics of rainfall in each cluster.

Correlation structure of 20 stations representing the 20 districts in the region has been studied by computing pairwise correlation among the monthly, monsoon and annual series of rainfall and monsoon and annual series of rainy days. It was seen that the spatial correlation structure, i.e the relationship between inter-station correlation and inter-station distance could be mathematically represented by an exponential relation. In the case of rainy days, the curve representing the above relation was decaying less monotonously indicating widespread occurrence of rainfall over space during the monsoon season.

Rainfall field has been simulated by the covariance model using the Williams and El Kadi algorithm. The rainfall field simulation for homogeneous rainfall regions within the study area has given satisfactory results.

The study has brought out some important findings regarding the rainfall behaviour in the semi arid monsoon climate. These are

(i) The rainfall and rainy days series for different time scales such as month, season (monsoon) and an year are, generally, random and there is no persistence.

(ii) There is no trend in the series of either rainfall or rainy days excepting in a few cases which have indicated positive or negative trends .

(iii) The Thomas Fiering model using square root transformation was found to be suitable for generation of monthly rainfall data for regions with semi arid monsoon climate.

(iv) The transition probability matrix method was found to be satisfactory for generation of daily rainfall data in regions of semi arid climates with a prominent humid season.

(v) Spatial correlation structure is well defined and could be represented mathematically.

(vi) The covariance model was found to be capable of simulating the rainfall field satisfactorily.

It is believed that the analysis and procedures used in the present study would be useful for similar studies in other semi arid regions for a better understanding of the behaviour of rainfall occurrence and its space time characteristics.

The study has pointed towards some topics needing further investigation. These include the assessment of effects of afforestation and deforestation on rainfall and monitoring of dust content in the atmosphere close to the ground and studying its influence on rainfall in semi arid regions.

ACKNOWLEDGEMENTS

I would like to express my deep sense of gratitude to my supervisors Dr Satish Chandra and Dr S M Seth for their valuable guidance and encouragement in the completion of the studies leading to the thesis.

The useful suggestions and help rendered by Shri R D Singh, Scientist E, NIH Roorkee are gratefully acknowledged.

I would also like to place on record my gratitude for the help and cooperation extended by Prof. B. S. Mathur, Head and other faculty members of Department of Hydrology, University of Roorkee from time to time.

Finally, the constant encouragement and cooperation by my wife Padmaja in pursuing the studies is remembered with affection.

K S RAMASASTRI

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LIST OF NOTATIONS

The notations and symbols used most commonly are listed here. Other notations and symbols are described wherever they appear in the text.

ARP	-	Alternating renewal process
C_v	-	Coefficient of variability
F	-	Fisher's F used for F test
Γ	-	Gamma function
IMD	-	India Meteorologcal Department
ν	-	Number of degrees of freedom
ρ	-	Correlation coefficient
σ	-	Standard deviation
SGD	-	Shifted Gamma distribution
SRRG	-	Self recording raingauge
t	-	Student's t used for t test
TNBD	-	Truncated negative binomial distribution
TPM	-	Transition probability matrix

CHAPTER I

INTRODUCTION

1.1 General

Rainfall is the single most important physical environmental factor affecting human activities. The amount of rainfall received over an area is an important parameter for assessing the amount of water available for various uses such as agriculture, industry, irrigation, generation of hydropower, navigation etc.

Hydrological processes in general and rainfall process in particular are random in space and time. In order to increase the accuracy in estimation in a number of hydrological problems such as design and forecasting, it is essential to extend the knowledge on the spatial and temporal behaviour of rainfall process.

Agriculturists all over the world and particularly those who live in the semi arid areas, have long recognised the importance of seasonal and annual variability of rainfall. Semi arid and arid areas occupy nearly 40 % of the geographical area in India. Agriculture in these regions is generally rainfed. For a few places where irrigation is possible, availability of surface water and ground water is limited and uncertain. The semi- arid and arid areas are characterised by large amplitudes of fluctuations of diurnal and annual temperatures, strong wind regimes and high evaporation. Rainfall in these areas is not only marginal but also highly variable from year to year and from place to place. Periodic droughts some times lead to famine conditions causing a lot of human misery. An understanding of the temporal and spatial distribution of rainfall is, therefore, crucial in semi arid regions for proper assessment and management of the available water resources.

Rajasthan in western India is a typical state which has both semi arid and arid climates. Gradual modifications in the climate in the region are likely due to changing land use pattern with a large area progressively being covered under irrigation while forest cover is depleting under pressures of increasing population.

One of the characteristics of rainfall in this region is that rainfall generally occurs in a few big storms of short duration. At many stations, the highest rainfall in a week during monsoon season exceeds even the mean annual rainfall. Distribution of rainfall is, therefore, skewed. The skewness increases when rainfall over shorter durations like a day are considered.

In deciding the agricultural operation policies one needs to analyse and model the precipitation at daily scale. In this context the important need is the development of suitable models for daily precipitation occurrences.

Attempts have been made in the past to study the trends and fluctuations in the rainfall and temperature data of the region based on the analysis of individual stations using varying lengths of historical data. Few studies have been conducted on the rainfall series for Rajasthan for annual and monsoon season data. However, no studies have been done on monthly and daily rainfall. Also, no detailed analysis on the spatial characteristics of rainfall have been conducted. A systematic study of the space time characteristics of the rainfall in east Rajasthan has, therefore, been undertaken which would help in planning the cropping pattern and agricultural operations on a more scientific basis and in an effective way.

1.2 Objective and Scope of the Study

The main objective of the study is to analyse the characteristics of rainfall and rainy days in a semi arid area with mesoscale variations within the region using data of east Rajasthan. The essential components of the study include :

(i) identifying the presence of persistence or trend in the time series of rainfall and rainy days

(ii) examining the linkages between rainfall, rainy days and mean rainfall intensity

(iii) application and validation of appropriate models for generation of sequences of daily and monthy rainfall data in time.

(iv) investigation of regional pattern of interstation correlation of the two variables namely rainfall amount and rainy days, and the simulation and generation of seasonal rainfall data in space.

The scope of the study is limited to only testing of the models for their applicability to generate rainfall data in time and space. No attempt has been made to forecast the future trends of rainfall.

1.3 Layout of the Thesis

Chapter II presents a review of the literature relevant to the analysis carried out in the present study. It deals with the time series analysis , modeling of rainfall in space and time with particular reference to spatial correlation structure and data generation.

Chapter III gives a description of the study area east Rajasthan, its climate, raingauge network, availability of data and other details of the study area.

Chapter IV deals with the analysis of variability of annual rainfall for the state of Rajasthan and recommendations for network in the twenty districts and river catchments in east Rajasthan

Chapter V deals with the processing and screening of the data for testing randomness and stationarity of the time series and discusses the results of preliminary analysis.

Chapter VI discusses the analysis carried out for testing the persistence and presence of trend in the time series of rainfall and rainy days.

In Chapter VII the use of stochastic models for generation of daily rainfall and their performance in simulation of monthly totals in comparison to models used for generation of monthly rainfall data are discussed. The comparative performance of two methods of daily rainfall generation namely the transition probability matrix method and the alternating renewable process method is presented and discussed.

In Chapter VIII the analysis of spatial characteristics of rainfall, namely the clustering of rainfall stations into homogeneous groups, the spatial correlation structure and the method used for generating rainfall in space are presented and discussed.

Chapter IX presents the conclusions from the study and outlook for further studies.

CHAPTER II
LITERATURE REVIEW

2.1 General

Rainfall is a natural process which results from the interaction of complex atmospheric processes. The structure of rainfall patterns has been studied extensively using radar and detailed rain gauge measurements. Austin and Houze (1972) identified structures which consist of rain cells embedded within mesoscale rainfall areas within synoptic storm systems (figure 2.1). Because of the complexity of the process, rainfall cannot be described in purely deterministic terms. The rainfall process also contains periodic components due to the seasonal variation within the year and persistence in both time and space. Recent hydrologic descriptions of rainfall have emphasised the simultaneous variability of rainfall intensity over time and space (Waymire et al.,1984; Rodriguez-Iturbe and Eagleson,1987; Sivapalan and Wood,1987).

2.2 Time Series Analysis

A sequence of values collected over time on a particular variable is a time series. A time series may be composed of only deterministic events, only stochastic events or a combination of the two. A time series of hydrological data may exhibit jumps and trends owing to inconsistency and non-homogeneity. Trends in rainfall time series can result from gradual natural or man made changes in the land use and environment.

Though a lot of literature on time series analysis is available, the review presented here relates to application of

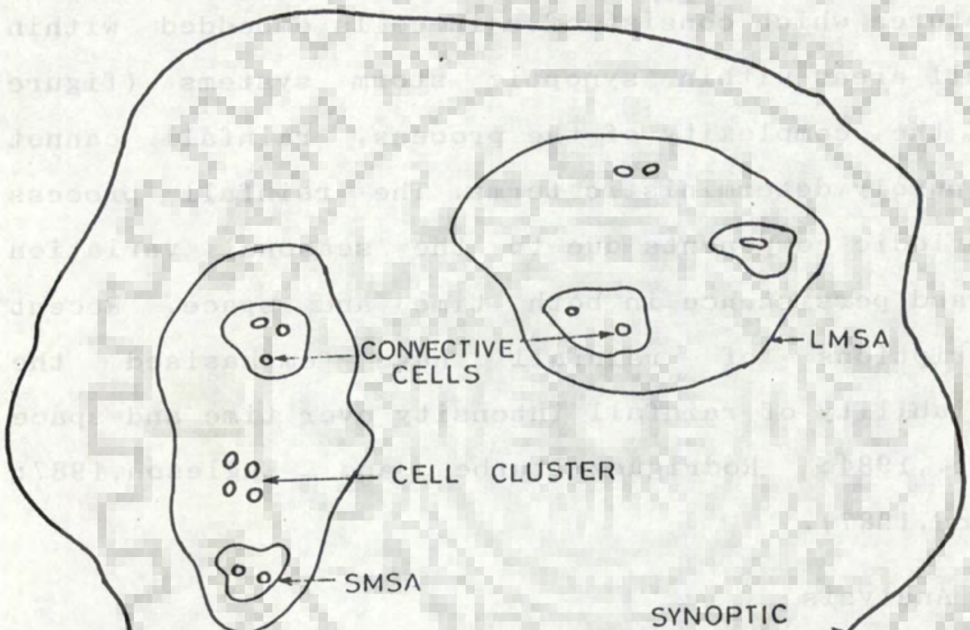


Fig. 2·1 A schematic picture of subsynoptic rainfall features.

(Courtesy : Austin and Houze, 1972)

time series analysis to rainfall only.

Yevjevich (1972) has suggested that hydrologic time series can be modeled by a deterministic component and a stochastic component. The deterministic component is composed of trends, jumps and periodicities.

Several authors have studied trends in annual rainfall series. The methods used in general were Spearman rank correlation and Mann Kendall test (Ramasastri, 1979; Olaniran, 1991) or power spectrum analysis (Rao et al,1973; Kane and Teixeira,1991).

Olaniran (1991) analysed annual series of rainfall in Nigeria based on data for the period 1919 to 1985. Each series was examined for evidence of pattern of decrease and increase in dry and wet years, the overall trend and the occurrence of dry and wet years.

Kane and Teixeira (1991) used the maximum entropy spectral analysis of the annual rainfall series of Massachusetts (USA) for 90 years (1887-1976). The analysis indicated a 17.8 year and a 2.72 year quasi biennial oscillation (QBO) cycles.

Blanford (1886) was the first meteorologist who made extensive studies of Indian rainfall. The analysis of 19 year (1867 - 1885) annual rainfall data for India as a whole did not reveal any significant oscillation or systematic trend in the rainfall.

The second study on rainfall variation was conducted by Walker (1910) who examined the summer monsoon rainfall over India from 1841 to 1908 and concluded that there was no perceptible climate change. On detailed analysis, he found a tendency for monsoon rainfall over northwest India to increase to a maximum between 1891 and 1894, and to decrease to a minimum upto

1899. The rainfall started showing increasing tendency in subsequent years.

In a systematic study Pramanik and Jagannathan (1953) analysed 60 to 100 years annual rainfall data over 30 Indian stations and concluded that there was no short period cycle in annual rainfall and also in the distribution of rainfall particularly in the arid and semi arid regions of northwest India.

Rao et al (1973) studied the cyclicity in drought occurrence through spectral analysis of Palmer drought index for 22 meteorological sub-divisions in India. In case of east Rajasthan no periodicity was indicated. In case of west Rajasthan, however, two cycles of 4.18 and 10.5 years were indicated.

Winstanley (1973) while dealing with the aridity in the Sahel zone has established a 200 and 700 years harmonic cycle in the behaviour of rainfall and has included Bikaner and Jodhpur in west Rajasthan also in this cycle.

Ramasastri (1979) studied the trends in annual rainfall of west Rajasthan based on 56 years (1921 - 76) data and concluded that there was a tendency of increased rainfall after 1970.

Sharma (1986) analysed 25 years of monsoon rainfall (1961-85) in Rajasthan. Comparison of the 25 years rainfall for the state of Rajasthan as a whole with rainfall normals for the period 1901 -50 indicated that in 12 districts in the state the rainfall has increased while in 15 districts, the rainfall decreased. The behaviour of monsoon conditions in the state during 1961 - 85 is shown in figure 2.2. Further it was noted that the onset of monsoon over the state was getting delayed. The author concluded that the Arabian sea branch of monsoon was lagging behind the Bay of Bengal branch.

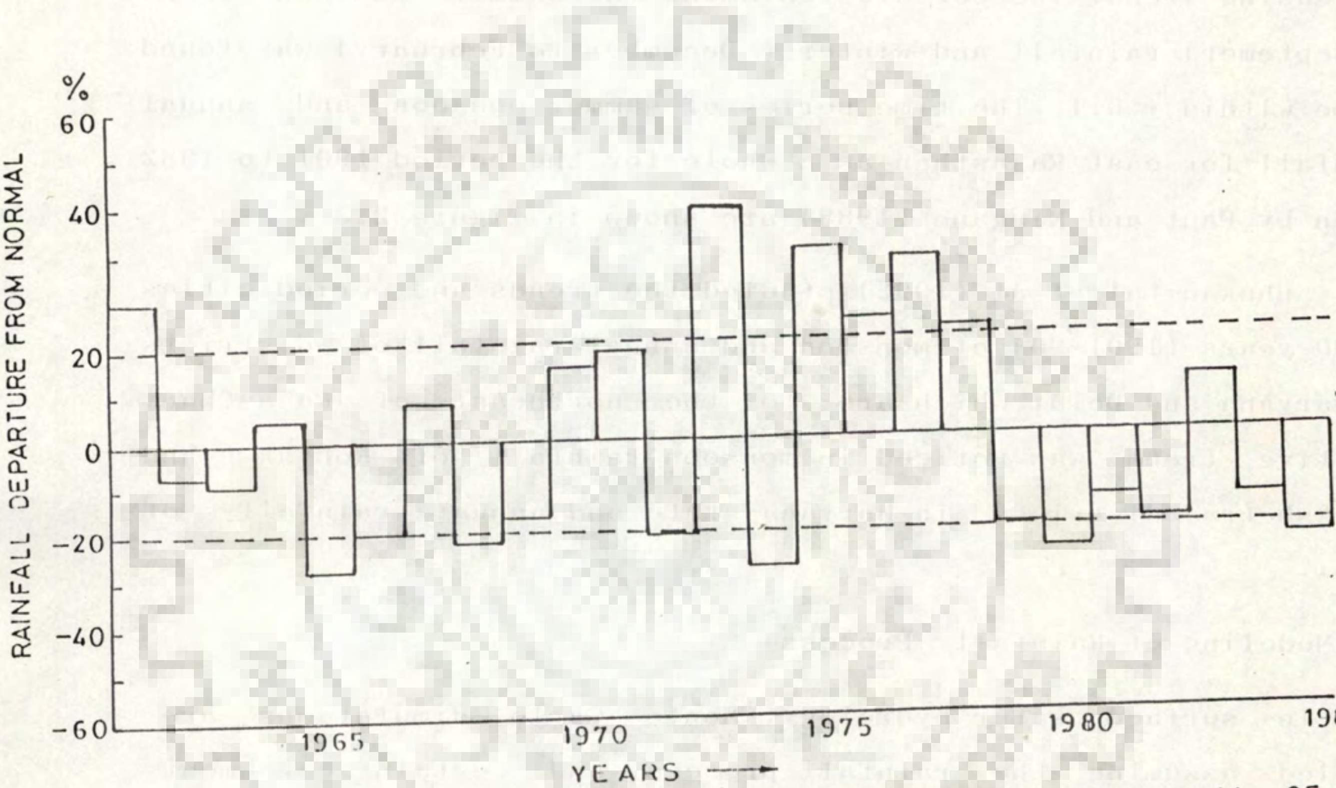


FIG. 2.2 MONSOON RAINFALL CONDITION IN RAJASTHAN DURING 1961 - 85

(**Courtesy : Sharma, 1986**)

Pant and Hingane (1988) studied the climate changes in and around the Rajasthan desert during the 20th century. Rainfall and temperature data during the period 1901 - 1982 were studied. The mean annual and southwest monsoon season (June to September) rain fall series over most of the region comprising East Rajasthan, west Madhya Pradesh, Punjab and Haryana indicated a conspicuous increasing trend. The correlation among the summer monsoon (June to Septemer) rainfall and winter (December to February) was found to be within $\pm$ 0.1 .The time series of summer monsoon and annual rainfall for east Rajasthan as a whole for the period 1901 to 1982 given by Pant and Hingane (1988) are shown in figure 2.3 .

Bhukan Lal et al (1992) studied the trends and periodicities of 90 years (1901-90) of monsoon and annual rainfall of districts in Haryana and Delhi which are to the northeast of Rajasthan. Positive trend was noticed in monsoon rainfall of Rohtak and Kurukshetra districts in Haryana state and annual rainfall of Delhi.

2.3 Modeling of Rainfall Process

In surface water hydrology, Monte Carlo simulations are applied assuming the rainfall process and certain catchment characteristics to be stochastically varying in space and/or time. In an effort to provide more concise models of daily rainfall, several investigators have proposed stochastic models describing both rainfall occurrence and the distribution of rainfall amounts at a point in space.

Several stochastic rainfall models have been developed during the last two decades for the daily rainfall. Early studies assumed that each storm was made up of a random number of rain cells which occur in space and time according to a three dimensional point

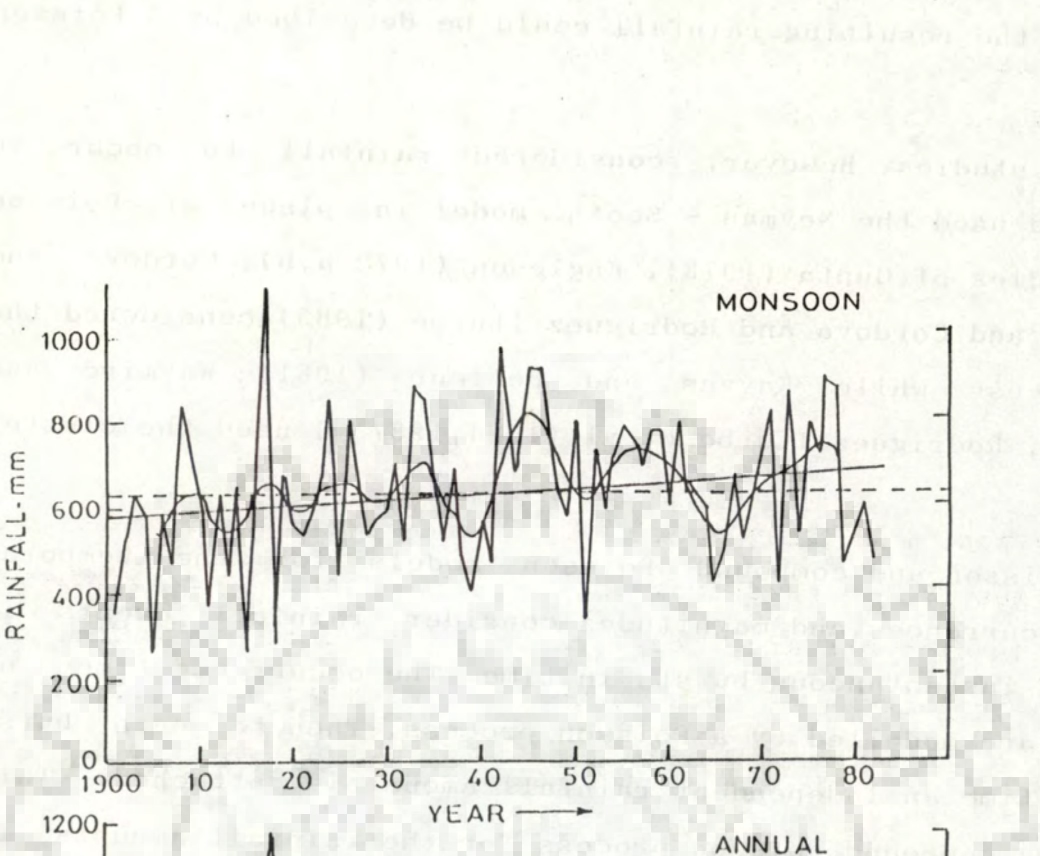


FIG. 2.3 MONSOON AND ANNUAL RAINFALL EAST RAJASTHAN
(COURTESY: PANT AND HINGANE, 1988)

process and the resulting rainfall could be described by a Poisson process.

Recent studies, however, considered rainfall to occur in clusters and used the Neyman - Scott model in place of Poisson models. Studies of Gupta (1973), Eagleson (1978 a,b), Cordova and Bras (1981) and Cordova and Rodriguez Iturbe (1985) considered the Poisson process while Kavvas and Delleur (1981); Waymire and Gupta(1981), Rodriguez Iturbe et al (1984,1987) used the cluster models.

The Poisson and compound Poisson models for the temporal rainfall occurrences and magnitudes consider rainfall events in the form of instantaneous bursts in time. The occurrence times of the bursts are modelled by a Poisson process. Then to each burst occurrence time an independent rainfall amount is attached. This results in a compound Poisson process for the rainfall amounts in time.

Smith and Karr (1983) developed a variant of this model and applied it to summer season rainfall occurrences in the Potomac river basin. In their model the occurrence intensity process was considered as a Markov process with two states, one being zero the other being positive. They found from the rainfall data that the interval times follow a renewal process. The model was developed in terms of its counts and inter-arrival time statistics. The two state Markovian nature of the intensity process of the model suggests that the clustering of the rainfall occurrences are obtained in this model by the alternation of wet and dry periods.

Thompson (1984) developed a model for monthly rainfall based on the Poisson process with an independent exponentially distributed rainfall amount. The Poisson distribution was said to have fitted the monthly rainfall totals extremely well.

The Neyman Scott cluster model for the occurrence of rainfall events in time is a two level process (Kavvas and Delleur,1976). At the primary level, there is the occurrence process of the rain fall generating mechanism (RGM) which represents cyclonic fronts or convective cloud systems. At the secondary level of the process, to each RGM there corresponds a random number of individual rainfall events which form a cluster around the RGM, and which are independently located in time according to a common distribution.

Cluster centers in the Neyman scott model are not rain cells, but are just points around which the density of cells is larger than in other regions. Each cluster has associated with it a number of rain cells which is a random variable, independent and identically distributed for each cluster center (Bras et. al,1988)

Chang et al (1984) observed that the Neyman-Scott cluster model, in its continuous form is inappropriate for the description of discrete time rainfall processes. Chang et al (1984) developed various models from the auto-regressive family and applied the models to the daily rainfall data of Indiana. They concluded that the DARMA family of models can preserve various desirable statistical properties of the daily rainfall process.

Rodriguez-Iturbe and Eagleson (1987) and Sivapalan and Wood discussed event based space-time rain cell model. The basic assumptions of the Rodriguez Iturbe and Eagleson (1987) model are: 1) storm events are made up of a random number of circular rain cells with centers distributed over space according to a two dimensional Poisson process with mean cell density λ (L^{-2}).

2) the birth time of each cell (relative to the beginning of the storm) is an exponentially distributed random variable with an average birth rate of β (T^{-1}).

3) the life time of each cell is an exponentially distributed random variable with an average life time α (T^{-1}).

4) the rainfall intensity at the center of each cell at cell birth is an exponentially distributed random variable with mean $\bar{i}_o$ (LT^{-1}).

5) rainfall from each cell spreads out from the center according to a quadratic exponential decay function with a characteristic cell radius D (L).

6) all of the cells move together with a common velocity U (LT^{-1}).

Rodriguez-Iturbe and Eagleson (1987) further discussed more complex extensions to the basic model which provide for clustering, random cell sizes and moving storms.

2.4 Data Generation

Data generation techniques or Monte Carlo simulation have been widely used in hydrology. These range from generating large samples of data from known probability distributions to studying the probabilistic behaviour of complex hydrological processes. The value of the model depends on its ability to generate new rainfall series which correctly reproduce in a statistical sense characteristics that are observed in the historical series.

Many rainfall models have been proposed for generating daily rainfall data. The methodology used for the generation of daily rainfall consist of two parts : the first determines the occurrence of dry and wet days and the second generates the rain fall depth on wet days. For reproducing the occurrence of the rain and no rain events, the techniques as discussed in the following sections have been used.

2.4.1. Markov Chain

In this approach events are considered to belong to a certain number of states. No rain is one state, and the other states, which are wet may be only one or several. The probability of a day belonging to a certain state is dependant on the occurrence of several previous states.

Gabriel and Newman (1962) found that a simple Markov chain probability model fitted Tel Aviv data of daily rainfall occurrence. Several authors (Caskey,1963; Weiss, 1964) used the first order Markov chain model for modeling daily rainfall occurrences.

Raudkivi and Lawgun (1970) used a first order Markov chain to model the durations, yields and the distribution of the rainfall within the storm. The intervals between rainfalls are generated by sampling from a frequency distribution fitted to the historical data.

A two state first order Markov chain model was adopted by Selvalingam and Miura (1978). This involved the construction of transition probabilities for each calendar month. Richardson (1981) also used a two state first order Markov chain and fitted a fourier series for modeling the occurrence of rain.

Haan et al (1976) developed a stochastic model based on a first order Markov chain to simulate daily rainfall at a point. The model uses historical rainfall data to estimate the Markov transitional probabilities. The model was said to be capable of simulating daily rainfall records of any length based on the estimated transitional probabilities and the frequency distribution of rainfall amounts.

Swift and Schreuder (1981) fitted several statistical distributions namely log-normal,gamma, Weibull, S_B, and beta distributions to daily rainfall for each calendar month for a 38 year period. The data was from the southern Appalachian mountains. The S_B distribution which is a generalisation of the log normal distribution was consistently found to be a best fit distribution. Higher order Markov Chains up through fifth order were found to have described the data better than the lower order chains.

Roldan and Woolhiser (1982) and Woolhiser and Roldan (1982) used a first order Markov chain as the occurrence process and a mixed exponential distribution for the daily rainfall. They compared the Markov chain mixed exponential model with several alternatives for five widely scattered stations in the United States. The model was found to be superior to the alternatives studied including chain dependent models i.e. where the distribution of precipitation on wet day is dependent on the state of the previous day.

2.4.2 Alternating renewal process

This process consists of alternating wet and dry spells. Wet spells are assumed independent and belong to a particular distribution. Similarly dry spells are assumed independent and belong to another distribution.

Cole and Sheriff (1972) generated wet and dry sequences by sampling alternatively for the length of wet and dry spells using empirical distributions.

Buishand (1978) used truncated negative binomial distribution for the length of wet and dry spells. For rainfall stations with long dry season, he found difficulty to fit distributions to the length of wet and dry spells during dry season and during the transition.

After the sequences of wet and dry spells are modeled the rainfall amounts within the wet spells are generated by the Monte Carlo method of sampling from a two parameter Gamma distribution. Cole and Sheriff (1972) made three distinct analyses of rainfall amounts based on the following : a solitary wet day, the first day of a wet spell, and the remaining days of a rainy spell.

Haan et al (1976) used a multi state 7 x 7 Markov chain model and employed a uniform distribution for each of the wet states except for the last for which an exponential distribution was assumed. The model was tested on data of seven rainfall stations in Kentucky. A separate transition probability matrix was used for each month. The class boundaries for the states in the Markov chain were found by using geometric progression. The comparison of simulated rainfalls with observed rainfalls indicated that the model generated rainfalls exceeded the historical rainfalls on average by about 2.5 %.

Selvalingam and Miura (1978) modified the above procedure by having twelve parameters for the exponential distribution. However, they obtained the parameters empirically by trial and error until the model adequately reproduced the daily maximum rainfalls in a month. Further they assumed the rainfall amounts on wet days of each month to be independent and fitted a three parameter Gamma distribution to the square root transformed values of the data. The general rainfall on wet days in this way did not preserve the correlation between rainfall amount and the duration of the rainfall event.

Carey and Haan (1975) used transition probabilities only for transitions into the state corresponding to no rain. A two parameter Gamma distribution was used to generate the rainfall depths on wet days. Buishand (1978) adopted a Gamma distribution. The mean rainfall on a wet day was related to its position in a wet spell in the following way

(i) solitary wet day;
(ii) wet days bounded on one side by a wet day;
(iii) wet days bounded on each side by a wet day.

Richardson (1978) developed a model based on a multivariate normal distribution for generating daily rainfall. The square root of daily rainfall was found to approximate a sample from a uni-variate normal distribution that had been truncated at zero. The model has however, the limitation that where there were large number of zeros.

Srinivasan and Gomes (1988) used the analysis of variance model for the generation of synthetic rainfall sequences of daily rainfall in a semi arid region in northeast Brazil. Data for a period of seven years (1970-76) in the Oscar Barros watershed was used. The basin mean rainfall was generated for seven years using a Gamma distribution. The individual station rainfalls were then generated by considering the rain gauge network as a matrix. The basin was divided into grids so that each grid area was represented by a rain gauge station. Based on the study, the authors concluded that the analysis of variance model explained adequately the spatial variability of the rainfall in a basin and could be used to generate synthetic rainfall sequences of different individual stations.

In India, Seth and Obeysekera (1979) used the transition probability matrix method for generation of daily rainfall data in the Naula catchment of Ramganga basin in north India. The generated data has been used with a deterministic rainfall runoff model for generation of daily streamflow data.

Rao and Rees (1991) used the alternating renewal process model for simulation of daily rainfall during monsoon season for one station in western India. The authors mentioned that in addition to simulating the monthly means and variances of the historical series well the model also predicted the distributions of the wet and dry spells of different lengths adequately.

Studies for Rajasthan included those of Gupta (1965) and Singh and Kripalani (1982). Gupta (1965) analysed the frequencies of wet and dry spells at five stations in Rajasthan namely Bikaner, Jodhpur, Ajmer, Jaipur and Udaipur for the southwest monsoon period. The study was based on the daily rainfall data of these stations for the period 1891 to 1919. It was seen that the frequencies of rain spells of less than 5 days were common and those of more than 10 days were extremely rare. Frequencies of dry spells of less than 5 days were common for all five stations. Frequencies of dry spells are greater than 15 days were also common at Bikaner, Jodhpur, and Ajmer but were less frequent (20 percent of the total days) at Jaipur and Udaipur.

Singh and Kripalani (1982) studied the dependence in daily rainfall of 12 stations and in daily rainfall of 10 meteorological regions during the summer monsoon by (i) analysing the rainfall as stochastic point process by fitting several types of models like log model, Markov chains of order 1 and 2 to station data and (2) fitting auto regressive and ARMA models to spatially averaged data. The significant findings of the study were :

(i) Rainfall amounts on successive days within a rainy spell were uncorrelated but the rain amount on the second day of a rain spell was more than on first or last day which in turn was more than rain on isolated days.

(ii) rain intensity of wet spells increased as the length increased.

(iii) the auto regressive model of order 1 fitted the time series of spatially averaged daily rainfall satisfactorily .

2.5 Spatial variability

Studies on spatial variation of rainfall have been carried out by a number of authors. Statistical techniques such as correlation analysis have been used for the design of network of rain gauges (Caffey, 1965; Hershfield, 1965; Hendrick and Comer, 1970; Stol, 1970). Correlation analysis has been found to be useful for dealing quantitatively with localised rainfall.

The field of correlation of annual rainfall has been computed by Caffey (1965) for many regions in western United States. He showed that an elliptical shape of the correlation response surface about a control gauge is characteristic.

Using storm rainfall for a number of eastern watersheds in the United states Hershfield (1965) showed how the correlation field which is sensitive to rainfall amount may be used to estimate the spacing of rain gauges required to adequately define the isohyetal pattern.

Hendrick and Comer (1970) examined space variations of daily rainfall over the Sleepers river watershed in northern Vermont, USA. A correlation field function was derived which was then used to determine rain gauge density and configuration required for specified accuracy of watershed estimates of rainfall. The correlation analysis indicated that meteorological factors such as storm size, storm direction or direction of atmospheric moisture flux predominate over topographic features in determining spatial association in daily rainfall variations.

Ramasastri (1986-87) used the interstation correlation for modeling the movement of four tropical storms in Naramada basin in central India. Hourly rainfall data of 12 to 15 self recording rain gauges during the storm period was used for the study. The plot of inter-station correlation of hourly rainfall vs inter-station distance is shown in figure 2.4. It was seen that the points are scattered widely and no particular trend was noticed.

Corradini and Melone (1989) studied the surface rainfall field structure over a region in upper Tiber river basin located in central Italy within the Mediterranean area. Two storm types within the cold front system are considered. The study region was divided into seven homogeneous zones based on spatial inter-dependence determined through cross correlation. It was seen that the structure of the homogeneous zones was practically unrelated with that of the average rainfall field but somehow linked to the orography. The rainfall field was found to be mainly determined by random mesoscale rainfall areas with limited effects of hilly orography.

Ramasastri (1988) studied the space time characteristics of rainfall in a semi urban catchment in the state of Uttar Pradesh

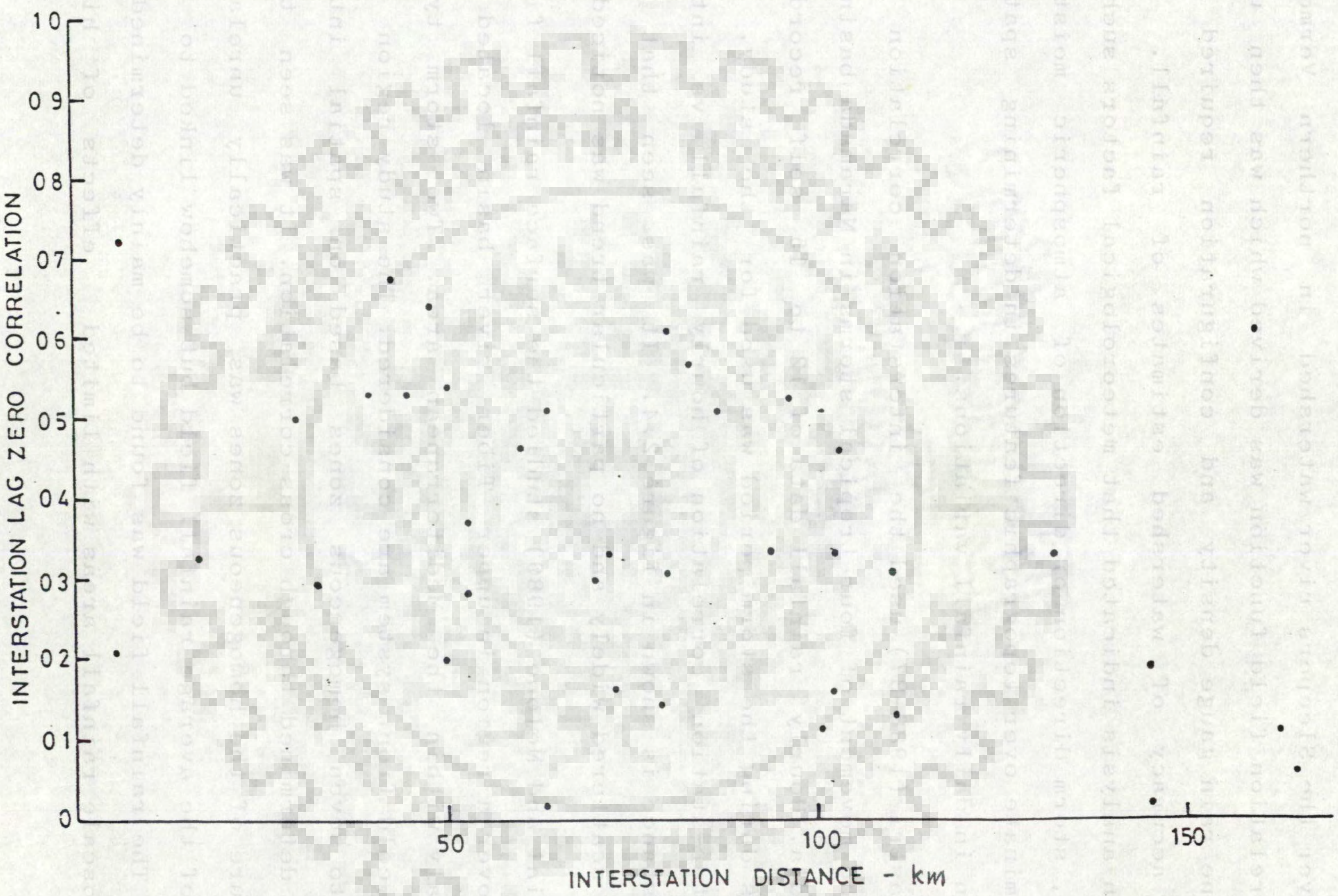


FIG. 2.4 INTERSTATION DISTANCE Vs INTERSTATION CORRELATION (AUG. 1978)

in India. Based on the analysis of the short duration rainfall of three observatories over a three year period (1985-87), it was concluded that (i) there was no persistence in the 15 minute rainfall series (ii) the 15, 30, 45 and 60 minutes rainfall intensities were spatially coherent as indicated by the high interstation correlation.

Wheater et al (1991) presented the general spatial and temporal characteristics of rainfall of five wadis in southwest Saudi Arabia. Hourly data of 100 autographic rain gauges for a period of two years (1984 and 1985) was used for the study and model development. Most point rainfalls were observed to be of 1 to 2 hr duration. The analysis of spatial structure indicated essentially independent point occurrences. The probability of joint occurrence and cross correlation of hourly rainfall even over small distances (8 to 20 km) were small. A two stage hourly rainfall model for hourly rainfall was formulated on the assumption that point rainfall properties were independent of location. First the occurrence of a catchment rain day was simulated and secondly, the locations at which rainfall occurs and the point temporal characteristics were generated. The simulation was said to have faithfully reproduced all the characteristics such as the distribution of event durations, hourly depths, and start times.

2.5.1 Correlation function

Analysis of the spatial structure of observed rainfall is preliminary to the spatial simulation of rainfall field. The correlation between rainfall values is expected to decrease as the distance between their locations increases.

Stol (1972) proposed two versions of an exponential model adopted to isotropic fields in the Netherlands in which he found no direction related variations of the correlation - distance relationship. Stol also derived separate correlation functions for each month and proposed an inclusive model for correlation functions as they change throughout the rainy season.

Hendrick and Comer (1970) used a linear model in which isotropy of the precipitation field in respect to the correlation function was not assumed. The models used in both the studies mentioned assumed a monotonous decrease of the correlation function with increasing distance.

Sharon (1974) based on analysis with data of daily rainfall for New England found that the correlation does not monotonously decrease with increasing distance. He suggested that correlation functions should be derived separately for groups of days which are homogeneous to the nature of rainfall (stratiform, cellular etc.)

Upadhyay et al (1990) studied the space correlation structure of rainfall field for 21 meteorological homogeneous regions in India. For this purpose rainfall data of 2000 stations during the period 1901 - 1970 has been used.

Beek et.al (1992) studied the spatial variation of daily rainfall in Europe over an area of 450,000 km^2 covering Belgium, The Netherlands, Luxemburg and parts of Germany. Spatial dependence was modeled by means of semi variograms.

2.5.2 Simulation of Rainfall field

Estimation of spatial phenomenon has important applications. Simulation could be used to supplement data for the field outside the boundary of a rain gauge network as estimation techniques could not be used for the purpose. The resulting field may be used for analysing a storm structure or may be input to a distributed rainfall runoff model.

Many methods have been proposed and applied to rainfall fields to estimate point or average values at ungauged sites. These range from simple methods to sophisticated methods. The simple methods include the nearest neighbor method and the arithmetic mean. The sophisticated methods include (i) spline surface fitting, (ii) optimal interpolation proposed by Gandin (WMO,1970), (iii) the kriging method, and (iv) interpolation based on empirical orthogonal functions.

Creutin and Obled (1982) made a comparative study of the six methods described above over a region with high variability of rainfall in France. Based on the study the authors concluded that none of the statistical methods are able to fully account for climatologically and spatially, the statistical properties of rainfall fields. The authors suggested that the problem could be partially overcome by using analytical transformation of the raw variable such as log transformation. Nevertheless, the authors recommended use of the statistical methods and preferred the optimum interpolation method of Gandin over the Kriging method considering the relative computational ease of the former.

Perry and Shafer (1990) described a spatially varied rainfall model. Basically the rainfall model was a function of frequency, global position, eccentricity, and orientation of the storm pattern. Given the location of the rainfall model center and the centroid of the sub basin, the distance and bearing of the sub basin with respect to the center of the rainfall model were determined. The authors modified the NUDALLAS flood hydrograph generation package so that multiple storm centers could be simulated simultaneously. The modified program simulated a grid placed over the drainage basin and analysed a new storm center at each intersection of the grid which was used to produce the peak flood at the basin outlet.

2.6 Summary

From the review of some of the relevant studies by different authors the following important points could be noted :

(i) The methods used by various authors for analysis of statistical characteristics of rainfall series such as randomness, persistance and trend are generally similar and follow the procedure recommended in WMO (1966). However, in the methods used for simulation of rainfall especially, the daily rainfall there is wide variation. These methods used range from Markov chain to the Poisson process and Neyman-Scott cluster models.

In India, the studies carried out for rainfall are generally statistical analysis of monsoon and annual rainfall for climatological purposes. Most of the studies are on meteorological sub-division basis. Very few studies (Seth and Obeysekara,1979 Rao and Rees, 1991) were done for simulation of rainfall data and its generation for hydrological or agricultural purposes.

Studies for Rajasthan are limited to only analysis of monsoon and annual rainfall for identifying trends and periodicities. No studies have been done for simulation and generation of rainfall data for Rajasthan.

(ii) Comparatively few studies for simulation of rainfall in space are reported. The widely used methods are kriging and covariance methods while turning bands method (Kottegoda and Kassim, 1991) is reported recently.

The review did not bring out any Indian studies for simulation of rainfall field. The only study (Upadhyay et al, 1990) was on correlation structure and its mathematical formulation which was done for meteorological sub-divisions. The study also covered the two meteorological sub-divisions of Rajasthan namely east and west Rajasthan.

(iii) The literature review indicated that complex models for simulation of rainfall are avilable which have been developed mostly in USA and other extra tropical countries. Rainfall in these countries is mainly caused by movement of frontal systems while in Rajasthan the rainfall is mostly caused by moving tropical storms, local thunder storms and mid tropospheric troughs during the monsoon season and western disturbances during winter. Distribution of rainfall is skewed because of large number of dry days and occasional severe rain storms.

The simpler Markov chain based models were thought to be appropriate for modeling rainfall in east Rajasthan and were used in this study for simulation and generation of rainfall data and reported in Chapter VII. For simulation of rainfall field the covariance model has been used and the generation of the rainfall field is described in Chapter VIII.

CHAPTER III

STUDY AREA

3.1 General :

The state of Rajasthan lies in an area bounded by 23° 03' N and 30° 12' N latitude and 69° 30' E and 78° 17' E longitude. The state has a total area of 3,42,239 sq.km. The state has a population of approximately 41 million as per the 1991 census. The water requirement for domestic purposes was estimated at 0.1332 million hectare metre in 1991.

The present drainage system comprising of 59 river catchments covers an area of 1,59,611 sq.km (47%) but only the Chambal and the Mahi catchment (1,10,341 sq.km i.e 32 %) contribute dependable supplies. The agricultural production in the state is dependant on rainfall. The principal crops of the state are jowar (sorghum), bajra (pearl millet), maize, gram, wheat, oil seeds, cotton, sugar cane and tobacco.

3.2 Physiography

The distinguishing feature of the state is the Aravali range (Figure 3.1). Presence of moderate orographic effect and absence of maritime air influence to a large extent the climate of the state.

The entire west Rajasthan between 24° 37'N and 27° 42'N lat and 70° 05'E and 70° 22'E long. is sandy and sterile. The only important river in west Rajasthan is Luni (meaning salty river).

3.3 Climate:

The climate of the state is mainly semi arid in east Rajasthan and arid in west Rajasthan. A small pocket in the south

Figure: 3·1 PHYSICAL FEATURES

With Courtsey from:
CLIMATE OF RAJASTHAN STATE
Published by:
INDIA METEOROLOGICAL DEPARTMENT, PUNE

east and around Mount Abu has climates of sub-humid and humid type.

The winter season November - March is followed by pre-monsoon Apr. - June. The period from July to middle of September constitutes the south west monsoon season and the period from the later half of September to October forms the post monsoon period.

The SW monsoon sets in over the eastern parts of the State by last week of June and covers the entire state by first week of July. The monsoon season (June- Sep.) contributes nearly 80 to 90% of annual rainfall. The two principal rainy months are July and August each accounting individually for about 30 % of annual rainfall. In each of these months there are 2 - 7 rainy days in west Rajasthan and 7-14 rainy days in east Rajasthan (IMD, 1988).

The withdrawl of the SW monsoon begins from North Western parts of the state around 1st Sept and by 15th Sept it withdraws from the entire state.

3.3.1 Rainfall

The mean annual rainfall of west Rajasthan is 31.7 cm and east Rajastan is 68.3 cm (IMD,1988) . The monsoon season rainfall decreases from 50 cm in the east to 10 cms in the west. Scantiness of monsoon rain in west Rajasthan is attributed to different physical processes namely subsidence and absence of mechanism to break up the inversion between lower moist air mass and upper dry air mass.

During winter (Nov. - Mar) east and west Rajasthan receive 2.6 and 1.7 cm of rainfall respectively. This occurs in association with the western disturbances which move from west to east over the state.

Variability of rainfall in general is high over the state. The C.V is about 30 to 50 % over east Rajasthan and 50 to 80 % over west Rajasthan. C.V is high in winter, summer and post monsoon seasons.

The normal annual rainfall computed on the basis of 85 years (1901 - 85) data and the corresponding coefficient of variability are shown in figures 3.2 to 3.3 respectively.

3.3.2 Temperature

Day temperatures are more or less uniform over the plains and increase southwards and northeastwards. In general, the night temperatures are lower in higher latitudes except during the southwest monsoon season when they are more or less uniform. Both day and night temperatures are lower over plateau and at high level stations than over plains.

May is hottest month with mean maximum temperature at $41^{o}C$ in plains. The highest temperature recorded was $50^{o}C$ in June 1934 at Ganganagar. January is the coldest month. Mean minimum temperature varies from 5^{o} to $11^{o}C$. July and August have the smallest diurnal temperature range.

3.3.3 Humidity

The relative humidity is generally high during the period June - Sept. It is about 46 % in June, 70 % and 76 % respectively in west Rajasthan and east Rajasthan in August. The relative humidity is low in summer. In west Rajasthan it varies from 15 to 34 % and in east Rajasthan from 14 to 37 %.

3.3.4 Evapotranspiration

The annual values of potential evapotranspiration computed by Penman's formula (Rao et al, 1971) vary from 206 cm in the west

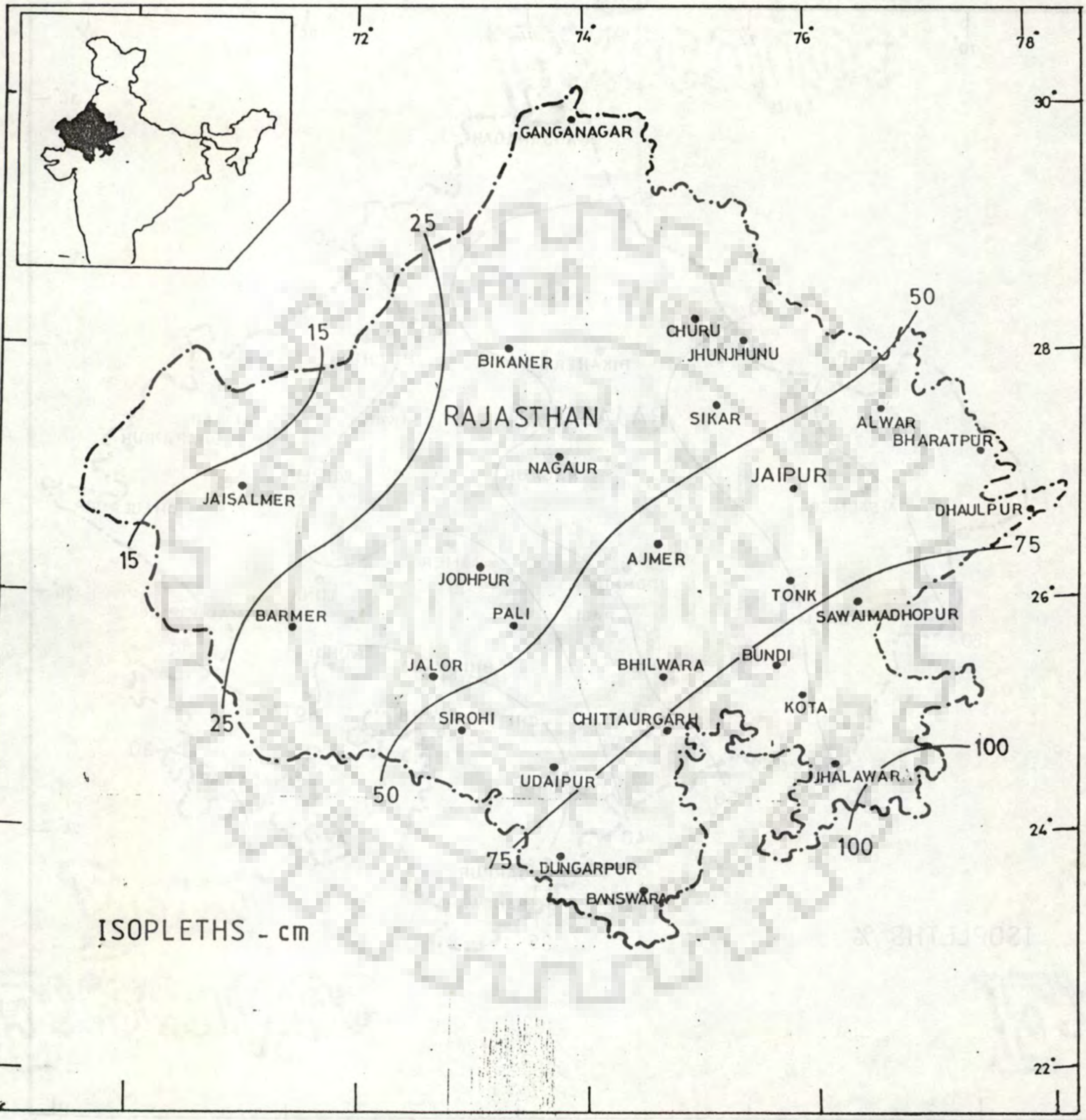


Figure 3.2 Mean Annual Rainfall - cm

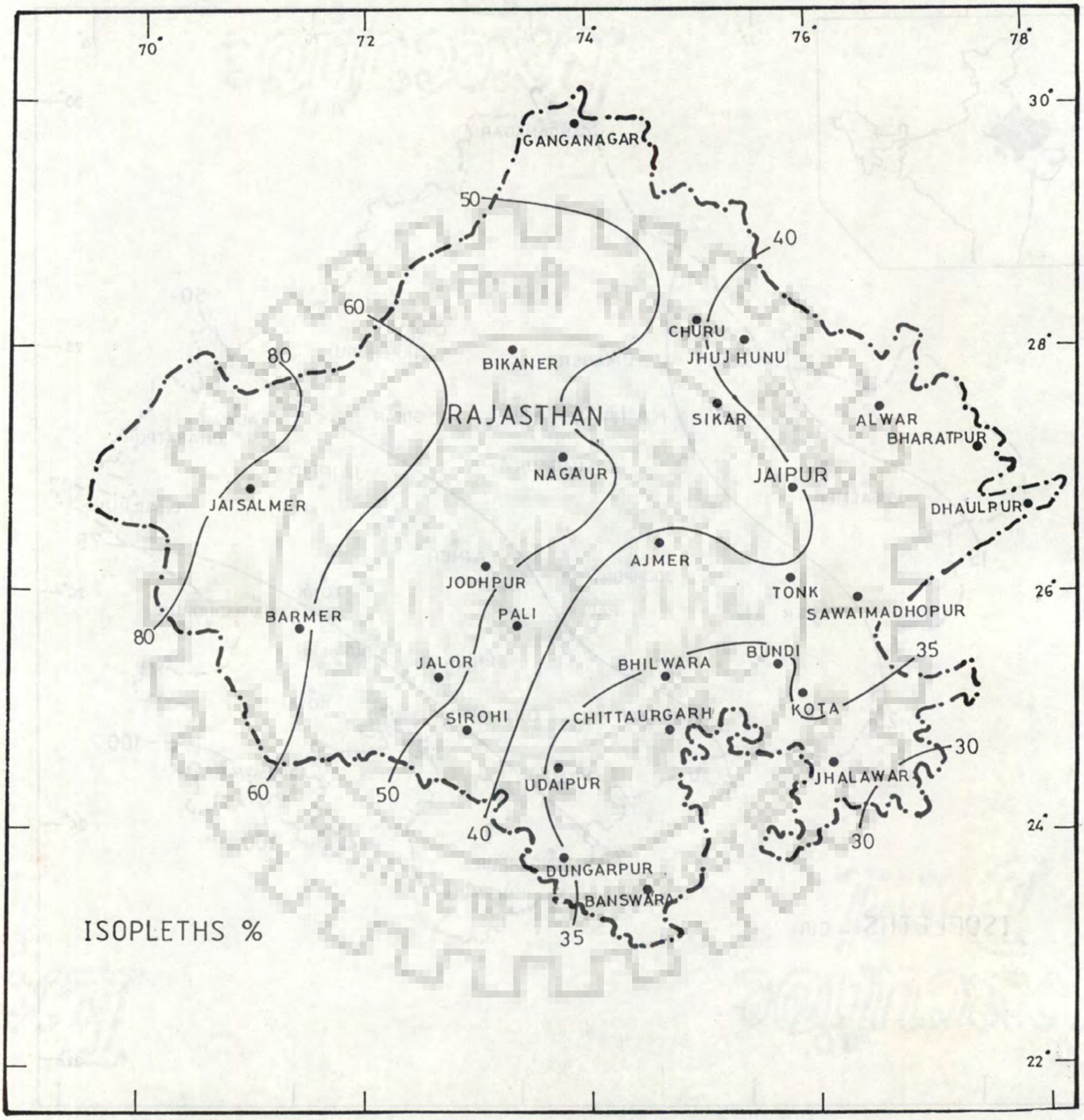


Figure 3.3 Coefficient of Variability - Annual Rainfall

to 138 cm in the south.

3.3.5 Droughts

Thirteen districts in the state have been declared as drought prone (Central Water Commission, 1982). Seven of these are in east Rajasthan and six in west Rajasthan. They are listed below.

East Rajasthan

1. Ajmer	5. Nagaur
2. Banswara	6. Pali
3. Dungarpur	7. Udaipur
4. Jhun Jhunu	

West Rajasthan

1. Barmer	4. Jaisalmer
2. Bikaner	5. Jalore
3. Churu	6. Jodhpur

Sharma (1988) analysed the frequency of drought occurrence in Rajasthan based on rainfall data for 30 years (1957 to 1986). For this purpose, the drought was classified as moderate and severe according as the year's annual rainfall was deficient by 25 to 50% or more than 50% of the normal annual rainfall. The frequency of moderate and severe droughts is given in tables 3.1 and 3.2 and is also shown in figure 3.4 .

Based on IMD (1988) and Sharma (1988) the drought years (years annual rainfall less than 75 % of normal annual rainfall) in east and west Rajasthan are listed below :

East Rajasthan

1877, 1898, 1899, 1901, 1905, 1907, 1911, 1913, 1915, 1918, 1925, 1929, 1939, 1941, 1951, 1965, 1966, 1972, 1979, 1984, 1985, 1986, 1987

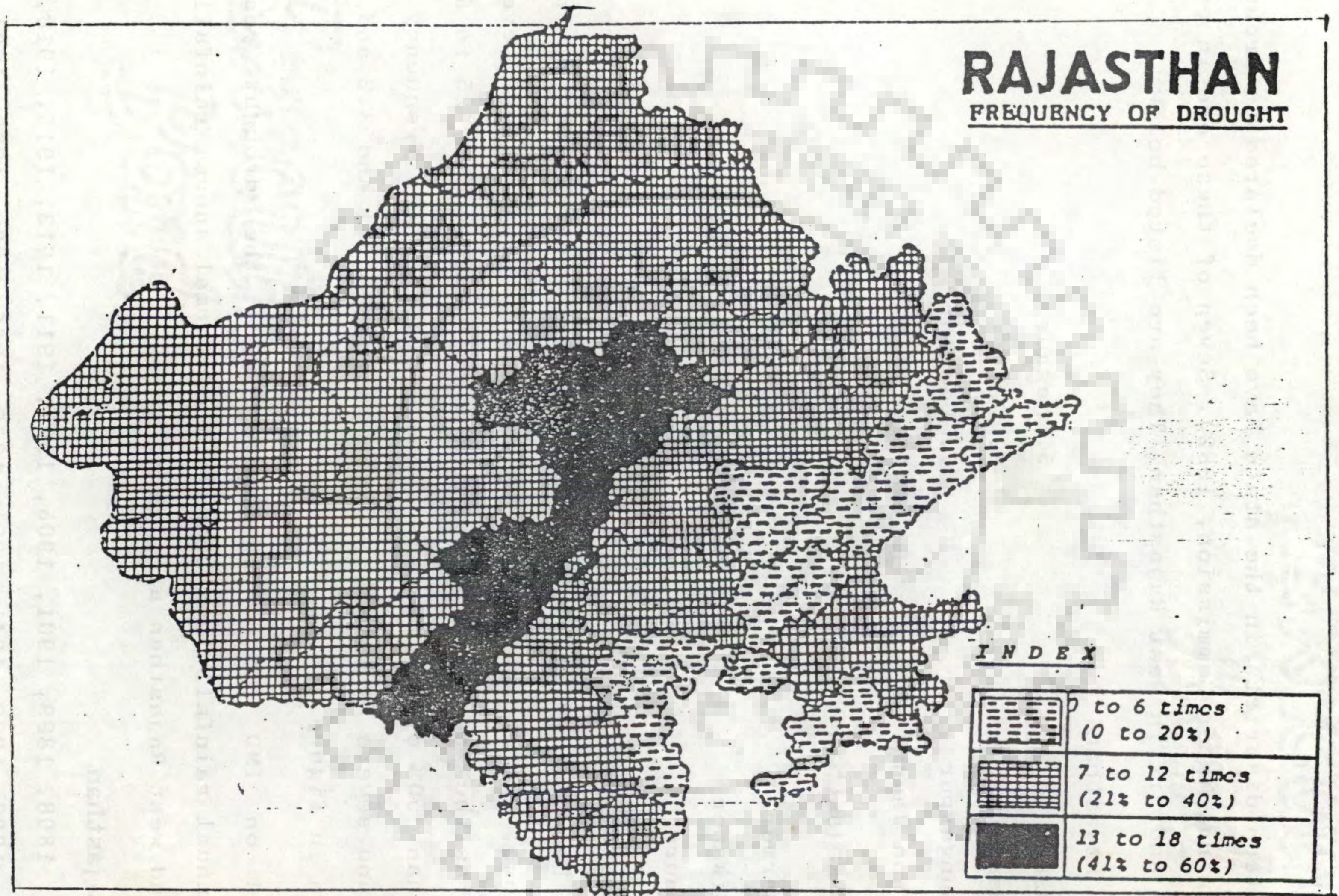


Figure : 3.4 Frequency of Droughts in Rajasthan during 30 years (1957-1986) (Courtesy : Sharma. 1988)

Table 3.1 Frequency (out of 30 years) of occurrence of moderate drought

Frequency		Districts
One	(3.3%)	Sawai Madhopur
Two	(6.7%)	none
Three	(10.0%)	Bharatpur
Four	(13.3%)	Ganganagar, Nagaur, Dholpur, Bundi
Five	(16.7%)	Bikaner, Barmer, Jalore, Sikar, Chittorgarh
Six	(20.0%)	Jaisalmer, Jhalawar, Jodhpur, Tonk, Udaipur
Seven	(23.3%)	Ajmer, Churu, Jaipur, Jhun Jhunu
Eight	(26.7%)	Banswara, Dungarpur, Kota, Sirohi
Nine	(30.0%)	Bhilwara

Table 3.2 Frequency (out of 30 years) of occurrence of severe drought

Frequency		Districts
One	(3.3%)	Alwar, Banswara, Bhilwara, Dungarpur, Jaipur, Tonk
Two	(6.7%)	Ajmer, Bharatpur, Jhun Jhunu, Sawai Madhopur
Three	(10.0%)	Bikaner
Four	(13.3%)	Jalore, Jodhpur, Pali
Five	(16.7%)	Sikar
Six	(20.0%)	Barmer, Jaisalmer, Sirohi
Seven	(23.3%)	Nagaur

West Rajasthan

1877, 1883, 1885, 1887, 1891, 1899, 1901, 1903, 1904, 1905, 1911, 1913, 1915, 1918, 1920, 1925, 1938, 1939, 1951, 1963, 1968, 1969, 1971, 1974, 1980, 1981, 1982, 1985, 1986, 1987,

3.3.6 Excess rainfall

The years of successive rainfall excess (year's annual rainfall more than 120 % of normal rainfall) in each district of east Rajasthan are listed below.

S.No	District	Years
1.	Ajmer	1908-09, 1916- 17, 1926-27, 1933-34
2.	Alwar	1908-09
3.	Bundi	1916-17,1945-47
4.	Bharatpur	1916-17
5.	Chittorgarh	1916-17, 1928-29
6.	Jaipur	1916-17,1933-34
7.	Jhalawar	1916-17,1933-34, 1942-48
8.	Jhunjhunu	1908-09,1916-1917
9.	Kotah	1916-17,1923-24,1933-34,1945-46
10.	Sirohi	1907-09,1926-27,1943-45
11.	Sawai Madhopur	1933-34
12.	Tonk	1907-09,1916-17,1923-24,1945-46
13.	Udaipur	1916-17,1926-27

Some of the years like 1907-09, 1916-17, 1926-27, 1933-34 and 1944-45 were also the years of excess rainfall in west Rajasthan.

3.3.7 Severe rainstorms

The semi arid regions also receive extreme storms with very heavy rainfalls. Ramasastri and Seth (1984-85) studied the characteristics of the severe storms in semi arid Rajasthan and neighbouring arid Saurashtra and Kutch region. Some of the severe rain storms on record were :

(i) 9 - 11 Sept 1924 with centres at Dausa and Samodh (maximum one day point rainfall 42.5 cm)

(ii) 16 - 18 July 1979 with centre at Bilara and Borunda in Guhya sub basin of Luni basin (maximum one day point rainfall 48.5 cm)

(iii) 18 - 20 July 1981 with centre at Kanota near Jaipur (maximum one day point rainfall Kanota :58.9 cm, Dausa : 55.0 cm and Bamanwas : 50.5 cm)

The study of Ramasastri and Seth (1984-85) showed that the highest one day rainfalls received at the respective storm centres were having return periods of more than 1000 years.

3.4 Hydrometeorological Network :

The hydrometeorological network in the state comprises of the raingauge stations of the state and observatories of IMD . There are 535 raingauge stations , 43 self recording raingauge stations and 51 meteorological observatories distributed in 28 districts and 59 catchments. The districtwise distribution of raingauges is shown in table 3.3

3.5 Availability of Rainfall Data

The rainfall data of all the raingauge stations in the state was published by the state Irrigation Department from 1957 (when the state of Rajasthan was formed) till 1977. Data for the period after 1977 is available in manuscript form. Prior to 1957 the data was published by the respective princely states. IMD published

Table 3.3 Districtwise Distribution of Raingauges in Rajasthan

S.No	District	Revenue	Irrigation	I.M.D	Total
1.	Alwar	16	3	1	20
2.	Ajmer	19	-	1	20
3.	Banswara	15	3	1	19
4.	Barmer	6	3	1	10
5.	Bharatpur	9	9	-	18
6.	Bhilwara	12	12	1	25
7.	Bikaner	5	-	1	6
8.	Bundi	5	1	-	6
9.	Chittorgarh	14	13	-	27
10.	Churu	7	-	1	8
11.	Dholpur	7	1	1	9
12.	Dungarpur	12	-	1	13
13.	Sri Ganganagar	12	38	1	51
14.	Jaipur *	20	13	2	35
15.	Jaisalmer	6	-	1	7
16.	Jalore	5	3	-	8
17.	Jhun Jhunu	4	-	1	5
18.	Jhalawar	11	3	1	15
19.	Jodhpur	5	6	2	13
20.	Kota	15	17	3	35
21.	Nagaur	8	1	1	10
22.	Pali	7	39	1	47
23.	Sawai Madhopur	11	8	-	19
24.	Sikar	7	-	1	8
25.	Sirohi	6	19	1	26
26.	Tonk	6	13	1	20
27.	Udaipur	18	18	5	41

* includes present Dausa district - indicates nil

data of monthly and annual rainfall and rainy days for the period 1901 - 1950.

3.6 Soils

The soils of the state can be divided into eight broad groups. Based on the morphological, climatological and physiographical characteristics, soils of the state have been grouped under 12 basic soil associations. Desert soils cover major part of the state followed by Gray brown alluvial soils and yellowish brown soils (Department of Agriculture, Govt of Rajasthan 1970).

3.7 Land Use

Agriculture is the main land use in the state. The area under forest is less than 10 % of the total area of the state(Dept. of Economics and Statistics, Govt of Rajasthan, 1990).

CHAPTER IV

VARIABILITY OF ANNUAL RAINFALL OF RAJASTHAN STATE

4.1 General

Climates of Rajasthan state are classified under arid and semi arid types. While frequent droughts are a common phenomenon all over the state, extreme events like floods also occur occasionally. A good network of rain gauge stations at the block (administrative unit smaller than a district) level is, therefore, necessary for assessing the effects of droughts , planning relief measures and for evolving contingency plans for possible drought proofing efforts. Towards this objective, a systematic study of the variability of annual rainfall over the state has been carried out using the data from 521 long term and short term rain gauges in the state.

Information on the variability has been further used for assessing the adequacy of the existing rain gauge and self recording rain gauge network in east Rajasthan using the procedure recommended by the Bureau of Indian Standards (1968) and the Kagan's (1966) technique . Based on the study the number of rain gauges and recording rain gauges required from climatological and hydrological considerations are recommended.

4.2 Methodology

For the purpose of the study, data of annual rainfall from long term and short term rain gauges in all the districts of the state has been considered. Keeping in view the large size of the state, instead of considering the state as a whole, district which is the administrative division is considered for studying the variability. The study is carried out for 26 districts as were in existence in 1985.

4.2.1 Network design using average rainfall

Bureau of Indian Standards (1968) recommended use of the following formula for the determination of the number of rain gauges required using information of the mean (normal) rainfall at each of the rain gauges located in a given catchment.

$$N = \left(\frac{C_v}{p}\right)^2 \qquad (4.1)$$

where p is the desired degree of error in the rainfall estimated from the rainfall data at the existing gauges.

4.2.2. Network design using interstation correlation

Kagan (1966) introduced a correlation function , $\rho(d)$ as a function of the distance between rain gauge stations. The form of the function depends on the spatial variability of rainfall and can be expressed as

$$\rho(d) = \rho(0)\, e^{-d/d_o} \qquad (4.2)$$

where $\rho(d)$ is the correlation function of the distance between rain gauge stations and $\rho(0)$ is the correlation coefficient corresponding to 0 distance and is estimated graphically from the plot of inter station distance against inter station correlation coefficient (figure 4.1), d_o is the distance at which correlation is reduced to 1/e times the correlation corresponding to zero distance.

Theoretically $\rho(0)$ must be equal to 1 as it is the correlation corresponding to zero distance. However, the micro-climatic variations and the random errors in measurement of

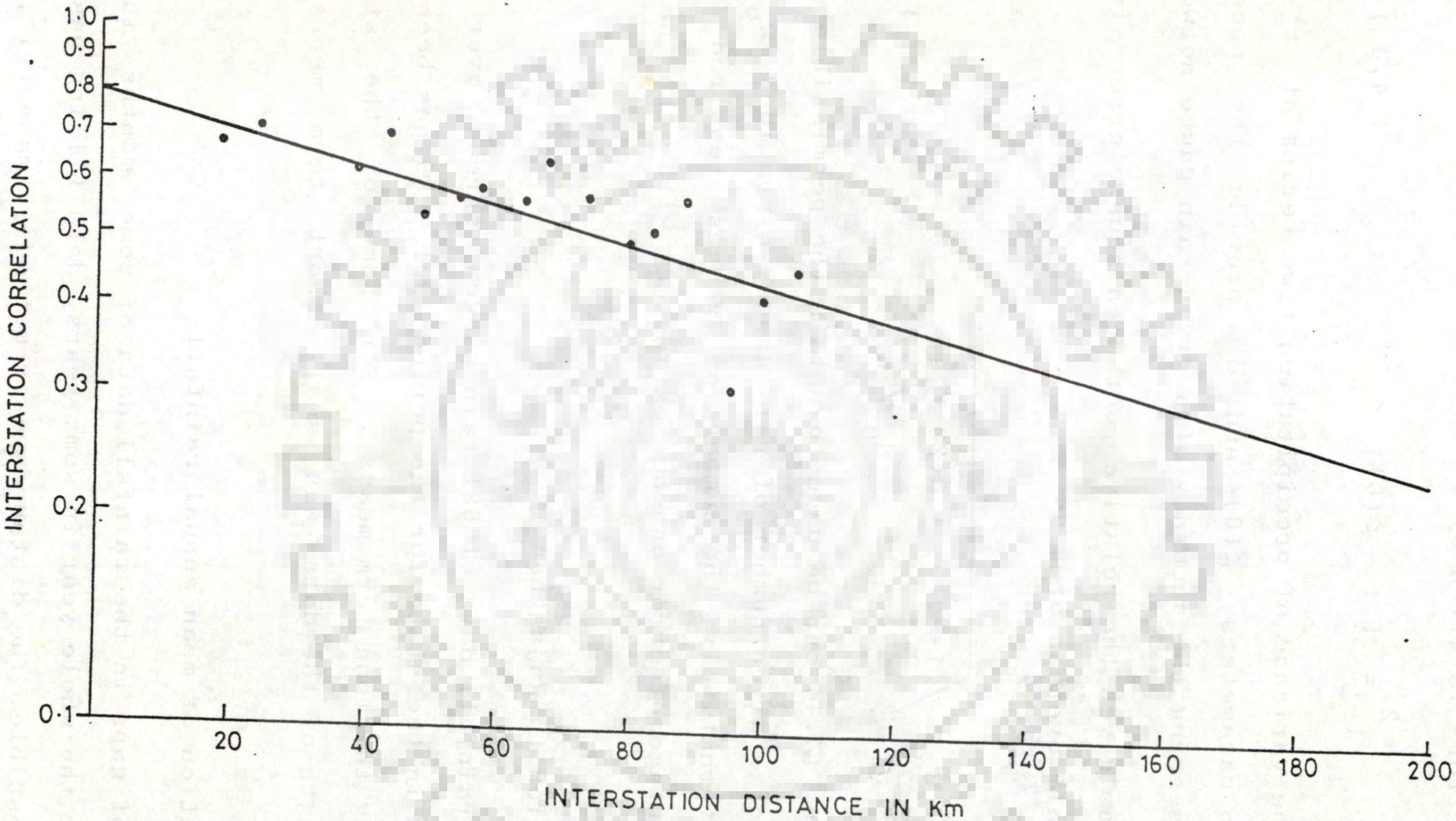


FIG. 4.1 RELATIONSHIP BETWEEN INTERSTATION DISTANCE AND INTERSTATION CORRELATION

rainfall make $\rho(0)$ as being less than unity and the variance of these random errors is given by

$$\sigma_1^2 = [1 - \rho(0)] \, \sigma_n^2 \qquad (4.3)$$

where σ_n^2 is the variance of precipitation time series at a fixed point. The two parameters $\rho(0)$ and d_o provide the necessary values for assessing the accuracy of a given rain gauge network.

Kagan has given the relative root mean square error in the average rainfall over an area as

$$Z = \frac{C_v}{\sqrt{n}} \sqrt{1 - \rho(0) + \frac{0.23 \sqrt{s}}{d_0 \sqrt{n}}} \qquad (4.4)$$

Equation (4.4) can be used to obtain the permissible value of error Z for a given number of rain gauges n provided ρ_o and d_o are known. Alternatively, the number of gauges required for a desired percentage of error can be estimated with the help of equation (4.4).

4.3 Application to Rajasthan

Annual rainfall data of 521 rain gauges spread over twenty six districts in the state for the period 1901 - 85 has been used for estimating the long term means . For some of the stations where the length of the data was small short term means were computed.

4.3.1 Computation of mean annual rainfall

Because of gaps in the rainfall data of some months in some years and for the whole year in some years, data filling has been done where possible. The distance power method (Ramasastri , 1989) with a value of 2 for the power has been used to fill the data. Where the data gaps were more than two years, either continuously or otherwise, the data has not been filled up and the stations have been omitted from the analysis. However, where the stations have been commissioned late i.e far later than 1901 the short period means have been calculated. Thus, the annual means of rainfall included those based on long term data (1901 to 1985) and also means based on short periods of varying lengths but not less than 25 years in any case.

4.3.2 Expected error

The error in the areal rainfall for a given number of rain gauges has been estimated using the formula given in (4.1) and the Kagan's inter station correlation technique. In table 4.1, the values of expected error corresponding to different number of rain gauges is given for each district.

In table 4.2, the requirement of rain gauges for the twenty districts in east Rajasthan used for the study is shown. A criterion of 5 % error in the estimated mean areal rainfall is used.

4.3.3 Network based on hydrological considerations.

As mentioned earlier under Chapter III, the important river systems in the state are the Chambal, Mahi, Luni and Sahibi rivers. Being arid there are only a few rivers in west Rajasthan. The catchment wise rain gauge network requirement, therefore, has been done only for the rivers in east Rajasthan.

Because of the rather non uniform rain gauge distribution some of the sub-catchments are not covered by even a single rain gauge, while some have only one or two rain gauges. As the number

Table 4.1 Relative Error of Mean Areal Rainfall for a Given Number of Raingauges

Sl No	District	Relative error of mean areal rainfall for				
		n = 2	n = 5	n = 8	n = 10	n = 15
1.	Ajmer	6.52	3.77	2.88	2.53	2.02
2.	Alwar	2.96	1.77	1.37	1.21	0.98
3.	Banswara	2.95	1.76	1.36	1.21	0.97
4.	Barmer	4.67	2.47	1.80	1.55	1.19
5.	Bharatpur*	3.02	1.83	1.42	1.26	1.02
6.	Bhilwara	5.12	2.94	2.23	1.96	1.56
7.	Bikaner+					
8.	Bundi	1.97	1.12	0.85	0.75	0.59
9.	Chittorgarh	5.15	2.49	1.90	1.68	1.34
10.	Churu	3.27	1.91	1.48	1.29	1.04
11.	Dungarpur	3.51	2.15	1.68	1.50	1.21
12.	Ganganagar	7.09	3.85	2.84	2.47	1.93
13.	Jaipur#	4.46	2.47	1.85	1.61	1.26
14.	Jaisalmer+					
15.	Jalore+					
16.	Jhalawar	2.67	1.55	1.19	1.05	0.84
17.	Jhun Jhunu	4.04	2.30	1.74	1.53	1.21
18.	Jodhpur	7.44	4.09	3.04	2.65	2.07
19.	Kota	4.28	2.53	1.94	1.72	1.38
20.	Nagaur	3.35	1.91	1.45	1.27	1.01
21.	Pali	5.70	3.26	2.49	2.10	1.74
22.	Sawaimadhopur	3.27	1.89	1.44	1.27	1.01
23.	Sikar	3.94	2.28	1.74	1.53	1.22
24.	Sirohi	1.63	0.87	0.62	0.54	0.41
25.	Tonk	2.19	1.23	0.92	0.80	0.63
26.	Udaipur	4.12	2.22	1.63	1.41	1.09

* includes present Dholpur and # includes present Dausa districts

\+ could not be computed as length of data was not adequate.

Table 4.2 District-wise Requirement of Rain gauges in East Rajasthan

Sl. No	District	Area in km^2	Rain gauges existing	required	balance
1.	Ajmer	8504	20	7	nil
2.	Alwar	8394	20	1	nil
3.	Banswara	5042	19	4	nil
4.	Bharatpur *	8100	27	1	nil
5.	Bhilwara	10448	25	6	nil
6.	Bundi	5564	6	4	nil
7.	Chittorgarh	10446	27	4	nil
8.	Dungarpur	3781	13	1	nil
9.	Jaipur @	13969	35	3	nil
10.	Jalore	11699	8	3	nil
11.	Jhalawar	6229	15	1	nil
12.	Jhunjhunu	5913	5	10	5
13.	Kota	12417	35	4	nil
14.	Pali	12441	14	17	3
15.	Sawai Madhopur	10541	19	5	nil
16.	Sirohi	5127	26	2	nil
17.	Tonk	7163	20	2	nil
18.	Udaipur	17642	41	4	nil

* includes present Dholpur and

@ includes present Dausa district

of rain gauges in a majority of the sub-catchments was less than four, the inter station correlation method could not be used. The number of rain gauges has, therefore, been estimated only using the Eq 4.1 considering the data of gauges in the neighbouring catchments also. The requirement of rain gauges in different sub-catchments in east Rajasthan worked out on this basis is given in table 4.3

4.3.4 Self recording rain gauges

The large scale flooding in Jaipur city and neighbouring areas in 1981 had emphasized the need to have adequate number of self recording rain gauges (SRRG) in the various river catchments. At present besides the eleven SRRGs maintained by IMD, there are only six SRRGs of the irrigation department.

A criterion of one SRRG for each of those catchments with catchment area between 1000 sq km and 5000 sq.km and two SRRGs for those with more than 5000 sq km catchment area has been adopted to determine the requirement of SRRGs. For catchments with areas less than 1000 sq km, the rainfall time distribution could be worked out on the basis of the nearby SRRG.

4.4 Results

From table 4.1 it is seen that the error of mean areal rainfall is less than 10% for even 2 rain gauges in case of all the districts and only in case of five districts namely Ajmer, Chittorgarh, Ganganagar, Jodhpur and Pali the error is more than 5% for 2 rain gauges.

In the 58 sub-catchments, five do not have even a single rain gauge while ten sub-catchments have 10 - 15 gauges and seven have more than 15. In majority of the sub-catchments the existing

Table 4.3 Catchment-wise Requirement of Non-recording and Recording Raingauges

Sl.No	Sub catchment	Catchment area km	Non-recording			Recording		
			Existing	Estimated	Balance	Existing	Estimated	Balance
Shekhawati valley								
1.	Kantli	2810	1	11	10	-	1	1
2.	Dohan	993	1	1	-	-	-	-
3.	Navalgarh Nallah	479	1	1	-	-	-	-
4.	Krishanwati	322	-	1	1	-	-	-
5.	Ranoli	492	-	1	1	-	-	-
Sabi								
6.	Sabi	4566	13	2	-	1	1	-
7.	Barah	3146	11	3	-	1	1	-
Banganga								
8.	Banganga	6747	20	1	-	-	2	2
Gambhir								
9.	Gambhir	4786	12	1	-	-	1	1
Parbati								
10.	Parbati	1898	6	1	-	1	-	-
11.	Menda	4235	11	3	-	1	1	-
Banas								
12.	Mashi	7000	16	1	-	-	2	2
13.	Morel	5991	14	1	-	3	2	-
14.	Dhil	800	2	1	-	-	-	-
15.	Kalisil	751	2	1	-	-	-	-
16.	Sohodra	1541	5	1	-	-	1	1
17.	Dia	2991	5	3	-	-	1	1
18.	Khari	6760	19	2	-	-	2	2
19.	Kothari	2320	5	1	-	1	1	-
20.	Banas I	6089	11	1	-	-	2	2
21.	Banas II	6058	14	11	-	1	2	1
22.	Berach	8550	23	6	-	1	2	1

. . . contd.

Table 4.3 Catchment-wise Requirement of Non-recording and Recording Raingauges (contd.)

Sl.No	Sub catchment	Catchment area km	Non-recording Existing	Non-recording Estimated	Non-recording Balance	Recording Existing	Recording Estimated	Recording Balance
<u>Chambal</u>								
23.	Chambal	2103	7	1	-	2	1	-
24.	Chakan	891	2	1	-	-	-	-
25.	Nej	5672	10	1	-	-	2	2
26.	Eru	363	-	1	1	-	-	-
27.	Alnia	549	3	1	-	-	-	-
28.	Parbati	5000	8	2	-	-	1	1
29.	Kuru	699	1	1	-	-	-	-
30.	Parwan	3051	5	1	-	-	1	1
31.	Kalisindh	7400	15	2	-	-	2	2
32.	Choti Kalisindh	389	1	1	-	-	-	-
<u>Mahi</u>								
33.	Jakham	2458	6	1	-	1	1	-
34.	Som	6130	16	1	-	1	2	1
35.	Moran	1012	1	1	-	-	1	1
36.	Anas	1436	4	3	-	-	1	1
37.	Mahi	5918	18	5	-	1	2	1
<u>Sabarmati</u>								
38.	Bhadar Vartak	1049	2	1	-	-	1	1
39.	Wakal	2023	1	1	-	-	1	1
40.	Sei	799	1	1	-	-	-	-
41.	Sabarmati	425	3	1	-	-	-	-

. . . contd.

Table 4.3 Catchment-wise Requirement of Non-recording and Recording Raingauges (contd.)

Sl.No	Sub catchment	Catchment area km	Non-recording			Recording		
			Existing	Estimated	Balance	Existing	Estimated	Balance
<u>Luni</u>								
42.	Jojri	4864	4	1	-	-	1	1
43.	Luni I	3911	5	11	6	-	1	1
44.	Luni II	4260	3	1	-	-	1	1
45.	Luni III	1738	-	1	1	-	1	1
46.	Guhiya	3841	8	7	-	-	1	1
47.	Sukri Hemawas	1269	5	1	-	-	1	1
48.	Bandi Hemawas	1502	2	1	-	-	1	1
49.	Sukri	1347	1	1	-	-	1	1
50.	Sukri	1715	7	1	-	-	1	1
51.	Milhri	1305	6	1	-	-	1	1
52.	Jawai	3248	18	1	-	1	1	-
53.	Khari	2507	4	1	-	-	1	1
54.	Sukri	1214	-	1	1	-	1	1
55.	Bandi	943	2	1	-	-	-	-
56.	Sagi	948	1	1	-	-	-	-
57.	West Manas	1870	12	1	-	1	1	-
58.	Sukli	945	5	1	-	-	-	-

number of rain gauges is adequate even considering an accuracy requirement of 5 % as seen from table 4.3. However, in the case of 21 sub-catchments, there is requirement of additional gauges which varies between 1 to 10 gauges.

After considering the 17 existing SRRGs, the requirement of additional gauges would be 38.

4.5 Remarks

The analysis indicated that the variability of rainfall within the districts is less . Also, the existing network of rain gauges in many districts and catchments is more than adequate. Only a few districts and catchments needed more rain gauges. However, the network of recording rain gauges in many catchments is inadequate and needed improvement as indicated by the study.

CHAPTER V

DATA PROCESSING AND PRELIMINARY ANALYSIS

5.1 General

It is common experience that the rainfall data in its raw form would contain many gaps and inconsistant values. As such processing of rainfall data is essential before it could be put to further use in analysis. Processing of the data has two major objectives. One is to evaluate the data for its accuracy and the other is to prepare the data in a form suitable for subsequent analysis.

5.2 Availability of Rainfall Data :

Daily rainfall data of the state for the period 1901 to 1970 was obtained from the India Meteorological Department (IMD) on magnetic tapes . Data of daily rainfall for the period 1976 to 1990 was collected from the office of Deputy Director (Hydrology), Irrigation Department, Rajasthan from manuscript records.

The data for the period 1901 to 1956 was recorded in inches and cents while for the later period (1957 onwards) it is being recorded in mm and tenths of mm.

5.3 Processing of Data

The data was processed on the VAX/11/780 computer system available with the National Institute of Hydrology at Roorkee to check for gaps and inconsistencies in the data. A computer program has been prepared and used for the processing.

5.3.1 Seasonal and annual totals

For the purpose of the study, the period from June to September has been considered as monsoon and the period October to

May as non-monsoon. Any day with a rainfall of more than 2.5 mm is considered to be a rainy day as per the norms of IMD. Monthly, seasonal (monsoon and non - monsoon) and annual totals of rain fall and rainy days were computed.

5.3.2 Tests for randomness

While carrying out statistical analysis it is necessary to see whether the rainfall of a particular time duration is dependant on the rainfall magnitude of the previous duration. One of the simplest tests for testing the randomness of the series is the turning point test.

Turning point test :

Given a sequence of variable (Y_t), t = 1,2,.....n the non randomness will be exhibited by a smaller number of peaks and troughs than would be expected if (Y_t) were really random.

A peak is defined as the occurrence of a value Y_t satisfying $Y_{t-1} < Y_t > Y_{t+1}$ and a trough by the occurrence of a Y_t satisfying $Y_{t-1} > Y_t < Y_{t+1}$.

The number of peaks and troughs are computed. The total score is approximately normally distributed with mean $\frac{2}{3}(N-2)$ and variance (16N-29)/9. The normal deviate computed from the score is compared with the table value for 5% level of significance which is 1.96.

The turning point test was applied for testing the randomness of the series of the four monsoon months June to September, monsoon season and annual rainfall. The results are shown in tables 5.1 to 5.6. It may be seen that the series are generally random except in case of some stations. These are the June series of Jhun Jhunu, monsoon series of Ajmer, Sirohi and the annual series of Sirohi.

Table 5.1 RESULTS OF TURNING POINT TEST FOR JUNE RAINFALL SERIES

S.No	Station	No of Peaks	No of Troughs	No of Turn Pts.	Z value	Remarks
1.	Ajmer	29	29	58	.6934	Random
2.	Alwar	30	30	60	1.2135	Random
3.	Banswara	27	26	53	-.6067	Random
4.	Bharatpur	27	27	54	-.3467	Random
5.	Bundi	29	28	57	.4334	Random
6.	Dausa	28	27	55	-.0867	Random
7.	Dholpur	28	26	54	-.3467	Random
8.	Dungarpur	27	26	53	-.6067	Random
9.	Jalore	30	27	57	.4334	Random
10.	Jaipur	28	27	55	-.0867	Random
11.	Jhun Jhunu	24	23	47	-2.1670	Not Random
12.	Khanpur	26	26	52	-.8668	Random
13.	Kota	27	26	53	-.6067	Random
14.	Pali	30	26	56	.1734	Random
15.	Pratapgarh	28	28	56	.1734	Random
16.	Sawai Madhopur	27	27	54	.3467	Random
17.	Shapura	26	27	53	-.6067	Random
18.	Sirohi	27	26	53	-.6067	Random
19.	Tonk	26	24	50	-1.3869	Random
20.	Udaipur	26	26	52	-.8668	Random

The value of Z is 1.96 at 5 % level of significance

TABLE 5.2 RESULTS OF TURNING POINT TEST FOR JULY RAINFALL SERIES

S.No	Station	No of Peaks	No of Troughs	No of Turn Pts.	Z value	Remarks
1.	Ajmer	30	30	60	1.2135	Random
2.	Alwar	28	28	56	.1734	Random
3.	Banswara	26	25	51	-1.1268	Random
4.	Bharatpur	26	26	52	-.8668	Random
5.	Bundi	26	25	51	-1.1268	Random
6.	Dausa	30	30	60	1.2135	Random
7.	Dholpur	26	26	52	-.8668	Random
8.	Dungarpur	25	24	49	-1.6469	Random
9.	Jalore	27	29	56	.1734	Random
10.	Jaipur	27	27	54	-.3467	Random
11.	Jhun Jhunu	31	31	62	1.7336	Random
12.	Khanpur	28	28	56	.1734	Random
13.	Kota	26	27	53	-.6067	Random
14.	Pali	29	29	58	.6934	Random
15.	Pratapgarh	27	26	53	-.6067	Random
16.	Sawai Madhopur	29	29	58	.6934	Random
17.	Shapura	29	29	58	.6934	Random
18.	Sirohi	30	30	60	1.2135	Random
19.	Tonk	30	30	60	1.2135	Random
20.	Udaipur	27	27	54	-.3467	Random

The value of Z is 1.96 at 5 % level of significance

TABLE 5.3 RESULTS OF TURNING POINT TEST FOR AUGUST RAINFALL SERIES

S.No	Station	No of Peaks	No of Troughs	No of Turn Pts.	Z value	Remarks
1.	Ajmer	26	25	51	-1.1268	Random
2.	Alwar	27	28	55	-.0867	Random
3.	Banswara	26	26	52	-.8668	Random
4.	Bharatpur	28	27	55	-.0867	Random
5.	Bundi	29	29	58	.6934	Random
6.	Dausa	28	29	57	.4334	Random
7.	Dholpur	29	30	59	.9535	Random
8.	Dungarpur	27	27	54	-.3467	Random
9.	Jalore	27	26	53	-.6067	Random
10.	Jaipur	29	30	59	.9535	Random
11.	Jhun Jhunu	28	28	56	.1734	Random
12.	Khanpur	30	31	61	1.4735	Random
13.	Kota	26	26	52	-.8668	Random
14.	Pali	28	27	55	-.0867	Random
15.	Pratapgarh	29	27	56	.1734	Random
16.	Sawai Madhopur	28	28	56	.1734	Random
17.	Shapura	29	29	58	.6934	Random
18.	Sirohi	27	26	53	-.6067	Random
19.	Tonk	29	28	57	.4334	Random
20.	Udaipur	26	27	53	-.6067	Random

The value of Z is 1.96 at 5 % level of significance

Table 5.4 RESULTS OF TURNING POINT TEST FOR SEPTEMBER RAINFALL SERIES

S.No	Station	No of Peaks	No of Troughs	No of Turn Pts.	Z value	Remarks
1.	Ajmer	29	28	57	.4334	Random
2.	Alwar	31	30	61	1.4735	Random
3.	Banswara	29	28	57	.4334	Random
4.	Bharatpur	25	25	50	-1.3869	Random
5.	Bundi	27	24	51	-1.1268	Random
6.	Dausa	28	26	54	-.3467	Random
7.	Dholpur	30	28	58	.6934	Random
8.	Dungarpur	27	26	53	-.6067	Random
9.	Jalore	29	26	55	-.0867	Random
10.	Jaipur	29	28	57	.4334	Random
11.	Jhun Jhunu	27	25	52	-.8668	Random
12.	Khanpur	29	28	57	.4334	Random
13.	Kota	25	24	49	-1.6469	Random
14.	Pali	28	24	52	-.8668	Random
15.	Pratapgarh	26	24	50	-1.3869	Random
16.	Sawai Madhopur	25	25	50	-1.3869	Random
17.	Shapura	30	29	59	.9535	Random
18.	Sirohi	29	27	56	.1734	Random
19.	Tonk	28	27	55	-.0867	Random
20.	Udaipur	26	24	50	-1.3869	Random

The value of Z is 1.96 at 5 % level of significance

Table 5.5 RESULTS OF TURNING POINT TEST FOR MONSOON RAINFALL SERIES

S.No	Station	No of Peaks	No of Troughs	No of Turn Pts.	Z value	Remarks
1.	Ajmer	32	31	63	1.9936	Random
2.	Alwar	29	29	58	.6934	Random
3.	Banswara	25	24	49	-1.6469	Random
4.	Bharatpur	27	27	54	-.3467	Random
5.	Bundi	29	28	57	.4334	Random
6.	Dausa	31	31	62	1.7336	Random
7.	Dholpur	27	28	55	-.0867	Random
8.	Dungarpur	26	25	51	-1.1268	Random
9.	Jalore	26	26	52	-.8668	Random
10.	Jaipur	27	27	54	-.3467	Random
11.	Jhun Jhunu	26	25	51	-1.1268	Random
12.	Khanpur	29	30	59	.9535	Random
13.	Kota	25	25	50	-1.3869	Random
14.	Pali	28	27	55	-.0867	Random
15.	Pratapgarh	29	28	57	.4334	Random
16.	Sawai Madhopur	30	30	60	1.2136	Random
17.	Shapura	28	27	55	-.0867	Random
18.	Sirohi	24	23	47	-2.1670	Not Random
19.	Tonk	30	29	59	.9535	Random
20.	Udaipur	28	27	55	-.0867	Random

The value of Z is 1.96 at 5 % level of significance

Table 5.6 RESULTS OF TURNING POINT TEST FOR ANNUAL RAINFALL SERIES

S.No	Station	No of Peaks	No of Troughs	No of Turn Pts.	Z value	Remarks
1.	Ajmer	27	26	53	-.6067	Random
2.	Alwar	28	28	56	.1734	Random
3.	Banswara	26	25	51	-1.1268	Random
4.	Bharatpur	30	30	60	1.2135	Random
5.	Bundi	28	27	55	-.0867	Random
6.	Dausa	28	28	56	.1734	Random
7.	Dholpur	28	29	57	.4334	Random
8.	Dungarpur	26	25	51	-1.1268	Random
9.	Jalore	27	26	53	-.6067	Random
10.	Jaipur	28	28	56	.1734	Random
11.	Jhun Jhunu	26	25	51	-1.1268	Random
12.	Khanpur	29	30	59	.9535	Random
13.	Kota	25	25	50	-1.3869	Random
14.	Pali	28	27	55	-.0867	Random
15.	Pratapgarh	30	29	59	.9535	Random
16.	Sawai Madhopur	31	31	62	1.7336	Random
17.	Shapura	26	26	52	-.8668	Random
18.	Sirohi	24	23	47	-2.1670	Not Random
19.	Tonk	30	29	59	.9535	Random
20.	Udaipur	27	26	53	-.6067	Random

The value of Z is 1.96 at 5 % level of significance

Table 5.7 RESULTS OF TURNING POINT TEST FOR MONSOON RAINYDAYS SERIES

S.No	Station	No of Peaks	No of Troughs	No of Turn Pts.	Z value	Remarks
1.	Ajmer	28	30	58	.6934	Random
2.	Alwar	31	31	62	1.7336	Random
3.	Banswara	22	23	45	-2.6870	Not Random
4.	Bharatpur	29	28	57	.4334	Random
5.	Bundi	29	28	57	.4334	Random
6.	Dausa	28	28	56	.1734	Random
7.	Dholpur	29	28	57	.4334	Random
8.	Dungarpur	27	26	53	-.6067	Random
9.	Jalore	25	24	49	-1.6469	Random
10.	Jaipur	28	28	56	.1734	Random
11.	Jhun Jhunu	23	22	45	-2.6870	Not Random
12.	Khanpur	28	28	56	.1734	Random
13.	Kota	30	27	57	.4334	Random
14.	Pali	26	23	49	-1.6469	Not Random
15.	Pratapgarh	29	29	58	.6934	Random
16.	Sawai Madhopur	25	27	52	-.8668	Random
17.	Shapura	27	28	55	-.0867	Random
18.	Sirohi	23	24	47	-2.1670	Not Random
19.	Tonk	26	27	53	-.6067	Random
20.	Udaipur	27	26	53	-.6067	Random

The value of Z is 1.96 at 5 % level of significance

Table 5.8 RESULTS OF TURNING POINT TEST FOR ANNUAL RAINYDAY SERIES

S.No	Station	No of Peaks	No of Troughs	No of Turn Pts.	Z value	Remarks
1.	Ajmer	28	28	56	0.1734	Random
2.	Alwar	28	27	55	-.0867	Random
3.	Banswara	26	26	52	-.8668	Random
4.	Bharatpur	29	30	59	0.9535	Random
5.	Bundi	28	28	56	0.1734	Random
6.	Dausa	27	27	54	-.3467	Random
7.	Dholpur	24	26	50	-1.3869	Random
8.	Dungarpur	26	25	51	-1.1268	Random
9.	Jalore	26	26	52	-.8668	Random
10.	Jaipur	25	24	49	-1.6469	Random
11.	Jhun Jhunu	23	24	47	-2.1670	Not Random
12.	Khanpur	26	27	53	-.6067	Random
13.	Kota	28	28	56	.1734	Random
14.	Pali	24	23	47	-2.1670	Not Random
15.	Pratapgarh	31	29	60	1.2135	Random
16.	Sawai Madhopur	28	27	55	-.0867	Random
17.	Shapura	27	26	53	-.6067	Random
18.	Sirohi	24	23	47	-2.1670	Not Random
19.	Tonk	27	26	53	-.6067	Random
20.	Udaipur	28	27	55	1.7336	Random

The value of Z is 1.96 at 5 % level of significance

The series of the monsoon and annual rainy days were also tested using this test. The results are shown in tables 5.7 and 5.8. It is seen that the series are generally random except for the series of a few stations. These are the monsoon rainy days series of Banswara, Jhun Jhunu and Sirohi and the annual rainy days series of Jhun Jhunu, Pali and Sirohi.

5.3.3 Tests for stationarity of series

In addition to testing the series for randomness, the stability of the variance and mean of the series also need to be tested. It is necessary to test for the stability of the variance first. The reason being, instability of the variance implies that the series is not stationary.

5.3.3.1 F test for stability of variance

The test statistic is the ratio of the variance of two split, non - overlapping subsets of the time series. The distribution of the variance ratio of samples from a normal distribution is known as the F (Fisher) distribution. Even if the samples are not from a normal distrbution, the F test will give an acceptable indication of stability of variance.

The test statistic is $F_t = \frac{\sigma_1^2}{\sigma_2^2} = \frac{s_1^2}{s_2^2}$ where s^2 is variance. The null hypothesis for the test $H_0 : s_1^2 = s_2^2$, is the equality of the variance. The alternative hypothesis is $H_1: s_1^2 <> s_2^2$. The rejection region U is bounded by :

$\{ 0, F\{\nu_1, \nu_2, 2.5\%\}\} \cup \{ F\{\nu_1, \nu_2, 97.5\%\}, +\infty \}$ where $\nu_1 = n-1$ is the number of degrees of freedom for numerator and $\nu_2 = n-2$ is the degrees of freedom for denominator and n_1 and n_2 are the number of data in each subset. In other words, the variance of the time series is stable if $F\{\nu_1, \nu_2, 2.5\%\} < F_t < F\{\nu_1, \nu_2, 97.5\%\}$

5.3.3.2 t test for the stability of mean

The t test for stability of the mean involves computing the means of two or three non - overlapping sub sets (corresponding to sub sets used for testing stability of variance) of the time series and comparing them. The statistic for testing null hypothesis $H_0 : \bar{x}_1 = \bar{x}_2$ against the alternative hypothesis $H_1 : \bar{x}_1 <> \bar{x}_2$ is

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\left[\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} * \left(\frac{1}{n_1} + \frac{1}{n_2} \right) \right]^{1/2}} \qquad (5.1)$$

where n is the number of data in the subset, $\bar{x}$ is the mean of the subset and s^2 is its variance. In samples from normal distribution t has a student's t distribution. t test can also be applied to skewly distributed data provided the length of the sub sets is equal or nearly equal. For t the two sided critical region U is

$$\{-\infty, t\{\nu, 2.5\%\}\} \cup \{t\{\nu, 97.5\%\}, +\infty\}$$

with $\nu = n_1 - 1 + n_2 - 1$ degrees of freedom i.e total number of data minus 2. In other words the mean of time series is considered stable if $t\{\nu, 2.5\%\} < t < t\{\nu, 97.5\%\}$

5.4 Application to Data and Results

The DATSCR software for processing of rainfall data developed by ILRI (1990) of The Netherlands was used for the processing. The annual and monsoon series of rainfall and rainy days have been tested for stationarity by splitting the data into two nearly equal subsets of 43 years (1901 - 1943) and 42 years (1944 to 1985). Also monthly series of four monsoon months June to September used in the study have been tested for stationarity. In tables 5.9 to 5.12 the values of F and t for rainfall (monsoon and annual) and rainy days (monsoon and annual) respectively are presented for each of the 20 stations used in the study. Excepting for a few stations the series in general are found to be stationary. The annual rainfall series whose variance is not stable are those of Alwar, Banswara, Bharatpur, Sawai Madhopur. The annual rainfall series whose variance is stable but the mean is not stable are Dausa, Pratapgarh, and Sirohi.

The monsoon rainfall series whose variance is not stable are those of Alwar, Bharatpur, and Sawai Madhopur. The monsoon rain fall series whose variance is stable but the mean is not stable are Banswara, Dausa, Pratapgarh and Sirohi.

In case of rainy days also the series in general are stationary except for a few stations. The annual rainy days series whose variance is not stable are those of Alwar and Udaipur only. There were no cases where the variance was stable but the mean was not stable. In the case of monsoon rainy days series, only the variance of the series of Bharatpur is not stable.

The non-randomness indicated by the tests for randomness as well as the non stationarity observed in the mean and standard deviation in the rainfall and rainy days series of some of the stations indicate the possibility of presence of trend or persistance in the series which was examined further and discussed in the chapter VI .

Table 5.9 Test for Stationarity of Monsoon Rainfall Series

S.No	Station	Period I (1901-43) mean	Period I (1901-43) std.dev	Period II (1944-85) mean	Period II (1944-85) std.dev	F	t
1.	Ajmer	449.6	224.8	519.8	187.0	1.444	-1.561
2.	Alwar	565.4	238.4	587.8	166.2	2.057*	-0.501
3.	Banswara	836.8	277.9	997.9	374.2	0.552	-2.249*
4.	Bharatpur	580.2	262.9	609.1	170.4	2.381*	-0.599
5.	Bundi	680.2	283.6	720.2	222.2	1.629	-0.727
6.	Dausa	485.0	222.9	607.1	227.2	0.963	-2.501*
7.	Dholpur	637.0	248.5	660.7	222.4	1.248	-0.465
8.	Dungarpur	661.0	271.3	733.1	255.4	1.127	-1.261
9.	Jaipur	510.8	229.6	597.9	225.4	1.037	-1.763
10.	Jalore	311.4	164.9	382.2	199.0	0.686	-1.790
11.	Jhun Jhunu	320.3	134.4	366.9	139.9	0.923	-1.564
12.	Khanpur	911.7	283.3	837.4	290.0	0.955	1.196
13.	Kotah	685.5	276.7	733.1	265.8	1.084	-0.808
14.	Pali	369.4	186.7	411.9	195.8	0.909	-1.024
15.	Pratapgarh	733.0	250.8	863.9	316.0	0.635	-2.118*
16.	Sawai Madhopur	815.7	444.4	791.0	298.4	2.218*	0.301
17.	Shahpura	598.9	242.1	580.8	179.6	1.876	0.392
18.	Sirohi	509.5	240.4	637.2	308.2	0.609	-2.133*
19.	Tonk	575.5	263.3	639.1	249.2	1.118	-1.142
20.	Udaipur	581.5	189.6	600.5	199.1	0.907	-0.450

* Significant at 5 % level of significance

Table 5.10 Test for Stationarity of Annual Rainfall Series

S.No	Station	Period I (1901-43)		Period II (1944-85)		F	t
		mean	std.dev	mean	std.dev		
1.	Ajmer	521.2	232.6	573.7	199.3	1.362	-1.117
2.	Alwar	618.6	252.8	669.0	181.5	1.940*	-1.052*
3.	Banswara	893.3	272.4	1067.7	372.8	0.534*	-2.467*
4.	Bharatpur	662.7	266.1	667.2	176.9	2.262*	-0.092
5.	Bundi	730.0	286.6	781.0	230.9	1.541	-0.902
6.	Dausa	516.2	222.2	671.9	237.6	0.874	-3.121*
7.	Dholpur	711.6	244.5	716.6	244.9	0.996	-0.095
8.	Dungarpur	716.0	279.6	787.3	255.6	1.197	-1.225
9.	Jaipur	581.6	251.5	664.8	244.3	1.060	-1.548
10.	Jalore	360.9	173.5	422.0	202.9	0.731	-1.491
11.	Jhun Jhunu	379.1	142.4	433.7	150.3	0.898	-1.719
12.	Khanpur	971.2	304.1	894.1	306.2	0.986	1.164
13.	Kotah	745.7	290.1	782.1	270.7	1.149	-0.598
14.	Pali	400.7	193.1	438.6	203.2	0.903	-0.882
15.	Pratapgarh	785.9	282.6	939.4	309.3	0.835	-2.389*
16.	Sawai Madhopur	862.4	447.8	850.6	307.8	2.116*	0.141
17.	Sirohi	552.8	249.4	683.6	313.5	0.633	-2.132*
18.	Shahpura	647.8	251.8	612.9	185.1	1.841	0.728
19.	Tonk	627.7	273.3	700.4	253.0	1.168	-1.272
20.	Udaipur	620.7	194.6	652.9	200.7	0.940	-0.782

* Significant at 5 % level of significance

Table 5.11 Test for Stationarity of Monsoon Rainyday Series

S.No	Station	Period I (1901-43) mean	std.dev	Period II (1944-85) mean	std.dev	F	t
1.	Ajmer	24.6	8.5	26.0	6.5	1.695	-0.876
2.	Alwar	28.7	8.6	30.1	6.7	1.637	-0.878
3.	Banswara	36.6	9.6	39.1	9.7	0.981	-1.155
4.	Bharatpur	29.3	9.4	27.5	6.8	1.882*	0.986
5.	Bundi	30.9	9.3	31.5	8.0	1.329	-0.315
6.	Dausa	26.8	9.3	29.7	7.1	1.711	-1.628
7.	Dholpur	32.7	8.1	30.3	7.6	1.140	1.345
8.	Dungarpur	32.9	9.9	32.7	9.2	1.168	0.105
9.	Jaipur	28.0	10.4	30.3	7.9	1.738	-1.125
10.	Jalore	16.2	7.3	17.3	6.9	1.097	-0.682
11.	Jhun Jhunu	19.9	6.9	20.4	5.8	1.417	-0.362
12.	Khanpur	36.7	8.6	34.4	8.3	1.072	1.173
13.	Kotah	31.5	8.3	32.4	8.3	1.015	-0.496
14.	Pali	17.1	6.5	17.9	7.0	0.842	-0.458
15.	Pratapgarh	28.4	8.9	27.7	7.7	1.327	0.375
16.	Sawai Madhopur	32.9	9.9	32.8	8.9	1.219	0.048
17.	Shahpura	28.4	8.9	27.7	7.7	1.327	0.375
18.	Sirohi	22.7	8.5	23.4	7.9	1.149	-0.409
19.	Tonk	27.9	8.8	28.8	8.3	1.135	-0.475
20.	Udaipur	28.9	8.2	29.5	6.2	1.732	-0.331

* Significant at 5 % level of significance

Table 5.12 Test for Stationarity of Annual Rainyday Series

S.No	Station	Period I (1901-43) mean	Period I (1901-43) std.dev	Period II (1944-85) mean	Period II (1944-85) std.dev	F	t
1.	Ajmer	30.3	10.3	30.0	8.1	1.620	-0.253
2.	Alwar	35.9	10.4	36.1	7.6	1.865*	-0.363
3.	Banswara	40.8	10.4	42.0	10.1	1.067	-0.531
4.	Bharatpur	35.8	10.2	32.2	7.6	1.842	1.841
5.	Bundi	35.3	10.1	34.7	9.3	1.184	0.268
6.	Dausa	32.2	10.6	34.9	7.9	1.814	-1.326
7.	Dholpur	38.1	9.0	35.3	9.2	0.948	1.388
8.	Dungarpur	36.5	10.5	34.8	9.2	1.302	0.792
9.	Jaipur	34.6	12.1	35.8	9.4	1.648	-0.512
10.	Jalore	18.4	7.9	19.8	7.6	1.086	-0.797
11.	Jhun Jhunu	26.4	7.8	26.0	6.7	1.351	0.221
12.	Khanpur	41.8	10.7	39.0	9.9	1.175	1.284
13.	Kotah	38.6	9.5	36.4	9.7	0.970	0.130
14.	Pali	19.6	7.4	19.9	7.6	0.956	-0.228
15.	Pratapgarh	40.5	10.9	40.9	11.0	0.991	-0.165
16.	Sawai Madhopur	36.7	10.3	37.7	9.8	1.096	-0.150
17.	Shahpura	32.6	9.4	30.9	8.6	1.196	0.902
18.	Sirohi	26.3	9.3	26.2	8.7	1.146	0.057
19.	Tonk	32.7	9.9	33.1	9.3	1.109	-0.225
20.	Udaipur	33.7	9.5	33.4	6.8	1.958*	0.125

* Significant at 5 % level of significance

CHAPTER VI

TIME SERIES ANALYSIS OF RAINFALL AND RAINY DAYS

6.1 General

A time series is composed of variable observed at discrete times, averaged or cumulated over a particular time interval like a week, month, season or year. A time series may be composed of only deterministic events, only stochastic events or a combination of the two. Generally, hydrologic time series are composed of a stochastic component superimposed on a deterministic component. The deterministic components may be classified as a periodic component, a trend, a jump or a combination of these. Trends in hydrologic time series can be due to natural factors like climate changes, changes brought about by man's developmental activities or over exploitation of natural resources like deforestation and grazing by animals.

The state of Rajasthan was known to be rich in natural vegetation in the past, but man's activities have modified the ecoclimate considerably to the extent that doubts were expressed about the possible extension of the desert conditions towards east. It was, therefore, thought necessary to study the changes in the rainfall pattern if any in east Rajasthan through time series analysis.

6.2 Methodology

The basic steps in the procedure for time series analysis are

(i) testing the time series for absence of persistence by computing the lag 1 serial correlation coefficient

(ii) plotting the totals for different time periods such as a month, season or year and note any trends or discontinuities

(iii) testing the time series for presence of trend

A time series of hydrological data are strictly stationary if its statistical properties like mean, standard deviation and higher order moments are stable. The tests for stability of variance and mean verify not only the stationarity of a time series, but also its consistency and homogeneity.

6.2.1 Analysis for persistence :

Time series of annual and seasonal totals of rainfall are usually independent. Some series, however, show dependence. Such series are tested for persistence through lag one serial correlation coefficient r_1. The lag 1 serial correlation describees the strength of relation between a value in the series and that preceding it by one time interval. For strictly random sequences, the value of r_1 differs from zero only by sampling variation. For series with strong persistence the value of r_1 approaches unity. Negative values are not uncommon. This implies that large values are followed by small values and vice-versa.

The generalised expression for lag one serial correlation is

$$r_1 = \frac{\frac{1}{N-1}\sum_{t=1}^{N=1}(y_t-\bar{y})(y_{t+1}-\bar{y})}{\frac{1}{N}\sum_{t=1}^{N}(y_t-\bar{y})^2} \qquad (6.1)$$

r_1 is tested by seeing whether r_1 lies within the range defined by

$$-\frac{1}{(N-1)}+1.96\frac{(N-2)}{(N-1)^{3/2}} \quad \text{and} \quad \frac{1}{(N-1)}-1.96\frac{(N-2)}{(N-1)^{3/2}}$$

If r_1 lies outside the range there is evidence of it being significantly different from zero.

Lagged serial correlation is computed for lags of higher order and the plot of serial correlation versus lag provides the correlogram.

6.2.2 Analysis for trend

A method for testing the series for presence of trend is the Spearman rank correlation method. It is simple and distribution free i.e it does not require the assumption of an underlying statistical distribution. Yet another advantage is its nearly uniform power for linear and non - linear trends (WMO,1966). The Spearman rank correlation is denoted by R_s which is given by

$$R_s = 1 - \frac{6 \sum_{i=1}^{n} D_i^2}{n(n^2 - 1)} \quad (6.2)$$

where n is the total number of data, D is the difference and i is the chronological order number.

The difference in the rankings is computed with

$$D_i = K x_i - K y_i \quad (6.3)$$

where $K x_i$ is the rank of the variable x_i which is the chronological order number of the observations. The series of observations y_i is transformed to its rank equivalent $K y_i$ by assigning the chronological order number of an observation in the original series to the corresponding order number in the ranked series y_i. The R_s is tested by computing t_t

$$t_t = R_s \left[\frac{n - 2}{1 - R^2} \right]^2 \quad (6.4)$$

where t_t has Student's t distribution with n - 2 degrees of freedom. At a significance level of 5 percent, t_t is bounded by

$-\infty$, $t(\nu, 2.5\%)$ and $t(\nu, 97.5\%)$, ∞

The series is considered to have no trend if t_t lies within the above limits.

6.2.2.1 decadal means

Decadal means were computed for comparison with long term mean of the respective rainfall series. A test of 'null' hypothesis of randomness (WMO,1966) has been applied to determine whether the difference of means are not larger than would be compatible with the null hypothesis

$$T_k = \frac{\bar{x}_k - \bar{x}}{\sigma} \qquad (6.5)$$

where $\bar{x}_k$ is the mean of any k observations,

$\bar{x}$ is the mean of the whole period and

σ is the standard deviation of the whole period series

The statistic $t_k = \left[\frac{K(N-2)}{N-K-KT_k^2} \right]^{1/2} T_k$ is distributed as Student's t with n-2 degrees of freedom which could be used to test the significance of non-randomness

6.2.2.2 linear and curvilinear trend

Linear and polynomial regression (2nd order) has been fitted to the rainfall and rainy day series for examining the possibilty of trend in the rainfall/rainy days series. The linear regression was tested using the t test while the polynomial regression was tested using the F test.

6.3 Application and Results

The series of monthly (June to September), monsoon and annual rainfall and monsoon and annual rainy days for the period 1901 - 85 were tested for persistence and trend using the methods described under section 6.2.

It is generally believed that unlike the stream flow, the rainfall in a particular month or season does not depend on the rainfall during the previous month or season.

The dependence of non-monsoon season (Oct - May) rainfall on the previous monsoon season was examined by correlating the rainfall series of the two seasons. The correlation coefficient was low (within + or - 0.25) for all the twenty stations used in the analysis thereby indicating the lack of dependence of the non-monsoon rainfall on the rainfall received during the previous summer monsoon.

Further, the correlation among the rainfall series of each of the monsoon months among themselves and the rainfall of each of the monsoon months with the total monsoon season rainfall was computed. The correlation coefficient is small indicating the lack of any relationship among the monthly rainfall series within the monsoon season and also the series of each of the monsoon months with the series of the total monsoon rainfall. In tables 6.1 to 6.4, the correlation of each of the monsoon month's rainfall with corresponding monsoon season total is given. The grouping of the stations in the tables is done on the basis of homogeneous groups identified through cluster analysis discussed in Chapter VIII. The matrix of correlation coefficients is presented in tables 6.5 to 6.8 for four selected stations representing the four groups.

Table 6.1 Correlation of Rainfall Series of Monsoon Months and Monsoon Rainfall

Station	June	July	August	September
Alwar	.1784	.4861	.6400	.6661
Bharatpur	.1259	.5745	.5597	.4825
Bundi	.2317	.5339	.6422	.4795
Dausa	.1117	.6085	.6438	.4919
Dholpur	.1173	.6102	.6780	.5010
Jhun Jhunu	.1967	.5736	.6168	.4819
Shahpura	.1924	.4054	.5235	.4238

Table 6.2 Correlation of Rainfall Series of Monsoon Months and Monsoon Rainfall

Station	June	July	August	September
Banswara	.3422	.5947	.6058	.3795
Dungarpur	.3969	.7197	.3907	.4575
Khanapur	.2940	.6888	.5144	.3272
Kotah	.2999	.6659	.5920	.6099
Pratapgarh	.4297	.5624	.5722	.5690
Sawai Madhopur	.3969	.7100	.6593	.4799

Table 6.3 Correlation of Rainfall Series of Monsoon Months and Monsoon Rainfall

Station	June	July	August	September
Jalore	.2773	.5311	.6187	.3580
Pali	.2741	.4201	.6966	.4593
Sirohi	.2892	.5385	.6248	.4813
Udaipur	.3543	.3475	.5652	.3844

Table 6.4 Correlation of Rainfall Series of Monsoon Months and Monsoon Rainfall

Station	June	July	August	September
Ajmer	.2901	.5552	.5708	.6014
Jaipur	.2933	.6746	.5681	.5229
Tonk	.2666	.6466	.6064	.5551

Table 6.5 Correlation Among Rainfall Series of Monsoon Months
Station : Ajmer

Month	June	July	August	September	Monsoon season
June	1.000	-.0289	-.0051	.0050	.2901
July		1.000	-.0938	.1083	.5552
August			1.000	.2308	.5708
September				1.000	.6014

Table 6.6 Correlation Among Rainfall Series of Monsoon Months
Station : Alwar

Month	June	July	August	September	Monsoon season
June	1.000	-.1137	-.2099	.1623	.1784
July		1.000	.1365	-.0015	.4861
August			1.000	.1092	.6400
September				1.000	.6661

Table 6.7 Correlation Among Rainfall Series of Monsoon Months
Station : Banswara

Month	June	July	August	September	Monsoon season
June	1.000	.0176	.0476	.0972	.3422
July		1.000	.0436	.0582	.5947
August			1.000	-.1432	.6058
September				1.000	.3795

Table 6.8 Correlation Among Rainfall Series of Monsoon Months
Station : Sirohi

Month	June	July	August	September	Monsoon season
June	1.000	.1520	-.0592	-.0379	.2892
July		1.000	-.0827	.0325	.5385
August			1.000	.0378	.6248
September				1.000	.4813

6.3.1 Serial correlation

The serial correlation was computed for the rainfall and rainy days series of all the twenty stations used in the study. The upper and lower confidence limits were computed as 0.20 (UCL) and -0.22 (LCL) respectively corresponding to a value of 85 for n the number of years.

The serial correlation for lag 1 was found to be within the limits for all the series. In case of a few stations, however, the serial correlation for lag 2 and other lags was found to be higher than UCL or lower than LCL. In table 6.9 the lag 1 and lag 2 serial correlation for monsoon and annual rainfall and rainy days for all the twenty stations used in the analysis is presented. The correlograms of those stations whose lag 2 serial correlation is beyond the UCL or LCL are shown in figures 6.1 to 6.4.

The serial correlation analysis indicated that there is a possibility of trend in the rainfall series of Dausa and Pratapgarh and the rainy days series of Dholpur and Sawai Madhopur. This is examined further in the analysis for trend.

6.3.2 Decadal means

The decade means of annual rainfall at each rain gauge station have been worked out and compared with the long term mean of the respective rainfall series. The means along with corresponding T_k are given in table 6.10. In Figure 6.5 the decadal means of annual rainfall of a few selected stations are presented against their respective long term mean. From the analysis it was seen that rainfall during the period 1941-50 was above the long term mean for seventeen out of twenty stations two of them significant at 5% level. In the decade 1951-60, it was more than the long term

Table 6.9 : Serial Correlation Coefficient of Monsoon and Annual Rainfall and Rainy days series

Station	Monsoon Rainfall		Annual Rainfall		Monsoon Rainydays		Annual Rainydays	
	lag1	lag2	lag1	lag2	lag1	lag2	lag1	lag2
Ajmer	0.02	-0.01	0.02	-0.03	0.01	0.12	-0.09	-0.07
Alwar	-0.15	0.04	-0.02	0.12	-0.07	0.03	-0.08	0.08
Banswara	0.00	-0.18	0.01	-0.11	-0.02	-0.12	-0.08	0.00
Bharatpur	-0.10	0.08	-0.08	0.15	-0.06	0.05	-0.07	0.13
Bundi	-0.03	-0.03	0.00	-0.01	0.01	0.16	0.09	0.19
Dausa	0.03	0.30*	0.17	0.30*	-0.03	0.19	-0.02	0.14
Dholpur	-0.08	0.14	-0.03	0.18	-0.03	0.21*	0.10	0.22*
Dungarpur	0.00	-0.21	-0.01	-0.18	-0.01	-0.03	0.02	0.05
Jalore	0.01	0.02	0.02	0.04	-0.01	0.00	0.00	0.05
Jaipur	-0.04	0.04	-0.08	0.10	0.01	0.12	-0.01	0.12
Jhun Jhunu	0.17	0.00	0.20	-0.01	0.18	-0.15	0.17	-0.04
Khanpur	-0.01	0.07	-0.08	0.10	0.02	0.05	0.10	0.05
Kota	0.12	0.01	0.10	0.00	0.02	0.13	0.07	0.18
Pali	-0.02	0.02	-0.01	0.01	0.10	0.01	0.15	0.00
Pratapgarh	0.10	0.14	0.19	0.19	-0.04	0.08	0.01	0.12
Sawai Madhopur	0.19	0.17	0.18	0.16	0.03	0.21*	0.01	0.21*
Shahpura	-0.02	0.00	0.00	0.02	0.00	0.00	0.02	0.04
Sirohi	0.02	-0.01	0.03	-0.02	0.02	-0.12	0.00	-0.11
Tonk	-0.02	0.01	0.00	0.04	0.11	0.07	0.05	0.10
Udaipur	-0.12	-0.15	-0.08	-0.18	-0.21	-0.01	-0.19	0.04

Upper Confidence Limit : 0.20 Lower Confidence limit : - 0.22

* indicates that serial correlation is beyond the limits

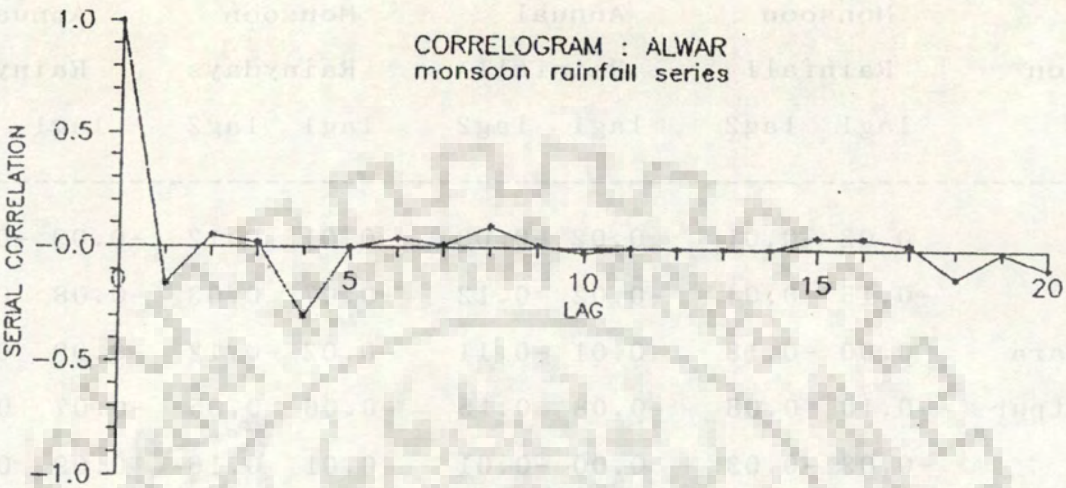


Figure 6.1

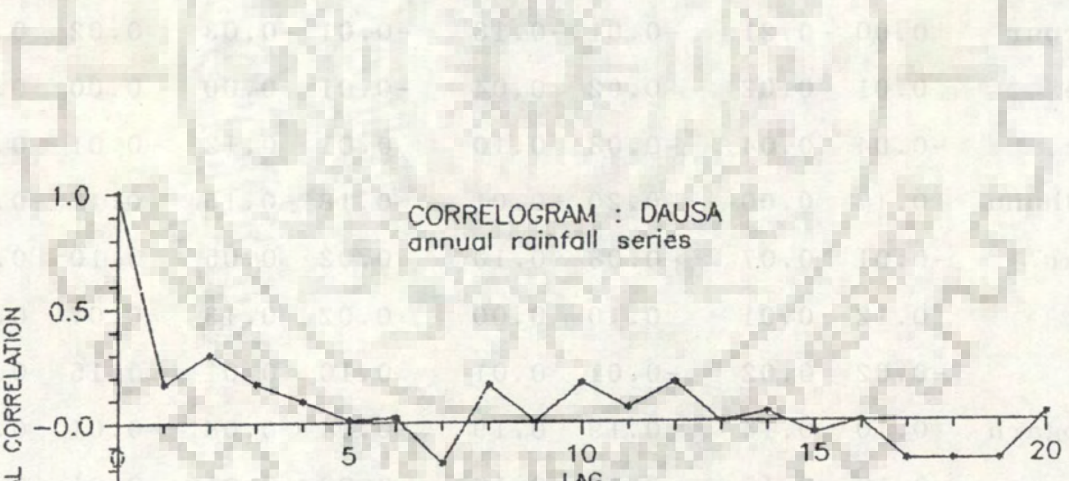


Figure 6.2

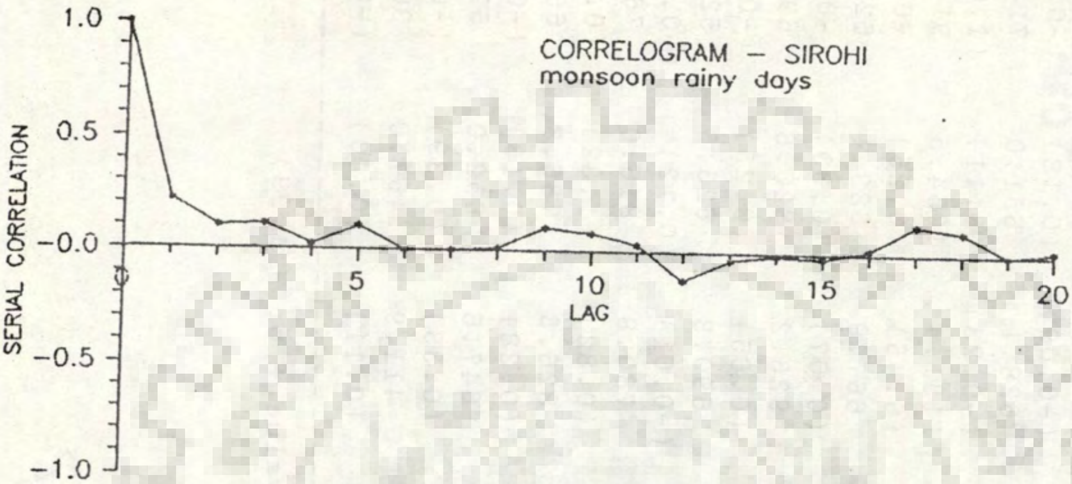


Figure 6.3

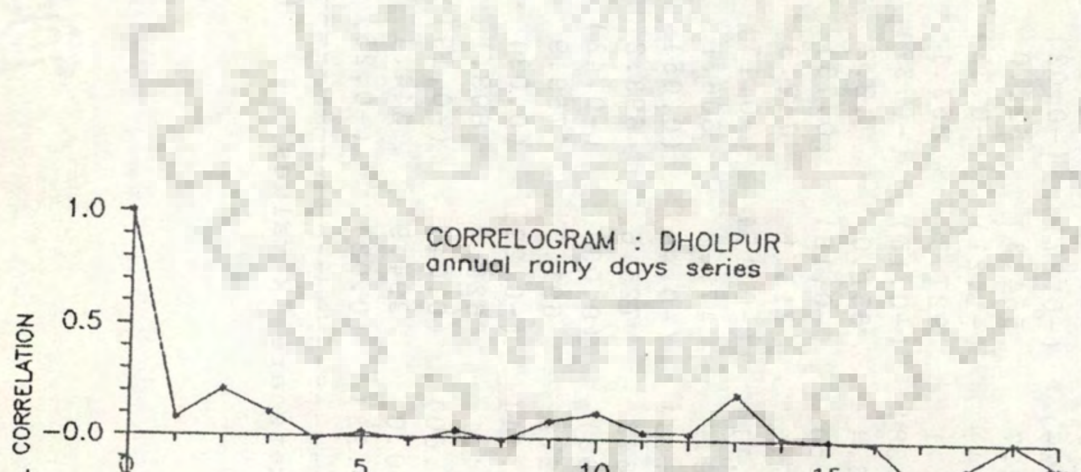


Figure 6.4

Table 6.10 Decade Means and Tk Values of Annual Rainfall Series Unit : mm

Station	1901-10	1911-20	1921-30	1931-40	1941-50	1951-60	1961-70	1971-80
Ajmer	483.6	488.8	543.4	557.0	527.1	585.5	507.2	662.8
	(-0.29)	(-0.27)	(-0.02)	(0.05)	(-0.09)	(0.18)	(-0.18)	(0.53)
Alwar	652.7	564.3	622.0	624.2	628.1	651.0	714.9	698.7
	(0.14)	(-1.21)	(-0.33)	(-0.29)	(-0.23)	(0.11)	(1.08)	(0.84)
Banswara	851.1	927.3	853.1	893.0	1131.4	1064.5	919.6	1196.2
	(-0.38)	(-0.15)	(-0.37)	(-0.26)	(0.45)	(0.25)	(-0.18)	(0.65)
Bharatpur	726.4	651.0	712.2	611.6	667.9	683.1	628.1	646.8
	(0.95)	(-0.18)	(0.73)	(-0.77)	(0.07)	(0.30)	(-0.52)	(-0.24)
Bundi	727.3	715.1	712.3	710.2	926.2	820.6	698.8	745.0
	(-0.11)	(-0.15)	(-0.17)	(-0.17)	(0.65)	(0.25)	(-0.22)	(-0.04)
Dausa	489.9	477.2	606.1	497.1	590.8	623.5	525.4	757.9
	(-0.43)	(-0.48)	(0.05)	(-0.40)	(-0.01)	(0.12)	(-0.28)	(0.68)
Dholpur	746.2	725.6	693.2	667.9	780.8	816.0	768.3	647.0
	(0.32)	(0.03)	(-0.43)	(-0.79)	(0.82)	(1.32)	(0.64)	(-1.09)
Dungarpur	632.2	691.5	759.9	752.6	826.3	786.8	661.6	891.2
	(-0.44)	(-0.22)	(0.03)	(0.01)	(0.28)	(0.13)	(-0.33)	(0.52)
Jaipur	504.1	625.4	608.1	605.8	647.6	652.0	572.2	733.3
	(-1.60)	(0.04)	(-0.19)	(-0.23)	(0.33)	(0.39)	(-0.67)	(1.49)
Jalore	350.0	394.9	344.4	358.8	411.9	467.0	301.4	483.2
	(-0.22)	(0.02)	(-0.25)	(-0.17)	(0.11)	(0.40)	(-0.47)	(0.48)

Values in brackets are Tk values (table t value + or - 1.99)

Table 6.10 (contd.) Decade Means and Tk Values of Annual Rainfall Series   Unit : mm

Station	1901-10	1911-20	1921-30	1931-40	1941-50	1951-60	1961-70	1971-80
Jhun Jhunu	361.8	403.3	372.6	366.8	431.7	448.6	438.9	470.6
	(-1.01)	(-0.07)	(-0.76)	(-0.89)	(0.57)	(0.95)	(0.73)	(1.46)
Khanpur	904.6	1003.3	983.1	962.2	1102.6	906.9	821.7	852.8
	(-0.09)	(0.02)	(0.16)	(0.09)	(0.55)	(-0.09)	(-0.37)	(-0.26)
Kota	722.1	720.2	773.0	785.9	927.3	784.9	614.8	727.1
	(-0.32)	(-0.35)	(0.26)	(0.41)	(2.10)	(0.40)	(-1.59)	(-0.27)
Pali	444.8	398.4	374.9	390.5	447.7	479.3	413.8	477.5
	(0.13)	(-0.11)	(-0.23)	(-0.15)	(0.14)	(0.30)	(-0.03)	(0.29)
Pratapgarh	630.7	769.1	853.6	839.2	1051.8	912.6	757.7	1095.0
	(-0.76)	(-0.30)	(-0.03)	(-0.07)	(0.62)	(0.17)	(-0.34)	(0.77)
Sawai	667.7	822.3	810.8	986.0	1152.4	935.2	750.3	880.5
Madhopur	(-1.67)	(-0.30)	(-0.40)	(1.13)	(2.68)*	(0.69)	(-0.93)	(0.21)
Shahpura	589.1	641.1	718.8	636.4	701.9	595.6	574.4	631.8
	(-0.19)	(0.05)	(0.40)	(0.03)	(0.32)	(-0.16)	(-0.25)	(0.005)
Sirohi	524.3	533.4	576.6	507.8	726.9	633.6	663.6	779.0
	(-0.32)	(-0.29)	(0.14)	(-0.38)	(0.38)	(0.06)	(0.16)	(0.56)
Tonk	563.3	638.4	695.4	593.4	845.5	678.2	608.1	666.6
	(-1.25)	(-0.29)	(0.44)	(-0.86)	(2.42)*	(0.22)	(-0.67)	(0.07)
Udaipur	598.1	616.4	692.0	577.0	693.2	710.6	633.6	579.9
	(-0.19)	(-0.10)	(0.28)	(0.30)	(0.29)	(0.37)	(0.02)	(-0.33)

Values in brackets are Tk values   (table t value + or - 1.99)

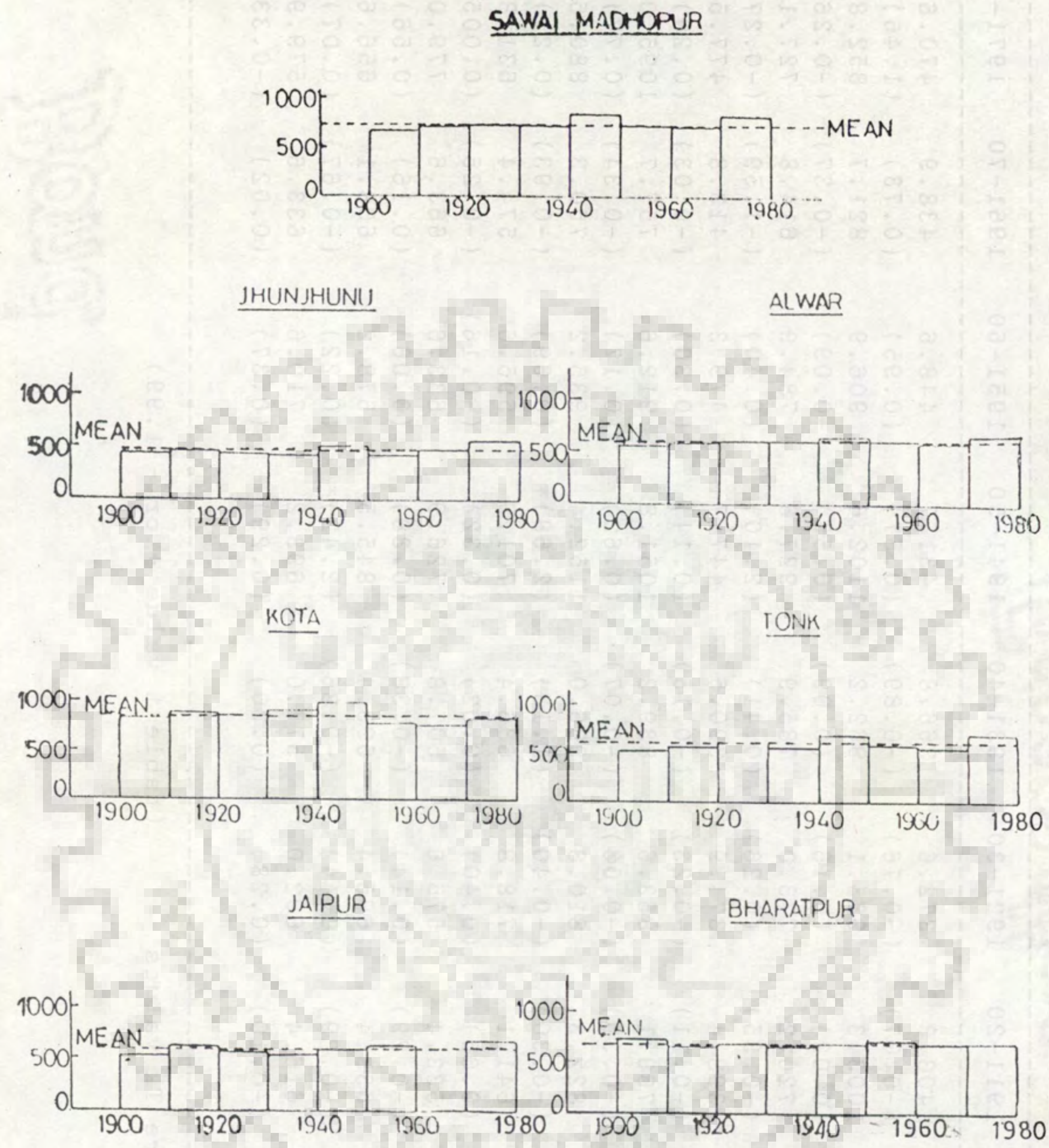


Figure 6.5 Comparison of Decade mean and Long Period Mean

mean for eighteen stations whereas in the decade 1971 - 80 fourteen stations indicated a positive trend though none of them are significant.

6.3.3 Trend analysis

The monthly, monsoon and annual series of rainfall and monsoon and annual series of rainy days were analysed for presence of trend using both the Spearman rank correlation (Eq.6.2) and linear regression of the form

$$Y_i = m X_i + c \qquad (6.6)$$

where Y_i is taken to represent either the rainfall or rainy day and X_i is the year taken as 1,2...n. The coefficient m indicates the presence of a rising or falling trend depending on its value being positive or negative.

Analysis of Spearman rank correlation has indicated a positive or negative trend in the rainfall and rainy days series of a few stations. In table 6.11, the t values corresponding to the Spearman rank correlation are shown. The significance is tested by comparing with the table value of t corresponding to 83 (number of years - 2) degrees of freedom which in this case is $\pm$ 1.99 . Significant positive trend (at 5% level) is seen in the rainfall series of two stations namely Ajmer and Dausa and negative trend in the rainfall series of Pratapgarh. The t values of Sirohi are very close to being significant at 5% level indicating a decreasing trend in rainfall.

In the case of rainy days, the series of Bharatpur and Dholpur have shown a negative trend. The two stations incidentally are in neighbouring districts. The regression coefficients along with the correpond- ing 't' values are given in tables 6.12 and

Table 6.11 't' values of Spearman rank correlation

Station	Rainfall		Rainy days	
	monsoon	annual	monsoon	annual
Ajmer	2.600*	2.087*	0.647	0.295
Alwar	1.032	1.262	1.162	0.603
Banswara	1.419	1.800	0.707	0.439
Bharatpur	0.091	-0.208	-1.757	-2.422*
Bundi	0.601	0.791	-0.040	-0.570
Dausa	2.899*	3.435*	1.392	1.386
Dholpur	-0.371	-1.129	-2.008*	-2.133*
Dungarpur	1.517	1.740	0.325	-0.752
Jaipur	1.839	1.838	1.374	1.005
Jalore	0.940	1.139	0.331	0.754
Jhun Jhunu	1.352	1.410	0.483	-0.410
Khanpur	-1.640	-1.540	-1.122	-0.930
Kota	-0.029	-0.177	-0.102	-0.581
Pali	0.459	0.245	-0.060	0.128
Pratapgarh	2.347*	2.993*	1.022	0.994
Sawai Madhopur	0.055	0.244	-0.395	-0.419
Shahpura	-0.100	-0.388	-0.196	-0.717
Sirohi	1.938	1.903	0.044	0.228
Tonk	0.546	0.664	0.241	0.187
Udaipur	-0.326	0.256	-0.703	-1.035

* Significant at 5 % level of significance

Table 6.12 Linear Regression Coefficients of Monsoon and Annual Rainfall Series

Sl. No	Station	Monsoon Corr. coeff.	Monsoon Regression coefficient	Monsoon t value	Annual Corr. coeff.	Annual Regression coefficient	Annual t value
1.	Ajmer	.259	2.19	2.44	.199	1.75	1.85
2.	Alwar	.082	0.68	0.75	.123	1.09	1.12
3.	Banswara	.208	2.83	1.93	.238	3.24	2.23
4.	Bharatpur	.024	-0.21	-0.22	.086	-0.78	-0.79
5.	Bundi	.027	0.28	0.25	.038	0.41	0.35
6.	Dausa	.320	3.01	3.08*	.377	3.69	3.70*
7.	Dholpur	.049	-0.46	-0.45	.050	-0.48	-0.77
8.	Dungarpur	.147	1.58	1.36	.174	1.90	1.61
9.	Jalore	.129	0.96	1.18	.143	1.10	1.32
10.	Jaipur	.197	1.84	1.83	.175	1.77	1.62
11.	Jhunjhunu	.146	0.82	1.34	.156	0.94	1.44
12.	Khanpur	.180	-2.10	-1.67	.164	-2.03	-1.51
13.	Kotah	.002	0.03	0.02	.052	-0.61	-0.48
14.	Pali	.035	0.27	0.32	.029	0.23	0.27
15.	Pratapgarh	.251	2.96	2.37	.273	3.42	2.63*
16.	Sawai Madhopur	.009	-0.15	-0.09	.013	0.20	0.12
17.	Shahpura	.087	-0.81	-0.80	.065	-0.58	-0.59
18.	Sirohi	.226	2.58	2.11	.234	2.73	2.19
19.	Tonk	.054	0.56	0.49	.060	0.64	0.55
20.	Udaipur	.024	-0.19	-0.22	.014	0.12	0.13

* Significant at 5 % level of significance (table t value ± 1.99)

Table 6.13 Linear Regression Coefficients of Monsoon and Annual Rainy days Series

Sl. No	Station	Monsoon Corr. coeff.	Monsoon Regression coefficient	Monsoon t value	Annual Corr. coeff.	Annual Regression coefficient	Annual t value
1.	Ajmer	.072	0.02	0.66	.005	0.00	0.05
2.	Alwar	.128	0.04	1.18	.046	0.02	0.42
3.	Banswara	.111	0.04	1.01	.062	0.03	0.56
4.	Bharatpur	.179	-0.06	-1.66	.273	-0.10	-2.59*
5.	Bundi	.025	-0.01	-0.22	.093	-0.04	-0.85
6.	Dausa	.151	0.05	1.39	.125	0.05	1.15
7.	Dholpur	.211	-0.07	-1.96	.241	-0.09	-2.26*
8.	Dungarpur	.011	0.00	-0.10	.053	-0.02	-0.49
9.	Jalore	.038	0.01	0.35	.080	0.03	0.73
10.	Jaipur	.113	0.04	1.04	.061	0.03	0.57
11.	Jhunjhunu	.038	0.01	0.35	.057	-0.02	-0.52
12.	Khanpur	.123	-0.04	-1.13	.122	-0.05	-1.12
13.	Kotah	.034	-0.01	-0.31	.087	-0.03	-0.80
14.	Pali	.038	0.01	0.35	.034	0.01	0.31
15.	Pratapgarh	.122	0.05	1.12	.076	0.03	0.69
16.	Sawai Madhopur	.023	-0.01	-0.21	.020	-0.01	-0.18
17.	Shahpura	.025	-0.01	-0.23	.082	-0.03	-0.75
18.	Sirohi	.004	0.00	0.04	.016	-0.01	-0.14
19.	Tonk	.027	0.01	0.24	.079	0.02	0.71
20.	Udaipur	.035	-0.01	-0.32	.088	-0.03	-0.81

* Significant at 5 % level of significance
(table t value $\pm$ 1.99)

6.13 respectively for rainfall and rainy days.

The series whose trend is significant are the July month rainfall series of Ajmer, Khanpur, Pali and Sirohi, monsoon rainfall series of Ajmer, Pratapgarh and Sirohi and annual rainfall series of Ajmer, Banswara, Dausa, Jalore, Sawai Madhopur and Sirohi .

The rainy days series where trend was noticed are the monsoon series of Dholpur and annual series of Bharatpur and Dholpur. The trend in the monsoon series of Dholpur is, however, not significant.

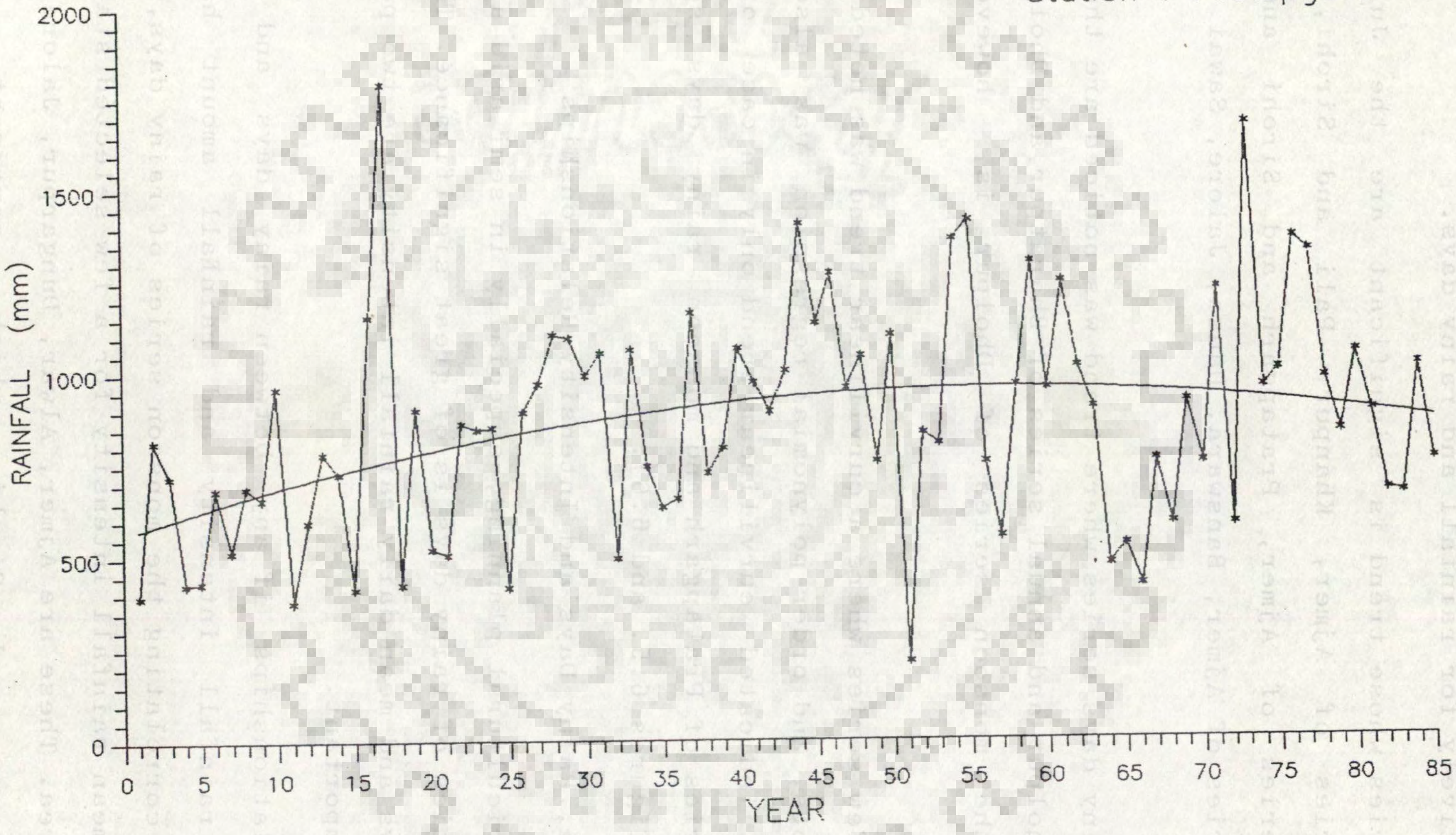
For a few series where a curvilinear trend was noted in the rainfall plots, 2nd order polynomial regression was also tried. The results indicated curvilinear trend only in case of annual rainfall series of Pratapgarh and monsoon rainy days series of Banswara (figures 6.5. and 6.6).

6.4 Rainfall, Rainy Days and Intensity Relationships

For agricultural planning, especially in semi arid areas, the characteristics of rainy days is of great significance. The number of rainy days and mean daily rainfall intensity are two parameters which are important.

The relationships if any between rainy days and rainfall amount and rainfall intensity and rainfall amount have been examined by correlating the monsoon series of rainy days, rainfall amount and mean rainfall intensity for a few selected stations in the study area. These are Ajmer, Alwar, Dungarpur, Jalore, Kotah, Sawai Madhopur and Sirohi which represent different homogeneous groups within the study area. The results are presented in table 6.14 .

Figure : 6.6 Annual Rainfall Time series
Station : Pratapgarh



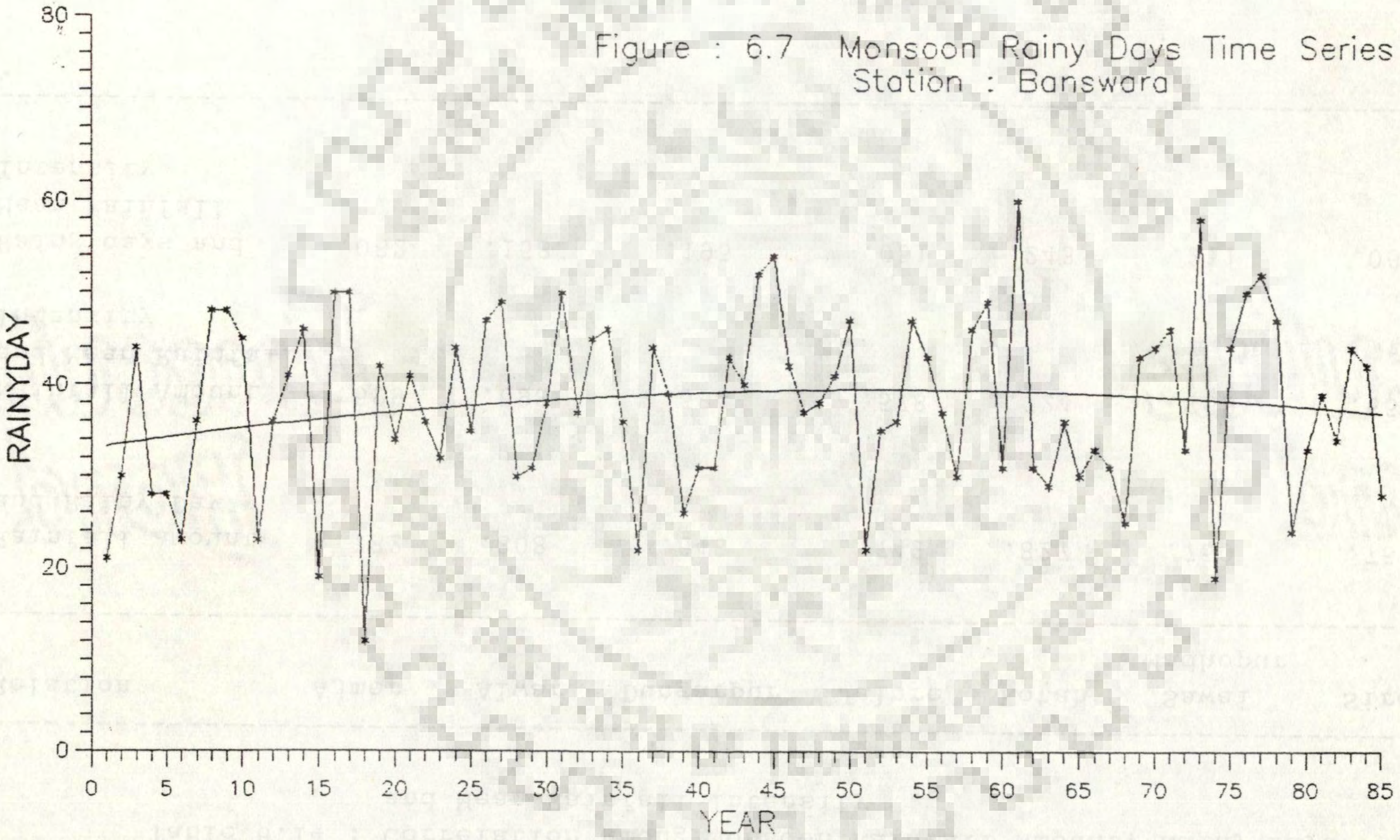


Figure : 6.7 Monsoon Rainy Days Time Series
Station : Banswara

Table 6.14 : Correlation Among Monsoon Rainfall Amount, Rainy Days and Mean Rainfall Intensity

Relation	Ajmer	Alwar	Dungarpur	Jalore	Kotah	Sawai Madhopur	Sirohi
Rainfall Amount and Rainy Day	.782	.808	.648	.742	.827	.750	.757
Rainfall Amount and Mean Rainfall Intensity	.599	.698	.584	.578	.724	.769	.657
Rainy days and Mean Rainfall Intensity	.082	.158	.195	.051	.243	.211	.062

The analysis indicated that the number of rainy days influence to some extent the total rainfall amounts received in a month or season. Correlation between rainfall amount and intensity (amount of rainfall per rainy day) is comparatively less and there is no relation between rainy days and intensity.

This indicated the random occurrence of rainfall in time which is made up of both low intensity long duration rain spells and high intensity short duration bursts which are characteristic of semi arid areas.

6.5 Remarks

The analysis presented in this chapter brought out the following points :

(i) The serial correlation coefficient of the rainfall and rainy days series in general is nearer to zero indicating the lack of any persistence. However, rainfall series of two stations namely Dausa and Pratapgarh and rainy days series of two stations namely Dholpur and Sawai Madhopur is either nearer to or beyond the confidence limits indicating persistence.

(ii) The trend analysis using decadal means, Spearman rank correlation, linear and polynomial trend all indicated trend in the following :

(a) July month rainfall series of Ajmer, Khanpur, Pali and Sirohi

(b) monsoon rainfall series of Ajmer, Pratapgarh and Sirohi

(c) annual rainfall series of Ajmer, Banswara, Dausa, Jalore, Sawai Madhopur and Sirohi

(d) monsoon rainy days series of Dholpur and

(e) annual rainy days series of Bharatpur and Dholpur

(iii) Number of rainy days to a certain extent determine the total amount of monsoon rainfall. There is some relationship between rainfall intensity and total rainfall. There is no relation between rainfall intensity and the number of rainy days.

(iv) Some of the stations which have indicated either a positive or negative trend in rainy days have not indicated any trend in the rainfall. This indicates the possibility of increase in rainfall intensities at some locations and decrease in rainfall intensities at others. This could be attributed to decrease in dust content due to irrigation on the one hand and increase in dust and pollutants due to industrialisation on the other.

In an earlier study Ramasastri and Vibha Jain (1990) have shown the effects of industrialisation around Ranchi in Bihar Plateau (India) on the rainfall and temperature around the town. Based on the study the authors concluded that the climate around Ranchi has changed resulting in decrease in annual rainfall and increase in night temperatures.

CHAPTER VII

SIMULATION OF RAINFALL

7.1 General

In many semi arid regions rainfall is characterised by sequences of short wet spells interspersed with long dry periods. The imbalances between demand and supply could be handled by appropriate planning and operation of the water resources projects and agricultural operations in these areas. This, however, would require long historical records of stream flow. Where the historical records are short, the generation of synthetic sequences of stream flow provides alternate data series for planning decisions.

Because of continuous development and short streamflow records, observed streamflow data are generally not representative of current catchment conditions. On the other hand, rainfall records are generally longer than stream flow records and are generally, not affected by developments in the catchment. Also, for a given length of record the statistical characteristics of rainfall can be defined with relatively less error than in the case of stream flow and hence can be used with stochastic data generation models. The generated rainfall can be used as input to deterministic models for synthesis of stream flow data.

The objective of the analysis is to generate synthetic sequences of monthly and daily rainfall series for monsoon period with minimum data from the study area which faithfully reproduce the statistical characteristics of the observed rainfall series.

7.2 Methodology

As indicated in literature review, it was considered appropriate to use Thomas Fiering model for generating synthetic sequences of monthly rainfall. The Thomas Fiering model has been used and suitable modifications have been introduced to arrive at satisfactory simulation. For simulation of daily rainfall sequences, two models namely the Transition Probability Matrix (TPM) model and the Alternating Renewal Process (ARP) model have been used and the tests carried out to compare their performance.

7.2.1 Thomas Fiering model

The Thomas Fiering model (Clarke, 1973) has been developed for generation of monthly discharge data. Using the Thomas Fiering notation, the model may be written as

$$q_{i+1} = \bar{q}_{j+1} + b\,(q_i - \bar{q}_j) + z_i\, S_{j+1} \sqrt{(1 - r^2)} \qquad (7.1)$$

In Eq. 7.1 q_i and q_{i+1} are the volumes of discharge during the ith and (i+1) th month respectively, $\bar{q}_j$ and $\bar{q}_{j+1}$ are the mean monthly discharges during the jth and (j+1)th months respectively, within a repetitive annual cycle of 12 months. b_j is the regression coefficient for estimating volume of discharge in the (j+1) month from the jth month. Z_i is random normal deviate with zero mean and unit variance; S_{j+1} is the standard deviation of discharges in the (j+1) month; and r_j is the correlation coefficient between flows in the jth and (j+1) th months.

The steps for using the Thomas Fiering model are described below:

(i) the monthly means and standard deviations are computed for the station

(ii) the monthly series are standardised by subtracting the respective monthly means and dividing by the respective standard deviation. For example $Q_1 = (Q_J - \bar{Q}_J) / S_J$ . . . (7.2)

Selvalingam and Miura (1978) used the Thomas Fiering model for generation of monthly rainfall even though the month to month correlations were weak. The statistical parameters calculated for comparison of the monthly generation model are mean, standard deviation and coefficient of skewness, relative frequency of zero values and the maximum rainfall amount for each month.

The Thomas Fiering model in its original form as recommended for generation of streamflows was first used for generation of monthly rainfalls. The parameters were estimated using the harmonic analysis.

The model has been modified keeping in view the lack of correlation among the rainfall series of the four monsoon months. The parameters were estimated by computing only the harmonics and neglecting the correlation among the series. As an alternative, appropriate transformations (logarithm, square root and power transformation) were also tried with the original model for generation of monthly rainfall series. The performance with these five methods was compared for selcting suitable approaches.

7.2.2 Transition probability matrix method :

The essential features of this method are

(i) the range over which rainfall is expected to vary is divided into a set of discrete intervals.

(ii) a matrix corresponding to the intervals is built up from the observed rainfall sequences by tabulating the number of times the observed data went from state i to state j denoted by n_{ij} as follows

$$
\begin{array}{c|cccccc}
\text{starting state} & \multicolumn{6}{c}{\text{final state}} \\
 & 0 & 1 & 2 & 3 & \cdots & \\
\hline
0 & n_{00} & n_{01} & n_{02} & n_{03} & \cdots & \\
1 & n_{10} & n_{11} & n_{12} & n_{13} & \cdots & \\
2 & n_{20} & n_{21} & n_{22} & n_{23} & \cdots & \\
3 & n_{30} & n_{31} & n_{32} & n_{33} & \cdots & \\
\vdots & & & & & &
\end{array}
\qquad (7.3)
$$

(iii) The m x m transitional probabilities matrix is then represented by

$$
P = [\,p_{ij}\,] =
\begin{array}{c|ccccc}
\text{starting state} & \multicolumn{5}{c}{\text{final state}} \\
 & 0 & 1 & 2 & 3 & \cdots \\
\hline
0 & p_{00} & p_{01} & p_{02} & p_{03} & \cdots \\
1 & p_{10} & p_{11} & p_{12} & p_{13} & \cdots \\
2 & p_{20} & p_{21} & p_{22} & p_{23} & \cdots \\
3 & p_{30} & p_{31} & p_{32} & p_{33} & \cdots \\
\vdots & & & & &
\end{array}
\qquad (7.4)
$$

$$\text{where } p_{00} = n_{00}/(n_{00} + n_{01} + n_{02} + \cdots) \qquad (7.5)$$

$$p_{10} = n_{10}/(n_{10} + n_{11} + n_{12} + \cdots) \qquad (7.6)$$

and so on each p_{ij} being obtained by dividing n_{ij} by the corresponding row total of the n_{ij}.

(iv) After the transitional probabilities are estimated the next step is the simulation of rainfall using appropriate distribution. The synthetic sequences were generated by dividing the rainfall into a number of classes (intervals) The sequences of states are built up by selecting a pseudo random number u between 0 and 1 and then assigning the state according as the value of u is less than or greater than $p_{01} + p_{00}$ and then moving to the next state and so on as described in Clarke (1973).

Better results could be obtained if the rainfall is divided into finer intervals. However, that would not only require large amount of data but also requires more computer time. After trying as many as 13 classes Haan et al (1976) found six classes to be a reasonable choice. They used a uniformly distributed model for the first five classes an an exponentially distributed model for the last class.

Srikanthan and McMahon (1982) used seven classes. The rainfall in the last class was generated using a shifted exponential distribution . The approach of Srikanthan and McMahon (1982) was considered appropriate and was adopted for the simulation and generation of daily rainfall data using the TPM method. A few alternatives were studied by changing the limits of rainfall for the classes.

7.2.3 Alternating renewal process

The process consists of alternating dry and wet spells. The wet spells are independent and belong to a certain distribution. Similarly, the dry spells are independent and have another distribution. Further, the two random sequences are independent. The following definitions apply:

(i) A wet spell is a sequence of wet days bounded on either side by a dry day.

(ii) A dry spell is defined likewise.

(iii) Spells are assigned to the periods (usually months or seasons) in which they begin.

(iv) A day is defined as wet if the rainfall exceeds a threshold value δ mm.

The first two assumptions could be satisfied by analysing data on a monthly or seasonal basis. The third assumption is checked by computing the correlation between wet and dry spells in each month.

Several distributions can be fitted to the data to model the lengths of wet and dry spells. Commonly used distributions for wet and dry runs are ; the truncated negative bionomial distribution (TNBD) and the shifted negative bionomial distribution (SNBD) . Kottegoda and Horder (1980) tested both TNBD and SNBD for fitting to wet spells and dry spells using the alternating renewal process. They found both TNBD and SNBD fitted equally well. The TNBD was preferred by the authors for mathematical convenience as it includes the geometric distribution as well as as the logarithmic series distribution. Rao and Rees (1991) also used the TNBD in their study. For the present analysis, therefore, the truncated negative bionomial distribution (TNBD) is used. The probability density function of the TNBD is given by

$$p\,(x = k \mid x \geq 1) = \left[\frac{k + r - 1}{k}\right] \frac{p^{r}\,(1-p)^{r}}{1-p^{r}} \quad \ldots (7.7)$$

in which x is the random variable, k is the length of the spell and p and r are parameters ($0 < p < 1$; $-1 < r$) .

If the rainfall is modeled on monthly basis, 24 parameters are required to be estimated for Eq (7.7) for the whole year. The number of parameters to be estimated, however, could be reduced by estimating them on seasonal basis. For the genration of daily rainfall only rainfall for the monsoon season (June to September) is considered as rainfall during other months in east Rajasthan is negligible.

In general, the development of rainfall model based on the alternating renewal process requires long data series so that sufficient number of wet and dry spells could be included. Data of 25 to 30 years when used for only a season are known to have performed well.

The model for rainfall amounts must be one which describes the distribution of rainfall amounts on days when it rains. The distribution is highly skewed and since the wet day is defned as a day on which rainfall exceeds a threshold value δ mm, a shifted or truncated distribution would model the rainfall amounts well.

The shifted two parameter gamma distribution (SGD) has been frequently used to fit the rainfall amounts (Stern and Coe, 1984). The probability density function of this distribution is given by:

$$f(y) = \frac{\lambda^{\nu} \; y^{\nu} \; \exp(-y\lambda)}{\Gamma \nu} \quad . \quad . \quad . \quad . \qquad (7.8)$$

in which y is the rainfall amount, Γ is the gamma function, and ν and λ are parameters.

The mean rainfall of a wet spell depends on the length of the spell (Buishand,1978) . To account for this, three tyes of rainfall are distinguished. These are :

(i) wet spells with a solitary wet day (type 0)

(ii) a wet day with one adjacent day also wet (type 1)

(iii) a wet day with both adjacent days wet (type 2)

The probability density function in Eq (7.8) is derived separately for each type of wet spell for each month.

The estimation of parameters p and r in Eq. (7.7) and ν and λ in Eq (7.8) is done using the method of maximum likelihood. For

Eq (7.7) daily rainfall values greater than δ are considered. For estimating the parameters of Eq (7.8) by the maximum likelihood the difficulty is they are sensitive to small changes in values of rainfall. To overcome this Buishand (1977) suggested ignoring values of rainfall below a certain specified value of rainfall and considering only their number while estimating the parameters of this function. Thus only values of rainfall greater than ($\delta+\varepsilon$) mm are considered for estimating the parameters ν and λ in Eq (7.8). Appropriate values of δ and ε can be arrived at by trial and error. Buishand (1977) found that the value of δ ranged from 0.1 mm to 3.0 mm for various locations in the world. For rainfall series of three Indian stations form north, south and east he found that the values of δ = 0.2 mm and ε = 1.0 mm were most suitable.

The generation of daily rainfall sequences is carried out in two steps. First, the legths of wet spells and dry spells are generated by coupling a uniform random number in the interval (0,1) to the cumulative distribution function of TNBD. For wet spells of type 0, type 1 or type 2 the appropriate random gamma variates are generated to obtain the values of daily rainfall.

7.3. Simulation of Monthly Rainfall using Thomas Fiering Model

The simulation of monthly rainfall has been carried out for four stations each one representing a homogeneous group derived on the basis of cluster analysis (described in Chapter VIII). The statistical properties used for comparing the observed and simulated series were :

(i) mean, standard deviation and coefficient of skewness

(ii) frequency of zero monthly rainfall and

(iii) magnitude of maximum monthly rainfall

7.3.1 Simulation with original Thomas Fiering model

Data of 30 years each for three different overlapping periods 1951 - 1980, 1956- 1985 and 1961 - 1990 and 40 years for the period 1951 - 1990 were used for simulating 30 and 50 years of monthly rainfall. The results for the data generated with the Thomas Fiering model for the four monsoon months (June to September) are presented in tables 7.1 to 7.4 respectively for Alwar, Banswara, Jalore and Jaipur.

7.3.2 Simulation using modified Thomas Fiering model

Based on data of 40 years for the period 1951 - 90, monthly rainfall for the same set of stations has been generated using the modified method (considering the series as uncorrelated). In tables 7.5 to 7.8 the results of the generated data are presented.

7.3.3 Comparison of results from original and modified Thomas Fiering model

It is seen from the results presented in tables 7.1 to 7.4 and 7.5 to 7.8 that the three statistical parameters of generated data chosen as criteria for testing namely the mean, standard deviation and coefficient of skewness are generally comparable with the respective parameters of the observed data. Also, the highest observed monthly rainfall is comparable at all stations in the monsoon months excepting in extreme cases like July 1981 in case of Jaipur and July 1983 in case of Jalore. Thus, both the methods have provided comparable results while the results from the modified model are better.

7.3.4 Simulation using Thomas Fiering model with transformation of observed series

In the generated data from the above two methods, the frequency of zero rainfall occurrence is more than in the observed

Table 7.1 (a) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Alwar

Parameter	OBSERVED SERIES (1951-80)				SIMULATED 30 years				SIMULATED 50 years			
	Jun.	Jul.	Aug.	Sept.	Jun.	Jul.	Aug.	Sept.	Jun.	Jul.	Aug.	Sept.
Mean (mm)	48.8	212.1	228.9	123.1	42.2	213.0	236.0	118.6	40.3	214.0	215.3	113.6
Standard (mm) Deviation	38.2	85.9	118.3	107.6	33.6	94.7	136.3	101.3	31.7	95.3	130.5	101.8
Coefficient of skewness	.777	.045	.896	1.773	.329	-.460	-.206	.344	.340	-.25	.021	.546
Frequency of Zero rain	2/30	0	0	1/30	5/30	1/30	2/30	5/30	7/50	1/50	2/50	9/50
Maximum Monthly rain (mm)	139.7	417.2	587.8	468.0	110.8	374.6	464.5	325.7	110.8	374.6	464.5	378.0

Table 7.1 (b) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Alwar

Parameter	OBSERVED SERIES (1956-85)				SIMULATED 30 years				SIMULATED 50 years			
	Jun.	Jul.	Aug.	Sept.	Jun.	Jul.	Aug.	Sept.	Jun.	Jul.	Aug.	Sept.
Mean (mm)	42.7	224.7	233.8	121.7	35.2	225.8	237.0	118.0	33.5	226.9	227.0	112.8
Standard (mm) Deviation	32.8	79.4	111.7	110.4	28.6	89.3	131.6	104.7	27.0	89.9	125.6	105.0
Coefficient of skewness	.683	.031	1.184	1.630	.357	-.464	-.242	.385	.369	-.256	-.008	.585
Frequency of Zero rain	2/30	0	0	2/30	6/30	0	2/30	8/30	9/50	0/50	2/50	13/50
Maximum Monthly rain (mm)	120.0	417.2	587.8	468.0	94.0	376.0	454.0	335.8	94.0	378.3	454.0	387.3

Table 7.1 (c) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Alwar

Parameter	OBSERVED SERIES (1961-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	45.2	208.9	215.7	110.8	38.7	215.2	220.7	114.7	37.6	216.8	213.2	110.2
Standard (mm) Deviation	32.0	93.8	92.6	102.9	27.0	105.7	111.5	99.2	25.5	110.8	105.3	100.5
Coefficient of skewness	.606	-.139	.532	1.700	.306	-.339	-.323	.338	.281	-.217	-.062	.546
Frequency of Zero rain	2/30	0	0	3/30	2/30	2/30	1/30	6/30	3/50	2/50	1/50	12/50
Maximum Monthly rain (mm)	120.0	417.2	412.6	468.0	92.1	404.3	404.0	328.4	92.1	404.3	404.0	377.1

Table 7.1 (d) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Alwar

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	46.0	200.7	215.2	115.9	39.6	203.0	221.8	114.2	38.2	203.5	212.8	108.9
Standard (mm) Deviation	35.7	89.4	108.2	107.1	30.6	97.9	124.0	97.9	28.7	99.3	117.9	99.7
Coefficient of skewness	.856	-.040	1.115	1.563	.313	-.385	-.217	.325	.312	-.205	.020	.564
Frequency of Zero rain	2/40	0	0	3/40	5/30	2/30	2/30	6/30	7/50	2/50	2/50	12/50
Maximum Monthly rain (mm)	139.7	417.2	587.8	468.0	102.4	371.6	438.1	306.0	102.4	372.1	438.1	376.9

Table 7.2 (a) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Banswara

Parameter	OBSERVED SERIES (1951-80) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	119.2	345.5	332.6	208.1	103.3	376.8	339.5	222.7	98.6	374.0	319.6	212.8
Standard (mm) Deviation	102.9	226.7	158.0	204.8	100.4	293.4	231.5	232.4	94.4	313.7	223.2	239.3
Coefficient of skewness	2.553	2.054	.775	1.135	.642	.347	-.041	.536	.612	.274	.168	.274
Frequency of Zero rain	0	0	0	2/30	9/30	6/30	4/30	11/30	13/50	13/50	5/50	19/50
Maximum Monthly rain (mm)	530.2	1090.8	811.9	774.8	330.8	977.0	784.6	695.3	330.8	977.0	784.6	959.9

Table 7.2 (b) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Banswara

Parameter	OBSERVED SERIES (1956-85) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	105.2	328.6	364.5	179.0	100.2	336.8	386.2	177.8	96.9	335.4	370.6	169.3
Standard (mm) Deviation	103.1	173.7	191.2	164.5	85.3	180.9	220.1	146.4	80.0	188.0	208.7	151.3
Coefficient of skewness	2.783	2.060	1.355	1.111	.451	-.211	-.176	.273	.430	-.103	.060	.553
Frequency of Zero rain	0	0	0	1/30	7/30	3/30	1/30	5/30	9/50	3/50	1/50	11/50
Maximum Monthly rain (mm)	530.2	986.6	811.9	591.5	283.7	661.9	790.7	447.9	283.7	661.9	790.7	587.2

Table 7.2 (c) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Banswara

Parameter	OBSERVED SERIES (1961-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	109.1	296.8	360.0	165.2	118.4	312.7	412.3	182.7	113.7	311.3	390.6	174.7
Standard (mm) Deviation	103.7	133.3	190.7	163.4	106.2	168.9	268.9	167.5	99.8	175.9	257.8	171.8
Coefficient of skewness	2.596	.457	1.439	1.225	.530	-.200	-.090	.378	.505	-.098	.128	.707
Frequency of Zero rain	1/30	0	0	4/30	7/30	3/30	3/30	8/30	9/50	3/50	3/50	15/50
Maximum Monthly rain (mm)	530.2	621.3	964.0	591.5	351.5	617.1	918.0	502.4	351.5	617.1	918.0	671.8

Table 7.2 (d) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Banswara

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	106.2	321.3	344.2	179.1	89.5	323.2	345.5	175.9	85.7	319.7	325.0	168.1
Standard (mm) Deviation	94.8	210.1	179.4	190.7	85.1	241.4	236.6	184.7	80.0	258.5	228.3	190.2
Coefficient of skewness	2.661	2.077	1.358	1.343	.607	.266	-.036	.535	.579	.210	.172	.951
Frequency of Zero rain	0	0	0	5/40	8/30	6/30	5/30	11/30	12/50	10/50	6/50	19/50
Maximum Monthly rain (mm)	530.2	1090.8	964.0	774.8	280.5	807.2	800.6	552.3	280.5	807.2	800.6	763.7

Table 7.3 (a) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Jalore

	OBSERVED SERIES (1951-80)				SIMULATED 30 years				SIMULATED 50 years			
Parameter	Jun.	Jul.	Aug.	Sept.	Jun.	Jul.	Aug.	Sept.	Jun.	Jul.	Aug.	Sept.
Mean (mm)	30.6	134.7	149.7	64.6								
Standard (mm) Deviation	25.6	111.4	124.0	90.9	Meaningless values generated							
Coefficient of skewness	.307	.869	1.701	2.111	Statistics not computed							
Frequency of Zero rain	5/30	1/30	0	5/30								
Maximum Monthly rain (mm)	75.7	387.6	597.2	345.8								

Table 7.3 (b) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Jalore

	OBSERVED SERIES (1956-85)				SIMULATED 30 years				SIMULATED 50 years			
Parameter	Jun.	Jul.	Aug.	Sept.	Jun.	Jul.	Aug.	Sept.	Jun.	Jul.	Aug.	Sept.
Mean (mm)	30.2	146.6	133.2	53.4	25.0	211.1	214.9	91.8	22.8	224.0	187.7	86.3
Standard (mm) Deviation	25.4	134.9	117.4	73.9	31.8	258.4	231.4	123.4	29.4	269.1	227.9	131.6
Coefficient of skewness	.386	1.703	2.233	2.385	1.205	1.164	.685	1.140	1.205	.945	.851	1.776
Frequency of Zero rain	5/30	1/30	0	3/30	13/30	11/30	13/30	15/30	23/50	20/50	25/50	27/50
Maximum Monthly rain (mm)	75.7	619.6	597.2	343.2	108.2	850.8	781.7	387.0	108.2	850.8	781.7	592.2

Table 7.3 (c) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Jalore

Parameter	OBSERVED SERIES (1961-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	25.0	147.0	132.6	47.2	18.1	176.6	174.3	65.3	16.7	184.5	152.5	61.5
Standard (mm) Deviation	25.9	147.1	130.0	71.4	21.9	196.9	181.4	82.5	20.3	205.8	179.0	88.2
Coefficient of skewness	.678	1.855	1.921	2.790	1.084	-.998	.586	1.004	1.065	.814	.760	1.635
Frequency of Zero rain	7/30	1/30	1/30	4/30	13/30	11/30	13/30	15/30	22/50	20/50	24/50	26/50
Maximum Monthly rain (mm)	74.6	619.6	597.2	343.2	73.8	647.7	608.1	261.9	73.8	647.7	608.1	393.1

Table 7.3 (d) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Jalore

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	26.1	151.5	142.1	53.7	17.1	66.0	145.5	58.6	16.6	156.4	130.5	55.5
Standard (mm) Deviation	25.2	143.0	121.8	81.9	16.0	63.5	128.3	66.8	15.0	148.8	126.7	71.0
Coefficient of skewness	.618	1.589	1.645	2.456	.594	.437	.313	.730	.549	.501	.506	1.305
Frequency of Zero rain	8/40	1/40	1/40	7/40	8/30	9/50	8/30	14/30	12/50	17/50	17/50	25/50
Maximum Monthly rain (mm)	75.7	619.6	597.2	345.8	53.0	461.9	427.6	211.1	53.0	461.9	427.6	305.7

Table 7.4 (a) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Jaipur

Parameter	OBSERVED SERIES (1951-80) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	64.5	203.2	235.9	90.1	67.8	211.4	257.5	88.1	64.9	209.1	245.6	83.8
Standard (mm) Deviation	73.3	119.6	126.7	78.1	63.6	123.0	156.6	71.2	59.8	130.5	149.3	73.7
Coefficient of skewness	2.295	.561	.878	.870	.585	-.067	-.131	.257	.563	-.029	.096	.533
Frequency of Zero rain	2/30	0	0	3/30	8/30	1/30	2/30	6/30	10/50	1/50	2/50	11/50
Maximum Monthly rain (mm)	319.2	458.2	539.8	281.0	209.5	439.4	548.8	219.1	209.5	439.4	548.8	286.5

Table 7.4 (b) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Jaipur

Parameter	OBSERVED SERIES (1956-85) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	59.0	236.2	232.5	85.1	56.8	250.7	242.5	83.6	54.6	247.1	232.9	79.4
Standard (mm) Deviation	74.5	182.0	124.3	76.1	55.1	166.7	139.0	65.5	51.8	178.7	131.5	68.6
Coefficient of skewness	2.382	2.056	0.816	.992	.650	.088	-.145	.221	.608	.074	.088	.527
Frequency of Zero rain	3/30	0	0	4/30	8/30	4/30	1/30	5/30	13/50	8/50	1/50	10/50
Maximum Monthly rain (mm)	319.2	941.0	539.8	281.0	182.2	572.1	507.0	207.3	182.2	572.1	507.0	271.5

Table 7.4 (c) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Jaipur

Parameter	OBSERVED SERIES (1961-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	58.6	227.1	209.3	74.6	55.5	242.3	218.9	74.7	53.2	239.1	208.7	71.2
Standard (mm) Deviation	74.0	181.4	123.2	74.2	54.2	165.9	135.4	63.5	50.9	177.7	128.9	65.9
Coefficient of skewness	2.455	2.169	1.151	1.369	.653	.131	-.111	.295	.618	.108	.115	.619
Frequency of Zero rain	2/30	0	0	4/30	9/30	4/30	2/30	6/30	14/50	8/50	2/50	13/50
Maximum Monthly rain (mm)	319.2	941.0	539.8	281.0	178.8	565.0	476.4	195.8	178.8	565.0	476.4	259.2

Table 7.4 (d) Statistical parameters of observed and simulated monthly rainfall series
Method : Thomas Fiering Station - Jaipur

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	55.3	219.0	220.7	77.8	53.5	232.9	233.4	76.8	51.5	229.7	223.3	73.1
Standard (mm) Deviation	65.7	168.6	125.6	73.6	50.1	155.0	139.8	63.0	47.1	166.0	132.8	65.5
Coefficient of skewness	2.689	2.140	.837	1.067	.588	.092	-.133	.266	.556	.076	.096	.569
Frequency of Zero rain	3/40	0	0	5/40	8/30	4/30	2/30	5/30	12/50	7/50	2/50	12/50
Maximum Monthly rain (mm)	319.2	941.0	539.8	281.0	165.5	531.3	497.0	195.4	165.5	531.3	497.0	256.9

Table 7.5 Statistical parameters of observed and simulated monthly rainfall series
Station - Alwar

Modified Thomas Fiering Method

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	46.0	200.7	215.2	115.9	38.9	202.2	221.3	115.0	38.0	202.6	212.5	109.4
Standard (mm) Deviation	35.7	89.4	108.2	107.1	30.6	99.0	124.9	94.6	28.7	100.4	118.3	98.1
Coefficient of skewness	.856	-.040	1.115	1.563	.363	-.410	-.173	.272	.334	-.226	.063	.562
Frequency of Zero rain	2/40	0	0	3/40	5/30	2/30	1/30	5/30	6/50	2/50	1/50	12/50
Maximum Monthly rain (mm)	139.7	417.2	587.8	468.0	103.0	373.3	452.6	291.2	103.0	373.3	452.6	382.3

Table 7.6 Statistical parameters of observed and simulated monthly rainfall series
Station : Banswara

Modified Thomas Fiering Method

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	106.2	321.3	344.2	179.1	89.6	323.1	345.6	176.1	85.8	319.7	325.1	168.2
Standard (mm) Deviation	94.8	210.1	179.4	190.7	85.1	241.6	236.4	184.9	80.0	258.7	228.2	190.3
Coefficient of skewness	2.661	2.077	1.358	1.343	.604	.266	-.039	.541	.578	.210	.170	.952
Frequency of Zero rain	0	0	0	5/40	8/30	6/30	4/30	11/30	12/50	11/50	5/50	19/50
Maximum Monthly rain (mm)	530.2	1090.8	964.0	774.8	280.4	807.2	798.9	552.0	280.4	807.2	798.9	763.0

Table 7.7 Statistical parameters of observed and simulated monthly rainfall series
Station - Jalore

Modified Thomas Fiering Method

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	26.1	151.5	142.1	53.7	17.3	154.2	145.7	59.0	16.6	156.6	130.6	55.6
Standard (mm) Deviation	25.2	143.0	121.8	81.9	16.0	141.5	127.8	68.4	15.0	148.7	126.4	71.8
Coefficient of skewness	.618	1.589	1.645	2.456	.565	.607	.279	.779	.539	.500	.472	1.295
Frequency of Zero rain	8/40	1/40	1/40	7/40	7/30	8/30	8/30	14/30	11/50	16/50	14/50	24/50
Maximum Monthly rain (mm)	75.7	619.6	597.2	345.8	52.8	462.5	417.4	210.2	52.8	462.5	417.4	303.4

Table 7.8 Statistical parameters of observed and simulated monthly rainfall series
Station : Jaipur

Modified Thomas Fiering Method

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 30 years Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	53.3	219.0	220.7	77.8	53.8	232.9	233.7	76.7	51.6	229.7	223.4	73.0
Standard (mm) Deviation	65.7	168.6	125.6	73.6	50.1	155.1	139.5	63.5	47.1	166.2	132.6	65.7
Coefficient of skewness	2.689	2.140	.837	1.067	.580	.095	-.141	.276	.554	.078	.089	.569
Frequency of Zero rain	3/40	0	0	5/40	6/30	4/30	2/30	5/30	10/50	7/50	2/50	12/50
Maximum Monthly rain (mm)	319.2	941.0	539.8	281.0	165.3	531.3	493.8	195.1	165.3	531.3	493.8	256.4

especially at Jalore where the frequency of zero rainfall is more even in the observed data as compared to other stations. Also, there are few cases where the generated rainfall is zero in three consecutive months.

The slightly higher values of standard deviation in the generated series of the month of August in Banswara are also due to the more number of zero rain in the generated data.

To overcome the problem of zero rain in the generated monthly series the original data series were transformed using appropriate transformation approaches.

7.3.4.1 use of log transformation

In the first case the observed series were transformed by logarithmic transformation before applying them with the Thomas Fiering (original) model. The generated values were converted back to obtain the series in the normal form. The results of the analysis are presented in Table 7.9. For the sake of comparison of the generated series with the original series, the following criteria were used.

(i) Number of monthly rainfall values (frequency) of less than 10 mm.

(ii) Number of monthly rainfall values (frequency) of more than 100 mm.

(iii) Magnitude of maximum rainfall.

It is seen that though there are very few cases of zero rainfall a number of values of less than 10 mm and less than 100 mm have been generated. This is especially in the case of June and September, the relatively drier months and for all the four monsoon months in case of Jalore which has an arid climate.

Table 7.9 (a) Statistical parameters of observed and simulated monthly rainfall series

Method : Thomas Fiering with logtransform Station - Jalore

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Frequency of rain < 10 mm	17/40	3/40	2/40	14/40	33/50	8/50	9/50	26/50
Frequency of rain > 100 mm	0	19/40	23/40	8/40	0	22/50	28/50	0
Maximum (mm) monthly rain	75.7	619.6	597.2	345.8	812	4447	2697	54176

Table 7.9 (b) Statistical parameters of observed and simulated monthly rainfall series

Method : Thomas Fiering with logtransform Station - Jaipur

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Frequency of rain < 10 mm	6/40	0	0	10/40	23/50	0	0	25/50
Frequency of rain > 100 mm	4/40	29/40	36/40	15/40	8/50	36/50	37/50	12/50
Maximum (mm) monthly rain	319.2	941.0	539.8	281.0	1212	812	812	44356

The magnitude of maximum rainfall is also very high. Thus, the the log transformation did not yield satisfactory results and is found to be of only limited use for data generation in semi arid areas with monsoon climate.

7.3.4.2 use of square root transformation :

In view of the poor results obtained by log transformation, another transforamtion namely square root transformation was tried. The results based on data generated for 50 years from a sample of 40 years (1951 - 1990) for the stations Banswara, Jalore and Jaipur are presented in table 7.10 .

It is seen from the results that not only the statistical properties namely mean, standard deviation and coefficient of skewness are reasonably preserved, but also the other properties like frequency of rainfall less than 10 mm and highest observed monthly rainfall are also comparable for the observed and generated series for all the three stations which represent high (Banswara), moderate (Jaipur) and low (Jalore) rainfall regions.

7.3.4.3 use of power transformation :

To further examine the effect of other transformation procedures on the generated data, power transformation has been used on the original series before using them for generation of data with the Tomas Fiering model. This has been done for two stations namely Jalore and Jaipur. The results are presented in Table 7.11 . From the results it is seen that the series generated after the transformation have values of mean, standard deviation and skewness comparable to those of the original series. The maximum rainfall also, is generally comparable to those seen in the observed series. However, the number of values below 10 mm are more in the generated series especially in the case of Jalore.

Table 7.10 (a) Statistical parameters of observed and simulated monthly rainfall series
Method : Square Root transform Station - Banswara

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	106.2	321.3	344.2	179.1	92.0	334.8	351.9	167.1
Standard (mm) Deviation	94.8	210.1	179.4	190.7	63.4	215.9	184.1	188.9
Coefficient of skewness	2.661	2.077	1.358	1.343	.827	.366	.425	1.776
Frequency of rain < 10 mm	2/40	0	0	6/40	0	1/50	0	9/50
Maximum Monthly rain (mm)	530.2	1090.8	964.0	774.8	269.0	789.6	800.9	948.6

Table 7.10 (b) Statistical parameters of observed and simulated monthly rainfall series
Method : Square Root transform Station - Jalore

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	26.1	151.5	142.1	53.7	21.2	200.6	159.3	69.8
Standard (mm) Deviation	25.2	143.0	121.8	81.9	21.2	181.5	139.6	87.2
Coefficient of skewness	.618	1.589	1.645	2.456	1.191	.761	.781	2.15
Frequency of rain < 10 mm	17/40	3/40	2/40	14/40	21/50	5/50	5/50	18/50
Maximum Monthly rain (mm)	75.7	619.6	597.2	345.8	88.4	625.0	542.9	458.0

Table 7.10 (c) Statistical parameters of observed and simulated monthly rainfall series
Method : Square Root transform Station - Jaipur

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	55.3	219.0	220.7	77.8	45.4	225.4	225.4	69.1
Standard (mm) Deviation	65.7	168.6	125.6	73.6	40.6	154.7	136.2	73.0
Coefficient of skewness	2.689	2.140	.837	1.067	1.094	.411	.529	1.637
Frequency of rain < 10 mm	6/40	0	0	10/40	11/50	3/50	0	12/50
Maximum Monthly rain (mm)	319.2	941.0	539.8	281.0	169.0	557.0	576.0	364.8

Table 7.11 (a) Statistical parameters of observed and simulated monthly rainfall series

Method : Power transformation Station - Jalore

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	26.1	151.5	142.1	53.7	35.7	124.5	229.6	26.3
Standard (mm) Deviation	25.2	143.0	121.8	81.9	36.4	135.5	188.1	35.9
Coefficient of skewness	.618	1.589	1.645	2.456	.953	1.916	1.267	1.880
Frequency of rain < 10 mm	17/40	3/40	2/40	14/40	19/50	6/50	1/50	25/50
Maximum Monthly rain (mm)	75.7	619.6	597.2	345.8	142.2	706.8	670.2	166.4

Table 7.11 (b) Statistical parameters of observed and simulated monthly rainfall series

Method : Power transformation Station - Jaipur

Parameter	OBSERVED SERIES (1951-90) Jun.	Jul.	Aug.	Sept.	SIMULATED 50 years Jun.	Jul.	Aug.	Sept.
Mean (mm)	55.3	219.0	220.7	77.8	86.4	192.9	239.2	70.9
Standard (mm) Deviation	65.7	168.6	125.6	73.6	84.3	205.8	125.4	64.5
Coefficient of skewness	2.689	2.140	.837	1.067	1.547	2.530	.407	1.123
Frequency of rain < 10 mm	6/40	0	0	10/40	3/50	0	0	8/50
Maximum Monthly rain (mm)	319.2	941.0	539.8	281.0	352.6	1173.0	530.6	302.8

7.3.5 Generation of monthly rainfall data with selected models

Considering the relatively better performance of using the Thomas Fiering model with square root transformation and power transformation approaches, monthly rainfall data for 90 years has been generated using these two approaches with forty years of historical data for the perod 1951 - 1990. The 90 years of generated data was divided into three samples of 30 years each and the statistical parameters for each of the samples from the two approaches were compared. In tables 7.12 and 7.13 the comparative performance of the two approaches is presented. Comparison of the statistics in these two tables with the corresponding values for the observed series given in tables 7.3(d) and 7.4(d) indicate that the mean and standard deviation and to some extent the coefficient of skewness have been preserved in the data generated by the square root transformation approach while the frequency of rain less than 10 mm and highest obsered monthly rainfall have been generated equally well by both the approaches with square root transformation approach performing slightly better.

7.4 Generation of Daily Rainfall Data

Generation of daily rainfall for one station Jaipur which represents the average rainfall conditions of east Rajasthan as a whole has been done by both the TPM and ARP approaches described in 7.2.2 and 7.2.3. Using 30 years (1961 - 1990) of historical daily rainfall data, ninety years of data are generated. The statistics used for the comparison of historical and simulated series are :

(i) mean and standard deviation of monthly rainfall

(ii) average number of wet days in the season (monsoon)

Table 7.12 (a) Statistical parameters of observed and simulated monthly rainfall series Station : Jalore Sample I

Parameter	Method : Square root transform Jun.	Jul.	Aug.	Sept.	Power transform Jun.	Jul.	Aug.	Sept.
Mean (mm)	23.0	198.7	173.7	73.1	39.6	127.3	260.4	33.6
Standard (mm) Deviation	23.7	174.4	146.7	76.0	38.1	119.7	204.8	40.3
Coefficient of skewness	1.256	1.017	.641	1.037	.847	.909	1.453	1.685
Frequency of rain < 10 mm	12/30	1/30	4/30	10/30	10/30	3/30	0	12/30
Maximum Monthly rain (mm)	88.4	625.0	542.9	262.4	142.2	413.1	917.6	166.4

Table 7.12 (b) Statistical parameters of observed and simulated monthly rainfall series Station - Jalore Sample II

Parameter	Method : Square root transform Jun.	Jul.	Aug.	Sept.	Power transform Jun.	Jul.	Aug.	Sept.
Mean (mm)	26.7	177.2	161.1	57.6	33.7	118.3	198.9	28.9
Standard (mm) Deviation	28.9	178.0	148.4	93.4	38.9	141.8	172.2	54.7
Coefficient of skewness	1.581	0.874	0.922	3.075	1.181	2.733	.851	2.854
Frequency of rain < 10 mm	11/30	6/30	1/30	11/30	13/30	3/30	1/30	17/30
Maximum Monthly rain (mm)	102.0	620.0	533.6	458.0	136.4	706.8	623.6	238.5

Table 7.12 (c) Statistical parameters of observed and simulated monthly rainfall series Station - Jalore Sample III

Parameter	Method : Square root transform Jun.	Jul.	Aug.	Sept.	Power transform Jun.	Jul.	Aug.	Sept.
Mean (mm)	25.0	166.2	133.0	96.9	26.8	150.7	204.6	39.2
Standard (mm) Deviation	22.3	150.3	117.7	152.9	31.6	243.6	194.4	47.7
Coefficient of skewness	1.206	0.912	2.093	3.952	2.428	3.964	1.561	1.543
Frequency of rain < 10 mm	9/30	3/30	1/30	4/30	9/30	6/30	1/30	11/30
Maximum Monthly rain (mm)	81.0	492.8	552.3	323.6	144.5	1309.3	797.8	184.0

Table 7.13 (a) Statistical parameters of observed and simulated monthly rainfall series Station : Jaipur Sample I

Method :	Square root transform				Power transform			
Parameter	Jun.	Jul.	Aug.	Sept.	Jun.	Jul.	Aug.	Sept.
Mean (mm)	48.1	224.0	237.5	71.6	72.2	180.6	249.3	58.7
Standard (mm) Deviation	45.2	150.8	145.0	65.2	68.3	162.2	124.1	51.2
Coefficient of skewness	1.196	0.499	0.339	0.792	1.504	1.447	.296	.713
Frequency of rain < 10 mm	7/30	3/30	0	5/30	2/30	0	0	6/30
Maximum Monthly rain (mm)	169.0	557.0	576.0	228.0	276.4	623.7	464.3	168.1

Table 7.13 (b) Statistical parameters of observed and simulated monthly rainfall series Station - Jaipur Sample II

Method :	Square root transform				Power transform			
Parameter	Jun.	Jul.	Aug.	Sept.	Jun.	Jul.	Aug.	Sept.
Mean (mm)	56.5	209.6	224.8	61.2	93.3	218.7	228.0	100.4
Standard (mm) Deviation	54.4	151.1	142.6	76.8	95.1	253.6	170.5	99.8
Coefficient of skewness	1.433	0.568	0.580	2.464	1.429	2.431	1.680	1.500
Frequency of rain < 10 mm	5/30	0	1/30	8/30	4/30	0	1/30	4/30
Maximum Monthly rain (mm)	201.6	542.9	533.6	364.8	352.6	1172.9	832.7	397.1

Table 7.13 (c) Statistical parameters of observed and simulated monthly rainfall series Station - Jaipur Sample III

Method :	Square root transform				Power transform			
Parameter	Jun.	Jul.	Aug.	Sept.	Jun.	Jul.	Aug.	Sept.
Mean (mm)	25.0	166.2	133.0	96.9	81.7	142.7	245.6	75.0
Standard (mm) Deviation	22.3	150.3	117.7	152.9	63.7	106.0	128.9	68.7
Coefficient of skewness	1.206	0.912	2.093	3.952	.641	1.165	1.089	.760
Frequency of rain < 10 mm	3/30	0	0	5/30	3/30	0	0	7/30
Maximum Monthly rain (mm)	158.8	453.7	580.8	610.1	234.8	421.1	607.8	252.2

(iii) magnitude of maximum daily rainfall during the 30 years of historical and simulated rainfall

The comparison is done only for the monsoon season since rainfall during the remaining part of the year is not significant.

7.4.1 Generation of daily rainfall data using TPM method.

For generation of daily rainfall data with the transition probability matrix (TPM) method, seven classes of rainfall are used. After a few trials with different values for the class limits, the following class boundaries have been decided.

Table 7.14 Class boundaries (Trial I)

Class number	Class boundary in mm	
	Lower	Upper
1	0.001	0.9
2	1.0	2.9
3	3.0	6.9
4	7.0	14.9
5	15.0	30.9
6	31.0	62.9
7	63.0	∞

Depending on the highest observed rainfall and the average number of rainy days in each month, varying number of classes have been used for different months. If the number of classes is k, the upper class boundary for the k th class will be infinity. All the class boundaries given in table 7.14 above, therefore, apply only to a month where all the seven classes have been used. The classes used in different months are given below :

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Classes	4	4	3	3	5	6	7	7	6	4	4	4

Using the TPM model with the Box-Cox transformation for the last class and the appropriate number of classes for different months as above, ninety years of data has been generated. The generated data has been split into three samples of 30 years each and the different parameters for comparison with the historical series have been computed and averaged. The results are presented in tables 7.15 (a) to 7.15 (c) .

The mean and standard deviation of the monthly rainfall computed from the generated daily rainfall data compares well with those of the observed series. The mean number of wet days (days of daily rainfall more than 1.0 mm) in the generated series are the same as in the observed when the season as a whole was considered. In individual months also, there is reasonable comparison with the observed. In case of the highest observed rainfall, however, the generated series are not able produce the same magnitude of rainfall.

To generate the extreme rainfall matching with the observed maximum one day rainfall another trial has been made by changing the limits of the last class and making modifications to retain seven classes. The limits of the seven classes have been taken as given in table 7.16 . The 90 years generated data have been divided into three samples of 30 years each as above. The results of comparison are presented in tables 7.17 (a) to 7.17(c)

It was seen that the generated data with class boundaries as in trail II was able to generate extreme rainfall values comparable in magnitude to the observed extreme one day rainfall at Jaipur in July 1981. Also, the mean and standard deviation and the number of wet days in the different months of monsoon season were comparable with the corresponding statistics relating to historical rainfall data.

Table 7.15 (a) Mean and standard deviation of historical and simulated rainfall for monsoon months Station : Jaipur

Method : TPM Trial I Units : mm

Month	Historical		Simulated (I)		Simulated (II)		Simulated (III)	
	mean	s.d	mean	s.d	mean	s.d	mean	s.d
June	58.6	74.0	81.4	66.1	49.1	31.9	62.3	54.3
July	227.1	181.4	250.6	125.8	198.3	122.0	175.4	115.3
August	209.3	74.6	221.1	72.3	221.0	98.0	213.5	94.4
September	74.6	74.2	69.3	39.7	70.6	49.6	92.0	55.6

Table 7.15 (b) Average number of wet days* for monsoon months

Method : TPM Trial I Station : Jaipur

Month	Historical	Simulated (I)	Simulated (II)	Simulated (III)
June	4.4	5.0	5.0	4.4
July	12.4	12.3	11.7	11.7
August	13.0	13.4	13.9	13.9
September	5.6	5.9	5.7	6.5
Season	35.4	36.6	36.3	36.5

* A day with rainfall of 1.0 mm or more

Table 7.15 (c) Magnitude of maximum daiy rainfall during 30 years

Method : TPM Trial I Station : Jaipur Units : mm

Historical	Simulated (I)	Simulated (II)	Simulated (III)
287.0 in July	130.4 in June	168.0 in July	160.8 in July

Table 7.16 Class boundaries (Trial II)

Class number	Class boundary in mm	
	Lower	Upper
1	.001	0.9
2	1.0	6.9
3	7.0	14.9
4	15.0	30.9
5	31.0	62.9
6	63.0	124.9
7	125.0	α

It may be, therefore, said that the TPM method was able to generate daily rainfall data which could be cumulated to obtain monthly rainfall values having similar statistical characteristics as those of the historical data.

7.4.2 Generation of daily rainfall data using ARP method

The simulation and data generation has been done only for the daily rainfall during the monsoon season.

7.4.2.1 fitting the TNBD to wet and dry runs

The data were analysed on monthly basis to satisfy the assumptions of the alternating renewal process. The validity of the assumption that the wet and dry sequences were independent was tested by computing the correlation coefficients between the wet and dry runs. The correlation coefficients were nearly zero indicating the independence of the wet and dry sequences.

The TNBD fits the sequences of wet and dry runs well as was indicated by the significance of chi square statistic. Though

Table 7.17 (a) Mean and standard deviation of historical and simulated rainfall for monsoon months Station : Jaipur

Method : TPM Trial II Units : mm

Month	Historical		Simulated (I)		Simulated (II)		Simulated (III)	
	mean	s.d	mean	s.d	mean	s.d	mean	s.d
June	58.6	74.0	73.7	70.7	80.7	65.4	74.5	57.1
July	227.1	181.4	224.6	146.9	265.9	168.2	230.3	134.7
August	209.3	74.6	221.9	118.5	219.5	79.8	192.9	78.2
September	74.6	74.2	77.7	59.7	78.9	60.4	78.1	60.2

Table 7.17 (b) Average number of wet days* for monsoon months

Method : TPM Trial II Station : Jaipur

Month	Historical	Simulated (I)	Simulated (II)	Simulated (III)
June	4.4	5.1	4.9	5.1
July	12.4	12.7	12.2	12.5
August	13.0	12.6	13.7	13.4
September	5.6	6.3	6.5	6.2
Season	35.4	36.7	37.3	37.2

* A day with rainfall Of 1.0 mm or more.

Table 7.17 (c) Magnitude of maximum daily rainfall during 30 years

Method : TPM Trial II Station : Jaipur Units : mm

Historical	Simulated (I)	Simulated (II)	Simulated (III)
287.0	255.0	252.7	277.8

Note : The observed and generated heaviest rainfalls were in July

The TNBD fits the sequences of wet and dry runs well as was indicated by the significance of chi square statistic. Though use of parameters derived on seasonal basis would reduce the number of values to be estimated, deriving values of p and r for each of the four monsoon months separately was preferred.

7.4.2.2 fitting gamma distribution function to rainfall amounts :

For wet spells defined by those above the threshold rainfall δ = 1.0 mm, the gamma distribution function was fitted to the observed rainfall for each of the monsoon months June to September. Rainfall amounts exceeding (δ + ε) were considered. The parameters λ and ν of gamma distribution were derived separately for Type 0, Type 1 and Type 2 rainfalls for different values of ε. The parameters corresponding to ε = 1.0 were found to be significant.

7.4.2.3. generation of rainfall

The generation of daily rainfall sequences is carried out in two steps. First, the lengths of wet spells and dry spells were generated by mapping a uniform random number in the interval (0,1) on to the cumulative distribution function of the TNBD. For wet spells of type 0, type 1 and type 2, the appropriate random gamma variates were genereated to obtain the daily values of rainfall.

The parameters P and r of TNBD and λ and ν of Gamma distribution obtained from the calibration are given in table 7.18 (a) and Table 7.18 (b). Thirty years of daily rainfall data for the period 1961 - 90 has been used for generating 30 years of data . The statistics of mean and standard deviation of (monsoon) monthly rainfall, number of wet days and magnitude of highest daily rainfall are presented in tables 7.19 (a) to 7.19 (c)

The results indicated that :

(i) the ARP was able to generate data well for the month of July only.

(ii) the ARP was not able to reproduce the number of wet days in the months of August and September properly. In some years the wet days in August were as low as 1 while in September they were high.

(iii) the highest daily rainfall generated was only 190.2 mm as against the highest observed rainfall of 281.0 mm.

7.4.3 Comparison of results from use of TPM and ARP methods

From a comparison of the tables 7.17 (a) to 7.17 (c) of TPM method with tables 7.19(a) to 7.19 (c) of ARP method, it is seen that the TPM method has performed better than the ARP method. In the case of ARP method, the mean and standard deviation of the generated rainfall in different months was different from the historical series except for the month of July. Also, the magnitude of highest maximum daily rainfall generated by the ARP method was lower than the observed . Further, the number of wet days in the generated data of August month were lower and September month were higher in comparison to those of the historical series in case of ARP method while these have been reproduced very well by the TPM method. The relatively better performance of TPM method may be because in the TPM method, each month was considered separately for the purpose of data generation while in the case of ARP method the daily rainfall in the whole monsoon season was considered continuously. The comparatively poor performance may also be due to inadequate data base used for the simulation.

7.5 Remarks

The analysis carried out has provided significant findings.

(i) The Thomas Fiering model using transformations has been found to be a very promising method for generation of monthly rainfall data in semi arid areas with monsoon type climate. The square root and power transformations generated data preserving many of the statistics of the historical series with the former performing comparatively better.

(ii) The TPM method with Box-Cox transformation for the largest class was found to be an appropriate method for generation of daily rainfall data in semi arid regions with monsoon climate.

(iii) Of the TPM and ARP methods used for generation of daily rainfall data , the former performed better, especially, for the months when the daily rainfall is zero and with occasional heavy rainfalls in the historical series.

Based on the study, it can be said that in general the models used can generate satisfactory and reliable daily and monthly rainfall data for semi arid regions with monsoon climate.

CHAPTER VIII

SPATIAL VARIABILITY

8.1 General

Rainfall exhibits spatial variability due to meteorological and topographical conditions such as presence of mountains, distance from sea etc. Rainfall at one location will be generally, similar to rainfall at a neighbouring location, but at larger distances the amounts differ appreciably. If the rainfall occurs due to synoptic scale weather systems such as depressions, rainfall over short distances does not vary.

In hydrological analysis, often point measurements representative of a particular area need to be interpolated towards unobserved locations. When data is needed to be interpolated or generated at unobserved locations, it is important to make use of the spatial dependence between the observations. A basic advantage inherent in statistical interpolation is that the method relates the statistical structure of the estimated parameter to the configuration of the data points used for interpolation. Apart from applying spatial variability patterns for interpolation, the study of spatial variability patterns may also reveal particular structures in climatological conditions. Large variations in the spatial structure of rainfall are observed as a result of meteorological conditions.

The literature review has indicated the use of interstation correlation and cluster analysis as useful means for understanding the spatial variability and mathematically representing the spatial correlation structure. The review further brought out the suitability of covariance model for simulation of rainfall field over a homogeneous rainfall region.

The objective of the analysis is to classify or group the rain gauge stations into homogeneous regions within the larger study area and to fit a mathematical relationship to the spatial correlation structure of rainfall over the study area. The results from the study are used for generating rainfall field within a homogeneous region.

8.2 Methodology

The spatial variability of rainfall over the study area has been analysed by identifying the homogeneous groups of rainfall stations using the cluster analysis (Davis, 1973) and interstation correlation between pairs of stations. The rainfall field for monsoon rainfall within two homogeneous groups of different rainfall regime were simulated using the covariance model.

8.2.1 Cluster analysis

If n represents the number of stations and m the number of data points, the data set forms a n x m matrix. For grouping the stations into homogeneous regions on the basis of rainfall, some measure of resemblance or similarity is computed between every pair of objects (rain gauge stations in this case). Several coefficients of resemblance could be used such as the correlation coefficient or a standardized m space Euclidean distance.

In the next step the stations are arranged into a hierarchy Dendrogram so that stations with highest mutual similarity are placed together. Then groups or clusters of stations are associateed with other groups which they most closely resemble, and so on until all the stations are arranged into a classification scheme.

In the case of storm rainfall the cluster analysis has been carried out both by correlation and the Heuristic approach. Of the heuristic algorithms, the simplest is based on considering each object just once and immediately allocating it to a cluster. For each NMAX (the number of clusters to be formed) from N1, N1+1,.... N2 the assignment to a particular cluster is carried out. The threshold RHO is computed using RHO $= J * \delta$ with J + 1,....JMAX, JMAX being the first J for which all objects are assigned to clusters (P_i= 1,....m). P_i is the cluster number and $P_i = 0$ indicates no assignment. The object X_i is allocated to a cluster according as the element distance is less than RHO or not. As the value of NMAX increases the number of clusters would, naturally, increase and would decrease with the increase in the value of RHO. The clustering is dependant on the ordering of the sequence and alternatives, therefore, need to be tried.

8.2.2 Spatial correlation structure

If there are n stations in a given meteorologically homogeneous area, there will be nC_2 correlation coefficients (r) and the same number of distances (s) between the stations. It is possible to establish a functional relationship r = f(s) between the two variables. This relationship describes the correlation structure of rainfall over an area. It is generally expected that the correlation decreases as the distance increases. Rodriguez-Iturbe and Mejia (1974) have shown that the functional relation f(s) can be any one of the following :

(i) $r = a\, e^{-bs}$ (exponential) (8.1)

(ii) $r = a - bs$ (linear) (8.2)

(iii) $r = bs\, k_1(bs)$ (modified Bessel) (8.3)

where a and b are constants.

8.2.3 Simulation of rainfall field

Several methods of generating the spatial field of rainfall are available which include multivariate or matrix decomposition

(Wilson et. al.,1979), Turning Bands method (Matheron, 1973 ; Kottegoda and Kasim, 1991). For the present study the matrix decomposition method is, used with the algorithm developed by Williams and El-Kadi(1986).

The lower upper triangular matrix (LU) decomposition technique can be used to produce Gaussian stationary random fields. If $C_x(i,j)$ is the covariance of a zero mean stationary random field and the simulations are required at m grid points, for a given covariance model (exponential, gaussian, spherical etc.) $c_x(i,j)$ $(i,j = 1,2, \ldots m)$ the corresponding covariance matrix of size m x m may be constructed as

$$C_x = \begin{bmatrix} c_x(1,1) & \ldots & \ldots & c_x(1,m) \\ c_x(2,1) & \ldots & \ldots & c_x(2,m) \\ \ldots & \ldots & \ldots & \ldots \\ c_x(m,1) & \ldots & \ldots & c_x(m,m) \end{bmatrix} \quad \ldots \quad (8.4)$$

The above expression is a positive definite covariance matrix which can be decomposed into a product of lower and upper triangular matrices by means of the Choleski algorithm resulting in

$$C_x = L \cdot U \quad \text{where } U = L^T \quad \ldots \quad (8.5)$$

Once the decomposition is completed the simulation is performed. If Y is a stationary random function with a mean μ, for which simulations are required at m x m grid points the values of Y in the field at specified grid nodes may be estimated from

$$Y = L.\varepsilon + \mu \quad \ldots\ldots (8.6)$$

where ε is a vector of m independent standard Gaussian random variables. (ε is normally distributed with zero mean and unit variance). The field simulated by LU decomposition is expected to preserve the mean and covariance ,structure of the observed rainfall field.

8.3 Cluster Analysis and Correlation Structure.

Though the cluster analysis and interstation correlation are broadly same, the results from the two analyses are expected to be different and could be put to different uses as discussed in the following sections.

Cluster analysis was used for clustering rainfall stations on the basis of monthly, monsoon and annual rainfall. The hueristic algorithm was used for clustering stations on the basis of storm rainfall data for a few severe rainstorms during 1991 and 1992. Spatial correlation structure was analysed using data of monthly, monsoon and annual rainfall and monsoon and annual rainy days.

8.3.1 Cluster analysis

The identification of clusters (groups) in the study area has been attempted by applying the cluster analysis to the annual, monsoon and monthly (July and August) rainfall series of the twenty stations selected for the study. Based on the analysis Dendrograms are prepared from each of the analyses. A typical dendrogram for the monsoon rainfall is shown in figure 8.1

The analysis indicated that the stations are grouped as follows when annual rainfall was considered.

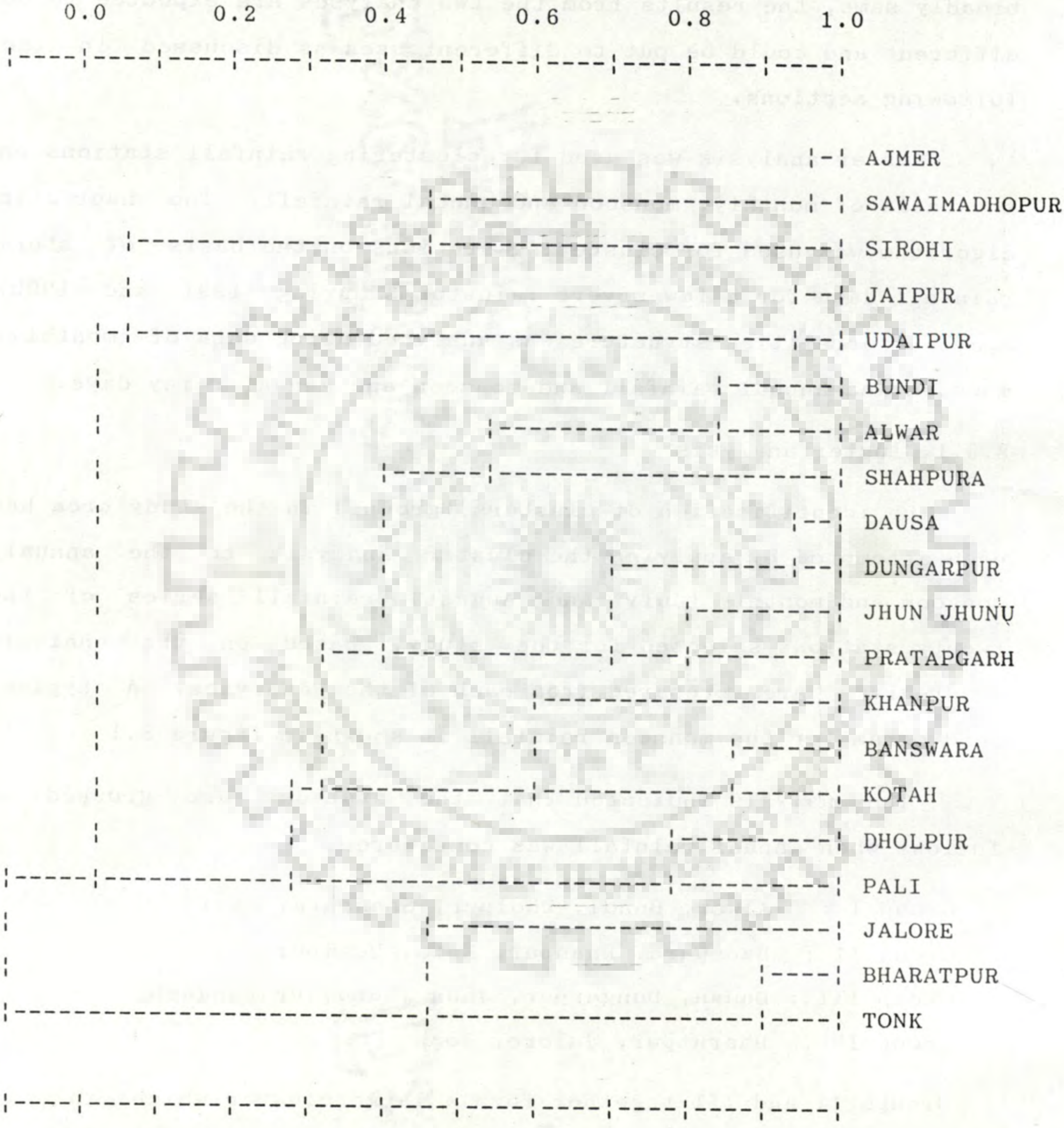
Group I : Alwar, Bundi, Dholpur, Shahpura, Pali

Group II : Banswara, Khanpur, Kota, Udaipur

Group III : Dausa, Dungarpur, Jhun Jhunu, Pratapgarh

Group IV : Bharatpur, Jalore, Tonk

Groups II and III together form a large cluster which in turn together with Group I forms the major cluster. Clustering of a different group of stations was noticed when monsoon rainfall was



Values along X axis are Similarities

Figure 8.1 : DENDROGRAM FOR MONSOON RAINFALL

considered (figure 8.1) or when the monthly rainfall was considered. In general the clustering followed the geographical proximity (near neighbours) with the exceptions like Jhun Jhunu in Group III and Jalore in Group IV above.

Analysis of clustering using the Hueristic algorithm for the storm rainfall has revealed altogether different pattern which was based more on the magnitude of storm rainfall rather than on the geographical location. The clustering for one storm is given in Table 8.1 .

The rainfall producing systems in Rajasthan could be placed under the sub synoptic and micro scale systems of the scheme defined by Austin and Houze (1972). However, occasional synoptic scale systems also do occur in the region under the influence of tropical depressions originating from Bay of Bengal and Arabian sea. The clustering of far off stations like Bharatpur and Jalore; Alwar and Pali could be attributed to the sub-synoptic and synoptic scale systems whose area of influence extends to more than ten thousand square kilometers. Also, the influence of the Aravali mountains reduces as one moves away from Sirohi district where Mount Abu is located.

8.3.2 Spatial correlation structure

The spatial correlation structure of rainfall and rainy days for the study area is formulated by computing the inter station correlation between pairs of stations among the 20 stations. For the 20 stations used the number of correlations would be nC_2 which is 190 . Two types of relationship are dereived. These are

(i) $r = a + b \log_e s$ (8.7)

and (ii) $r = a \times e^{-bs}$ (8.8)

where r, s , a and b have the same notation as in Eq. (8.1)

Table 8.1 Clustering using Hueristic Algorithm

INPUT DATA

Station :	Rainfall (mm)	Station :	Rainfall (mm)
Ajmer :	109.0	Jaipur:	52.0
Alwar :	0.0	Jhalawar :	0.0
Banswara :	38.0	Jhun Jhunu :	0.0
Bhilwara :	15.0	Kotah :	9.0
Bundi :	15.0	Pali :	0.0
Bharatpur :	29.0	Pratapgarh:	0.0
Dausa :	23.0	Sawai Madhopur :	120.0
Dholpur:	58.0	Sirohi :	8.0
Dungarpur:	54.0	Tonk :	59.0
Jalore:	0.0	Udaipur :	13.0

OUTPUT

M = 20 L = 1 DELTA = 5.0

Rainfall in order of magnitude :

120.0 109.0 63.0 59.0 58.0 56.0 54.0 52.0 38.0 29.0
23.0 15.0 15.0 13.0 9.0 .0 .0 .0 .0 .0

Station numers in order of magnitude of rainfall	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
CLUSTER NUMBER	1	1	2	2	2	2	2	2	3	3	3	4	4	4	4	4	4	4	4	4

This analysis has been done for (i) monthly (June - Sept), monsoon and annual rainfall and (ii) monsoon and annual rainy days. The relationships obtained are given in tables 8.2 and 8.3. In figures 8.2 to 8.5 the graphs showing the relationships are presented for July, August, monsoon rainfall and monsoon rainy days respectively.

It was noticed that the correlation at short distances in the June and September months was higher as compared to July and September months. In these months rainfall is not only highly variable but also does not occur uniformly in space. The high correlation over short distances was, probably,due to the convective storms which are localised in nature and are common before and after the monsoon..

In the case of monthly rainfall a few correlations were noticed which are high even at large distances and can be seen being away from the general pattern of decreasing correlation with increasing distance. The relationships have been worked out again by ignoring these set of relations. However, no appreciable difference in the values of coefficients a and b in the functional relationship was noticed. The absence of monotonous decrease of the correlation with distance was also reported in the study of Sharon (1974).

In the case of rainy days, the correlation was found to be higher than that of rainfall. Also, the coefficient of the exponential function is higher indicating that the decrease of correlation with distance is comparatively less monotonous than that observed in the case of rainfall.

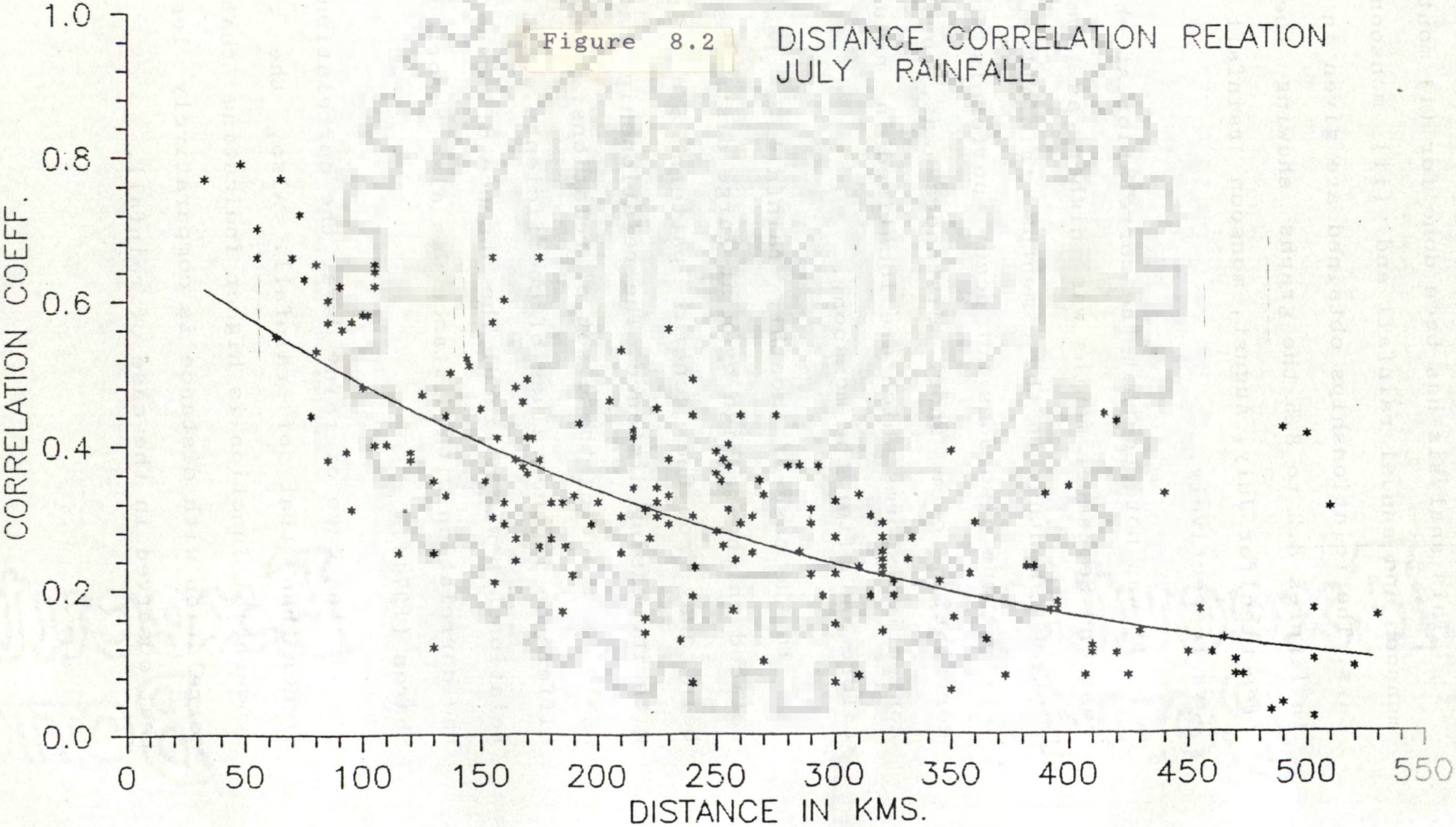

DISTANCE CORRELATION RELATION
JULY RAINFALL
CORRELATION COEFF.
DISTANCE IN KMS.
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
250
300
350
400
450
500
550

Figure 8.2

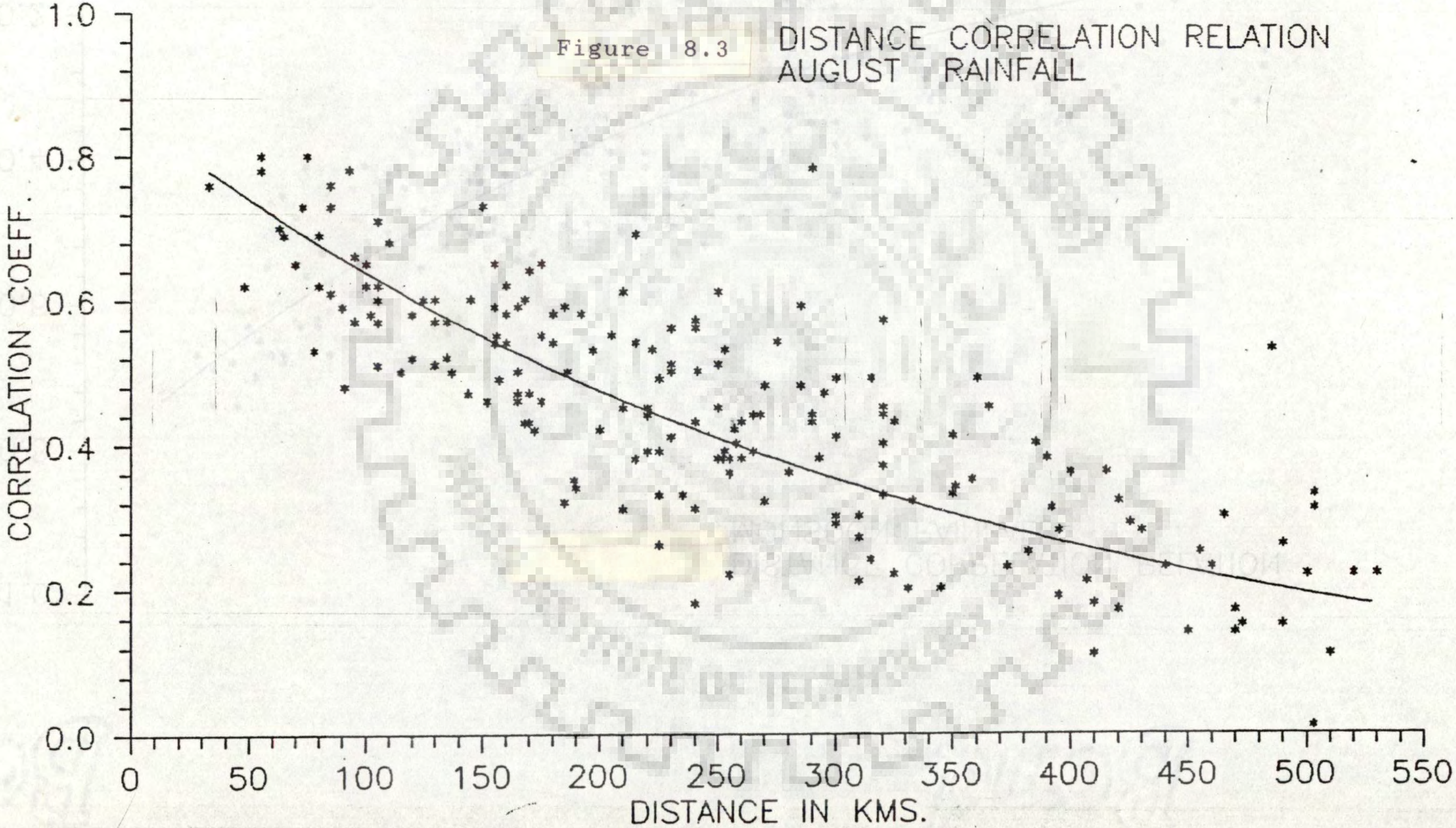


Figure 8.3 DISTANCE CORRELATION RELATION AUGUST RAINFALL

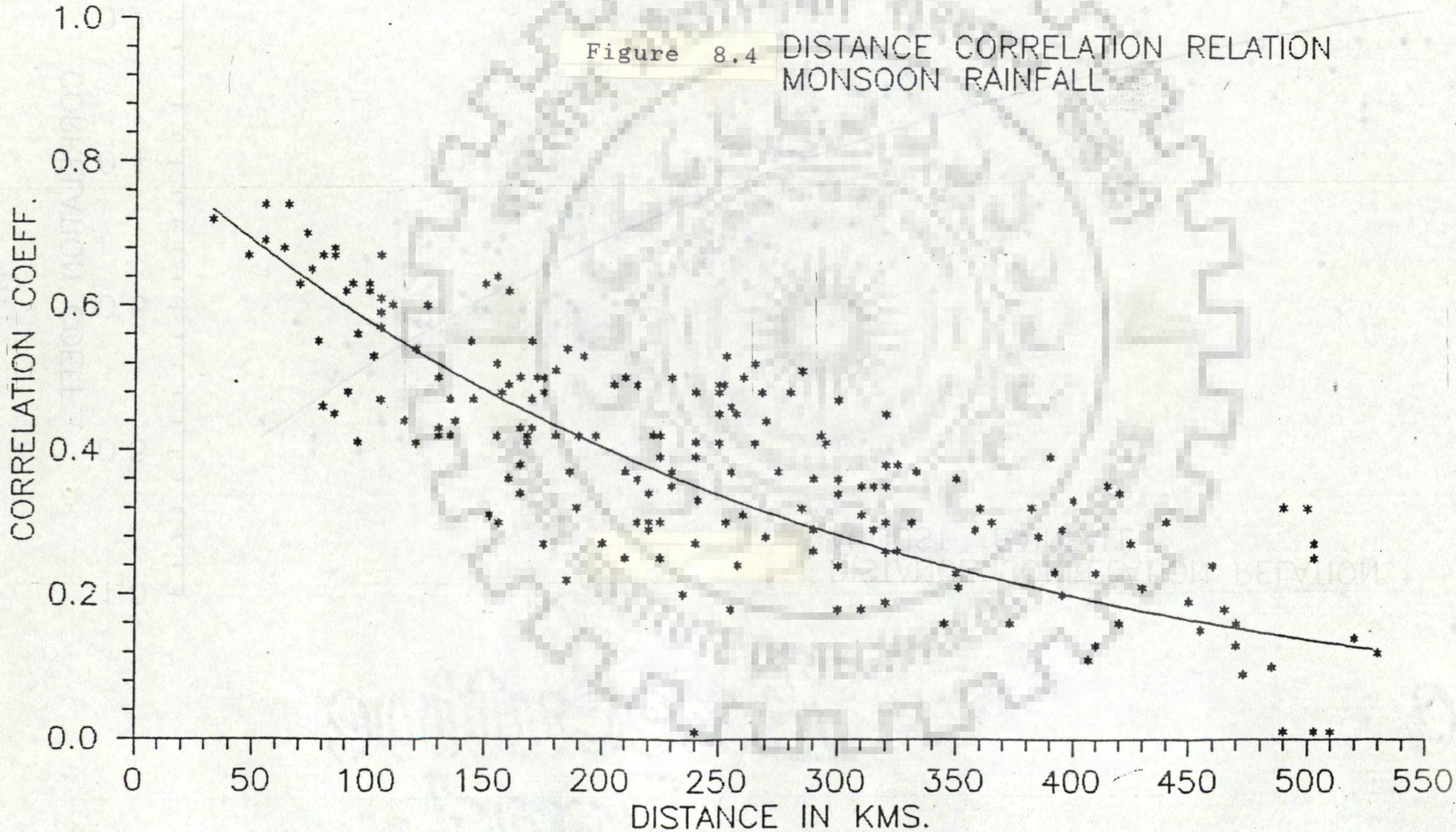


Figure 8.4 DISTANCE CORRELATION RELATION
MONSOON RAINFALL

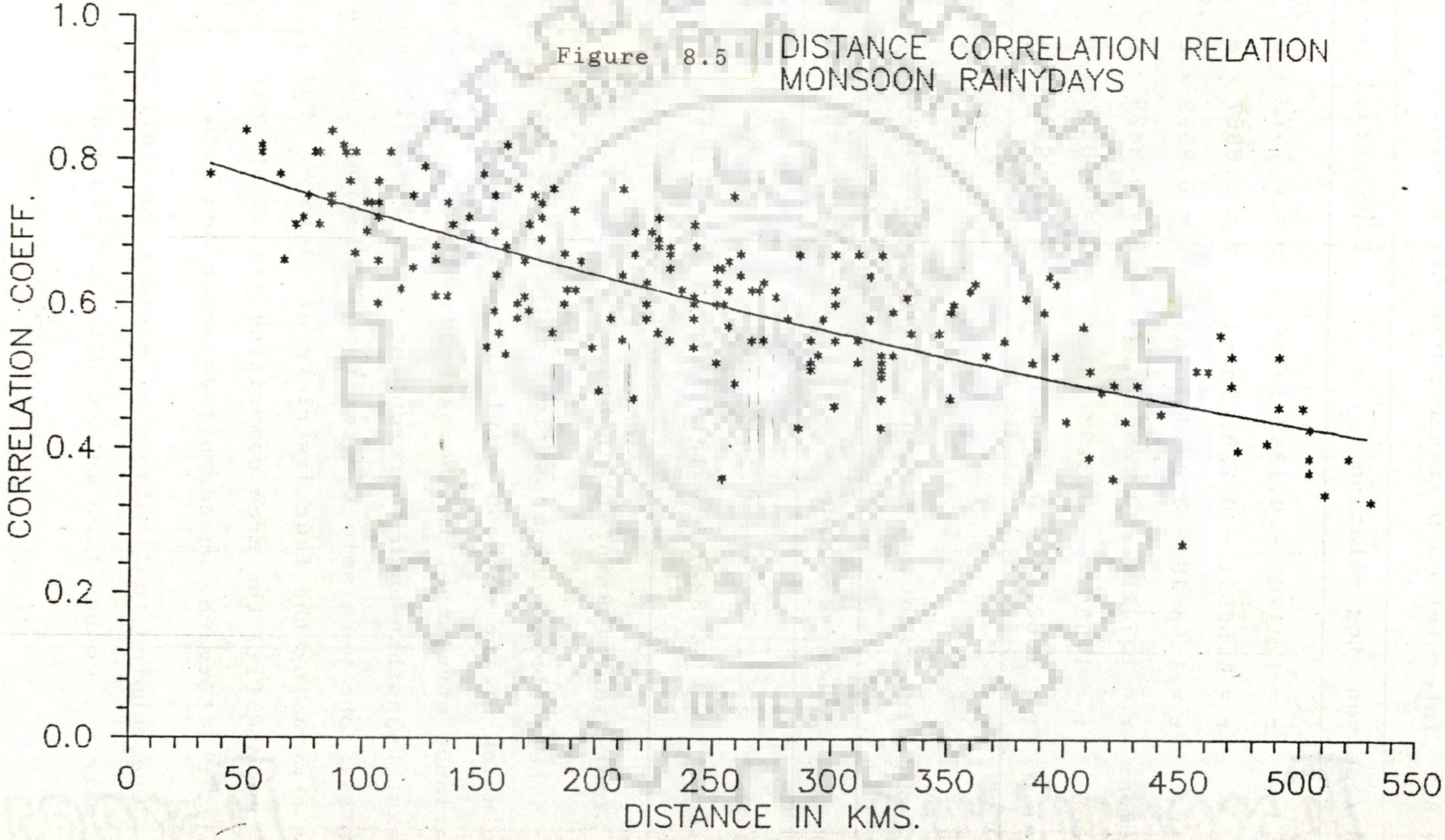


Figure 8.5 DISTANCE CORRELATION RELATION
MONSOON RAINYDAYS

Table 8.2 Interstation Distance correlation relation - Rainfall

Month / season	Log relation	Exponential relation
June	r = 1.44767 - 0.1899 ln(s)	$r = 0.7576 \times e^{-.00271 s}$
July	r = 1.55951 - 0.2282 ln(s)	$r = 0.6957 \times e^{-.00363 s}$
August	r = 1.68548 - 0.2300 ln(s)	$r = 0.8599 \times e^{-.00298 s}$
September	r = 1.73114 - 0.2266 ln(s)	$r = 0.8829 \times e^{-.00241 s}$
Monsoon	r = 1.56694 - 0.2192 ln(s)	$r = 0.8249 \times e^{-.00357 s}$
Annual	r = 1.63164 - 0.2309 ln(s)	$r = 0.8507 \times e^{-.00375 s}$

Table 8.3 Interstation Distance correlation relation - Rainy days

Season	Log relation	Exponential relation
Monsoon	r = 1.45777 - 0.1572 ln(s)	$r = 0.8285 \times e^{-.00129 s}$
Annual	r = 1.43221 - 0.1515 ln(s)	$r = 0.8371 \times e^{-.0013 s}$

8.4 Simulation of Rainfall in Space

The matrix decomposition method was used to produce simulation of the monsoon rainfall field using the exponential covariance structure. Two homogeneous areas in the southern part of east Rajasthan each representing a low rainfall and a medium rainfall zone were selected for the simulation. These are (i) the area comprising the four districts of Jalore, Pali, Sirohi and Udaipur and (ii) the area comprising six districts of Banswara, Bundi, Chittorgarh, Dungarpur, Jhalawar and Kota.

One hundred realisations of monsoon rainfall were made using the matrix decomposition method with correlation length of 0.3 and

0.5 . The mean and standard deviation used as input for the generation was based on data of monsoon rainfall for periods ranging from 50 to 85 years for the respective areas. Since the rainfall field is simulated assuming a normal distribution, the series of long term means of 18 stations in the four districts in area (i) and of 46 stations located in the six districts in group (ii) were transformed to represent a Gaussian rainfall field. The realisations obtained thus were transformed back to obtain the simulated rainfall field for the respective areas.

In figures 8.6 to 8.9 the mean monsoon rainfall field and is shown for the two areas for correlation lengths of 0.3 and 0.5 .

8.5 Remarks

The study area, east Rajasthan inspite of being a semi arid region with high degree of variability of rainfall in time, however, exhibited systematic spatial correlation structure facilitating its mathematical formulation.

The clustering is broadly on the pattern of geographical proximity with exception of a few cases. Clustering in case of storm rainfall was based more on the rainfall magnitude rather than on geographical location.

Simulation of rainfall field with the covariance model has been satisfactory considering the data used as input to the model.

Figure 8.7 Monsoon rainfall (cm) Average of 100 simulations - Banswara, Bundi, Chittorgarh, Dungarpur, Jhalawar, Kotah (Correlation length 0.3)

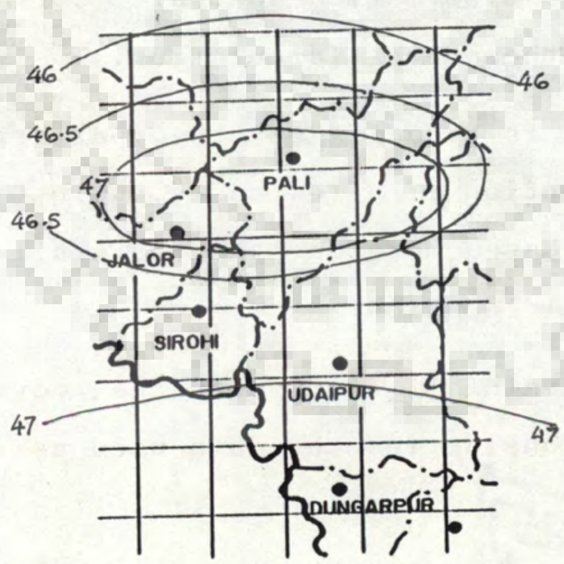


Figure 8.8 Monsoon rainfall (cm) Average of 100 simulations - Jalore, Pali, Sirohi, Udaipur (Correlation length 0.3)

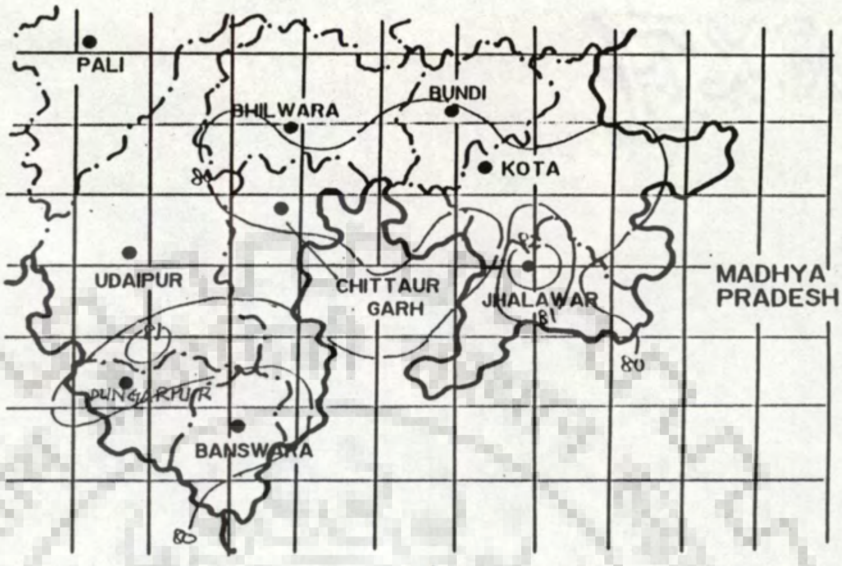


Figure 8.9 Monsoon rainfall(cm) Average of 100 simulations - Banswara, Bundi, Chittorgarh, Dungarpur, Jhalawar, Kotah (Correlation length 0.5)

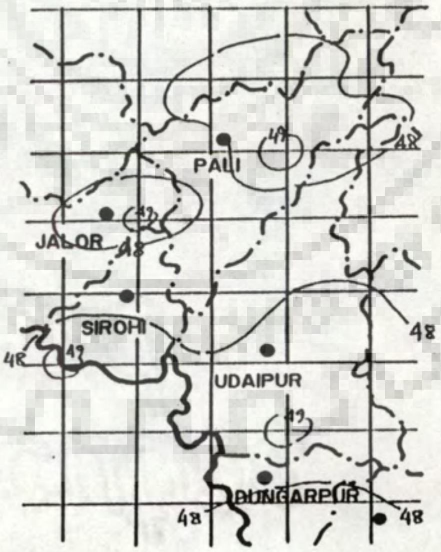


Figure 8.10 Monsoon rainfall(cm) Average of 100 simulations - Jalore, Pali, Sirohi, Udaipur (Correlation length 0.5)

CHAPTER IX

CONCLUSIONS

A systematic study of space time characteristics of rainfall has been done using data of east Rajasthan representing typical semi arid monsoon climate. Climatological analysis of rainfall and rainy days has been carried out and modeling of rainfall in time and space has been done using statistical methods.

The use of two transformation procedures namely square root transformation and power transformation have proved the utility of Thomas - Fiering model for generation of monthly rainfall data. Comparison of the transition probability matrix and alternating renewal process models for generation of daily rainfall data has brought out the limitations of applying such models to semi arid areas where isolated heavy rain storms occur occasionally. Cluster analysis and interstation correlation techniques are useful for delineating homogeneous rainfall regions. The covariance model has been used satisfactorily for simulation of rainfall field.

Based on the study and analysis of space time characteristics of rainfall in east Rajasthan using monthly and daily rainfall data, the following conclusions could be drawn

(i) The rainfall and rainy days series are in general random and there is no persistence. There is, therefore, no definite pattern in the occurrence of wet and dry years.

(ii) Rainfall in a particular month or season is not dependant on the rainfall in a previous month or season.

(iii) A few stations have indicated trend in rainfall as well as for rainy days. In some cases it was negative and in some cases it was positive. The trend might be more due to local factors and has no regional pattern and does not indicate any climate change.

(iv) The mean rainfall intensity has no relation to the total amount of rainfall and is expected to have an important influence on the planning of agricultural operations.

(v) Monthly and daily rainfall data could be generated using simple stochastic models while preserving the general statistical characteristics of the historical series. For monthly series, data transformation using square root or power transformation approaches may be needed for normalising the series.

(vi) Cluster analyis has shown that the rainfall stations in east Rajasthan could be grouped into homogeneous rainfall groups. Similar results are indicated by interstation correlation study.

(vii) Spatial correlation structure of rainfall in east Rajasthan follows a pattern which can be mathematically represented. This formulation could be used for the interpolation of rainfall with a reasonable degree of dependability.

(viii) Spatial correlation in case of rainy days was found to be higher and the slope of the regression was flatter indicating the widespread occurrence of rainfall over large areas. This indicates that spatial variability of rainy days is less. This feature is of significance for agricultural planning in east Rajasthan

9.1 Outlook for Further Studies

Some of the stations which have indicated either a positive or negative trend in rainy days have not indicated any trend in the rainfall, which shows that the rainfall intensities have either increased or decreased. The industrialisation and water resources development creating large reservoirs of open water and canal and irrigation systems might have influenced the hydrological processes and the rainfall pattern to some extent. This aspect may need further investigation.

In the context of arid and semi arid monsoon climates, the other relevant subject areas which need study are :

(i) assessment of the effects of afforestation and deforestation on hydrological regime at micro level and

(ii) monitoring the dust levels in the atmosphere immediately close to the ground and relating them to rainfall activity over the region.

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