CHARACTERIZATION OF 1994-95 DROUGHT IN NORTH WESTERN REGION OF BANGLADESH AND ITS IMPACT ON AGRICULTURE

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Submitted by

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In partial fulfillment of the requirement for the degree of Master of Science in Engineering (Water Resources)

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TO MY

MOTHER AND FATHER

CERTIFICATE OF RESEARCH

This is to certify that this thesis work has been done by me and neither this thesis nor any part thereof has been submitted elsewhere for the award of any degree or diploma.

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We hereby recommend that the thesis work prepared by Asim Krishna Sajjan entitled "**Characterization of 1994-95 Drought in North Western Region of Bangladesh and its Impact on Agriculture**" be accepted as fulfilling this part of the requirements for the degree of Master of Science in Engineering (Water Resources).

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ABSTRACT

This study involves meteorological characterization of drought and water deficit in north western region. Estimation of crop yield and income losses for 1994-95, together with an assessment of shortage of drinking water and increase in disease incidences are also investigated through questionnaire survey.

The daily rainfall records of 35 sites in the north-western region of Bangladesh and three evaporation stations are used for this study. The analysis involves whether the selected rainfall series from a number of measuring sites of a region are discordant and determining the different sequential property with a view to apply simple analytical solutions to various problems related to stochastic behavior of wet and dry spells of rainfall sequences. The discordancy measure identifies no unusual sites. The daily rainfall record of monsoon period are persistenct in nature whereas in the premonsoon it is devoid of persistency. The persistent behavior of wet and dry spells are modeled by Markov (order 1) process using the theory of runs. As such, to build the model blocks, Poisson probability density function of the occurrence of spells is coupled with geometric distribution for the length of spells and the Weibull, normal, lognormal and gamma distributions for the total rain of wet spells. Random model appears to be a poor simulator and Markov model inferred as a promising one. Longest wet and dry periods are obtained by Markov model and largest rain-sum by Markov-Weibull model. Contour maps of longest dry or wet spells and largest rain-sum at different probability are drawn to identify the regional variation characteristics. The maximum longest dry spell is at lower part of Dinajpur and Rangpur districts which is 12-13 days at 50 perecnt probability and 19-20 days at 90 percent probability while the largest rain-sum (Sm) is at upper part consisting of Panchagarh, Nilphamari, Lalmonirhat and Kurigram which is about 350-450 mm at 50 percent probability while at 90 percent is 650-750 mm. The maximum longest wet spell (Lwm) is at upper part of Rangpur, Kurigram, Lalmonirhat and Panchagarh.

Water availability and 10-day water deficit (i.e. demand) is calculated for the period of record 1976-96. 1994-95 has the higher deviation of 1132 mm from the average rainfall. Extreme value type 1 (EV1) distribution is fitted to 10-day maxima for each station. Overall, EV1 distribution seems to fit the demand well.

To make an estimate of the agricultural damages, socio-economic and environmental impact, data related to these parameters are collected through questionnaire survey in Badarganj and Kishoreganj areas. Production and income losses are 30 and 60 percent respectively at Badarganj whereas at Kishoreganj it appears 15 and 25 percent. Badraganj is more severely affected area than Kishoreganj. In 1994-95 Boro and Aman crops were affected more than other crops. During the drought period there is no doubt about the increase of temperature and dust compared to normal years. Decline in water table below normal levels are also estimated. It has been observed that in 1994-95 groundwater level is about 2 m below than the other years.

LIST OF ABBREVIATION

ARIMA	Autoregressive Integrated Moving Average
BARC	Bangladesh Agricuture Research Council
BS's	Block Supervisor's
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
DAE	Directorate of Agricultural Extension
DARMA	Discrete Autoregressive Moving Average
ffGn	fast fractional Gaussian noise
NE	North-East
NW	North-West
PDSI	Palmer Drought Severity Index
PWMs	Probability Weighted Moments
SC	South-Central
SD	Stress Day
SDI	Stress Day Index
SE	South-East
SI	Stress Index
SMI	Soil Moisture Index
SW	South-West
WRE	Water Resources Engineering

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Chapter 1

Introduction

1.1 General

Bangladesh, an agricultural based country, is under the proliferation of natural calamities like flood, cyclone, tornado, tidal bore, drought etc. Water, the most important input for crop production, occurs abundantly in Bangladesh. But the distribution it holds is extremely skewed in time. As a nature of consequence, water availability may become super and/or sub-normal with respect to its requirement at many places. In this respect, controlling the flood has achieved momentum due to its wide publicity in national as well as in international media. The near past floods of 1987 and 1988 have drawn lot of attention not only in disaster preparedness program but also in our national development program due to its severe appearance. On the other hand, although the recurrent occurrences of drought are setting unprecedented damages to the nature, are getting less attention due to its silent effect and lack luster publicity. However, the effects are silent but the consequences are persistent in nature. As the damages are wide-spread, complete eradication of drought is quite expensive and in many cases impossible also.

Management of drought as interdisciplinary in exertion, indeed, provide many externalities which are indigenous in origin. Therefore, drought study need case-wise careful analysis and management program thereby. Drought must be related to the particular crops or animals in the agrarian system. The lack of precipitation during both the growing and non-growing seasons can have many adverse ramification on present and future agricultural activities. For example, an unusually low rainfall in the recent period (1994-95) of Bangladesh significantly damaged the aman and boro crops, and it is likely that losses have extended over next aus season because of delayed onset of monsoon. The 1994 dry monsoon has made adverse effects on surface and groundwater. The north-western districts of Bangladesh have been affected largely due to the reduction of water normally available for irrigation.

Most of the criteria used to identify drought have been arbitrary because a drought is a "non-event" as opposed to a distinct event such as a flood. Drought has no distinct onset and is recognizable only after a period of time. In addition, this period is variable because the time required for a drought to develop depends on many interacting variables.

At times the level of persistence may be negligible and such processes are termed independent. Regardless of whether the process is independent or Markov, a dry or wet spell may extend to a long period. In hydrology it is a well known fact that if the time series is considered to be dependent, then high values tend to follow high values and low values tend to follow low values. This can be interpreted in different ways by saying that in the case of dependent series, the periods of wet and dry spells tend to be greater than in the case of independent series. Such a property has been termed "persistence" in hydrology. The autocorrelation analysis is a means of measuring linear dependence between any two observations. Sen (1976) applied autorun analysis to some mean annual flow series. He concluded that autorun analysis is identical to classical autocorrelataion analysis in case of normal distribution. The longest period days of several long spells is of crucial importance in planning agricultural activities and managing the associated water supply systems. Likewise, the total rain over a wet spell is of importance in designing rainwater harvesting systems and predicting runoff volumes and rates. This total rain over a wet spell is designated as the "rain-sum". In probability theory these spells are termed as "runs" and the rain total over a wet spell as "run-sum". In classical terms a run is defined as a sequence of observations of the same kind preceded and succeeded by one or more observations of a different kind. The "negative run-length" represents the duration of a drought. The runs of the continuous sequence of a stochastic variable, or a combination of stochastic and deterministic components making a composite sequence, may be defined according to Yevjevich (1972) in various ways. Fig. 1.1 represents a continuous series of a variable x_t. By selecting an arbitrary value x_0 the series is intersected at many places and the relation of the constant value x_0 to all other values of x_t serves as the basis for various definitions of runs. Some of them are as follows : τ_1 - distance between upcrosses, τ_2 - distance between downcrosses, τ_3 - distance between successive peaks, τ_4 - distance between successive troughs, τ_5 - distance between the consecutive upcross and downcross, τ_6 - distance between the consecutive downcross and upcross, S - integral of positive deviations between the consecutive upcross and downcross, ND - integral of negative deviations between the consecutive downcross and upcross, I_1 - maximum positive deviation for any given τ_5, I_2 - minimum negative deviation for any given τ_6, s - average positive deviation (S/τ_5), d - average negative deviation (ND/τ_6), etc.

Basically, any hydrologic drought involves duration, severity (intensity), areal extent, probability of recurrence, and initiation (or termination), which means its location in absolute time. The rainfall all over Bangladesh during the year 1994 was less than the normal rainfall of the near previous years. North-western part of the country, contains a distinct hydrogeological setting within the territory of Bangladesh and is of particular concern for the current research because, most of the drought hard hit areas are within this region. For such a research, runs as statistical properties of sequences, both in time and area, may represent the best basic parameters for an objective definition of drought. Hosking and Wallis (1993) suggested a number of nonparametric statistics which can be helpful in the identification of homogeneous collection of sites. In particular, for any objective analysis in a region one can employ their discordancy measure to determine whether a given data series is discordant with a group of data series as a whole.

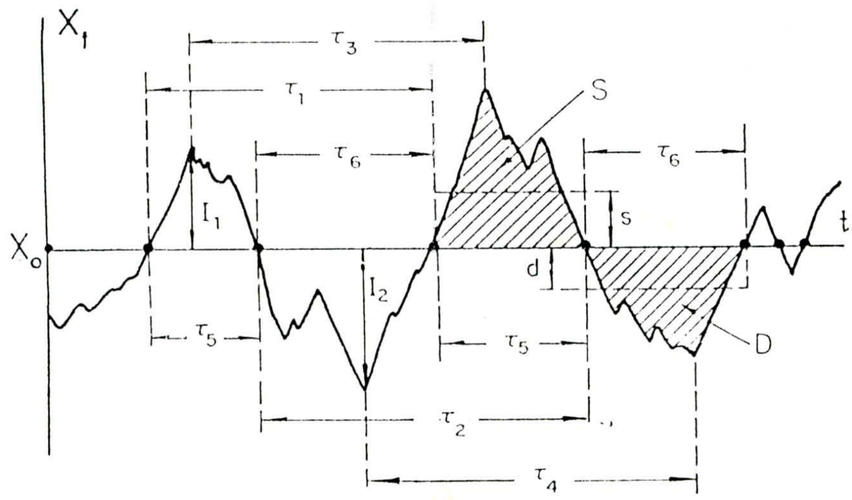

Fig. 1.1 Various Definitions of Runs for a Given Constant Crossing Level, X_0

The hydrologist is concerned withstreamflow; the meteorologist is concerned with rainfall or snowfall and agriculturist is concerned with soil moisture and the economist is concerned with drought in the context of a period of low water supply which affects society's productive and consumptive activities.

Each local area would require separate analysis of the drought problem. The evaluation of drought is a relative measure, and accumulated rain itself is not an adequate index of a drought condition. According to Burnash and Ferral (1972), a better index is the availability of useful moisture. Generally, useful moisture can be considered to exist in three forms: (1) soil moisture available for shallow rooted plants, (2) soil moisture available for deeper rooted vegetation, and (3) the volume of water available for streamflow and for pumping from wells. The lack of any one of these elements produces a drought syndrome which may impair the utilization of the land. This lack is only significant if there is an unfilled need.

In Bangladesh land crop-field generally lacks sufficient soil moisture during winter season (dry period), and farmers started growing winter crops (e.g., irri, boro) in an incremental rate mostly depending on groundwater to satisfy its demand for extra food. Monsoon rainfall has a direct effect on groundwater recharge. Due to subnormal rainfall in 1994-95, winter season experienced a lowering of water table below suction level. The predominantly shallow tubewell zones of north-western region of Bangladesh, fell short of supplying its irrigation requirements from the underground source. It is of particular interest to interrelate the statistical analysis of dry and wet spells in monsoon season with the groundwater deficit prevailing in the winter season. It will provide an indication of the amount of dependable water resources available in the area concerned to supply its irrigation requirements.

The rainfall sequence like most hydrologic variables is random in character, and, therefore, any phenomena like flood and drought derived from it will also represent a random character. These phenomena, which are very significant from the water resources planning and design point of view, dictate the estimation of its durations and magnitudes objectively. At the selected rain gages, rainfall (x) is generally observed on a daily basis, and this evolves a discrete time series information of rainy and non-rainy days during a rainy season. These represent events of uninterrupted wet ($x > 0$) and dry ($x \leq 0$) spells. In probability theory these spells are termed as runs and the rain total over a wet spell as run-sum. Generally the persistence of dry (drought) and wet (flood) spells during a rainy season are modeled by first-order Markov process. The stochastic behavior of the longest dry and wet spells can be predicted using theory of runs, where Poisson probability density functions of the occurrence of spells along with geometric distribution of the length of spells and Weibull, normal, lognormal and gamma distributions of the total rain over a wet spell are coupled.

Existing data base reveals that the north-western part of the country was most severely hit by drought as a whole. Traditionally the area has a high potential for agricultural production round the year. The area came under severe hit of drought in the 1994-95 season, and naturally was the focus of news media and public concern. Also, it has revealed that the region comes under frequent drought attack since long back. The methodology that has been applied here has been illustrated with the use of daily rainfall records of 35 rainfall stations in the north-western region. Data are acquired from Bangladesh Water Development Board (BWDB) having a record available from 1962 to 1995. To estimate the amount of water deficiency, evaporation data has also been collected surrounding the severely drought affected areas. To make an estimate of the agricultural, socio-economic and environmental damages, data related to these parameters are collected through questionnaire survey in Badarganj and Kishoreganj areas. Groundwater utilization deficit is also worked out for these thanas.

1.2 Objectives

To characterize the behavior of the much publicized 1994-95 drought in the north-western region of Bangladesh, some statistical as well as groundwater level analysis will provide some insight about the nature of the disaster occurred. A field survey on crop damages in a number of representative places will further enhance the knowledge from the affected farmers point of view. With the above perspective, the analysis will be performed under the following 3 major categories:

1. Stochastic Behavior

To find out the stochastic behavior of the longest dry and wet spells.

2. Climatological Behavior

To find out the climatological behavior of 1994-95 drought in terms of rainfall and evapotranspiration sequences to obtain the unfilled irrigation demand.

3. Crop Damage Assessment

To determine the damages caused to different types of crop production in 1994-95.

To estimate the groundwater decline for the year 1994-95.

1.3 Organization of the Thesis

This thesis consists of eight chapters in total. Introductory aspects such as causes of drought, study area, study objectives, etc are discussed in chapter one. Chapter two presents definition of drought and methods of drought analysis. Types of data and how the data are collected are discussed in chapter three. Chapter four deals with whether sites are homogeneous within the region. Sequential properties are also investigated in this chapter. Stochastic model of rainfall are developed in chapter five. Poisson probability density function of the occurrence of spells is coupled with geometric distribution for the length of spells and the Weibull, normal, lognormal and gamma distributions for the total rain of wet spells are found out in this chapter. Estimation of water availability and deficit are discussed in chapter six. To find out the drought impact questionnaire survey data are summarized in chapter seven. In this chapter the main two parts are; crop damage assessment, and socio-economic and environmental impact assessment. Conclusion and recommendation are discussed in chapter eight.

Chapter 2
Literature Review

2.1 Introduction

Two of the most important extreme fluctuations of hydrologic phenomena are droughts and floods which are directly related to socio-economic conditions of a region. Being a rapid evolving disaster, floods cause loss of property and human life. On the otherhand the unprecedented increase in population, industry and living standards of modern time give rise to significant water shortages. Although the floods have been investigated empirically and theoretically by various researchers for a long time, there have been very little studies performed on drought (Sen 1980b).

There is no universally agreed definition of drought but a definition which may be generally accepted is "severe water shortage". The definition of drought will vary with the nature and intensity of land and water use. While many attempts have been devoted to defining drought, there has been no consensus (Kibler et al. 1987; Chang 1987; Alley 1985; Dracup et al. 1980). There exists widely diverse view about the interpretation of droughts among the scientist of different disciplines. Several authors have tried to define drought under different conditions which are as a whole agricultural, hydrological, and meteorological in nature. In a very general term, drought is a condition of moisture deficit sufficient to have an adverse effect on vegetation, animals and man over sizable area (Warrick 1975). However, prolonged lack of precipitation is often closely associated with drought (Russel et al. 1970). From the previous studies one can assemble a number of definition as follows:

2.2 Definition of Drought

Definition of drought raises the question somewhat, as it requires a further definition of shortage or alternatively the specification of the amount of water needed. Water need depends on the type and number of animal and plant communities that exist. The availability of water depends largely on rainfall. Rainfall is the best single index of drought. Although the definition of drought will vary with the nature and intensity of land and water use, the only objective method of characterizing drought is to specify minimum water needs for a particular purpose. Thus if the minimum water need for a given period of time is met by rainfall of a given amount "x", drought may be said to occur whenever the rainfall during that time interval is less than "x" and the severity of drought is related to the rainfall amount by which the amount is less than the requirement (Gibbs and Maher 1967). Drought by definition consists of a sustained period of deficit perhaps lasting a few months or even many years. Conditions within a drought may vary considerably in space and time in accordance with the irregularity of the rainfall distribution and with the heterogeneity of the hydrological responses of the river basins that are affected. Thus, character of drought may be different for different climatological and hydrological regimes that are found in the world. Droughts differ from other meteorological phenomena in their temporal aspect. It is difficult to tell at what date a drought started, what date it is terminated, and thus how long it lasted.

Thomas (1965) notes that meteorological drought is sometimes defined as a prolonged and abnormal moisture deficiency. Agricultural drought is usually described in terms of crop production without any reference to streamflow. Agricultural drought is said to exist when soil moisture is depleted so that yield of plants is reduced considerably. Both meteorological and agricultural droughts can be terminated by rainfall, or in the case of agricultural drought by the end of cropping season. Hydrologist can thought of drought as a period during which the actual water supply is less than the minimum water supply necessary for normal operation in a particular region.

The most commonly used drought definitions (Rasmusson et. al 1993) are based on (1) meteorological and/or climatological conditions, (2) agricultural problems, (3) hydrologic conditions, and (4) economic considerations. Meteorological drought is defined as an interval of time, generally of the order of months or years, during which the actual moisture supply at a given place cumulatively falls short of climatically appropriate moisture supply. Agricultural drought is typically defined as a period when soil moisture is inadequate to meet evapotranspirative demands so as to initiate and sustain crop growth. Another facet of agricultural drought is a deficiency of water for livestock or other farming activities. Hydrologic drought typically refers to periods of below-normal streamflow and/or depleted reservoir storage. Closely related to the concept of low flow in defining drought is the use of the number of consecutive months that a streamflow was deficient, that is, within the lowest 50 percent of records for the monthly records. Economic drought are a result of physical processes but concern the economic areas of human activity affected by drought. The human effects, including the losses and benefits in the local and regional economy, are often a part of this definition.

NWP (1991) described that uneven and inadequate rainfall can greatly reduce crop production. They define drought very severe, severe, moderate, and slight according to yield loss.

Practically, drought can be defined by indicators such as precipitation, groundwater and streamflow. Based on climatological data the Palmer drought was developed (Palmer 1965), defined as an interval of time, generally of the order of months or years in duration during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply. Further the severity of drought is considered as being a function of both the duration and magnitude of moisture deficiency. Lowing (1987) defined climatic drought as the difference between potential evaporation and precipitation. Hudson and Hazen (1964) defined “drought” to periods of unusually low water supply, irrespective of a demand for water in specific place.

Concerning droughts for the purpose of water resources system analysis, Sen (1980b) modified Palmar (1965) drought definition as: "the several of time generally of the order of several days, months or years in duration during which the actual water supply at a given location rather consistently falls short of the demand". Linsley et al. (1975) defined the hydrological drought as a period during which streamflows could not supply established uses under a given water management plan. In this context a drought is the deficiency in water supply over a significant time to meet demand necessary for various human activities. The deficiencies are determined with respect to annual flows.

Meteorological drought based on rainfall data was defined by Herbst et al. (1966). An "absolute drought" is defined for statistical purposes as a period of at least 15 consecutive days without 0.25 mm of rain on any one day, whereas a "partial drought" is a period of 29 consecutive days the mean rainfall of which does not exceed 0.25 mm per day. Two American authors have defined drought in terms of deviation from the normal rainfall. Hoyt (1942) concluding that in humid and semi-arid regions drought conditions exist where there is an annual precipitation deficit of 15 percent or more, whereas Bates in a study of climatic characteristics of the plains region in relation to the possibility of shelter planting, used two methods as a base (i) full calendar years having less than 75 percent of the normal precipitation and (ii) 4-month droughts in which the precipitation during each month was less than 60 percent of the normal precipitation for that month.

Yevjeivich (1967) gave definition of drought on the basis of runs theory and stationary time series. A drought is defined as the deficiency in the water supply over significant time to meet water demand for various human activities. Chang et al. (1984) developed the application of run length distribution for daily precipitation modeling where dry run is related to the drought by using three-step stochastic model called Binary-DARMA (Discrete Auto Regressive-Moving Average).

Dracup et al. (1980) notes that the problem of drought definition is caused by the different concepts held by a variety of academic fields of study. For example, the hydrologist is concerned with drought in the context of a period of below normal streamflow and depleted reservoir storage; the meteorologist is concerned with drought in the context of a period of below normal rainfall or snowfall. The agriculturist is concerned with drought in the context of a period during which soil moisture is insufficient to support crops; and the economist is concerned with drought in the context of a period of low water supply which affects societies productive and consumptive activities. In addition, the concept of drought varies among regions of differing climates. In Bali any period of 6 days or more without rain is considered a drought, while in Libya, drought is only recognized after 2 years without rain (Hudson and Hazen, 1964). Although the concepts are based on different viewpoints, they depend upon the effects of prolonged weather conditions with deficient moisture (Frick et al. 1990). Whipple (1966) defined drought generally conceived of as a deficiency of precipitation and its effect on vegetation as well as water supply.

2.3 Methods of Drought Analysis

Drought forecasting is a field of study in which much work remains to be done, because it is difficult to clearly define drought and thus come up with a unified treatment of the phenomenon. This results different criteria and different kinds of water shortage for the various applied fields of hydrology such as agriculture, water supply engineering for irrigation, municipal or industrial uses, sanitary engineering and even navigation. Various methods i.e., theory of runs, hydrological analysis, Palmer index, agricultural analysis etc. were developed during the past decades for identification of drought problems. Likewise flood and other natural calamities, drought is a great disaster for the civilization. Several researchers around the world have been showing their interest in the analysis of drought in terms of duration, magnitude and severity. Every water user has its own concept of drought. Horn (1989) applied the runs theory to annual steamflow sequences in Idaho which permitted the assignment of return periods to historical drought events based on the statistical characteristics of the streamflow record.

Thus, various methods of analysis of drought relevant to specific water uses or to specific disciplines have been classified. Analysis based on hydrological, agricultural, and meteorological domains developed in the past for identification of drought problem are presented in the following sub-sections for better understanding of the drought characteristics. In this regard, broad based statistical tools are applied for the hydrological and meteorological droughts analysis. Agricultural droughts are viewed as the effect arising from the hydrological and meteorological droughts.

2.3.1 Hydrological Analysis

Gumble (1963) defined drought as the smallest annual value of daily streamflow. By this definition, a drought event occurs exactly once a year. Gooch (1966) used three components to characterize drought: duration, runoff during drought, and net reservoir-surface evaporation during drought. Whipple (1966) applied the station-year method of regional frequency analysis to multiyear hydrologic droughts.

Yevjevich et al. (1975) determined the joint probability distribution of hydrologic droughts for two hydrologic time series, concurrently observed at two locations. He found the relations of characteristics of probability distributions of joint drought occurrence at two locations and the statistical parameters of the corresponding two hydrologic time series. He also initiated a methodology of studying droughts of hydrologic periodic stochastic processes exemplified by monthly time series.

Sen (1976) presented a method to provide simple analytical solutions to various problems concerning probabilities and statistical properties of wet and dry periods by using streamflow sequences. Droughts are representative of dry periods in a streamflow sequence during which successive flow values remain less than a given reference value, x_0.

Sen (1977) developed a methodology on the basis of random sum of random variables for determining various run-sum properties of a given hydrologic process. This paper provides simple analytical solutions to various problems concerning the amount of water over a dry or wet periods in water-resources system design.

Sen (1978) developed a methodology which is referred to as the "autorun analysis" to investigate the sequential properties of a hydrologic time series on the basis of wet and dry spells which are directly related to the run properties.

Sen (1980a) developed a drought-generating mechanism from an observed streamflow time series and formulated simple analytical solutions of the probabilistic behavior of extreme droughts by making use of Markov process.

Dracup et al. (1980) performed several statistical tests on streamflow series for the purpose of analyzing multi-year drought events. The test results and their implications are discussed in relation with the characterization of high-flow and drought event which give an indication of the maximum response of watershed in terms of drought duration and severity during the period of record.

Ahmed (1982) studied the return period of the Ganges river drought. The study compared the results of drought frequency analysis by several methods and appraised the relative reliability of these methods. Four theoretical distributions had been applied to the same set of low flow data of the Ganges. The distributions used are the Extreme Value Type-I, Pearson Type-III, Log-Pearson Type-III and the Lognormal. He showed that the Log-Pearson Type-III distribution fitted the drought data best.

Khan (1985) presented a paper on drought analysis of aquifer recharge using probability distribution. Here the author applied the commonly used distributions for low flow analysis in case of drought recharge analysis for the unconfined chalk aquifer of the river Itchen catchment in Hampshire, United Kingdom.

Mohan and Rangacharya (1988) developed a method to identify the characteristics of drought by its duration, areal extent and its severity. To identify these parameters from the available historic/forecasted flow data a method is proposed following a modified procedure of Herbst et al. (1966) which was originally suggested for analysis of drought using rainfall data. This modified methodology is applied to 52 years streamflow series (1930 to 1981) of Bhadra river Karnataka in India.

Salazar (1988) described a potential technique for drought analysis of periodic stochastic processes. The first alternative in treating the drought of periodic stochastic series is to remove trends and periodicites in parameters, using either the parametric or nonparametric method of their removal. The second alternative is to use the supply less demand series. The third alternative used for analyses is the "drought magnitude and drought duration criteria". A fourth alternative is based on a simultaneous generation of annual and monthly series by jointly preserving their parameters such as the variance, and serial correlation co-efficients among others.

Majumdar (1988) carried out drought analysis and synthetic generations on two Indian rivers Damodar and Cauveri using ARIMA and fast fractional Gaussian noise model (ffGn). The quality of generated data regarding preserving the historical basic properties like mean, variance as well as long term properties like Hurst co-efficient (H) and run lengths of low flow generation as depicted by drought curve was investigated.

The problems of regional drought and flood analysis by Sen (1980b) has been approached theoretically on the basis of random fields. Necessary formulations for the regional drought descriptors such as the deficit area, the total areal deficit and maximum deficit intensity have been derived.

Chang (1990) studied the effect of drought on streamflow characteristics. He defined drought events as a period of flow below specified truncation levels. For a truncation level there may be one, several or no drought events. Different truncation levels can be used to reflect different levels of drought severity. The drought intensity function was developed to investigate drought severity in the basin.

Sen and Tabios (1995) performed a drought study of the Sacramento river basin using the combined annual flows of the four major rivers contributing to Sacramento river. The analysis was based on the theory of runs considering the presence of reservoirs and without reservoirs.

2.3.2 Meteorological Analysis

Herbst et al. (1966) developed a technique for the evaluation of drought based on monthly rainfall data. In this method it is possible to determine the duration and intensity of droughts. A drought index is calculated which enables to ascertain the intensity of drought of a station. This method can be programmed for an electronic computer to facilitate the investigation of data from a large number of rainfall stations. A modification to Herbst et al. (1966) method is suggested by Datta (1997) using fortnightly rainfall data of north-western region of Bangladesh.

Brutsaert et al. (1972) presented a method to find out the availability of moisture as it relates to drought. He covered a broad area of topics and provided a variety of examples of contemporary recent attempts for solving drought related problems

Lowing (1987) defined a climatic drought as the difference between potential evapotranspiration and precipitation. This type of drought analysis is more relevant for supplementary irrigation project design. He also studied low flows by taking a discharge value of x as an arbitrary reference level. He used three parameters to describe low flow x, which are: (i) duration, (ii) minimum value, and (iii) overall deficit.

Sharma (1996) developed a model using a Markov (order 1) process. This model describes the behavior of dry and wet spells using the theory of runs, in combination with Poisson, geometric and Weibull distributions for occurrence of spells, run lengths, and total rain-sum of a wet spell, respectively. In this regard the longest period of dry and wet spells and the corresponding largest rain-sum value can be deduced by applying the theory of the extremes of random number of a random variable (Todorovic and Woolhiser 1975).

Palmer (1965) developed the Palmer Drought Severity Index (PDSI) by means of measuring the severity of drought. This index has sometimes been referred to simply as the Palmer index, since it also evaluates wet conditions. However here interest centered on droughts. He developed a method for evaluating the meteorological anomaly in terms of an index which permits time and space comparisons of drought severity. A method for computing the required precipitation is demonstrated. The difference between actual precipitation and the computed precipitation represents a fairly direct measure of the departure of the moisture aspect of the weather for normal.

Alley (1985) investigates the relationships between PDSI for climatic divisions and streamflow and groundwater conditions within each divisions. In his paper the PDSI for climatic divisions in New Jersy has been compared to the occurrence within each climatic divisions of streamflows in their lower quartile for the month (streamflow index) and groundwater levels in the lower quartiles for the month (groundwater index).

Palmer index has been used to illustrate the areal extent and severity of various drought episodes (Palmer 1967; Karl and Quayle 1981) and to study the spatial and temporal characteristics of drought as well as to explore the periodic behavior of droughts.

Very few results of investigations on areal drought coverage are available. Even a descriptive method of areal characteristics of drought has not been well developed. Little has been done on applying the quantitative statistical methods on areal coverage. Pinkayan (1966) studied the probability of occurrence of wet and dry years over a large area. Gibbs and Maher (1967) analyzed the areal extent of past droughts in Australia by classifying the annual precipitation by using the decile range.

Delleur et al. (1989) and Chang et al. (1984,1987) developed a family of statistical models for the simulation of sequences of dry and wet days. The models are based on the discrete autoregressive-moving average (DARMA) family of stochastic processes, which include the Markov chain as a particular case.

Sastry and Chakravarty (1984) gave an idea about dry-day and dry-week concept and severity of atmospheric drought.

Alam (1994) studied the statistical characteristics of climatic drought which is defined as the difference between potential evapotranspiration and rainfall. Ten-day basis drought maxima in a year was calculated by him for five rainfall stations in the Teesta barrage project area.

2.3.3 Agricultural Analysis

A methodology (Karim et al. 1990) has been developed by using the agroecological data base at BARC to categorize drought situations and estimate loss of different crop yields due to drought. Following the delineation of the drought prone areas, a computerized model of yield reduction of crops has been established. To avoid crop loss and to increase cropping intensities in the drought prone an irrigation schedule for different crops has been worked out. Based on available information droughts in Bangladesh have been categorized into two types. One is Kharif and another is Rabi and Pre-kharif. They again have been subdivided into several classes depending on the intensity of the drought such as very severe, severe, moderate, and slight.

Hershfield et al. (1972) studied some measures of agricultural drought. The frequency of dry-day sequences for both precipitation and streamflow is used as a drought discriminant or as an indicator of the reliability of precipitation input to the agricultural system in time. The analysis is based on the premise that sequence lengths, as statistical properties of time series, provide useful parameters in drought investigation.

Karim (undated) developed a methodology to quantify the effect of moisture stress on the yield of a crop which can be used for planning irrigation project. He calculated stress day (SD), stress day index (SDI), stress index (SI) and drought yield (YDi) of crops. He showed how crop yield decreases with water stress in a region.

Bidwell (1972) studied about the methodology for analyzing agricultural drought. In this study he introduced techniques of constructing and analyzing models to simulate the relationship between hydrologic drought to crop yields.

Victor and Sastry (1984) made an evaluation of agricultural drought using probability distribution of soil moisture index (SMI) for some Kharif crop.

Narayana et al. (1984) performed a statistical study on incidence of drought in relation to agricultural production. Here they showed how yield declined with increase of probability of drought.

In my study I have focused mainly as a meteorologist concerned with drought in the context of a period below normal rainfall or snowfall.

Chapter 3
Data Collection

3.1 Types of Data Collected

The definition of drought requires a further definition of "shortage" or alternatively the specification of the amount of water needed. Water need depends on the nature of the agricultural practice, cultural heritage and environmental preservation, the community demands so that the concept of drought can't be separated from the use to which water is put.

The availability of water depends largely on rainfall, although losses (such as evaporation or wasteful use of water) and gains (such as storage in soil, in artificial reservoirs or in aquifers) must be taken into account (Gibbs and Maher 1967). Under the above circumstances, considering the socio-economic and environmental conditions of the north west region, the present study needs two types of data as (i) hydro-meteorological data and (ii) agricultural, socio-economic and environmental data.

Hydro-meteorological data includes rainfall, evaporation and groundwater level data. Rainfall and evaporation data are needed to characterize drought and to determine the moisture deficiency. To estimate the groundwater utilization deficit for the year 1994-95, departure of water table fluctuations from normal suction levels are essential. To determine the extent of damages and socio-economic and environmental impact, data related crop damage and socio-economic and environment are also need to be collected. All the hydro-meteorological data are collected from secondary source, the Bangladesh Water Development Board. A questionnaire survey was conducted in the study area to collect data relating to agriculture, socio-economic conditions, fisheries and environment.

3.2 Hydro-Meteorological Data

Stations for analysis have been selected on the basis of data availability and closeness to study region. Data on rainfall, evaporation and groundwater level are available from Bangladesh

Water Development Board (BWDB). On the basis of hydrologic unit, Bangladesh may be divided into five regions; (i) North-West (NW), (ii) North-East (NE), (iii) South-West (SW), (iv) South-East (SE), and (v) South-Central (SC). The north west (NW) region of Bangladesh is bounded by the Brahmaputra river to the east, the Ganges to the south, and the international border to the north and west. In the northern area of the region up to the Dinajpur-rangpur railway line the land slopes uniformly toward the south east at 50 m per 100 km; in the south the slope gradually flattens to 10 m per 100 km. The average ground elevation varies from 90 m PWD in the north west to below 10 m PWD in the south east. The NW region covers a catchment area of around 32,000 km^2 and includes over 1200 km of rivers. The Karatoya-Atrai-Baral and the Jamuneswari-Karatoya-Bangali are the two main systems draining the greater part of the north west region. Other river systems in the region are the Teesta, Dudhkumar, Dharla and the Tangon-Punarbhaba-Mohananda. There are as many as 94 rainfall recording stations in NW region (Fig. 3.1). The stations listed in Table 3.1 (rainfall station code begin with abbreviation "R") are selected which contain less missing data. Daily evaporation data are not available for all the tabulated rainfall stations. Evaporation data are collected only for the three stations as listed in Table 3.1 with code number beginning with "E". These stations are nearest to the questionnaire survey area. Groundwater level data is collected only for eight stations in greater Rangpur district and name of those stations are also shown in Table 3.1. Consistency of data are checked by double mass curve analysis.

3.3 Agricultural, Socio-Economic and Environmental Related Data

A questionnaire was prepared for surveying the agricultural damages and assessing the socio-economic and environmental impact which are usually not available from any known sources. Due to time and resource constraints, survey was conducted for a limited number of households which has been selected randomly from the two thanas of the study area. For getting reliable information, careful attention was given to questionnaire design, sampling technique and administration of the questionnaire. Questionnaire survey was conducted in the Kishoreganj and Badarganj thanas from 7 to 23 June, 1996.

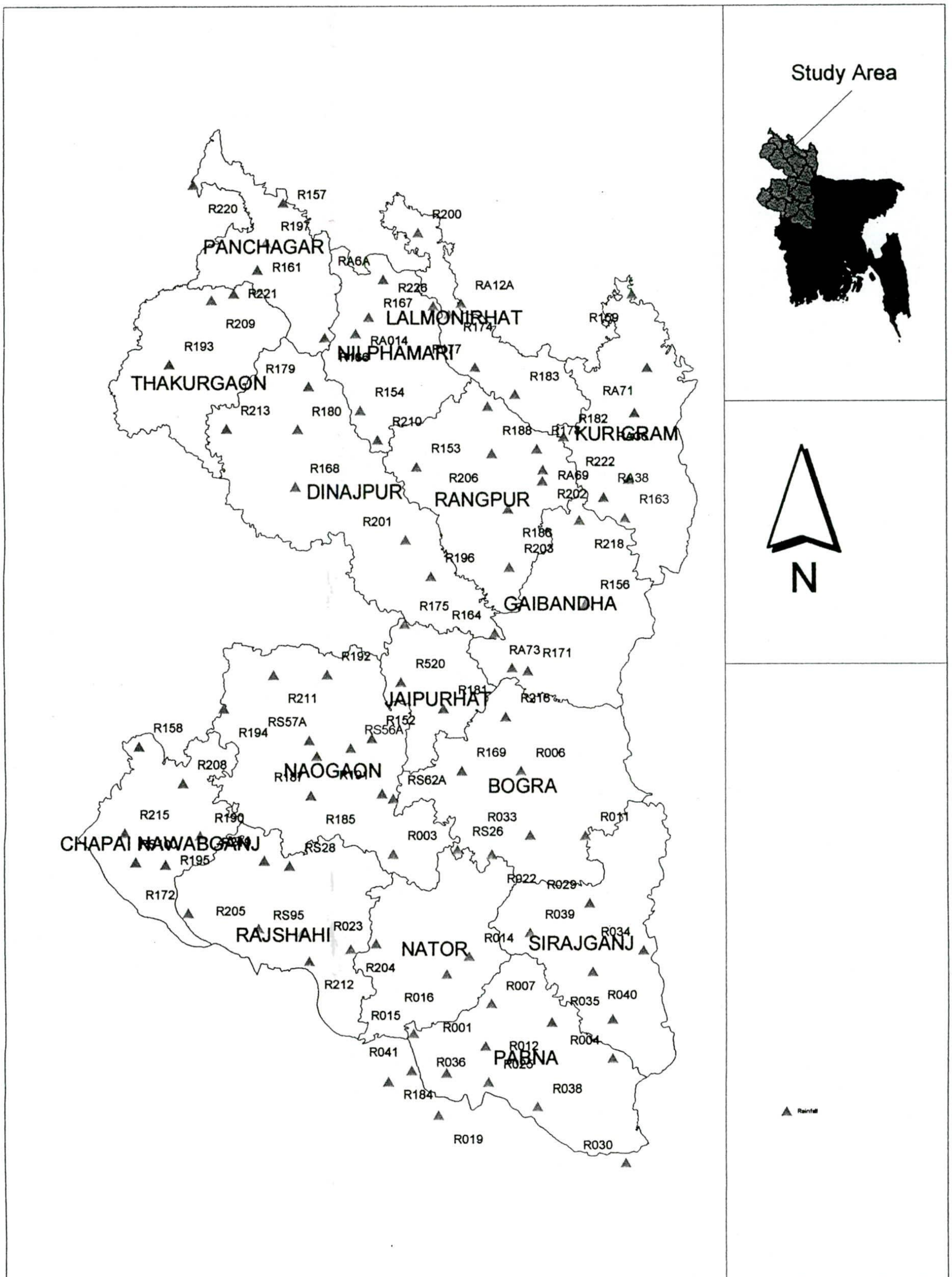

Fig. 3.1 Hydrometerological Stations of North West Region of Bangladesh

Table 3.1 Data Collected for Rainfall, Evaporation and Groundwater Stations

Type	Small Districts	Serial Number	Rainfall Stations		Collected Period	
			Code No.	Name	Start Year	End Year
Rainfall	Panchagarh	1	R - 161	Boda	1962	1996
	Thakurgaon	2	R - 193	Nekmand	1962	1996
	Nilphamari	3	R - 167	Dimla	1962	1996
	Lalmonirhat	4	R - 177	Kaliganj	1962	1996
	Kurigram	5	R - 159	Bhurungamari	1962	1996
		6	R - 182	Kurigram	1962	1996
		7	R - 163	Chilmari	1962	1996
	Dinajpur	8	R - 179	Khansama	1962	1996
		9	R - 213	Setabganj	1962	1996
		10	R - 168	Dinajpur	1962	1996
		11	R - 196	Nawabganj	1962	1996
		12	R - 164	Goraghat	1962	1996
	Rangpur	13	R - 188	Mohipur	1962	1996
		14	R - 178	Kaunia	1962	1996
		15	R - 206	Rangpur	1962	1996
		16	R - 153	Badarganj	1962	1996
		17	R - 186	Mithapukur	1962	1996
	Gaibandha	18	R - 156	Bhawaniganj	1962	1996
	Jaipurhat	19	R - 181	Khetlal	1962	1996
	Naogaon	20	R - 192	Patnitala	1962	1996
		21	R - 185	Manda	1962	1996
		22	R - 003	Atrai	1962	1996
	Bogra	23	R - 006	Bogra	1962	1996
		24	R - 033	Sherpur	1962	1996
	Chapai N. Ganj	25	R - 158	Bholhat	1962	1996
		26	R - 215	Shibganj	1962	1996
	Rajshahi	27	R - 219	Tanore	1962	1996
		28	R - 205	Rajshahi	1962	1996
	Natore	29	R - 036	Singra	1962	1996
		30	R - 184	Lalpur	1962	1996
	Sirajganj	31	R - 011	Dhunot	1962	1996
		32	R - 034	Sirajganj	1962	1996
		33	R - 039	Taras	1962	1996
	Pabna	34	R - 001	Atgharia	1962	1996
		35	R - 004	Bera	1962	1996
Evaporation	Lalmonirhat	1	E18	Kaliganj	1976	1995
	Rangpur	2	E32	Rangpur	1976	1995
		3	E22	Mohipur	1979	1995
Groundwater	Nilphamari	1	RA06A	Khogagari	1986	1996
	Lalmonirhat	2	RA12A	Hatibanda	1986	1996
	Nilphamari	3	RA14	Bargacha	1986	1996
	Kurigram	4	RA36	Nageswari	1986	1996
	Kurigram	5	RA38	Ulipur	1986	1996
	Rangpur	6	RA69	Hariswari	1986	1996
	Kurigram	7	RA71	Pateswri	1986	1996
	Gaibandha	8	RA73	Gobindaganj	1986	1996

3.3.1 Questionnaire Design

The questionnaire was designed carefully in order to meet the objectives of the study. A preliminary questionnaire was prepared on the basis of knowledge of some similar previous questionnaires. It was aimed to make the questionnaire a structured, target oriented and at the same time flexible enough to accommodate the general impression of the farmers about the overall effect of drought in the area. Before finilize the questionnaire was pre-tested during the early field visits finalized. Few corrections and modifications were identified during pre-testing. A sample questionnaire is presented in Appendix A.

3.3.2 Sampling Technique

Questionnaires were filled up by interviews with different category of farmers. There were a total of 120 farmers interviewed. For getting a representative sample, a two-stage sampling procedure was followed. In the first stage, drought affected six unions were selected for the questionnaire survey. These are Kishoreganj, Nitai and Putimari from Kishoreganj thana and Ramkrishnapur, Ramnathpur and Radanagar from Badarganj thana.

In the second stage of sampling, farmers were selected randomly from blocks of the selected unions. These farmers were divided into four categories according to the amount of land they owned. Category wise the number of farmers participated in the interview are shown in Tables 3.2. Table 3.3 contains some general information (BBS 1995) of the Kishoreganj and Badarganj thanas, where from farmers were interviewed.

Table 3.2 Number of Farmers Interviewed

Thana	Landless 0.0 decimal	Marginal 0-50 decimal	Middle 50-300 decimal	Big >300 decimal	Total
Kishoreganj	0	6	36	18	60
Badarganj	5	1	18	26	60

3.3.3 Administration of the Questionnaire

Eight Block Supervisors (BSs) from the respective areas were hired for helping the interview with the local people. These BSs are the government employees under the Directorate of Agricultural Extension (DAE). They are all specially trained people, for motivating and organizing the local people. Their main task is to provide with agricultural extension services to the farmers of the locality. In this regard the motivation for selecting these BSs were that they are familiar with the local problem and at the same time they are conversant with the local colloquia. They were given training for interviewing the farmers. After completion of the training, the BSs interviewed the selected farmers in their houses. The BUET research team were also present during the interview sessions for ensuring the uniformity in the procedure. The team consist of five member.

Table 3.3 General Information of Badarganj and Kishoreganj Thanas

Items		Kishoreganj	Badarganj
Position	Latitude	25° 49′ - 25° 59′ North	25° 32′ - 25° 46′ North
	Longitude	88° 57′ - 89° 12′ East	88° 56′ - 89° 10′ East
District		Nilphamari	Rangpur
Area (Sq. Km)		265	301
Population (1991)	Male	126,032	109,453
	Female	120,169	103,978
	Total	246,201	213,431
Density (Per Sq. Km)		929	708
Literacy (Percent)		18.2	23.9
Geographic Unit	Union	11	10
	Mouza	70	64
	Village	72	119
Urban Population (Percent)		2.3	10.9

Chapter 4
Homogeneity and Autorun Analysis

4.1 Introduction

Regional frequency analysis uses data from a number of measuring sites. A "region" is a group of sites each of which is assumed to have data drawn from the same frequency distribution. The analysis involves the assignment of sites to regions, testing whether the proposed regions are indeed homogeneous, and choice of suitable distributions to fit to each region's data. Wet and dry spells are directly related to the run properties. To investigate the sequential properties of a hydrologic time series "autorun analysis" has been developed (Sen 1978). The relevance of the methodology as a potential tool in water engineering applications as well as in statistics, is due to its distribution free behavior. In hydrology it is wellknown fact that if the time series is considered to be dependent, then high values tend to follow high values and low values tend to follow low values.

As with any statistical analysis there should be a close inspection of the data, so that gross errors and inconsistencies can be eliminated. Hosking and Wallis (1993) suggested a number of nonparametric statistics which can be helpful in identification of homogeneous collection of sites. In particular, one can employ their discordancy measure to determine whether a given data series is discordant with a group of data series as a whole. This identifies unusual sites as those whose at site L moments are markedly different from those of other sites in the data set.

4.2 Homogeneity

L moments are used to summarize the statistical properties. The first, second, third and fourth L moments are mean, variance, skewness and kurtosis respectively. L moments can be written as functions of probability weighted moments (PWMs), β_r, which can be defined as (Stedinger et al. 1993)

$$\beta_r = E\left\{x[F(x)]^r\right\} \qquad (4.1)$$

where E is the expectation, F(x) is the cdf for x probability moments, and r is the order, i.e., 1, 2, 3 ..... To estimate PWMs one employs the ordered observation or the order statistics, $x_n \leq \cdots \leq x_1$. Here x_i is the monsoon total rainfall for the i th ordered in the n number of years. The sample estimators of β_r (Stedinger et al. 1993) can be written as follows:

$$b_0 = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (4.2)$$

$$b_1 = \frac{1}{n}\sum_{i=1}^{n} \frac{i-1}{n-1} x_i \qquad (4.3)$$

$$b_2 = \frac{1}{n}\sum_{i=1}^{n} \frac{(i-1)(i-2)}{(n-1)(n-2)} x_i \qquad (4.4)$$

$$b_3 = \frac{1}{n}\sum_{i=1}^{n} \frac{(i-1)(i-2)(i-3)}{(n-1)(n-2)(n-3)} x_i \qquad (4.5)$$

For any distribution L moments are easily calculated in terms of PWMs from

$$l_1 = b_0 \qquad (4.6)$$

$$l_2 = 2b_1 - b_0 \qquad (4.7)$$

$$l_3 = 6b_2 - 6b_1 + b_0 \qquad (4.8)$$

$$l_4 = 20b_3 - 30b_2 + 12b_1 - b_0 \qquad (4.9)$$

where l_1, l_2, l_3, and l_4 are the first, second, third and fourth L moments estimators. L coefficients of variation, skewness and kurtosis can be obtained by

$$L - cv \cdot (\tau_2) = l_2 / l_1 \qquad (4.10)$$

$$L - skewness \cdot (\tau_3) = l_3 / l_2 \qquad (4.11)$$

$$L - kurtosis \cdot (\tau_4) = l_4 / l_2 \qquad (4.12)$$

4.2.1 Discordancy

Given a group of sites, the aim is to identify those sites that are grossly discordant with a group as a whole. Discordancy is measured in terms of the L moments (Hosking and Wallis 1993) of the sites data.

Heuristic Description

The L moments (Lcv, L skewness and L kurtosis) of a site has been considered as a point in a three dimensional space. A group of sites will yield a cloud of such points. Any point that is far from the center of cloud, is an unusual station (Hosking and Wallis 1993).

Formal Description

Let $u_i = \left[\tau_2^{(i)}, \tau_3^{(i)}, \tau_4^{(i)}\right]^T$ be a vector containing τ_2, τ_3, τ_4 values for site i, $\bar{u} = \frac{1}{n}\sum_{i=1}^{N_s} u_i$, be the unweighted group average, where N_s=number of station. Define the sample covariance matrix

$$M = \frac{1}{n-1}\sum_{i=1}^{N_s}(u_i - \bar{u})(u_i - \bar{u})^T \qquad (4.13)$$

Hosking and Wallis (1993) define the discordancy for site i as

$$\psi = \frac{1}{3}(u_i - \bar{u})^T M^{-1}(u_i - \bar{u}) \qquad (4.14)$$

Discordancy values are found out by writing a FORTRAN77 programme (Appendix D). Large values of ψ indicates that are most discordant from the group as a whole. Hosking and Wallis (1995) defines critical values for the discordancy statistics ψ as given in Table 4.1.

Table 4.1 Critical Values for the Discordancy Statistic ψ

Number of Sites in a Region	5	6	7	8	9	10	11	12	13	14	≥ 15
ψ	1.333	1.648	1.917	2.140	2.329	2.491	2.632	2.757	2.869	2.971	3.000

4.2.2 Analysis, Results and Discussions

All the daily rainfall data for monsoon and pre-monsoon from 35 stations of north western region of Bangladesh are used for testing whether sites are discordant within the region. Calculated L moment ratios and ψ values are presented in Table 4.2. Plotting of L moments are shown in Fig. 4.1. It is seen that all the points form a cloud except one point. If this point is discordant or not, can be checked by numerical measure (ψ). No data series are found to be discordant with respect to others. The largest ψ value is 2.74 for station Bhawaniganj (R156) which is less than the critical ψ value of 3 (Hosking and Wallis 1993). If we consider the top few discordancy values for monsoon, Table 4.2 shows the stations R177, R179, R213, R196, R156 and R215 are in higher discordant measure than others. It might be worthy to shift these sites to another region if there are physical grounds for doing so. There is no evidence of gross errors in the data. But the entire group of sites at this stage is considered under one homogeneous region. Based on this observation all stations in north-western regions have considered to be in a homogeneous region for further stochastic simulation of wet and dry spells.

4.3 Autorun Analysis

Autorun can be interpreted in different ways by saying that in the case of dependent series, the periods of wet and dry spells tend to be greater than in the case of independent series. Such a property has been termed "persistence" in hydrology. To measure "persistence" three methods are used in (Sen 1978) (i) autocorrelation (ii) autorun and (iii) autocorrelation by autorun.

4.3.1 Autocorrelation

The investigation of the sequential properties of a series by autocorrelation analysis is the classical statistical technique. It is used to determine the linear dependence among the successive values of a series. The autocorrelation co-efficients θ_k of the order k, or of the lag-k, is defined for the discrete series by the product moment correlation co-efficient (Yevjevich 1972) between the members of that series are k items or k lags or k interval apart is given by

Table 4.2 L Moment Ratios and Discordancy at Different Stations

Districts	Serial No.	Station No.	Station Name	June Sept. (monsoon)				March May (premonsoon)			
				L-cs	L-cv	L-kurt	Di	L-cs	L-cv	L-kurt	Di
Panchagarh	1	R - 161	Boda	0.139	0.123	0.117	1.10	-0.049	0.246	0.031	0.59
Thakurgaon	2	R - 193	Nekmand	0.061	0.145	0.200	0.81	0.097	0.276	0.183	0.24
Nilphamari	3	R - 167	Dimla	0.122	0.114	0.115	1.38	0.188	0.238	0.245	1.45
Lalmonirhat	4	R - 177	Kaliganj	0.274	0.158	0.320	1.84	0.159	0.255	0.328	2.28
	5	R - 159	Bhurungamari	-0.026	0.153	0.121	1.26	0.126	0.209	0.209	1.46
Kurigram	6	R - 182	Kurigram	0.050	0.164	0.036	1.06	-0.014	0.198	0.146	0.91
	7	R - 163	Chilmari	0.281	0.186	0.188	1.15	0.033	0.229	0.132	0.30
	8	R - 179	Khansama	0.005	0.111	0.176	1.82	0.106	0.242	0.070	1.38
	9	R - 213	Setabganj	-0.013	0.152	0.174	1.73	0.070	0.321	0.158	1.14
Dinajpur	10	R - 168	Dinajpur	0.119	0.161	0.177	0.09	0.063	0.247	0.107	0.19
	11	R - 196	Nawabganj	0.348	0.210	0.299	2.18	0.254	0.322	0.202	1.06
	12	R - 164	Goraghat	0.071	0.190	0.151	1.28	0.303	0.400	0.240	2.68
	13	R - 188	Mohipur	0.013	0.166	0.117	0.92	-0.023	0.203	0.132	0.80
	14	R - 178	Kaunia	0.173	0.184	0.178	0.35	0.128	0.239	0.189	0.64
Rangpur	15	R - 206	Rangpur	0.072	0.166	0.140	0.31	-0.064	0.224	0.103	0.91
	16	R - 153	Badarganj	0.139	0.162	0.092	0.52	-0.067	0.223	-0.004	1.06
	17	R - 186	Mithapukur	0.183	0.205	0.182	1.17	-0.001	0.237	0.096	0.26
Gaibandha	18	R - 156	Bhawaniganj	0.227	0.149	0.349	2.74	0.041	0.291	0.077	0.21
Jaipurhat	19	R - 181	Khetlal	0.161	0.153	0.096	0.74	0.033	0.324	0.011	1.06
	20	R - 192	Patnitala	0.019	0.150	0.065	0.58	0.036	0.285	0.173	1.00
Naogaon	21	R - 185	Manda	0.159	0.138	0.159	0.44	0.006	0.280	0.081	0.36
	22	R - 003	Atrai	0.113	0.160	0.063	0.78	0.110	0.330	0.067	0.61
Bogra	23	R - 006	Bogra	0.123	0.133	0.080	0.96	0.030	0.256	-0.031	1.82
	24	R - 033	Sherpur	0.203	0.155	0.185	0.34	-0.018	0.256	0.134	0.81
Chapai N. Ganj	25	R - 158	Bholhat	0.158	0.199	0.118	1.25	0.061	0.337	0.002	1.32
	26	R - 215	Shibganj	0.298	0.210	0.260	1.64	0.354	0.403	0.199	3.09
Rajshahi	27	R - 219	Tanore	0.093	0.127	0.138	0.48	0.128	0.277	0.103	0.42
	28	R - 205	Rajshahi	-0.017	0.148	0.002	1.46	0.049	0.308	0.167	1.29
Natore	29	R - 036	Singra	0.092	0.140	0.150	0.16	0.229	0.322	0.165	0.87
	30	R - 184	Lalpur	0.029	0.145	0.123	0.38	0.078	0.323	0.069	0.53
	31	R - 011	Dhunot	0.042	0.123	0.157	0.80	0.022	0.287	0.007	0.68
Sirajganj	32	R - 034	Sirajganj	0.109	0.130	0.067	1.10	0.186	0.264	0.211	0.78
	33	R - 039	Taras	0.102	0.140	0.175	0.25	-0.025	0.274	0.106	0.92
Pabna	34	R - 001	Atgharia	0.286	0.162	0.232	1.14	0.110	0.242	0.198	0.48
	35	R - 004	Bera	0.214	0.192	0.239	0.77	0.000	0.249	-0.025	1.39

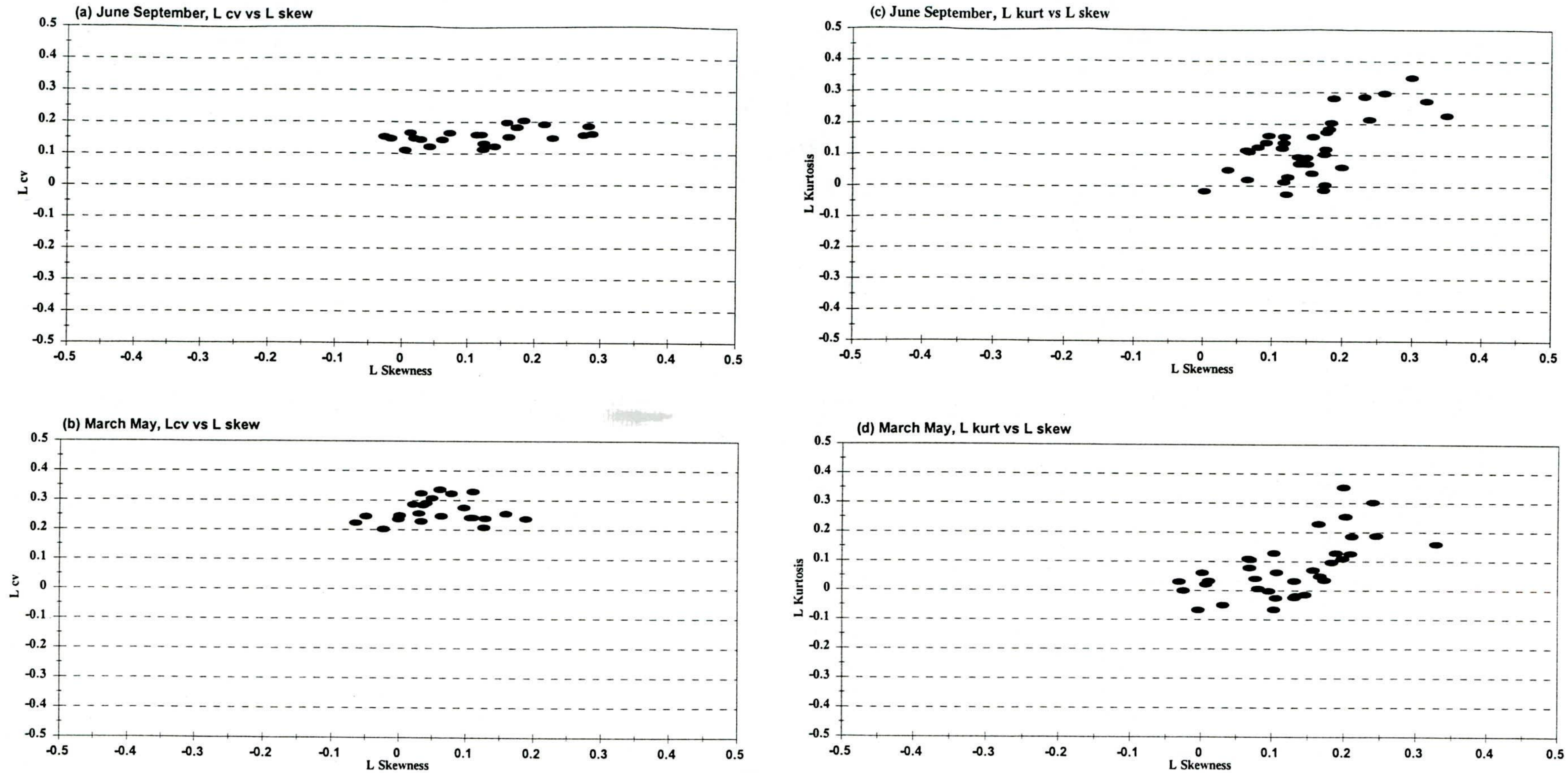

Fig. 4.1 L Moment Ratios of the North Western Regions for (a), (c) Monsoon and (b), (d) Pre-monsoon for the Period 1962-95.

$$\theta_k = \frac{\sum_{j=1}^{n-k} x_j x_{j+1} - \frac{1}{n-k}\left(\sum_{j=1}^{n-k} x_j\right)\cdot\left(\sum_{j=2}^{n} x_j\right)}{\left[\sum_{j=1}^{n-k} x_j^2 - \frac{1}{n-k}\left(\sum_{j=1}^{n-k} x_j\right)^2\right]^{0.5} \cdot \left[\sum_{j=2}^{n} x_j^2 - \frac{1}{n-k}\left(\sum_{j=2}^{n} x_j\right)^2\right]^{0.5}} \tag{4.15}$$

where x_1, x_2,........ x_j are the sucessive daily rainfall values.

4.3.2 Autorun

For the lag-1 Markov process a new parameter c_1, called autorun co-efficient has been defined by Sen (1976) as a conditional probability of an observation, x_l, being greater than the truncation level given that the preceding observation is greater than $x_{0.}$ That is

$$c_1 = P\left[x_i > x_0 \middle| x_{i-1} > x_0\right] \tag{4.16}$$

Eq. (4.16) has been written (Sen 1976) in terms of joint probability of x_i and x_{i-1} as

$$c_1 = \frac{P\left[x_i > x_0, x_{i-1} > x_0\right]}{P\left[x_{i-1} > x_0\right]} \quad \text{or} \quad c_1 = \frac{P\left[x_i > x_0, x_{i-1} > x_0\right]}{p} \tag{4.17}$$

where p is the probability of any day being wet.

The autorun co-efficient has to be estimated from the data. An estimate of c_k can simply be obtained (Sen 1978) by considering the classical definition of probability. In a sequence of n observations there exist (n - k) possible alternatives for two observations lag-k apart being simultaneously greater than x_0. As a result if the number of events ($x_i > x_0$, $x_{i-k} > x_0$) in a given sequence of length n is n_k . Then

$$P\left[x_i > x_0, x_{i-k} > x_o\right] = \frac{n_k}{n-k} \tag{4.18}$$

and it can be written (Sen 1978) as

$$c_k = \frac{P[x_i > x_0, x_{i-k} > x_0]}{p} \tag{4.19}$$

Hence

$$c_k = \frac{n_k}{p(n-k)} \tag{4.20}$$

4.3.3 Autocorrelation by Autorun

When the generating mechanism of observations is of Markovian nature, then the joint probability of two successive observations being greater than the given value is given by Sheppard (1900) as

$$P[x_i > x_0, x_{i-k} > x_o] = \frac{1}{4} + \frac{1}{2\pi} \arcsin \rho_k \tag{4.21}$$

in which ρ_k = lag-k autocorrelation co-efficient by autorun.

Eq. (4.21) can be written as (Sen 1976)

$$P[x_i > x_0 | \; x_{i-k} > x_o] = \frac{1}{2} + \frac{1}{\pi} \arcsin \rho_k \tag{4.22}$$

and thus Eq. (4.22) can be rewritten in terms of r_k as (Sen 1976)

$$\rho_k = \sin\pi(c_k - 0.5) \tag{4.23}$$

c_k is calculated by using Eq. (4.20)

4.3.4 Analysis, Results, and Discussion

In order to show the efficiency of autorun analysis, daily rainfall data for monsoon season (June September) and pre-monsoon season (March May) have been selected for 35 stations. The classical autocorrelations, autoruns, and autorun autocorrelations are obtained by using the Eqs. (4.15), (4.20), and (4.23) respectively. In order to show the applicability of the autoruns over other two coefficients, Tables 4.3 and 4.4 have been obtained for lag-1 and the maximums and minimums of those co-efficients in between lag-1 and lag-20. As suggested in Sen (1978), it is interesting to notice from Eq. (4.15) that when $c_k > 0.5$ then $\rho_k > 0$, the neighbouring observations tend to yield clusters of surpluses, when $c_k < 0.5$, then $\rho_k < 0$, and there will be a lack of clustering. For Markov model, those stations whose p_k values are less than 0.0, can not be used. Sample plot of all the above co-efficients for one station is shown in Fig. 4.2. From the figure it is seen that for rainy season lag-1 autorun coefficients have values equal or above 0.5. Whereas for premonsoon these values are less than 0.5 except two station. For this reason the later analysis are performed only for monsoon season. Autorun co-efficient is distribution free and does not distort the dependence structure of the original process (Sen 1978). From the figure it is seen that for rainy season autorun coefficients for almost all stations are more persistent whereas for pre-monsoon season more fluctuating in nature and also autorun co-efficients for monsoon season are greater than that of pre-monsoon season.

Table 4.3 Classical Autocorrelations, Autorun Autocorrelations and Autorun coefficients for Lag-1 and Maximum and Minimum in Lag-1 to Lag-20 for Monsoon

Station	Autocorrelation (Classical)			Autocorrelation (Autorun)			Autorun		
	Lag-1	Maximum	Minimum	Lag-1	Maximum	Minimum	Lag-1	Maximum	Minimum
R161	0.22	0.22	-0.08	0.47	0.47	0.05	0.66	0.66	0.52
R193	0.21	0.21	-0.06	0.24	0.24	-0.25	0.58	0.58	0.42
R167	0.24	0.24	-0.07	0.58	0.58	0.13	0.70	0.70	0.54
R177	0.22	0.22	-0.06	0.68	0.68	0.35	0.74	0.74	0.61
R159	0.34	0.34	-0.08	0.59	0.59	0.00	0.70	0.70	0.50
R182	0.25	0.25	-0.05	0.45	0.45	-0.16	0.65	0.65	0.45
R163	0.28	0.28	-0.07	0.53	0.53	-0.10	0.68	0.68	0.48
R179	0.15	0.15	-0.07	0.34	0.34	-0.22	0.61	0.61	0.43
R213	0.26	0.26	-0.06	0.51	0.51	-0.03	0.67	0.67	0.49
R168	0.20	0.20	-0.07	0.50	0.50	0.05	0.67	0.67	0.52
R196	0.18	0.18	-0.07	0.21	0.21	-0.55	0.57	0.57	0.32
R164	0.17	0.17	-0.05	0.26	0.26	-0.18	0.59	0.59	0.45
R188	0.29	0.29	-0.10	0.66	0.66	0.06	0.73	0.73	0.52
R178	0.22	0.22	-0.07	0.47	0.47	-0.09	0.66	0.66	0.47
R206	0.22	0.22	-0.07	0.68	0.68	0.16	0.74	0.74	0.55
R153	0.20	0.20	-0.06	0.38	0.38	-0.13	0.62	0.62	0.46
R186	0.29	0.29	-0.06	0.44	0.44	-0.39	0.65	0.65	0.38
R156	0.31	0.31	-0.06	0.46	0.46	-0.17	0.65	0.65	0.45
R181	0.18	0.18	-0.05	0.22	0.22	-0.24	0.57	0.57	0.43
R192	0.19	0.19	-0.05	0.21	0.21	-0.06	0.57	0.57	0.48
R185	0.21	0.21	-0.05	0.43	0.43	-0.26	0.64	0.64	0.42
R003	0.26	0.26	-0.06	0.40	0.40	-0.04	0.63	0.63	0.49
R006	0.25	0.25	-0.06	0.49	0.49	0.07	0.67	0.67	0.53
R033	0.22	0.22	-0.06	0.40	0.40	0.08	0.63	0.63	0.53
R158	0.27	0.27	-0.02	0.32	0.32	-0.22	0.60	0.60	0.43
R215	0.21	0.21	-0.03	0.19	0.19	-0.36	0.57	0.57	0.39
R219	0.19	0.19	-0.05	-0.02	-0.02	-0.47	0.49	0.49	0.35
R205	0.20	0.20	-0.05	0.49	0.49	0.10	0.67	0.67	0.53
R036	0.24	0.24	-0.06	0.20	0.20	-0.37	0.57	0.57	0.38
R184	0.19	0.19	-0.06	0.32	0.32	-0.18	0.61	0.61	0.44
R011	0.22	0.22	-0.07	0.45	0.45	-0.07	0.65	0.65	0.48
R034	0.17	0.17	-0.06	0.49	0.49	0.10	0.66	0.66	0.53
R039	0.17	0.17	-0.07	0.17	0.17	-0.22	0.55	0.55	0.43
R001	0.21	0.21	-0.05	0.46	0.46	0.08	0.65	0.65	0.53
R004	0.23	0.23	-0.07	0.28	0.28	-0.23	0.59	0.59	0.43
Average	**0.01**	**0.22**	**-0.06**	**0.40**	**0.40**	**-0.11**	**0.63**	**0.63**	**0.47**
Maximum	**0.34**	**0.34**	**-0.02**	**0.68**	**0.68**	**0.35**	**0.74**	**0.74**	**0.61**
Minimum	**0.15**	**0.15**	**-0.10**	**-0.02**	**-0.02**	**-0.55**	**0.49**	**0.49**	**0.32**

Table 4.4 Classical Autocorrelations, Autorun Autocorrelations and Autorun coefficients for Lag-1 and Maximum and Minimum in Lag-1 to Lag-20 for Premonsoon

Station	Autocorrelation (Classical)			Autocorrelation (Autorun)			Autorun		
	Lag-1	Maximum	Minimum	Lag-1	Maximum	Minimum	Lag-1	Maximu	Minimum
R161	0.13	0.13	-0.05	-0.34	-0.34	-0.88	0.39	0.39	0.16
R193	0.11	0.11	-0.04	-0.58	-0.58	-0.90	0.30	0.30	0.14
R167	0.15	0.15	-0.02	-0.14	-0.14	-0.80	0.45	0.45	0.21
R177	0.20	0.20	0.00	0.09	0.09	-0.68	0.53	0.53	0.26
R159	0.25	0.25	-0.01	0.02	0.02	-0.69	0.51	0.51	0.26
R182	0.16	0.16	0.00	-0.10	-0.10	-0.72	0.47	0.47	0.24
R163	0.13	0.17	0.02	-0.11	-0.11	-0.75	0.46	0.46	0.23
R179	0.10	0.10	-0.02	-0.30	-0.30	-0.82	0.40	0.40	0.19
R213	0.12	0.12	-0.02	-0.37	-0.37	-0.88	0.38	0.38	0.16
R168	0.14	0.14	-0.04	-0.40	-0.40	-0.86	0.37	0.37	0.17
R196	0.17	0.17	-0.03	-0.30	-0.30	-0.94	0.40	0.40	0.11
R164	0.13	0.13	-0.02	-0.30	-0.30	-0.90	0.40	0.40	0.14
R188	0.19	0.19	-0.01	0.02	0.02	-0.75	0.51	0.51	0.23
R178	0.17	0.17	0.01	-0.21	-0.21	-0.77	0.43	0.43	0.22
R206	0.15	0.15	-0.01	-0.03	-0.03	-0.67	0.49	0.49	0.26
R153	0.12	0.12	-0.04	-0.27	-0.27	-0.80	0.41	0.41	0.21
R186	0.18	0.18	-0.04	-0.23	-0.23	-0.84	0.43	0.43	0.18
R156	0.18	0.18	-0.02	-0.19	-0.19	-0.76	0.44	0.44	0.23
R181	0.05	0.08	-0.04	-0.62	-0.62	-0.93	0.29	0.29	0.12
R192	0.07	0.07	-0.04	-0.58	-0.58	-0.91	0.30	0.30	0.13
R185	0.03	0.03	-0.03	-0.70	-0.70	-0.96	0.25	0.25	0.09
R003	0.11	0.11	-0.04	-0.43	-0.43	-0.93	0.36	0.36	0.12
R006	0.11	0.11	-0.05	-0.34	-0.34	-0.86	0.39	0.39	0.17
R033	0.04	0.08	-0.03	-0.40	-0.40	-0.85	0.37	0.37	0.18
R158	0.00	0.01	-0.03	-0.86	-0.80	-1.00	0.17	0.20	0.00
R215	0.06	0.06	-0.03	-0.70	-0.70	-1.00	0.25	0.25	0.00
R219	0.06	0.06	-0.05	-0.76	-0.76	-0.96	0.22	0.22	0.09
R205	0.06	0.06	-0.05	-0.44	-0.44	-0.91	0.35	0.35	0.14
R036	0.04	0.04	-0.03	-0.70	-0.70	-0.94	0.25	0.25	0.11
R184	0.07	0.07	-0.04	-0.62	-0.62	-0.96	0.29	0.29	0.09
R011	0.07	0.10	-0.03	-0.49	-0.49	-0.89	0.34	0.34	0.15
R034	0.10	0.10	-0.03	-0.27	-0.27	-0.75	0.41	0.41	0.23
R039	0.07	0.07	-0.04	-0.44	-0.44	-0.91	0.35	0.35	0.13
R001	0.13	0.13	-0.04	-0.34	-0.34	-0.81	0.39	0.39	0.20
R004	0.11	0.11	-0.04	-0.43	-0.43	-0.84	0.36	0.36	0.18
Average	**0.11**	**0.12**	**-0.03**	**-0.37**	**-0.37**	**-0.85**	**0.37**	**0.38**	**0.16**
Maximum	**0.25**	**0.25**	**0.02**	**0.09**	**0.09**	**-0.67**	**0.53**	**0.53**	**0.26**
Minimum	**0.00**	**0.01**	**-0.05**	**-0.86**	**-0.80**	**-1.00**	**0.17**	**0.20**	**0.00**

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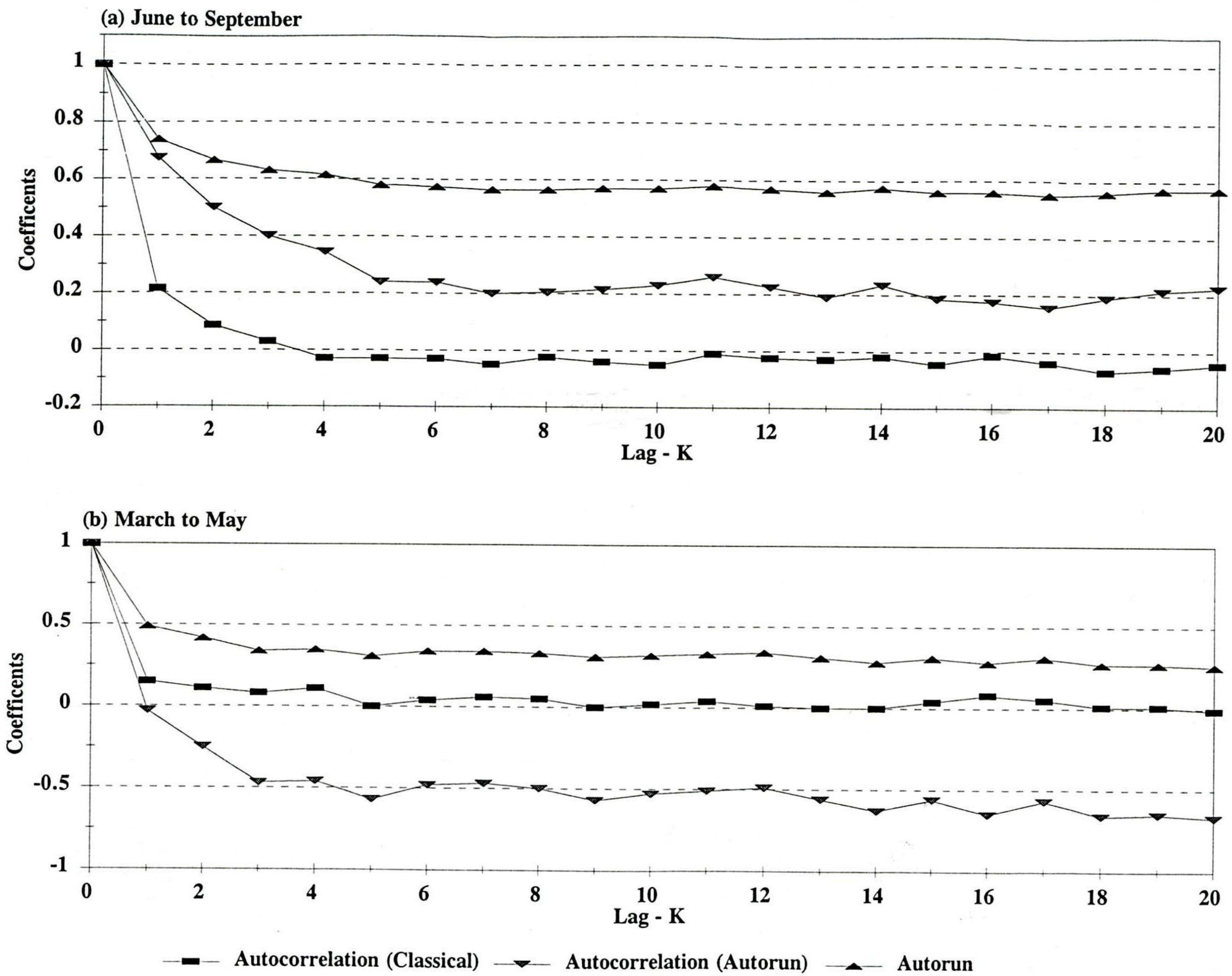

Fig. 4.2 Autocorrelations and Autorun Functions for the Season (a) June to September and (b) March to May for Rangpur (R206), Rangpur

Chapter 5
Rainfall Analysis by Stochastic Model

5.1 Stochastic Process

Sequences characterized by statistical properties are called stochastic processes. A stochastic process is the mathematical abstraction of an empirical process, with its development governed by probability laws. Nearly all hydrologic processes can be characterized as stochastic process, or as a combination of deterministic and stochastic process (Yevjevich 1972, pp. 4).

The stochastic behavior of the longest dry and wet spells can be predicted using theory of runs, where Poisson probability density function for the occurrence of spells, geometric distribution for the length of spells and Weibull, Normal, Lognormal and Gamma distributions for the total rain over a wet spell (designated as rain-sum) are coupled. A day with a rainfall more than a given reference value x_0 designated as a wet day and one with rainfall less than x_0 be designated as dry day. If a time series of daily rainfall (x) during a season is plotted, events of uninterrupted wet and dry spells will emerge along the time axis. In a season of N days there will occur runs of dry and wet days. The number of these spells are designated as N_w (wet) and N_d (dry). A wet or dry spell shall last for L_w or L_d days and the duration of a spell is known as the length of run or spell. L_w or L_d days take on values 1,2,3,....,j (Fig. 5.1).

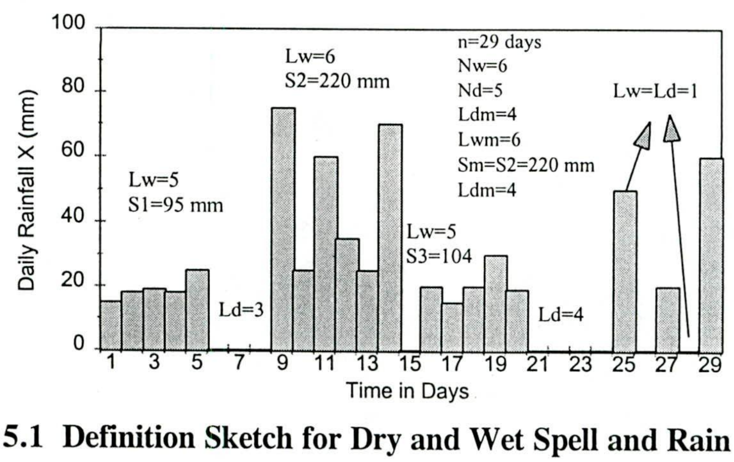

Fig. 5.1 Definition Sketch for Dry and Wet Spell and Rain Sum

Spell which has longest L_w and L_d designated as L_{wm} and L_{dm} respectively. For water harvesting and runoff prediction purposes interest lies in the largest rain-sum designated as S_m. This analysis can be carried by using only five parameters namely p, pp, qq, μ and σ^2, where p is the probability of any day being a wet day, pp is the probability of a wet day followed by the previous wet day, qq is the probability of a dry day followed by the previous dry day, μ is the mean and σ^2 is the variance of daily rainfall sequences.

The phenomena of dry and wet spells are random. At times the level of persistence may be negligible and such processes are independent. If level of persistence is high, such processes are termed as dependent. One powerful model to describe the persistence is that of Markov process of order one, in which today's state is dependent only up to one day behind. The degree of persistence is quantified through conditional probability or lag-1serial correlation co-efficient. So, two models will be described, one is under Markov process and the other one under random independent process (Random model).

Primary condition for develop a model and frequency analysis of data series is that data series should be homogeneous over time. This implies that the sequence of data in the time series must random and free from trend and shift. The requirement of homogeneity arises from the condition that the sample events are to be from the same population. Non homogeneous data series should be appropriately adjusted to make it suitable for analysis. Some common causes of non-homogeneity are relocating gages, deforestation or urbanization, etc. The homogeneity of time series can be checked qualitatively by visual inspection of time series and quantitative statistical test for randomness, independence and stationary. A number of parametric and non parametric tests for trend have been suggested by Salas (1993) such as Mann-Kendall test for trend and Mann-Whitney test for shift in the mean. In this study data series assumed to be free from trend, shift or jump.

5.2 Markov Model

Lag-one Markov model is employed to represent the rainfall data. Various important probabilistic and statistical properties of the lag-one Markov process run lengths have been previously derived either by Monte Carlo techniques on digital computers or by approximate analytical expressions.

5.2.1 Probability Density Function of the Occurrences

The distribution of occurrences of the wet or dry spells can be regarded as following the well-known Poisson distribution (Gupta and Duckstein 1975; Sen 1980a). Probability density functions for this process with an average rate of occurrences equal to np(1 - pp) under Markovian dependence can be written as (Sen 1980a);

$$P(N_w = i) = \frac{\exp[\ -np(1-pp)\ ][\ -np(1-pp)\ ]^i}{i!} \tag{5.1}$$

where P (N_W = i) is the probability of number of wet spell equal to particular value i; n is the sample size in a particular season.

5.2.2 Distribution of Length of Run

Likewise the distribution of length of the run can be modeled using geometric distribution (Sen 1980a; Bogardi et al. 1988). The probability of positive run length to be equal or greater than j (Feller 1957) is

$$P(L_w > j) = P(j^+) + \sum_{k=1}^{\infty} P(k^-, j^+) \tag{5.2}$$

in which $P(j^+)$ = the probability that all of the successive j variables are simultaneously positive; and $P(k^-, j^+)$ = the joint probability of simultaneous occurrence of j positives to be followed by k negative values (i.e. wet day followed by dry day). Generally, the computation of $P(k^-,j^+)$ can be achieved through the multiple integration of the joint probability density function (pdf) of variables, x_1, x_2, x_3, ...,x_k, x_{k+1},......,x_{k+j}, which can be written as:

$$P(k^-, j^+) = \int_{-\infty}^{x_0} \cdots\cdots \int_{-\infty}^{x_0} \int_{x_0}^{+\infty} \cdots\cdots \int_{x_0}^{+\infty} f(x_1, x_2, x_3, \cdots\cdots, x_k, x_{k+1}, \cdots$$

$$\cdots\cdots, x_{k+j})dx_1 dx_2 dx_3 \cdots\cdots dx_k dx_{k+1} \cdots\cdots dx_{k+j} \tag{5.3}$$

in which $f(x_1, x_2, x_3 \cdots\cdots\cdots x_{k+j})$ =the multiple pdf.

The integration operation has been carried out numerically by Saldarriga and Yevjevich (1970) by employing the characteristics function and tetrachoric series expansion. By assuming rainfall to be normally, independently and identically distributed the multivariate pdf simplifies down to k+j factors, which renders the multiple integration into its simplest form as:

$$P\left(k^-, j^+\right) = \prod_{i=1}^{k} \int_{-\infty}^{x_0} f(x_i)dx_i \prod_{i=k+1}^{i=k+j} \int_{x_0}^{+\infty} f(x_i)dx_i \tag{5.4}$$

or in terms of probabilities

$$P(k^-, j^+) = \prod_{i=1}^{k} P(x_i \le x_0) \prod_{i=k+1}^{k+j} P(x_i > x_0) \tag{5.5}$$

and the same time

$$q = P(x_i \le x_0) = \int_{-\infty}^{x_0} f(x_i)dx_i \quad \text{and} \quad p = 1 - q = P(x_i > x_0) = \int_{x_o}^{+\infty} f(x_i)dx_i \tag{5.6}$$

$$P(k^-, j^+) = \prod_{i=1}^{k} q \prod_{i=k+1}^{k+j} p = p^j q^k \tag{5.7}$$

when k=0, $p(j^+)=p^j$ (5.8)

$$P(L_w > j) = P(j^+) + \sum_{k=1}^{\infty} P(k^-, j^+) \tag{5.9}$$

$$= p^j + qp^j + q^2p^j + q^3p^j + \cdots\cdots\cdots + \infty$$

$$= p^j (1 + q + q^2 + q^3 + \cdots\cdots\cdots + \infty)$$

$$= \frac{p^j}{1-q} = \frac{p^j}{p} = p^{j-1}$$

$$P(L_w > j) = p^{j-1} \tag{5.10}$$

In the light of preceding calculations, it is now possible to use the sequential property. In the lag-one Markov process the current observations is affected by the immediate predecessor of this observation. Therefore, in light of the foregoing equations, the multivariate pdf of variables for the lag-one Markov process becomes:

$$f(x_1, x_2, x_3 \cdots x_{k+j}) = f(x_1) f(x_2 | x_1) \cdots\cdots f(x_{k+j} | x_{k+j-1}) \tag{5.11}$$

substituting this in Eq. (5.3), we obtain

$$P(k^-, j^+) = \int_{-\alpha}^{x_0} f(x_1) \prod_{i=2}^{k} \int_{-\infty}^{x_0} f(x_i | x_{i-1}) dx_i \prod_{i=k+1}^{k+j} \int_{x_0}^{+\infty} f(x_i | x_{k+j-1}) dx_i \tag{5.12}$$

or in terms of probability

$$\begin{aligned} &P(k^-, j^+) = \\ &P(x_1 < x_0) \prod_{i=2}^{k-1} P(x_i < x_0 | x_{i-1} < x_0) P(x_{k+1} > x_0 | x_k < x_0) \prod_{i=k+2}^{k+j} P(x_i > x_0 | x_{i-1} > x_0) \end{aligned} \tag{5.13}$$

The calculation of these multiple integrals for the lag-one Markov process can be reduced to a simpler form, which requires only the integration of the conditional probability of the current value given the previous observation. The conditional probabilities can be written as:

$$P(x_i > x_0 | x_{i-1} > x_0) = \frac{p(x_i > x_0, x_{i-1} > x_0)}{p} \tag{5.14}$$

The plane space of x_i and x_{I-1} can be divided in to four regions as in Fig. 5.2

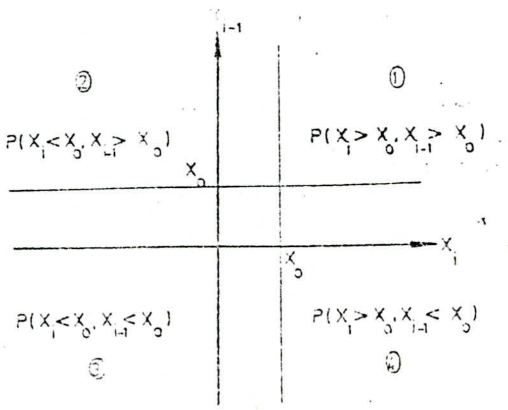

Fig. 5.2 Definition of Four Probability Regions

The relevant relationships among these four regions can simply be seen by employing the basic principles of probability theory (Sen 76). In light of the aforementioned conditional probability and applied algebra Eq. (5.13) can be written as (Sen 1976):

$$P(k^-,j^+) = p(1-pp)\left[1-\frac{p}{q}(1-pp)\right]^{k-1} pp^{j-1} \qquad (5.15)$$

or in the case in which k=0; Eq. (5.15) yields

$$P(j^+)=p\times pp^{j-1} \qquad (5.16)$$

Thus substituting Eqs. (5.15) and (5.16) in to the following equation, we can derive

$$P(L_w > j) = P(j^+) + \sum_{k=1}^{\infty} P(k^-, j^+)$$

$$= p \times pp^{j-1} + p \times pp^{j-1}(1-pp)\sum_{k=1}^{\infty}\left\{1-\frac{p}{q}(1-pp)\right\}^{k-1}$$

$$= p \times pp^{j-1} + p \times pp^{j-1}(1-pp)\left[1+\frac{q-p(1-pp)}{q}+\left\{\frac{q-p(1-pp)}{q}\right\}^2+\cdots+\infty\right]$$

$$= p \times pp^{j-1} + p \times pp^{j-1}(1-pp)\times\frac{1}{1-\dfrac{q-p(1-pp)}{q}}$$

$$= p \times pp^{j-1} + p \times pp^{j-1}(1-pp)\times\frac{q}{p(1-pp)}$$

$$= pp^{j-1}(p+q)$$

$$= pp^{j-1}$$

$\therefore P(L_w > j) = pp^{j-1}$ (5.17)

The longest period of wet and dry spells can be deduced by applying the theorem of extremes of random numbers of a random variable (Todorovic and Woolhiser 1975). The probabilistic relationship for a sample size n to find out the longest period of wet spell can be written as (Sen 1980):

$$P(L_{wm} \le j) = P(N_w = 0) + \sum_{i=1}^{\infty} P(L_w \le j)^i P(N_w = i)$$

$$= \frac{\exp\{-np(1-pp)\}\{np(1-pp)\}^0}{0!} + \sum_{i=1}^{+\infty}(1-pp^{j-1})^i \frac{\exp\{-np(1-pp)\}\{np(1-pp)\}^i}{i!}$$

$$= \exp\{-np(1-pp)\}\left[1 + \frac{np(1-pp)(1-pp^{j-1})}{1!} + \frac{\{np(1-pp)(1-pp^{j-1})\}^2}{2!} + \cdots\cdots + \infty\right]$$

$$= \exp\{-np(1-pp)\}\exp\{np(1-pp)(1-pp^{j-1})\}$$

$$= \exp\{-np(1-pp) + np(1-pp) - np(1-pp)pp^{j-1}\}$$

$$= \exp\{-np(1-pp)pp^{j-1}\}$$

$P(L_{wm} \le j) = \exp\left[-np(1-pp)P(L_w > j)\right]$ (5.18)

and mean, variance, and skewness of L_w are (Sen 76)

$E(L_w) = \dfrac{1}{1-pp}$ (5.19)

$V(L_w) = \dfrac{pp}{(1-pp)^2}$ (5.20)

$\gamma_{L_w} = \dfrac{pp(1-pp)}{pp^{3/2}}$ (5.21)

Similar relationship can be written for dry days but q, qq will be used instead of p, pp.

5.2.3 Distribution of Run Sum

The amount of water over a wet or dry period known as run-sum, is important in water resources system design. One of the main problems in water resources system design is to predict the total amount of water available over an operational period of the project considered. For instance, in reservoir design, if the total amount of water is in excess of the demand, the excess water will be stored, whereas during a deficit period the extraction of water is necessary. Therefore to found out the run-sum, cdf's of largest run-sum were evaluated and compared to their observed counterpart using both Markov and random models in conjunction with Weibull, normal, lognormal and gamma pdf's.

Weibull

The extreme value type III distribution for minimum values is known as the Weibull distribution. This distribution has found its greatest use in hydrology as the distribution of low streamflows. Naturally low flows are bounded by zero on the left.

In the present analysis Weibull probability law (Benjamin and Cornell 1970) has been used for the theorem of the extremes of random numbers to model the rain-sum (S) sequences. Hann (1977) has derived the following relationship

$$P(S > D) = \exp\left[-\left(\frac{D}{b}\right)^{a}\right] \qquad (5.22)$$

where P (S > D) is the probability of rain-sum greater than a particular value D; and a and b are parameters of Weibull distribution and can be estimated using the method of moments. The mean and variance of the distribution are

$$E(S) = b\,\Gamma(1+\frac{1}{a}) \qquad (5.23)$$

$$V(S) = b^2[\ \Gamma(1+\frac{2}{a}) - \Gamma^2(1+\frac{1}{a})\ ] \qquad (5.24)$$

The sequences of S are based on rainy days over wet spells and therefore E(S) and V(S) can be estimated using statistics E(x) and V(x) of the daily rainfall sequence as follows (Sen 1978, 1980; Llamas 1987):

$$E(S) = \frac{\omega E(x)}{p} \tag{5.25}$$

$$V(S) = \left[\frac{pV(x) + qE^2(x)}{p^2}\right] \cdot \left[\omega + 2\rho \frac{\omega(1-\rho) - (1-\rho^{\omega})}{(1-\rho)^2}\right] \tag{5.26}$$

Where ρ is the lag-1 serial correlation co-efficient between daily rainfalls

$$\rho = \sin\pi(pp - 0.5) \tag{5.27}$$

is obtained from Eq. (4.23) and

$$\omega = \frac{1}{1-pp} \tag{5.28}$$

Applying the theorem of the extremes of random numbers of a random variable (Todorovic and Woolhiser 1975), the probabilistic relationship for a sample size n to find out the largest rain-sum value can be written as (Sen 1980a):

$$P(S_m \le D) = P(N_w = 0) + \sum_{i=1}^{\infty} P(S \le D)^i P(N_w = i) \tag{5.29}$$

$$= \frac{\exp\{-np(1-pp)\}\{np(1-pp)\}^0}{0!} + \sum_{i=1}^{+\infty}\left\{\left[1-\exp\left\{-\left(\frac{D}{b}\right)^a\right\}\right]^i \frac{\exp\{-np(1-pp)\}\{np(1-pp)\}^i}{i!}\right\}$$

$$= \exp\{-np(1-pp)\}\left[1 + \frac{np(1-pp)\left[1-\exp\left\{-\left(\frac{D}{b}\right)^a\right\}\right]}{1!} + \frac{\left\{np(1-pp)\left[1-\exp\left\{-\left(\frac{D}{b}\right)^a\right\}\right]\right\}^2}{2!} + \cdots\cdots + \infty\right]$$

$$= \exp\{-np(1-pp)\}\exp\left\{np(1-pp)\left[1-\exp\left\{-\left(\frac{D}{b}\right)^a\right\}\right]\right\}$$

$$= \exp\left[-np(1-pp) + np(1-pp) - np(1-pp)\exp\left\{-\left(\frac{D}{b}\right)^a\right\}\right]$$

$$= \exp\left[-np(1-pp)\exp\left\{-\left(\frac{D}{b}\right)^a\right\}\right]$$

$$\therefore P(S_m \leq D) = \exp[-np(1 - pp)P(S > D)] \quad (5.30)$$

The crucial element of the above equation is the evaluation of P(S>D) which requires identification of the pdf of S. The pdf of S which gives the best correspondence between the observed and predicted cdf's of S_m should be regarded as right one. In the above cdf of Weibull distribution has been shown. The aforesaid cdf's of some other distributions can be written as follows:

Normal

The most widely used and most important continuous probability distribution is the Gaussian or normal distribution. In a strict theoretical sense, most hydrologic variables cannot be normally distributed because the range on any random variable that is normally distributed is the entire real line ($-\infty$ to $+\infty$). Thus non-negative variables such as rainfall, streamflow, reservoir storage, etc., cannot be strictly normally distributed. Since run sum is the sum of different individual values, the sum may be normally distributed. The cdf can be written as:

$$P(S \leq D) = \frac{1}{\sqrt{2\pi}\sigma_s} \int_0^D \exp\left\{-\frac{1}{2}\left(\frac{S - \mu_s}{\sigma_s}\right)^2\right\} dS \quad (5.31)$$

In which μ_s and σ_s are parameters of the distribution and equal to mean E(S) and standard deviation $\sqrt{V(S)}$ of the rain-sum sequence, S. Value of above integration are calculated by using a polynomial given by Chow et al. (1988).

Lognormal

The lognormal distribution has the advantage over the normal distribution that it is bounded for $x > 0$ and the log transformation tends to reduce the positive skewness commonly found in hydrologic data, because taking logarithm reduces large numbers proportionately more than it does small numbers. The cdf can be written as:

$$P(S \le D) = \frac{1}{\sqrt{2\pi\sigma_y}} \int_{\alpha}^{y_D} \exp\left\{-\frac{1}{2}\left(\frac{y-\mu_y}{\sigma_y}\right)^2\right\} dy \tag{5.32}$$

In which y=ln S and y_D=ln D, μ_y and σ_y are the parameters of the distribution and can be evaluated by the following relationships:

$$\sigma_y^2 = \ln\left[\left\{V(S)/E(S)\right\} + 1\right] \tag{5.33}$$

$$\mu_y = \ln\left(E(S) - \frac{\sigma_y^2}{2}\right) \tag{5.34}$$

Gamma

The gamma distribution has a smoothly varying form like the typical probability density function and is useful for describing skewed hydrologic variables without the need for log transformation. It has been applied to describe the distribution of depth of precipitation in storms. The two parameter gamma distribution has a lower bound at zero, which is a disadvantage for application to hydrologic variable that have a lower bound larger than zero. The cdf of gamma distribution function (Hann 77) can be written as:

$$P(S \le D) = \int_0^D \frac{\lambda^\eta S^{\eta-1} e^{-\lambda S}}{\Gamma(\eta)} dS \quad \text{for } S>0 \tag{5.35}$$

In which λ and η are parameters of the distribution and Γ stands for notation of gamma function. Estimation of parameters by the method of moments can be written as

$$\lambda = E(S)/V(S) \tag{5.36}$$

$$\eta = \lambda E(S) \tag{5.37}$$

Values of cdf can be evaluated using Table E.8 (Hann 1977, pp. 342-347).

5.3 Random Model

If the level of persistence is negligible and such process are known as random. For random process in the above equation p will be used instead of pp and $\rho=0$.

Probability Density Function of the Occurrences

$$P(N_w = i) = \frac{\exp\left[-np(1-p)\right]\left[-np(1-p)\right]^{i}}{i!} \tag{5.38}$$

Distribution of Length of Run

$$P(L_w > j) = p^{j-1} \tag{5.39}$$

The longest period of wet spell can be written as:

$$P(L_{wm} \le j) = \exp\left[-np(1-p)P(L_w > j)\right] \tag{5.40}$$

and mean, variance, and skewness of L_w are

$$E(L_w) = \frac{1}{1-p} \tag{5.41}$$

$$V(L_w) = \frac{p}{(1-p)^2} \tag{5.42}$$

$$\gamma_{L_w} = \frac{p(1-p)}{p^{3/2}} \tag{5.43}$$

Distribution of Run Sum

$$P(S_m \le D) = \exp\left[-np(1-p)P(S > D)\right] \tag{5.43}$$

Similar relationship can be written for dry days but q and qq will be used instead of p and pp respectively

5.4 Analysis, Results and Discussions

The analysis requires the estimation of p, pp, qq, E(x) and V(x). Probability p, pp and qq are approximated by estimates of relative frequencies from the data of each season. Different tables are generated to calculate these values, which is given in Tables B.1 to B.35. These parameters are found out by using FORTRAN77 programme (Appendix D). Median values of p, pp and qq are used for this analysis. Values of E(x) and V(x) are estimated using N years of daily rainfall including zero values. $P(S_m \le D)$ are computed by assigning D equal to 0 -1000 mm with a step of 50 mm. The cumulative distribution function (cdf) of the longest wet spell is predicted using Eq. (5.18). The parameters for deriving the cdf's are shown in Table 5.1.

It has been shown by Sharma (1996) for Kenyan rainfall that the chi-square criterion for identifying the dependence structure of the runs is not as powerful as the graphical plot of cdf of the longest dry and wet spells. As such, for our purpose, graphical plots in Figs. C.1 (a, b) to C.35 (a, b) are used to show the simulated and observed cdf's. The close relationship between predicted and observed cdf also suggests that the analysis can be used as a powerful model for longest dry and wet spells. The random model grossly underestimates the observed behavior.

The median, mean and variance values of the longest wet and dry days and largest rain-sum are shown in Table 5.2. It has been observed in Table 5.2 that on average the longest wet spell is 13.65 days for Kaliganj (R177) whereas the average value for dry spells is 16.47 days in Bholhat (R158).

The analysis indicates that Kaliganj have on an average longer rainy days but more fluctuating character than other stations, while Bholahat have longer and more fluctuating dry days (except one station) than other stations.

Table 5.1 Values of Dry and Wet Spells and Rain-Sum Parameters for Monsoon

	p	pp	qq	E(x), mm	V(x), mm^2	a(Markov)	b(Markov)	a(random)	b(random)	MMR, mm(*)
Boda (R161)	0.52	0.66	0.61	15.60	925	0.83	79.69	0.92	59.97	2061
Nekmand (R193)	0.40	0.58	0.71	13.50	736	0.91	75.88	0.87	52.42	1660
Dimla (R167)	0.56	0.70	0.62	16.80	969	0.82	89.77	0.98	67.60	2077
Kaliganj (R177)	0.62	0.74	0.58	14.50	777	0.76	75.34	0.99	60.98	1865
Bhurungamari (R159)	0.51	0.70	0.68	19.15	1019	0.91	119.60	1.03	77.59	2463
Kurigram (R182)	0.49	0.65	0.68	13.75	774	0.83	73.52	0.89	52.09	1731
Chilmari (R163)	0.50	0.68	0.69	11.55	612	0.77	61.54	0.85	42.39	1472
Khansama (R179)	0.46	0.61	0.68	13.65	833	0.83	69.06	0.85	50.41	1756
Setabganj (R213)	0.48	0.67	0.70	12.20	627	0.81	68.75	0.87	45.55	1571
Dinajpur (R168)	0.52	0.67	0.63	11.85	571	0.80	60.04	0.90	45.15	1483
Nawabganj (R196)	0.36	0.57	0.78	11.50	553	0.93	72.68	0.86	46.57	1412
Goraghat (R164)	0.43	0.59	0.69	12.55	629	0.88	65.67	0.89	48.45	1550
Mohipur (R188)	0.56	0.73	0.64	13.85	725	0.78	80.17	0.95	54.86	1746
Kaunia (R178)	0.48	0.66	0.69	14.30	842	0.82	79.48	0.89	54.26	1787
Rangpur (R206)	0.57	0.74	0.65	13.25	762	0.74	74.69	0.91	51.07	1674
Badarganj (R153)	0.46	0.62	0.68	11.25	602	0.81	54.45	0.83	41.11	1430
Mithapukur (R186)	0.40	0.65	0.75	12.30	720	0.83	79.61	0.82	46.20	1603
Bhawaniganj (R156)	0.47	0.65	0.69	10.95	522	0.81	59.42	0.85	40.33	1382
Khetlal (R181)	0.41	0.57	0.69	10.40	467	0.89	55.82	0.86	39.86	1256
Patnitala (R192)	0.47	0.57	0.63	10.00	410	0.87	46.07	0.89	38.04	1233
Manda (R185)	0.40	0.64	0.74	8.20	317	0.83	51.68	0.83	31.01	1023
Atrai (R003)	0.45	0.63	0.69	9.95	318	0.93	58.30	0.95	39.41	1231
Bogra (R006)	0.51	0.67	0.65	10.80	394	0.87	58.91	0.96	42.47	1362
Sherpur (R033)	0.52	0.63	0.57	10.65	449	0.83	50.24	0.91	40.77	1340
Bholhat (R158)	0.43	0.60	0.73	8.70	307	0.89	48.42	0.87	33.18	1138
Shibganj (R215)	0.39	0.57	0.72	8.55	294	0.92	49.02	0.87	33.65	1093
Tanore (R219)	0.34	0.49	0.74	8.55	311	0.97	49.65	0.86	35.33	1070
Rajshahi (R205)	0.53	0.67	0.62	8.90	308	0.82	45.43	0.92	34.27	1095
Singra (R036)	0.39	0.57	0.74	9.85	395	0.92	55.75	0.87	38.59	1265
Lalpur (R184)	0.45	0.61	0.69	9.00	304	0.88	47.28	0.90	34.58	1129
Dhunot (R011)	0.48	0.65	0.67	11.45	463	0.87	63.52	0.93	44.26	1427
Sirajganj (R034)	0.54	0.66	0.61	9.90	385	0.81	48.13	0.92	38.27	1233
Taras (R039)	0.44	0.55	0.69	9.05	365	0.87	43.09	0.84	33.60	1122
Atgharia (R001)	0.52	0.65	0.64	9.45	323	0.84	47.38	0.95	37.04	1214
Bera (R004)	0.42	0.59	0.71	8.65	299	0.88	46.90	0.89	33.60	1079
Average	**0.47**	**0.63**	**0.67**	**11.56**	**552**	**0.85**	**63.00**	**0.90**	**44.71**	**1458**
Maximum	**0.62**	**0.74**	**0.78**	**19.15**	**1019**	**0.97**	**119.60**	**1.03**	**77.59**	**2463**
Minimum	**0.34**	**0.49**	**0.57**	**8.20**	**294**	**0.74**	**43.09**	**0.82**	**31.01**	**1023**

(*) MMR = Mean Monsoon Rainfall

Table 5.2 Statistics for Longest Spell Lengths (Days) and Largest Rain-Sums (mm)

	Median			Mean			Variance			50% Exceed. Prob			% Dev. of Median			80% Exceed. Prob.		
Statn.	L_{wm}	L_{dm}	S_m	L_{wm}	L_{dm}	S_m	L_{wm}	L_{dm}	S_m	L_{wm}	L_{dm}	S_m	L_{wm}	L_{dm}	S_m	L_{wm}	L_{dm}	S_m
R161	9.50	9.00	422	10.18	9.88	431	16.09	10.04	43868	9.00	8.00	350	-5.26	-11.11	-17.13	12.00	10.20	500
R193	7.50	12.00	353	8.26	13.21	371	11.55	15.28	22139	7.00	11.00	250	-6.67	-8.33	-29.16	9.00	14.20	400
R167	10.00	8.00	469	12.97	8.85	524	29.15	10.30	40468	10.60	8.20	400	6.00	2.50	-14.62	13.80	10.50	560
R177	12.00	6.50	395	13.65	7.32	467	33.46	7.22	43377	12.00	7.00	360	0.00	7.69	-8.77	15.80	9.20	550
R159	10.00	10.00	525	11.59	11.35	562	26.95	20.58	41387	10.20	9.60	450	2.00	-4.00	-14.33	13.50	12.60	620
R182	9.50	10.00	361	9.94	10.76	394	13.94	15.30	30795	9.00	8.60	340	-5.26	-14.00	-5.74	11.60	12.50	450
R163	9.50	9.50	368	10.74	11.15	426	17.08	26.48	43422	9.50	9.80	300	0.00	3.16	-18.54	12.40	13.00	450
R179	8.00	11.00	331	8.53	11.59	362	5.96	8.01	14938	8.00	9.80	310	0.00	-10.91	-6.37	10.20	13.00	450
R213	11.00	10.00	395	11.59	13.00	382	21.60	94.53	24307	9.20	10.20	305	-16.36	2.00	-22.72	12.10	13.20	450
R168	10.00	8.50	312	10.24	8.97	359	7.00	8.03	30335	9.20	8.50	280	-8.00	0.00	-10.31	12.00	11.00	400
R196	6.00	13.50	320	7.26	15.29	365	8.61	41.74	49199	7.00	13.80	250	-16.67	2.22	-21.76	9.00	18.00	360
R164	8.00	11.00	290	8.44	13.56	339	11.13	96.66	29969	7.40	10.20	260	-7.50	-7.27	-10.19	9.60	13.00	370
R188	12.00	9.00	426	12.56	10.35	435	25.66	15.40	33527	11.40	8.40	360	-5.00	-6.67	-15.57	15.00	11.00	550
R178	9.00	10.00	391	10.03	11.00	410	13.09	18.88	18463	9.00	10.00	350	0.00	0.00	-10.54	12.00	13.00	500
R206	11.00	9.00	381	12.24	9.18	392	20.94	7.85	29380	11.90	8.60	360	8.18	-4.44	-5.39	15.80	11.00	550
R153	9.00	9.50	322	8.85	10.50	343	6.36	10.78	17795	8.20	9.80	250	-8.89	3.16	-22.29	10.60	13.00	350
R186	8.00	13.00	374	9.47	13.59	423	22.84	26.24	40452	8.40	12.20	340	5.00	-6.15	-9.09	11.00	16.00	470
R156	9.00	10.50	330	9.53	10.68	350	12.54	11.57	32840	9.00	10.00	260	0.00	-4.76	-21.14	11.60	13.00	390
R181	7.00	11.00	244	8.12	12.00	273	11.16	18.65	15113	7.00	10.20	240	0.00	-7.27	-1.46	9.00	13.20	310
R192	8.00	10.00	240	7.76	11.03	237	5.30	18.09	10678	7.00	9.00	200	-12.50	-10.00	-16.81	9.00	11.00	270
R185	8.50	14.00	220	9.41	16.38	262	17.12	64.29	14245	8.20	12.00	220	-3.53	-14.29	0.23	11.00	16.00	305
R003	8.00	10.00	234	8.65	11.85	261	7.35	34.30	11809	8.20	10.20	220	2.50	2.00	-5.80	11.00	13.20	300
R006	10.00	10.00	297	10.06	12.41	307	10.58	182.83	16647	9.40	9.00	250	-6.00	-10.00	-15.91	12.00	11.70	350
R033	9.00	8.00	321	9.59	9.44	315	11.71	25.31	13397	8.80	7.20	250	-2.22	-10.00	-22.06	11.00	9.20	330
R158	8.00	13.50	252	9.38	16.47	295	25.88	115.01	25581	7.80	11.80	200	-2.50	-12.59	-20.73	10.00	15.00	260
R215	7.00	13.00	261	8.35	15.32	274	22.05	67.63	20980	7.00	11.00	180	0.00	-15.38	-31.07	9.00	14.80	250
R219	6.00	13.00	218	6.88	14.29	251	9.34	39.15	14050	7.90	12.20	170	31.67	-6.15	-21.89	7.30	16.00	250
R205	9.00	9.00	219	10.18	9.68	258	9.67	10.98	18456	9.30	8.20	205	3.33	-8.89	-6.26	12.20	11.00	300
R036	6.50	10.00	252	7.18	10.97	257	7.67	12.03	6327	7.00	12.00	220	7.69	20.00	-12.77	9.00	15.80	300
R184	8.00	10.50	234	9.21	11.56	259	16.10	17.89	15921	8.00	10.10	200	0.00	-3.81	-14.66	10.00	13.00	260
R011	9.00	10.00	278	9.03	10.65	291	12.15	14.76	10491	9.00	9.50	250	0.00	-5.00	-10.14	13.60	12.20	350
R034	9.50	8.00	280	9.88	8.74	291	7.40	14.72	14095	9.40	8.00	240	-1.05	0.00	-14.30	12.00	10.00	330
R039	8.00	10.50	232	7.97	10.74	261	9.32	11.14	13071	7.00	10.20	180	-12.50	-2.86	-22.30	9.00	13.40	250
R001	10.00	9.00	231	10.50	9.79	291	14.19	10.22	24315	7.00	8.60	220	-30.00	-4.44	-4.86	12.00	11.00	300
R004	7.00	11.50	247	8.24	11.38	286	10.71	11.24	20980	7.50	11.00	200	7.14	-4.35	-18.93	9.80	14.00	260
Ave	**8.79**	**10.31**	**315**	**9.61**	**11.51**	**343**	**14.62**	**31.80**	**24366**	**8.61**	**9.83**	**269**	**-1.23**	**-4.28**	**-14.38**	**11.25**	**12.80**	**381**
Max	**12.00**	**14.00**	**525**	**13.65**	**16.47**	**562**	**33.46**	**182.83**	**49199**	**12.00**	**13.80**	**450**	**31.67**	**20.00**	**0.23**	**15.80**	**18.00**	**620**
Min	**6.00**	**6.50**	**218**	**6.88**	**7.32**	**237**	**5.30**	**7.22**	**6327**	**7.00**	**7.00**	**170**	**-30.00**	**-15.38**	**-31.07**	**7.30**	**9.20**	**250**
Var	**2.20**	**3.03**	**5987**	**2.62**	**4.66**	**6437**	**52.57**	**1398.71**	**134042836**	**1.90**	**2.34**	**4698**	**95.78**	**48.94**	**56.06**	**4.00**	**4.20**	**10982**

Likewise the cdf of S_m was plotted with the model of run-sum. The parameters for deriving cdf are shown in Table 5.1. The estimation of probabilities $P(S_m \le D)$ for Weibull distribution for various rain-sum values is straightforward (Eq. 5.22). However, such estimation for normal, lognormal and gamma distribution requires integration of Eqs. (5.31), (5.32) and (5.35). Since a rain-sum is the sum of different individual values, the sum should tend to be normally distributed (Sen 1980a; Chander et al. 1981). Sen (1980a) has justified the use of normal pdf based on the argument of the central limit theorem, while Chander et al. (1981) normalized the annual runoff sequences using a power transformation and carried out the entire analysis in the normal probability domain. However, Sharma (1996) indicates the normal pdf to be less satisfactory for modeling rain-sums on a daily basis. Keeping in view the above findings, the present analysis have used Weibull distribution under the Markovian and random structure of occurrence of the monsoon wet spells. Here again the plots (Figs. C.1 (c, d) to C.35 (c, d)) clearly demonstrate the validity of the Markovian persistence as opposed to the random occurrence of the spells. Normal and lognormal pdfs appear to poorly represent the distribution of Sm. The Weibull and gamma pdf can be regarded to compete with each other and fits better. However, percent deviations of Markovian simulated 50 percent exceedances of L_{wm}, L_{dm}, and S_m from the empirical median values of the observed data are shown in Table 5.2. Range of percent deviations are -30 to 32, -15 to 20 and -31 to 0 and average deviations are -1.23, -4.28 and -14.38 for Lwm, Ldm and Sm respectively.

The plots show the remarkable performance of Markov model in predicting the longest wet and dry spells and Markov with Weibull and gamma models in predicting the largest rain-sum for Bangladeshi rainfall. Since for gamma model the integration of Eq. 5.35 is tedious, the Markov-Weibull model has analytical expression and thus, easier to apply for design purpose. The Markov-Weibull model for largest rain-sum can be used to derive the statistics for the design of runoff draining and rain harvesting systems. For example one may chose a value of 550 mm for Rangpur (R206), 350 mm for Dhunot (R011), and 300 mm for Rajshahi (R205) at a 80 percent level of non-exceedance probability for drainage and/or storage systems of the catchment. If a system is to be designed for 50 percent level of exceedance probability then the design parameters are 360, 250, and 205 mm respectively for Rangpur, Dhunot, and Rajshahi. It can be mentioned here that for the design of the above systems, joint probability distribution of the longest dry and wet spells and largest run-sum would provide optimum value. Values of L_{wm}, L_{dm}, and S_m are found out from analysis at different levels of probability and given in Table 5.3 and Figs. C.36 to C.53. From figures one can easily identify through visualisation the critical zones in a region, i.e., which area is comparatively more wet or dry which area is wet or dry. With a specification of probability the amount of water available in monsoon period is also obtained from these figures. From map it is clear that Panchagar, Lalmonirhat, Nilphamari, Kurigram, Sirajganj and Bogra area is more wetter than other area. From Fig. C.48 to C.53 it is clear that upper part of north west region is more wetter that the lower part of north west region. The result is more or less consistent with the isohyetal map given by National Water Management Plan (NWMP). It is seen from drought map prepared by Karim et al. in Kharif season Joypurhat, lower part of Dinajpur, Natore and Chapainawabganj area is more vulnerable than the other area. In Rabi and Pre-Kharif almost lower part of north western region is more drought risk area than the other. By comparing this result in present study there is some difference. From this study more information regarding supplementary irrigation system design is available.

Table 5.3 Values of Lwm, Ldm, and Sm at Different Probability

Districts	Serial No.	Station No.	Station Name	Values at 40 Percent			Values at 50 Percent			Values at 60 Percent			Values at 70 Percent			Values at 80 Percent			Values at 90 Percent		
				Lwm	Ldm	Sm	Lwm	Ldm	Sm	Lwm	Ldm	Sm	Lwm	Ldm	Sm	Lwm	Ldm	Sm	Lwm	Ldm	Sm
Panchagarh	1	R - 161	Boda	8.6	7.5	310	9.0	8.0	350	10.0	8.8	395	10.8	9.2	450	12.0	10.2	500	13.8	12.0	600
Thakurgaon	2	R - 193	Nekmand	6.8	10.2	260	7.0	11.0	250	7.8	12.0	330	8.2	13.0	350	9.0	14.2	400	10.8	16.6	470
Nilphamari	3	R - 167	Dimla	9.8	7.4	355	10.6	8.2	400	11.2	8.7	450	12.2	9.2	500	13.8	10.5	560	16.0	12.0	700
Lalmonirhat	4	R - 177	Kaliganj	11.0	6.7	330	12.0	7.0	360	13.0	7.8	420	14.0	8.2	480	15.8	9.2	550	18.0	10.6	660
Kurigram	5	R - 159	Bhurungamari	9.3	9.0	405	10.2	9.6	450	11.0	10.4	495	12.0	11.4	550	13.5	12.6	620	15.6	14.5	750
	6	R - 182	Kurigram	8.3	9.0	290	9.0	8.6	340	9.6	10.4	350	10.4	11.2	400	11.6	12.5	450	13.0	14.5	550
	7	R - 163	Chilmari	8.8	9.0	255	9.5	9.8	300	10.4	10.7	330	11.2	11.8	380	12.4	13.0	450	14.2	15.0	540
Dinajpur	8	R - 179	Khanshama	7.3	9.0	270	8.0	9.8	310	8.6	10.6	350	9.2	11.4	400	10.2	13.0	450	12.0	14.4	530
	9	R - 213	Setabganj	8.6	9.2	260	9.2	10.2	305	10.2	11.0	350	11.0	12.0	400	12.1	13.2	450	14.0	15.5	550
	10	R - 168	Dinajpur	8.8	7.9	250	9.2	8.5	280	10.2	9.2	315	11.0	10.0	350	12.0	11.0	400	14.0	13.0	500
	11	R - 196	Nawabganj	6.4	12.7	245	7.0	13.8	250	7.2	15.0	290	8.0	16.2	320	9.0	18.0	360	10.0	21.0	350
	12	R - 164	Goraghat	7.0	9.3	250	7.4	10.2	260	8.0	11.0	300	8.8	12.0	350	9.6	13.0	370	11.0	15.0	450
Rangpur	13	R - 188	Mohipur	10.7	7.9	330	11.4	8.4	360	12.4	9.1	410	13.8	10.0	450	15.0	11.0	550	17.0	13.0	650
	14	R - 178	Kaunia	8.6	9.2	315	9.0	10.0	350	9.9	11.0	390	10.8	12.0	450	12.0	13.0	500	14.0	15.0	600
	15	R - 206	Rangpur	11.0	8.0	330	11.9	8.6	360	13.0	9.2	415	14.0	10.0	480	15.8	11.0	550	18.0	13.0	670
	16	R - 153	Badarganj	7.4	9.1	230	8.2	9.8	250	9.0	10.6	270	9.8	11.4	310	10.6	13.0	350	12.0	14.6	440
	17	R - 186	Mithapukur	7.8	11.2	290	8.4	12.2	340	9.0	13.2	350	10.0	14.6	400	11.0	16.0	470	12.6	19.0	570
Gaibandha	18	R - 156	Bhawaniganj	8.2	9.2	245	9.0	10.0	260	9.4	11.0	300	10.3	12.0	350	11.6	13.0	390	13.0	15.0	450
Jaipurhat	19	R - 181	Khetlal	6.6	9.4	205	7.0	10.2	240	7.8	11.0	250	8.2	12.0	280	9.0	13.2	310	10.5	15.0	370
Naogaon	20	R - 192	Patnitala	6.9	8.1	170	7.0	9.0	200	7.8	9.2	220	8.2	10.0	250	9.0	11.0	270	10.4	13.0	340
	21	R - 185	Manda	7.6	11.0	190	8.2	12.0	220	9.0	13.0	250	10.0	14.0	270	11.0	16.0	305	12.5	18.0	380
	22	R - 003	Atrai	7.8	8.4	200	8.2	10.2	220	9.0	11.0	250	10.0	12.0	270	11.0	13.2	300	12.2	15.0	350
Bogra	23	R - 006	Bogra	8.6	8.2	220	9.4	9.0	250	10.2	9.6	250	11.0	10.4	300	12.0	11.7	350	14.0	13.4	400
	24	R - 033	Sherpur	8.0	7.0	210	8.8	7.2	250	9.2	7.9	250	10.0	8.6	280	11.0	9.2	330	13.0	10.6	395
Chapai N. ganj	25	R - 158	Bholahat	7.2	11.0	170	7.8	11.8	200	8.4	12.8	215	9.0	14.0	250	10.0	15.0	260	11.7	18.0	320
	26	R - 215	Shibganj	6.4	10.4	160	7.0	11.0	180	7.2	12.1	205	8.0	13.2	230	9.0	14.8	250	10.2	17.0	300
Rajshahi	27	R - 219	Tanore	5.2	11.2	150	7.9	12.2	170	6.2	13.2	190	7.0	14.6	220	7.3	16.0	250	8.6	19.0	280
	28	R - 205	Rajshahi	9.0	7.8	170	9.3	8.2	205	10.2	9.0	240	11.0	9.8	260	12.2	11.0	300	14.0	12.0	350
Natore	29	R - 036	Singra	6.6	11.0	195	7.0	12.0	220	7.2	13.0	240	8.0	14.0	260	9.0	15.8	300	10.2	18.0	350
	30	R - 184	Lalpur	7.2	9.2	160	8.0	10.1	200	8.6	11.0	220	9.2	12.0	250	10.0	13.0	260	11.9	15.3	320
Sirajganj	31	R - 011	Dhunot	8.2	9.0	240	9.0	9.5	250	9.4	10.2	290	10.4	11.2	320	13.6	12.2	350	13.0	14.0	440
	32	R - 034	Sirajganj	8.7	7.2	205	9.4	8.0	240	10.2	8.6	250	11.0	9.4	280	12.0	10.0	330	14.0	11.8	400
	33	R - 039	Taras	6.6	9.2	170	7.0	10.2	180	7.2	11.0	205	8.0	12.0	240	9.0	13.4	250	10.0	15.0	300
Pabna	34	R - 001	Atgharia	8.6	8.0	180	7.0	8.6	220	9.8	9.2	240	11.0	10.0	260	12.0	11.0	300	13.8	13.0	350
	35	R - 004	Bera	7.0	10.0	170	7.5	11.0	200	8.0	11.8	220	8.8	13.0	250	9.8	14.0	260	11.0	16.2	310

Chapter 6

Water Availability and Deficit

6.1 Introduction

Rainfall is a major source of fresh water, responsible for the availability, distribution and consumptive use of surface water and groundwater. It is well known that the annual variation of rainfall is very high all over Bangladesh, where more than 80 percent rainfall occurs in the monsoon period, June to September. It has been reported that there was almost no rainfall in the 1994-95 winter in the study area and its immediate surroundings. To get an idea how severe drought occurred, several objective analyses are done by using daily rainfall data of the study area considered. These daily rainfall data are used to get the monthly and yearly totals. In this regard, the deviation of 1994-95 rainfall from the average year is apparent from the following analyses. Water deficit analysis is essential for irrigation project design where the amount of water available need to be estimated accurately. If the estimate is too large the project features are likely to have been designed larger than optimum and the project might be in financial difficulties. Underestimation may cause under development of potential and consequent wastes of resources.

6.2 Water Availability

Total and average rainfall for each month and each year for the period 1976-96 to 1995-96 are presented in Table 6.1. Monthly total rainfall for each year of records are compared in Fig. 6.1. It has been shown that the highest monthly total rainfall occurs in the months of June and July. On the average, the months November to February, have very low total rainfall. Total rainfall values of each month of 1994-95 and average monthly rainfall for the 20 year period are extracted from Table 6.1 and plotted in Fig. 6.2. It has been shown that for all the months of 1994-95, rainfall is less than the average of the time series (Fig. 6.2). The months of July of 1994-95 and 1987-88 have the lowest (182.5 mm) and highest (1378.6 mm) rainfall, respectively. This figure shows that each month of 1994-95 received less rainfall from average monthly value. Thus it can be said that 1994-95 was a dry year compared to the average year. Percent deviation of monthly total rainfall for each year from

Table 6.1 Total and Average Rainfall (mm) for each Month and each Year for the Period from 1976-77 to 1995-96

Year	April	May	June	July	August	September	October	November	December	January	February	March	Yearly	Deviation (*)	Percent (**)
76-77	74	155	566	884	458	180	40	0	0	0	2	0	2359	9	5.0
77-78	110	408	714	415	395	183	143	43	11	1	7	10	2441	91	5.2
78-79	149	254	468	466	176	456	46	18	0	3	11	0	2047	-302	4.4
79-80	30	57	150	468	559	478	89	13	15	0	15	26	1900	-450	4.0
80-81	33	325	401	288	605	305	123	0	0	15	6	13	2114	-235	4.5
81-82	139	378	105	600	486	474	0	0	38	0	0	5	2223	-127	4.7
82-83	129	114	616	518	259	330	87	14	0	3	0	45	2115	-235	4.5
83-84	88	388	329	491	282	298	289	0	37	0	6	17	2224	-126	4.7
84-85	114	367	839	728	254	698	202	0	11	1	17	47	3278	928	7.0
85-86	198	191	594	698	268	456	136	0	17	0	0	0	2558	208	5.4
86-87	117	241	442	436	271	468	230	20	4	0	29	102	2360	11	5.0
87-88	64	201	452	1379	525	396	240	0	0	0	28	40	3326	976	7.1
88-89	168	324	364	474	608	523	20	39	0	3	20	2	2544	195	5.4
89-90	0	398	208	706	95	402	75	0	2	0	47	103	2035	-315	4.3
90-91	155	405	391	307	389	543	293	0	0	45	0	15	2542	192	5.4
91-92	52	286	647	189	323	613	119	8	29	17	24	0	2306	-44	4.9
92-93	106	214	320	234	331	472	136	0	3	46	0	35	1896	-453	4.0
93-94	71	195	752	514	554	309	65	34	0	21	24	31	2570	220	5.5
94-95	55	183	409	183	78	188	110	0	0	3	9	2	1218	-1132	2.6
95-96	0	159	358	851	537	875	66	76	3	14	0	0	2938	589	6.3
Sum Total	1852	5243	9123	10829	7453	8643	2508	265	170	170	245	492	46993		
Average	93	262	456	541	373	432	125	13	9	9	12	25	2350		

(*) Deviation of each year rainfall from average for the period 1976-77 to 1995-96

(**) Total rainfall of each year is expressed as percent of total 20 year rainfall

Table 6.2 Percentage Deviations for each Month and each Year Rainfall from Average Monthly and Average Yearly Totals for the Period from 1976-77 to 1995-96

Year	April	May	June	July	August	September	October	November	December	January	February	March	Yearly
76-77	-20	-41	24	63	23	-58	-68	-100	-100	-100	-85	-100	0
77-78	19	56	57	-23	6	-58	14	226	26	-88	-40	-61	4
78-79	61	-3	3	-14	-53	5	-63	34	-100	-65	-13	-100	-13
79-80	-68	-78	-67	-14	50	11	-29	-5	80	-100	24	5	-19
80-81	-64	24	-12	-47	62	-29	-2	-100	-100	74	-49	-46	-10
81-82	50	44	-77	11	30	10	-100	-100	348	-100	-100	-80	-5
82-83	39	-56	35	-4	-30	-24	-31	6	-100	-71	-100	84	-10
83-84	-5	48	-28	-9	-24	-31	131	-100	330	-100	-54	-33	-5
84-85	24	40	84	35	-32	61	61	-100	34	-91	41	92	40
85-86	114	-27	30	29	-28	5	8	-100	103	-100	-100	-100	9
86-87	27	-8	-3	-20	-27	8	83	52	-49	-100	139	314	0
87-88	-31	-23	-1	155	41	-8	92	-100	-100	-100	129	64	42
88-89	82	24	-20	-13	63	21	-84	194	-100	-71	63	-94	8
89-90	-100	52	-54	30	-75	-7	-40	-100	-82	-100	284	319	-13
90-91	68	54	-14	-43	4	26	134	-100	-100	429	-100	-39	8
91-92	-44	9	42	-65	-13	42	-5	-40	241	100	92	-100	-2
92-93	15	-18	-30	-57	-11	9	8	-98	-65	435	-100	40	-19
93-94	-24	-26	65	-5	49	-28	-48	157	-100	147	96	26	9
94-95	-41	-30	-10	-66	-79	-57	-12	-100	-100	-65	-28	-94	-48
95-96	-100	-40	-22	57	44	102	-47	474	-65	65	-100	-100	25

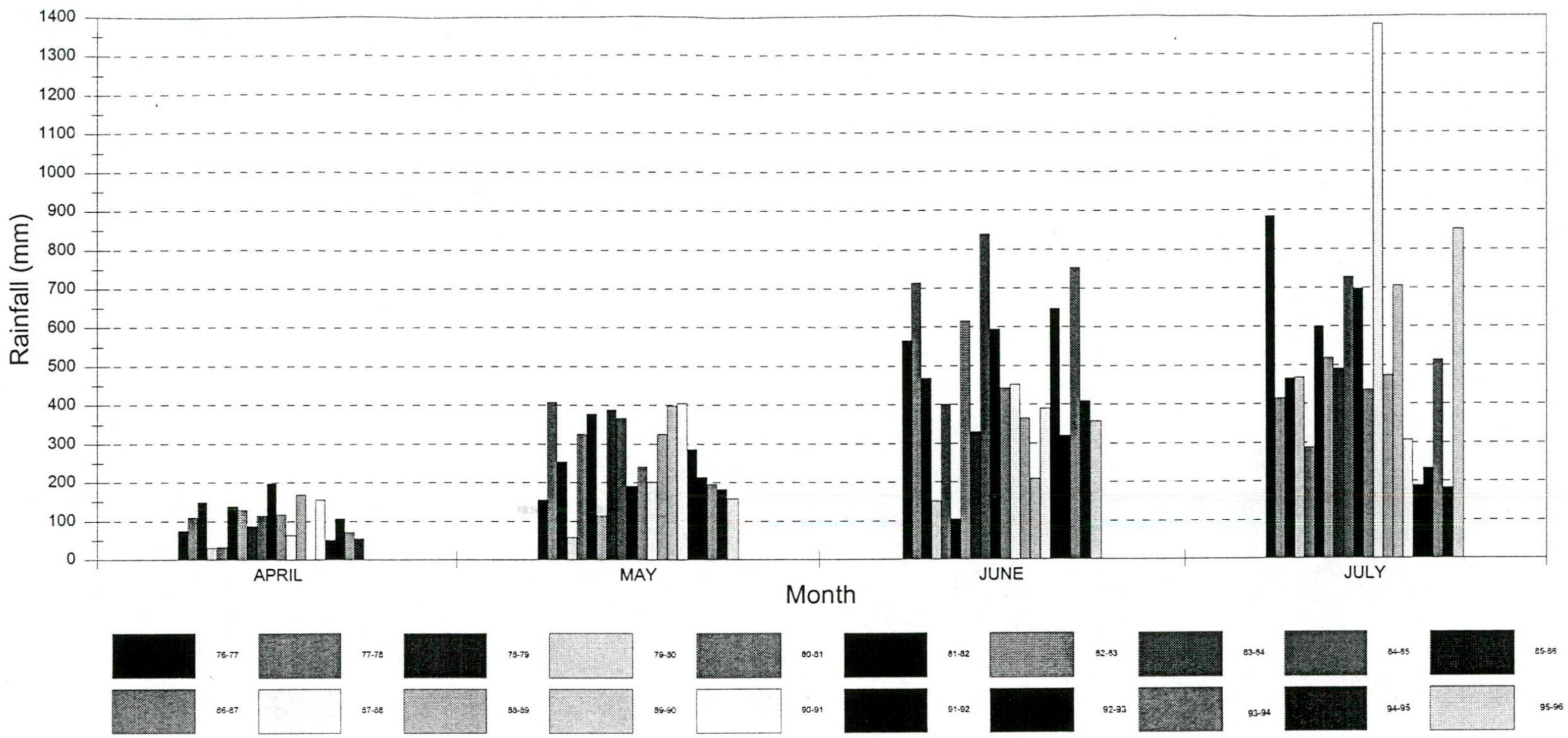

Fig. 6.1 Monthly Total Rainfall (mm) at Rangpur (R206) for the Period 1976-77 to 1995-96

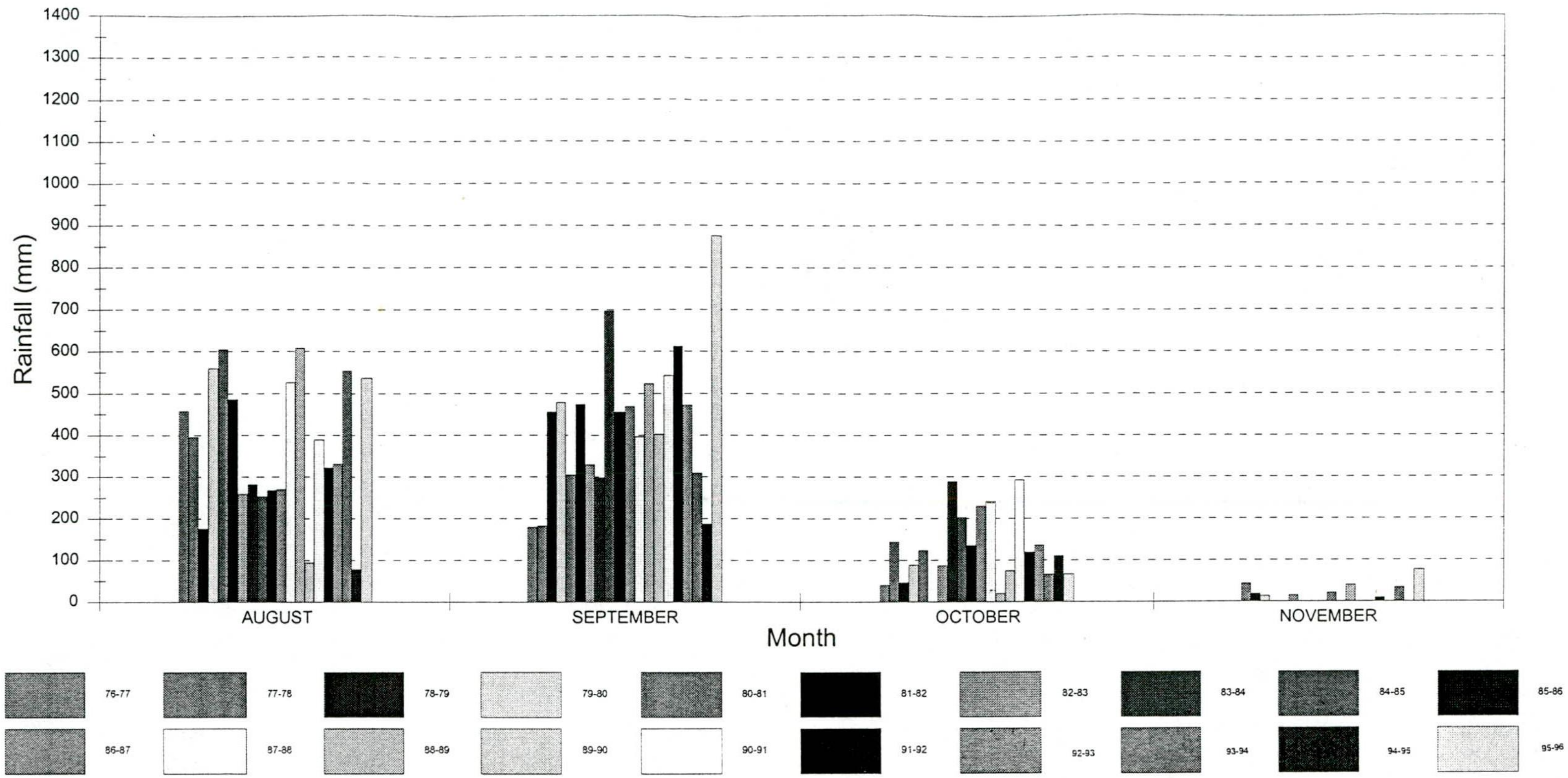

Fig. 6.1 (Continued)

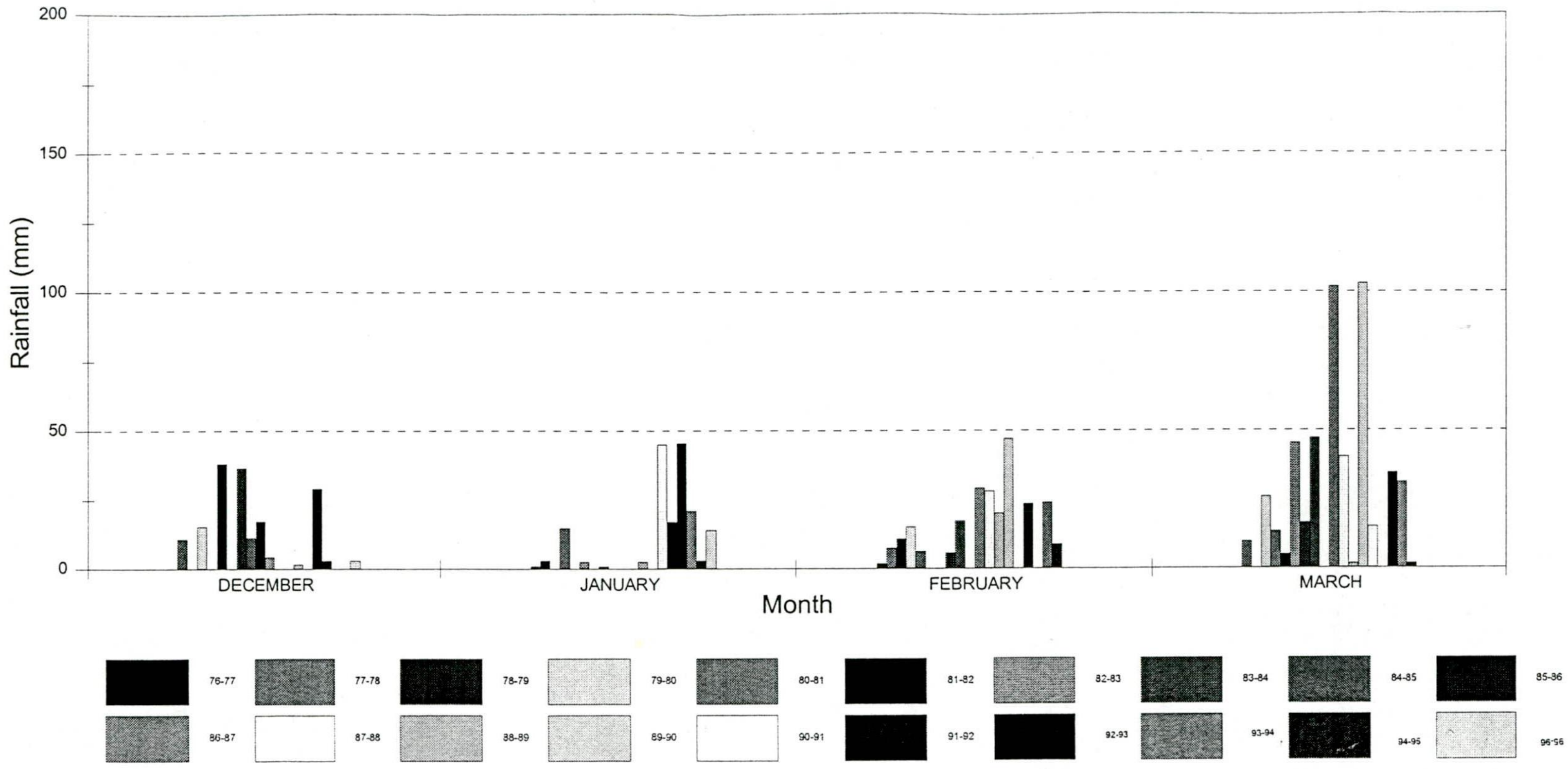

Fig. 6.1 (Continued)

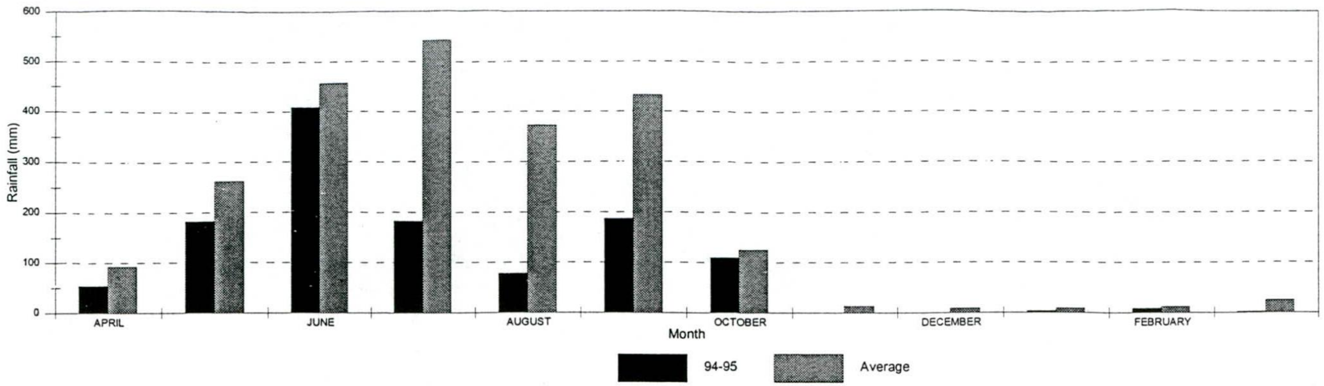

Fig. 6.2 Comparision of Average Monthly Total Rainfall with 1994-95 at Rangpur (R206)

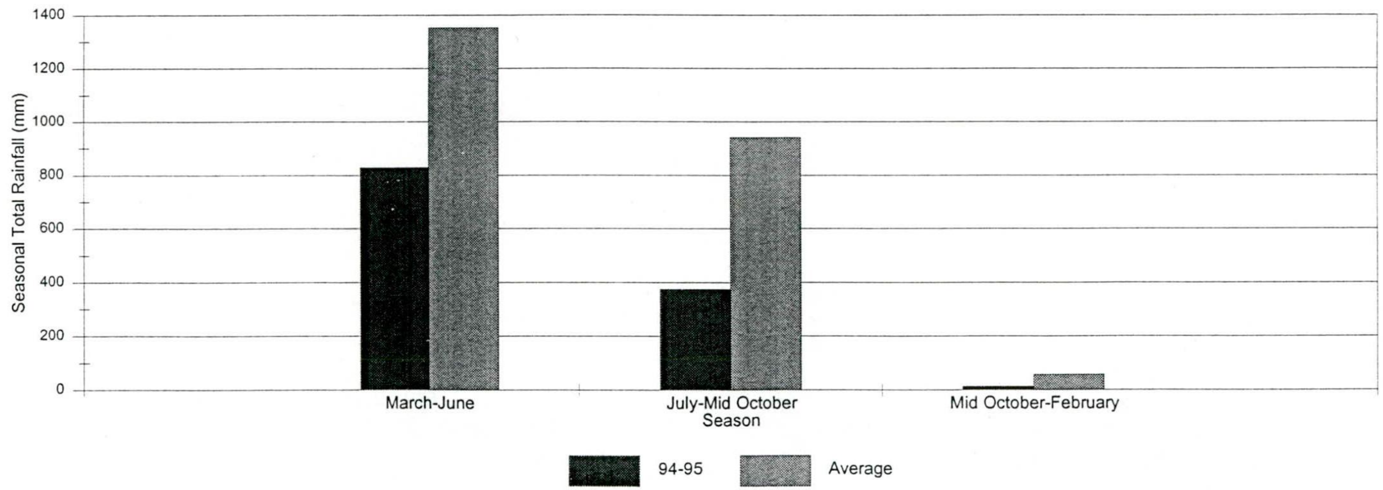

Fig. 6.3 Comparison of Average Seasonal Total Rainfall With 1994-95 at Rangpur (R206)

monthly average rainfall over 1976-77 to 1995-96 are also computed and given in Table 6.2. Percent deviation of yearly total rainfall are also computed. Table 6.2 indicates the highest percent (-48%) deviation of rainfall from the average annual total for the year 1994-95. Seasonal total rainfall for different season are extracted (Table 6.3) for the records 1976-77 to 1995-96. Average and 1994-95 seasonal total rainfall are also extracted and presented in Fig. 6.3. From figure it is seen that for all season of 1994-95 received less rainfall. From Table 6.1 it is seen that total rainfall for the 20 year period is 46,993 mm. Total rainfall for each year is expressed as percent of this 20 year total rainfall and presented in Fig. 6.4. Average year should have around 5 percent contribution in a series of 20 years record. From this figure it is observed total rainfall for in 1994-95 is only about 2.59 percent whereas these values for other year ranges from 4.0 to 7.1 percent. This shows that 1994-95 received much less rainfall. Deviation of yearly total rainfall (mm) from the yearly average value for the 20 year period is shown in Fig. 6.5. It has been seen that 1994-95 has the highest deviation of 1132 mm. Annual number of wet days having rainfall in excess 6 mm and 24 mm for the period 1976-77 to 1995-96 are also extracted and shown in Table 6.4. The number of wet days of 1994-95 are the lowest among the whole record. Frequency histograms are then plotted in Fig. 6.6 separately for days with rainfall > 6mm and day with rainfall > 24 mm. From figure it is seen that for the year 1994-95, frequency of rainfall days greater than or equal to 24 and 6 mm standout at the low end of the distribution indicating that values for these thresholds might be useful drought discriminators. The annual rainfall days greater than or equal to 24 mm depth plotted on a normal probability paper (Fig. 6.7). It indicates that all data appear to be approximated by a normal distribution. It is seen that the drought year 1994-95 stands at the lowest position on the graph. It may be regarded that the drought of 1994-95 comes out as a severe most phenomena.

Table 6.3 Seasonal Total rainfall for the Records 1976-77 to 1995-96

Year	March-June	July-Mid October	Mid October-February	Sum
76-77	1679	678	2	2359
77-78	1648	765	29	2441
78-79	1338	696	14	2047
79-80	705	1125	69	1900
80-81	1047	1033	34	2114
81-82	1221	959	43	2223
82-83	1377	690	48	2115
83-84	1296	870	59	2224
84-85	2048	1153	77	3278
85-86	1681	859	17	2558
86-87	1236	989	135	2360
87-88	2096	1162	68	3326
88-89	1330	1151	63	2544
89-90	1312	571	152	2035
90-91	1258	1225	60	2542
91-92	1173	1063	70	2306
92-93	874	939	83	1896
93-94	1532	962	76	2570
94-95	829	376	13	1218
95-96	1368	1554	17	2938
Average	1352	941	56	2350

Table 6.4 Number of Wet Days Having Rainfall in Excess 6 mm and 24 mm for the Period 1976-77 to 1995-96

Year	Number of Rainfall Days	
	> 24 mm	> 6 mm
76-77	24	52
77-78	33	83
78-79	28	59
79-80	23	57
80-81	30	60
81-82	33	62
82-83	26	70
83-84	31	74
84-85	42	76
85-86	29	66
86-87	34	71
87-88	37	79
88-89	41	70
89-90	28	62
90-91	33	70
91-92	32	64
92-93	22	54
93-94	28	72
94-95	19	48
95-96	26	58

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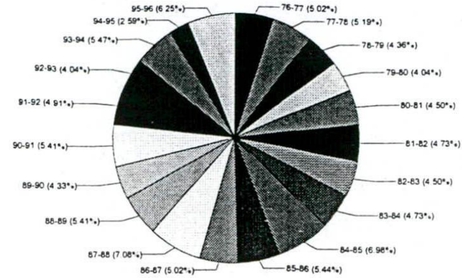

Fig. 6.4 Annual Total Rainfall at Rangpur for the Period 1976-96

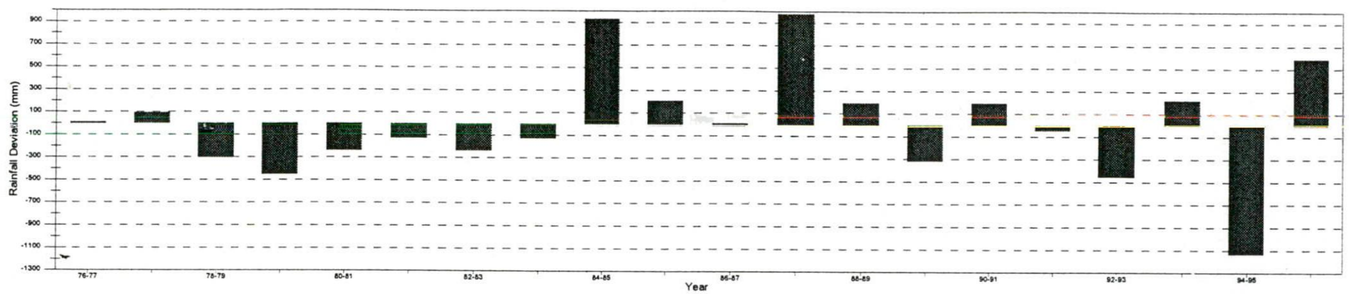

Fig. 6.5 Annual Total Rainfall Deviation from Average for the Period 1976-96 at Rangpur (R206)

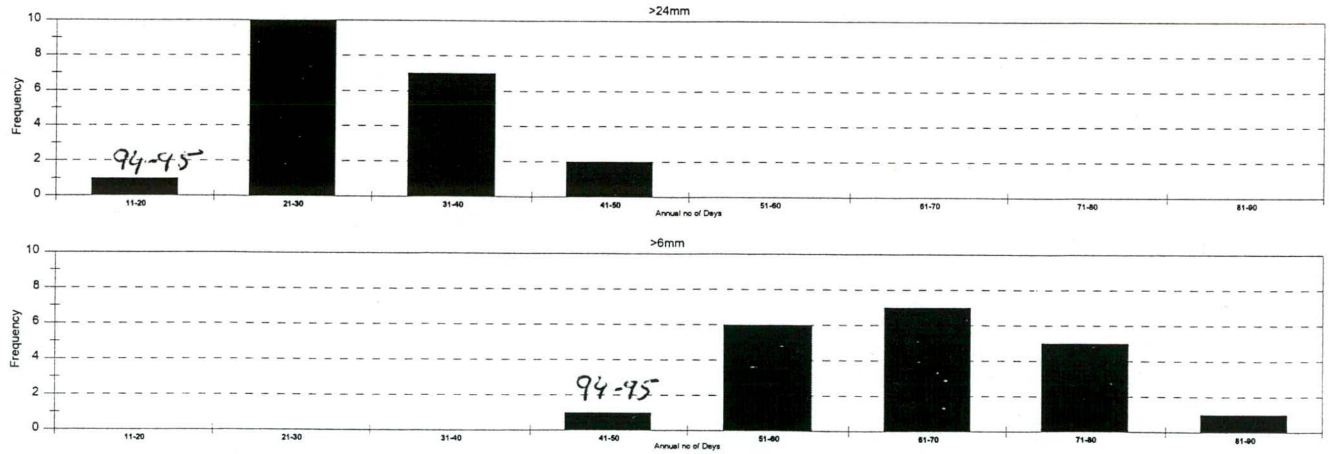

Fig. 6.6 Distribution of Annual Number of Wet Days at Rangpur for the Period 1976-96

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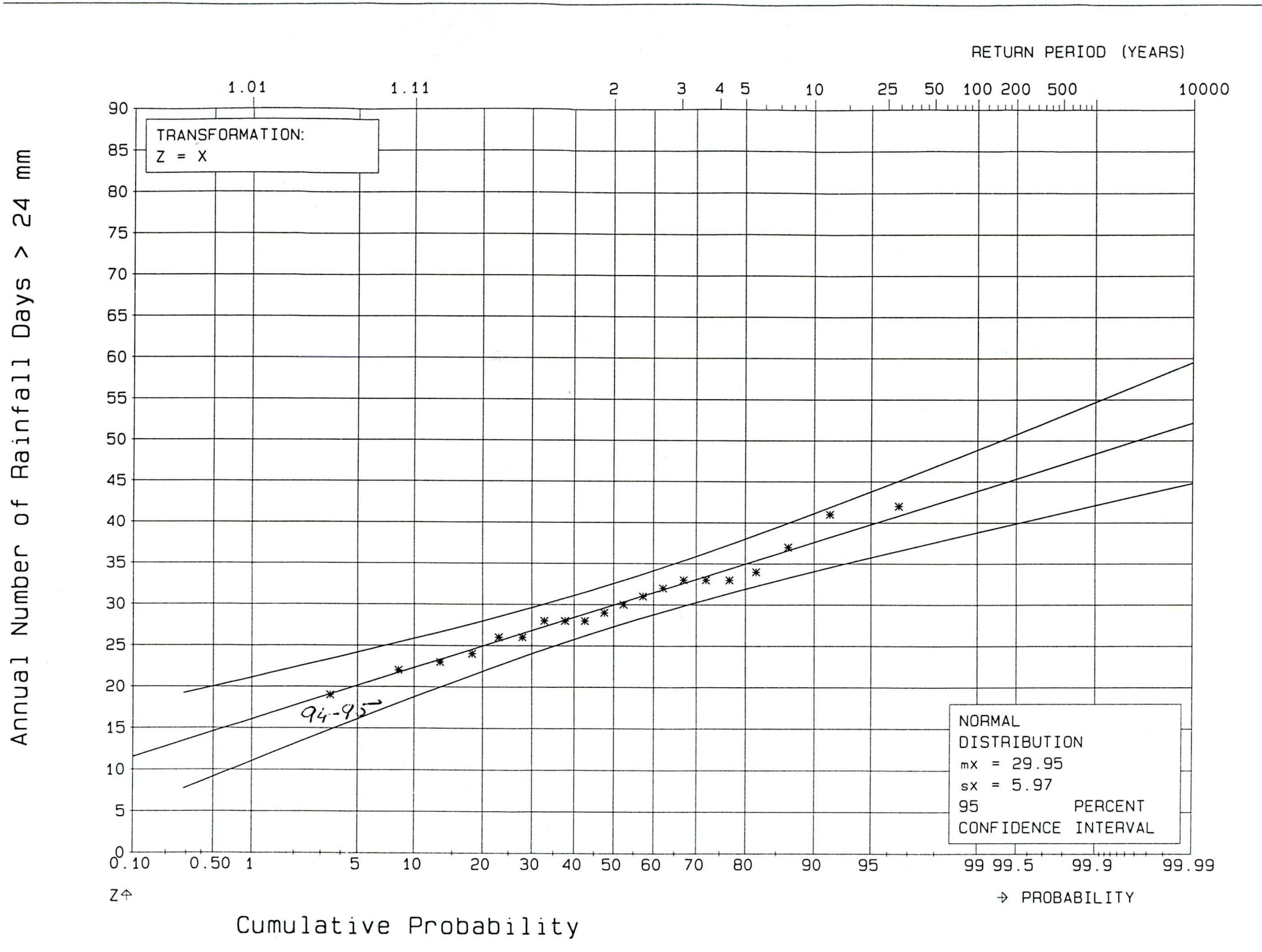


Fig. 6.7 Normal Distribution of Annual Number of Days with Rainfall > 24 mm

6.3 Water Deficit

The water deficit is the difference of potential evapotranspiration and precipitation (Lowing 1987). It is assumed that evaporation data from BWDB is equal to potential evapotranspiration. The negative values are assumed as zeroes. The 10-day deficit maximums are found to-fit empirical and theoretical distributions. Ten-day deficits are found by computing moving totals of daily drought for 10-day periods, such as 1-10 November, 2-11 November, ... 22-31 March and thus the entire season extending from November to March is covered. In this way 142 values of 10-day deficit values for the season are obtained (Total 151 days). Out of these values, one 10-day maximum deficit (∂_{max}) values in November to March season of each year is found out. Similarly for the season June to September is found out. For frequency analysis all the years maximum deficit totals are arranged in descending order. Deficit values are plotted in an extreme value probability paper. Plotting position is computed by Weibull formula. Plotting position for non-excedence probability

$P(\partial_{max} \leq d_m)$ is $$P_m = 1 - \frac{m}{n+1} \qquad (6.1)$$

m = rank

n = total number of years

The empirical return period T_m of a deficit magnitude d_m is given by

$$T_m = \frac{1}{1-P_m} \qquad (6.2)$$

For any return period the deficit value can be calculated by theoretical frequency relationship (Chow et al. 1988)

$$x_T = x_0(1+bK_T) \qquad (6.3)$$

Where, x_T is the magnitude of event having a return period T, x_0 is the mean, b is the co-efficient of variance, K_T is the frequency factor. For extreme type 1 distribution Chow (1951) has presented the following relationship for frequency factor

$$K_T = -0.7797\left[0.5772 + \ln\left\{\ln\left(\frac{T_m}{T_m - 1}\right)\right\}\right] \qquad (6.4)$$

6.4 Analysis, Results, and Discussion

For water deficit analysis three rainfall and evaporation stations from the Badarganj and Kishoreganj areas are selected. The summary of computed results are given in Tables. 6.5 to 6.7. It contains the 10-day deficit values for the season June to September and November to March with corresponding standard deviation, co-efficient of variance, and frequency factor. Using the frequency equation the 10-day deficit values for a given return period can be computed. From Figs. 6.10 to 6.11 it is revealed that drought values for Mohipur is less than other stations. If we propose at Rangpur sizing the project so as to satisfy irrigation requirements during monsoon period for the five-year return period, drought value is 37 mm (Fig. 6.8). This is equivalent to 370 m^3 of storage per irrigated hectare per year. If we design the project for dry period (November March) drought value is 48 mm (Fig. 6.10). From Figs. 6.8 to 6.13 it is clear that drought value in monsoon fits better than the dry period. Reference to Figs. 6.8 to 6.13 show that all drought values appear to be approximated by extreme value distribution.

Table 6.5 Deficit Value and its Period at Different Stations

	Rangpur				Mohipur				Kaliganj			
	June-September		November - March		June-September		November - March		June-September		November - March	
Year	Max 10-day -D	Period	Max 10-day -D	Period	Max 10-day -D	Period	Max 10-day -D	Period	Max 10-day -D	Period	Max 10-day -D	Period
76-77	35.2	27/8	52.9	17/3					27.3	04/9	56.3	22/3
77-78	37.6	29/6	42.1	20/3					29.5	03/8, 01/9	41.8	22/3
78-79	29.3	29/8	53.6	22/3								
79-80	48.1	01/6	50.1	23/3								
80-81	33.7	21/6, 24/6	30.6	14/3	25.3	22/6	20.5	16/3	25.2	23/7	53.4	21/3,22/3
81-82	36	09/6, 10/6	40.9	19/3,20/3	25.2	18/9	29.7	16/3,17/3	26.6	03/6	55.2	20/3
82-83	34.9	10/8	53.6	11/3	27.1	8/8	35	1/3,2/3	27.8	10/7	45.7	10/3
83-84									34.4	6/7, 7/7, 8/7	52.1	22/3
84-85									21.4	08/8	57.1	20/3,21/3
85-86	22.5	27/8, 28/8	54	19/3	28.3	23/9	35.7	19/3	19.9	05/8, 12/8	35.3	21/3,22/3
86-87	36.8	12/7	38.7	21/3	28.7	7/7, 8/7	30.8	25/1	26.1	08/8, 9/8	27	22/3
87-88	22.7	04/6, 05/6	35.85	23/3	14.6	3/6, 4/6, 5/6, 6/6	37.85	23/3	29	18/7	34.35	23/3
88-89	30.7	01/6	43.2	22/3	32.4	18/9	47.1	22/3	39.2	01/6, 02/6	41.45	21/3
89-90	30.6	21/6	37.1	15/3	30	25/7, 26/7	37.1	17/11	21.6	20/8, 21/8	28.2	19/3
90-91	33.5	17/8,18/8	27.4	15/3	23.4	25/6	34.3	1/3,2/3	27.2	17/8	40.3	18/3
91-92	28.5	20/7	45.6	22/3	16.5	21/9	35.5	11/3	28.8	19/7	51	22/3
92-93	32.5	03/9, 04/9, 05/9	35.4	15/3,16/3	31.2	14/8..19/8	37.65	14/3	29.6	13/6	40.6	18/3
93-94	33.8	26/7	34.5	22/3	24.4	9/9	34.8	1/3	26.3	14/8	27.7	20/3
94-95	34.8	06/8	41	22/3	35.2	24/8	35.8	23/2	31	10/7	35.7	22/3

Table 6.6 Deficit Values in Descending Order, Return Period and Probability

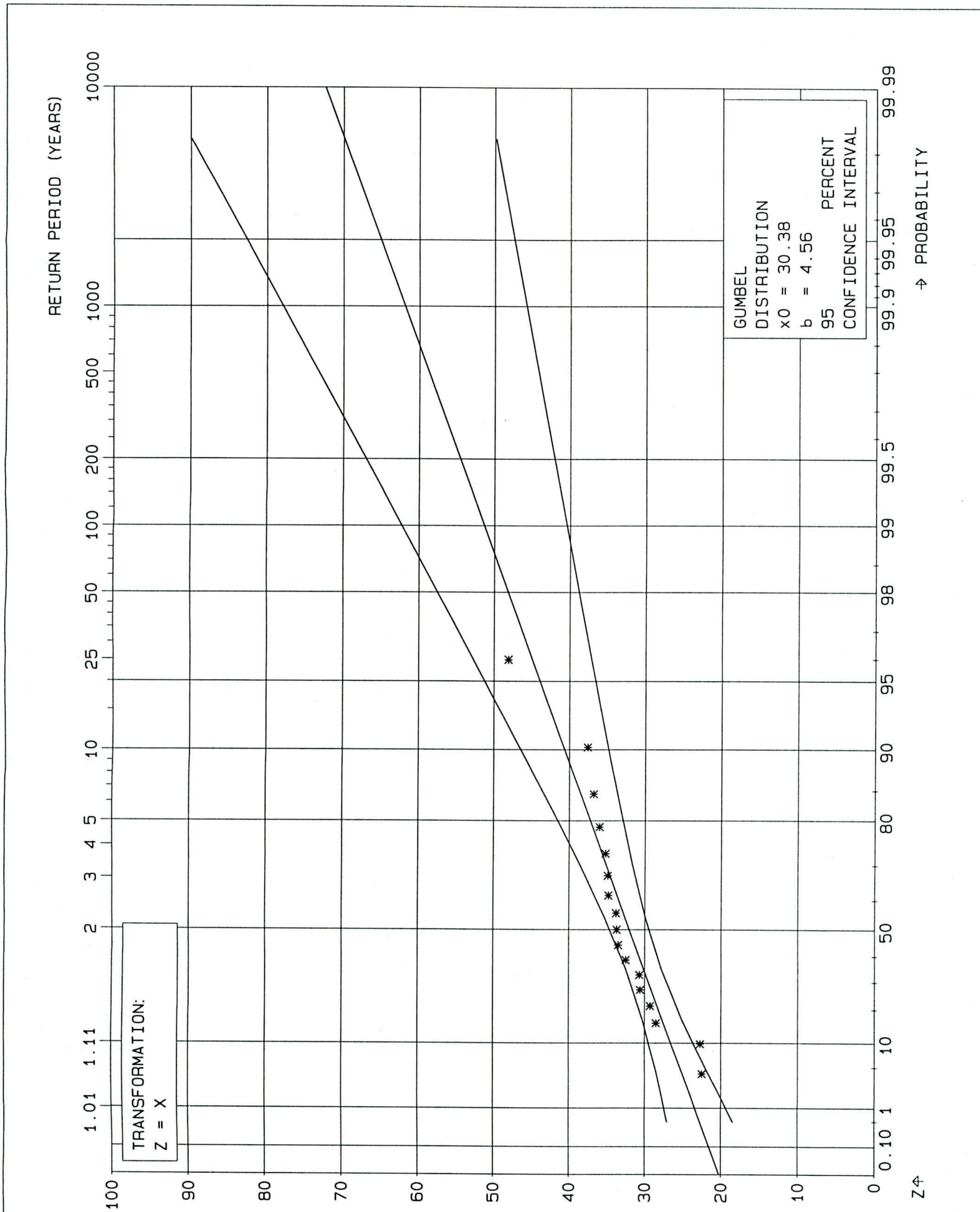
	Rangpur					Mohipur					Kaliganj				
Rank	June- Sept.	Nov.-March	Plot. Posi.	Ret. Peri.	Non Ex. Prob.	June-Sep	Nov-Mar	Plot. Posi.	Ret. Peri.	Non Ex. Prob.	June-Sep	Nov-Mar	Plot. Posi.	Ret. Peri.	Non Ex. Prob.
1	48.1	54	5.56	18.00	94.44	36	47.1	7.14	14.00	92.86	39.2	57.1	5.56	18.00	94.44
2	37.6	53.6	11.11	9.00	88.89	35.2	37.85	14.29	7.00	85.71	34.4	56.3	11.11	9.00	88.89
3	36.8	53.6	16.67	6.00	83.33	32.4	37.65	21.43	4.67	78.57	31	55.2	16.67	6.00	83.33
4	36	52.9	22.22	4.50	77.78	31.2	37.1	28.57	3.50	71.43	29.6	53.4	22.22	4.50	77.78
5	35.2	50.1	27.78	3.60	72.22	28.7	35.8	35.71	2.80	64.29	29.5	52.1	27.78	3.60	72.22
6	34.8	45.6	33.33	3.00	66.67	28.3	35.7	42.86	2.33	57.14	29	51	33.33	3.00	66.67
7	34.8	43.2	38.89	2.57	61.11	27.1	35.5	50.00	2.00	50.00	28.8	45.7	38.89	2.57	61.11
8	33.7	42.1	44.44	2.25	55.56	25.3	35	57.14	1.75	42.86	27.8	41.8	44.44	2.25	55.56
9	33.5	41	50.00	2.00	50.00	25.2	34.8	64.29	1.56	35.71	27.3	41.45	50.00	2.00	50.00
10	32.5	40.9	55.56	1.80	44.44	24.4	34.3	71.43	1.40	28.57	27.2	40.6	55.56	1.80	44.44
11	30.7	38.7	61.11	1.64	38.89	23.4	30.8	78.57	1.27	21.43	26.6	40.3	61.11	1.64	38.89
12	30.6	37.1	66.67	1.50	33.33	16.5	29.7	85.71	1.17	14.29	26.3	35.7	66.67	1.50	33.33
13	29.3	35.85	72.22	1.38	27.78	14.6	20.5	92.86	1.08	7.14	26.1	35.3	72.22	1.38	27.78
14	29	35.4	77.78	1.29	22.22						25.2	34.35	77.78	1.29	22.22
15	28.5	34.5	83.33	1.20	16.67						21.6	28.2	83.33	1.20	16.67
16	22.7	30.6	88.89	1.13	11.11						21.4	27.7	88.89	1.13	11.11
17	22.5	27.4	94.44	1.06	5.56						19.9	27	94.44	1.06	5.56

Table 6.7a Summary of Water Deficit Drought Analysis

	Rangpur		Mohipur		Kaliganj	
	June-Sept.	Nov-March	June-Sept.	Nov-March	June-Sept.	Nov-March
X	33.012	42.15	26.331	34.754	27.673	40.933
S	5.674	8.151	5.627	5.705	4.19	9.503
Cv	0.172	0.193	0.214	0.164	0.151	0.232

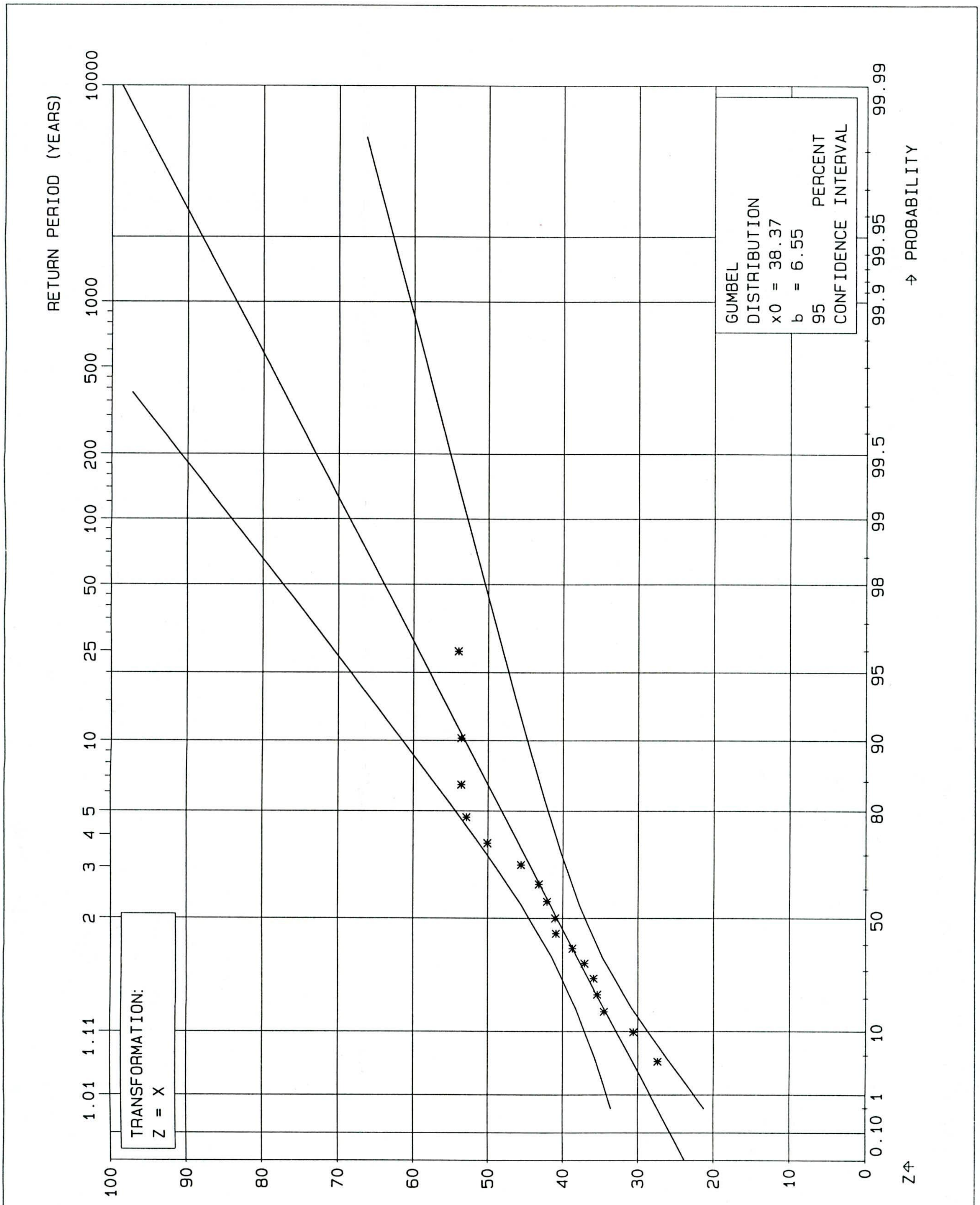
Table 6.7b Magnitude of Deficit Having Different Return Period

Magnitude of the Event Having Return Period T Years							
Return Period (T)	Freq. Factor (Kt)	Rangpur		Mohipur		Kaliganj	
		June - Sept	Nov. - Marc	June - Sept	Nov. - Marc	June - Sept	Nov. - March
2	-0.164	32.080	40.811	25.406	33.817	26.985	39.372
5	0.719	37.094	48.014	30.379	38.858	30.688	47.770
10	1.305	40.414	52.783	33.672	42.196	33.139	53.330
20	1.866	43.598	57.358	36.830	45.398	35.491	58.664



Deficit (mm)

Fig. 6.8 Ten Day Deficit (mm) for the Season June September at Rangpur



Deficit (mm)

Fig. 6.9 Ten Day Deficit (mm) for the Season Novemeber March at Rangpur

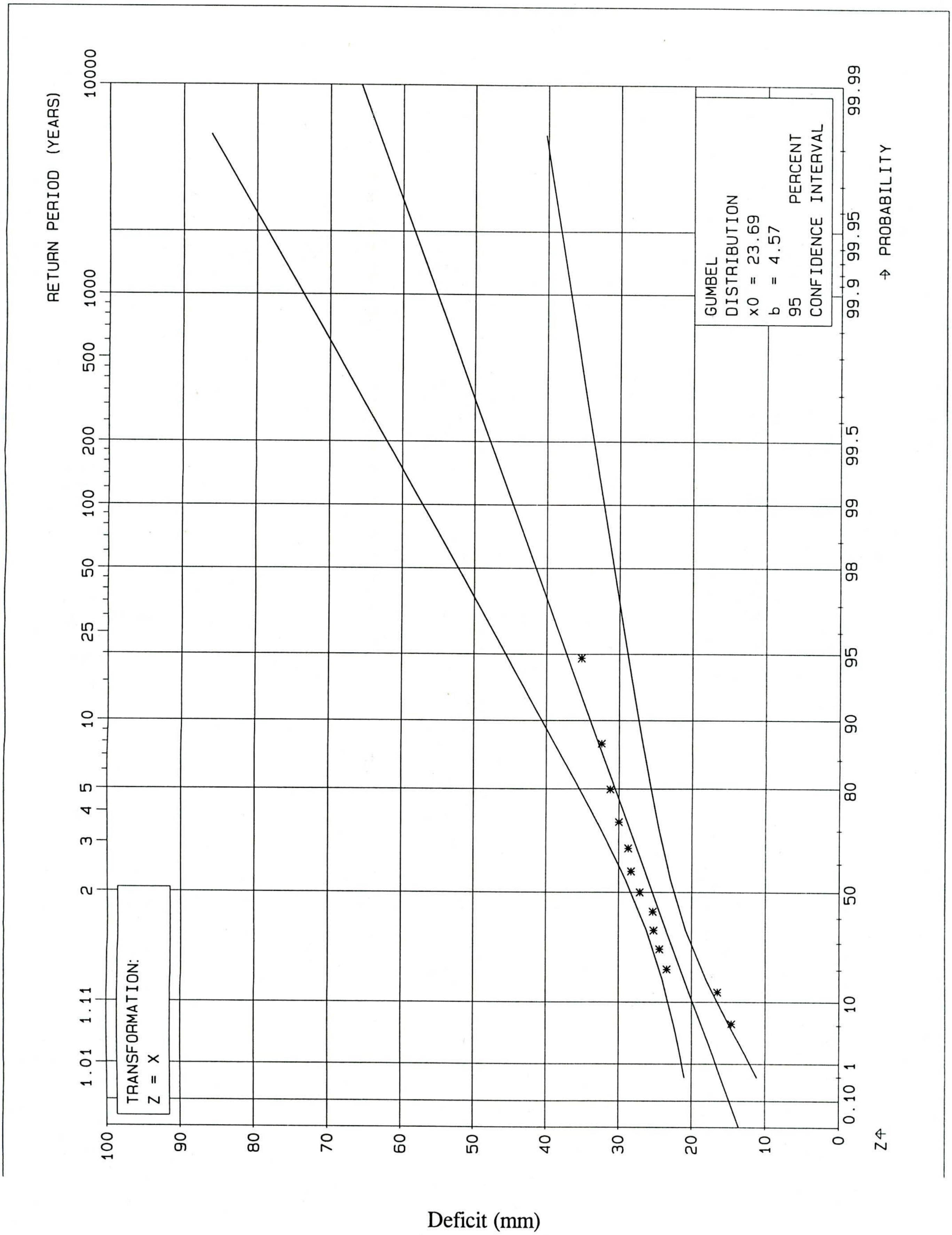


Fig. 6.10 Ten Day Deficit (mm) for the Season June September at Mohipur

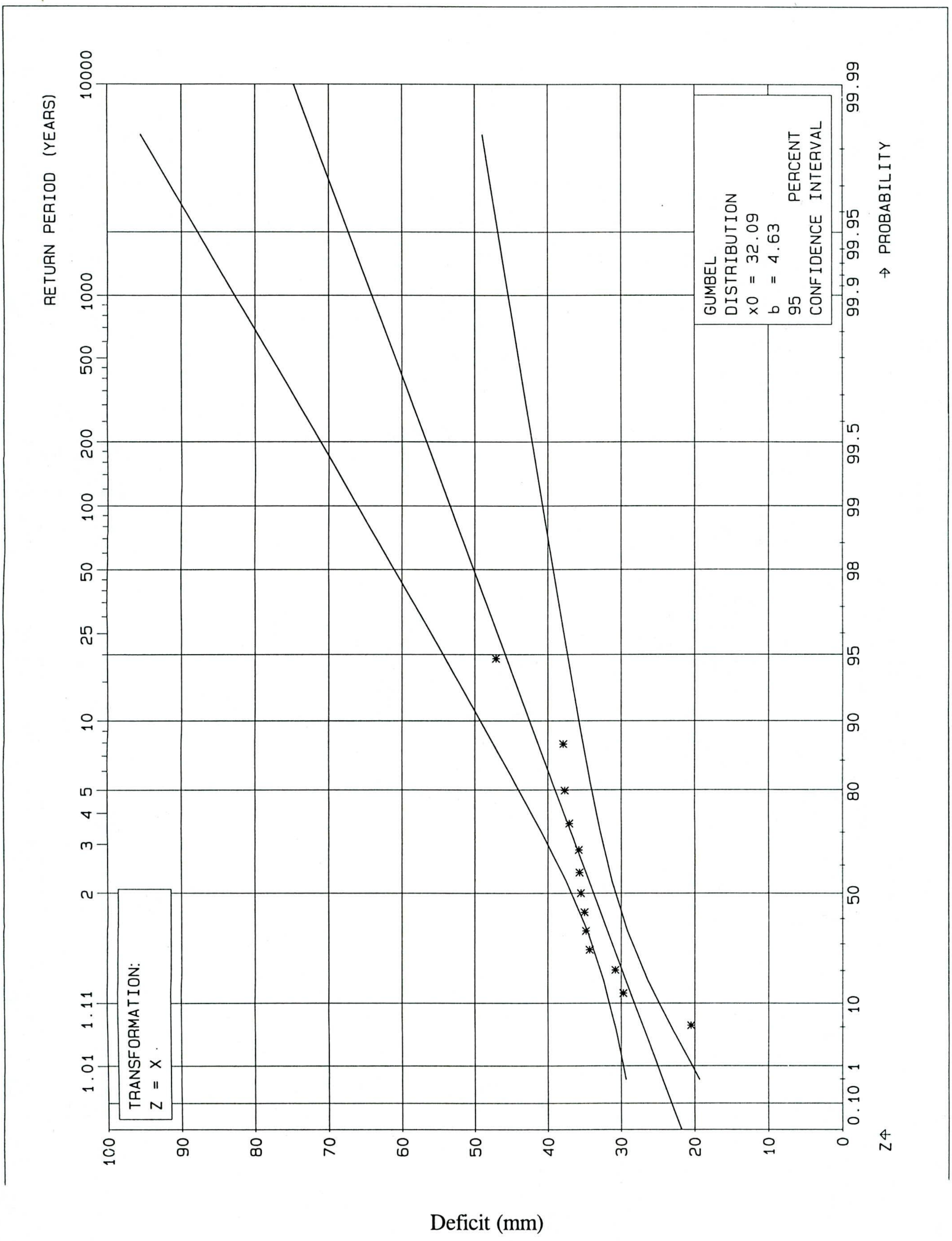


Fig. 6.11 Ten Day Deficit (mm) for the Season November March at Mohipur

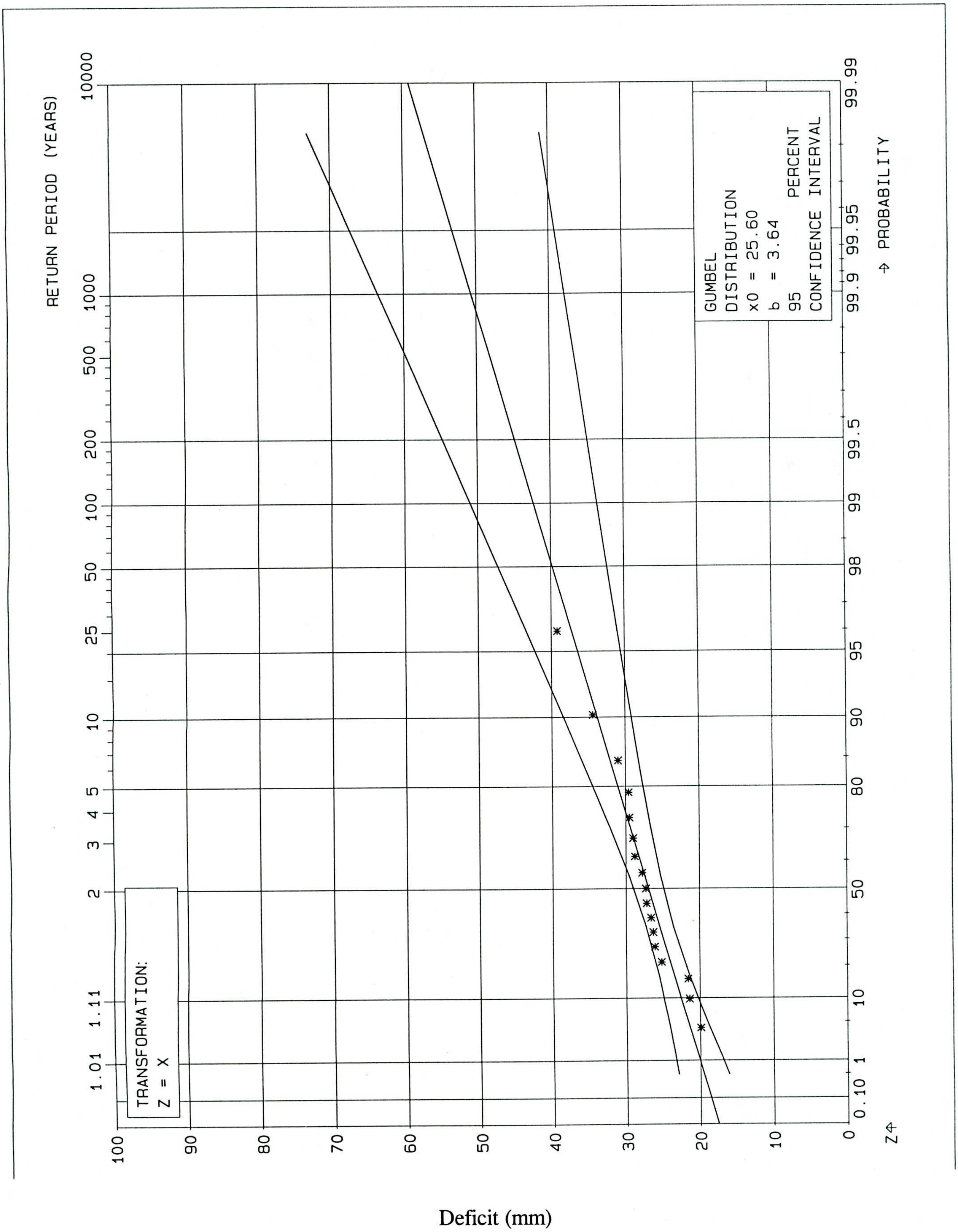


Fig. 6.12 Ten Day Deficit (mm) for the Season June September at Kaliganj

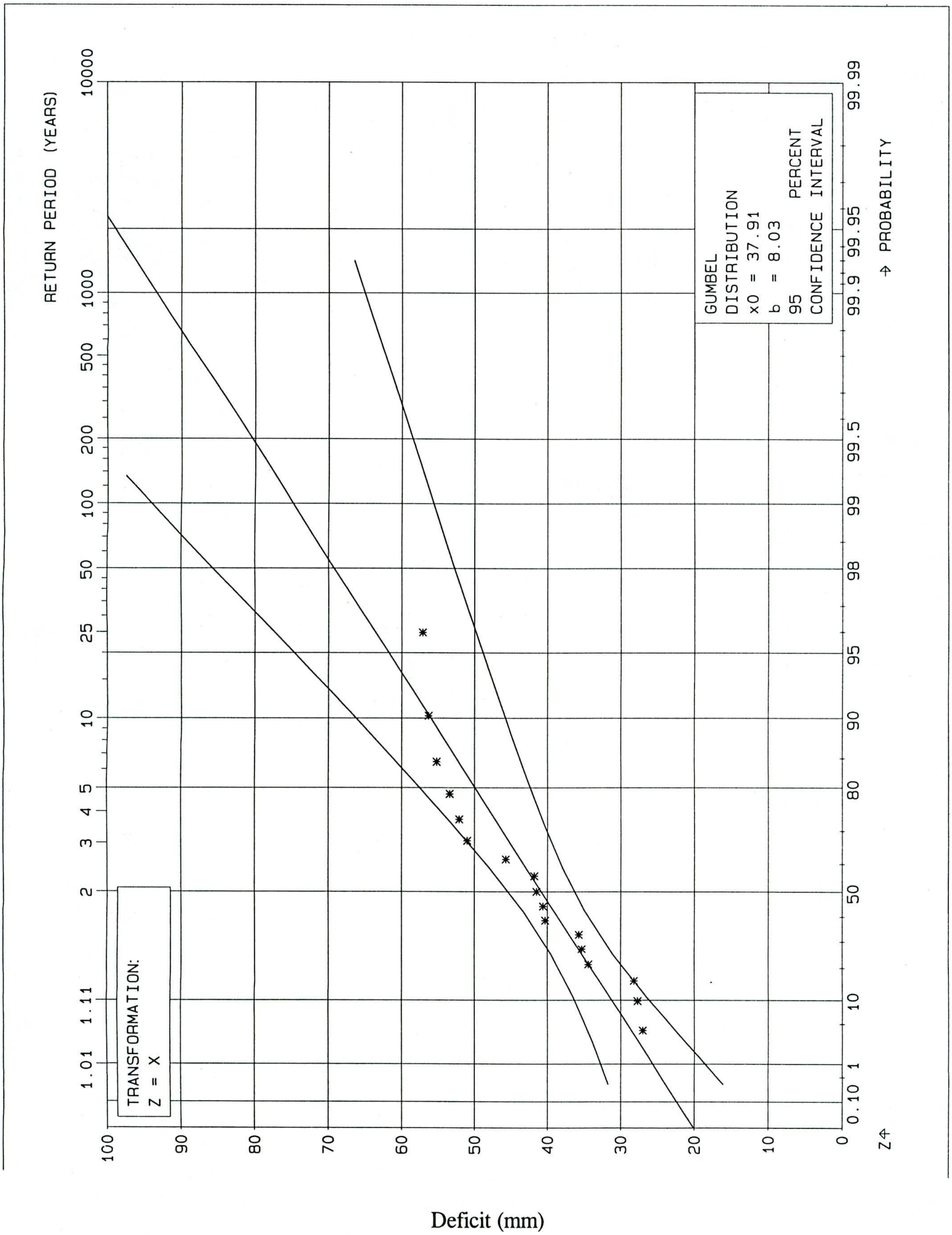


Fig. 6.13 Ten Day Deficit (mm) for the Season November at Kaliganj

Chapter 7

Impact on Crop, Socio-Economic and Groundwater Declination

7.1 Introduction

Drought that has occurred in 1994-95 in Bangladesh, particularly with a severe outbreak in the north-western part of the country has left the farmers in a precarious condition. The irrigation system in the country's agricultural sector almost collapsed as most of the deep, shallow and hand tubewells went dry and posed a serious threat to foodgrain production. According to media report the drought might have damaged about 50 percent of the crops in those region. The situation turned worse due to drying up of surface water bodies like canals, ponds, beels, and rivers in the region. The groundwater level dropped to an abnormally low level in 1994-95 compared to the level in previous years. Most of the shallow and the deep tubewells had been inoperative or not functioning with full capacity.

A questionnaire was prepared for surveying the agricultural damages and assessing the socio-economic and environmental impacts which are usually not available from known sources. Due to time and resource constraints, survey is conducted for a limited number of households which has been selected randomly from Badarganj and Kishoreganj thana. Groundwater data is collected only for eight stations from greater Rangpur district.

7.2 Crop Damage Assessment

Field data are summarised using spreadsheet package. All the 120 farmers responses are presented in BUET-DUT (1996). Yield and income for major crops of the respondent of two thanas are presented in BUET-DUT (1996). Yield and yield losses of the major crops and the accompanied income losses are estimated in Tables E.1 to E.14. The main crops that the farmers of Kishoreganj normally cultivate are boro, wheat, potato, aus, aman, tobacco, jute, ginger. All respondents are not cultivating all crops. Most of them cultivate aman, boro, wheat and aus. At Kishoreganj for 60 respondents, yield losses per ha for boro, wheat, potato, aus, aman, tobacco, jute, ginger are 11.52, 7.05, 16.32, 23.77, 34.53, 2.51, 8.02, 6.99 tons respectively. The most severely affected crops were aman, aus, ginger, and boro. Income losses for these crops are Tk 2,23,000, Tk 1,34,300, Tk 1,11,700 and Tk 82,400 respectively. At Badarganj, major crops which were cultivated by the farmers are boro, wheat, aman, potato, jute and patal. Yield losse for these crops are 101.44, 13.68, 141.13, 25.6, 4.1 and 15.34 tons per ha respectively. Most severely affected crops were aman, boro and potato. Income loss for these crops were Tk 9,69,000, Tk 6,44,800 and Tk 75,000 respectively. For both the thanas most severely affected crops were boro and aman.

Tables E.15 to E.28 (Appendix E) presents average, minimum and maximum income and expenses for various items of the major crops. At Kishoreganj production/hectare for aman, wheat, boro, potato, ginger, aus, jute and tobacco crops are 3.13, 2.54, 4.28, 7.67, 8.07, 1.44, 1.5 and 1.5 ton respectively in 1994-95 while for the normal year are 4, 3.09, 5.15, 8.87, 11.76, 2.32, 2.14 and 1.76 tons respectively. Average production losses per ha of aman and boro are 0.87 and 0.87 tons respectively. At Badarganj production/hectare in tons for wheat, boro, potato, jute, aman, and patal crops are 1.93, 3.34, 5.53, 1.3, 2.46 and 5.26 respectively in 1994-95, while for normal year are 2.75, 5.02, 13.35, 1.94, 4.15 and 12.8. In 1994-95, expense for irrigating is higher than the normal year. In normal year expense for harvesting is higher than 1994-95. Expenses for other items are more or less the same.

Production loss, production, income, total expense and expenses in irrigation and fertiliser and pesticide per hectare are shown in Tables 7.1 and 7.2 and Figs. 7.1 to 7.6. From Fig. 7.1 it is seen that production and income losses are about 30 and 60 percent respectively for Badarganj whereas for Kishoreganj (Fig. 7.4), these losses are 15 and 25 percent. These indicates that Badarganj was more severely affected area than Kishoreganj. In Badarganj, middle class farmers are (production loss= 35 and income loss=65 percent) affected more than other category of farmers. Whereas in Kishoreganj (Fig. 7.4), marginal farmers are affected more (production loss= 20 and income loss=40 percent). The most severely affected crop is Boro at Kishoreganj and Aman at Badarganj. It has been observed (Fig. 7.2 and 7.5) that total expense for all classes of farmers and for all the crops in 1994-95 is greater than the normal year. This is because in drought year expenses for pesticide, irrigation and removal of weeds is more than normal year. Whereas expense for harvesting in normal year is more than drought year. This is due to more production in normal year and in drought years generally less weeds grow.

7.3 Socio-Economic and Environmental Impact

Summary of responses of farmers about socio-economic and environment related questions are presented in Tables 7.3 to 7.4. From Table 7.3 it is seen that income loss from pisciculture in Badarganj and Kishoreganj were around 52 percent and 80 percent, respectively. Table 7.4 indicates that all the farmers of both the thanas complained about groundwater and surface water decreases compared to the normal years. As a matter of fact these complain come out as no surprise in the questionnaire survey in those two thanas. All most all the respondents observed that the vegetation and plants have been severely affected by the drought. During the drought period there is no doubt about the increase of temperature and dust compared to normal years.

There were 11 and 19 day-laborers participated in the questionnaire survey from Kishoreganj and Badarganj, respectively. But none of them were found fully engaged as day-laborers during the period of drought. Table 7.5 shows the summation of 11 and 19 day-laborers season-wise total income and it is found that the income losses other than crop damages at Kishoreganj and Badarganj, respectively, are 6.6 percent and 5.7 percent.

In normal years the farmers in Kishoreganj and Badarganj suffer from fever as shown in Table 7.6. But in 1994-95, suffering from fever are relatively less while suffering from dysentery and diarrhea are in rise due to use of unsafe drinking water. Half of the respondents of Badarganj indicate that they do not consult the doctor during the normal years but during 1994-95 almost all of them are compelled to consult the doctor.

During questionnaire survey the local people gave an impression that their HTWs and STWs are not able to supply the same quantity of water as normal years. Also many HTWs went out of operation. Table 7.7 reveals an interesting fact that even in the scarcity of tubewell water during the 1994-95 year, they do not go for pond or other surface source of water bodies.

7.4 Groundwater Declination

Groundwater data of greater Rangpur district is collected. During the field visit held from 7 to 23rd June, 1996, it has been revealed that groundwater extraction technology in these areas are predominantly by shallow tubewells. Water table below land-surface is found out and represented in Fig. 7.7. From figure it has been observed that in 1994-95 groundwater level is much below than the other year. From Fig 7.7 it is clear that groundwater levels in 1994-95 at Nageshwari (RA36) and Pateshwari (RA71) are about 6 m whereas at other station are between 3 and 4 m. The maximum groundwater level below land-surface in the average year is 3 m whereas in 1994-95 is 4.5 m. May be the observation well does not represent DTW properly or observation well are situated far from the influence zone of DTW.

Table 7.1 Production Loss (%), Production/ha etc. for Different Category of Farmers (a) Marginal, (b) Middle, and (c) Big in Badarganj.

(a) Marginal

	Production Loss (%)	Income Loss (%)	Production/ha		Total Expense/ha		Expense in Irrigation/ha		Expense in Fertilizer & Pesticide/h	
			1994-95	Normal	1994-95	Normal	1994-95	Normal	1994-95	Normal
Boro	31.15	56.15	2.49	3.62	16670	16059	4821	4249	4720	4714
Wheat	30.99	59.84	2.34	3.39	9013	8755	1099	841	2318	2318
Aman	41.43	60.51	2.17	3.70	8880	8015	927	56	2748	2747

(b) Middle

	Production Loss (%)	Income Loss (%)	Production/ha		Total Expense/ha		Expense in Irrigation		Expense in Fertilizer & Pesticide/h	
			1994-95	Normal	1994-95	Normal	1994-95	Normal	1994-95	Normal
Boro	35.70	78.66	3.22	5.00	15316	14828	3954	3484	4556	4558
Wheat	38.42	84.17	1.77	2.87	9567	9322	1048	696	2943	2945
Aman	37.90	64.84	2.61	4.21	8542	8058	465	0	2735	2723

(c) Big

	Production Loss (%)	Income Loss (%)	Production/ha		Total Expense/ha		Expense in Irrigation		Expense in Fertilizer & Pesticide/h	
			1994-95	Normal	1994-95	Normal	1994-95	Normal	1994-95	Normal
Boro	33.74	69.07	3.31	5.00	16293	15703	4451	4026	4555	4462
Wheat	30.80	62.81	1.80	2.60	9450	9251	860	663	2591	2584
Aman	44.16	65.62	2.19	3.92	9382	9078	316	91	2741	2706

Table 7.2 Production Loss(%), Production/ha etc. for Different Category of Farmers (a) Marginal, (b) Middle, and (c) Big in Kishoreganj.

(a) Marginal

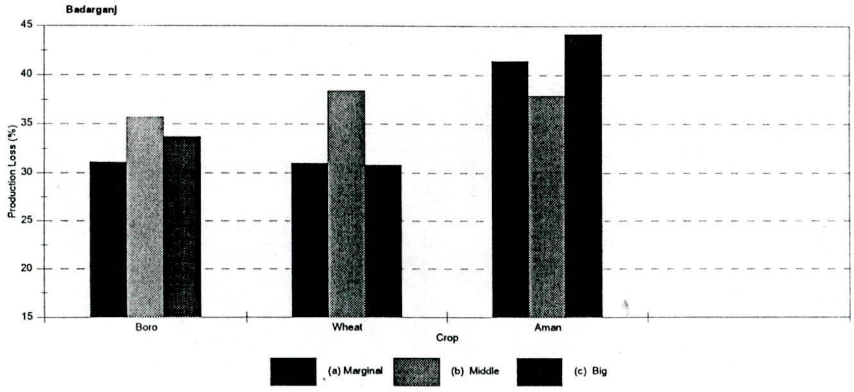
	Production Loss (%)	Income Loss (%)	Production/ha		Total Expense/ha		Expense in Irrigation		Expense in Fertilizer & Pesticide	
			1994-95	Normal	1994-95	Normal	1994-95	Normal	1994-95	Normal
Boro	23.28	56.98	4.83	6.30	16712	15423	5096	3846	5231	5192
Wheat	28.65	91.20	1.77	2.48	9902	9952	978	673	1957	2067
Aman	14.20	21.06	3.12	3.63	6511	6597	395	368	6829	7737
Tobacco	7.92	47.37	2.26	2.45	11986	11268	1943	1634	3314	3024

(b) Middle

	Production Loss (%)	Income Loss (%)	Production/ha		Total Expense/ha		Expense in Irrigation		Expense in Fertilizer & Pesticide	
			1994-95	Normal	1994-95	Normal	1994-95	Normal	1994-95	Normal
Boro	16.17	38.74	4.31	5.22	14827	13923	4258	3318	3629	3658
Wheat	15.56	34.85	2.40	2.84	10135	9811	1055	798	2250	2208
Aman	16.38	25.03	3.40	4.06	8391	8204	189	44	2906	2842
Tobacco	17.15	34.15	1.49	1.77	10969	10425	2664	1937	2661	2615

(c) Big

	Production Loss (%)	Income Loss (%)	Production/ha		Total Expense/ha		Expense in Irrigation		Expense in Fertilizer & Pesticide	
			1994-95	Normal	1994-95	Normal	1994-95	Normal	1994-95	Normal
Boro	19.42	35.03	4.05	5.03	15058	14259	4168	3485	5084	5014
Wheat	18.75	31.96	2.78	3.42	9593	9352	1063	859	2373	2361
Aman	25.01	34.81	3.01	4.01	7867	7779	199	22	2680	2690
Tobacco	15.86	26.55	1.43	1.70	10721	10101	2220	1561	2911	2842



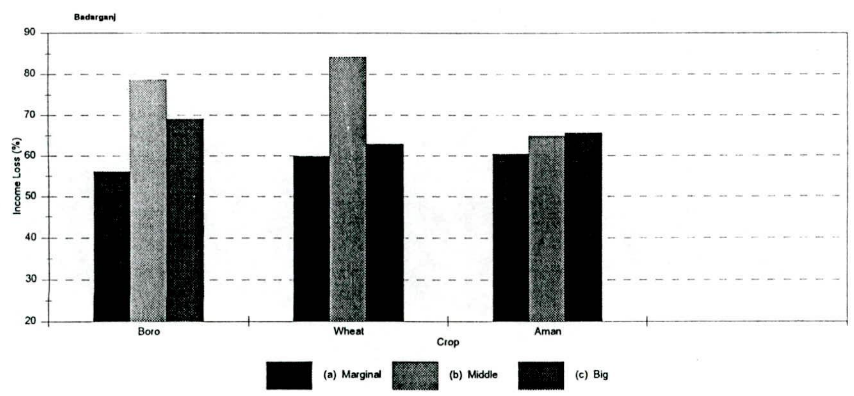
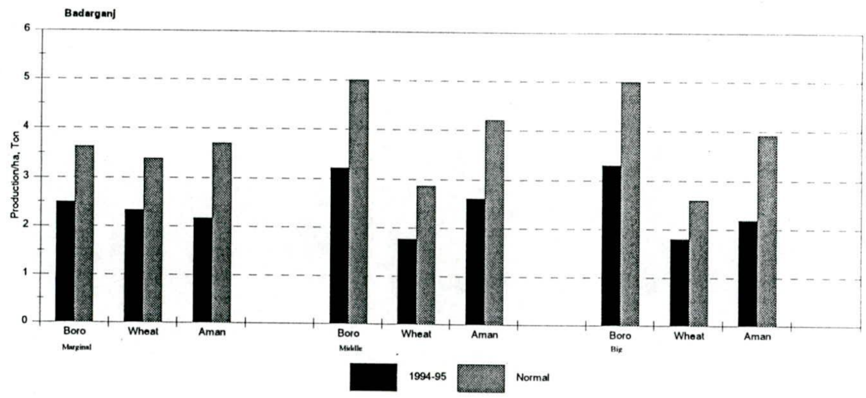


Fig. 7.1 (a) Production Loss and (b) Income Loss for Different Crops for Different Category of Farmers in Badarganj



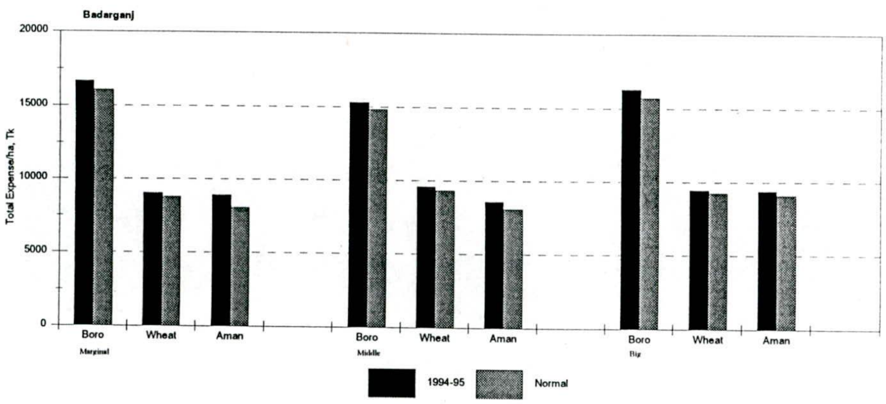


Fig. 7.2 (a) Production/ha and (b) Total Expense /ha for Different Crops for Different Category of Farmers in Badarganj

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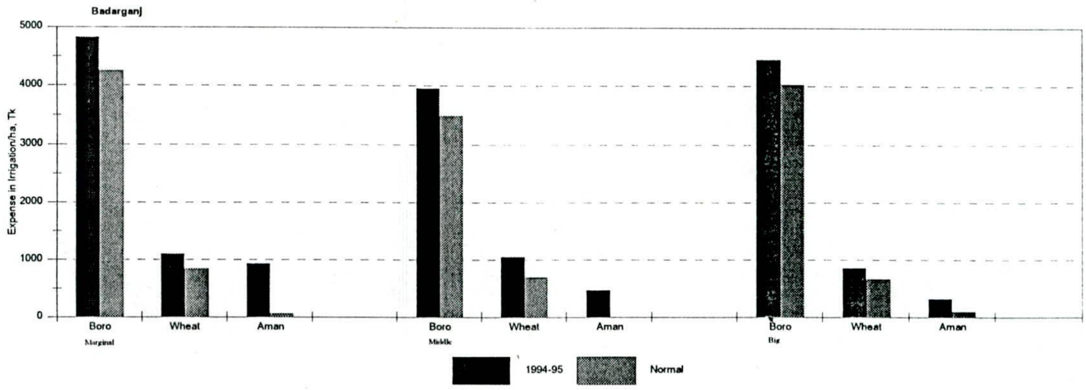


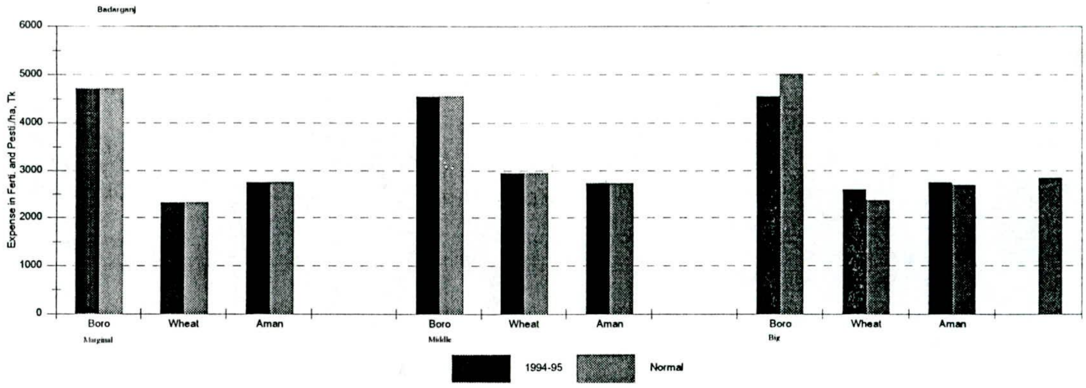
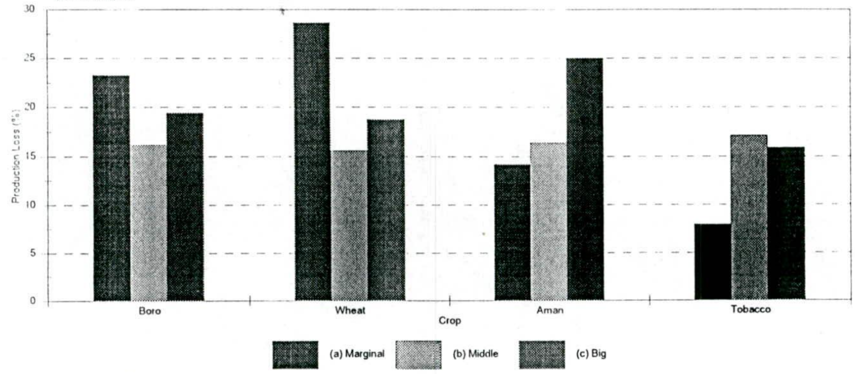


Fig. 7.3 Expense in (a) Irrigation/ha and (b) Fert. and Pest. /ha for Different Category of Farmers in Badarganj



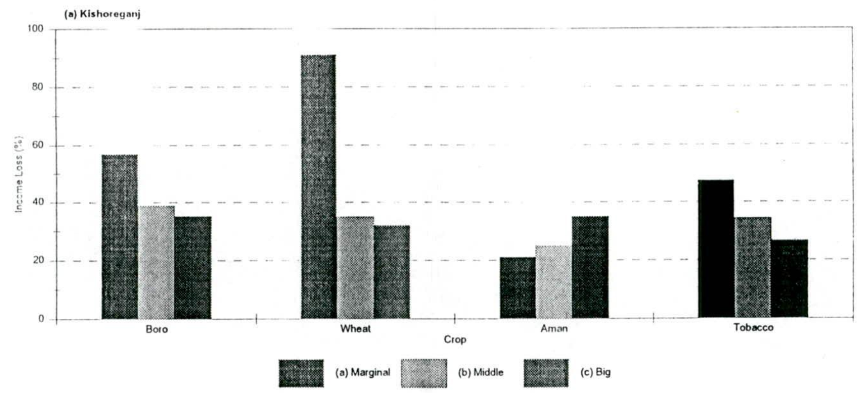
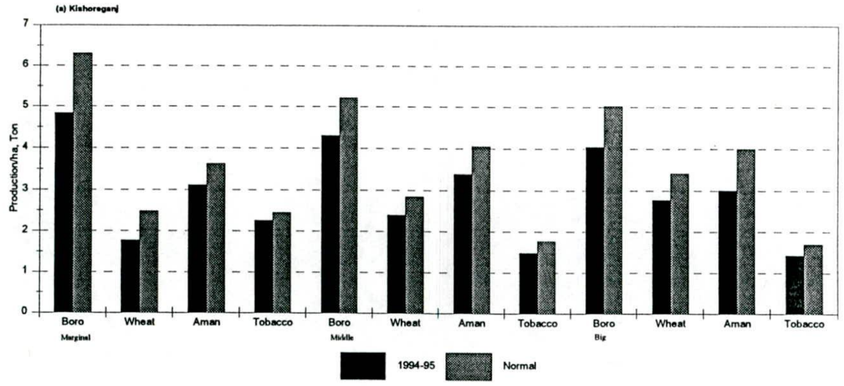


Fig. 7.4 (a) Production Loss and (b) Income Loss for Different Crops for Different Category of Farmers in Kishoreganj



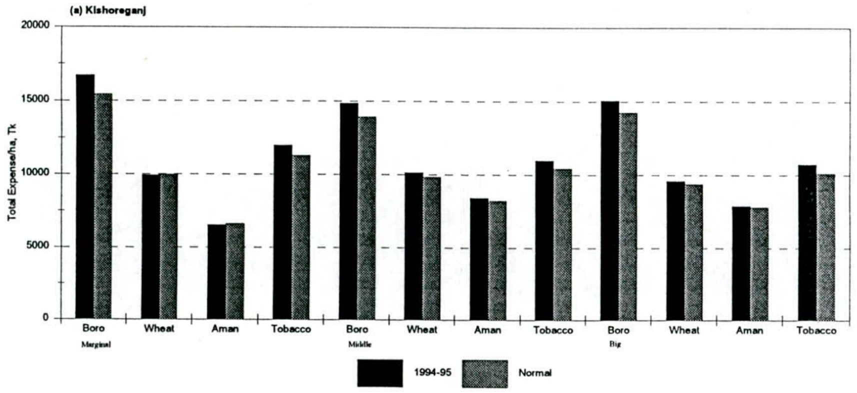
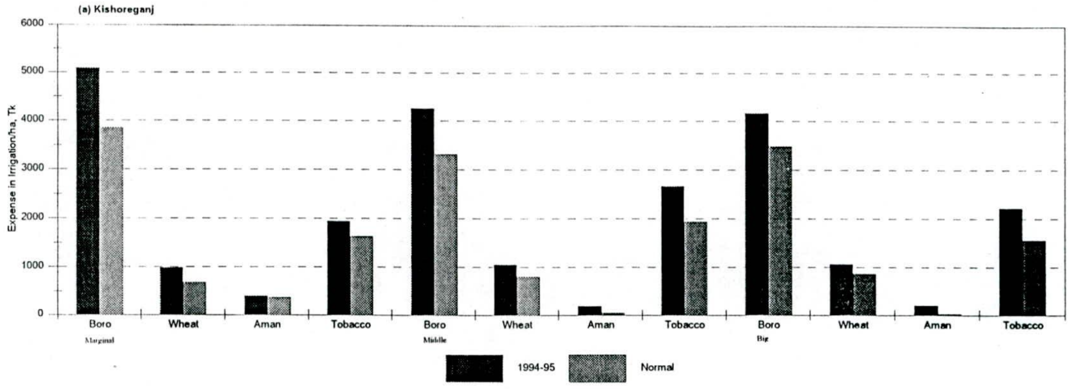


Fig. 7.5 (a) Production/ha and (b) Total Expense/ha for Different Crops for Different Category of Farmers in Kishoreganj



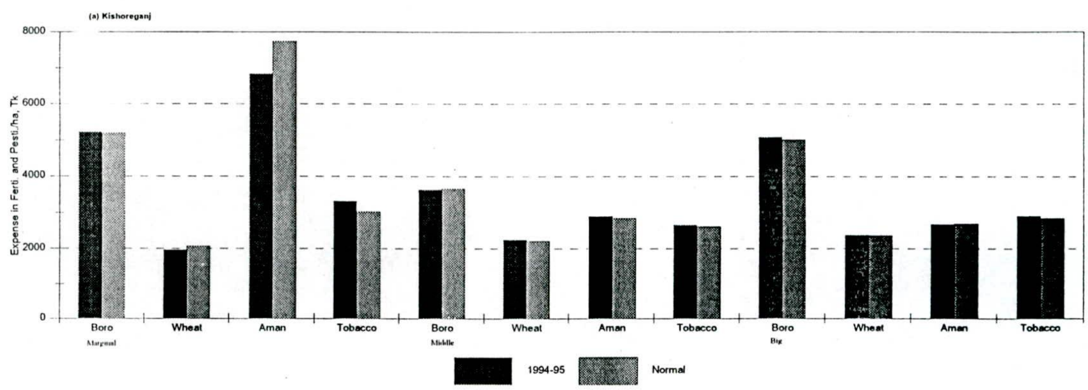


Fig. 7.6 Expense in (a) Irrigation/ha and (b) Fert. and Pest. /ha for Different Category of Farmers in Kishoreganj

Table 7.3 Income from Pisciculture

Item	Badarganj	Kishoreganj
Quantity of waterbody,ha	7.42	2.06
Gross Income in 1994-95, Tk	4854	1990
Gross Income in Normal yr, Tk	10142	9733
Income Loss, Tk	5287	7743
Income Loss, %	52.1	79.6

Table 7.4 Environmental Impact (Compared to Normal Year)

Item	Number of Respondent in Kishoreganj			Number of Respondent in Badarganj		
	Increase	Decrease	No Change	Increase	Decrease	No Change
GW level(*)	0	60	0	0	60	0
SW availability(**)	0	60	0	0	60	0
Vegetation	0	57	3	0	58	2
Plants	0	57	3	0	58	2
Temp.	60	0	0	60	0	0
Dust	60	0	0	60	0	0

* Groundwater
** Surfacewater

Table 7.5 Total Income and Income Loss (Tk) for Day Laborer

	Kishoreganj (*)		Badarganj (**)		Income Loss, Tk		Income Loss, %	
Season	Normal	1994-95	Normal	1994-95	Kishoreganj	Badarganj	Kishoreganj	Badarganj
Rabi season	27390	25410	123640	122870	1980	770	7.23	0.62
Kharif I	22725	21225	74400	70650	1500	3750	6.60	5.04
Kharif II	21450	20175	88650	76725	1275	11925	5.94	13.45
Total	71565	66810	286690	270245	4755	16445	6.64	5.74

(*) 11 Respondent (**) 19 Respondent

Table 7.6 Health Realated Responses

Item	Number of Incidences in Kishoreganj		Number of Incidences in Badarganj	
	1994-95	Normal	1994-95	Normal
Malaria	0	0	0	0
Diarrhea	20	5	14	2
Typhoid	1	3	1	2
Fever	41	52	33	42
Dysentery	31	6	34	6
other	3	1	5	3
No Disease	0	3	2	13
Consult the Doctor	60	56	58	34

Table 7.7 (a) Shortage of Drinking Water Related (Badarganj) Responses

Item	1994-95						Normal					
	Drinking Water		Bathing Water		Cattle's Water		Drinking Water		Bathing Water		Cattle's Water	
	No. of Respondent	Avg. Dist. (m)	No. of Respondent	Avg. Dist. (m)	No. of Respondent	Avg. Dist. (m)	No. of Respondent	Avg. Dist. (m)	No. of Respondent	Avg. Dist. (m)	No. of Respondent	Avg. Dist. (m)
Dug Well	0	-	0	-	0	-	0	-	0	-	0	-
River Water	0	-	0	-	4	50	0	-	0	-	4	-
Pond	0	-	0	-	11	-	0	-	5	-	22	-
HTW	56	-	56	-	30	-	60	-	55	-	28	-
STW/DTW	4	-	4	50	10	50	0	-	0	-	2	50

Table 7.7 (b) Shortage of Drinking Water Related (Kishoreganj) Responses

Item	1994-95						Normal					
	Drinking Water		Bathing Water		Cattle's Water		Drinking Water		Bathing Water		Cattle's Water	
	No. of Respondent	Avg. Dist. (m)	No. of Respondent	Avg. Dist. (m)	No. of Respondent	Avg. Dist. (m)	No. of Respondent	Avg. Dist. (m)	No. of Respondent	Avg. Dist. (m)	No. of Respondent	Avg. Dist. (m)
Dug Well	0	-	2	200	1	0	0	-	17	30	5	10
River Water	0	-	2	-	6	500	0	-	2	200	4	400
Pond	0	-	0	-	17	400	0	-	4	-	20	20
HTW	60	50	56	30	26	20	60	30	37	10	17	-
STW/DTW	0	-	0	-	3	500	0	-	0	-	7	50

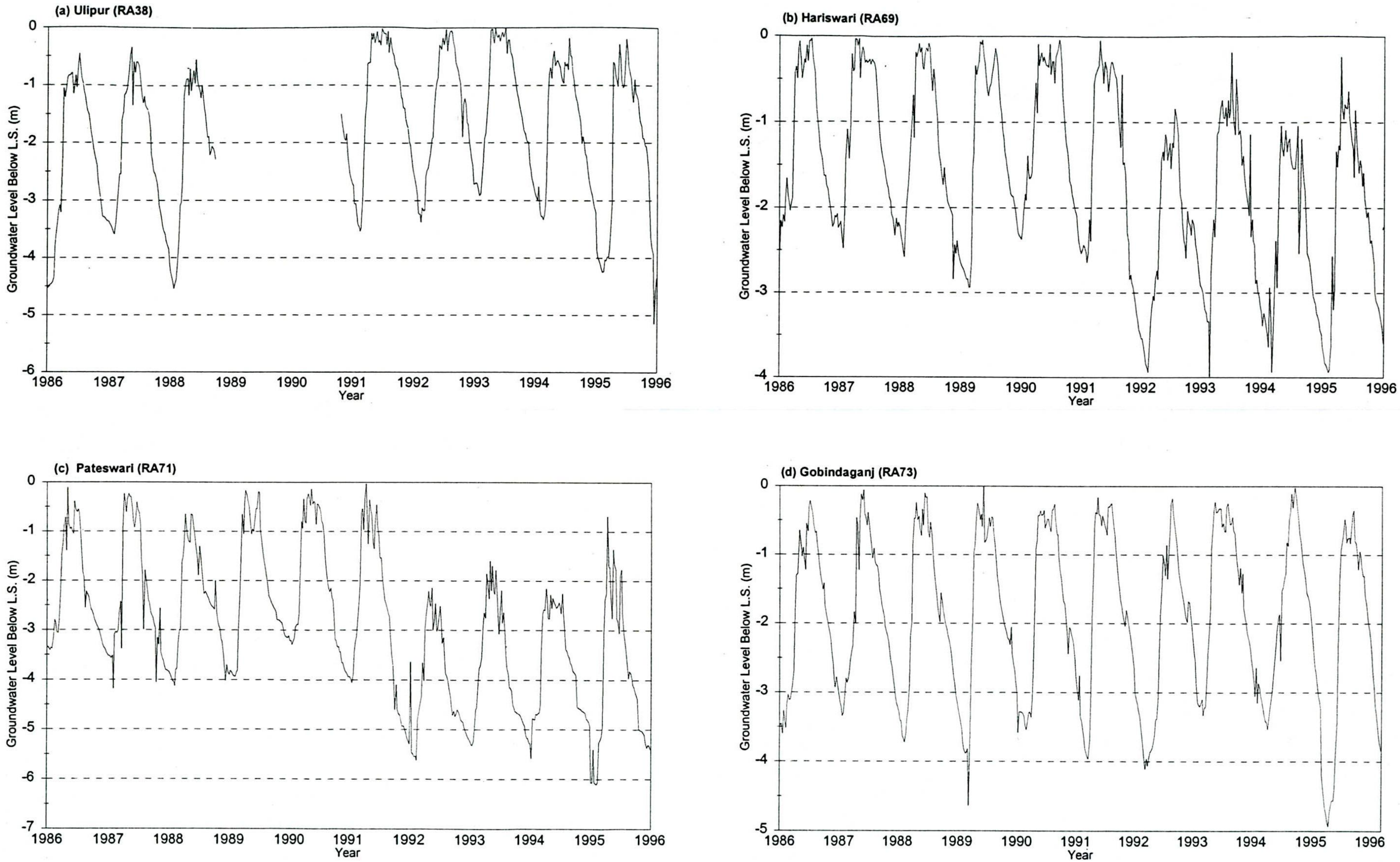


Fig. 7.7 (a), (b), (c), (d), (e), (f), (g), and (h) Groundwater Level Below Land Surface at Different Stations for the Period 1986-96.

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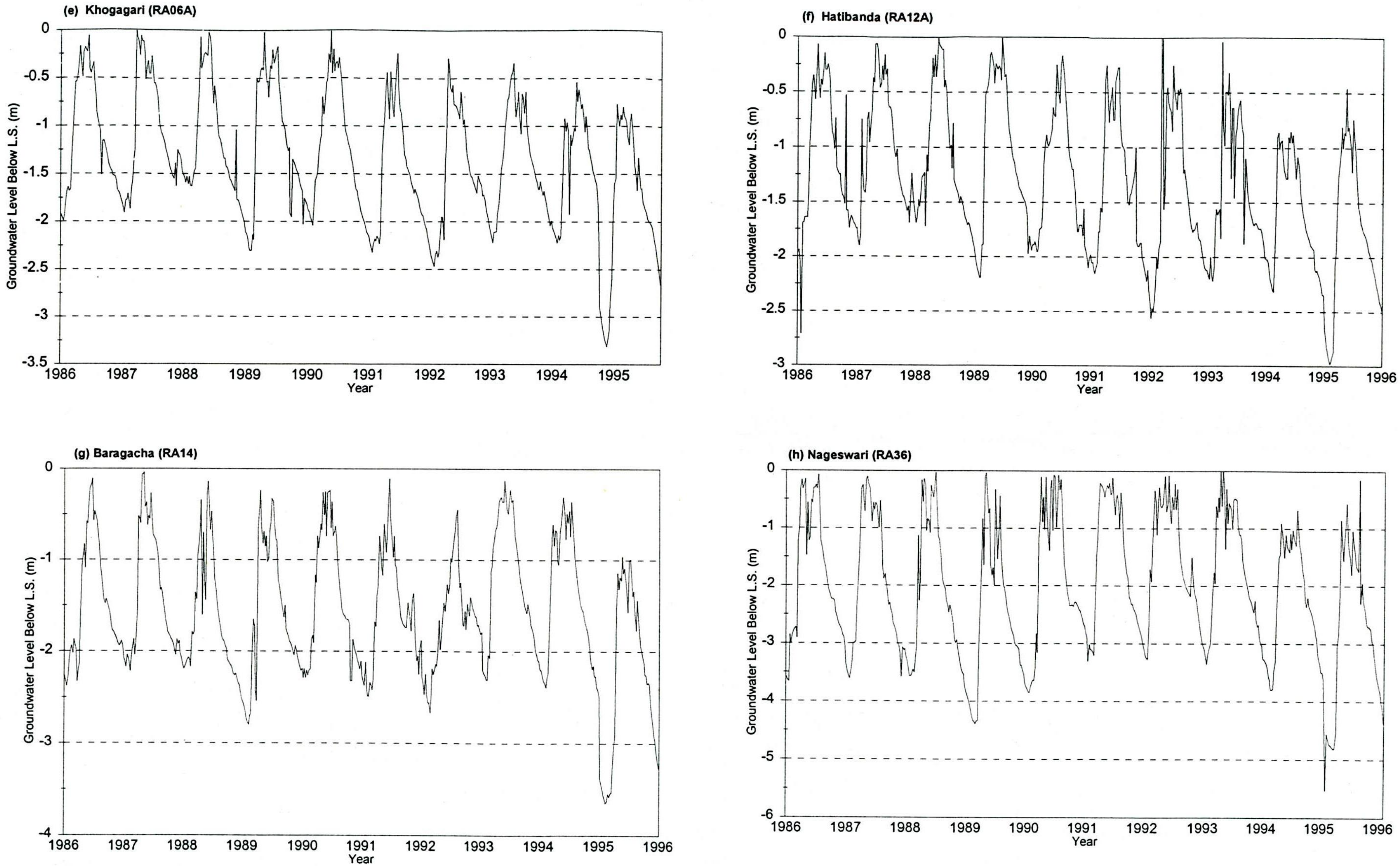

Fig. 7. 7 (Continued)

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Chapter 8

Conclusions and Recommendations

The relatively dry monsoon in 1994-95 has made adverse effect on surfacewater and groundwater availability in Bangladesh. The north-west region of Bangladesh has been affected largely due to the reduction of water available for irrigation. In this regard it is obvious that the information concerning the extremes is more important for agriculture than the average conditions in a region. The longest dry or wet period is of crucial importance in planning agriculture activities and managing the associated water supply systems. Likewise, the total rain over a wet spell is of importance in designing rainwater harvesting systems and predicting runoff volumes and rates.

The present study is mainly divided into 4 parts: these are (i) to find out the stochastic behavior of the longest dry and wet spells in the north-west region of Bangladesh, (ii) to find out the water demand behavior in two small selected drought hard hit areas, (iii) to estimate the groundwater lowering trends in the above two areas compared to the normal years, and (iv) to estimate the damages caused to different types of crops in 1994-95 in the above two areas.

8.1 Conclusions

The following important conclusions can be drawn from the study :

(1) The presented stochastic method under the theory of runs is applied to determine whether an independent or lag-one Markov process are capable of simulating the length of the longest spells and the largest rain-sums during monsoon season in north-west region of Bangladesh. While the independent model appears to be poor simulator of the above process, the Markov model inferred as a promising one just by comparing the simulated and observed cdfs. The above probabilistic expressions for the longest period of spells that one happened to be analytical in nature, are obtained through the application of the theorem of the extremes of

random numbers of a random variable under the coupled substitution from Poisson probability density function of the occurrence of spells and geometric distribution of the length of spells. Likewise, only one analytical probabilistic relationship for the longest rain-sum is obtained by substituting the Weibull and Poisson distribution, respectively for the total rain over a wet spell and for the occurrence of wet spells, in the above extreme theorem. Other distributions (normal, lognormal, gamma pdfs). that are used for the determination of the rain-sum sequences are not resulting into analytical expressions and thus need to apply some tedious integration technique. Although both the Weibull and gamma distribution happened to shows close and better fits in their cdfs, Weibull is going to provide powerful means for rain-sum simulation of any region.

The above entire analysis can be carried out by using five parameters, i.e., mean, variance of the daily rainfall sequences, probability of wet day (p), and conditional probability of wet days (pp) and dry days (qq).

The autorun analysis is applied to different rainfall sequences to determine its dependence structure. It is found that during the pre-monsoon period most of the stations have auto-correlation (c_1) less than 0.5, on the otherhand all the stations selected in the study area have $c_1 > 0.5$ during the monsoon season. The present method that is used for the simulation of largest rain-sums, thus can only be applied for monsoon season. As with any statistical analysis, the first stage is a close inspection of the data for errors and inconsistencies. The discordancy measure that is applied for all the 35 stations in the north-west region of Bangladesh identifies no unusual sites. The contour maps of longest dry or wet spell and largest rain-sum that are drawn for designing any water supply system in the area at different levels of probability, help to identify the regional variation characteristics for longest period of spells and largest rain-sum by visual inspection.

(2) The annual total rainfall in 1994-95 is less than the average rainfall. Water demand analysis provides estimation of irrigation water requirement at different return periods. News media publicised that in 1994-95, the northwest region was affected severely due to water shortage. However it is seen that in 1994-95 the water deficit is not more than the other years. This may be due to the fact that presently farmers are cultivating more irrigated Boro crops than before to meet the increasing food demand. For this reason they need more water than the previous years for irrigation. If the increased water demand can be fulfilled by DTW or from any other source then there may be less loss of crops.

(3) It shows that on an average groundwater levels declined more by 1.5 to 2.0 m in the Kishoreganj and Badaraganj areas compared to other normal years. As a result STWs operated under suction-mode could have run dry earlier and thus deficit in irrigation water was apparent.

(4) Impact of 1994-95 drought on crop and socio-economic condition were obtained by questionnaire survey. In 1994-95 Boro and Aman crops were affected more than other crops. Badarganj was more severly affected area than Kishoreganj.

8.2 Recommendations for Further Study

- The analysis have been carried out using 35 rainfall stations. Further study may be continued covering all other stations available in the region.

- Present study has covered north-west region of Bangladesh and can be extended further to include other regions of the country.

- In the present study 34 years (1962-96) data are used. Future studies can be undertaken by random data generation in order to increase the record length to obtain more reliable analysis.

- In the stochastic analysis Markov process of order one is applied. For further study Markov process of higher order can be applied.

- Irrigation requirement demand analysis is carried out for the Jamuneswari basin under Rangpur districts based on 3 evaporation stations. Future studies can be made for the entire North-West region.

- Questionnaire survey was done after six to seven months of drought period. A survey immediately after the drought may be considered for any further studies in this regard.

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