Application of Palmer Method in Analyzing Drought in Northwest Region of Bangladesh

Submitted by

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CERTIFICATION OF THESIS

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LIST OF ABBREVIATION

τ	Mean Annual Rainfall
μ_r	Mean Half-monthly Rainfall
$\overline{D}$	Mean of Absolute Values of d (Precipitation Excess or Deficiency)
ρ	Probability Plot Correlation Coefficient
α	Coefficient of Evapotranspiration
α	Level of Significance
δ	Coefficient of Loss
β	Coefficient of Recharge
γ	Coefficient of Runoff
Δ	Half-monthly Increment,
ν	Weighted Value
μ_d	Mean Half Monthly Deficit
AWC	Available Water Holding Capacity
BARC	Bangladesh Agricultural Research Council
BMD	Bangladesh Meteorological Department
BWDB	Bangladesh Water Development Board
c	Carry Over (excess or deficit rainfall)
CAFEC	Climatically Appropriate For Existing Conditions
CMI	Crop Moisture Index
d	Precipitation Excess or Deficiency
DARMA	Discrete Autoregressive –Moving Average
DMB	Disaster Management Bureau
E_d	Excess Deficit
ET	Evapotranspiration
EV 1	Extreme Value Type 1
FAO	Food and Agricultural Organization
FAP	Flood Action Plan
ffGn	Fast Fractional Gaussian Noise
f_t	Half-monthly Weighting Factor
G(x)	Cumulative Probability of Non-zero Values of x
H	Hurst Coefficient
H(x)	Cumulative Probability of x
I	Index of Drought Intensity,
in.	Inches
K	Monthly Weighting Factor
L	Loss
LN-2	2-parameter Log-Normal Distribution
L_s	Loss from the Surface Layer Soil
L_u	Loss from the Underlying Layer Soil
Mm^3	Million Cubic Meter
MARD	Mean Annual Rainfall Deficit
mm	Millimeter
n	Sample Size
NW	Northwest

NWMP	National Water Management Plan
NWP	National Water Plan
NWPo	National Water Policy
P	Precipitation
P3	Pearson Type III Distribution
PDSI	Palmer Drought Severity Index
PE	Potential Evapotranspiration
P_e	Probability to End a Drought or Wet Spell
PL_s	Potential Loss from the Surface Soil
PL_u	Potential Loss from the Underlying Soil
PR	Potential Recharge
PRO	Potential Runoff
PSI	Palmer Severity Index
q	Probability that x is Zero
Q	Total Amount of Wetness/Dryness Required to End a Drought/wet Spell
R	Recharge
R_a	Actual Rainfall Value
R_e	Effective Rainfall
RO	Runoff
R_s	Recharge to Surface Layer Soil
R_u	Recharge to Underlying Layer Soil
S	Weighted Drought Severity Index
SD	Stress Day
SDI	Stress Day Index
SI	Stress Index
SMI	Soil Moisture Index
SPI	Standard Precipitation Index
S_s'	Surface Layer Soil Moisture at the Beginning of a Month
STW	Shallow Tube well
S_u'	Underlying Layer Soil Moisture at the Beginning of a Month
T	Drought Period
t	Student's t Statistics
UNDP	United Nations Development Program
V	Total Amount of Wetness/Dryness Achieved for the Month being Considered
V_d	Effective Dryness
V_w	Effective Wetness
WARPO	Water Resources Planning Organization
X	Drought Severity
X1	Probability to Begin a Wet Spell
X2	Probability to Begin a Drought Spell
X3	Severity of an Established Spell
YDi	Drought Yield
z	Moisture Anomaly Index
z_e	z Value to End a Drought/wet Spell in a Single Month

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ABSTRACT

In the present study, an attempt has been made for applying the Palmer method in drought analysis in the Northwest (NW) region of Bangladesh. Palmer Drought Severity Index (PDSI) actually uses a supply and demand model for the amount of moisture in the soil. The method defined drought period as an interval of time during which the actual moisture supply at a given place falls short of the climatically expected or appropriate moisture supply.

In the study the PDSI was calculated on monthly basis as per original formulation by Palmer, though a shorter timescale is more appropriate for irrigation scheduling in Bangladesh. The drought analysis by the method showed that all of the stations of NW region experienced some degrees of drought conditions. The method quantified the average occurrence of drought in the region in 34 percent of the study time from 1972 to 2002. The available literature shows that the average occurrence of drought is once in 2.5 years. The method identified the most common drought occurrences in years like 1972-73, 1975-76, 1976-77, 1978-79, 1979-80, 1982-83, 1992-93, 1994-95, 1999 and 2001-2002 in selected fifteen stations in the region. Thus the method could identify the historical drought occurrences of Bangladesh like the year 1975, 1979, 1981-82, 1984, 1989, 1992-93 and 1994-95. The occurrences of extreme drought conditions were observed only in 3.6 percent of total time. In the study, the Palmer method has identified the month of October rather than November or December as the beginning of highest percentage of drought spells in the region. The method could identify Kharif droughts during the period from June/July to October. The method has identified the month of April rather than May or June as the ending of highest percentage of drought spells in the region.

The suitability of the application of the Palmer method as a drought analyzing tool in NW region of Bangladesh has been assessed in the study by comparing the results of this method with those obtained from two other methods: i) the Standard Precipitation Index (SPI) method and ii) the Herbst method. The comparison was made in terms of several drought features such as the onset and termination of drought, duration and severity. The SPI is a standardized transform of the probability of the observed

precipitation. The method used half-monthly observed rainfall data to analyze drought on the monthly time scale. The Herbst method quantified droughts on a half-monthly time scale using different drought parameters such as mean half-monthly rainfall, weighting factors, carry over, mean half monthly deficit etc. The method has no drought severity scale rather provides relative measures of droughts. The average occurrence of drought was in 22.3 percent and 22 percent of study time in the SPI and the Herbst methods respectively. These two methods have also identified the same drought years in NW region as in the Palmer method in the present study. The highest percentage of beginning of drought spells occur in the months of March and November respectively in the SPI and Herbst methods while the highest percentage of ending of drought spell occurs in the month of April in the SPI method and in May/June in the Herbst method.

While applying Palmer method in drought analysis of NW region of Bangladesh, some limitations were noticed in addition to those already identified by many researchers. Despite these limitations, the performance of the method in comparison with the SPI and Herbst methods seems realistic in NW region of Bangladesh in terms of drought occurrences and severity. But a more detailed study is recommended for quantitative assessment of the influence of soil moisture on drought occurrences in Bangladesh. The Palmer method can be used extensively for monitoring drought conditions and for making operational water management decisions in Bangladesh after some modifications to the method.

Chapter 1
INTRODUCTION

1.1 General

The climatic environment of uncertainty is one of the major threats in water resources management. Drought as environmental phenomenon is an integral part of climatic variability. Droughts are regional events and their occurrences are governed by regional climatic parameters like precipitation, evapotranspiration, temperature etc. So the characteristics and consequences of drought vary with respect to climatic regimes around the world. Despite this, analysis of drought events is very crucial for managing water resources in a sustainable manner.

Drought means various things to various people depending on their specific interest (Palmer, 1965). To the farmer drought means a shortage of moisture in the root zone of crops. To the hydrologist drought means below average water levels in the streams, lakes, reservoirs and the like. To the economist, drought means a shortage which affects the established economy (Palmer, 1965). Wilhite and Glanz (1985) recognized four types of drought, 1) meteorological, 2) hydrological, 3) agricultural and 4) socio-economic. Meteorological droughts are deemed to occur when rainfall is below the range of values considered as normal (Panu and Sharma, 2002). Linsley et al. (1975) considered hydrological drought as a period during which stream flows are inadequate to supply established uses under a given water management system. Agricultural drought is said to exist when soil moisture is depleted so that yield of plants is reduced considerably. Meteorological and hydrological droughts are the subject of numerous researches since all other types of drought occur as a result of these two types. If one is interested in determining the causes of drought events, attention should be focused on precipitation occurrence; if one is interested in determining the effects and impacts of drought events, attention should be focused on agricultural production (Draucup et al., 1980).

Droughts may be classified as i) permanent drought, ii) seasonal drought, iii) contingent drought and iv) invisible drought (Thornthwaite, 1947). Permanent drought occurs in desert areas where rainfall never equals water requirements in any season. Seasonal drought occurs in regions that have well-defined rainy and dry seasons. These droughts occur each year and result from large scale seasonal circulation changes. Contingent drought results from irregular and non-uniform distribution of rainfall. This drought occurs in sub-humid and humid areas as a result of non-occurrence of rain over a significant period. Invisible drought is not easily recognizable. It may occur at any time when moisture supply fails to satisfy water demands of plants. The last three types of droughts are likely to occur in Bangladesh (DMB, 1998).

1.2 Background of the study

The National Water Management Plan (NWMP) considers occurrences of drought as a major water deficiency related issue in northwest region of Bangladesh (WARPO, 2001). Inadequate water availability due to less rainfall than normal resulting reduced groundwater recharge, inferior ecosystem maintenance and subsequent low-grade cropping and household works is termed as drought in respect of Bangladesh. National Water Plan (NWP, 1991) described that uneven and inadequate rainfall can greatly reduce crop production. They defined droughts as very severe, severe, moderate and slight according to yield loss. Average occurrence of drought in the country is once in 2.5 years (Adnan, 1993; Ericksen et al., 1993; Hossain, 1990). Between 1960 and 1991, nineteen droughts have been occurred in Bangladesh (Mirza and Paul, 1992). World Bank (2000) identified very severe droughts occurred in 1951, 1961, 1975, 1979, 1981-82, 1984 and 1989. The year 1994-95 was also a severe drought year in Bangladesh (Rahman, 1995, Sajjan, 1998). The 1994-95 drought was felt very severely among the farmers because of scarcity of irrigation water in the dry season for the recently introduced HYV paddy in the region. The same intensity of drought in the far past was not of such concern when there was no irrigation demand for HYV paddy, particularly in the dry season. Droughts severely affect the crop output of Bangladesh. Saleh et al. (1996) studied that droughts affect crops in the most at two stages of the crop season in a rainfed lowland rice system – i) prior to transplantation and ii) at the beginning of ripening period. Karim et al. (1990) identified two critical drought periods – (i) Rabi and pre-

Kharif droughts (January – May) due to cumulative effect of dry days, higher temperatures and low soil-moisture availability, and (ii) Kharif droughts (June/July – October) due to sub-humid and dry condition in the highland and medium high land areas. Apart from loss to agriculture, droughts have significant effects on land degradation, livestock population, employment and health. Past droughts have typically affected about 47 percent area of the country and 53 percent of the population (Task Force, 1991). Climate change issue also would bring Bangladesh at higher risk due to droughts (World Bank, 2000).

Most of the research activities of Bangladesh emphasized on floods rather than droughts. This may be due to the fact that droughts have silent impact to the society while floods have immediate adverse effects (Bhuiyan et al., 2002). National Water Policy (NWPo) gives emphasize on drought monitoring and contingency plans for regions experiencing recurrent seasonal shortage of water. The drought early warning system required by NWPo has two basic components: a data collection and reporting system and an analysis system (NWPo, 2000).

In order to assess the impacts of drought it is necessary to detect several drought features such as the onset of drought, duration and severity (Dalezious et al., 2000). There is an extensive literature for the quantitative assessment of droughts including indices, models and water balance simulations (Palmer, 1965; Alley, 1985; Karl et al., 1987; Prout et al., 1986; Lana and Burgueno, 1998; Fernandez and Vergara, 1998; Stahl and Demuth, 1999). In Bangladesh, Karim et al. (1990), Alam (1994), Saleh et al. (1996), Datta (1997), Sajjan (1998), Bhattacharyya (1999), BARC (2001) and many others studied drought using different approaches. The Palmer Drought Severity Index (PDSI) has not yet used in Bangladesh for quantification of drought. The PDSI was world-wide used in many research studies, namely, Karl (1986), Kothavala (1997), Piechota and Dracup (1999). It was also applied on an operational basis in the United States (Lohani and Loganathan, 1997). There are also successful applications of the PDSI in Canada (Louie, 1986), Argentina (Scian and Dounari, 1997), Hungary (Szinell et al., 1998), Australia (Kothavala, 1999) and Greece (Dalezios et al., 2000).

In this research, an attempt was made to assess the suitability of widely accepted Palmer method for analyzing drought in Bangladesh.

1.3 Objectives of the study

The present study has been carried out with a possible outcome of developing an effective method of drought analysis in Bangladesh. The Palmer method is a widely accepted drought analyzing tool. In this study the applicability of the Palmer method in drought analysis of Bangladesh has been examined and compared with other methods to see its performance. Thus the specific objectives of this research are:

1. To identify the onset and termination of drought spells by the Palmer method.
2. To determine the duration of drought spells, their severity and frequency of occurrences by the Palmer method.
3. To compare the results of the Palmer method with two other drought analyzing methods: i) Herbst et al. (1966) and ii) McKee et al. (1993).
4. To recommend the suitability of the Palmer method in drought analysis of Bangladesh.

1.4 Organization of the thesis

The thesis has been organized in eight chapters. Introductory aspects like background of the study, objectives of the study etc. are discussed in chapter one. Chapter two contains the available literature related to drought studies carried out in Bangladesh and also in other countries. Chapter three deals with the study area and data collected for the study. Chapter four describes the Palmer (1965) method while chapter five describes details of the other two drought analyzing methods used in the study namely the Standard Precipitation Index (SPI) method (Mckee et al., 1993) and the method of Herbst et al. (1966). The findings of the Palmer method such as occurrences of drought, their duration, severity etc. are presented in chapter six. The Palmer method is compared with two other methods in chapter seven to see its performance as a drought analyzing tool in Bangladesh. Conclusions are drawn and some recommendations are made in chapter eight.

Chapter 2
LITERATURE REVIEW

2.1 General

The lack of precise and objective definition of drought is one of the principal obstacles to the investigation of drought (Yevjevich, 1967). This often leads to confusion among decision makers about what constitutes a drought. Drought may occur in high as well as low rainfall areas. Drought is a creeping hazard since it develops slowly and has a prolonged duration (Smith, 2000). Its impacts are different in different regions even if all the natural conditions are the same. So drought is considered as a relative term. Generally drought refers to a deficiency of adequate water from established sources to meet the need of users. The availability of water depends largely on rainfall. That is why occurrence of rainfall is considered as the best single index of drought. Drought can be characterized by specifying minimum water needs for a particular purpose. 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 by which the amount is less than the requirement (Gibbs and Maher, 1967). In the following sections, the available literature on different methods of drought analysis is briefly described.

2.2 Methods of drought analysis

Every water user has its own concept of drought. Various methods of drought analysis relevant to specific water uses or to specific disciplines have been classified. Statistical tools are usually applied for hydrological and meteorological drought analysis. Horn (1989) applied the theory of runs to streamflow sequences in Idhao which permitted the assignment of return periods to historical drought events based on statistical characteristics of the streamflow record. Agricultural droughts are viewed as the effect arising from the hydrological and meteorological droughts. Several researchers around the world are interested in analysis of drought in terms of duration, magnitude and severity. Analyses based on hydrological, agricultural and meteorological domains developed for identification of drought are presented in the following sub-sections.

2.2.1 Meteorological drought analysis

Palmer (1965) developed an index known as Palmer Drought Severity Index (PDSI) for quantifying severity of the effects of meteorological drought. The PDSI is widely used in many drought studies. Scale of PDSI runs from "mild" to "moderate" to "severe" to "extreme". The normal range of PDSI values are from –0.5 to +0.5. Any PDSI value above +4.0 or below –4.0 falls into the "extreme" categories of wet spell or drought. Palmer described the severity of a drought effect is proportional to the relative change in climatic parameters. It defined drought period as an interval of time during which the actual moisture supply at a given place falls short of the climatically expected or appropriate moisture supply. Palmer considered the severity of drought as a function of both the duration and magnitude of the moisture deficiency. A given PDSI value represents not only the current conditions, but also recent past conditions to a certain extent. Thus it reflects the progression of the trends, whether it is a drought or a wet spell. Since PDSI identifies wet spells in addition to drought spells, it is also called as Palmer Severity Index (PSI). Palmer (1968) developed another index known as Crop Moisture Index (CMI) to evaluate moisture conditions. While PDSI evaluates long-term meteorological dry and wet spells, CMI evaluates week-to-week crop conditions. CMI is based on the mean temperature and total precipitation for each week within a climatic division, as well as CMI value from the previous week.

Alley (1985) investigates the relationships between PDSI for climatic divisions and streamflow and groundwater conditions within each division. In his paper the PDSI for climatic divisions in New Jersy has been compared to the occurrence within each climatic division of streamflows in their lower quartile for the month (streamflow index) and groundwater levels in the lower quartile for the month (groundwater index). 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. 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 the 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 occurrences 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 extremes of random number of a random variable (Todorovic and Woolhiser, 1975). 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 drought in Australia by classifying the annual precipitation using the decile range. The distribution of occurrences over a long term precipitation record was divided into tenths of the distribution. Each of these categories was called deciles. The first decile range and the tenth decile range were considered as abnormally dry or drought and abnormally wet respectively. Delleur et al. (1989) and Chang et al. (1984) 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 process, which include the Markov chain as a particular case.

Mckee et al. (1993) developed a drought index known as the Standard Precipitation Index (SPI) to enhance the detection of onset and monitoring of drought. The SPI is a simpler measure of drought than PDSI and is based solely on the probability of precipitation for a given time period. A key feature of the SPI is the flexibility to measure drought at different time scales of interest (1 month, 3 months, 6 months, 12 months, 48 months, etc.). The severity of drought can be compared to the average condition for a particular station or region. Values range from 2.00 and above (extremely wet) to -2.00 and less (extremely dry) with near normal conditions ranging from 0.99 to -0.99.

Chowdhury and Hussain (1983) studied the aridity and drought conditions of Bangladesh. In that study, the aridity index (Martonne, 1926) was used to find out the aridity condition while the decile concept of Gibbs and Maher (1967) was used to investigate drought conditions of Bangladesh. The aridity index was calculated considering precipitation and temperature data. Disaster Management Bureau of Bangladesh (DMB, 1998) studied drought conditions using the index developed by Bhalme and Mooley (1980). Only precipitation data was used for the analysis. The index values range from greater than +4.0 (extreme wet condition) to less than -4.0 (extreme dry condition) with the normal conditions ranging from 0.99 to -0.99.

Northwest region is considered as drought prone area in Bangladesh specially Barind Tract. Several studies were carried out for analyzing meteorological drought in northwest region. Alam (1994) studied the statistical characteristics of climatic drought in the Teesta Barrage project area. In the study, drought was defined as the difference between potential evapotranspiration and rainfall. The study calculated 10-day yearly drought maxima since irrigation requirement is usually applied on 10-day basis. The Extreme Value Type I (EV1) distribution was fitted to 10-day drought maxima. Sajjan (1998) studied 1994-95 drought characteristics in northwest region. The persistent behavior of dry and wet spells of rainy seasons was studied using Markov (order 1) process under the theory of runs. Markov model was seemed to be promising for determining the drought and wet periods. Bhattacharyya (1999) studied drought in northwest region in terms of deficiency of crop water requirement. The characteristics of surplus and deficiency of crop water requirements in periodic stochastic process were studied on the basis of theory of runs and direct enumeration technique. In the present study drought analysis in northwest region would be carried out by the Palmer method and the results would be compared with the methods developed by Mckee et al. (1993) and Herbst et al. (1966).

2.2.2 Hydrological drought analysis

Gumbel (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. These are 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 in 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 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 (1980) 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 those 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 periodicities 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 analysis is the 'drought magnitude and drought duration criteria'. A fourth alternative is based on simultaneous generation of annual and monthly series by jointly preserving their parameters such as the variance and serial correlation coefficients among others. Majumder (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. Chang (1990) studied the effect of drought on stream flow characteristics. He defined drought events as periods 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. Shen 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.

2.2.3 Agricultural drought analysis

BARC (2001) developed a practical national methodology for drought assessment in Bangladesh. In the study drought was considered as an imbalance (on the dry side) between water availability and water demand. The researchers selected precipitation, water flows, storage of groundwater and surface water and soil moisture as drought defining components. According to the study, the drought can be caused by one of these deficits or a combination: i) lack of precipitation, ii) lack of surface water or groundwater availability for irrigation purposes and iii) lack of irrigation water due to failing technical means. The agricultural drought occurred due to lack of rainfall and/or irrigation water causes reduction of crop yield. The relationship among drought defining components is shown in Figure 2.1. In 1990, BARC produced two drought classification maps by using the agro-ecological database (FAO/UNDP, 1988) to categorize drought situations. In the study, droughts were classified as Kharif drought and pre-Kharif drought.

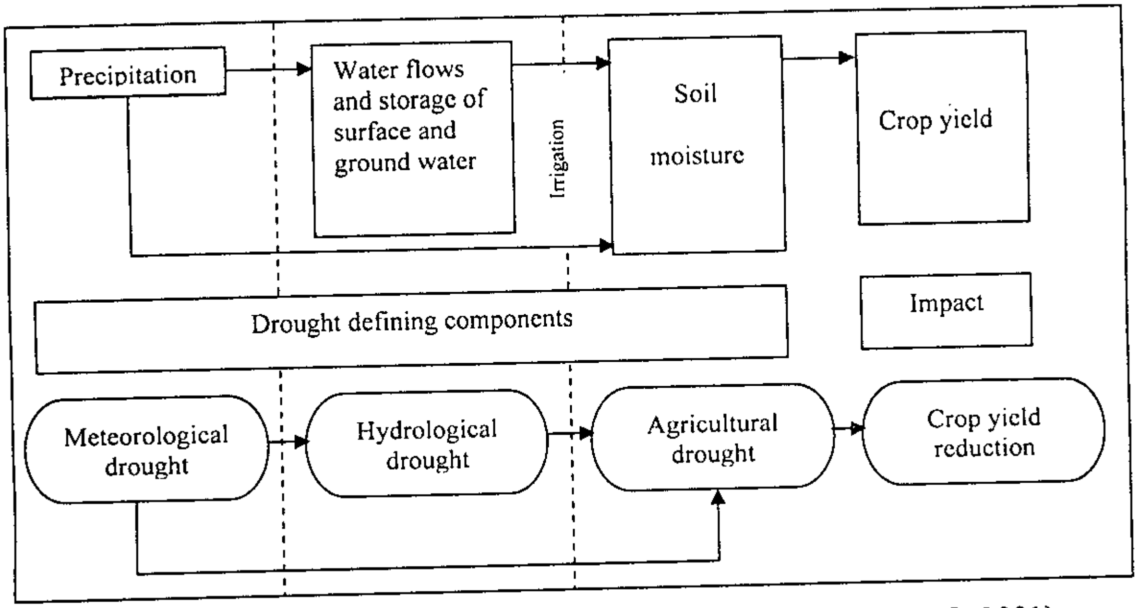


Figure 2.1 Relation among drought defining components (Source: BARC, 2001)

Karim et al. (1990) developed a methodology 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 intensity in the drought prone areas, 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. Kharif drought was delineated based on the percentage of sub-humid and dry decades present in each Kharif humid period. The dry sub-humid decades were defined as a period when precipitation is less than half of the potential evapotranspiration, while the dry decades were defined as a period when there is no precipitation. The total number of dry days was derived from the percentage of decades in each Kharif humid period. Using these parameters and available soil moisture in the highland and medium highland, Kharif drought prone areas were classified. Rabi and pre-Kharif drought was classified based on the cumulative effects of dry days, higher temperature during pre-Kharif season and low soil moisture storage. Droughts have been again subdivided into several classes depending on the intensity 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 property of time series, provide useful parameter 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 the methodology for analyzing agricultural drought. In the study, techniques of constructing and analyzing models have been introduced to simulate the relationship between hydrologic droughts to crop yields. Saleh et al. (1996) analyzed the nature, extent and frequency of droughts in the monsoon season in a rainfed lowland rice system of north-west Bangladesh by using the method of water balance from long term rainfall data and from two-year field studies. The study shows that droughts are expected at the beginning of the crop season prior to transplantation and from the beginning of the ripening period. 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.

Chapter 3

STUDY AREA AND DATA USED

3.1 Study area

The North-West (NW) region of Bangladesh (Figure 3.1) spanning from the latitude 23°50′ N to 26°30′ N and longitude 88°10′ E to 89°45′ E is selected for the present study, since it is the most drought prone area of the country. The region is bounded by the two major rivers in two sides, the Jamuna in the east and the Ganges in the South. The Indian borders are on the north and west sides of the region. It slopes from the north towards the southeast with an altitude range of 90 m to less than 10 m above sea level. The Barind and alluvial tracts are the main physiographic units of the region. The Barind Tract consists mainly of non-alluvial soils at the middle of the region while the alluvial tract has the Himalayan piedmont plains in the north, and lowlands along the Jamuna and the Ganges system. The region occupies a total area of 32000 km^2 (SWMC, 1996) with a population density of about 980 persons per sq. km.

Out of seven hydrological units of Bangladesh, the NW region is more vulnerable to climatic variations. The region has a typical monsoon climate. Average annual rainfall ranges from less than 1500 mm to 3000 mm with a regional average of about 1900 mm. Eighty percent of the annual rainfall occurs during the five months monsoon season between May and September. In the midst of monsoon, an occasional short dry period up to 23 days-known as monsoon break (Mahalnobis, 1927; FAP-25, 1992) persists in the NW region of Bangladesh (Bhuiyan and Sajjan, 1998). Occasional rainfall occurs in dry season from November to February. Due to subtropical location, temperature variations are more pronounced in NW region. Maximum temperature ranges from 35°C in April/May to 25°C in January and the minimum temperature varies from 20°C in August to 10-11°C in January. The humidity levels are consistently very high during the monsoon season and drop significantly at the end of dry season. Sunshine levels are low during monsoon and high from November to May. Wind speeds are maximum in the early monsoon and drops at the beginning of the dry season. Evapotranspiration reaches maximum in April when temperature, sunshine and wind are all at or close to the maximum value for the year, while humidity is less than maximum. Evapotranspiration is exceeded by average rainfall during May to October, but for the remaining months it is higher than rainfall. WARPO (2000) estimated soil moisture available in 1 m of soil in NW region considering rainfall, flooding condition, thickness of root zone, the soil type and the flood phase.

NW region is highly developed agriculturally with the largest irrigated area among all the regions supplied mainly by Shallow Tube Wells (STWs). The annual (gross) usable recharge is 322 mm in NW region (WARPO, 2000) or 10156 Mm^3 and the usable recharge by STW is 8726 Mm^3. Variations in seasonal rainfall are of great concern due to intense cultivation in the region. Aus (Kharif I), Aman (Kharif II) and Boro (Rabi) are three important crops grown in NW region. Aus grown in Karif I season often suffers from drought in early part of the season due to insufficient rainfall and its uneven distribution. Aman cultivation in Kharif II is sometimes delayed due to early drought and resulted in a delay in harvesting. Normal rainfall in the post monsoon season is also very important for early Rabi and seedlings of Boro crops.

3.2 Data used in the study

In the present study drought analysis were carried out in the NW region by the Palmer method (1965) based on 31 years meteorological data starting from 1972. It was assumed that the analysis based on recent meteorological data would provide a reasonable assessment of drought condition at any time. The suitability of the Palmer method was examined by comparing the method with two other methods developed by i) MacKee et al. (1993) and ii) Herbst et.al (1966). The monthly total rainfall, monthly mean temperature, and soil moisture data were used in the Palmer method for characterization of drought. Temperature data were used to calculate the potential evapotranspiration by the Thornthwaites' formula (1955). Half monthly total rainfall data were used in the other two methods for quantification of drought.

Meteorological data

For the rainfall data, fifteen rainfall stations out of 94 rainfall stations in NW region of Bangladesh Water Development Board (BWDB) have been selected. The selection of stations depends on the quality and length of record of available data as well as with the concern so that the stations are uniformly distributed over the region. The temperature data are collected from five meteorological stations of the Bangladesh Meteorological Department (BMD). The geographic locations of the selected stations are shown in Figure 3.2. The meteorological data collected for the present study are listed in Table 3.1. Temperature data are not available in the BWDB rainfall measuring sites. In that case, temperature data were taken from the nearest temperature measuring station to concerned rainfall site.

Soil moisture data

The Palmer method considers the available soil moisture of the area being studied. Available soil moisture is different in different soil texture classes. The soil texture varies in different agroecological zones. FAO/UNDP (1988) divided Bangladesh into different agroecological zones. The agroecological zones (FAO/UNDP, 1988) of the NW region are shown in Figure 3.3. The majority of soils of NW region have loamy and clayey textures. The texture referred to is that of the subsoil, approximately the layer between 20-50 cm. It is the layer which is generally most important in storing soil moisture which plants can use. In the present study, the available soil moisture for the fifteen stations is estimated considering their soil texture and agroecological zones of FAO/UNDP (1988). In FAO/UNDP (1988), the readily available moisture by agroecological region according to soil texture was estimated assuming readily available moisture equivalent to two-thirds of total available soil moisture holding capacity. Details of the available soil moisture data used in the study are given in Table 3.2.

3.3 Consistency and homogeneity tests of rainfall data

Prior to processing the rainfall data, it is necessary to assess the reliability and quality of the available observations and to correct unreliable data by filling the missing data. Inter station correlation of rainfall data is determined in the study to fill the missing data of any station. The missing data of the test station has been filled with the data of nearby station with which it is highly correlated. For example, half-monthly rainfall of the station Rangpur (CL 206) has a good correlation of 0.80 with the neighbouring staion, Kaunia (CL 178). Thus any missing data of Rangpur is filled with the observations of Kaunia. If any station has no good correlation with neighbouring stations, the missing data is filled by using the normal ratio method. In that case the rainfall amounts at the index station are weighted by the ratios of normal annual precipitation values (Summer, 1988).

Kohler (1949) and Berndtsson and Niemczynowicz (1986) noted that a double mass curve may be derived to test short and long periods of rainfall data for homogeneity over time. The mass curve for half-monthly rainfall will normally approach a straight line. If consistent changes in the rainfall regime are present, a clear inflection will appear on the mass curve near the point where the changes occur (Cornish, 1977). In this study, the mass curves are examined in order to know whether the available data are consistent and homogeneous or not. Mass curve results show that the rainfall data of all fifteen stations follow a straight line, which implies that the data are consistent and homogeneous. Some of the double mass curves for half-monthly rainfall data considering Bogra as a base station are shown in Figure 3.4.

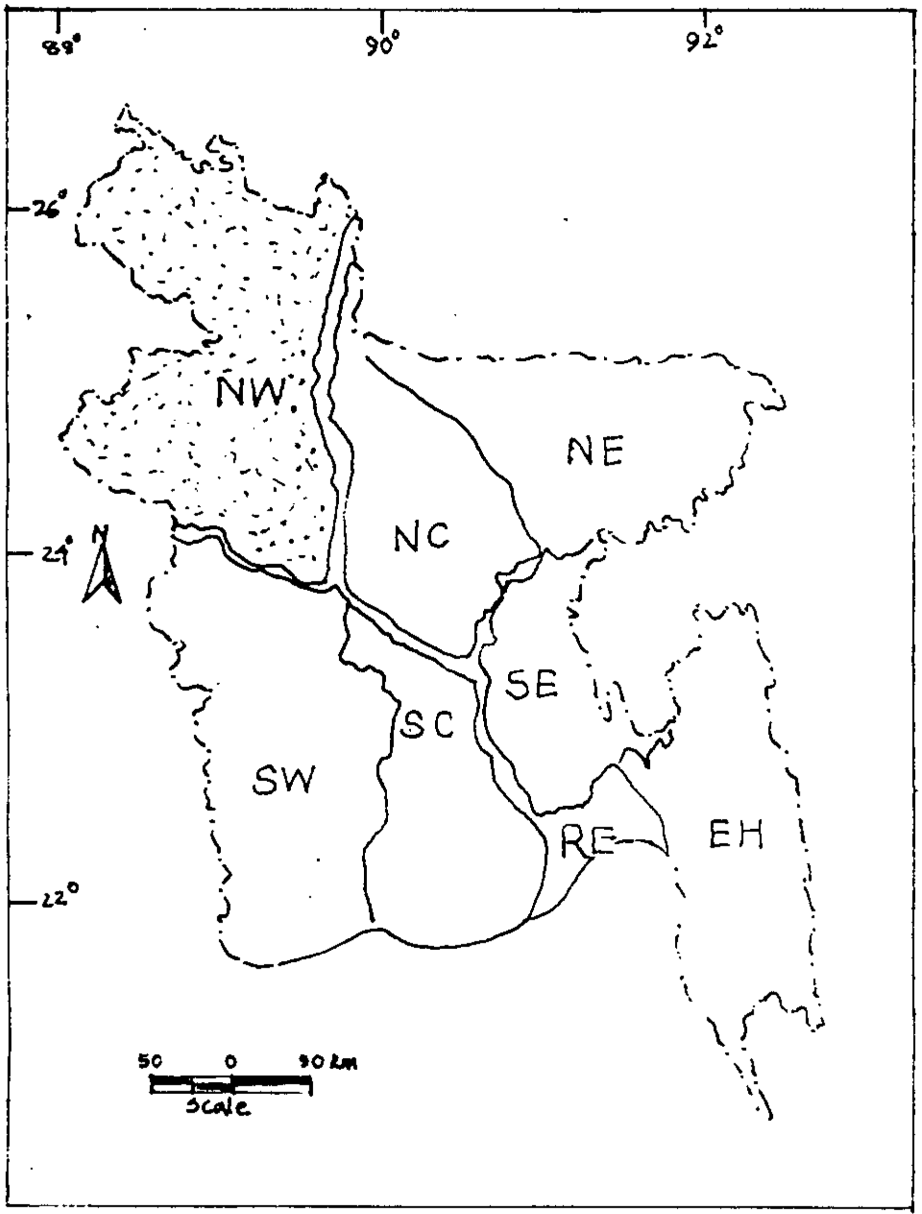


Figure 3.1 Hydrological regions of Bangladesh

Table 3.1 Details of the meteorological data

Types of data	Source of data	Station ID	Station name	Length of record
Daily rainfall	BWDB	CL 001	Atghoria	1972-2002
Daily rainfall	BWDB	CL 006	Bogra	1972-2002
Daily rainfall	BWDB	CL 011	Dhunot	1972-2002
Daily rainfall	BWDB	CL 034	Sirajganj	1972-2002
Daily rainfall	BWDB	CL 036	Singra	1972-2002
Daily rainfall	BWDB	CL 168	Dinajpur	1972-2002
Daily rainfall	BWDB	CL 177	Kaliganj	1972-2002
Daily rainfall	BWDB	CL 178	Kaunia	1972-2002
Daily rainfall	BWDB	CL 186	Mithapukur	1972-2002
Daily rainfall	BWDB	CL 188	Mahipur	1972-2002
Daily rainfall	BWDB	CL 192	Nazipur	1972-2002
Daily rainfall	BWDB	CL 193	Nekmand	1972-2002
Daily rainfall	BWDB	CL 205	Rajshahi	1972-2002
Daily rainfall	BWDB	CL 206	Rangpur	1972-2002
Daily rainfall	BWDB	CL 215	Shibganj	1972-2002
Mean daily temperature	BMD	10120	Dinajpur	1972-2002
Mean daily temperature	BMD	10208	Rangpur	1972-2002
Mean daily temperature	BMD	10320	Rajshahi	1972-2002
Mean daily temperature	BMD	10408	Bogra	1972-2002
Mean daily temperature	BMD	10910	Ishurdi	1972-2002

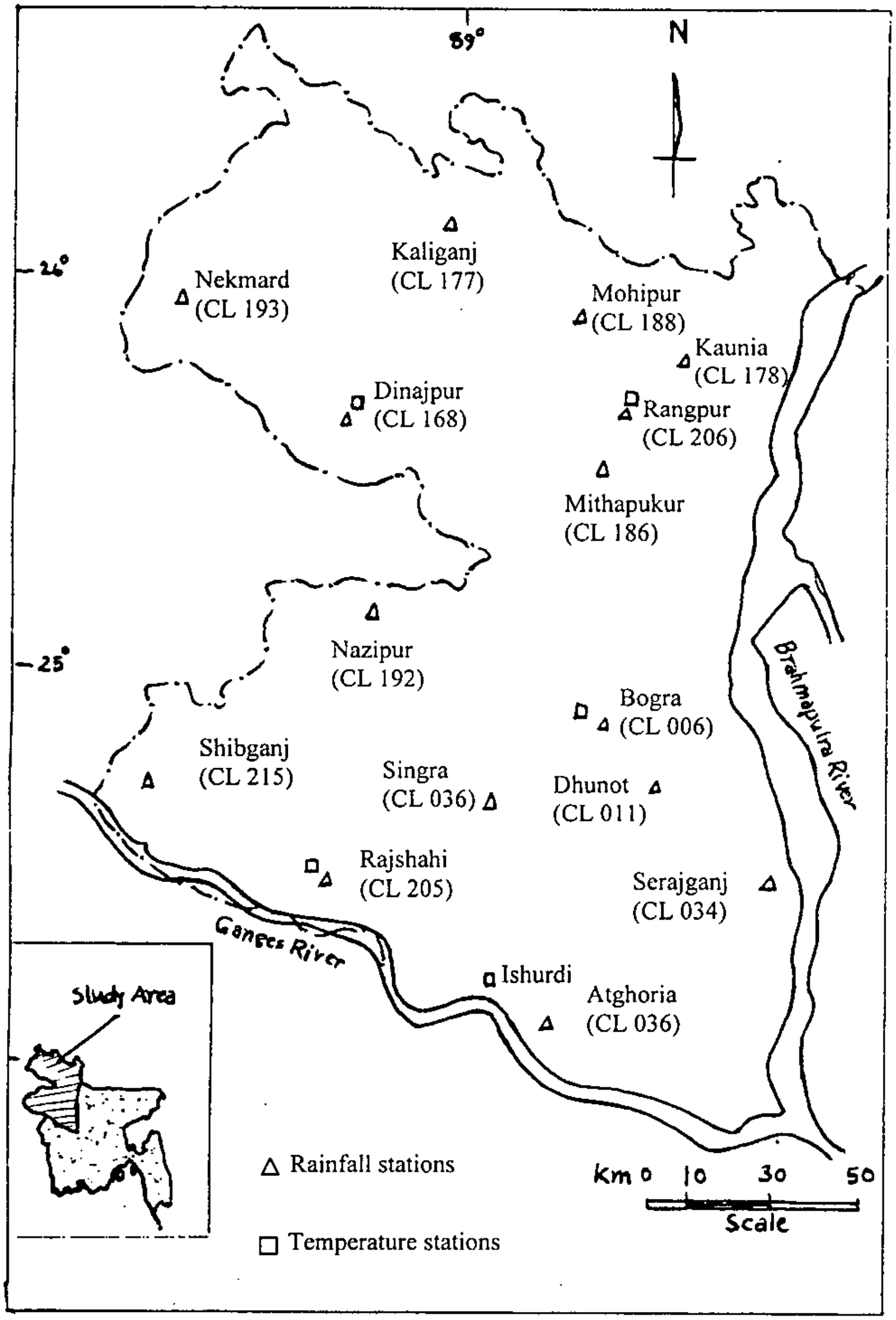


Figure 3.2 Locations of selected stations of Northwest region

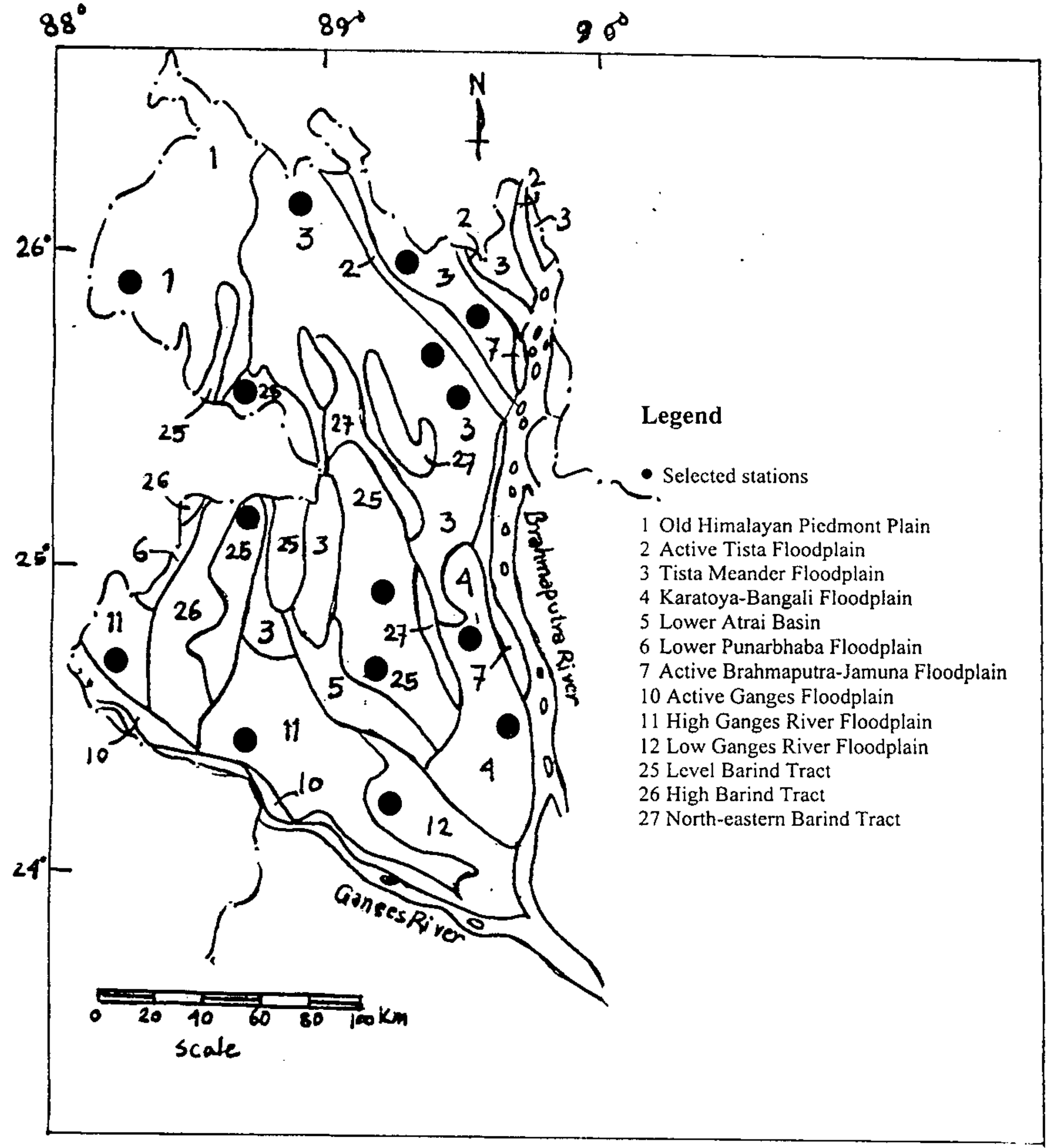


Figure 3.3 Agroecological zones in Northwest region of Bangladesh

(Source: FAO/UNDP, 1988)

Table 3.2 Details of soil moisture data (Source: FAO/ UNDP, 1988)

Name of station	Name of district	Agroecological zone	Main soil texture	Available soil moisture (in/ft)
Atghoria	Pabna	Low Ganges River Floodplain	Clayey	2.34
Bogra	Bogra	Level Barind Tract	Clayey	1.80
Dhunot	Bogra	Karatoya-Bangali Floodplain	Clayey	1.60
Sirajganj	Sirajganj	Karatoya-Bangali Floodplain	Loamy	3.06
Singra	Natore	Level Barind Tract	Clayey	1.80
Dinajpur	Dinajpur	Level Barind Tract	Clayey	1.80
Kaliganj	Lalmonirhat	Tista Meander Floodplain	Loamy	3.60
Kaunia	Rangpur	Tista Meander Floodplain	Loamy	3.60
Mithapukur	Rangpur	Tista Meander Floodplain	Loamy	3.60
Mahipur	Rangpur	Tista Meander Floodplain	Loamy	3.60
Nazipur	Naogaon	Level Barind Tract	Clayey	1.80
Nekmard	Thakurgaon	Old Himalayan Piedmont Plain	Loamy	3.60
Rajshahi	Rajshahi	High Ganges River Floodplain	Loamy	2.96
Rangpur	Rangpur	Tista Meander Floodplain	Loamy	3.60
Shibganj	Nawabganj	Old Himalayan Piedmont Plain	Loamy	2.96

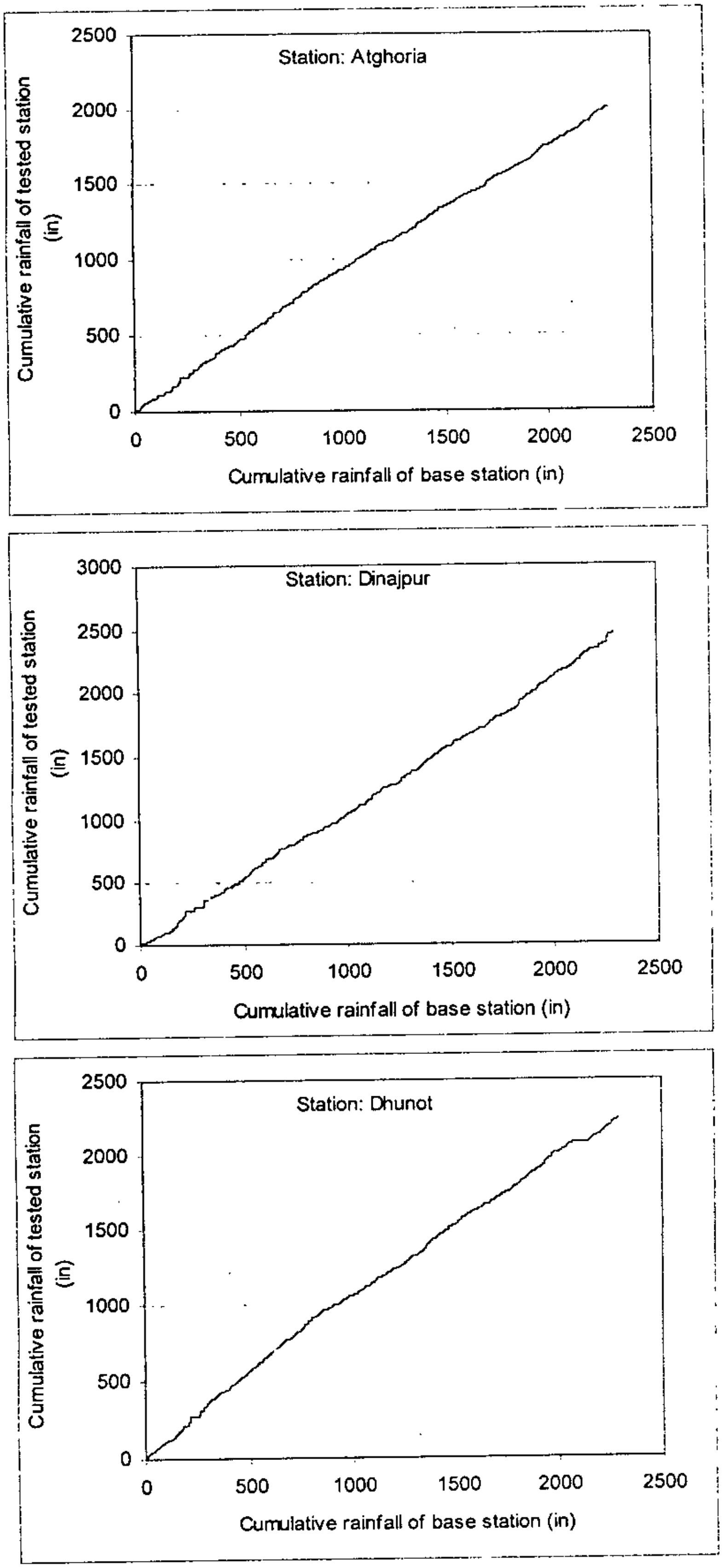


Figure 3.4 Double mass curves for some stations considering Bogra as a base station

Chapter 4
THE PALMER METHOD

4.1 General

Different methods have been used in Bangladesh for analysis of the meteorological droughts in NW region. The present study has mainly focused on the Palmer method (1965) to examine the suitability of the method as a drought analyzing tool in Bangladesh in comparison with other two methods developed by 1) McKee et al. (1993) and 2) Herbst et al. (1966). Those two methods would be treated in the study as the Herbst method and the Standard Precipitation Index (SPI) method respectively. The Herbst method considers the carry over effect to the subsequent half-month to characterize drought. The Palmer method also considers the recent past conditions along with current conditions to determine the drought severity index. On the other hand, the SPI was developed to give a better representation of abnormal wetness and dryness than the Palmer Indices (Guttman, 1998). With these considerations, the Herbst and the SPI methods are chosen in the study to compare with the Palmer method. The concept and methodology of the Palmer method would be described in this chapter while the details of the other two methods would be discussed in the following chapter.

4.2 The concept of the method

Palmer (1965) developed an index known as Palmer Drought Severity Index (PDSI) for quantifying the severity of effects of meteorological drought. The PDSI actually uses a supply and demand model for the amount of moisture in the soil. The supply is the amount of moisture in the soil plus the amount that is absorbed into the soil from rainfall. The demand is the amount of moisture lost from the soil.

Scale of PDSI runs from "mild" to "moderate" to "severe" to "extreme". The normal range of PDSI values are from –0.5 to +0.5. Any PDSI value above +4.0 or below –4.0 falls into the "extreme" categories of wet spell or drought. Palmer described the severity of a drought effect is proportional to the relative change in climatic parameters. It defined drought period as an interval of time during which the actual moisture supply at a given place falls short of the climatically expected or appropriate moisture supply. Palmer considered the severity of drought as a function of both the duration and magnitude of the moisture deficiency. A given PDSI value represents not only the current conditions, but also recent past conditions to a certain extent. Thus it reflects the progression of the trends, whether it is a drought or a wet spell. Since PDSI identifies wet spells in addition to drought spells, it is also called as Palmer Severity Index (PSI). Palmer (1965) assessed droughts using only monthly data of precipitation and temperature. Details of the Palmer method are described in the following sections.

4.3 Considerations and assumptions of the method

The following assumptions were made in the Palmer method by Palmer (1965) for developing drought assessment tool in different climatic regions:

1. The soil is divided into two layers where the upper layer is called the surface layer and roughly equivalent to the plough layer, the other is called the underlying layer.
2. Availability of water in the soil is the combined available capacity of both surface and underlying layers of soils.
3. Surface layer of the soil is assumed to contain 1 inch of available moisture at field capacity.
4. Potential evapotranspiration is the measure of the amount of moisture to be used when the supply is not limited.
5. It is assumed that evaporation takes place at the potential rate from the surface layer until all the available moisture in the layer is removed.
6. Potential loss is assumed as the amount of moisture lost from the soil when precipitation is zero.
7. It is also assumed that there is no recharge to the underlying soil layer until the surface layer is brought to field capacity.
8. Potential recharge is assumed as the amount of moisture required to bring the soil to field capacity.
9. It is assumed that no runoff occurs until both layers of the soil reach field capacity.

10. Potential runoff is assumed as the maximum runoff when potential evapotranspiration is zero. It is also assumed to be a function of the amount of soil moisture available.

11. Potential precipitation is assumed to be equal to available water holding capacity of soil.

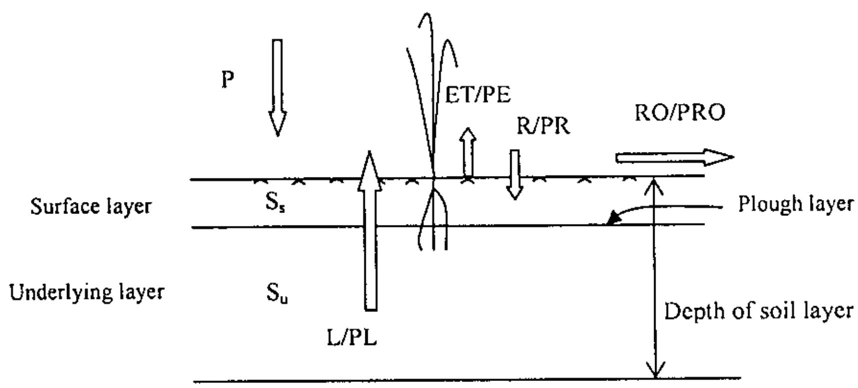
4.4 Steps followed in the method

Palmer used the water balance or hydrologic accounting approach for drought analysis. The procedure considers precipitation, evapotranspiration and soil moisture conditions. The steps followed in the Palmer method to determine the PDSI are listed below:

1. Carrying out a hydrologic accounting by months from a long series of years.
2. Determine coefficients which are dependent on the climate of the area being analyzed using the results obtained in step 1.
3. Determining the amount of moisture required for normal weather during each month using the derived coefficients.
4. Determining the departures and converting the departures to indices of moisture anomaly.
5. Determining the beginning and ending of drought/wet periods and drought/wet severity.

Step 1: Hydrologic accounting

The computation of the PDSI begins with a climatic water balance using long series of monthly precipitation and temperature records as inputs. The parameters considered in hydrologic accounting are shown in Figure 4.1.



P= Precipitation, S_s=Soil moisture in the surface layer
S_u=Soil moisture in the underlying layer, ET/PE=Evapotranspiration and potential evapotranspiration
R/PR=Recharge and potential recharge, RO/PRO=Runoff and potential runoff
L/PL=Loss and potential loss from the soil

Figure 4.1 Parameters considered in the hydrologic accounting

i) Availability of water in soil (AWC)

AWC is the combined available water holding capacity of both surface and underlying layers of soil. It must be representative of the area being considered for drought analysis. The surface layer soil moisture is denoted by S_s while the underlying layer soil moisture by S_u . The available capacity of underlying layer soil depends on the depth of the soil and on the soil characteristics in the area under study.

ii) Evapotranspiration

Potential evapotranspiration (PE) is computed using Thornthwaite's formula (1955) in the Palmer method. In the present study, this formula has also been used to estimate the PE values in order to keep consistency with the original Palmer method. The Thornthwaite's formula (1955) is described in Appendix I.

Actual evapotranspiration (ET) is a function of potential evapotranspiration and the dryness of the soil. Estimates of ET depend on realistic volume of AWC of soils in the study area. It also depends on loss (L) of the soil.

<u>Computation of ET</u>:

If $P \geq PE$, $ET=PE$ ....(4.1)

If $P<PE$, $ET=P+L$ ....(4.2)

iii) Loss from the soil

Actual loss (L) consists of surface layer loss (L_s) and underlying layer loss (L_u). Thus

$L = L_s + L_u$ ....(4.3)

It is assumed that the loss from the underlying layer depends on initial moisture content, PE and AWC of the soil.

<u>Computation of L</u>:

If $P \geq PE$, $L_s = 0$, $L_u = 0$ ....(4.4)

If $P<PE$,

$$\left.\begin{array}{l} \text{i) if } (PE-P)>S_s',\ L_s = S_s' \\ L_u = (PE-P-L_s)\times(S_u'/AWC) \end{array}\right\} \text{------} \quad (4.5)$$

$$\left.\begin{array}{l} \text{ii) if } (PE-P)<S_s',\ L_s = PE-P \\ L_u = 0 \end{array}\right\} \text{----------} \quad (4.6)$$

where S_s' and S_u' are the amounts of available moisture at the beginning of the month in the surface and the underlying layers respectively.

Potential loss (PL) is defined as

$PL = PL_s + PL_u$ ....(4.7)

where, PL_s is the potential loss from the surface layer

and PL_u is the potential loss from the underlying layer

<u>Computation of PL</u>:

$$\left.\begin{array}{l} \text{If } S_s' \geq PE,\ PL_s = PE \\ PL_u = 0 \end{array}\right\} \text{----------} \quad (4.8)$$

$$\left.\begin{array}{l} \text{If } S_s'<PE,\ PL_s = S_s' \\ PL_u = (PE-PL_s)\times(S_u'/AWC) \end{array}\right\} \text{----------} \quad (4.9)$$

iv) Recharge

Actual recharge (R) consists of recharge to surface layer (R_s) and recharge to underlying layer (R_u). Thus

$R = R_s + R_u$ ....(4.10)

<u>Computation of R</u>:

$$\left.\begin{array}{l} \text{If } P \geq PE, \text{ i) if } (P-PE) > (1-S_s'),\ R_s = 1 - S_s' \\ \qquad\qquad \text{if } (P-PE-R_s) \geq (AWC-1-S_u'),\ R_u = AWC-1-S_u' \\ \qquad\qquad \text{if } (P-PE-R_s) < (AWC-1-S_u'),\ R_u = P-PE-R_s \end{array}\right\} \text{----------} \quad (4.11)$$

$\qquad$ ii) if $(P-PE) \leq (1-S_s')$, $R_s = P-PE$, $R_u = 0$

If $P < PE$, $R_s = 0$, $R_u = 0$ ....(4.12)

Potential Recharge (PR) is a measure of moisture that is added when rainfall is enough. PR is defined as the amount of moisture required to bring the soil to field capacity. PE is the maximum water requirement of a region. If precipitation exceeds PE, there is addition of soil moisture instead of depletion. Then PE values remain invariant and moisture requirements during the period are related to the PR. <u>Computation of PR</u>:

$PR = AWC - S'$ ....(4.13)

$S' = S_s' + S_u'$ ....(4.14)

v) Runoff

<u>Computation of actual runoff (RO)</u>

$$\left.\begin{array}{l} \text{If } P > PE, \text{ i) } (P-PE) > (1-S_s'), \\ \qquad\qquad \text{if } (P-PE-R_s) < (AWC-1-S_u'),\ RO = 0 \\ \qquad\qquad \text{if } (P-PE-R_s) \geq (AWC-1-S_u'),\ RO = (P-PE-R) \end{array}\right\} \text{------------} \quad (4.15)$$

$\qquad$ ii) $(P-PE) < (1-S_s')$, $RO = 0$.

If $P < PE$, $RO = 0$ ....(4.16)

Potential Runoff (PRO) is equal to the precipitation minus the amount that could be added to the soil.

<u>Computation of PRO:</u>

$PRO = AWC - PR = S'$ ....(4.17)

Here potential precipitation is equal to AWC.

S′ is the amount of soil moisture available at the beginning of the month.

Step 2: Determination of coefficients

The calibration of the water balance model for normal level is accomplished by simulating the water balance over the period of available historical records of temperature and precipitation so that the four coefficients for the study area are derived. The four following monthly coefficients are computed using the four potential terms, potential evapotranspiration (PE), potential recharge (PR), potential runoff (PRO) and potential loss (PL). The overbars in determining each coefficient indicate the average values from the historical records for each month of the year from January to December.

i) Coefficient of evapotranspiration, α

$$\alpha_i = \frac{\overline{ET_i}}{\overline{PE_i}} \qquad [4.18(a)]$$

where i = Jan, Feb, Mar,................., Nov, Dec.

α_i is used to estimate the amount of ET for a month i of the year, that is normal for a particular place considering moisture demand (PE) during that month

ii) Coefficient of recharge, β

$$\beta_i = \frac{\overline{R_i}}{\overline{PR_i}} \qquad [4.18(b)]$$

where i = Jan, Feb, Mar,................., Nov, Dec.

β_i is used to estimate the amount of R for a month i of the year, that is normal for the conditions of time and place being considered.

iii) Coefficient of runoff, γ

$$\gamma_i = \frac{\overline{RO_i}}{\overline{PRO_i}} \qquad [4.18(c)]$$

where i = Jan, Feb, Mar,................., Nov, Dec.

γ_i is used to estimate the amount of RO for a month i of the year, that is normal for the conditions of time and place being considered.

iv) Coefficient of loss, δ

$$\delta_i = \frac{\overline{L_i}}{\overline{PL_i}} \quad \text{[4.18(d)]}$$

where i = Jan, Feb, Mar,................., Nov, Dec.

δ_i is used to estimate the amount of L for a month i of the year, that is normal for the conditions of time and place being considered.

Thus 12 values of each of α, β, γ and δ for 12 months of the year are determined using Eqns 4.18(a)-4.18(d).

Step 3: Determination of CAFEC Precipitation

The derived coefficients are used to reanalyze *the time series*, in order to determine the amount of moisture required for "normal" weather during *individual months*. In particular, the Climatically Appropriate for Existing Conditions (CAFEC) values are computed and they are denoted by circumflex (^). Thus the CAFEC values for each month of the time series are:

$$\left.\begin{aligned} \hat{ET}_j &= \alpha_i.PE_j \\ \hat{R}_j &= \beta_i.PR_j \\ \hat{RO}_j &= \delta_i.PRO_j \\ \hat{L}_j &= \delta_i.PL_j \end{aligned}\right\} \quad (4.19)$$

where PE_j, PR_j, PRO_j and PL_j are the potential evapotranspiration, potential recharge, potential runoff and potential loss respectively for the *current month* j.

Here j=1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, ...,24, 25, ...12xN.

N is the total number of years.

i = Jan, Feb, Mar,................., Nov, Dec.

Thus the CAFEC precipitation, $\hat{P}_j$ is computed as;

$$\hat{P}_j = \hat{ET}_j + \hat{R}_j + \hat{RO}_j - \hat{L}_j \quad \text{.....(4.20)}$$

$$\hat{P}_j = \alpha_i.PE_j + \beta_i.PR_j + \gamma_i.PRO_j - \delta_i.PL_j \quad \text{.....(4.21)}$$

($\hat{ET}_j + \hat{R}_j + \hat{RO}_j$) represents the amount of moisture that is needed in order to maintain the water resources of the area at a normal level. This does not represent the amount of precipitation that is "needed" because there is some moisture at the beginning of the month in the soil that is expected to supply a part of the evapotranspiration, if necessary.

Step 4: Determination of precipitation excess and deficiency (d) and moisture anomaly (z)

Precipitation excess and deficiency (d)

For each month j of the time series, the difference between the actual precipitation and the CAFEC precipitation is an indicator of the water deficiency or surplus for that month at the station under study. This is expressed as:

$$d_j = P_j - \hat{P}_j \quad \text{.....(4.22)}$$

Moisture anomaly index, z

The departures, d are converted into moisture anomaly index (z), known as z-index by the following equation:

$$z_j = d_j \times K_j \quad \text{.....(4.23)}$$

where K_j is the weighting factor for the month j

The departures are now been weighted and regarded as index numbers. Each number expresses the departure of the weather of the month from the average moisture climate of the month.

Monthly weighting factor, K

Palmer (1965) showed that K depends on average water supply ($\overline{P}+\overline{L}$) and moisture demand ($\overline{PE}+\overline{R}+\overline{RO}$) and varies inversely with $\overline{D}$, the mean of the absolute values of d.

Monthly weighting factor,

$$K_i = 17.67 \frac{K_i'}{\sum_{i=1}^{12}(\overline{D}K')_i} \quad \text{.......(4.24)}$$

where

$$K_i' = 1.5\log_{10}[(\frac{\overline{PE_i}+\overline{R_i}+\overline{RO_i}}{\overline{P_i}+\overline{L_i}}+2.8)/\overline{D_i}]+0.5 \quad \text{.......(4.25)}$$

Here the subscript i refers to the months of the year, i.e.,

i= Jan, Feb, Mar, ..., Nov, Dec.

K_i' is the weighting factor computed first for each month by Eqn. (4.25) which is developed from Figure 4.2. The figure is a semi-logarithmic plot evolved after some experimenting with various empirical relationships. Palmer (1965) considered climatologically different nine areas of USA. K_i' is adjusted using Eqn. (4.24) to obtain more comparable drought analysis results. The value of 17.67 in Eqn. (4.24) is also an empirical value, which is the mean sum of $\overline{D}K'$ of the nine areas. The adjusted monthly weighted factor, K_i takes into account the spatial variability of departure d, such that they are independent of time and space.

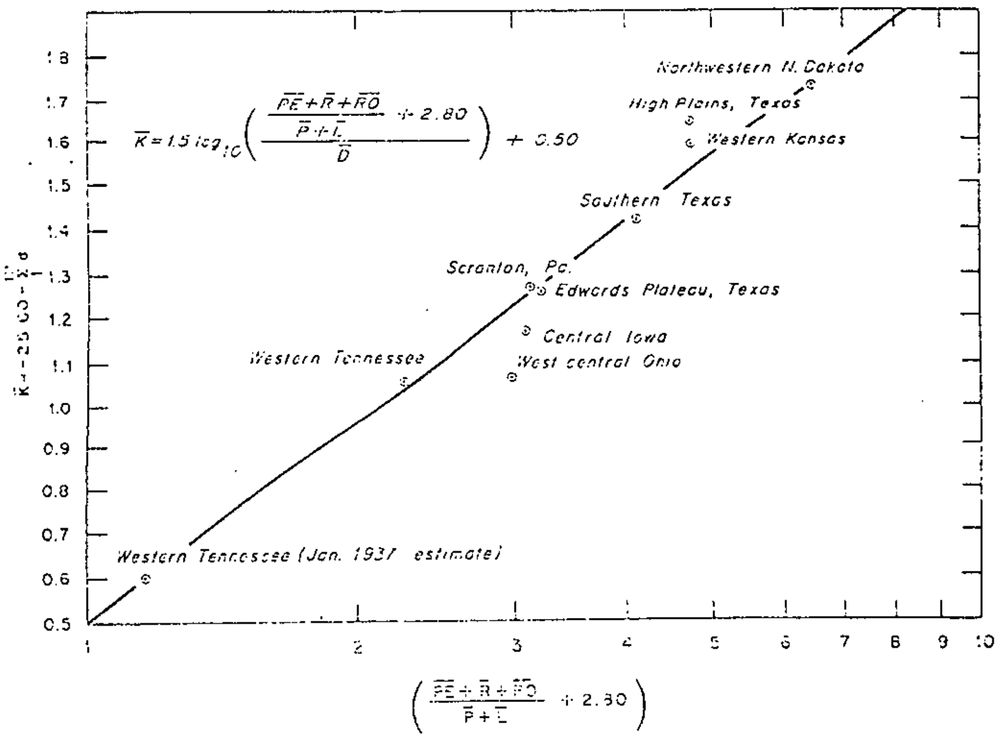


Figure 4.2 Mean annual weighting factor as related to average moisture demand, average moisture supply, and average absolute moisture departure

(Source: Palmer, 1965)

Step 5: Determination of drought severity, X

In this step, the z index time series is analyzed to develop criteria for the beginning and end of the periods of drought and a formula for determining drought severity. Palmer (1965) decided to evaluate the contribution of each month to the severity of drought. The contribution to drought severity of each month was computed as:

$\Delta X_j = z_j/3 - 0.103X_{j-1}$ ....(4.26)

Finally, the severity of drought for the month j is

$$X_j = X_{j-1} + \Delta X_j$$

$$X_j = X_{j-1} + \left(\frac{z_j}{3} - 0.103X_{j-1}\right) \quad \text{(4.27)}$$

Where z_j is the value of moisture anomaly index or z index for the j th month and X_j is the value of PDSI for the j th month.

Incipient drought occurs when X is between -0.49 and –0.99 and drought spell begins when X reaches –1.0. It is difficult to determine the beginning and ending of dry period without recognizing and taking account of the wet period. The classification of weather based on PDSI (Palmer, 1965) is shown in Table 4.1.

Table 4.1 Classification of weather using PDSI (Palmer, 1965)

PDSI value	Class
≥ 4.00	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.99	Slightly wet
0.50 to 0.99	Incipient wet spell
0.49 to –0.49	Near normal
-0.5 to –0.99	Incipient drought
-1.00 to –1.99	Mild drought
-2.00 to –2.99	Moderate drought
-3.00 to –3.99	Severe drought
≤ -4.00	Extreme drought

Step 6: Determining the end of a drought spell

It was assumed that drought is definitely terminated as soon as the drought index reaches the "near normal" category. The z value that will end a drought in a single month is,

z_e=-2.691X_{j-1}-1.5..(4.28)

Any value of z ≥ -0.15 will tend to end a drought and effective wetness (U_w) is

U_w= z+0.15

After a drought has definitely begun (X≤ -1.00), (U_w= z+0.15) is applied to the first wet month when z ≥ -0.15

U_w is computed for each successive month until the computations show either a 0 percent or a 100 percent likelihood that the drought has ended. If z_e is greater than

U_w for the month, drought severity will decrease, but the drought has not definitely ended. z_e will be smaller for the next month and the total amount of wetness required to end the drought will be

$$Q = z_e + \sum_{k=0}^{k=k^*} (U_w)_{j-k} - (U_w)_j \qquad (4.29)$$

where, j=the month being considered

k=number of month of lag; k*= the first month of the current wet spell

The percentage probability that drought has ended,

$$P_e = \frac{\sum_{k=0}^{k=k^*} (U_w)_{j-k}}{z_e + \sum_{k=0}^{k=k^*} (U_w)_{j-k} - (U_w)_j} * 100 = \frac{100V}{Q} \qquad (4.30)$$

Step 7: Determining the end of a wet spell

The drought formula (Eqns. 4.26-4.27) are also applicable to wet period.

The z value to end the wet spell in a single month is

$z_e = -2.691 X_{j-1} + 1.5$ ....(4.31)

And any value of $z \leq 0.15$ will tend to end a wet spell and effective dryness (U_d) is

$U_d = z - 0.15$

The same equation (Eqn. 4.30) as in determining the percentage probability that a drought has ended is used to compute the probability that a wet spell has ended.

The methodology is illustrated in the following section with an example.

4.5 Illustration of the methodology for determination of PDSI

The station Dhunot (CL 011) has been selected to illustrate the methodology for determining the PDSI. The 31 years time series spanning from 1972 to 2002 of rainfall and temperature data are used in the study.

Carrying out hydrologic accounting

The hydrologic accounting procedure for Dhunot is shown in Table 4.2. The calculation has been started from July/1972. The previous month June was relatively wet. It was assumed that at the end of June both layers of the soils have reached at field capacity. The AWC of soil is taken as 1.6 inch/feet in Dhunot (FAO/UNDP, 1988). A difficulty has been encountered while selecting the depths of soils for hydrologic accounting. It has been found more realistic to take the root zone depth of rice crop as the depth of soil for soil moisture accounting. While determining the potential runoff (PRO), Palmer assumed that potential precipitation would be equivalent to available moisture of soil at field capacity. This assumption has produced unrealistic values of PRO. The values of PRO are sometimes less than the actual RO values. As such, the values of PRO are needed to be increased to make them realistic. A sensitivity analysis has been performed with one year data from July/1972 to June/1973. The changes in total recharge (R), runoff (RO) and potential runoff (PRO) in a year with changes in surface layer soil moisture (S_s) and available soil moisture at field capacity (AWC) have been observed. The results of the analysis are presented in Figures 4.3-4.5. Figure 4.3 shows that the values of R increase with the values of both S_s and AWC. Figures 4.4-4.5 shows that the values of RO and PRO decreases and increases respectively with increases in AWC but decrease marginally for both RO and PRO with the increase of S_s. The increase in PRO with the increase of AWC is much higher than that of RO. Thus it becomes conceivable that PRO should be increased upto the point where RO becomes less than PRO using increased value of AWC of soil. The AWC of soil could only be increased if the soil depth is increased. The depth of soil can be increased to a depth, which can be containing soil moisture equivalent to standing water depth on the agricultural lands. Thus the depth of soils considered for soil moisture accounting is 15 feet. Thus the total moisture of the two soil layers is 24.0 inch at the beginning of July/1972. Since Palmer assumed 1.0 inch of soil moisture in the surface layer, the remaining 23.0 inch was assigned to the underlying soil. During July-September period, P>PE and the loss from the soil is zero (Col.8). So the soil moisture in both layers remains unchanged. Since there is no recharge in both layers, the excess precipitation (P-PE) is calculated as runoff (Col. 17) according to Eqn. (4.15). During October/1972, since P<PE, the excess water demand (PE-P) equal to (5.23-2.31) or 2.92 inch is satisfied from soil moisture of both layers. The 1.0 inch moisture is lost from the surface layer soil at the potential rate and the remaining 1.92 inch is from the underlying layer. The losses from the both layers of soil are carried out in Cols.6-8 according to Eqns. (4.3) to (4.5). Thus

the loss from the surface layer is 1.0 inch and from the underlying layer is 1.92×23.0/24.0 or 1.84 inch. Thus at the end of October, the soil moisture at the surface layer is zero (as shown in Col. 3) and at the underlying layer is (23.0-1.92×23.0/24.0) or 21.16 inch (as shown in Col. 4). If (PE-P) is less than 1.0 inch as in October, 1974, the excess demand is satisfied from the surface layer and the underlying layer soil moisture remains unchanged. Since P<PE in the month October/1972, there is no recharge and no run off [Eqns. (4.12) and (4.16)]. So the Cols. 15 and 17 show zeros for the month October/1972. In February/1973, P>PE and the surface layer soil moisture is zero at the beginning of the month, so excess precipitation (2.92-2.41) or 0.51 inch is assigned as recharge in surface layer [Eqn. (4.11)] as shown in Col. 13. Thus total recharge is 0.51 inch as shown in Col. 15. The runoff (RO in Col. 17) is calculated according to Eqn. (4.15). The ET is computed in Col. 12 according to Eqns. (4.1)-(4.2).

The potential recharge (PR in Col.16) is calculated according to Eqn. (4.13). PR is the amount of moisture required to bring the soil to field capacity. It measures the maximum condition that could exist when rainfall is enough. The potential loss (PL in Col. 11) is also a maximum condition that could exist. It is the amount of moisture that could be lost from the soil when the precipitation is zero. PL is computed according to Eqns. (4.7) to (4.9). The potential runoff (PRO in Col.18) is the maximum runoff when PR=0. The PRO is calculated according to Eqn. (4.17). During the period July-September/1972, the soil is at field capacity, so the PR is zero. At the end of October/1972, the soil moisture is less than field capacity, so in November/1972, PR is (24.0-21.16) or 2.84 inch (Col.16) and the PRO is equal to (24.0-2.84) or 21.16 inch (Col. 18). In this way, the parameters of hydrologic accounting are computed for the full time series and these values are used to determine the four climatic coefficients as illustrated in the next section.

Determination of climatic coefficients

To determine the four climatic coefficients α, β, γ and δ for each month from July to June of the year from historical data, the hydrologic parameters ET, PE; L, PL;

R, PR and RO, PRO are summarized. The values of α, β, γ and δ are calculated for each month according to Eqns. 4.18 (a-d) respectively and are given in Table 4.3.

Calculation of CAFEC precipitation, precipitation excess and deficiency

The CAFEC values of evapotranspiration, recharge, runoff and loss for each month of the time series are calculated from Eqn. (4.19) using the climatic coefficients listed in Table 4.3. Thus the CAFEC precipitation is determined for each month following the Eqn. (4.20). For each month, the water deficiency or surplus is calculated using the difference between the actual precipitation and the CAFEC precipitation [Eqn. (4.22)]. The departures, d are converted to moisture anomaly (z) indices using Eqn. (4.23). The monthly weighting factors for each month of the year are calculated from Eqns. (4.24) – (4.25). The monthly K values are listed in Table 4.4. The $\overline{D_i}$ is the mean of absolute values of d for the month i. Some of the calculated values of z are given in Table 4.5.

Determination of beginning and ending of drought spells and their severity

To determine the Palmer Drought Severity Index (PDSI), both the wet spells and drought spells are needed to be identified. For this reason, when there is no drought or wet spell, the probability of beginning of wet or drought spell is calculated in each month. When probability of beginning of a spell is 100 percent, it is necessary to determine the probability of ending of the current spell and at the same time the probability of beginning of the opposite spell. Table 4.6 shows a 41 months period of calculation of PDSI for the station Dhunot. Cols.4-9 are used to calculate the probability of ending a current spell. Col. 10 shows the probability of ending the current spell (P_e). The probability of beginning of a wet spell (X1) and that of a drought spell (X2) are shown in Col. 12 and Col. 13 respectively. Values of X1 and X2 also indicates the severity of the incipient wet and drought spells respectively. Col. 14 shows the severity of any drought or wet spell (X3) that has been established and Col. 15 shows the value of the PDSI.

Table 4.2 Hydrologic accounting for Dhunot

Year	Month	Monthly rainfall	Potential Evapo-Transpiration	Soil moisture at		Soil moisture	Moisture Loss from		Moisture Loss	Potential Loss from		Potential Loss	Evapo-Transpiration	Recharge in		Recharge	Potential recharge	Run off	Potential Runoff
				Surface layer	Underlying layer	Total	Surface layer	Underlying layer	Total	Surface layer	Underlying layer	Total		Surface layer	Underlying layer	Total	Total		
		P	PE	S_s'	S_u'	S'	L_s	L_u	L	PL_s	PL_u	PL	ET	R_s	R_u	R	PR	RO	PRO
		in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1972	Jul	14.73	8.04	1.00	23.00	24.00	0.00	0.00	0.00	1.00	6.75	7.75	8.04	0.00	0.00	0.00	0.00	6.70	24.00
1972	Aug	9.74	7.17	1.00	23.00	24.00	0.00	0.00	0.00	1.00	5.91	6.91	7.17	0.00	0.00	0.00	0.00	2.58	24.00
1972	Sep	8.58	6.72	1.00	23.00	24.00	0.00	0.00	0.00	1.00	5.48	6.48	6.72	0.00	0.00	0.00	0.00	1.86	24.00
1972	Oct	2.31	5.23	0.00	21.16	21.16	1.00	1.84	2.85	1.00	4.06	5.06	5.15	0.00	0.00	0.00	0.00	0.00	24.00
1972	Nov	0.00	2.78	0.00	18.70	18.71	0.00	2.45	2.45	0.00	2.45	2.45	2.45	0.00	0.00	0.00	2.84	0.00	21.16
1972	Dec	0.00	1.53	0.00	17.52	17.52	0.00	1.19	1.19	0.00	1.19	1.19	1.19	0.00	0.00	0.00	5.29	0.00	18.71
1973	Jan	0.47	1.23	0.00	16.96	16.96	0.00	0.56	0.56	0.00	0.90	0.90	1.03	0.00	0.00	0.00	6.48	0.00	17.52
1973	Feb	2.92	2.41	0.51	16.96	17.47	0.00	0.00	0.00	0.00	1.71	1.71	2.41	0.51	0.00	0.51	7.04	0.00	16.96
1973	Mar	0.63	4.28	0.00	14.73	14.73	0.51	2.22	2.73	0.51	2.67	3.18	3.36	0.00	0.00	0.00	6.53	0.00	17.47
1973	Apr	2.36	8.21	0.00	11.14	11.14	0.00	3.59	3.59	0.00	5.04	5.04	5.95	0.00	0.00	0.00	9.27	0.00	14.73
1973	May	13.00	6.24	1.00	16.90	17.90	0.00	0.00	0.00	0.00	2.90	2.90	6.24	1.00	5.76	6.76	12.86	0.00	11.14
1973	Jun	28.91	6.94	1.00	23.00	24.00	0.00	0.00	0.00	1.00	4.18	5.18	6.94	0.00	6.10	6.10	6.10	15.87	17.90
1973	Jul	11.06	8.33	1.00	23.00	24.00	0.00	0.00	0.00	1.00	7.02	8.02	8.33	0.00	0.00	0.00	0.00	2.73	24.00
1973	Aug	10.89	7.74	1.00	23.00	24.00	0.00	0.00	0.00	1.00	6.46	7.46	7.74	0.00	0.00	0.00	0.00	3.15	24.00
1973	Sep	22.66	6.25	1.00	23.00	24.00	0.00	0.00	0.00	1.00	5.03	6.03	6.25	0.00	0.00	0.00	0.00	16.41	24.00
1973	Oct	3.93	5.34	0.00	22.61	22.61	1.00	0.39	1.39	1.00	4.16	5.16	5.32	0.00	0.00	0.00	0.00	0.00	24.00
1973	Nov	1.05	2.95	0.00	20.82	20.82	0.00	1.79	1.79	0.00	2.78	2.78	2.84	0.00	0.00	0.00	1.39	0.00	22.61
1973	Dec	2.09	1.53	0.56	20.82	21.38	0.00	0.00	0.00	0.00	1.33	1.33	1.53	0.56	0.00	0.56	3.18	0.00	20.82
1974	Jan	0.00	1.27	0.00	20.20	20.20	0.56	0.61	1.18	0.56	0.61	1.18	1.18	0.00	0.00	0.00	2.62	0.00	21.38
1974	Feb	0.00	1.86	0.00	18.63	18.63	0.00	1.57	1.57	0.00	1.57	1.57	1.57	0.00	0.00	0.00	3.80	0.00	20.20
1974	Mar	2.34	3.56	0.00	17.68	17.68	0.00	0.95	0.95	0.00	2.76	2.76	3.29	0.00	0.00	0.00	5.37	0.00	18.63
1974	Apr	8.24	6.14	1.00	18.78	19.78	0.00	0.00	0.00	0.00	4.53	4.53	6.14	1.00	1.09	2.09	6.32	0.00	17.68
1974	May	14.04	6.70	1.00	23.00	24.00	0.00	0.00	0.00	1.00	4.46	5.46	6.70	0.00	4.22	4.22	4.22	3.11	19.78
1974	Jun	10.14	7.57	1.00	23.00	24.00	0.00	0.00	0.00	1.00	6.30	7.30	7.57	0.00	0.00	0.00	0.00	2.57	24.00
1974	Jul	26.49	6.72	1.00	23.00	24.00	0.00	0.00	0.00	1.00	5.48	6.48	6.72	0.00	0.00	0.00	0.00	19.78	24.00
1974	Aug	10.16	7.67	1.00	23.00	24.00	0.00	0.00	0.00	1.00	6.39	7.39	7.67	0.00	0.00	0.00	0.00	2.49	24.00
1974	Sep	10.43	6.16	1.00	23.00	24.00	0.00	0.00	0.00	1.00	4.95	5.95	6.16	0.00	0.00	0.00	0.00	4.27	24.00
1974	Oct	6.00	6.02	0.98	23.00	23.98	0.02	0.00	0.02	1.00	4.81	5.81	6.02	0.00	0.00	0.00	0.00	0.00	24.00
1974	Nov	0.00	3.60	0.00	20.49	20.49	0.98	2.51	3.49	0.98	2.51	3.49	3.49	0.00	0.00	0.00	0.02	0.00	23.98
1974	Dec	0.00	1.36	0.00	19.33	19.33	0.00	1.16	1.16	0.00	1.16	1.16	1.16	0.00	0.00	0.00	3.51	0.00	20.49

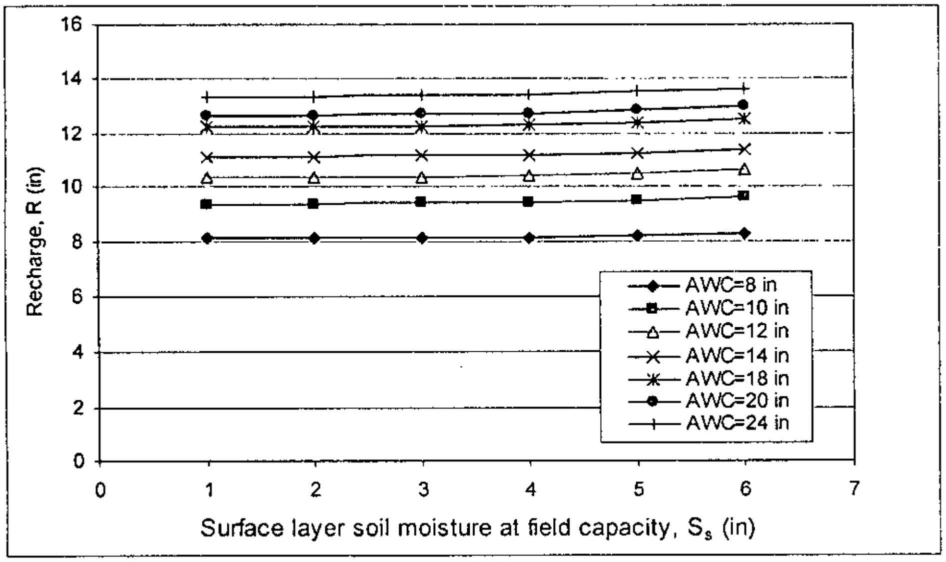


Figure 4.3 Changes in total recharge (R) in a year with changes in AWC and S_s

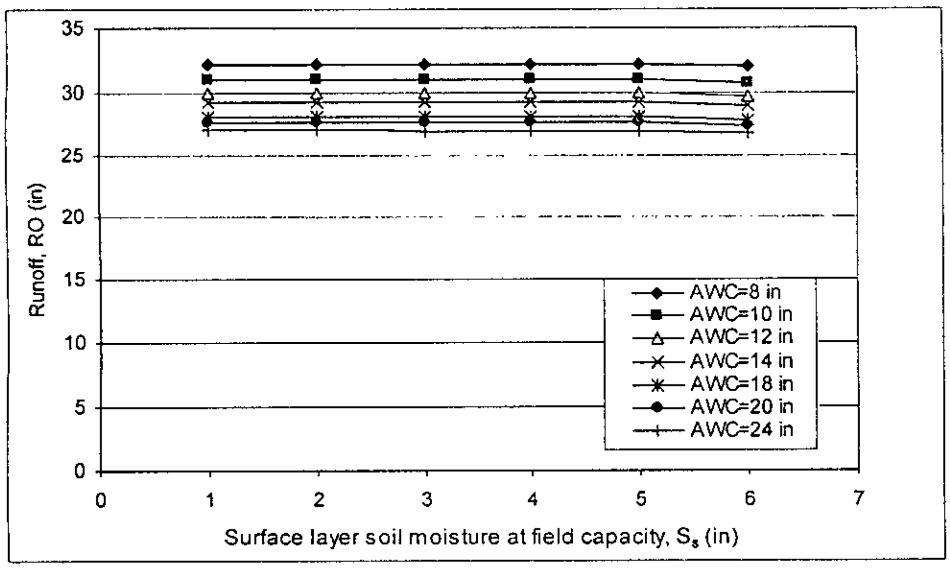


Figure 4.4 Changes in total runoff (RO) in a year with changes in AWC and S_s

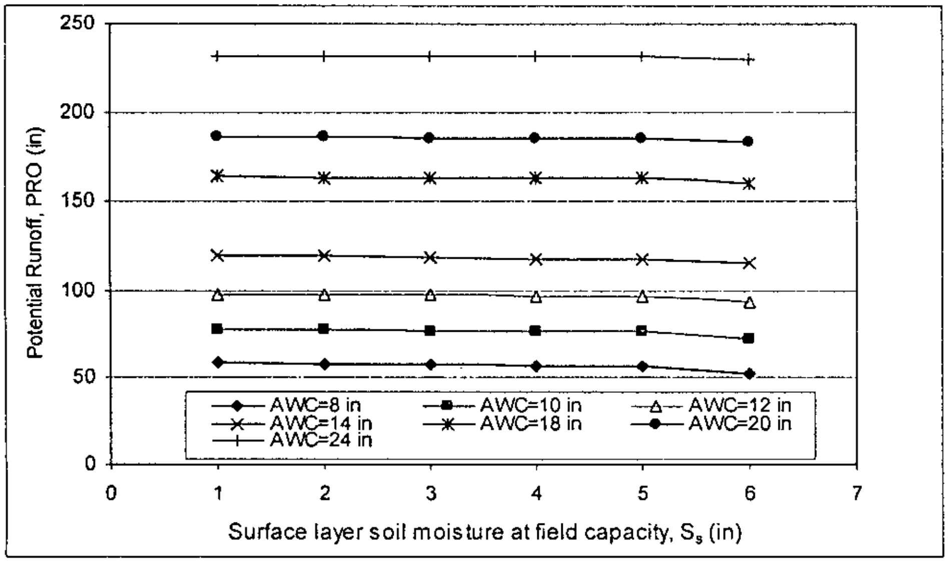


Figure 4.5 Changes in total potential runoff (PRO) in a year with changes in AWC and S_s

Table 4.3 Climatic coefficients of Dhunot

Month	α	β	γ	δ
July	0.97	0.60	0.27	0.02
August	0.97	0.12	0.19	0.08
September	0.97	0.45	0.22	0.05
October	0.94	0.04	0.06	0.32
November	0.87	0.03	0.00	0.87
December	0.81	0.03	0.00	0.82
January	0.82	0.01	0.00	0.77
February	0.78	0.01	0.00	0.77
March	0.73	0.00	0.00	0.78
April	0.76	0.05	0.00	0.54
May	0.90	0.33	0.03	0.16
June	0.96	0.37	0.20	0.09

Table 4.4 Determination of the monthly weighting factors

Month	$\overline{PE_i}$	$\overline{R_i}$	$\overline{RO_i}$	$\overline{P_i}$	$\overline{L_i}$	$\overline{D_i}$	K_i'	$\overline{D}_i K_i'$	K_i
July	7.89	3.53	4.88	15.94	0.13	5.56	0.25	1.41	0.26
August	7.79	0.29	4.17	11.49	0.53	4.48	0.40	1.77	0.41
September	6.54	1.22	4.74	11.99	0.29	5.07	0.32	1.60	0.32
October	5.32	0.07	1.37	4.81	1.50	3.15	0.63	2.00	0.65
November	2.94	0.09	0.00	0.48	2.18	0.70	1.63	1.13	1.68
December	1.56	0.16	0.00	0.44	0.99	0.70	1.63	1.15	1.68
January	1.38	0.09	0.00	0.43	0.79	0.48	1.88	0.90	1.94
February	2.22	0.05	0.00	0.54	1.25	0.65	1.70	1.10	1.75
March	4.66	0.02	0.00	1.04	2.38	1.17	1.33	1.56	1.36
April	7.03	0.51	0.03	3.78	2.12	2.48	0.82	2.05	0.85
May	7.46	3.98	0.32	10.38	0.61	5.20	0.31	1.60	0.32
June	7.79	3.24	3.13	13.39	0.44	6.72	0.13	0.89	0.14

In October/1981, the probability of ending an established wet spell (P_e) is 65.27 percent and the severity of the impending drought spell (X2) is -1.42, which is less than -1.0. X2=-1.42 also means that the probability of beginning a drought spell is greater than 100 percent. So, theoretically, drought should have begun during October/1981. But the severity of the established wet spell (X3) during the month shown in Col. 14 is 1.41 and the value of P_e has not reached 100 percent. So a drought spell cannot be considered to begin at this month. The months November/1981 and December/1981 are drier than normal and finally the probability of ending the established wet spell (P_e) has reached 100 percent during December/1981. P_e is calculated according to Eqn. (4.30). V_w and V_d are the numerator of Eqn. (4.30) corresponding to the determination of probabilities to end a drought spell and a wet spell respectively. Q is the denominator of Eqn. (4.30). The z_e is calculated according to Eqn. (4.31). The severity of the incipient drought spell (X2) is -1.88. So a new drought spell has begun in December/1981 and the severity of this established spell (X3) is -1.88 during December/1981. Since X3=X2 during December/1981, severity calculations have been shifted from Col. 13 to Col. 14. The months of January/1982 and February/1982 are drier than normal. So the probability of ending the established drought spell (P_e) is zero during these months. The month March/1982 is wetter than normal. So the value of P_e is 36.50 percent in this month and the severity of drought spell has been reduced to -1.52 from the previous month's drought severity of -2.27. In April/1982, the probability of ending the drought spell (P_e) is increased to 46.45 percent. In May/1982, the weather is much drier. So the value of P_e is zero and the severity of drought spell is increased to -1.97. June/1982 is wetter than normal and P_e becomes 24.95 percent and X3 reduces to -1.50. In August/1982, the weather is much wetter and the probability of ending the drought spell is 75.95 percent, but the next two months are much drier and P_e becomes zero again. Finally, the month March/1983 is the wettest and the probability of ending the drought spell has reached 100 percent and the severity of the incipient wet spell is 1.47, which is greater than 1.0. X1=1.47 also indicates that the probability of beginning a wet spell is greater than 100 percent. So a wet spell has begun in March/1983 and the value of X3 in Col. 14 is equal to 1.47. The drought spell that started in October/1981 has ended in February/1983 with the beginning of a new wet spell in March/1983. Now it is needed to determine the values of PDSI. Since probability of ending the wet spell has sequentially reached 100 percent during the period from October/1981 to December/1981, the values of PDSI for this period have been assigned as PDSI=X2. From January/1982 to February/1983, the drought spell was continued and the probability of ending the spell is 100 percent at March/1983. Thus for this period, PDSI=X3.

After established the new wet spell in March/1983, the calculation for determining the severity of the spell has been shifted from Col. 12 to Col. 14. From November/1983 to April/1984, the weather is drier and the probability of ending the wet spell has reached 100 percent in April/1984. But the value of X2 is less than -1.0. So a new drought spell has not begun at this month and X3 becomes zero. From March/1983 to October/1983, PDSI=X3 and from November/1983 to April/1984, PDSI=X1. The value of X1 i.e. the severity of the incipient wet spell has been calculated using Eqn. (4.27). Thus a wet spell begins in March/1983 and ends in Oct/1983. During May/1984 to June/1984, there have been occurred two months duration wet spell. Another drought spell began Oct/1984 and continued through February/1985. In August/1984 and September/1984, the value of PDSI is negative, but less than -1.0. So during the period, there is no established drought or wet spell.

Table 4.5 Calculation of moisture anomaly indices (z)

Year	Month	P in	$\hat{ET}$ in	$\hat{R}$ in	$\hat{RO}$ in	$\hat{L}$ in	$\hat{P}$ in	d in	K	z
1972	Jul	14.73	7.80	0.00	6.46	0.17	14.09	0.65	0.26	0.17
1972	Aug	9.74	6.95	0.00	4.65	0.54	11.06	-1.31	0.41	-0.54
1972	Sep	8.58	6.50	0.00	5.34	0.34	11.50	-2.92	0.32	-0.95
1972	Oct	2.31	4.94	0.00	1.48	1.60	4.83	-2.52	0.65	-1.65
1972	Nov	0.00	2.43	0.08	0.00	2.14	0.37	-0.37	1.68	-0.62
1972	Dec	0.00	1.24	0.16	0.00	0.97	0.43	-0.43	1.68	-0.73
1973	Jan	0.47	1.02	0.10	0.00	0.69	0.42	0.04	1.94	0.09
1973	Feb	2.92	1.89	0.05	0.00	1.32	0.62	2.30	1.75	4.02
1973	Mar	0.63	3.12	0.02	0.00	2.46	0.67	-0.04	1.36	-0.06
1973	Apr	2.36	6.27	0.46	0.03	2.71	4.04	-1.69	0.85	-1.43
1973	May	13.00	5.59	4.25	0.30	0.48	9.66	3.34	0.32	1.06
1973	Jun	28.91	6.65	2.28	3.66	0.47	12.12	16.79	0.14	2.30
1973	Jul	11.06	8.08	0.00	6.46	0.18	14.36	-3.31	0.26	-0.87
1973	Aug	10.89	7.50	0.00	4.65	0.58	11.57	-0.69	0.41	-0.28
1973	Sep	22.66	6.04	0.00	5.34	0.31	11.07	11.59	0.32	3.76
1973	Oct	3.93	5.04	0.00	1.48	1.63	4.89	-0.96	0.65	-0.63
1973	Nov	1.05	2.58	0.04	0.00	2.43	0.19	0.86	1.68	1.44
1973	Dec	2.09	1.24	0.09	0.00	1.08	0.26	1.83	1.68	3.08
1974	Jan	0.00	1.05	0.04	0.00	0.90	0.19	-0.19	1.94	-0.36
1974	Feb	0.00	1.46	0.03	0.00	1.21	0.27	-0.27	1.75	-0.48
1974	Mar	2.34	2.60	0.01	0.00	2.15	0.46	1.87	1.36	2.56
1974	Apr	8.24	4.69	0.31	0.03	2.43	2.60	5.63	0.85	4.78
1974	May	14.04	6.00	1.40	0.53	0.90	7.03	7.01	0.32	2.22
1974	Jun	10.14	7.25	0.00	4.90	0.66	11.50	-1.36	0.14	-0.19

Table 4.6 Procedure of determining the beginning and ending of drought spells and their severity

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Year	Month	z	U_w	U_d	V_w	V_d	Z_e	Q	P_e	Z/3	X1	X2	X3	PDSI
1981	Oct	-3.39	-	-3.54	-	-4.89	-6.14	-7.49	65.27	-1.13	0.00	-1.42	1.41	-1.42
1981	Nov	-1.26	-	-1.41	-	-6.30	-2.31	-7.21	87.44	-0.42	0.00	-1.69	0.85	-1.69
1981	Dec	-1.07	-	-1.22	-	-7.52	-0.79	-7.09	100.00	-0.36	0.00	-1.88	-1.88	[illegible]
1982	Jan	-1.24	-	-	-	-	-	-	0.00	-0.41	0.00	0.00	-2.10	-2.10
1982	Feb	-1.16	-	-	-	-	-	-	0.00	-0.39	0.00	0.00	-2.27	[illegible]
1982	Mar	1.53	1.68	-	1.68	-	4.60	4.60	36.50	0.51	0.51	0.00	-1.52	[illegible]
1982	Apr	0.16	0.31	-	1.99	-	2.60	4.28	46.45	0.05	0.51	0.00	-1.31	[illegible]
1982	May	-2.38	0.00	-	0.00	-	0.00	0.00	0.00	-0.79	0.00	-0.79	-1.97	[illegible]
1982	Jun	0.80	0.95	-	0.95	-	3.81	3.81	24.95	0.27	0.27	0.00	-1.50	-1.50
1982	Jul	-0.33	-0.18	-	0.77	-	2.54	3.49	22.02	-0.11	0.13	-0.11	-1.46	-1.46
1982	Aug	1.51	1.66	-	2.43	-	2.42	3.19	75.95	0.50	0.62	0.00	-0.81	[illegible]
1982	Sep	-3.37	-	-	-	-	-	-	0.00	-1.12	0.00	-1.12	-1.12	[illegible]
1982	Oct	-3.15	-	-	-	-	-	-	0.00	-1.05	0.00	0.00	-2.06	-2.06
1982	Nov	2.22	2.37	-	2.37	-	4.04	4.04	58.75	0.74	0.74	0.00	-1.11	[illegible]
1982	Dec	-1.25	-	-	-	-	-	-	0.00	-0.42	0.00	-0.42	-1.41	-1.41
1983	Jan	0.06	0.21	-	0.21	-	2.29	2.29	9.23	0.02	0.02	0.00	-1.24	-1.24
1983	Feb	-1.21	-	-	-	-	-	-	0.00	-0.40	0.00	-0.40	-1.52	-1.52
1983	Mar	4.41	4.56	-	4.56	-	2.59	2.59	100.00	1.47	1.47	0.00	1.47	1.47
1983	Apr	0.05	-	0.00	-	0.00	0.00	0.00	0.00	0.02	0.00	0.00	1.33	1.33
1983	May	1.27	-	0.00	-	0.00	0.00	0.00	0.00	0.42	0.00	0.00	1.62	1.62
1983	Jun	-0.75	-	-0.90	-	-0.90	-2.86	-2.86	31.59	-0.25	0.00	-0.25	1.20	1.20
1983	Jul	-0.02	-	-0.17	-	-1.08	-1.73	-2.64	40.81	-0.01	0.00	-0.23	1.07	1.07
1983	Aug	1.53	-	-	-	-	-	-	0.00	0.51	0.00	0.00	1.47	1.47
1983	Sep	1.67	-	-	-	-	-	-	0.00	0.56	0.00	0.00	1.88	1.88
1983	Oct	2.61	-	-	-	-	-	-	0.00	0.87	0.00	0.00	2.56	2.56
1983	Nov	-0.15	-	-0.30	-	-0.30	-5.38	-5.38	5.60	-0.05	0.00	-0.05	2.24	-0.05
1983	Dec	-0.27	-	-0.42	-	-0.72	-4.53	-4.83	14.97	-0.09	0.00	-0.14	1.92	-0.14
1984	Jan	-0.31	-	-0.46	-	-1.18	-3.67	-4.39	26.87	-0.10	0.00	-0.22	1.62	-0.22
1984	Feb	-0.35	-	-0.50	-	-1.68	-2.86	-4.04	41.62	-0.12	0.00	-0.32	1.34	-0.32
1984	Mar	-1.12	-	-1.27	-	-2.96	-2.10	-3.78	78.26	-0.37	0.00	-0.66	0.82	-0.66
1984	Apr	-0.74	-	-0.89	-	-3.84	-0.72	-3.67	100.00	-0.25	0.00	-0.84	0.00	-0.84
1984	May	3.06	-	-	-	-	-	-	0.00	1.02	1.02	0.00	1.02	1.02
1984	Jun	0.88	-	-	-	-	-	-	0.00	0.29	0.00	0.00	1.21	1.21
1984	Jul	-0.69	-	-0.84	-	-0.84	-1.74	-1.74	47.99	-0.23	0.00	-0.23	0.85	-0.23
1984	Aug	-1.99	-	-2.14	-	-2.98	-0.79	-1.63	100.00	-0.66	0.00	-0.87	0.00	-0.87
1984	Sep	0.38	-	-	-	-	-	-	0.00	0.13	0.13	-0.65	0.00	-0.65
1984	Oct	-1.59	-	-	-	-	-	-	0.00	-0.53	0.00	-1.11	-1.11	-1.11
1984	Nov	-0.70	-	-	-	-	-	-	0.00	-0.23	0.00	0.00	-1.23	-1.23
1984	Dec	-0.81	-	-	-	-	-	-	0.00	-0.27	0.00	0.00	-1.38	-1.38
1985	Jan	-0.93	-	-	-	-	-	-	0.00	-0.31	0.00	0.00	-1.54	-1.54
1985	Feb	-0.84	-	-	-	-	-	-	0.00	-0.28	0.00	0.00	-1.67	[illegible]

Chapter 5
THE STANDARD PRECIPITATION INDEX (SPI) AND HERBST METHODS

5.1 The Standard Precipitation Index (SPI) method

5.1.1 The concept of the method

Standard Precipitation Index (SPI) developed by McKee et al. (1993) is a relatively new drought index based on precipitation. The SPI is probability based and was designed to be a spatially invariant indicator of drought that recognizes the importance of time scales in the analysis of water availability and water use. It is essentially a standardizing transform of the probability of the observed precipitation. It can be computed for a precipitation total, observed over any duration desired by the user. Short term durations on the order of months (or even weeks) may be important to agricultural interests while long term durations spanning year may be important to water supply management interest.

5.1.2 Steps followed in the method

Technically, the SPI is the number of standard deviations that the observed value would deviate from the long-term mean, for a normally distributed random variable. The first step in calculating the SPI is to determine a probability density function that describes the frequency distribution of long term time series of precipitation observations. The series can be for any time duration (i.e, running series of total precipitation for 1 month, 2 months, 6 months, 1 year, 3 years etc). For example, if the observed data consist of a time series of monthly precipitation amounts, and the analyst is interested in three months events, then a new time series is constructed by summing the first three month amounts, then summing the amounts in months 2, 3 and 4, then summing the amounts in months 3, 4 and 5 etc. The SPI is then calculated from this new time series. In the present study, observed daily rainfall data are used to produce half-monthly rainfall time series. A month time was divided into two half months e.g. Jan-1, Jan-2, Feb-1, Feb-2 etc. Thus a year is divided into 24 half-months. The first fifteen days in a month were considered in the first half-month and the remaining days of the month were in the second half-month. In the present study, the monthly time scale is considered for drought analysis in SPI method. The time series of half-monthly precipitation is used to construct a new time series of monthly precipitation. Monthly precipitation is the running sum of two half-months rainfall. Figure 5.1 shows one year of the time series of half-monthly and monthly precipitation. The figure indicates that the precipitation value corresponding to a particular month, for example, Jan represents the total precipitation of the Jan 1 and Jan 2 half-months. Thus total 24 time series of precipitation for Jan, Jan-Feb, ..., Dec, Dec-Jan months can be generated from the 31 year long time series of monthly rainfall. This means that time series namely Jan consists of 31 years record of total precipitation of Jan 1 and Jan 2 half-months. The probability density functions were fitted to each of the 24 time series. Different distributions such as 2-Parameter Gamma distribution, the 3-Parameter Pearson Type III (P3) distribution and the 3-Parameter Generalized Extreme Value distribution were commonly used in the past studies for SPI calculation. In the present study the two types of distribution are used as fitted distributions to the time series of monthly running precipitation. The 2-Parameter Log-Normal (LN-2) distribution was used to fit the most of the 24 time series of precipitation during high rainfall period and the Extreme Value Type III (Weibull) distribution was used for the low rainfall period. Details of these distributions are described in Appendix II.

Once the probability density function is determined, the cumulative probability of an observed monthly precipitation for each of the 24 time series is computed. The inverse normal function, with mean zero and variance one, is then applied to the cumulative probability. The result is the SPI. Let, left hand side of Figure 5.2 denotes the cumulative probability of the fitted distribution of a monthly time series precipitation. The smooth curve on the right hand side of figure 5.2 denotes the cumulative probability distribution of the standard normal random variable (here it is the SPI) using the same probability scale of the empirical distribution and the fitted distribution on the left hand side of the figure. The standard normal variable SPI is denoted on the x-axis on the right hand side of the figure. This figure can be used to transform a given monthly precipitation observation to a SPI value. As an example, a

SPI value for a 2 inch precipitation observation is shown in the figure. Since it would be cumbersome to produce these types of figures for all stations for each month, the SPI value is more easily obtained using an approximation provided by Abramowitz and Stegun (1965) that converts the cumulative probability, H(x) to the standard normal random variable (SPI) using the following approximation:

$$\left.\begin{aligned} SPI &= -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad for \quad 0 < H(x) \le 0.5 \\ SPI &= +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad for \quad 0.5 < H(x) \le 1.0 \end{aligned}\right\} \text{............} \quad (5.1)$$

$$\text{where } t = \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)} \quad for \quad 0 < H(x) \le 0.5$$

$$t = \sqrt{\ln\left(\frac{1}{(1 - H(x))^2}\right)} \quad for \quad 0.5 < H(x) \le 1.0$$

$$c_0 = 2.515517$$
$$c_1 = 0.802853$$
$$c_2 = 0.010328$$
$$d_1 = 1.432788$$
$$d_2 = 0.189269$$
$$d_3 = 0.001308$$

For a given time scale, SPI values are positive (negative) for greater (less) than median precipitation. A value of zero corresponds to the median precipitation. The magnitude of the departure from zero is a probabilistic measure of the severity of a wet or dry event. The time series of the SPI can be used for drought monitoring by setting application-specific thresholds of the SPI for defining drought beginning and ending times. In the present study, the values of the SPI range from 2.00 and above (extremely wet) to -2.00 and less (extremely dry). The near normal conditions range from the SPI values of 0.99 to -0.99. The classification values for the SPI are shown in Table 5.1.

One year in the time series of half-monthly precipitation	One year in the time series of monthly precipitation
Jan 1, Jan 2	Jan
Jan 2, Feb1	Jan -Feb
Feb1, Feb 2	Feb
Feb 2, Mar 1	Feb-Mar
Mar 1, Mar 2	Mar
Mar 2, Apr1	Mar-Apr
Apr1, Apr 2	Apr
Apr 2, May 1	Apr-May
May 1, May 2	May
May 2, Jun 1	May-Jun
Jun 1, Jun 2	Jun
Jun 2, Jul 1	Jun-Jul
Jul 1, Jul 2	Jul
Jul 2, Aug 1	Jul-Aug
Aug 1, Aug 2	Aug
Aug 2, Sep 1	Aug-Sep
Sep 1, Sep 2	Sep
Sep 2, Oct 1	Sep-Oct
Oct 1, Oct 2	Oct
Oct 2, Nov 1	Oct-Nov
Nov 1, Nov 2	Nov
Nov 2, Dec1	Nov-Dec
Dec1, Dec 2	Dec
Dec 2, Jan 1	Dec-Jan

Figure 5.1 One year of the time series of half-monthly and monthly precipitation

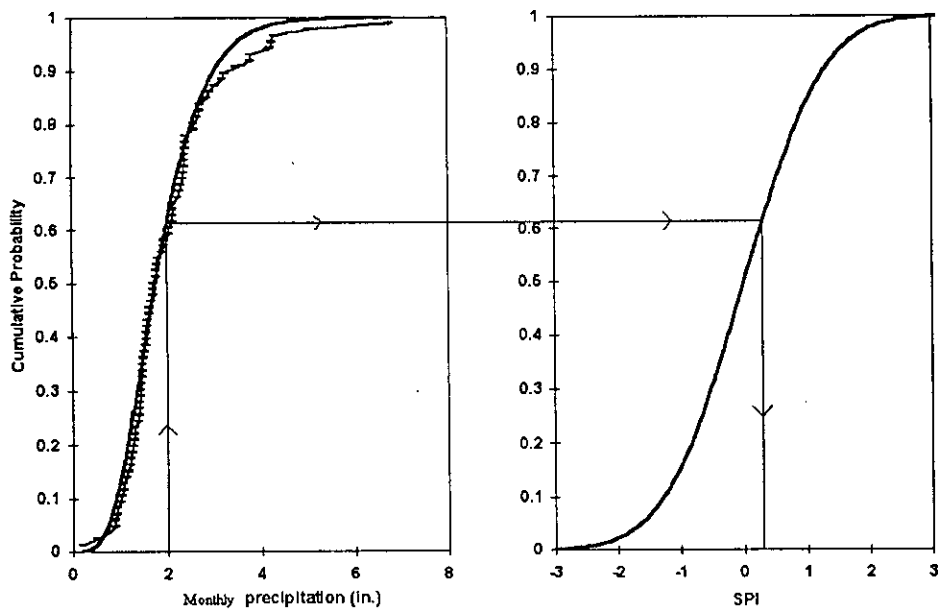


Figure 5.2 Example of equiprobability transformation from fitted distribution to the standard normal distribution (Source: http://www.wrce.sage.dri.edu/spi/spi.html)

Table 5.1 Classification of weather using SPI (Source: McKee et al., 1993)

SPI value	Drought Category
2.00 and above	Extremely wet
1.5 to 1.99	Very wet
1.00 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.00 to -1.49	Moderately dry
-1.50 to -1.99	Severely dry
-2.00 and less	Extremely dry

The drought event is defined when the SPI is continuously negative and reaches a value of -1.0 or less, and continues until the SPI becomes positive. Drought duration is defined by the interval between the beginning and end of that period. The magnitude of the drought event is measured by the sum of the SPI values for the period of drought. The methodology would be described with an example in the subsequent section.

5.1.3 Goodness of fit test

As mentioned earlier, the 24 time series of monthly precipitation for Jan, Jan-Feb, Feb,........., Nov-Dec, Dec, Dec-Jan of each of the selected station are either fitted to 2-Parameter Log-Normal (LN-2) distribution or Extreme Value Type III (Weibull) distribution. The consistency of the fitted distribution to monthly rainfall data of each series in any station is assessed with the help of goodness-of-fit analysis based upon probability plot correlation coefficient (Stedinger et al., 1993) and probability plot.

The Probability plot correlation coefficient gives the correlation between the ordered observations and the corresponding fitted quantiles determined by a plotting position. The Weibull plotting position formula used here is $p_i = \frac{i}{n+1}$, where p_i is the plotting probability and i is the rank in ordered observations with i=1 for the smallest observation in the sample. The data are arranged in ascending order of magnitudes so that $x_1 \leq ...... \leq x_i \leq ...... \leq x_n$, where n is the sample size. The probability plot correlation coefficient is given by

$$\rho = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\left[\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2\right]^{0.5}}$$

where, x_i is the observed i-th smallest precipitation

y_i is the computed value at the i-th plotting position

$\bar{x}$ is the average value of the observations and

$\bar{y}$ is the average of the computed value.

The maximum value of ρ can be equal to one. In the present study the values of ρ are tested at α =5% significance level using the Student's t-statistics. The t-statistic is defined as

$$t = \frac{\rho\sqrt{n-2}}{\sqrt{1-\rho^2}}$$

The null hypothesis that the observed and computed values are independent is rejected if $t > t_{crit}$, where t_{crit} is the point on the Student's t distribution with n-2 degrees of freedom that has a probability of exceedence of $\alpha / 2$.

5.1.4 Illustration of the methodology for determination of the SPI

The station Dhunot (CL 011) is selected here to illustrate the methodology for determination of the SPI. The 31 years daily rainfall data are used to form half-monthly time series. The time scale for the calculation of the SPI is considered as one month. Monthly precipitation is taken as the running sum of two half-months rainfall. This means that the precipitation value corresponding to a particular month, for example, Jan represents the total precipitation of the Jan 1 and Jan 2 half-months. Thus total 24 time series of precipitation for Jan, Jan-Feb, ……, Dec, Dec-Jan months has been generated from the 31 years long time series of monthly rainfall. Thus the time series namely Jan consists of 31 years record of total precipitation of Jan 1 and Jan 2 half-months. The probability density functions are fitted to each of the 24 time series. The LN-2 distribution is fitted to the time series of Jul, Jul-Aug, Aug, Aug-Sep, Sep, Sep-Oct, Oct, Oct-Nov and the Weibull distribution is fitted to the time series of Nov, Nov-Dec, Dec, Dec-Jan, Jan, Jan-Feb, Feb, Feb-Mar, Mar, Mar-Apr, Apr, Apr-May, May, May-Jun, Jun, Jun-Jul. The probability plots of the fitted LN-2 distribution with 90 percent confidence interval are shown is Appendix III. The statistical test based upon probability plot correlation coefficient also shows that the fitted distribution is accepted at 5% level of significance. The probability plot correlation coefficients and values of t-statistics for the fitted LN-2 distribution are given in Table 5.2. The goodness of fit of Weibull distribution is tested on the basis of cumulative probability plots. Sharma (1996) shows that the cumulative probability plot is a powerful technique to identify the dependence structure of the predicted and observed values. The cumulative probability plots using Weibull distribution are shown in Appendix IV. It is mentioned that the distribution has been fitted only using non-zero precipitation values. The cumulative probability of an observed precipitation is then determined from the fitted distribution. The zero precipitation values are treated following a standard procedure. If G(x) is the cumulative probability distribution of non zero values of x and q is the probability that x is zero, the cumulative probability, H(x) for all values of x is computed as follows (Hann, 1977),

$$H(x) = q + (1-q)G(x)$$

The cumulative probability of non exceedence of x, H(x) is then transformed to the standard normal random variable using Eqn. (5.1), which is the value of the SPI.

The SPI values of all precipitation observations in 24 time series are combined to obtain the SPI values for each half-month of the 31 years long time series. Table 5.3 shows the values of SPI of each observed monthly precipitation, x for the station Dhunot from Jan-2/1972 to Feb-1/1973. The value of x is the running sum of two half-months rainfall. Since full half-month time series is considered now, the half-months in a year are shown in Table 5.3 as in the format of Jan-1, Jan-2, Feb-1,......Dec-2. The value of x corresponding to Jan-2 half month shown in the Table is the same as the value of precipitation corresponding to Jan shown in Figure 5.1. So an additional column (Col.3) is added to the table for avoiding any confusion. H(x) is the cumulative probability of non-exceedence of x. The value of H(x) is computed using the cumulative distribution function of the fitted distribution with the treatment of zero precipitation as stated earlier. H(x) is then converted to SPI using Eqn. (5.1). When the values of SPI are continuously positive and reach to the value of 1.00, the wet spell has been considered to be started. Similarly, when the values of SPI are continuously negative and reach to the value of -1.00, the drought spell has been considered to be started. The drought spell would continue until next positive value of SPI occurs. In the table, a wet spell continues through Jan-2/1972 to Feb-2/1972. From Mar-1/1972 to Jun-1/1972, the SPI is continuously negative and reaches a value of -1.5 in May-2/1972. In Jun-2/1972 and Jul-1/1972, the SPI is positive. So the drought period is from Mar-1/1972 to Jun-1/1972 and the severity of this drought spell is -8.90, the sum of the all SPI values from Mar-1/1972 to Jun-1/1972. From Aug-1/1972 to Nov-1/1972, the SPI values are continuously negative, but did not reach -1.0. So there is no drought spell during the period. The SPI values have become positive again from Nov-2/1972 through Feb-1/1973.

Table 5.2 Probability plot correlation coefficient of fitted LN-2 distribution (Station: Dhunot)

Name of the series	Probability plot correlation coefficient ρ	Degrees of freedom n-2	t-statistic $t = \frac{\rho\sqrt{n-2}}{\sqrt{1-\rho^2}}$
Jun-Jul	0.987	29	34.03
Jul	0.932	29	13.84
Jul-Aug	0.988	29	34.78
Aug	0.984	29	29.56
Aug-Sep	0.991	29	39.34
Sep	0.987	29	33.12
Sep-Oct	0.914	29	12.12
Oct	0.971	29	21.85
Oct-Nov	0.984	24	27.16

Table 5.3 Procedure for determining the SPI

Year	Name of half-month in the time series of half – monthly precipitation	Name of half-month in the time series of monthly precipitation	Monthly precipitation x	Cumulative probability of x H(x)	SPI
1	2	3	4	5	6
1972	Jan-2	Jan	0.1	0.54	0.11
1972	Feb-1	Jan-Feb	1.42	0.94	1.56
1972	Feb-2	Feb	1.32	0.83	0.94
1972	Mar-1	Feb-Mar	0	0.12	-1.18
1972	Mar-2	Mar	0	0.15	-1.04
1972	Apr-1	Mar-Apr	0	0.12	-1.18
1972	Apr-2	Apr	0.2	0.08	-1.41
1972	May-1	Apr-May	0.2	0.07	-1.45
1972	May-2	May	1.1	0.07	-1.5
1972	Jun-1	May-Jun	4.9	0.12	-1.16
1972	Jun-2	Jun	15.3	0.6	0.26
1972	Jul-1	Jun-Jul	16	0.62	0.31
1972	Jul-2	Jul	14.74	0.49	-0.03
1972	Aug-1	Jul-Aug	16.15	0.7	0.52
1972	Aug-2	Aug	9.75	0.49	-0.04
1972	Sep-1	Aug-Sep	7.51	0.18	-0.93
1972	Sep-2	Sep	8.58	0.42	-0.19
1972	Oct-1	Sep-Oct	7.21	0.45	-0.12
1972	Oct-2	Oct	2.31	0.45	-0.13
1972	Nov-1	Oct-Nov	0	0.16	-0.99
1972	Nov-2	Nov	0	0.52	0.04
1972	Dec-1	Nov-Dec	0	0.77	0.75
1972	Dec-2	Dec	0	0.65	0.37
1973	Jan-1	Dec-Jan	0.47	0.78	0.78
1973	Jan-2	Jan	0.47	0.66	0.42
1973	Feb-1	Jan-Feb	0	0.52	0.04

(Shaded area shown in Col.6 indicates the drought spell)

5.2 The Herbst method

5.2.1 The Concept of the method

Herbst et al. (1966) developed a method for the determination of drought of the northern regions of South Africa. The onset and termination of drought event was determined from available monthly rainfall data. The method also determined the index of drought severity and the weighted drought severity index. In the present study droughts were analyzed on half monthly basis instead of monthly basis. Bhuiyan et al. (2002) studied this method to analyze drought in NW region of Bangladesh on half monthly basis. Details of the methodology were described in their study. The monthly rainfall data have been divided into two halves. The rainfall in the first half of a month is the sum of the rainfall in first fifteen days and that for the second half is the sum of the rainfall of remaining days of the month. Several drought parameters are used in the method to characterize the drought. These are mean half monthly rainfall, weighting factors, carry over (excess or deficit rainfall), mean half monthly deficit and mean annual deficit. The onset and termination of drought as well as drought intensity and severity are determined using these parameters. In the present study, the method has been used to assess the suitability of application of Palmer method in Bangladesh. So methodology of the Herbst method (Bhuiyan et al., 2002) is described in brief in the next section.

5.2.2 Steps followed in the method

Determination of drought parameters:

In the first step the drought parameters of the Herbst method mentioned above are calculated to determine the onset and termination of drought.

i) Mean half-monthly rainfall, μ_r

μ_r is the representative rainfall for a particular half month in a year calculated by summing the actual rainfall of the particular half month for the given time series and dividing the sum by the total number of years of the time series.

ii) Half-monthly weighting factor, f_t

f_t is used to calculate carry-over effect to the subsequent half of the month and is based on the fact that the carry over would be greater in the wetter months than in the normally drier month. The f_t is calculated as follows:

$$f_t = 0.1\left\{1 + 24\frac{\mu_r(t)}{\tau}\right\}$$

where, f_t is the weighting factor for the half-month t

t=1,2,3,................,24

τ is the mean annual rainfall calculated as the sum of 24 mean half-monthly rainfall (μ_r)

The value of f_t varies from more than 0.1 to about 0.4 indicating that carry-over only appreciably affects the first half month following it.

iii) Carry over (excess or deficit rainfall), c(t)

The c(t) value is the excess or deficit rainfall obtained by subtracting $\mu_r(t)$ for a particular half month from the effective rainfall, R_e(t) of the corresponding half month. R_e(t) is calculated by algebraic sum of actual rainfall value, R_a(t) and the weighted value, ν(t). The ν(t) for a particular half month is the product of the f(t) for the same half month with the carry-over value of the previous half-month, c(t-1). Initially for the first half-month, ν(t=1) is considered as zero. The positive c(t) value is considered as excess rainfall while negative c(t) value is treated as deficit rainfall.

iv) Mean half monthly deficit, μ_d(t)

μ_d(t) is the representative deficit for a particular half month in a year calculated from only deficit rainfalls, (i.e., considering negative c(t) values). The positive c(t) values are considered as zero in the calculation of μ_d(t) values. The μ_d(t) value for a particular half month in a year is calculated by summing all the deficit rainfall values for the given time series and dividing the sum by the total number of years of the time series.

v) Mean annual rainfall deficit, *MARD*

The summation of 24 values of μ_d(t) gives the value of *MARD*. The *MARD* is used for testing the onset and termination of drought. The excess deficit, E_d(t) values are calculated by subtracting the μ_d(t) values from the c(t) values. The positive E_d(t) values are considered as zero.

Another set of parameters necessary for determining the start and termination of drought is the value of highest mean half-monthly rainfall (μ_{hr}), the sum of the two highest values of μ_r and so on up to the twenty four values of mean half-monthly rainfall which is equivalent to mean annual rainfall, τ .

Test for the onset of drought:

The test is based on the comparison of the sum of the negative differences from the point in time at which the test begins, with a sliding scale of 24-values calculated by linear interpolation between the highest mean half-month rainfall (μ_{hr}) and the mean annual rainfall deficit (*MARD*). Thus a half-monthly increment, Δ is obtained from the following formula,

$$\Delta = \frac{MARD - \mu_{hr}}{23}$$

The first value on the sliding scale is equal to μ_{hr}. The second on the sliding scales is obtained by adding 1Δ to μ_{hr}, the third value by adding 2Δ to μ_{hr} and so on up to twenty-fourth value, that is , (μ_{hr}+23Δ) which is equal to *MARD*.

It is assumed that no drought is prevailed prior to the start of available rainfall record. If the first c(t) value of the record is positive, the potential drought is not signified. Then the c(t) values of the succeeding half-months are inspected until a half monthly record with a negative value is found. Such a half month is the start of a potential drought. Then the absolute values of the first excess deficit, E_d(t) is compared with the first value of the sliding scale, μ_{hr} and if the latter is equaled, a drought is deemed to have started. If μ_{hr} is not equaled, the next E_d(t) value is added to the previous E_d(t) and compared with the second value on the sliding scales, (μ_{hr}+1Δ). If this criterion is exceeded by the absolute value of the two E_d(t) combined, a drought is deemed to have started from the first half month. Thus the absolute value of the sum of all E_d(t) occurring from the first half-month record over a period of year is tested sequentially against the 24 values of the sliding scale. If at any time the summation of absolute value of the excess deficits from the first to the nth half-month record exceeds the value μ_{hr} + (n-1)Δ, a drought is deemed to have started from the first half-month record. But if the condition for a particular period is such that summation of excess deficits from the first to the nth half-month record does not exceed the value μ_{hr} + (n-1)Δ, there is no drought prevailing during the period.

Test for the termination of drought:

To test the termination of drought, a positive c(t) value of the half-monthly record occurring after the start of the month is noticed. A condition to be satisfied is that at least one of the two half-months following the initial half-month with a positive c(t) should also have a positive c(t). If this condition is satisfied, the summation of the actual rainfall, Ra (t) of these three successive half-months is compared with the sum of the three highest values of mean half monthly rainfall. If the actual rainfall is higher, the drought is considered to have been terminated at the first half-month. If it is not, the sum of the first four half-months' actual rainfall compared with the sum of the four highest values of mean half-monthly rainfall, and so on up to 24 values should the drought not yet have been terminated. In this case, if the summation of actual rainfall is less than summation of the highest values of mean half-monthly rainfall the drought is considered as temporarily broken up. As such, either the drought condition has been terminated or drought condition resumes after a temporary interruption. Once the termination is occurred, testing for the start of the next drought begins at the half-month with a negative difference following the half-month in which drought has ended.

Drought indices:

When the drought spells for the full time series are determined, the index of drought intensity, I for each spell is calculated as follows:

$$I = \frac{\sum_{t=1}^{T} E_d(t)}{\sum_{t=1}^{T} \mu_d(t)}$$

Where,

T is the period during which drought is continued

The weighted drought severity index, S is calculated as, $S = I * T$

If the index value for a particular spell of drought of a station for a given time series is high in comparison to the other drought spell(s), it represents that the actual rainfall for that particular spell of drought is low, i.e. during the period the severity of drought is high and vice versa. Figure 5.3 illustrates the conditions of onset and termination of droughts by using the Herbst method.

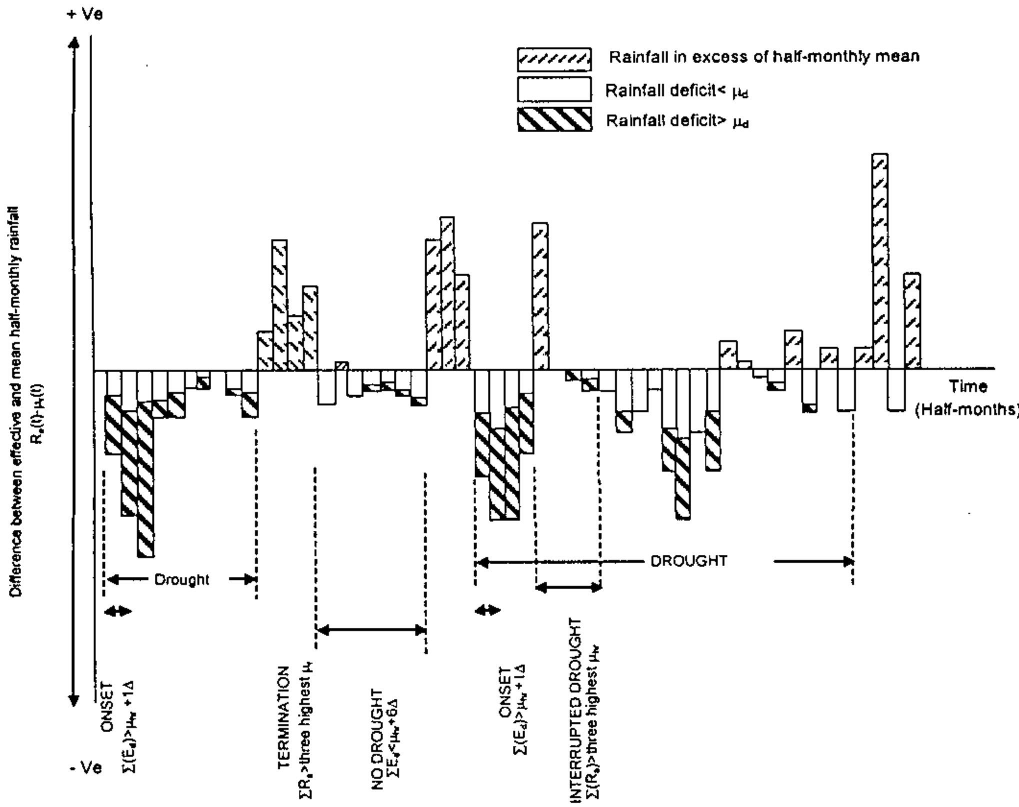


Figure 5.3 Conditions for determining the onset and termination of droughts according to the Herbst method

Chapter 6

DROUGHT ANALYSIS BY THE PALMER METHOD

6.1 General

The Palmer method considers soil moisture and evapotranspiration conditions of the selected areas in addition to rainfall pattern for determining the onset and termination of drought spells and their severity. In the present study the Palmer Drought Severity Index (PDSI) was calculated on monthly basis as per original formulation by Palmer (1965). This is for that the constants and the equations used in the Palmer method were originally derived analyzing regions having widely varying monthly rainfall and temperature. For shorter time scales, these coefficients and equations are required to derive following the same procedure for monthly timescale. The shorter timescale is more appropriate for irrigation scheduling in Bangladesh. Palmer (1965), however, concluded that weekly data would provide little closer realistic measure while the differences of results are slight. The occurrences of drought spells and their severity obtained in the approach would be discussed in the following sections.

6.2 Occurrences of drought spells

The occurrences of drought spells estimated by the Palmer method during the period from 1972 to 2002 in selected stations of NW region are summarized in Tables 6.1 - 6.2 and Figure 6.1. The time series of monthly PDSI and rainfall at the selected stations of NW region are shown in Appendix III.

The average occurrence of drought in NW region has been observed in 34 percent of study time from 1972 to 2002 while the average occurrence of drought in the country is once in 2.5 years (Adnan, 1993; Ericksen et al., 1993; Hossain, 1990). Thus the percent of occurrences of drought in NW region by the Palmer method are below the historical average drought occurrence of Bangladesh. The average occurrence of extreme droughts is 3.6 percent of total study time in the selected stations of the NW region while mild, moderate and severe droughts occur in average of 13.5 percent, 9.68 percent and 5.4 percent of total time respectively. Between 1960 and 1991, nineteen droughts have been occurred in Bangladesh (Mirza and Paul, 1992). World Bank (2000) identified severe droughts occurred in 1951, 1961, 1975, 1979, 1981-82, 1984 and 1989. The year 1994-95 was also a severe drought year in Bangladesh (Sajjan, 1998). The occurrences of drought spells in the Palmer method is shown in Figure 6.2. The method identified the most common drought occurrences in years like 1972-73, 1975-76, 1976-77, 1978-79, 1979-80, 1982-83, 1992-93, 1994-95, 1999 and 2001-2002 in selected fifteen stations in NW region. Thus the method could identify the historical drought occurrences of Bangladesh like the year 1975, 1979, 1981-82, 1984, 1989, 1992-93 and 1994-95.

The highest PDSI at each station of NW region and the corresponding drought duration is shown in Figure 6.3. The figure shows that the values of PDSI may be higher in a shorter duration drought spell. The percent of occurrences of drought and the percent of occurrences of the events that the potential evapotranspiration (PE) exceeds the rainfall (P) in total study time are shown in Figure 6.4. The figure shows that the percent of drought occurrences in the selected stations of the NW region are below than the percent of occurrence of the events, PE exceeds P. This reveals that only the values of PE do not affect the occurrences of drought, as mentioned earlier the Palmer method considers the antecedent soil moisture in addition to evapotranspiration and rainfall of the stations considered. When rainfall is not sufficient to satisfy the evapotranspiration demand, the excess demand is satisfied from the antecedent soil moisture. So it is noticeable that the effect of soil moisture condition of each station may be an important criterion for the occurrences of drought. It has been observed that the station Kaunia (CL 178) experiences drought in 50 percent of total time, which is the highest percentage of drought occurrence in the NW region, though the average monthly PE of the station is less and the average monthly rainfall is higher than those of the region (Figure 6.5). It is mentioned that average monthly PE or P of the station is the 31 years average of PE or P at a particular month while average monthly PE or P of the region is the average of mean monthly PE or P of all the stations. The percentage of occurrence of the event PE exceeds P at Kaunia is the highest in NW region (Figure 6.4). The occurrence of mild drought in the station is 20 percent of the total time, which is higher than the average occurrence of mild drought in the region.

The station Singra (CL 036) possesses the longest drought spell of 74 months in the NW region. During the drought period from Nov/1974 to Dec/1980, the monthly rainfall of Singra exceeds the mean monthly rainfall of the station in 61 percent of time as shown in Figure 6.6. In May/1979, the PDSI is -5.0, which indicates the extreme drought condition. In Jun/1979, high rainfall occurs, but it fails to bring the previous month extreme drought condition to normal climatic condition. Here PDSI considers not only the current but also the recent past conditions. Guttman (1998) showed that the inherent memory of the PDSI is higher due to the nature of water balance accounting approach upon which the index is based. A current month's contribution to the PDSI is highly dependent on antecedent soil and atmospheric moisture conditions. The potential evapotranspiration (PE) is also high in Jun/1979. After this month, the drought condition begins to improve, but not ended. In Jan/1981 when the PE is low and at the same time some rain occurs, the long duration drought spell has been ended.

6.3 Onset and termination of drought spells

The results of the Palmer method show that the percentage of beginning of drought spells (22.6 percent) is the highest at the month of October while the percentage of ending drought spells (14.8 percent) is the highest in the month of April. These are the transitional months of the two distinct seasons of Bangladesh. National Water Management Plan (Halcrow et al., 2000) considers the months from November to May as dry season in Bangladesh. About 16 percent of drought spells of NW region begins and 10.4 percent of drought ends in the month of May. On the other hand, 11.3 percent drought begins and 14.8 percent drought ends in April. Karim et al. (1990) identified Kharif droughts in June/July to October months resulting from sub-humid and dry conditions in Bangladesh. So occurrences of droughts during this period estimated by the Palmer method are realistic feature of Bangladesh.

The time series from 1972 to 2002 of monthly average precipitation (P) and potential evapotranspiration (PE) of the NW region for the months of April, May and October are shown in Figure 6.7. Here, the monthly average P and PE are the average value for the particular month of all stations. During October, the average P is exceeded by the average PE in most of the years. But in April average PE exceeds average P in all the years except 1981 and 2002. During May, the average P exceeds the average PE in more than 65 percent of time. So it seems more reasonable to begin drought spells in higher percentage of time and to end drought spells in lower percentage of time in April than those in May. These two cases needed to be explained. It may happen for soil moisture consideration in the Palmer method. But it demands further investigation to answer how soil moisture affects the beginning and ending of drought spells.

The pattern of monthly PE of the region obtained using the Thornthwaite's formula (1955) are compared with modified Penman method (Doorenbos and Pruitt, 1977) as shown in Figure 6.8. The modified Penman method (Doorenbos and Pruitt, 1977) has been used by Karim and Akhand (1982) to determine the evapotranspiration demands of crops in Bangladesh. The figure reveals that the values of PE obtained using the Thornthwaite's formula (1955) exceeds in the months from May to October from the values of modified Penman method (Doorenbos and Pruitt, 1977). The Thornthwaite's formula (1955) considers temperature only while estimating the values of PE while modified Penman method (Doorenbos and Pruitt, 1977) considers other factors such as vapor pressure, wind and radiation in addition to temperature. It can be assumed that use of any other method for estimating more realistic evapotranspiration demands would produce more reasonable results.

6.4 Limitations of the Palmer method

Overall limitations

Alley (1984) identified a number of limitations and deficiencies of the Palmer method in calculating the PDSI. These are the deficiencies of the water balance model and the limitations of the PDSI characteristics.

The deficiencies of the water balance model include:

i) The use of Thornthwaite's formula (1955) for estimation of the potential evapotranspiration, though other realistic methods could be employed. The Thornthwaite's formula was used as a simple method for estimation of potential evapotranspiration.

ii) The arbitrary amount of one inch moisture capacity is considered in the surface layer of soil. The moisture capacity could be widely varied depending on the climate, the soil texture and vegetation coverage of the area.

iii) The runoff is estimated assuming no time lag in the runoff distribution. The fraction of delayed runoff varies considerably depending on the depth and texture of the soil, the physiography and size of the basin and the nature of the groundwater system.

iv) The assumption that runoff does not occur until the moisture capacity of both surface and underlying soil layers are filled.

The limitations of the PDSI characteristics are as follows:

i) The arbitrary definition of PDSI classes was based on the data of some selected regions.

ii) The PDSI values are sensitive to the monthly weighting factors, while the duration of droughts are relatively insensitive to those factors.

Limitations regarding application in Bangladesh

The available literature (Karl, 1986; Kothavala, 1997; Lohani and Loganathan, 1997; Piechota and Dracup, 1999; Louie, 1986; Scian and Dounari, 1997; Szinell et al., 1998; Dalezios et al., 2000) reveals that Palmer method is more applicable in arid, semiarid and dry sub-humid regions. In the present study an attempt has been made for applying the method in the humid to sub-humid climate of NW Bangladesh. While applying Palmer method in drought analysis of NW region of Bangladesh, some limitations were noticed in addition to those identified Alley (1984). No allowance was provided in the method regarding excess rainfall flooding and transboundary flooding of the land. Difficulties arise in getting realistic values by applying Palmer method to a country like Bangladesh where most of the agricultural lands are flooded during the monsoon season. In addition to that, the assumption that the potential precipitation is equal to the available soil moisture capacity (AWC) of soil is not realistic in Bangladesh since during monsoon season, the precipitation generally exceeds AWC of soil. The depth of underlying layer soils was needed to increase beyond the root zone depth in order to incorporate the assumption. This is a great difficulty in assuming the appropriate soil depth for applying the method for situation in Bangladesh. Palmer (1965) considered 'recharge' as a part of moisture demand. Practically, recharge contributes to the soil moisture storage. So it should be considered as a part of moisture supply to soil. Moreover, Palmer (1965) defined 'potential recharge' as the amount of moisture needed to bring the soil to field capacity. In the context of Bangladesh, this definition is not realistic.

6.5 Modifications needed for applying the Palmer method in Bangladesh

With the consideration of the overall limitations, the Palmer method is widely used in many countries with arid or semiarid climatic characteristics. To apply the method more successfully to the climatic conditions of Bangladesh, the following modifications are suggested:

i) Use of appropriate method for determining more realistic potential evapotranspiration of Bangladesh.

ii) Determination of the coefficients and equations of the Palmer method by analyzing long term historical climatic data of Bangladesh.

iii) Consideration of reasonable value for moisture capacity of the surface layer soil

iv) Provision of standing water condition in agricultural land.

v) Modification of the assumption that the potential precipitation equal to the AWC of soil.

vi) Modification of definition of 'recharge' in the context of Bangladesh.

vi) Consideration of recharge as a part of moisture supply rather than a part of moisture demand.

Table 6.1 Occurrences of droughts in NW region during 1972-2002 estimated by the Palmer method

Name of the station	Starting of drought	Ending of drought	Maximum severity	Number of months				
				Mild	Moderate	Severe	Extreme	Total*
Atghoria CL 001	Oct/ 1972	Apr/ 1973	-2.29	5	2	-	-	7
	Mar/ 1975	Apr/ 1976	-2.47	8	1	-	-	14
	Sep/ 1978	Dec/ 1980	-4.20	13	10	-	3	28
	Sep/ 1982	Jul/ 1983	-3.29	3	3	4	-	11
	May/ 1985	Aug/ 1986	-2.35	10	4	-	-	16
	Apr/ 1992	Feb/ 1993	-2.41	2	9	-	-	11
	Aug/ 1994	Jul/ 1995	-3.47	8	1	3	-	12
	Jun/ 1996	Jun/ 1997	-2.6	7	3	-	-	13
	Feb/ 1999	Dec/ 1999	-3.95	2	5	4	-	11
	Aug/ 2001	May/ 2002	-2.69	3	7	-	-	10
Number of months				61	45	11	3	133
Percent of total time				16.4	12	3.0	0.80	35.8
Bogra CL 006	Apr/ 1975	Apr/ 1977	-4.03	14	6	4	1	25
	Oct/ 1978	Sep/ 1980	-4.2	1	12	8	4	25
	May/ 1982	Aug/ 1983	-2.86	4	9	2	-	16
	Apr/ 1985	Mar/ 1986	-1.47	7	-	-	-	12
	Oct/ 1989	Apr/ 1990	-2.0	5	1	-	-	6
	May/ 1994	May/ 1995	-5.7	2	2	6	3	13
	Apr/ 1999	Jul/ 1999	-1.5	4	-	-	-	4
	Jan/ 2001	Dec/ 2001	-3.29	3	3	6	-	14
Number of months				40	33	26	8	115
Percent of total time				10.8	8.9	7.0	2.2	30.9
Dhunot CL 011	Nov/ 1972	Dec/ 1972	-1.21	2	-	-	-	2
	Oct/ 1978	Apr/ 1980	-3.15	12	6	1	-	19
	Oct/ 1981	Feb/ 1983	-2.27	13	3	-	-	17
	Oct/ 1984	Aug/ 1986	-3.48	6	16	1	-	23
	Jul/ 1992	Dec/ 1992	-1.94	6	-	-	-	6
	Apr/ 1994	Oct/ 1995	-6.25	3	4	3	9	19
	Apr/ 1999	May/ 2002	-6.8	8	4	3	23	38
Number of months				50	33	8	32	124
Percent of total time				13.4	8.9	2.2	8.6	33.3
Sirajganj CL 034	Oct/ 1972	Dec/ 1972	-1.34	3	-	-	-	3
	Feb/ 1975	Mar/ 1977	-3.10	10	14	1	-	26
	Oct/ 1978	Dec/ 1980	-4.35	-	13	6	27	30
	May/ 1982	Jul/ 1983	-3.72	4	1	10	-	15
	Nov/ 1985	Aug/1986	-1.61	7	3	-	-	10
	Jul/ 1994	Jul/ 1995	-3.25	4	8	1	-	13
	Mar/ 1999	Jun/ 2002	-3.98	6	23	11	-	40
Number of months				34	62	29	27	137
Percent of total time				9.1	16.7	7.8	7.3	36.8

Table 6.1 Occurrences of droughts in NW region during 1972-2002 estimated by the Palmer method (continued)

Singra	Nov/ 1972	Apr/ 1973	-3.02	4	1	1	-	6
CL 036	Nov/1974	Dec/ 1980	-5.07	23	23	25	3	74
	Feb/ 1982	Feb/ 1983	-2.75	7	8	-	-	15
	Jun/ 1992	Apr/ 1993	-2.89	5	6	-	-	12
	May/ 1995	Jul/ 1995	-1.44	2	-	-	-	3
	Nov/2000	Jul/2002	-2.01	19	1	-	-	21
Number of months				60	39	26	3	131
Percent of total time				16.1	10.5	7.0	0.8	35.2
Dinajpur	Oct/1972	Aug/ 1973	-2.69	2	7	-	-	11
CL 168	Dec/ 1976	Mar/ 1977	-1.68	4	-	-	-	4
	Oct/ 1978	Oct/ 1979	-4.21	3	4	4	2	13
	Oct/ 1981	Nov/ 1983	-5.14	4	3	4	13	26
	Apr/ 1984	Sep/ 1986	-4.47	12	9	4	2	30
	Apr/1992	Oct/ 1992	-2.19	4	3	-	-	7
	May/1994	May/1995	-5.21	5	5	1	2	13
	May/ 1996	Dec/ 1996	-1.77	5	-	-	-	8
	Oct/ 1998	Jul/1999	-2.21	8	1	-	-	10
	Sep/2000	Jun/2001	-4.31	3	5	1	2	11
Number of months				39	31	13	19	112
Percent of total time				10.5	8.3	3.5	5.1	30.1
Kaliganj	Oct/1972	Apr/ 1973	-1.67	7	-	-	-	7
CL 177.	Feb/ 1975	Mar/ 1977	-2.88	12	13	-	-	27
	Jun/ 1978	Jan/1981	-6.14	16	5	5	5	33
	Oct/ 1981	Feb/1983	-3.28	5	8	4	-	17
	Jan/ 1989	May/ 1990	-3.69	8	6	1	-	17
	Sep/1994	Mar/ 1997	-4.89	13	10	3	3	31
	Nov/2000	Sep/ 2001	-3.77	4	3	4	-	11
Number of months				65	45	17	8	143
Percent of total time				17.5	12.1	4.6	2.2	38.4
Kaunia	Nov/ 1972	Apr/1973	-1.51	4	-	-	-	6
CL 178	Oct/ 1976	Sep/1977	-4.65	3	3	3	3	12
	Oct/ 1978	Apr/ 1983	-6.90	16	15	13	9	55
	Apr/1984	Feb/1985	-1.59	10	-	-	-	11
	Oct/1985	Jun/ 1986	-1.93	7	1	-	-	9
	Mar/1989	Feb/1990	-2.97	8	3	-	-	12
	Nov/1994	Oct/1995	-3.91	4	3	5	-	12
	Feb/1996	Jul/1998	-3.97	14	9	7	-	30
	Jan/1999	Mar/2002	-4.72	8	11	15	4	39
Number of months				74	45	43	16	186
Percent of total time				19.9	12.1	11.6	4.3	50.0

Table 6.1 Occurrences of droughts in NW region during 1972-2002 estimated by the Palmer method (continued)

Mithapukur CL 186	Jan/1975	Mar/1976	-1.48	3	-	-	-	3
	Nov/1976	Mar/1977	-1.69	5	-	-	-	5
	Oct/1978	Oct/1979	-5.67	-	5	2	6	16
	Oct/1981	Nov/1984	-3.85	19	12	6	-	38
	Apr/1989	Jan/1990	-2.93	6	4	-	-	10
	Apr/1992	Mar/1993	-1.95	12	-	-	-	12
	May/1994	May/1997	-7.07	15	8	3	10	37
	May/1999	Sep/1999	-1.89	5	-	-	-	5
	Apr/2000	Mar/2001	-2.94	8	4	-	-	12
Number of months				73	33	11	16	138
Percent of total time				19.6	8.9	3.0	4.3	37.1
Mohipur CL 188	Dec/1972	Apr/1973	-2.18	4	1	-	-	5
	Jan/1977	Sep/1977	-1.93	6	-	-	-	9
	Aug/1978	Jul/1980	-5.88	3	10	4	7	24
	Oct/ 1981	Sep/1983	-2.94	9	15	-	-	24
	Dec/1988	Jan/1990	-2.90	5	9	-	-	14
	Aug/1994	Oct/1995	-6.46	-	3	5	7	15
	Dec/1999	Sep/2001	-3.94	12	2	5	-	22
Number of months				39	40	14	14	113
Percent of total time				10.5	10.8	3.8	3.8	30.4
Nazipur CL 192	Oct/1972	Apr/1973	-2.24	6	1	-	-	7
	Dec/1974	Aug/1976	-3.57	5	5	11	-	21
	Oct/1976	Sep/1977	-3.57	9	1	-	-	12
	Nov/1990	Apr/1991	-2.21	4	2	-	-	6
	Jun/1992	May/1993	-2.97	6	4	-	-	10
	Apr/1995	Jun/1995	-2.43	1	2	-	-	3
	Apr/1996	Feb/1997	-3.99	6	3	1	-	10
	May/1999	May/2002	-7.06	-	6	17	14	37
Number of months				37	24	29	14	106
Percent of total time				9.9	6.5	7.8	3.8	28.5
Nekmard CL 193	Oct/1972	Apr/1973	-2.51	5	2	-	-	7
	Aug/1978	May/1981	-5.34	7	16	3	5	34
	Oct/1984	Aug/1986	-4.03	8	8	2	1	19
	Dec/1988	Apr/1989	-2.24	3	1	-	-	5
	May/1992	Sep/1992	-2.08	3	2	-	-	5
	May/1994	Mar/1997	-5.53	15	6	4	7	35
	Sep/1999	Mar/2000	-1.96	7	-	-	-	7
	Dec/2000	Sep/2001	-2.43	8	2	-	-	10
Number of months				56	37	9	13	122
Percent of total time				15.1	9.9	2.4	3.5	32.8

Table 6.1 Occurrences of droughts in NW region during 1972-2002 estimated by the Palmer method (continued)

Rajshahi CL 205	Dec/1972	Mar/1973	-1.10	3	-	-	-	4
	Jun/1974	Mar/1977	-5.66	3	12	6	13	34
	May/1982	Sep/1983	-3.66	6	3	7	-	17
	May/1992	May/1995	-4.52	15	6	6	2	38
	Nov/1999	Feb/2002	-4.44	10	5	5	2	28
Number of months				37	26	24	17	121
Percent of total time				9.9	7.0	6.5	4.6	32.5
Rangpur CL 206	Aug/1972	Apr/1973	-1.77	9	-	-	-	9
	Aug/1975	May/1976	-1.63	8	-	-	-	10
	May/1978	Apr/1980	-5.13	12	5	2	3	24
	Mar/1982	Apr/1983	-2.57	9	5	-	-	14
	May/1994	Oct/1995	-4.6	6	5	3	3	18
	Oct/1996	Nov/1997	-2.34	10	3	-	-	14
	Dec/2000	Mar/2002	-5.12	1	-	11	11	28
Number of months				55	18	16	17	117
Percent of total time				14.8	4.8	4.3	4.6	31.5
Shibganj CL 215	Nov/1972	Mar/1973	-2.10	4	1	-	-	5
	Oct/1974	Apr/1975	-4.22	1	4	1	1	7
	Nov/1976	Mar/1977	-1.72	5	-	-	-	5
	May/1979	Sep/1980	-3.55	6	9	2	-	17
	Jul/1982	Jun/1983	-4.32	4	4	3	1	12
	Sep/1992	Jul/1995	-4.26	9	9	15	2	35
	May/1999	Jul/2000	-5.66	1	2	3	9	15
	Mar/2001	Sep/2001	-1.88	6	-	-	-	7
Number of months				36	29	24	13	103
Percent of total time				9.7	7.8	6.5	3.5	27.7

* Total includes the incipient droughts in addition to tabulated four categories of droughts.

Table 6.2 Number of drought spells beginning and ending in different months of a year estimated by the Palmer method

Station name	Number of drought spells beginning in months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Atghoria CL 001	0	1	1	1	1	1	0	2	2	1	0	0
Bogra CL 006	1	0	0	3	2	0	0	0	0	2	0	0
Dhunot CL 011	0	0	0	2	0	0	1	0	0	3	1	0
Sirajganj CL 034	0	1	1	0	1	0	1	0	0	2	1	0
Singra CL 036	0	1	0	0	1	1	0	0	0	0	3	0
Dinajpur CL 168	0	0	0	2	2	0	0	0	1	4	0	1
Kaliganj CL 177	1	1	0	0	0	1	0	0	1	2	1	0
Kaunia CL 178	1	1	1	1	0	0	0	0	0	3	2	0
Mithapukur CL 186	1	0	0	2	2	0	0	0	0	2	1	0
Mohipur CL 188	1	0	0	0	0	0	0	2	0	1	0	3
Nazipur CL 192	0	0	0	2	1	1	0	0	0	2	1	1
Nekmard CL 193	0	0	0	0	2	0	0	1	1	2	0	2
Rajshahi CL 205	0	0	0	0	2	1	0	0	0	0	1	1
Rangpur CL 206	0	0	1	0	2	0	0	2	0	1	0	1
Shibganj CL 215	0	0	1	0	2	0	1	0	1	1	2	0
Total	5	5	5	13	18	5	3	7	6	26	13	9
Percentage of total drought spells	4.3	4.3	4.3	11.3	15.7	4.3	2.6	6.1	5.2	22.6	11.3	7.8

Table 6.2 Number of drought spells beginning and ending in different months of a year in NW region estimated by the Palmer method (continued)

Station name	Number of drought spells ending in months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Atghoria CL 001	0	1	0	2	1	1	2	1	0	0	0	2
Bogra CL 006	0	0	1	2	1	0	1	1	1	0	0	1
Dhunot CL 011	0	1	0	1	1	0	0	1	0	1	0	2
Sirajganj CL 034	0	0	1	0	0	1	2	1	0	0	0	2
Singra CL 036	0	1	0	2	0	0	2	0	0	0	0	1
Dinajpur CL 168	0	0	1	0	1	1	1	1	1	2	1	1
Kaliganj CL 177	1	1	2	1	1	0	0	0	1	0	0	0
Kaunia CL 178	0	0	2	1	2	0	1	1	1	1	0	0
Mithapukur CL 186	1	0	4	0	0	0	0	1	1	1	0	0
Mohipur CL 188	1	0	0	1	0	0	1	0	3	1	0	0
Nazipur CL 192	0	1	0	2	2	1	0	1	1	0	0	0
Nekmard CL 193	0	0	2	2	1	0	0	1	2	0	0	0
Rajshahi CL 205	0	1	2	0	1	0	0	0	1	0	0	0
Rangpur CL 206	0	0	1	3	1	0	0	0	1	1	0	0
Shibganj CL 215	0	0	2	1	0	1	2	0	2	0	0	0
Total	3	6	16	17	12	4	10	9	13	7	1	9
Percentage of total drought spells	2.6	5.2	13.9	14.8	10.4	3.5	8.7	7.8	11.3	6.1	0.9	7.8

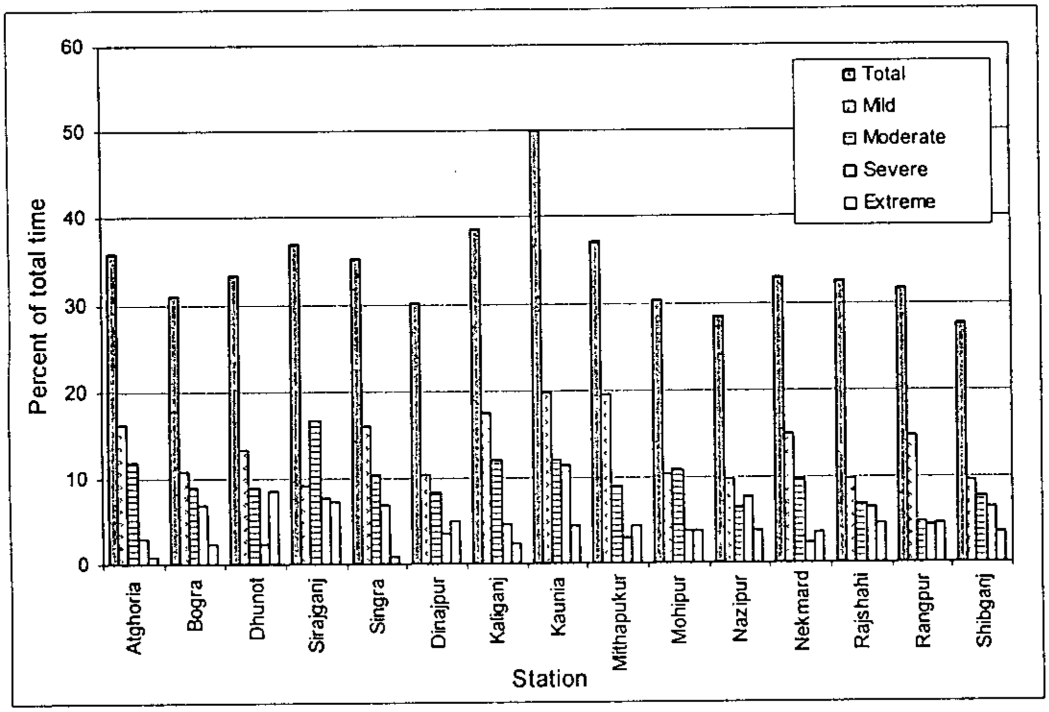


Figure 6.1 Occurrences of drought in NW region as percentage of total time

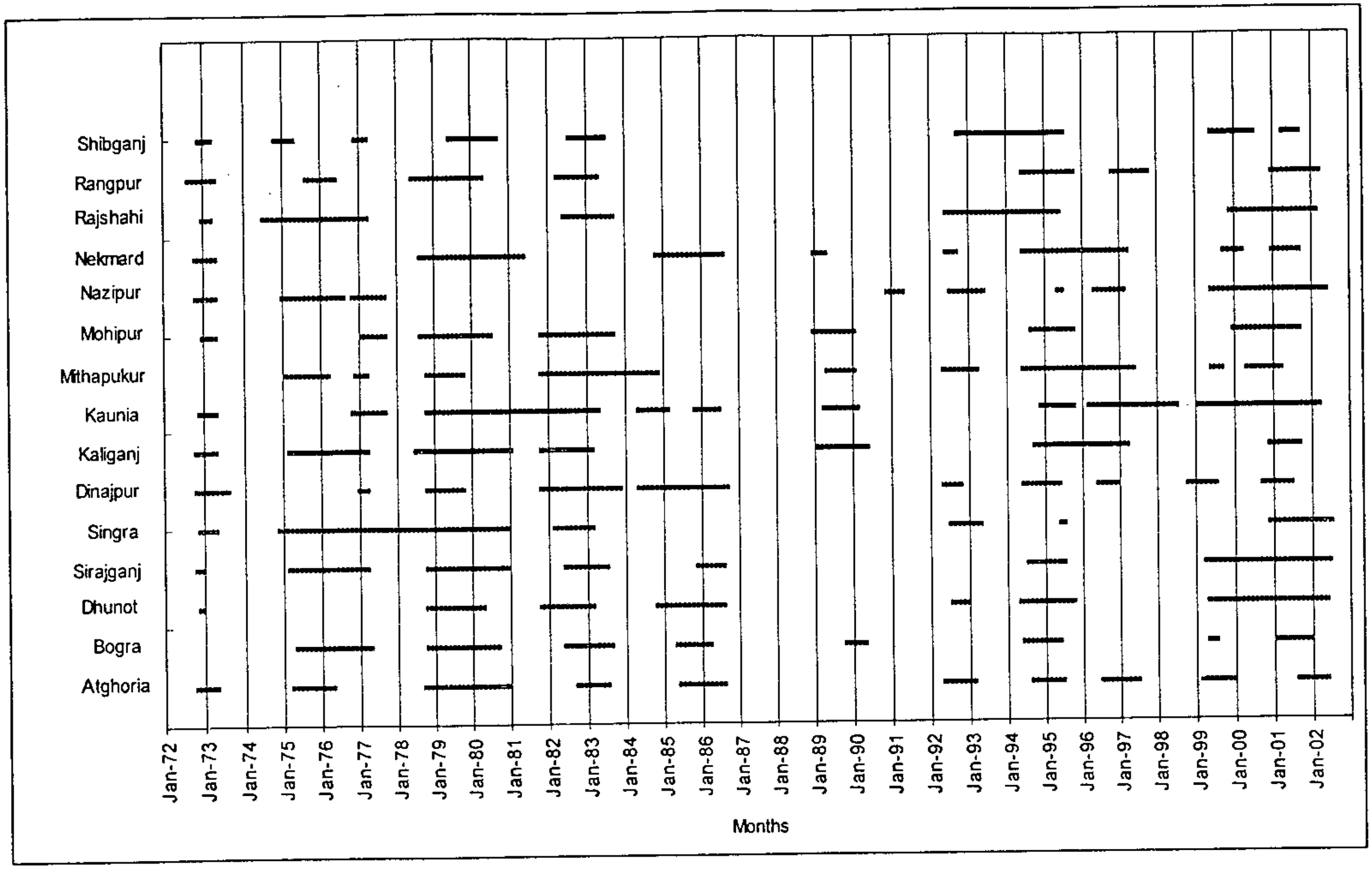


Figure 6.2 Occurrences of drought spells at selected stations in NW region

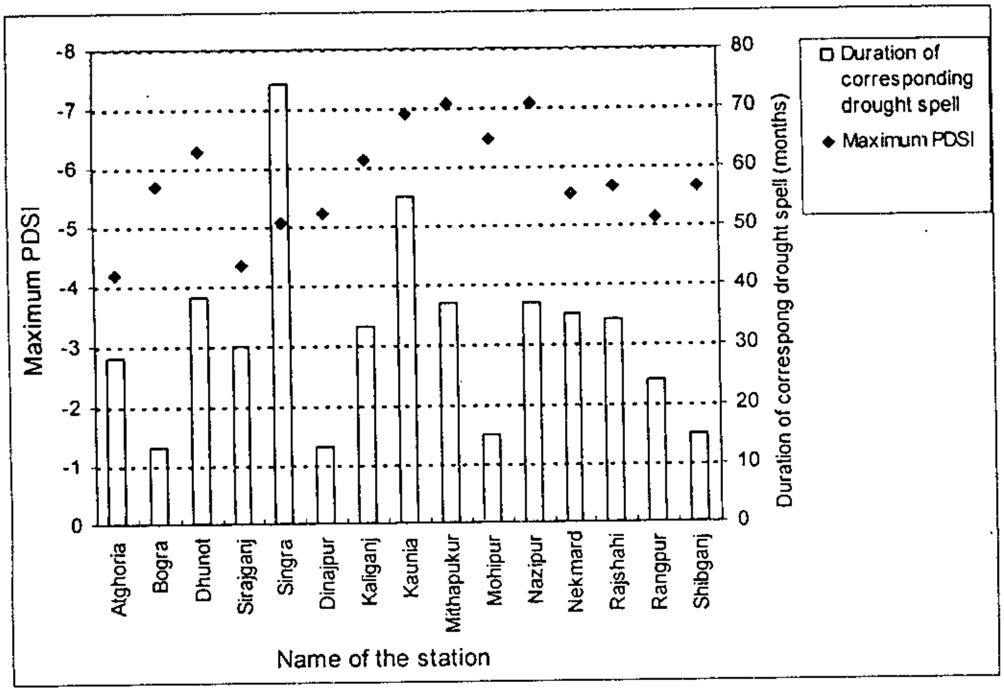


Figure 6.3 The maximum PDSI and the corresponding drought duration of each station of NW region

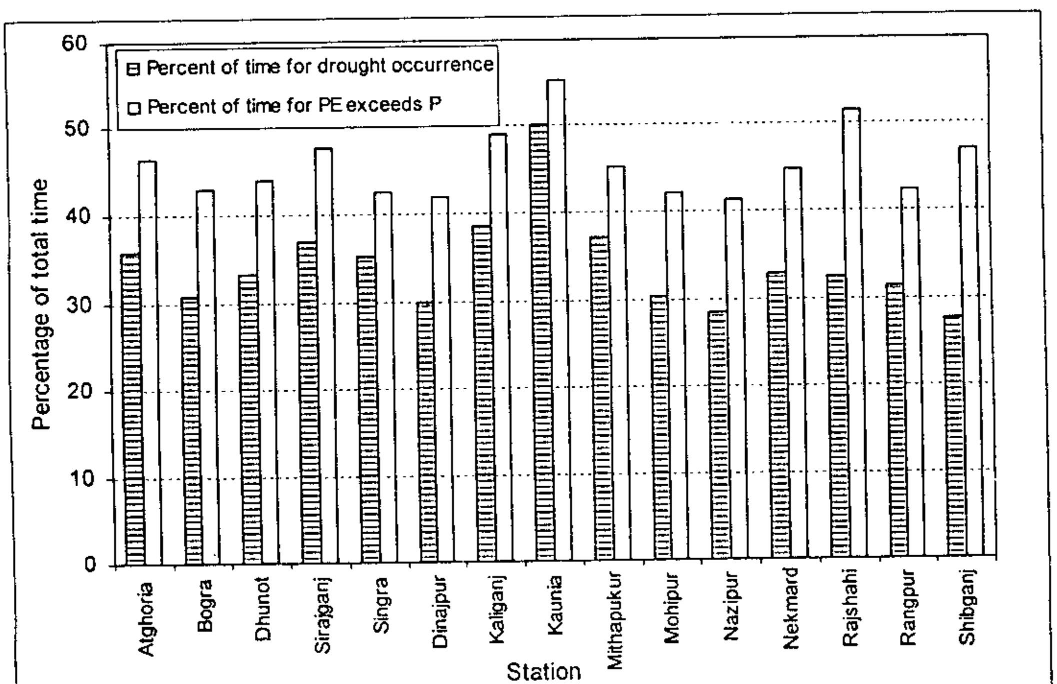


Figure 6.4 Occurrences of drought and the event that PE exceeds P in NW region

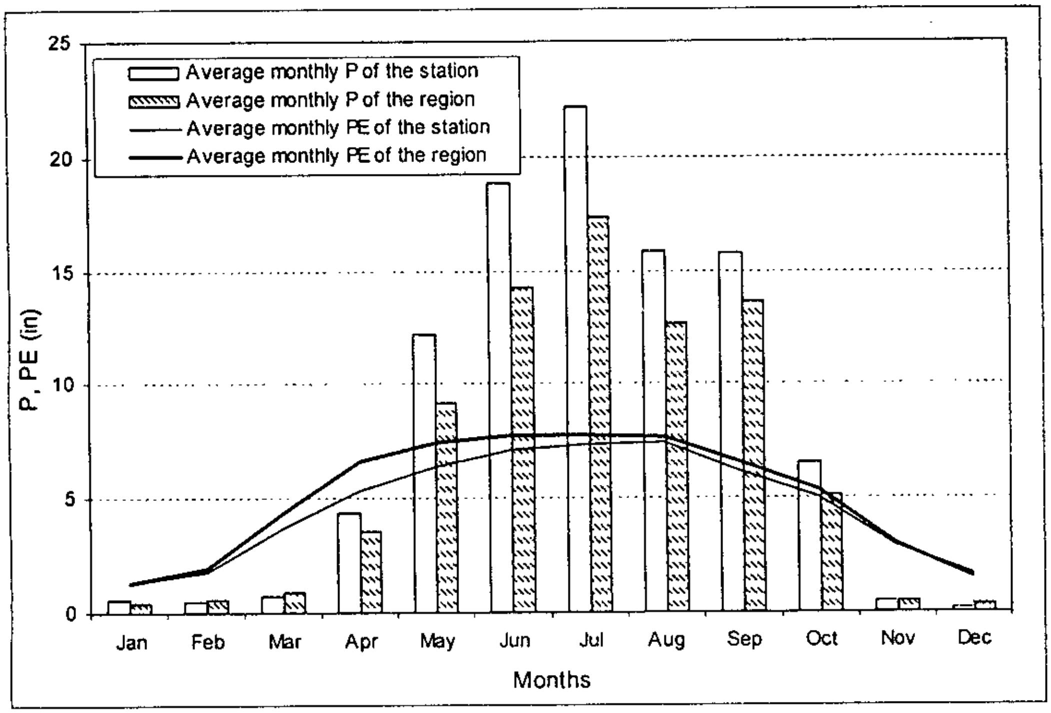


Figure 6.5 Average monthly P and PE of Kaunia (CL178) and NW region

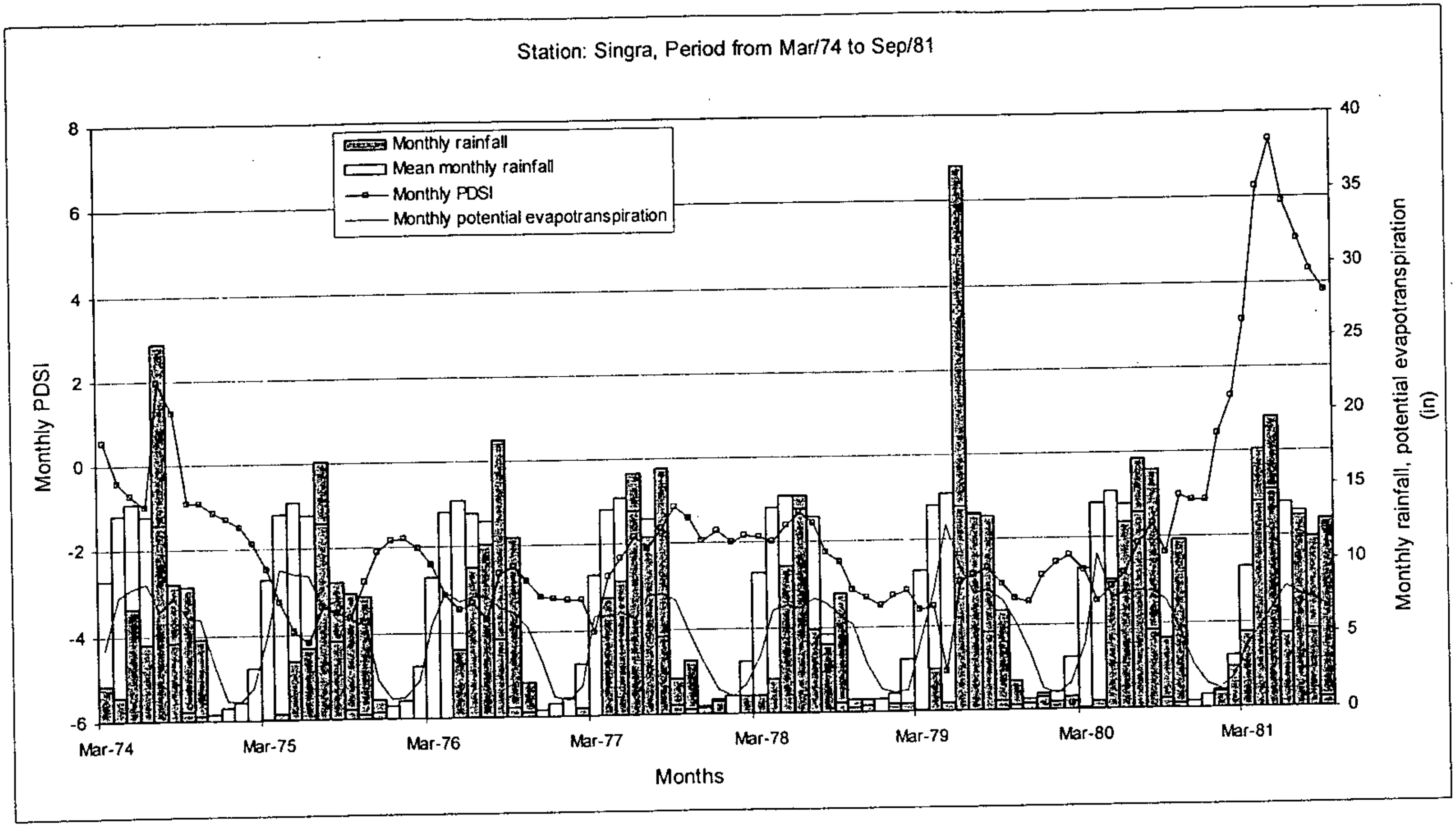


Figure 6.6 The longest drought spell of the NW region at Singra (CL 036) during November/1974 to December/1980

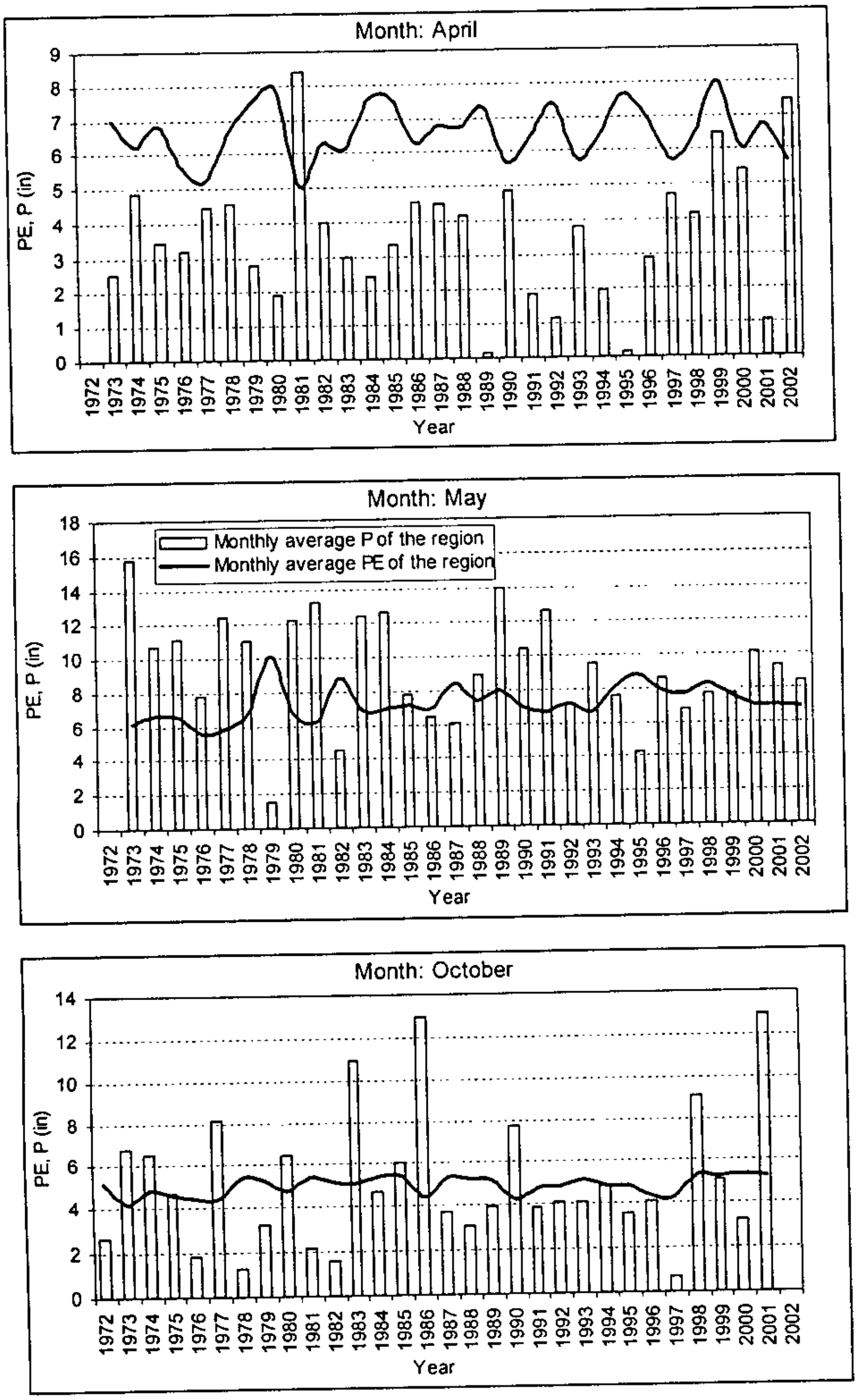


Figure 6.7 Time series of monthly average P and PE of the NW region from 1972-2002

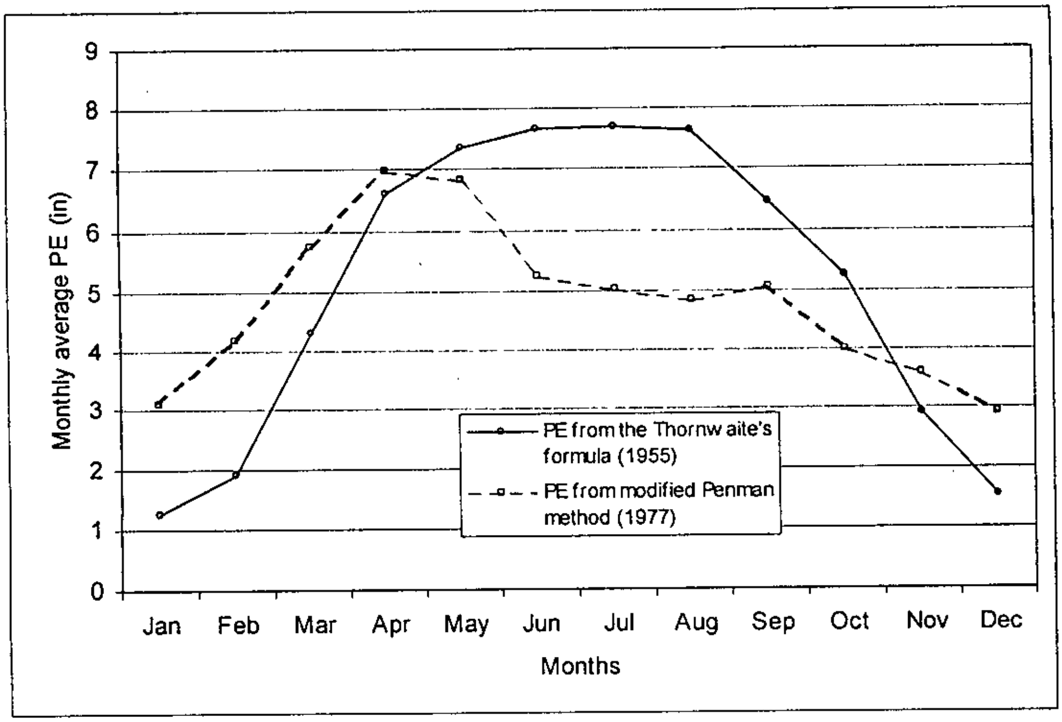


Figure 6.8 Monthly average PE of the NW region

Chapter 7
THE PALMER METHOD IN COMPARISON WITH THE SPI AND HERBST METHODS

7.1 General

In the present study, an attempt has been made for applying the Palmer method in drought analysis of Bangladesh. To assess the suitability of the application of the method, the results of the Palmer method have been compared in terms of occurrence, severity and duration of drought spells with that of the SPI and Herbst methods. The three approaches differ in the methodology. The SPI and Herbst methods consider only rainfall conditions of the selected stations while the Palmer method utilizes the soil moisture and temperature data in addition to rainfall data for analyzing droughts. The occurrences of drought spells and their severity obtained in the SPI and Herbst methods would be discussed in the following sections. Finally, the results of the Palmer method have been compared with that of the SPI and Herbst methods.

7.2 Drought analysis by the SPI method

In the SPI method, half-monthly rainfall time series are used for drought analysis on monthly time scale. The results obtained from the method are summarized in Tables 7.1 and 7.2. The average occurrence of drought is 22.3 percent of time from 1972 to 2002. It has been noticed that occurrences of drought spells are more frequent in the SPI method than that of the Palmer method, though the occurrence of drought as a percentage of total time is higher in the Palmer method. The station Shibganj (CL 215) experiences droughts in 28.2 percent of total time, which is the highest percentage of drought occurrence using the SPI method in NW region. The average occurrence of extreme drought condition is only 0.17 percent. The average occurrence of moderate, severe and extreme droughts in the region is in 9.9 percent of total study time. The Table 7.2 shows that 14.9 percent of dry spells begins in March while 23.7 percent dry spells begins during November-December period. About 35.6 percent of dry spells ends in the months of April and May.

The highest SPI for all the stations of NW region is shown in Figure 7.1. The magnitude of highest severity of the drought spells and their corresponding duration for each station of the NW region are shown in Figure 7.2. The figure reveals that the drought with longer duration possesses the higher severity index value. It is mentioned that the severity index of any drought spell in the SPI method is the sum of all the SPI values during the drought period.

Table 7.1 Occurrences of droughts in NW region during 1972-2002 estimated by the SPI method

Name of the station	Onset of drought (half-month)	Termination of drought (half-month)	Duration of drought spell (no. of half-months)	Highest SPI	Magnitude of drought severity
Atghoria CL 001	Jun-1/1972	Jul-2/1972	4	-1.69	-3.95
	Sep-1/1972	Dec-2/1972	8	-1.27	-6.54
	Jan-1/1974	Mar-1/1974	5	-1.29	-5.01
	Nov-2/1974	Apr-1/1975	10	-1.17	-5.19
	Mar-1/1976	Apr-2/1976	4	-1.47	-4.35
	Mar-2/1977	Apr-1/1977	2	-1.04	-1.18
	Mar-1/1979	Aug-1/1979	11	-1.63	-8.66
	Feb-1/1980	May-1/1980	7	-1.59	-4.61
	Sep-2/1980	Oct-2/1980	2	-1.49	-2.61
	Sep-2/1981	Nov-2/1981	5	-1.79	-6.50
	May-2/1982	Oct-2/1982	11	-1.59	-9.75
	Nov-1/1984	Mar-1/1985	9	-1.29	-7.22
	Mar-2/1989	May-1/1989	4	-1.34	-4.61
	Mar-1/1992	Aug-2/1992	12	-2.11	-10.20
	Jul-1/1994	Aug-2/1994	4	-1.43	-4.61
	Feb-1/1995	Jun-2/1995	10	-1.46	-8.70
	May-2/1996	Oct-1/1996	10	-1.69	-7.64
	Dec-2/1998	Jun-1/1999	12	-2.09	-14.74
	Jul-1/2000	Sep-1/2000	5	-1.68	-6.53
	Nov-2/2000	Apr-2/2001	11	-1.22	-8.35
	Jul-2/2001	Oct-1/2001	6	-1.86	-7.35
Total number of half-months			152		
Percent of total time			20.4		
Bogra CL 006	Jan-1/1972	May-2/1972	10	-1.42	-6.67
	Nov-2/1974	Apr-1/1975	10	-1.19	-6.51
	Jul-1/1978	Mar-2/1979	18	-1.32	-10.83
	Sep-1/1980	Oct-1/1980	3	-1.06	-2.58
	Sep-2/1981	Mar-1/1982	12	-1.65	-10.46
	Sep-2/1982	Jan-1/1983	8	-1.52	-7.69
	Nov-1/1983	Apr-2/1984	12	-1.02	-6.96
	Nov-1/1984	May-2/1985	14	-1.26	-11.60
	Jan-2/1986	Jun-2/1986	11	-1.30	-9.90
	Jan-1/1992	Jun-1/1992	11	-1.72	-8.03
	Oct-1/1993	Sep-2/1994	24	-2.02	-24.01
	Nov-1/1994	Jun-1/1995	15	-1.72	-14.24
	Mar-1/1996	Jun-1/1996	9	-1.19	-5.45
	Jan-2/1999	Jul-1/1999	12	-2.29	-16.61
	Sep-1/1999	Mar-2/2000	14	-1.40	-7.10
	Jun-2/00	Sep-1/00	6	-2.04	-7.29
	Nov-2/00	May-1/01	12	-2.06	-11.50
Total number of half-months			201		
Percent of total time			27.0		

Table 7.1 Occurrences of droughts in NW region during 1972-2002 estimated by the SPI method (continued)

Dhunot CL 011	Mar-1/1972	Jun-1/1972	7	-1.50	-8.89
	Jan-1/1974	Mar-1/1974	5	-1.06	-4.22
	Mar-1/1975	Apr-1/1975	3	-1.19	-2.57
	Jun-1/1975	Jul-1/1975	3	-1.52	-3.48
	Jan-2/1978	Mar-1/1978	4	-1.06	-3.60
	May-1/1979	Aug-2/1979	8	-1.59	-5.89
	Sep-2/1979	Nov-1/1979	4	-1.68	-5.19
	Sep-2/1981	Feb-2/1982	11	-1.65	-8.75
	Sep-2/1982	Oct-2/1982	3	-2.38	-6.08
	Jul-2/1985	Oct-1/1985	6	-1.34	-4.49
	May-1/1986	Jun-1/1986	4	-1.30	-4.01
	Mar-2/1989	May-2/1989	5	-1.46	-5.70
	Dec-1/1990	Mar-1/1991	7	-1.07	-5.37
	Feb-2/1992	May-1/1992	6	-1.72	-4.20
	Jun-1/1992	Sep-1/1992	7	-1.57	-6.52
	Apr-1/1994	Oct-1/1994	14	-1.56	-13.15
	Apr-1/1995	Jun-1/1995	5	-1.75	-5.88
	Dec-2/1998	Mar-2/2000	31	-2.34	-35.06
	Nov-2/2000	May-1/2001	12	-1.07	-9.50
Total number of half-months			145		
Percent of total time			19.5		
Sirajganj CL 034	Feb-1/1972	Apr-2/1972	6	-1.32	-5.89
	Dec-1/1972	Apr-2/1973	10	-1.47	-6.52
	Nov-2/1974	Apr-2/1975	11	-1.22	-6.49
	Sep-1/1978	Apr-1/1979	15	-1.42	-12.48
	Nov-1/1981	Mar-2/1982	10	-1.52	-11.94
	Sep-2/1982	Jan-2/1983	9	-1.48	-8.42
	Dec-1/1983	May-2/1984	12	-1.42	-10.21
	Nov-2/1984	Jan-2/1985	5	-1.17	-4.98
	Jun-1/1986	Sep-2/1986	8	-1.64	-12.83
	Jan-1/1989	Jun-1/1989	11	-1.42	-7.26
	Feb-2/1992	Aug-2/1992	13	-1.95	-14.25
	Nov-1/1992	May-1/1993	13	-1.74	-17.23
	Dec-1/1993	Jun-2/1994	14	-1.92	-21.12
	Nov-1/1994	Aug-1/1995	19	-1.85	-16.24
	Nov-1/1999	Apr-2/2000	12	-1.24	-8.10
	Decc-2/00	Apr-1/01	8	-1.45	-9.25
Total number of half-months			176		
Percent of total time			23.7		

Table 7.1 Occurrences of droughts in NW region during 1972-2002 estimated by the SPI method (continued)

Singra CL 036	Feb-1/1972	May-1/1972	7	-1.24	-6.72
	Mar-1/1975	Jun-1/1975	7	-1.12	-7.51
	Jan-2/1977	Apr-2/1977	7	-1.20	-7.50
	Mar-1/1979	Sep-1/1979	13	-1.42	-9.12
	Nov-2/1981	Feb-1/1982	6	-1.25	-6.42
	Sep-1/1982	Apr-2/1983	16	-1.24	-10.25
	Jul-2/1984	Oct-2/1984	7	-1.21	-6.37
	May-1/1986	Jul-2/1986	6	-1.40	-5.48
	Dec-1/1991	Apr-1/1992	8	-1.27	-9.45
	Nov-1/1992	May-2/1993	14	-1.57	-10.28
	Oct-1/1994	Jun-1/1995	17	-1.62	-21.04
	Dec-2/1999	Mar-2/00	7	-1.34	-8.97
	Nov-2/00	May-1/01	12	-1.07	-9.50
Total number of half-months			127		
Percent of total time			17.1		
Dinajpur CL 168	Apr-2/1972	Oct-2/1972	13	-1.74	-16.52
	Jul-1/1973	Sep-1/1973	5	-1.42	-4.10
	Mar-1/1975	Apr-2/1975	4	-1.59	-4.51
	Sep-1/1976	Mar-2/1977	14	-1.15	-10.38
	Aug-2/1978	Nov-1/1978	6	-1.47	-6.02
	Mar-2/1979	Jul-1/1979	8	-1.76	-9.28
	Sep-2/1981	Feb-2/1982	11	-1.61	-11.09
	Apr-2/1982	Oct-2/1982	13	-1.47	-12.09
	Jun-1/1983	Jul-1/1983	3	-1.63	-3.54
	Dec-2/1984	Apr-1/1985	8	-1.14	-5.64
	Mar-2/1989	Apr-1/1989	2	-1.14	-2.08
	Aug-2/1990	Sep-1/1990	2	-1.66	-2.13
	Jul-1/1991	Aug-2/1991	4	-1.33	-2.29
	Mar-1/1992	Apr-1/1992	3	-1.01	-2.73
	Jun-2/1992	Jul-1/1992	2	-1.30	-2.55
	Oct-2/1992	Nov-1/1992	2	-1.00	-1.18
	Jul-1/1993	Aug-1/1993	3	-1.61	-2.55
	Mar-1/1994	Apr-1/1994	3	-1.14	-2.74
	Jun-1/1994	Feb-1/1995	16	-1.68	-13.74
	May-1/1995	Jun-2/1995	4	-1.78	-5.32
	May-1/1996	Jun-1/1996	3	-1.56	-3.20
	Sep-1/1997	Nov-2/1997	6	-1.51	-4.29
	Jun-1/2000	Apr-1/2001	20	-1.91	-21.57
	Jul-1/2001	Aug-1/2001	3	-1.61	-3.86
Total number of half-months			158		
Percent of total time			21.2		

Table 7.1 Occurrences of droughts in NW region during 1972-2002 estimated by the SPI method (continued)

Kaliganj CL 177	Oct-2/1972	May-2/1973	15	-1.52	-12.52
	Jan-2/1975	May-1/1975	9	-1.48	-8.49
	Oct-1/1976	Apr-2/1977	14	-1.15	-9.38
	Mar-1/1979	Jul-2/1979	10	-1.62	-7.25
	Sep-2/1981	Mar-2/1982	13	-1.46	-10.95
	Jun-1/1982	Sep-1/1983	7	-1.53	-7.54
	Dec-2/1983	Apr-1/1984	8	-1.24	-6.91
	Mar-1/1985	Aug-1/1985	11	-1.05	-5.46
	Mar-1/1992	Jul-1/1992	9	-1.01	-7.52
	Oct-2/1992	Apr-2/1993	13	-1.02	-8.49
	Apr-1/1994	May-1/1995	27	-1.12	-21.25
	Dec-1/1995	Jun-1/1996	13	-1.20	-10.46
	Nov-1/2000	May-2/2001	14	-1.72	-16.12
Total number of half-months			163		
Percent of total time			21.9		
Kaunia CL 178	Mar-2/1972	May-1/1972	4	-1.55	-6.02
	Feb-1/1973	Apr-2/1973	6	-1.38	-6.95
	Oct-2/1975	May-2/1976	15	-1.53	-11.55
	Dec-1/1976	Mar-2/1977	8	-1.24	-8.95
	Mar-2/1979	Jun-1/1979	8	-1.64	-9.41
	Nov-2/1981	Apr-2/1982	11	-1.43	-10.12
	Jan-1/1983	May-1/1983	9	-1.13	-8.59
	Mar-1/1989	May-2/1989	6	-1.54	-4.95
	Feb-1/1991	Jul-2/1991	12	-1.13	-9.24
	Feb-2/1992	Aug-1/1992	12	-1.62	-11.48
	Apr-2/1994	May-2/1995	25	-1.46	-18.89
	Oct-2/1996	Jan-1/1997	6	-1.27	-4.36
	May-1/1999	Aug-2/1999	8	-1.56	-10.32
	Jul-1/2000	Apr-2/2001	20	-1.12	-17.06
Total number of half-months			150		
Percent of total time			20.2		
Mohipur CL 188	Apr-2/1972	Sep-1/1972	10	-1.45	-10.45
	Apr-1/1973	Jul-2/1973	8	-1.59	-7.46
	Aug-1/1975	Nov-1/1975	7	-1.62	-4.89
	Oct-1/1976	Mar-1/1977	11	-1.43	-12.42
	Mar-2/1979	Jul-2/1979	9	-1.72	-9.48
	Feb-2/1981	May-1/1981	7	-1.18	-6.72
	Dec-1/1982	Apr-1/1983	9	-1.14	-7.54
	Mar-2/1984	May-1/1984	4	-1.26	-3.95
	Feb-1/1991	Sep-2/1991	15	-1.11	-10.28
	Feb-2/1992	Oct-1/1992	17	-1.64	-18.94
	Mar-2/1994	Feb-2/1995	23	-1.57	-20.01
	Mar-2/1995	Jun-1/1995	7	-1.59	-10.38
	Feb-2/1996	Apr-2/1996	5	-1.84	-5.83
	Oct-2/1999	Apr-2/2000	13	-1.65	-11.15
	Apr-2/2001	Jul-2/2001	7	-1.87	-9.71
Total number of half-months			152		
Percent of total time			20.4		

Table 7.1 Occurrences of droughts in NW region during 1972-2002 estimated by the SPI method (continued)

Nazipur CL 192	Jan-1/1972	Apr-2/1972	8	-1.46	-8.67
	Nov-1/1972	Dec-2/1972	4	-1.35	-4.74
	Dec-1/1973	Mar-1/1974	7	-1.20	-7.43
	Nov-1/1975	Feb-2/1976	8	-1.45	-7.68
	Jul-1/1978	Mar-2/1979	18	-1.28	-14.94
	Sep-1/1980	Nov-1/1980	5	-1.06	-3.58
	Nov-1/1983	Apr-2/1984	12	-1.12	-10.60
	Feb-2/1985	May-2/1985	7	-1.26	-6.60
	Jan-2/1989	May-2/1989	9	-1.46	-8.92
	Nov-1/1990	Apr-2/1991	12	-1.58	-10.37
	Jan-1/1992	Sep-1/1992	17	-1.75	-16.83
	Dec-1/1993	Feb-2/1994	6	-1.98	-7.68
	Apr-1/1994	Feb-1/1995	21	-1.68	-18.24
	Jun-1/1995	Mar-2/1996	20	-1.54	-20.67
	Sep-1/1999	Apr-2/2000	16	-1.38	-9.15
	May-2/00	Sep-2/00	9	-1.82	-8.94
	Dec-2/00	May-2/01	11	-2.02	-10.50
Total number of half-months			190		
Percent of total time			25.5		
Nekmard CL 193	Feb-2/1972	Jul-2/1972	11	-1.64	-12.22
	Jun-1/1973	Aug-2/1973	6	-1.54	-5.63
	Mar-1/1975	Jun-2/1975	8	-1.42	-6.84
	Nov-1/1976	Mar-2/1977	10	-1.26	-10.34
	Jul-2/1978	Oct-1/1978	6	-1.45	-7.24
	Oct-2/1981	Mar-2/1982	11	-1.67	-12.20
	Jul-2/1982	Dec-2/1982	11	-1.42	-10.04
	Nov-2/1984	May-1/1985	12	-1.56	-11.89
	Mar-2/1989	May-1/1989	4	-1.17	-3.28
	Jul-1/1991	Aug-2/1991	4	-1.37	-3.64
	Jul-2/1992	Dec-2/1992	11	-1.42	-10.87
	Mar-2/1994	Apr-1/1995	27	-1.74	-22.76
	Feb-1/1996	Jul-1/1996	11	-1.89	-9.52
	Oct-1/1997	Nov-2/1997	4	-1.48	-3.52
	Aug-1/2000	Apr-1/2001	17	-1.65	-14.65
Total number of half-months			153		
Percent of total time			20.6		

Table 7.1 Occurrences of droughts in NW region during 1972-2002 estimated by the SPI method (continued)

Rajshahi CL 205	Feb-1/1972	Apr-2-1/1972	6	-1.55	-7.68
	Jan-1/1974	May-1/1974	9	-1.26	-5.25
	Mar-1/1975	Jun-1/1975	7	-1.20	-6.42
	Nov-2/1977	Apr-2/1978	12	-1.46	-10.46
	Jun-1/1979	Sep-2/1979	8	-1.62	-6.20
	Oct-2/1981	Jun-2/1982	17	-1.79	-14.05
	Jul-2/1985	Oct-2/1985	7	-1.34	-5.61
	Feb-2/1989	May-2/1989	7	-1.66	-8.90
	Dec-1/1990	May-2/1991	12	-1.29	-8.39
	Jan-2/1992	Sep-1/1992	16	-1.89	-12.16
	Feb-1/1994	Oct-2/1994	18	-2.24	-20.95
	Dec-1/1994	Jul-1/1995	15	-1.91	-18.61
	Mar-2/1999	Jun-2/1999	7	-1.75	-9.24
	Dec-2/2000	May-2/2001	11	-1.38	-10.98
Total number of half-months			152		
Percent of total time			20.4		
Rangpur CL 206	Apr-2/1972	Oct-1/1972	12	-1.65	-13.45
	Apr-1/1973	Apr-2/1973	2	-1.89	-2.46
	Feb-1/1974	Mar-1/1974	3	-1.14	-3.04
	Aug-1/1975	Sep-2/1975	4	-1.72	-3.86
	Mar-1/1976	Apr-2/1976	4	-1.89	-4.22
	Sep-1/1976	Mar-2/1977	14	-1.53	-12.09
	Oct-1/1978	Nov-1/1978	3	-1.16	-2.26
	Mar-1/1979	Jun-1/1979	9	-1.75	-10.49
	Jun-2/1980	Jul-2/1980	3	-1.42	-2.33
	Feb-2/1981	Mar-2/1981	3	-1.13	-1.76
	Oct-1/1981	Nov-2/1981	4	-1.49	-4.46
	Dec-1/1982	Mar-1/1983	7	-1.13	-4.59
	Jan-2/1986	Mar-2/1986	5	-1.13	-4.66
	Mar-2/1989	May-1/1989	4	-1.89	-5.95
	Feb-1/1991	Mar-2/1991	4	-1.13	-3.16
	Jul-1/1991	Aug-2/1991	4	-1.44	-2.43
	Mar-2/1992	Apr-1/1992	2	-1.89	-2.98
	May-2/1992	Aug-1/1992	6	-1.18	-4.72
	Apr-2/1994	May-2/1994	3	-1.67	-3.01
	Jun-2/1994	Feb-2/1995	17	-1.74	-13.99
	Mar-2/1995	Jun-1/1995	7	-1.89	-8.38
	Feb-2/1996	Apr-2/1996	5	-1.89	-5.87
	Sep-2/1996	Jan-1/1997	8	-1.67	-7.99
	Nov-2/1998	Mar-2/1999	9	-1.13	-6.80
	May-1/1999	Aug-1/1999	7	-1.51	-8.32
	Sep-2/1999	Mar-2/2000	13	-1.85	-13.15
	Jun-1/2000	Oct-1/2000	9	-1.74	-9.03
	Apr-2/2001	Aug-2/2001	9	-1.97	-13.67
Total number of half-months			180		
Percent of total time			24.2		

Table 7.1 Occurrences of droughts in NW region during 1972-2002 estimated by the SPI method (continued)

Shibganj CL 215	Feb-2/1972	Jun-2-1/1972	9	-1.61	-9.12
	Dec-1/1973	May-1/1974	11	-1.24	-10.03
	Apr-1/1975	Oct-1/1975	13	-1.32	-8.49
	Oct-2/1977	Apr-2/1978	13	-1.52	-12.01
	Jun-1/1979	Sep-2/1979	8	-1.46	-5.96
	Nov-2/1981	Jun-2/1982	15	-1.68	-13.65
	Dec-2/1982	Jul-2/1983	15	-1.14	-9.21
	Nov-1/1985	Apr-1/1986	11	-1.46	-8.62
	Feb-1/1989	Jun-2/1989	10	-1.68	-9.45
	Nov-1/1990	May-2/1991	14	-1.35	-10.65
	Dec-2/1991	Oct-1/1992	20	-2.06	-21.32
	Jan-1/1993	Apr-2/1993	8	-1.47	-9.13
	Mar-2/1994	Apr-2/1995	27	-2.30	-24.87
	Dec-1/1996	Jun-1/1996	13	-1.43	-9.87
	Feb-2/1999	Aug-1/1999	12	-1.62	-10.12
	Nov-2/2000	Apr-2/2001	11	-1.89	-9.78
Total number of half-months			210		
Percent of total time			28.2		
Mithapukur CL 186	Mar-2/1972	Jun-1/1972	6	-1.52	-7.52
	Dec-1/1973	Mar-1/1974	7	-1.28	-6.23
	May-1/1975	Jul-2/1975	6	-1.52	-4.92
	Nov-1/1976	Apr-2/1977	12	-1.61	-14.02
	Dec-1/1978	Jun-1/1979	13	-1.81	-9.46
	Jun-2/1980	Aug-1/1980	4	-1.38	-2.51
	Feb-2/1981	Apr-2/1981	5	-1.25	-2.85
	Oct-1/1982	Apr-2/1983	14	-1.43	-9.86
	Jan-2/1985	May-2/1985	9	-1.20	-6.84
	Mar-2/1989	May-1/1989	4	-1.72	-5.92
	Feb-1/1991	Aug-1/1991	13	-1.48	-10.12
	Jan-2/1992	Jun-2/1992	11	-1.89	-9.85
	Feb-2/1994	Jun-2/1994	9	-1.92	-11.23
	Oct-2/1994	May-2/1995	15	-1.81	-14.20
	Feb-2/1996	May-2/1996	7	-1.46	-6.02
	Jul-2/1996	Oct-2/1996	7	-1.52	-6.45
	Jan-1/1999	Apr-1/1999	7	-1.42	-6.92
	Nov-1/1999	Mar-2/2000	12	-1.79	-14.22
	Dec-1/2000	Jul-2/2001	16	-1.86	-12.63
Total number of half-months			177		
Percent of total time			23.8		

Table 7.2 Number of drought spells beginning and ending in different months of a year estimated by the SPI method

Station name	Number of drought spells beginning in months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Atghoria CL 001	1	2	5	0	2	1	3	0	3	0	3	1
Bogra CL 006	4	0	1	0	0	1	1	0	4	1	5	0
Dhunot CL 011	2	1	3	2	2	2	1	0	3	0	1	2
Sirajganj CL 034	1	2	0	0	0	1	0	0	2	0	6	4
Singra CL 036	1	1	2	0	1	0	1	0	1	1	3	2
Dinajpur CL 168	0	0	5	2	2	4	4	2	3	1	0	1
Kaliganj CL 177	1	0	3	1	0	1	0	0	1	3	1	2
Kaunia CL 178	1	3	3	1	1	0	1	0	0	2	1	1
Mithapukur CL 186	3	4	2	0	1	1	1	0	0	2	2	3
Mohipur CL 188	0	4	4	3	0	0	0	1	0	2	0	1
Nazipur CL 192	3	1	0	1	1	1	1	0	2	0	4	3
Nekmard CL 193	0	2	3	0	0	1	4	1	0	2	2	0
Rajshahi CL 205	2	3	2	0	0	1	1	0	0	1	1	3
Rangpur CL 206	1	4	5	4	2	3	1	1	3	2	1	1
Shibganj CL 215	1	3	1	1	0	1	0	0	0	1	4	4
Total	21	30	39	15	12	18	19	5	22	18	34	28
Percentage of total drought spells	8.0	11.5	14.9	5.7	4.6	6.9	7.3	1.9	8.4	6.9	13	10.7

Table 7.2 Number of drought spells beginning and ending in different months of a year estimated by the SPI method (continued)

Station name	Number of drought spells ending in months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Atghoria CL 001	0	0	2	4	2	2	1	3	1	4	1	1
Bogra CL 006	1	0	3	2	3	4	1	0	2	1	0	0
Dhunot CL 011	0	1	4	1	3	3	1	1	1	3	1	0
Sirajganj CL 034	2	0	1	6	2	2	2	1	0	0	0	0
Singra CL 036	0	1	1	3	3	2	1	0	1	1	0	0
Dinajpur CL 168	0	2	1	6	0	2	3	3	2	2	3	0
Kaliganj CL 177	0	0	1	3	4	1	2	1	1	0	0	0
Kaunia CL 178	1	0	1	3	5	1	1	2	0	0	0	0
Mithapukur CL 186	0	0	2	4	4	4	2	2	0	1	0	0
Mohipur CL 188	0	1	1	3	2	1	3	0	2	1	1	0
Nazipur CL 192	0	3	3	4	3	0	0	0	2	0	1	1
Nekmard CL 193	0	0	2	2	2	1	2	2	1	0	1	2
Rajshahi CL 205	0	0	0	2	4	3	1	0	2	2	0	0
Rangpur CL 206	1	1	8	4	2	2	1	4	1	2	2	0
Shibganj CL 215	0	0	0	5	2	4	1	1	1	2	0	0
Total	5	9	30	52	41	32	22	20	17	19	10	4
Percentage of total drought spells	1.9	3.4	11.5	19.9	15.7	12.3	8.4	7.7	6.5	7.3	3.8	1.5

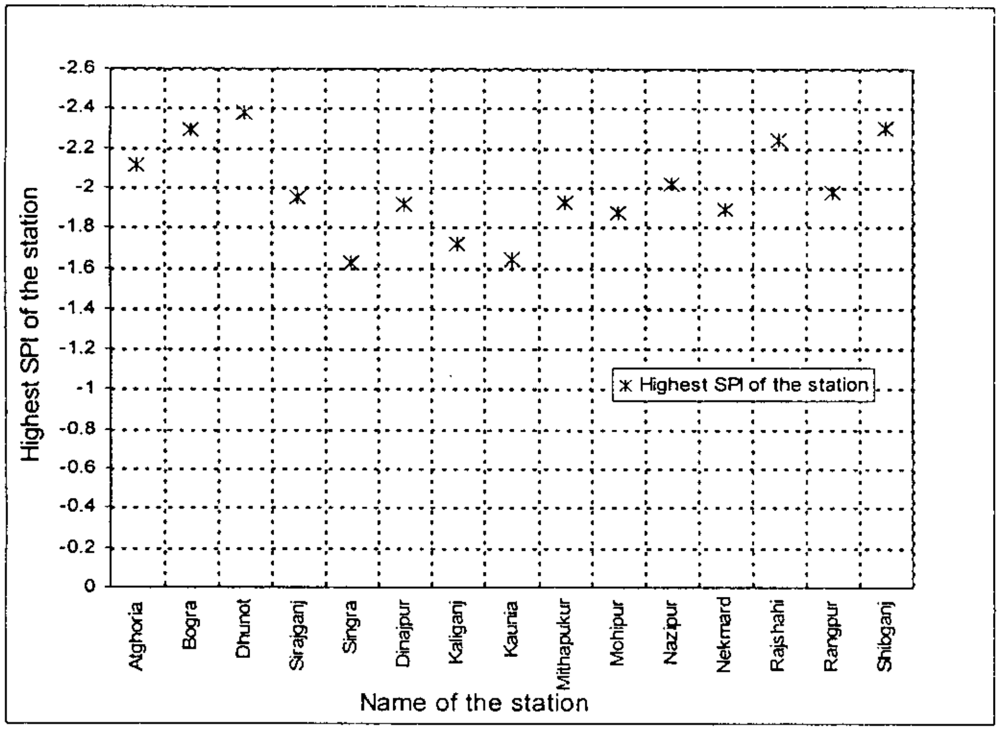
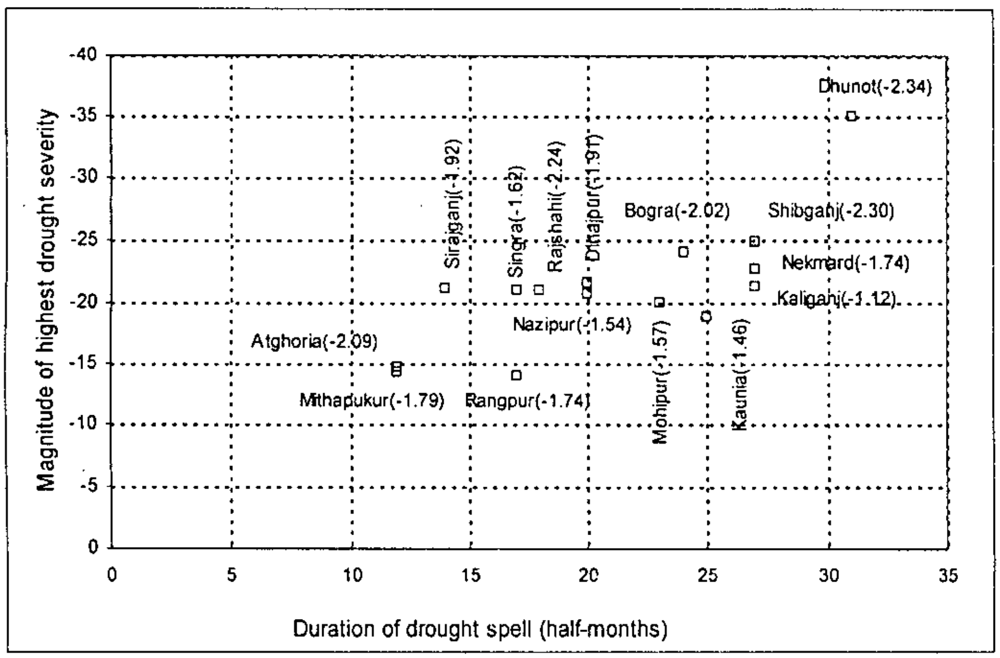


Figure 7.1 The highest SPI of each station of NW region



(Value of SPI is shown in the parenthesis)

Figure 7.2 The magnitude of highest severity of the drought spells and their duration in each station of the NW region estimated by the SPI method

7.3 Drought analysis by the Herbst method

In the Herbst method, droughts are analyzed on half monthly basis for a period from 1972 to 2002. Results obtained from the method are summarized in Tables 7.3 and 7.4. The average occurrence of drought is about 22 percent of total time which is below that of the Palmer method, but very closer to the SPI method. The station Kaunia (CL 178) experiences droughts in 29 percent of total time, which is estimated as the highest percentage of drought occurrence in NW region by the Herbst method.

About 30 percent of droughts begin in the months of October and November while 23 percent of drought begins in the months of July and August indicating that there may be sometimes insufficient rainfall during the monsoon season. About 47 percent of droughts end in May to July with the onset of monsoon. The onset and termination of droughts, their intensity and severity are determined in the Herbst method using some drought parameters such as mean half monthly value, carry over, mean half monthly deficit etc. The mean annual rainfall deficit plot against mean annual rainfall (Figure 7.3) for all the stations of NW region shows an increasing trend indicating that higher mean annual rainfall areas have higher mean annual rainfall deficit.

There is no distinct severity classification of drought spells in the Herbst method as they were in the Palmer and SPI methods. The drought severity index of a station gives a relative picture of severity comparing it with other drought spells in the station as well as in other stations. The highest drought intensity index obtained from this method for all the stations of NW region is shown in Figure 7.4. As shown in figure, the maximum drought intensity index occurs in the station Shibganj (CL 215). The highest drought severity index of the drought spells and their corresponding duration for each station of the NW region are shown in Figure 7.5. The figures reveal that the shorter duration drought spells with high drought intensity index may produce higher severity than longer duration drought with low drought intensity index. It is mentioned that the drought severity index of any drought spell in the Herbst method is the product of the drought intensity index and drought period of the spell.

Table 7.3 Occurrences of droughts in NW region during 1972-2002 estimated by the Herbst method

Name of the station	Onset of drought	Termination of drought	Duration of drought spell (no. of half months)	Drought intensity index	Drought severity index
Atghoria CL 001	Sep-1/ 1978	Aug-1/ 1979	23	1.35	31.14
	Feb-1/ 1999	Jun-2/ 1999	9	1.53	13.73
	Feb-2/ 2001	May-2/ 2002	31	1.14	35.40
Total number of half months			63		
Percent of total time			8.5		
Bogra CL 006	May-1/ 1975	May-1/ 1977	49	1.09	53.64
	Aug-1/ 1978	Oct-1/ 1980	53	1.19	63.08
	Dec-1/ 1996	Jun-1/ 1998	37	0.82	30.39
	Oct-1/ 2000	Nov-2/ 2001	28	0.84	23.46
Total number of half months			167		
Percent of total time			22.4		
Dhunot CL 011	Apr-1/ 1972	Apr-1/ 1973	25	0.98	24.38
	Aug-1/ 1975	Apr-1/ 1977	42	1.07	44.94
	Sep-2/ 1978	Apr-2/ 1980	39	1.18	45.98
	Dec-1/ 1996	Jun-1/ 1998	37	0.82	30.39
	Oct-1/ 2000	Oct-1/ 2001	25	1.05	26.36
Total number of half months			168		
Percent of total time			22.6		
Sirajganj CL 034	Aug-1/ 1978	Aug-1/ 1979	25	1.94	48.53
	Sep-2/ 1981	Mar-2/ 1983	37	1.13	41.84
	Mar-1/ 1994	Feb-1/ 1995	23	0.99	22.68
	Dec-1/ 1999	May-2/ 2002	60	0.95	57.29
Total number of half months			145		
Percent of total time			19.5		
Singra CL 036	Apr-1/ 1972	Apr-2/ 1973	26	1.54	40.03
	Jul-1/ 1974	Jul-2/ 1976	25	1.33	33.2
	Sep-1/ 1977	May-2/ 1979	42	1.48	62.14
	Nov-1/ 1985	Aug-2/ 1986	20	1.25	25.03
	Nov-2/ 1991	Mar-2/ 1993	32	0.94	29.90
Total number of half months			145		
Percent of total time			19.5		
Dinajpur CL 168	Apr-1/ 1972	Apr-1/ 1973	25	1.90	47.52
	Dec-2/ 1978	Apr-2/ 1980	33	0.83	27.39
	Oct-2/ 1993	Jun-2/ 1995	41	1.17	48.04
	Nov-2/ 1999	May-1/ 2001	36	1.33	47.92
Total number of half months			135		
Percent of total time			18.1		

Table 7.3 Occurrences of droughts in NW region during 1972-2002 estimated by the Herbst method (continued)

Kaliganj CL 177	Jun-1/ 1975	May-1/ 1977	47	1.65	77.69
	Dec-1/ 1977	Jul-1/ 1979	39	1.73	64.50
	Feb-2/ 1994	May-2/ 1995	31	1.53	47.58
	Aug-2/ 2000	Jul-2/ 2001	23	1.72	39.62
Total number of half months			140		
Percent of total time			18.8		
Kaunia CL 178	Apr-1/ 1972	Apr-2/ 1973	26	1.00	26.20
	Jul-2/ 1973	Sep-1/ 1973	4	2.18	8.73
	Nov-1/ 1975	May-1/ 1977	37	1.03	38.26
	Jul-1/ 1977	Jul-1/ 1979	49	1.70	83.45
	Aug-2/ 1985	Aug-2/ 1986	25	1.50	37.56
	Feb-2/ 1994	Jun-1/ 1995	32	0.92	29.40
	Oct-1/ 1999	Aug-2/ 2001	46	2.09	96.14
Total number of half months			219		
Percent of total time			29.4		
Mithapukur CL 186	Apr-1/1972	Apr-2/ 1972	26	1.65	42.88
	Nov-2/1978	Jul-1/1979	16	1.75	28.08
	Nov-1/1991	Mar-1/ 1993	33	1.16	33.24
	Oct-2/ 1993	Jun-1/ 1995	40	1.26	50.33
	Nov-2/ 1999	Apr-1/ 2001	34	1.13	38.42
Total number of half months			149		
Percent of total time			20.0		
Mohipur CL 188	Jun-1/ 1975	May-1/ 1978	71	1.30	92.35
	Jul-1/1978	Aug-1/ 1979	27	2.14	57.8
	Nov-2/ 1983	Feb-1/ 1985	30	1.27	38.15
	Dec-1/ 1988	Aug-2/ 1989	18	1.56	28.17
	Oct-2/ 1993	Jun-2/ 1995	41	1.27	52.23
	Oct-1/ 2000	Aug-2/ 2001	22	2.72	59.90
Total number of half months			209		
Percent of total time			28.1		
Nazipur CL 192	Apr-1/ 1972	Apr-2/ 1973	26	1.18	30.77
	Aug-1/ 1975	Jun-2/ 1976	22	1.32	29.07
	Feb-1/ 1994	Sep-1/ 1994	15	1.80	27.08
	Sep-1/ 1996	Jun-1/ 1997	19	1.22	23.11
	Nov-2/ 1999	Dec-2/ 2002	75	1.68	166.46
Total number of half months			157		
Percent of total time			21.1		
Nekmard CL 193	Apr-1/ 1972	Aug-1/ 1973	33	1.06	34.90
	Aug-2/ 1978	Jun2/ 1981	69	1.15	79.06
	Aug-2/ 1985	Jul-2/ 1986	23	1.21	27.74
	Feb-1/ 1992	Jun-2/ 1995	82	1.46	119.42
Total number of half months			207		
Percent of total time			27.8		

Table 7.3 Occurrences of droughts in NW region during 1972-2002 estimated by the Herbst method (continued)

Rajshahi CL 205	Jun-2/ 1974	Jul-1/ 1975	26	1.53	39.77
	Jan-1/ 1982	Sep-2/ 1983	42	1.19	50.20
	Jan-2/ 1992	Aug-1/ 1993	38	1.28	48.76
	Nov-1/ 1999	Mar-2/ 2000	10	1.38	13.80
Total number of half months			116		
Percent of total time			15.6		
Rangpur CL 206	Apr-1/ 1972	Apr-2/ 1973	26	1.22	31.73
	Nov-1/ 1974	May-2/ 1976	38	0.721	27.41
	Aug-2/ 1977	Jul-1/ 1979	46	1.544	71.01
	Nov-2/ 1993	Jun-2/ 1995	39	1.05	40.86
	Oct-1/ 1989	Aug-2/ 2001	46	2.14	98.44
Total number of half months			195		
Percent of total time			26.2		
Shibganj CL 215	Sep-1/ 1977	May-1/ 1980	66	0.89	59.40
	Jul-1/ 1982	May-2/ 1984	46	0.98	42.67
	Sep-2/ 1992	Jul-2/ 1995	69	0.91	62.62
	Apr-2/ 1999	Mar-2/ 2000	23	3.52	80.90
Total number of half months			204		
Percent of total time			27.4		

Table 7.4 Number of drought spells beginning and ending in different months of a year estimated by the Herbst method

Station name	Number of drought spells beginning in months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Atghoria CL 001	0	2	0	0	0	0	0	0	1	0	0	0
Bogra CL 006	0	0	0	0	1	0	0	1	0	1	0	1
Dhunot CL 011	0	0	0	1	0	0	0	1	1	1	0	1
Sirajganj CL 034	0	0	1	0	0	0	0	1	1	0	0	1
Singra CL 036	0	0	0	1	0	0	1	0	1	0	2	0
Dinajpur CL 168	0	0	0	1	0	0	0	0	0	1	1	1
Kaliganj CL 177	0	1	0	0	0	1	0	1	0	0	0	1
Kaunia CL 178	0	1	0	1	0	0	2	1	0	1	1	0
Mithapukur CL 186	0	0	0	1	0	0	0	0	0	1	3	0
Mohipur CL 188	0	0	0	0	0	1	1	0	0	2	1	1
Nazipur CL 192	0	1	0	1	0	0	0	1	0	1	1	0
Nekmard CL 193	0	1	0	1	0	0	0	2	0	0	0	0
Rajshahi CL 205	2	0	0	0	0	0	1	0	0	0	1	0
Rangpur CL 206	0	0	0	1	0	0	0	1	0	1	2	0
Shibganj CL 215	0	0	0	1	0	0	1	0	2	0	0	0
Total	2	6	1	9	1	2	6	9	6	9	12	6
Percentage of total drought spells	2.9	8.7	1.4	13	1.4	2.9	8.7	13	8.7	13	17	8.7

Table 7.4 Number of drought spells beginning and ending in different months of a year estimated by the Herbst method

Station name	Number of drought spells ending in months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Atghoria CL 001	0	0	0	0	1	1	0	1	0	0	0	0
Bogra CL 006	0	0	0	0	1	1	0	0	0	1	1	0
Dhunot CL 011	0	0	0	3	0	1	0	0	0	1	0	0
Sirajganj CL 034	0	1	1	0	1	0	0	1	0	0	0	0
Singra CL 036	0	0	1	1	1	0	1	1	0	0	0	0
Dinajpur CL 168	0	0	0	2	1	1	0	0	0	0	0	0
Kaliganj CL 177	0	0	0	0	2	0	2	0	0	0	0	0
Kaunia CL 178	0	0	0	1	1	1	1	2	1	0	0	0
Mithapukur CL 186	0	0	1	2		1	1	0	0	0	0	0
Mohipur CL 188	0	1	0	0	1	1	0	3	0	0	0	0
Nazipur CL 192	0	0	0	1	0	2	0	0	1	0	0	1
Nekmard CL 193	0	0	0	0	0	2	1	1	0	0	0	0
Rajshahi CL 205	0	0	1	0	0	0	1	1	1	0	0	0
Rangpur CL 206	0	0	0	1	1	1	1	1	0	0	0	0
Shibganj CL 215	0	0	1	0	2	0	1	0	0	0	0	0
Total	0	2	5	11	12	12	9	11	3	2	1	1
Percentage of total drought spells	0	2.9	7.2	16	17	17	13	16	4.3	2.9	1.4	1.4

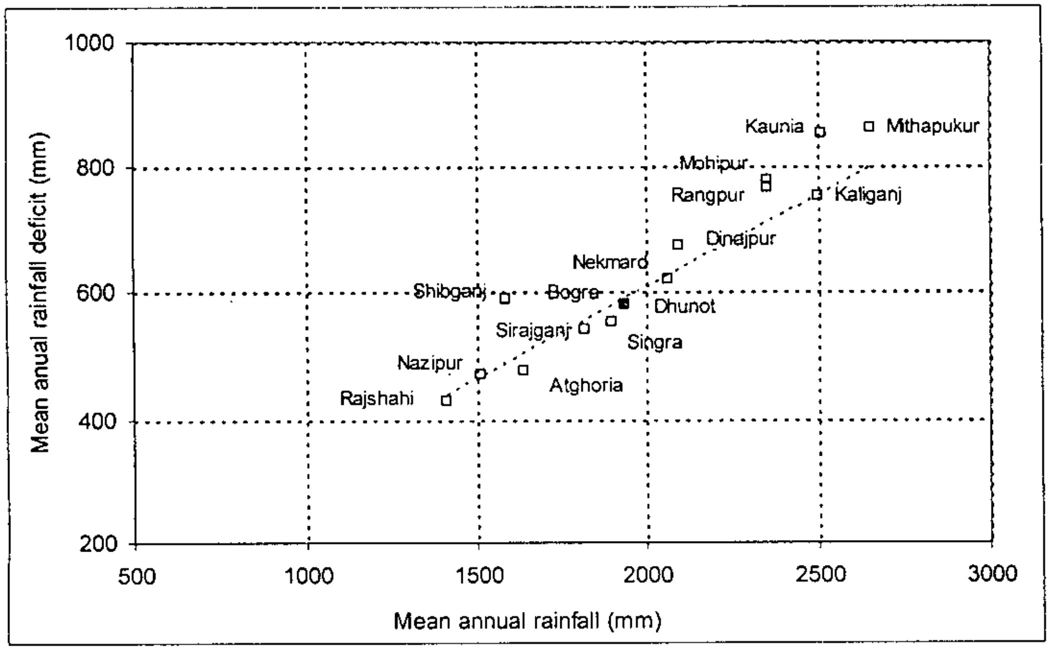


Figure 7.3 Trend of mean annual rainfall deficit with mean annual rainfall in NW region

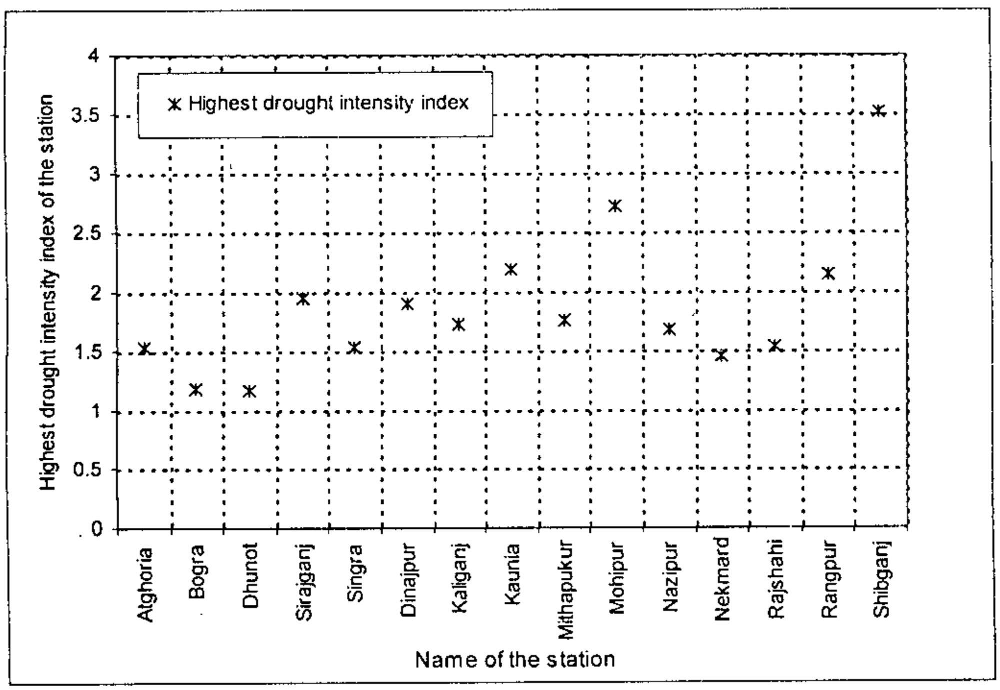
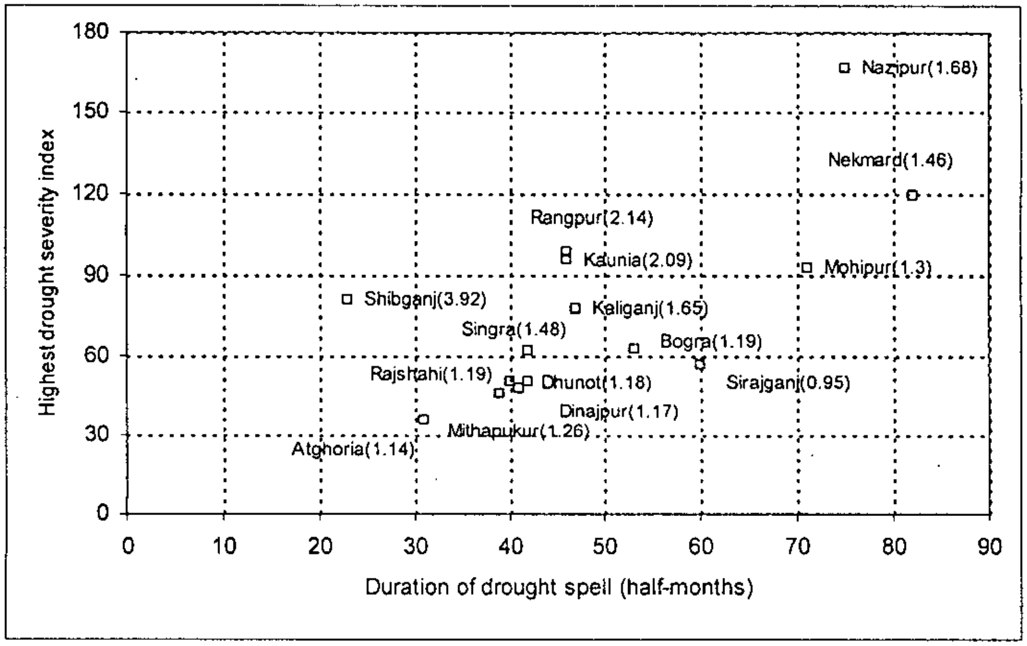


Figure 7.4 The highest drought intensity index of each station of NW region estimated by the Herbst method



(Value shown in the parenthesis is the drought intensity index)

Figure 7.5 The highest drought severity indices and their duration in each station of the NW region estimated by the Herbst method

7.4 Suitability of the Palmer method in comparison with the SPI and Herbst methods

In the present study, water deficits from 1972 to 2002 in the NW region are identified by SPI and Herbst methods along with the Palmer method for making an assessment of suitability of the Palmer method as a drought analyzing tool in Bangladesh. The average occurrences of drought in NW region are 34.0, 22.3 and 22.0 percent of the study time in the Palmer, SPI and Herbst methods respectively. It is mentioned here that the average occurrence of drought in the country is once in 2.5 years (Adnan, 1993; Ericksen et al., 1993; Hossain, 1990). The drought occurrences at different stations estimated by the three methods are summarized in Figure 7.6.

The Palmer method classified droughts into extreme, severe, moderate and mild condition depending on the values of the PDSI and the SPI method classified droughts into extreme, severe and moderate conditions depending on the SPI values. The Herbst method provides no such scale rather provides relative measures of droughts.

The occurrence of different drought conditions in NW region is shown in Figure 7.7. The figure shows that the Palmer and the SPI methods recognized the extreme droughts of the region in only 3.6 percent and 0.17 percent of total time. So it can be considered that there is a little chance to experience extreme drought in NW region due to the humid to sub humid climatic conditions of NW Bangladesh.

The Palmer method identified the most common drought occurrences in years like 1972-73, 1975-76, 76-77, 78-79, 79-80, 82-83, 1992-93, 94-95, 1999 and 2001-2002 in selected fifteen stations in NW region. Thus the method could identify the historical drought occurrences of Bangladesh like the year 1975, 1979, 1981-82, 1984, 1989, 1992-93 and 1994-95. The SPI and Herbst methods have also identified these drought years in NW region in the present study.

The percentage of total drought spells beginning and ending in different months of the year in three drought analyzing approaches are shown in Figures 7.8-7.9. The figure reveals that the highest percentage of beginning of drought spells occur in the months of October, March and November respectively in the Palmer, SPI and Herbst methods. The method identified the month of October as the month of highest percentage of beginning of drought spells. The National Water Management Plan (NWMP) has identified the months from November to May as dry season in Bangladesh (Halcrow et al., 2000). The Palmer method considers potential evapotranspiration (PE) and soil moisture conditions for drought analysis in addition to rainfall data. The method estimates the values of PE using the Thornthwaite's formula (1955). The formula overestimates the value of PE than the actual value in the month of October since the estimation is based on temperature only. So the percentage of drought spells beginning is higher in October than that of the other methods. The highest percentage of ending of drought spells occurs in the months of April in the Palmer and SPI methods while in May/June in the Herbst method. These are the transitional months of the two distinct seasons of Bangladesh. It is more realistic of ending of drought spells in the months of May or June instead of April, since more precipitation occurs during these months. It may happen for soil moisture considerations in the Palmer method. But a more detailed study is recommended for quantitative assessment of the influence of soil moisture on drought occurrences in Bangladesh. All of the three methods have identified the occurrences of Kharif droughts during June/July to October months resulting from sub-humid and dry conditions in Bangladesh.

All of the stations of NW region have experienced more or less drought conditions in the present study. There are some differences in results obtained from three approaches of drought analysis. As such no particular station has been characterized by the three studies as severe most water deficit station of the NW region.

Among the three methods, the Palmer method is only based on a monthly water balance accounting scheme that involves precipitation, evapotranspiration and soil moisture. The soil moisture condition of the station is an important consideration for drought analysis. So the method can be considered to be useful primarily for agricultural and other water uses that are sensitive to soil moisture. But in Bangladesh, soil moisture data are not readily available. In the present study the soil moisture data have been estimated. Thus in terms of availability of data, the Palmer method seems less convenient to apply in Bangladesh than the SPI and Herbst methods that consider only precipitation information.

As mentioned earlier that the Palmer method has several limitations. Despite these limitations, the performance of the Palmer method in comparison with the SPI and Herbst methods seems realistic in NW region of Bangladesh in terms of drought occurrences and severity. The Palmer method can be used extensively for monitoring drought conditions and for making operational water management decisions in Bangladesh after some modifications to the method as mentioned in the previous chapter.

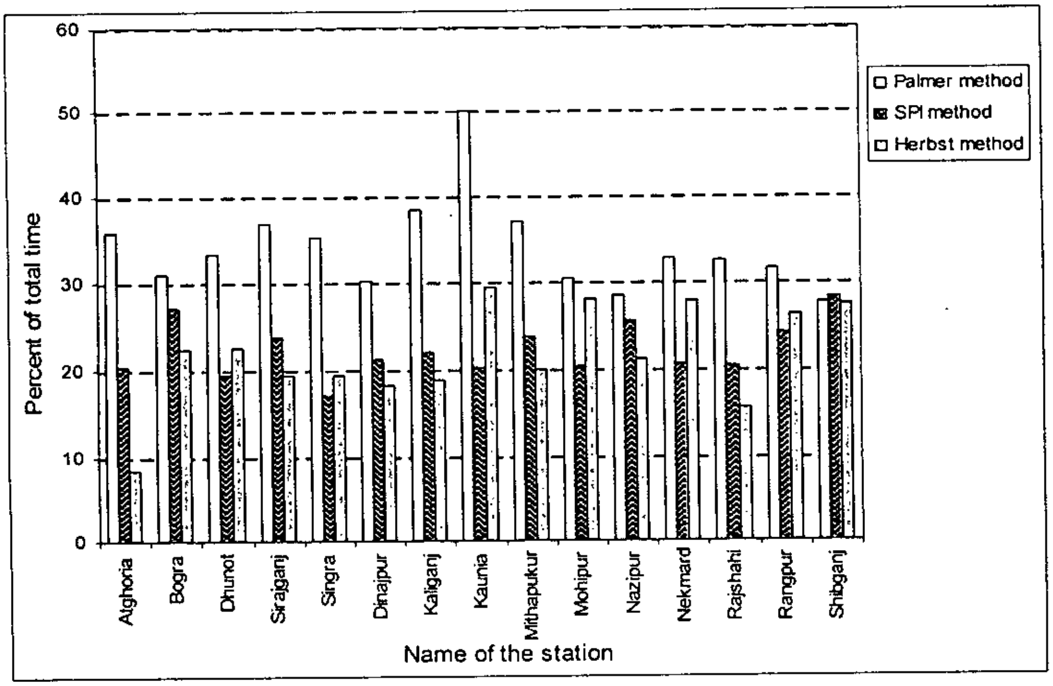


Figure 7.6 The occurrences of drought estimated by different methods in NW region of Bangladesh

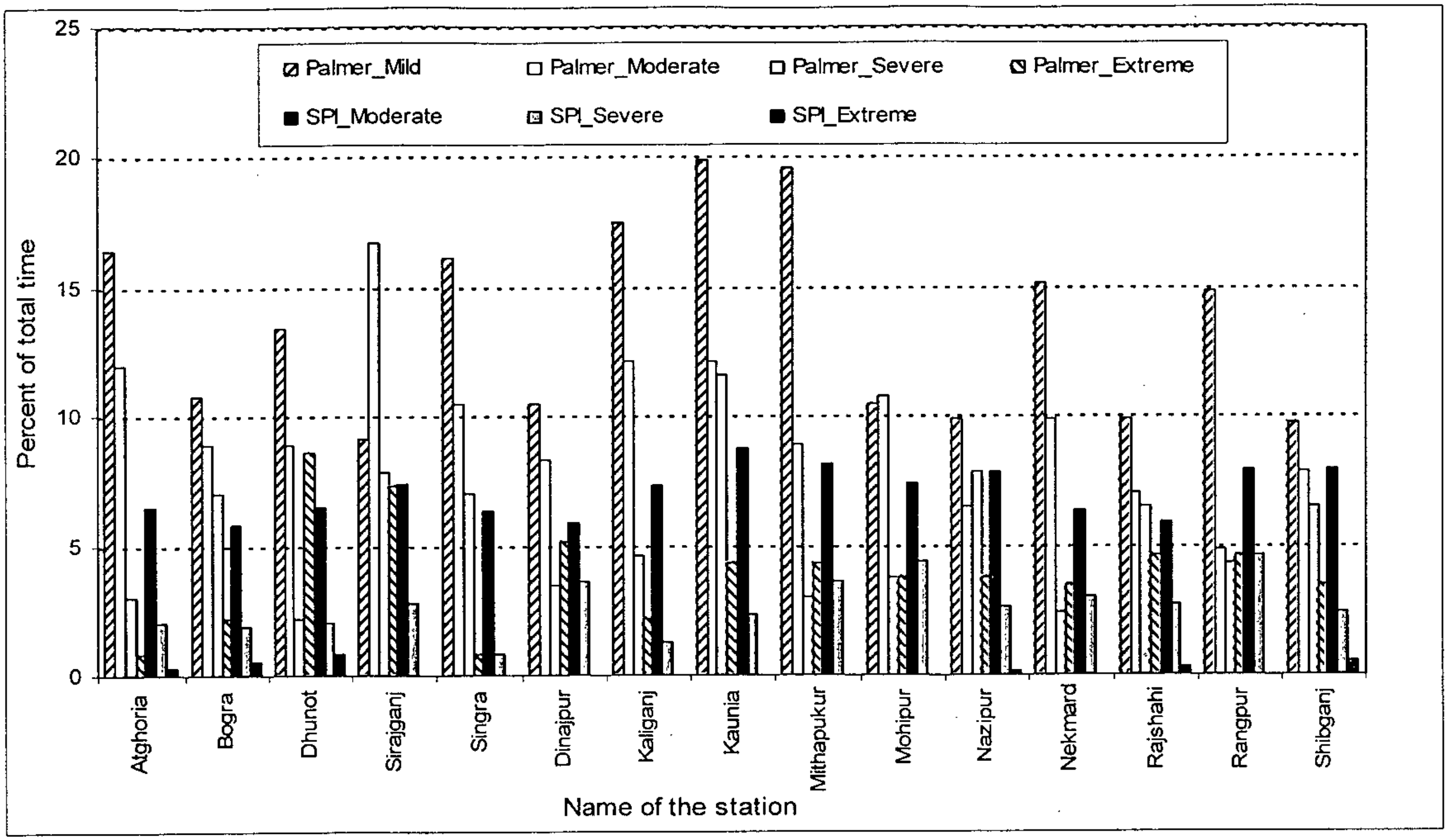


Figure 7.7 Occurrences of different drought conditions estimated by different methods in NW region of Bangladesh

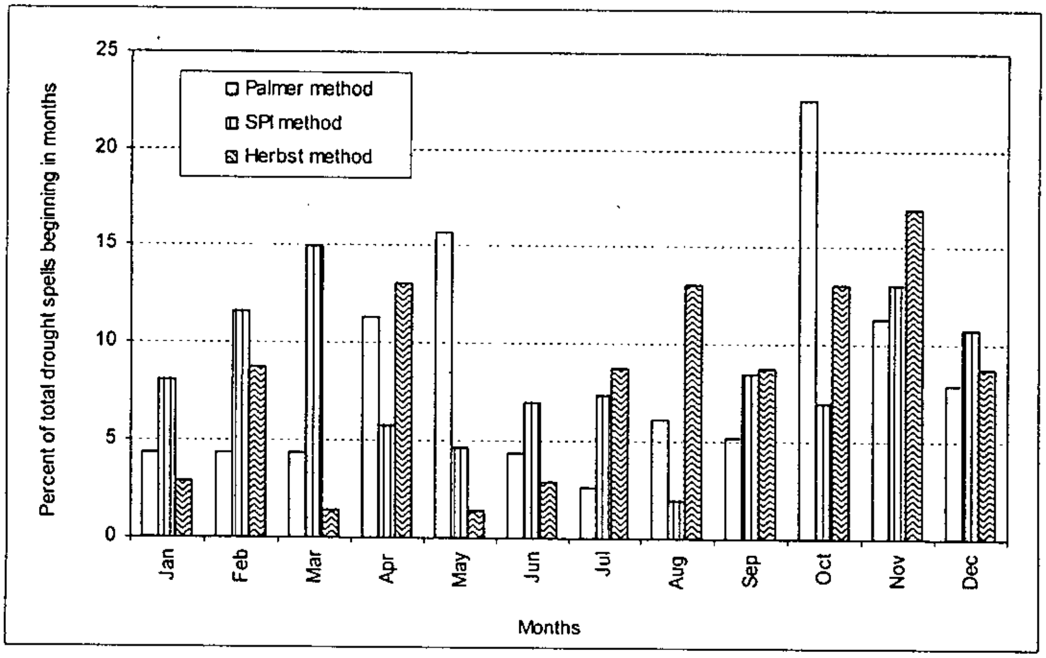


Figure 7.8 Percentage of total drought spells beginning in different months of a year using different methods

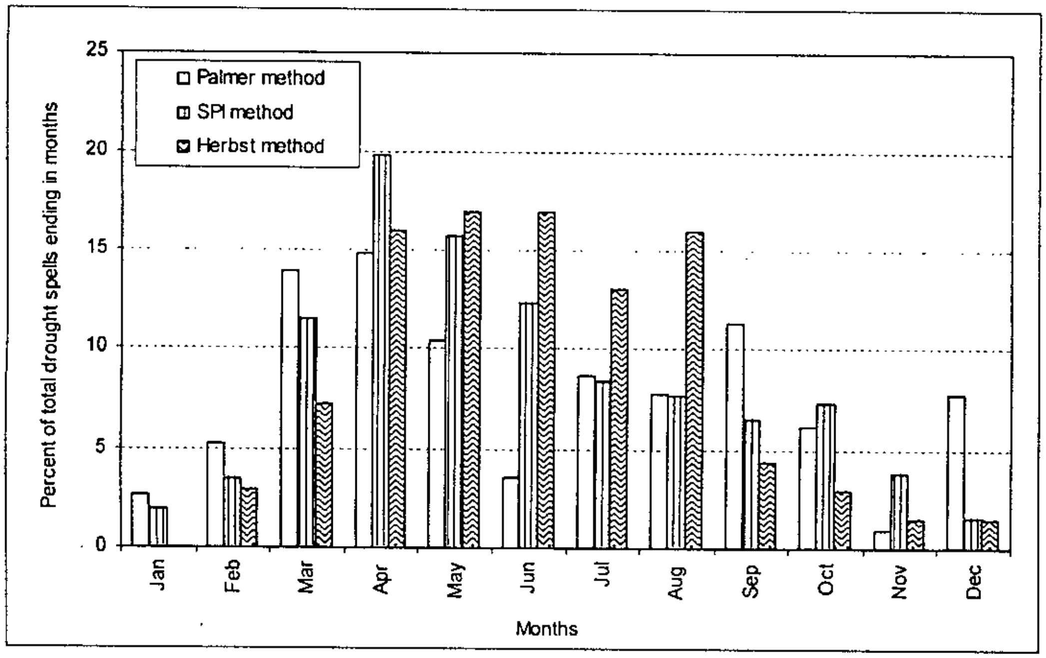


Figure 7.9 Percentage of total drought spells ending in different months of a year using different methods

Chapter 8
CONCLUSION AND RECOMMENDATION

8.1 Conclusion

Available literature shows that the Palmer method is more applicable in arid, semiarid and dry sub-humid regions. In the present study, an attempt has been made for applying the method for drought analysis in the humid to sub-humid climate of NW Bangladesh and the following conclusions have been drawn:

- The drought analysis by the Palmer method showed that all of the stations of NW region experienced some degrees of drought conditions. The method quantified the average occurrence of drought in NW region in 34 percent of the study time from 1972 to 2002.
- The method could identify the historical drought occurrences of Bangladesh like the year 1975, 1979, 1981-82, 1984, 1989, 1992-93 and 1994-95.
- The occurrences of extreme drought conditions were observed only in 3.6 percent of total time.
- The method has identified the month of October rather than November or December as the beginning of highest percentage of drought spells in NW region.
- The method could identify Kharif droughts during the period from June/July to October.
- The method has identified the month of April rather than May or June as the ending of highest percentage of drought spells in NW region.
- The comparison of the method with the Standard Precipitation Index (SPI) and the Herbst methods was made to see its performance in terms of several drought features such as the onset and termination of drought, duration and severity.
- The average occurrence of drought was in 22.3 percent and 22 percent of study time in the SPI and the Herbst methods respectively. These two methods have also identified the same drought years in NW region as in the Palmer method in the present study.
- The highest percentage of drought spells beginning occur in the months of March and November respectively in the SPI and Herbst methods and the highest

percentage of drought spell ending occurs in the months of April and May/June in the SPI and Herbst methods respectively.

- While applying Palmer method in drought analysis of NW region of Bangladesh, some limitations were noticed in addition to those already identified by many researchers.
- Despite these limitations, the performance of the Palmer method in comparison with the SPI and Herbst methods seems realistic in NW region of Bangladesh in terms of drought occurrences and severity.
- The method can be used extensively for monitoring drought conditions and for making operational water management decisions in Bangladesh after some modifications to the method.

8.2 Recommendations

While applying the widely used Palmer method in humid to sub-humid conditions of Bangladesh, it has been observed that several modifications are required to the assumptions of the method. The coefficients and equations of the original method are required to derive following the same procedure for monthly timescale by analyzing long term historical climatic data of Bangladesh. The shorter timescale is more appropriate for making operational water management decisions in Bangladesh. In addition, considerations of standing water of agricultural land in the Palmer method would produce more realistic picture of drought conditions of the country. A more detailed study is recommended for quantitative assessment of the influence of soil moisture on drought occurrences in the country. Several modifications are also required to the hydrologic accounting of the method for applying it as a drought analyzing tool in Bangladesh.

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Appendix I

THORNTHWAITE'S FORMULA

According to Thornthwaite (1955)

$$E_p = 1.6\left(\frac{10T}{I}\right)^a \quad \text{.......A1.1}$$

Where

E_p= potential evapotranspiration (cm/month, in months of 30 days, with a day-length of 12 hours)

T= average air temperature (^{0}C), calculated from daily means

I= annual heat index, i.e. the sum of the 12 monthly heat indices, i where

$$i = \left(\frac{T}{5}\right)^{1.514}$$

a= 0.000000675 I^3- 0.000077 I^2 +0.01792 I+0.49239

E_p obtained from eqn. (A1.1) is the potential evapotranspiration for a 30-day month with day-lengths of 12 hours. The correction factor to be used depending on the latitude and month is given in Table A1.1.

Table A1.1 Mean possible duration of sunlight in the Northern and Southern hemispheres expressed in units of 30 days of 12 hours each

Month/ Latitude	J	F	M	A	M	J	J	A	S	O	N	D
°N												
0	1.04	.94	1.04	1.01	1.04	1.01	1.04	1.04	1.01	1.04	1.01	1.04
5	1.02	.93	1.03	1.02	1.06	1.03	1.06	1.05	1.01	1.03	.99	1.02
10	1.00	.91	1.03	1.03	1.08	1.06	1.08	1.07	1.02	1.02	.98	.99
15	.97	.91	1.03	1.04	1.11	1.08	1.12	1.08	1.02	1.01	.95	.97
20	.95	.90	1.03	1.05	1.13	1.11	1.14	1.11	1.02	1.00	.93	.94
25	.93	.89	1.03	1.06	1.15	1.14	1.17	1.12	1.02	.99	.91	.91
26	.92	.88	1.03	1.06	1.15	1.15	1.17	1.12	1.02	.99	.91	.91
27	.92	.88	1.03	1.07	1.16	1.15	1.18	1.13	1.02	.99	.90	.90
28	.91	.88	1.03	1.07	1.16	1.16	1.18	1.13	1.02	.98	.90	.90
29	.91	.87	1.03	1.07	1.17	1.16	1.19	1.13	1.03	.98	.90	.89
30	.90	.87	1.03	1.08	1.18	1.17	1.20	1.14	1.03	.98	.89	.88
31	.90	.87	1.03	1.08	1.18	1.18	1.20	1.14	1.03	.98	.89	.88
32	.89	.86	1.03	1.08	1.19	1.19	1.21	1.15	1.03	.98	.88	.87
33	.88	.86	1.03	1.09	1.19	1.20	1.22	1.15	1.03	.97	.88	.86
34	.88	.85	1.03	1.09	1.20	1.20	1.22	1.16	1.03	.97	.87	.86
35	.87	.85	1.03	1.09	1.21	1.21	1.23	1.16	1.03	.97	.86	.85
36	.87	.85	1.03	1.10	1.21	1.22	1.24	1.16	1.03	.97	.86	.84
37	.86	.84	1.03	1.10	1.22	1.23	1.25	1.17	1.03	.97	.85	.83
38	.85	.84	1.03	1.10	1.23	1.24	1.25	1.17	1.04	.96	.84	.83
39	.85	.84	1.03	1.11	1.23	1.24	1.26	1.18	1.04	.96	.84	.82
40	.84	.83	1.03	1.11	1.24	1.25	1.27	1.18	1.04	.96	.83	.81
41	.83	.83	1.03	1.11	1.25	1.26	1.27	1.19	1.04	.96	.82	.80
42	.82	.83	1.03	1.12	1.26	1.27	1.28	1.19	1.04	.95	.82	.79
43	.81	.82	1.02	1.12	1.26	1.28	1.29	1.20	1.04	.95	.81	.77
44	.81	.82	1.02	1.13	1.27	1.29	1.30	1.20	1.04	.95	.80	.76
45	.80	.81	1.02	1.13	1.28	1.29	1.31	1.21	1.04	.94	.79	.75
46	.79	.81	1.02	1.13	1.29	1.31	1.32	1.22	1.04	.94	.79	.74
47	.77	.80	1.02	1.14	1.30	1.32	1.33	1.22	1.04	.93	.78	.73
48	.76	.80	1.02	1.14	1.31	1.33	1.34	1.23	1.05	.93	.77	.72
49	.75	.79	1.02	1.14	1.32	1.34	1.35	1.24	1.05	.93	.76	.71
50	.74	.78	1.02	1.15	1.33	1.36	1.37	1.25	1.06	.92	.76	.70
°S												
5	1.06	.95	1.04	1.00	1.02	.99	1.02	1.03	1.00	1.05	1.03	1.06
10	1.08	.97	1.05	.99	1.01	.96	1.00	1.01	1.00	1.06	1.05	1.10
15	1.12	.98	1.05	.98	.98	.94	.97	1.00	1.00	1.07	1.07	1.12
20	1.14	1.00	1.05	.97	.96	.91	.95	.99	1.00	1.08	1.09	1.15
25	1.17	1.01	1.05	.96	.94	.88	.93	.98	1.00	1.10	1.11	1.18
30	1.2	1.03	1.06	.95	.92	.85	.90	.96	1.00	1.12	1.14	1.21
35	1.23	1.04	1.06	.94	.89	.82	.87	.94	1.00	1.13	1.17	1.25
40	1.27	1.06	1.07	.93	.86	.78	.84	.92	1.00	1.15	1.20	1.29
42	1.28	1.07	1.07	.92	.85	.76	.82	.92	1.00	1.16	1.22	1.31
44	1.30	1.08	1.07	.92	.83	.74	.81	.91	.99	1.17	1.23	1.33
46	1.32	1.10	1.07	.91	.82	.72	.79	.90	.99	1.17	1.25	1.35
48	1.34	1.11	1.08	.90	.80	.70	.76	.89	.99	1.18	1.27	1.37
50	1.37	1.12	1.08	.89	.77	.67	.74	.88	.99	1.19	1.29	1.41

Appendix II

PROBABILITY DISTRIBUTION FUNCTIONS USED

Two Parameter Log-Normal (LN-2) distribution

The Log-Normal (LN-2) distribution is a familiar distribution in hydrology. If a random variable x has a LN-2 distribution, the log transformed variable has a normal distribution. The transformed variable is denoted by

y=ln(x), where x>0

The probability density function (pdf) of the LN-2 distribution is given by

$$f_x(x) = \frac{1}{x\sqrt{2\pi\sigma^2{}_y}} \exp\left[-\frac{1}{2}\left(\frac{y-\mu_y}{\sigma_y}\right)^2\right] \text{ for x>0} \quad \text{A2.1}$$

The mean and variance of LN-2 distribution are

$$E(x) = \exp(\mu_y + \frac{\sigma_y{}^2}{2}) \quad \text{A2.2}$$

$$Var(x) = \mu_x{}^2[\exp(\sigma_y{}^2) - 1] \quad \text{A2.3}$$

The skew coefficient is

$\gamma_x = 3CV_x + CV_x^3$ where CV_x is the coefficient of variation.

The maximum likelihood method is generally best for fitting the LN-2 distribution (Stedinger, 1980). The maximum likelihood method gives:

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} \ln(x_i) \quad \text{A2.4}$$

$$\sigma_y{}^2 = \frac{1}{n}\sum_{i=1}^{n}\left[\ln(x_i) - \bar{y}\right]^2 \quad \text{A2.5}$$

Estimate of precipitation for T-year return period can be obtained from,

$$x_T = e^{y_T} = e^{\bar{y} + z_T\sigma_y} \quad \text{A2.6}$$

Where z_T is the quantile of the standard normal distribution ($\mu = 0,\ \sigma^2 = 1$) corresponding to return period T. The z_T is also called standardized normal variate. The inverse of the cumulative distribution function (cdf) for the standard normal distribution is not available in closed form and hence the quantiles of the standard normal distribution cannot be obtained analytically. Selected values of the standardized normal variate z_T are given in Table A2.1.

Table A2.1 Quantiles of the standard normal distribution

p	0.5	0.8	0.9	0.95	0.98	0.99
T (years)	2	5	10	20	50	100
z_p or z_T	0	0.842	1.282	1.645	2.054	2.326

An approximation for the standard normal variate (Stedinger et al., 1993) is

$$z_p = \frac{(1-\frac{1}{T})^{.135} - \left(\frac{1}{T}\right)^{0.135}}{0.1975} \quad \text{.......A2.7}$$

Asymptotically, the variance of the quantile estimator is approximately given by

$$Var[x_T] \approx x_T{}^2[\frac{s_y{}^2}{n}(1+\frac{1}{2}z_T{}^2)] \quad \text{.......A2.8}$$

The approximate confidence interval for x_T is

$x_T \pm z_{1-p/2}\sqrt{Var[x_T]}$ where the values of $z_{1-p/2}$ are obtained from Table A2.1. Probability plots are constructed by plotting ordered y_i i.e. ordered logarithms $\ln(x_i)$ versus z_T .

Extreme Value Type III (Weibull) distribution

The Weibull distribution is greatly used as the distribution of low stream flows. In the present study three parameter Weibull distribution is used. The pdf of three parameter Weibull distribution is

$$f_x(x) = \alpha(x-\varepsilon)^{\alpha-1}(\beta-\varepsilon)^{-\alpha}\exp[-(x-\beta)/(\beta-\varepsilon)^{\alpha}] \text{ for x>0, } \alpha,\beta > 0 \quad \text{......A2.9}$$

The cdf of the distribution is

$$\left.\begin{aligned} F_x(x) &= 1-\exp\left[-\left(\frac{x-\varepsilon}{\beta-\varepsilon}\right)^{\alpha}\right] = 1-\exp(-y) \\ \mathit{where} \quad y &= \left[\frac{x-\varepsilon}{\beta-\varepsilon}\right]^{\alpha} \end{aligned}\right\} \quad \text{......A2.10}$$

and ε is the lower bound

The mean and variance of the three parameter distribution are

$$E(x) = \varepsilon + (\beta-\varepsilon)[(1+1/\alpha)] \quad \text{......A2.11}$$

$$Var(x) = (\beta-\varepsilon)^2[\Gamma(1+2/\alpha) - \Gamma^2(1+1/\alpha)] \quad \text{......A2.12}$$

The coefficient of skew is

$$\gamma = \frac{\Gamma(1+3/\alpha) - 3\Gamma(1+2/\alpha)\Gamma(1+1/\alpha) + 2\Gamma^3(1+1/\alpha)}{[\Gamma(1+2/\alpha) - \Gamma^2(1+1/\alpha]^{3/2}} \quad \text{......A2.13}$$

Eqs. (A2.11) and (A2.12) can be written as,

$$\beta = \mu + \sigma A(\alpha) \quad \text{......A2.14}$$

$$\varepsilon = \beta - \sigma B(\alpha) \quad \text{......A2.15}$$

where

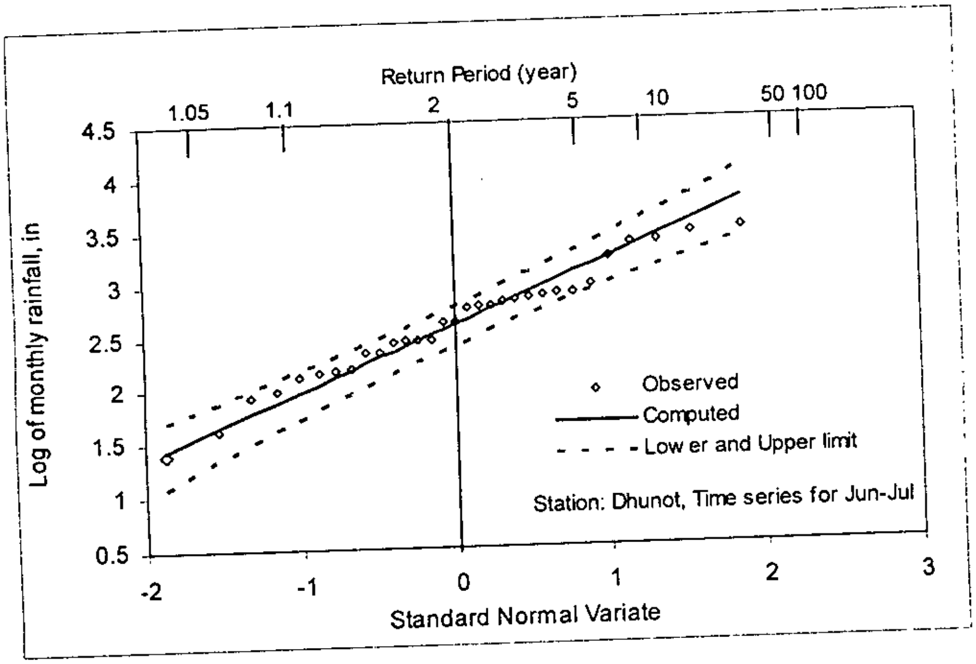
$$A(\alpha) = [1-\Gamma(1+1/\alpha)]B(\alpha) \quad \text{......A2.16}$$

$$B(\alpha) = [\Gamma(1+2/\alpha) - \Gamma^2(1+1/\alpha)]^{-1/2} \quad \text{......A2.17}$$

The moment estimates α, β, ε can be obtained by solving Eqs. (A2.13)-(A2.17). Hann (1977) provided a table for solution of the equations.

Appendix III

PROBABILITY PLOT OF FITTED LN-2 DISTRIBUTION (STATION: DHUNOT)



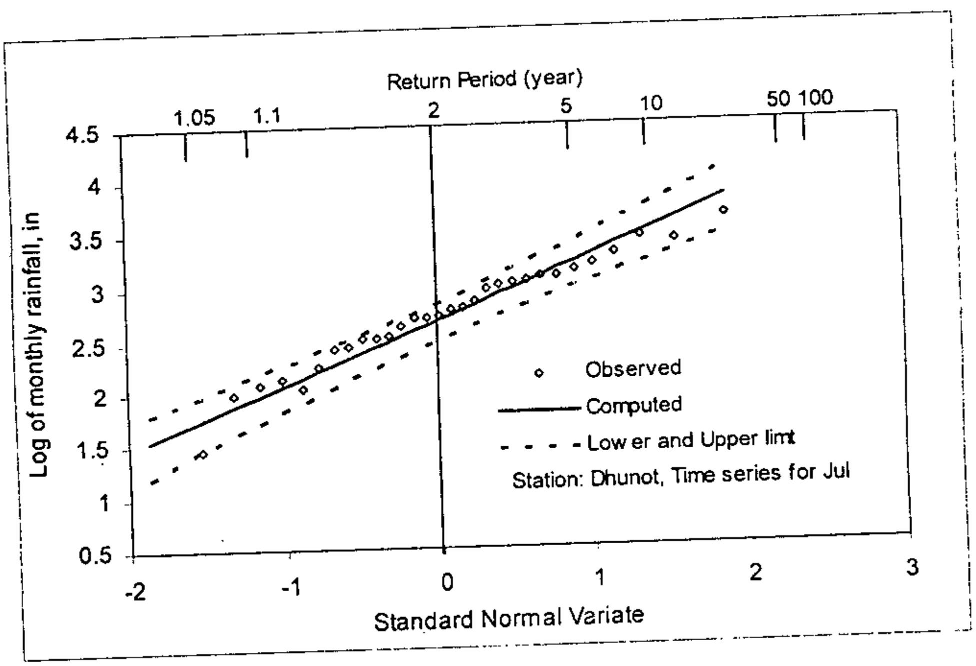
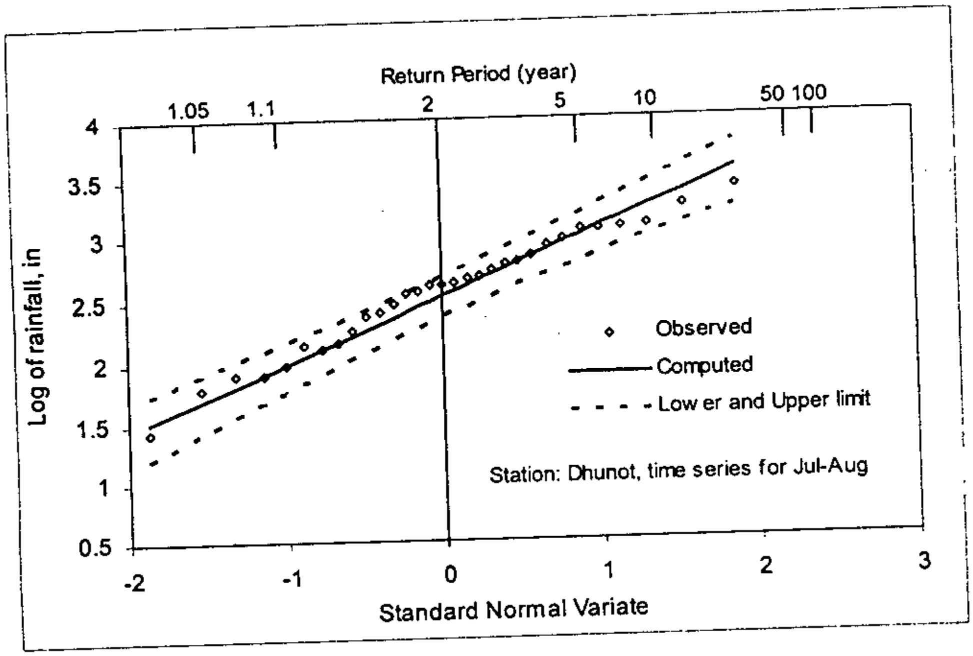


Figure A 3.1 Probability plot of fitted LN-2 distribution with 90 percent confidence interval



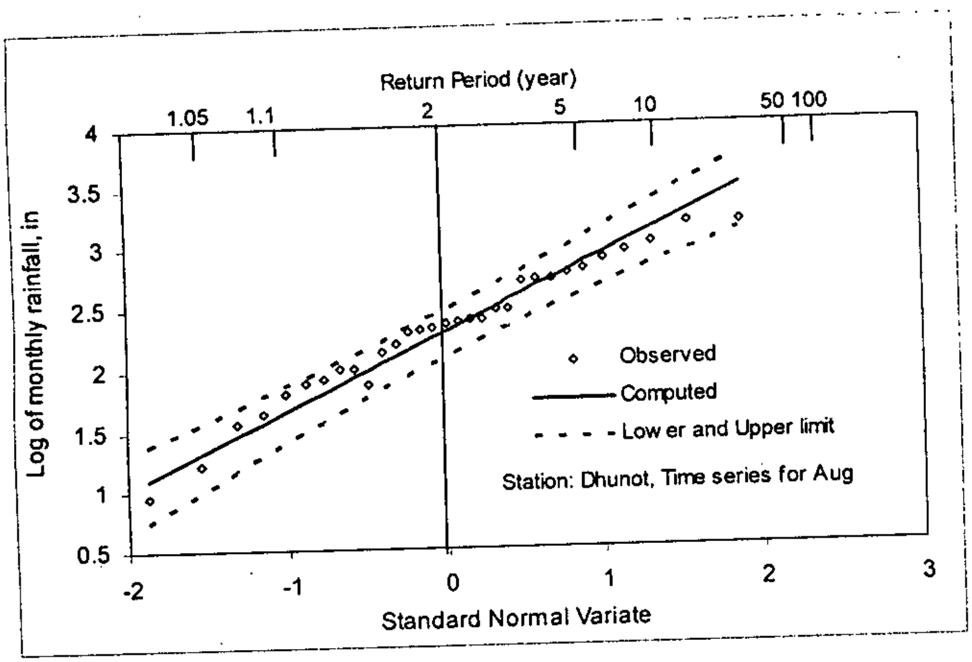
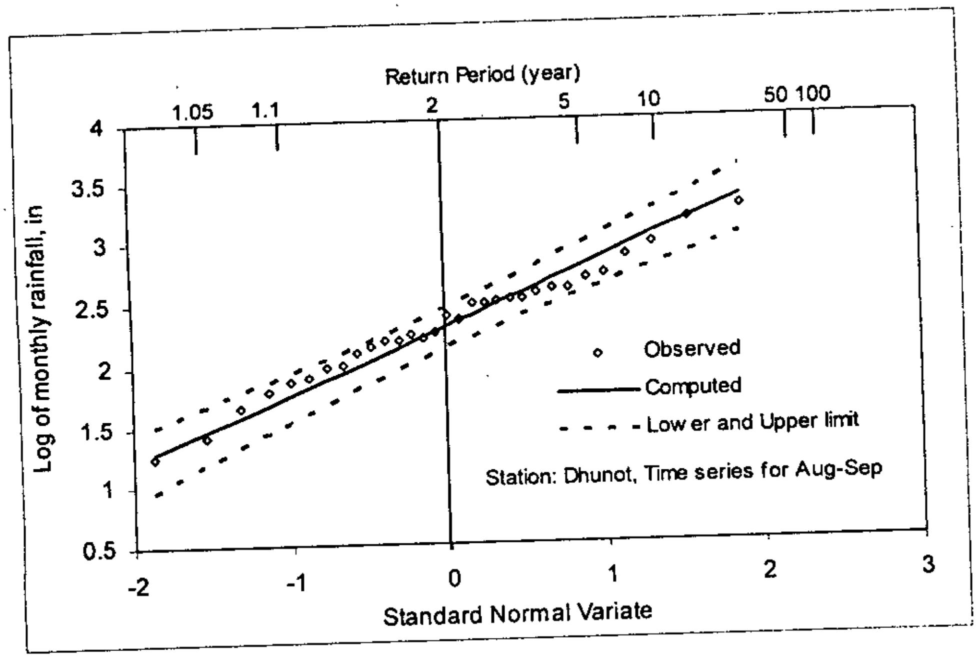


Figure A 3.1 Probability plot of fitted LN-2 distribution with 90 percent confidence interval (continued..)



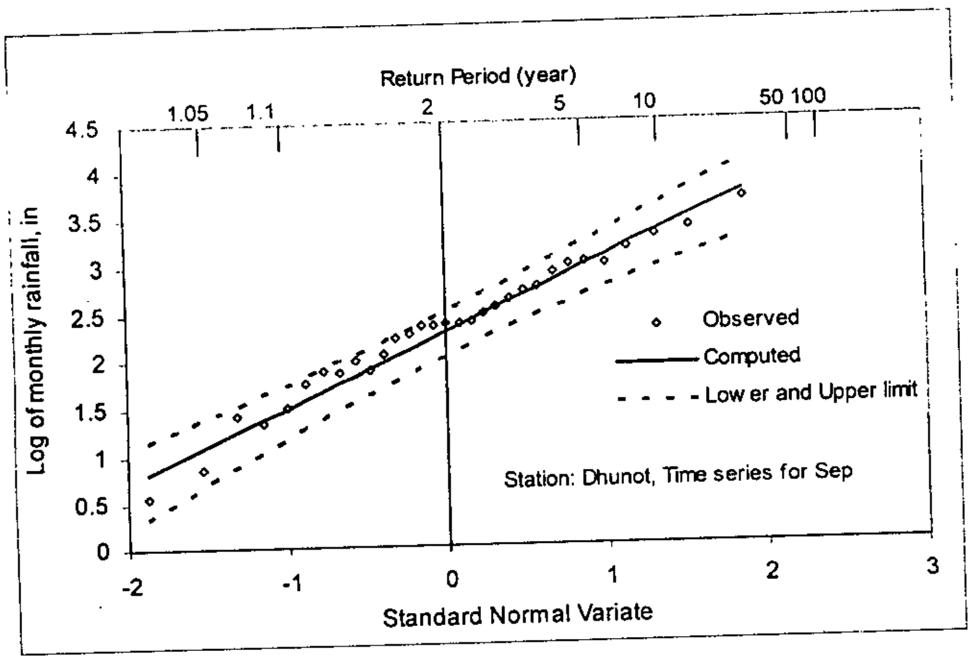
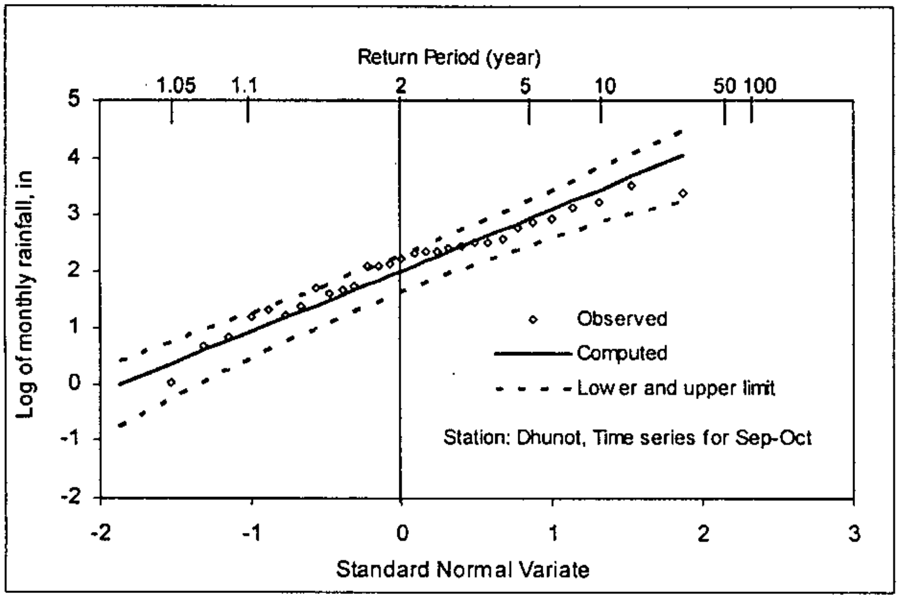


Figure A 3.1 Probability plot of fitted LN-2 distribution with 90 percent confidence interval (continued..)



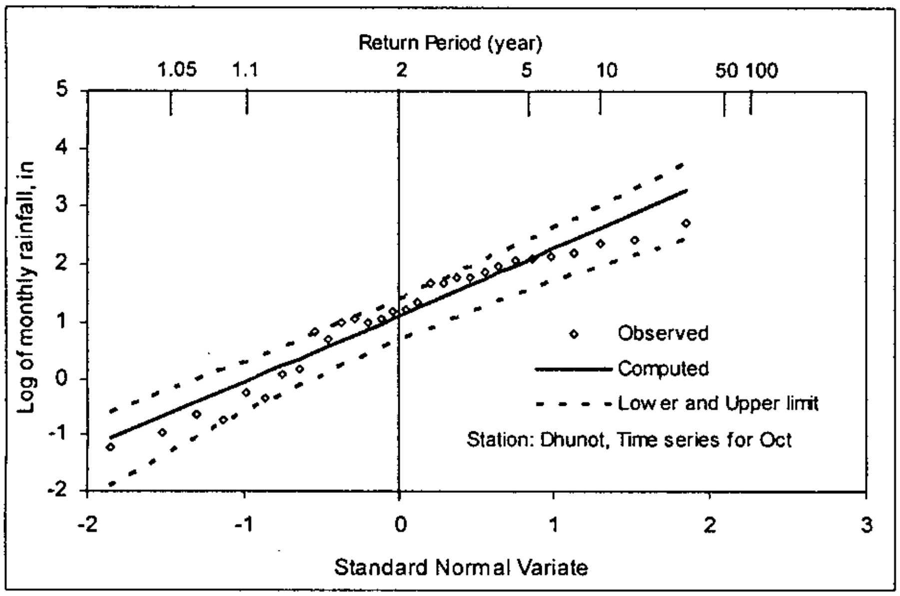


Figure A 3.1 Probability plot of fitted LN-2 distribution with 90 percent confidence interval (continued..)

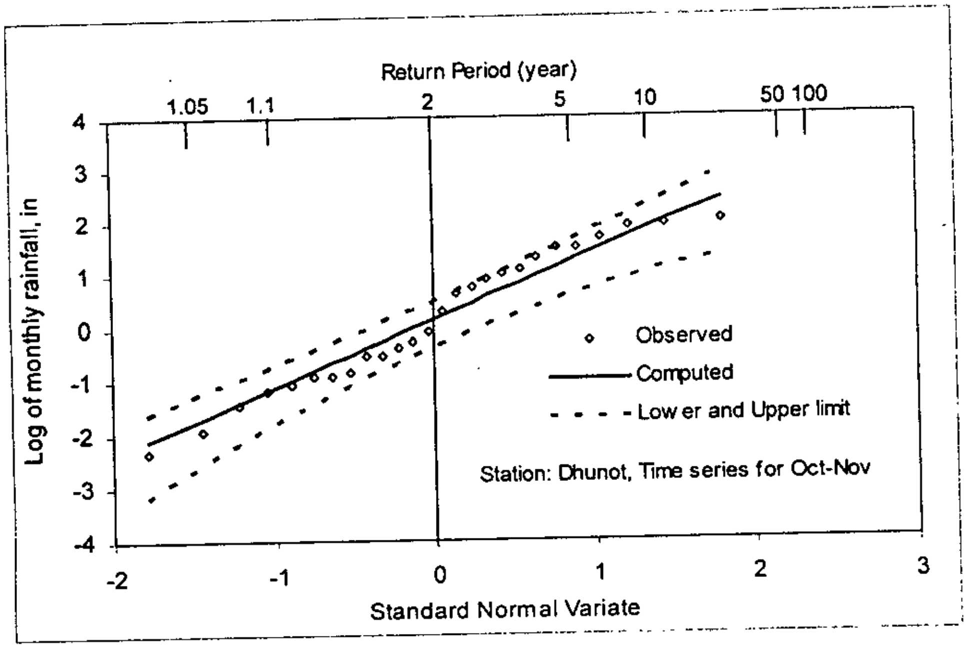
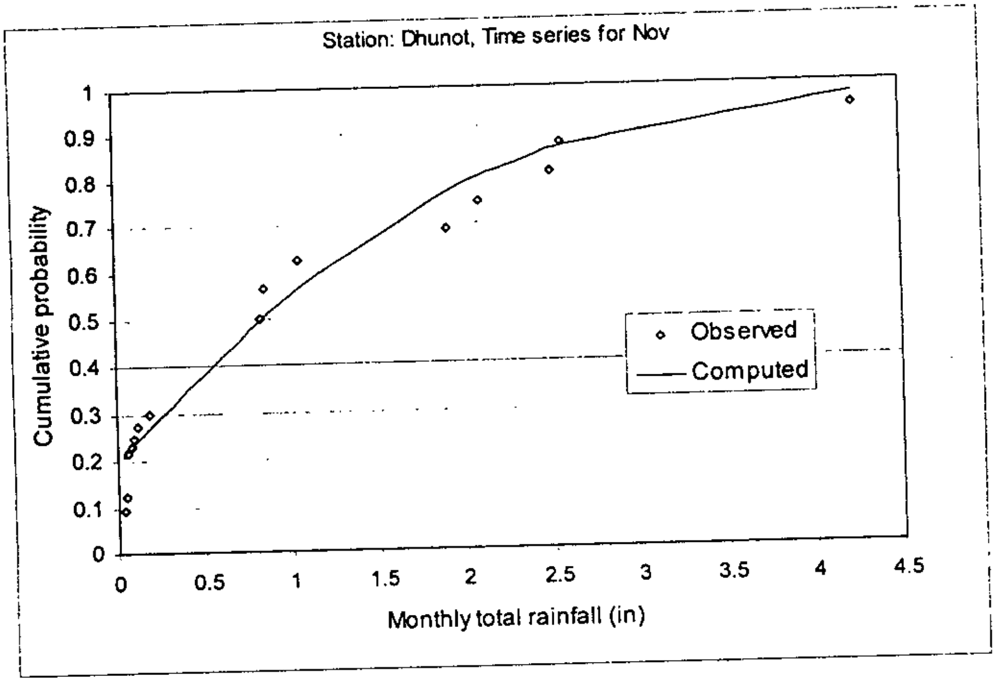


Figure A 3.1 Probability plot of fitted LN-2 distribution with 90 percent confidence interval

Appendix IV
CUMULATIVE PROBABILITY PLOT OF WEIBULL DISTRIBUTION

(STATION: DHUNOT)



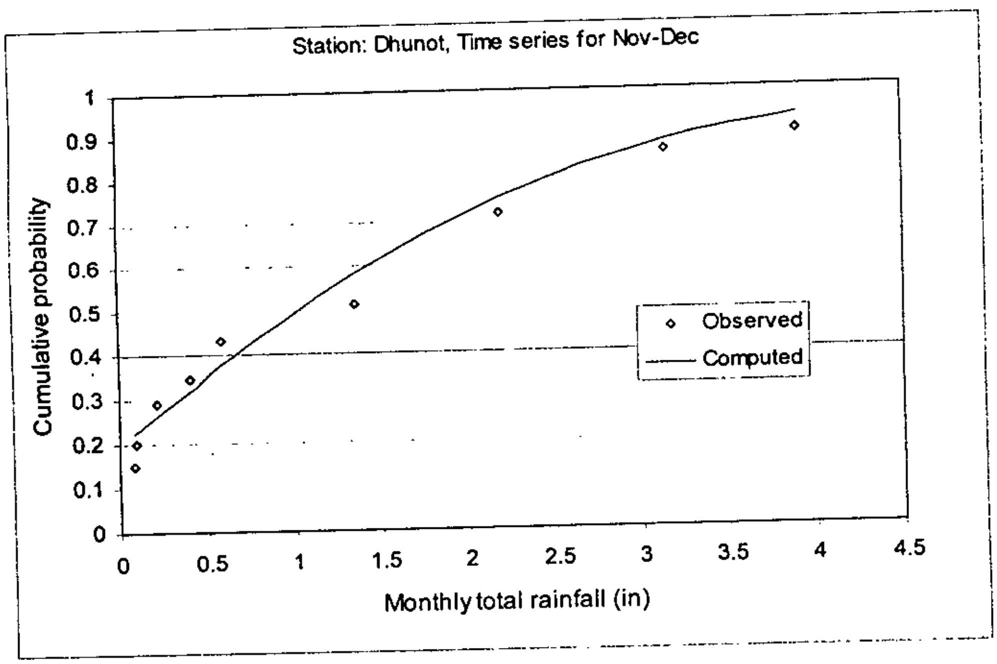
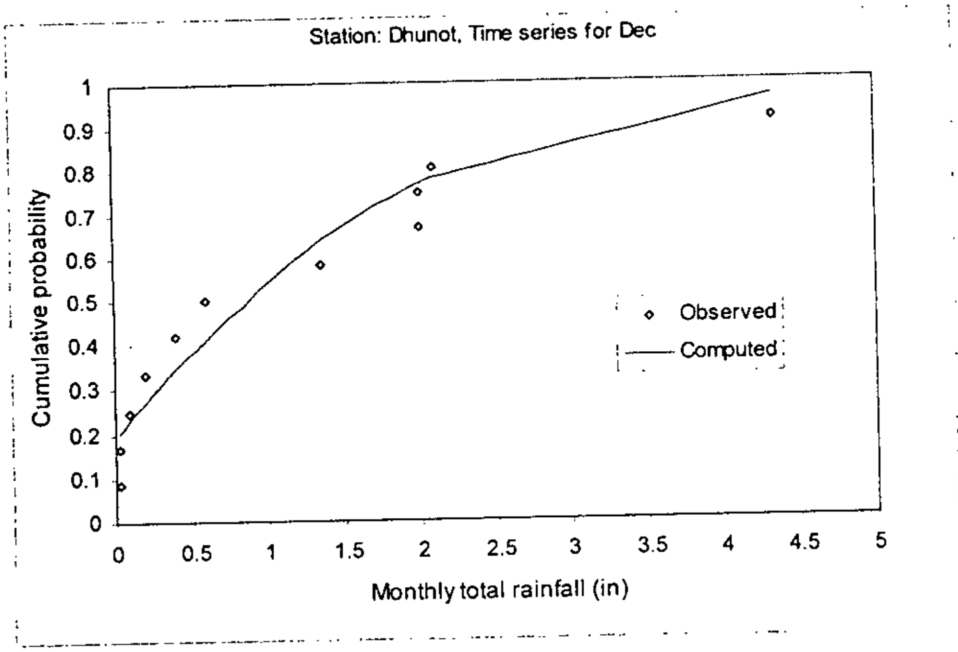


Figure A 4.1 Cumulative probability plot of Weibull distribution



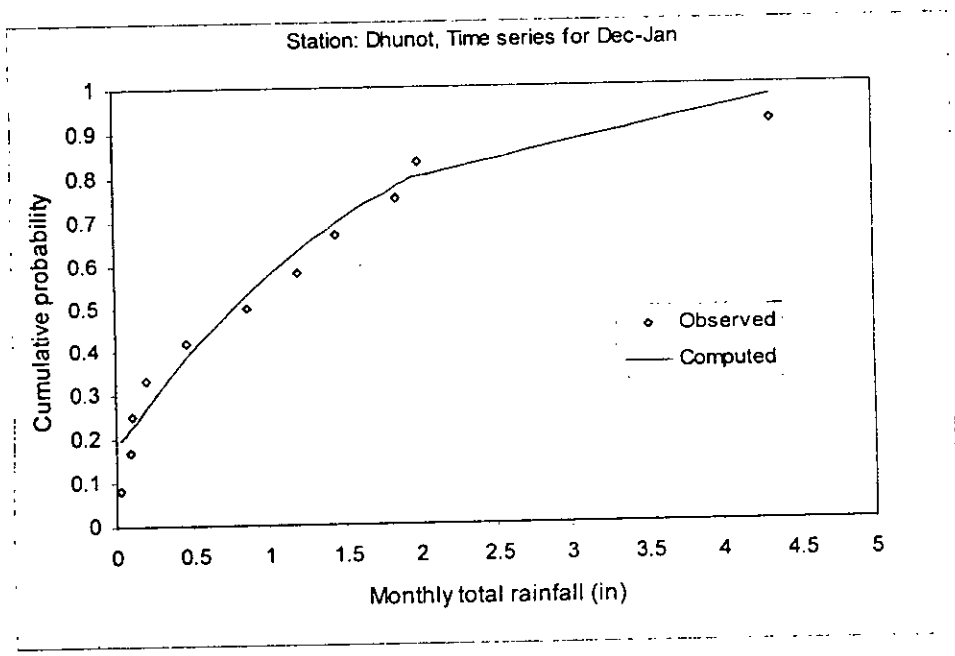
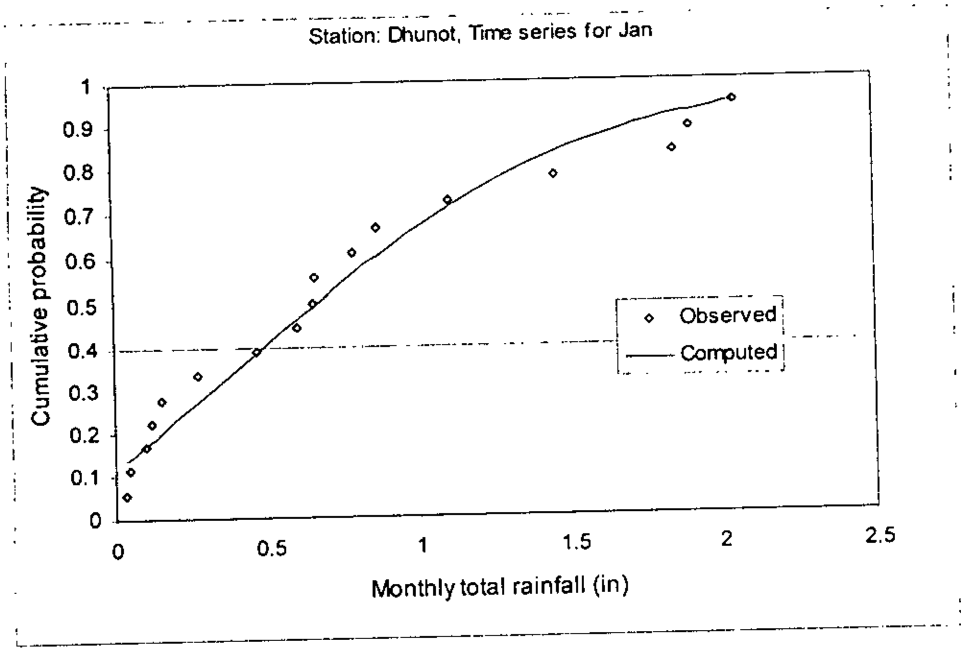


Figure A 4.1 Cumulative probability plot of Weibull distribution (continued….)



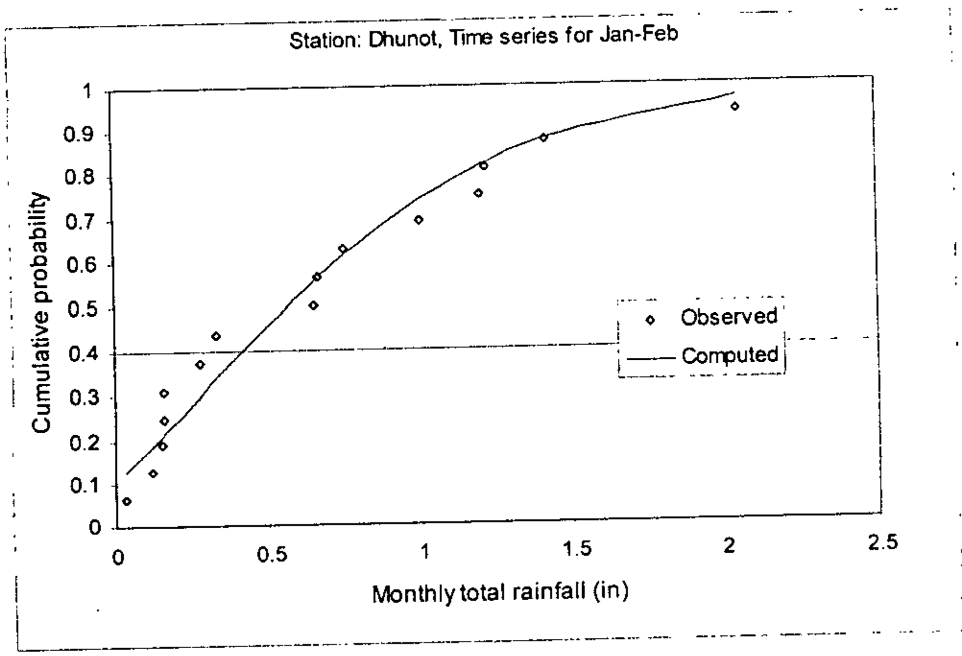
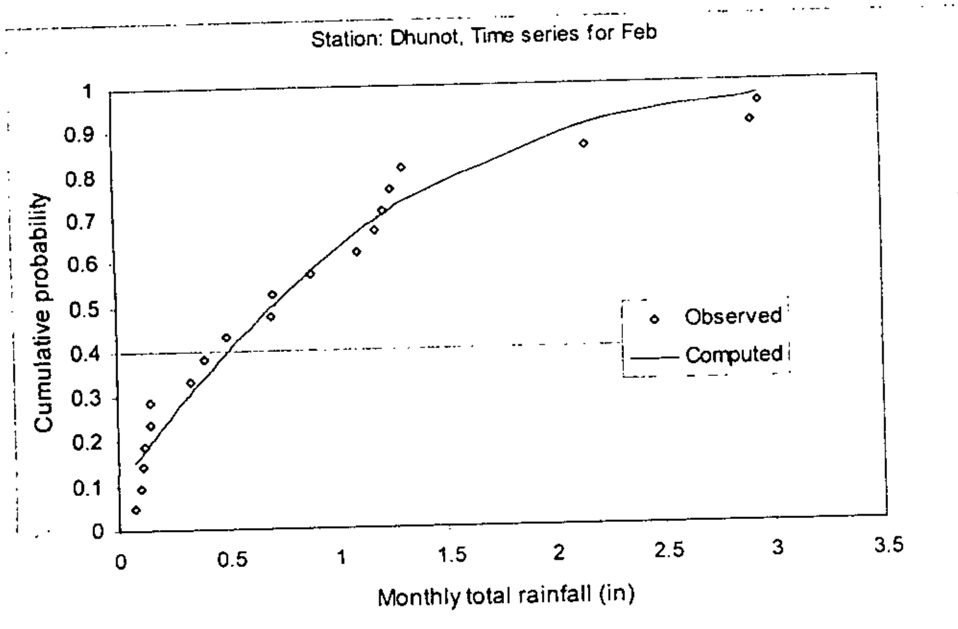


Figure A 4.1 Cumulative probability plot of Weibull distribution (continued....)



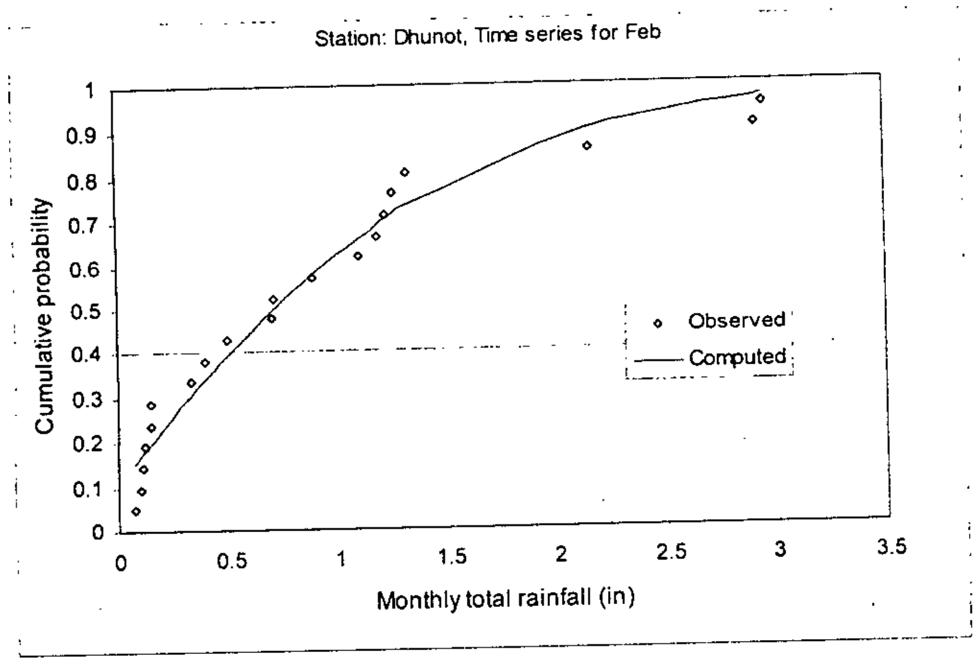
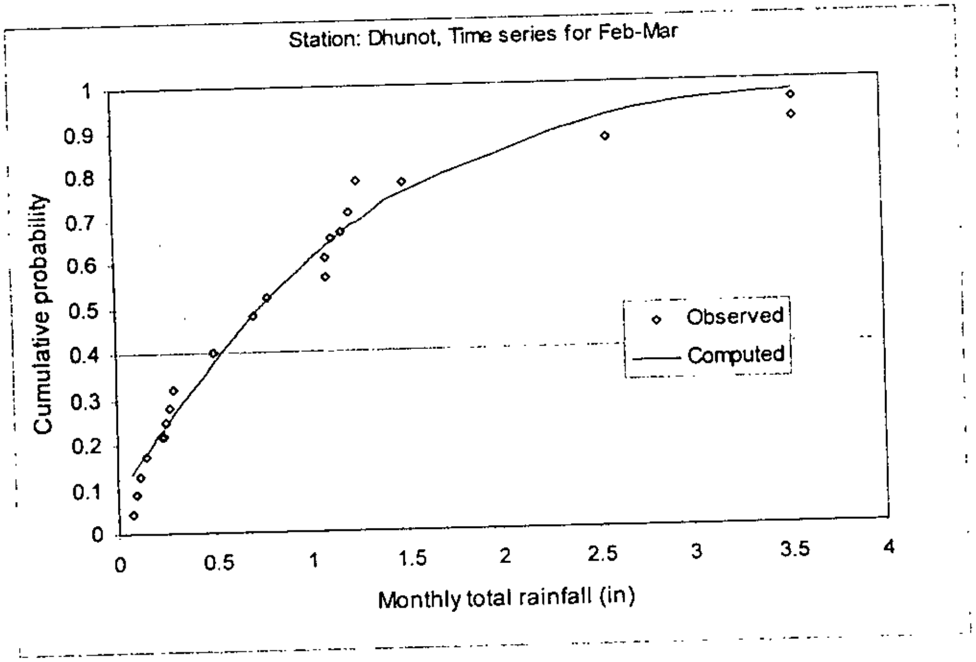


Figure A 4.1 Cumulative probability plot of Weibull distribution (continued....)



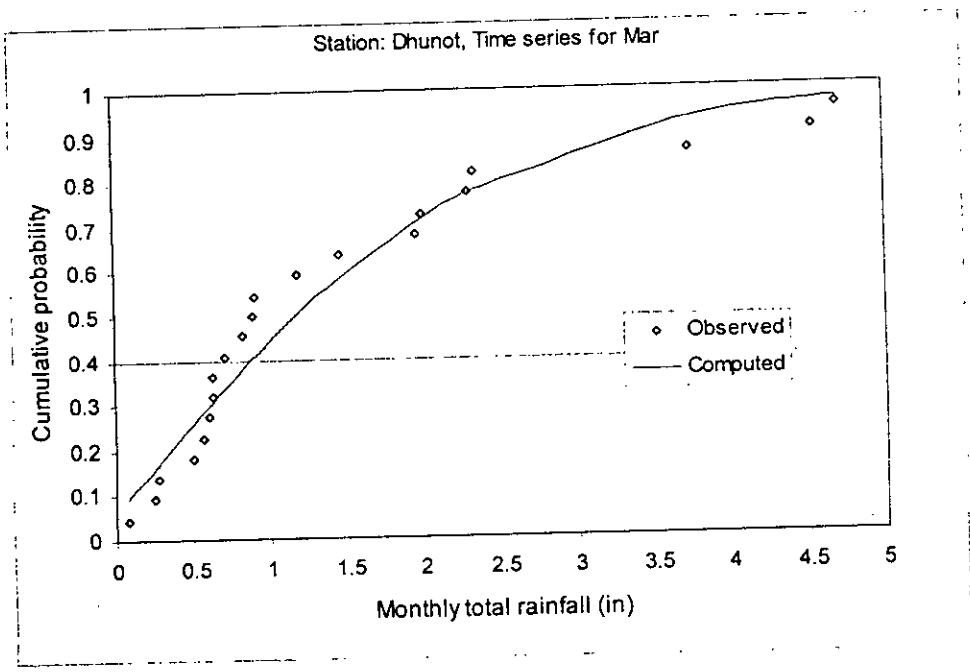
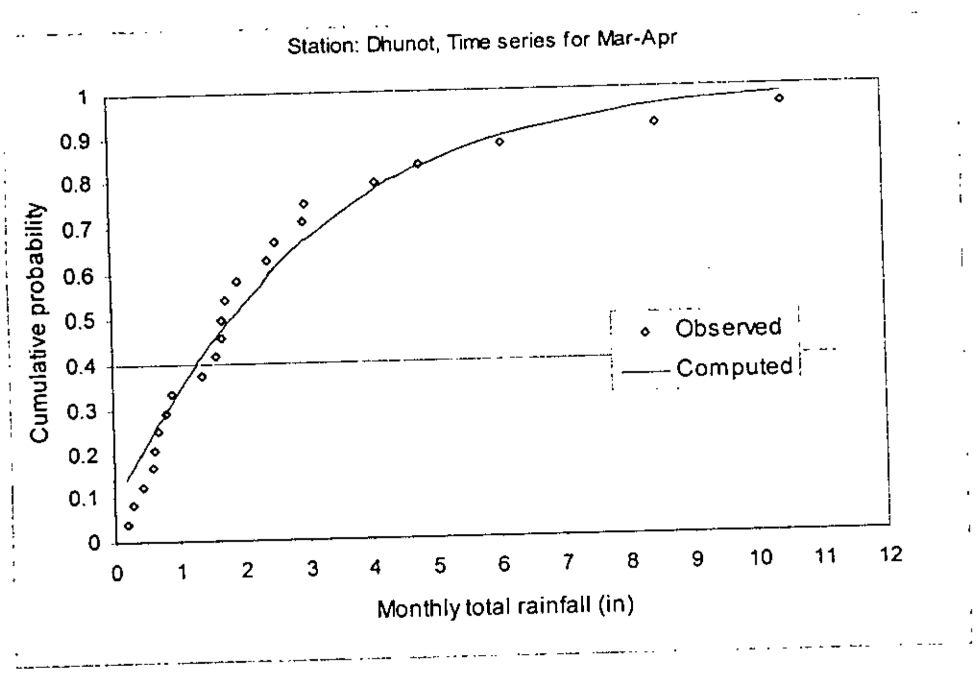


Figure A 4.1 Cumulative probability plot of Weibull distribution (continued….)



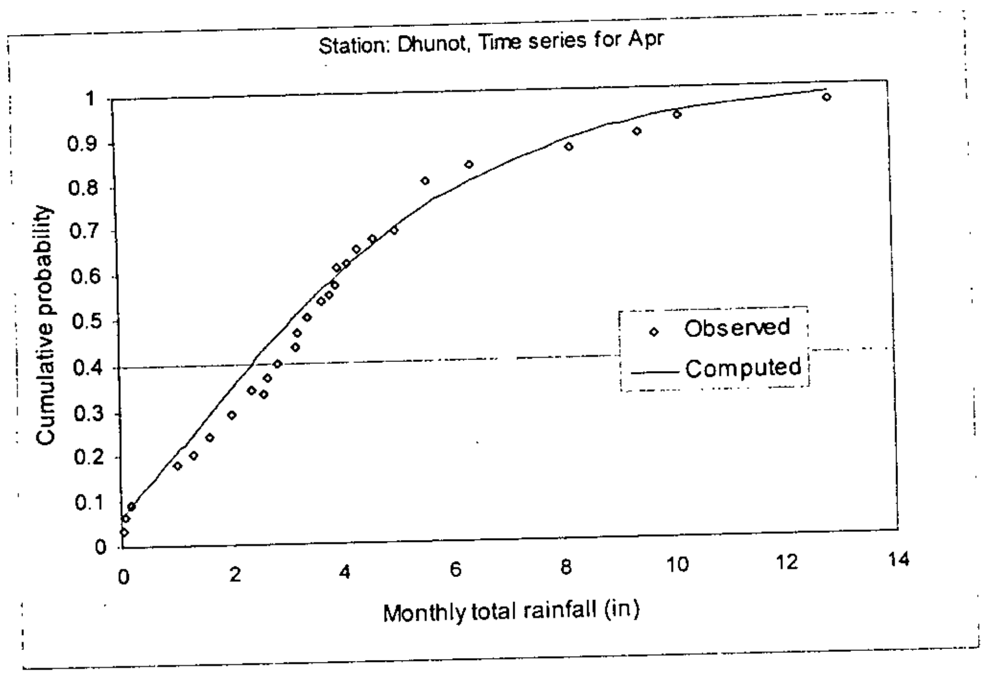
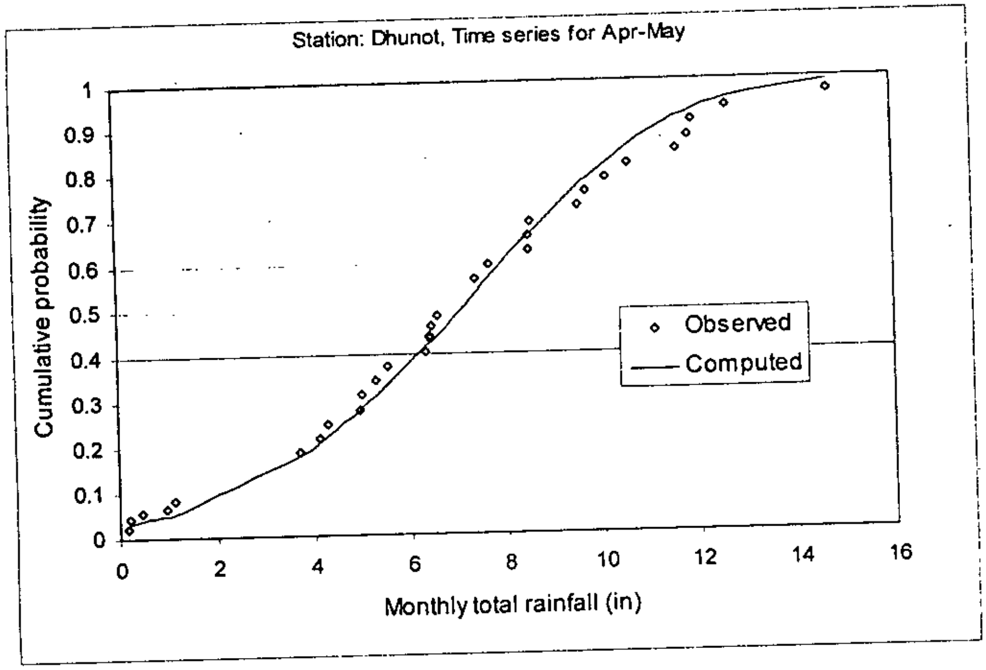


Figure A 4.1 Cumulative probability plot of Weibull distribution (continued....)



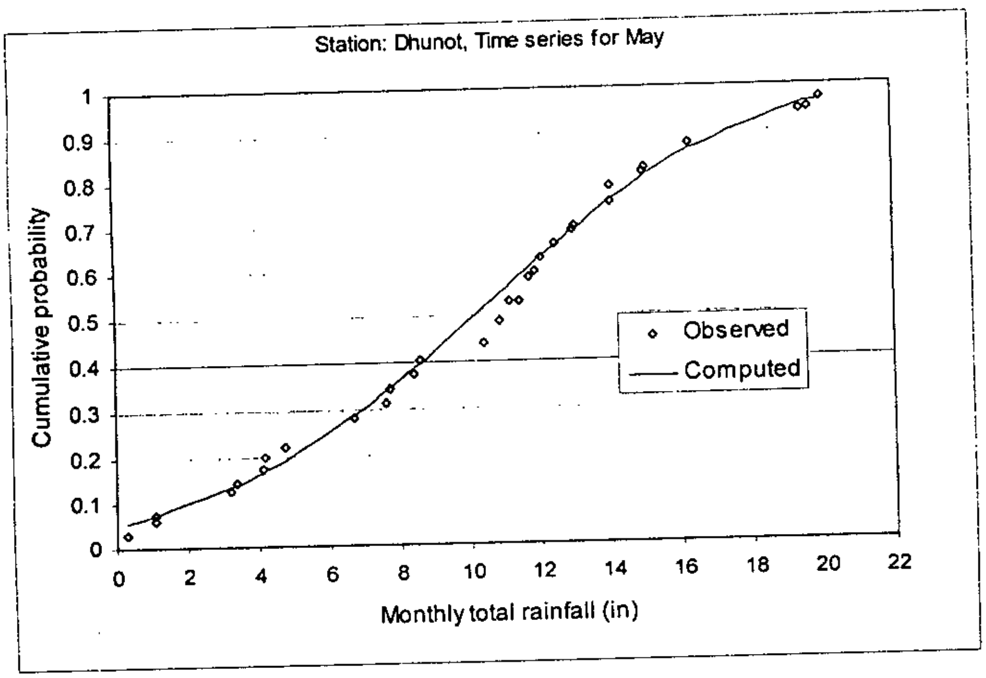
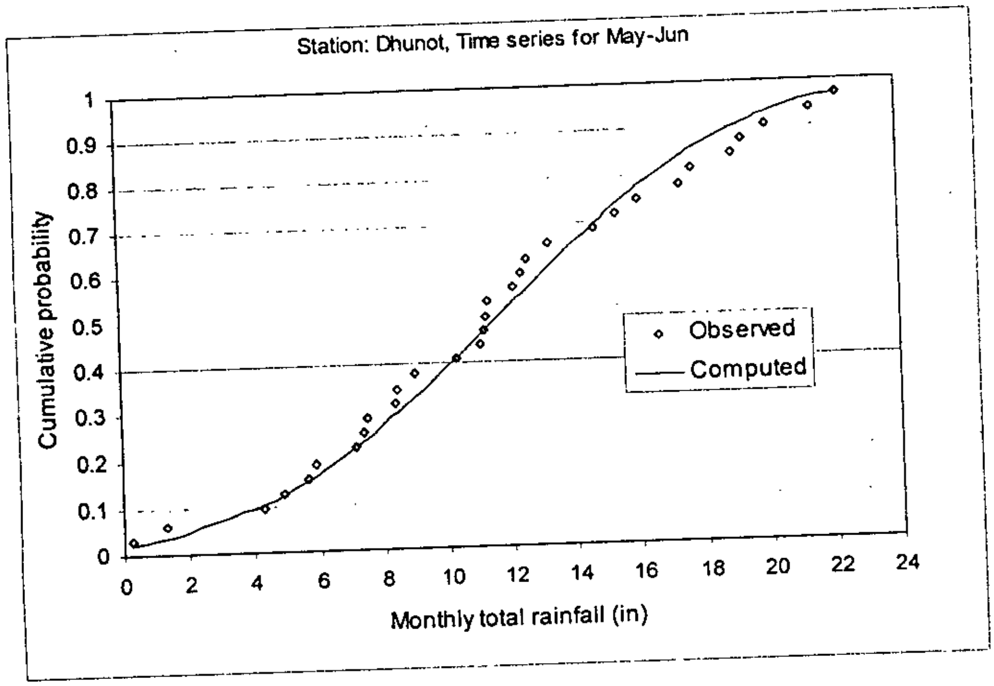


Figure A 4.1 Cumulative probability plot of Weibull distribution (continued….)



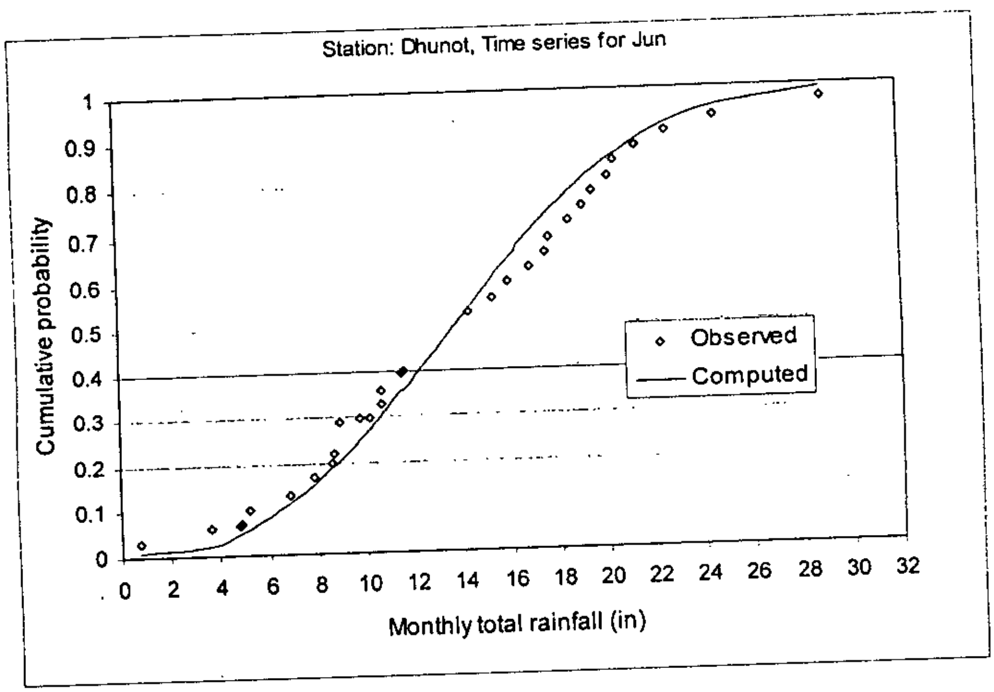
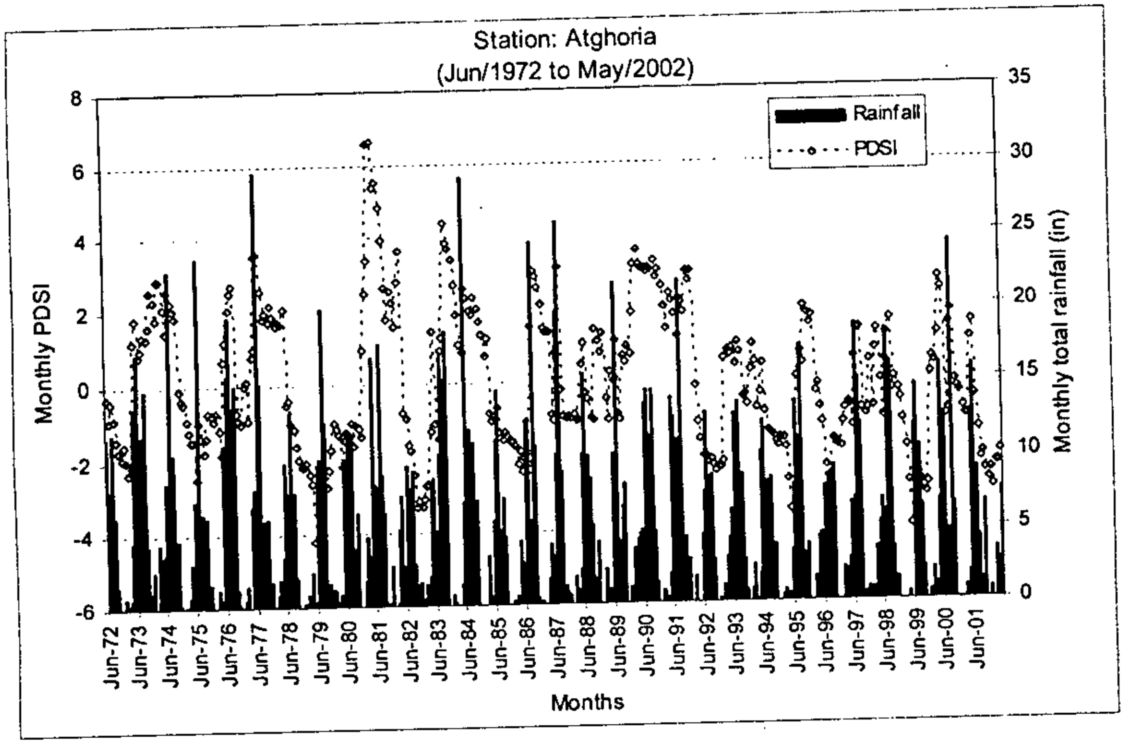


Figure A 4.1 Cumulative probability plot of Weibull distribution (continued....)

Appendix V
TIMESERIES OF MONTHLY RAINFALL AND PDSI OF NORTHWEST REGION



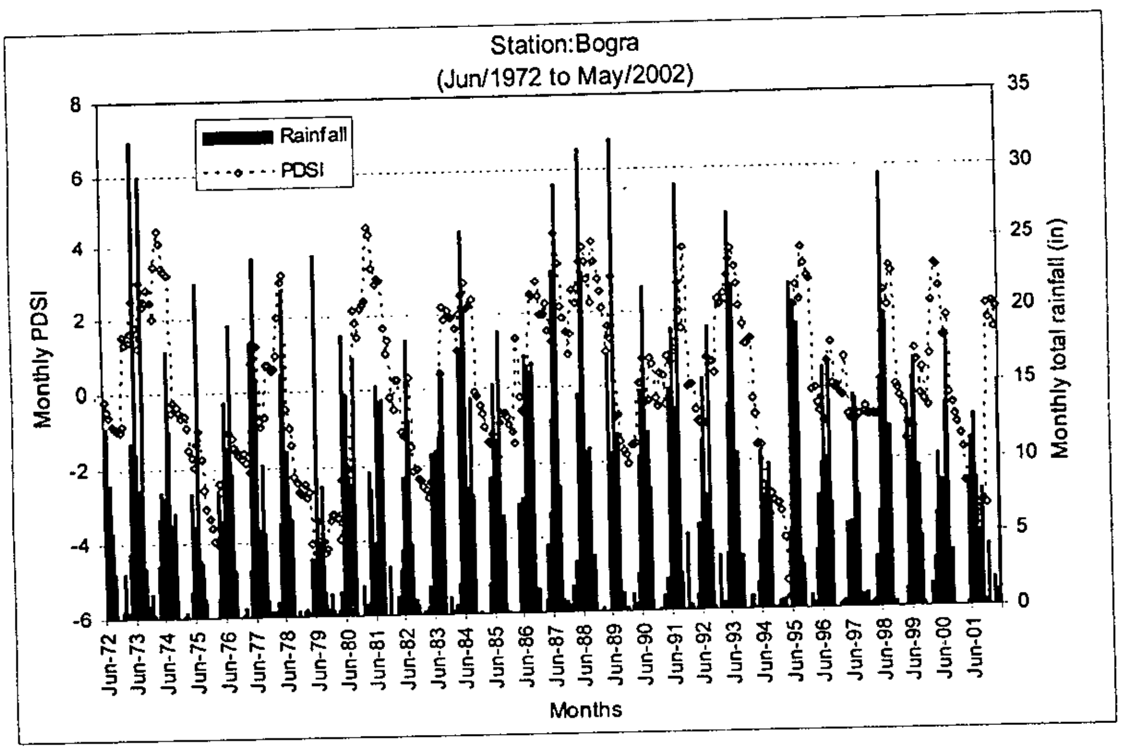
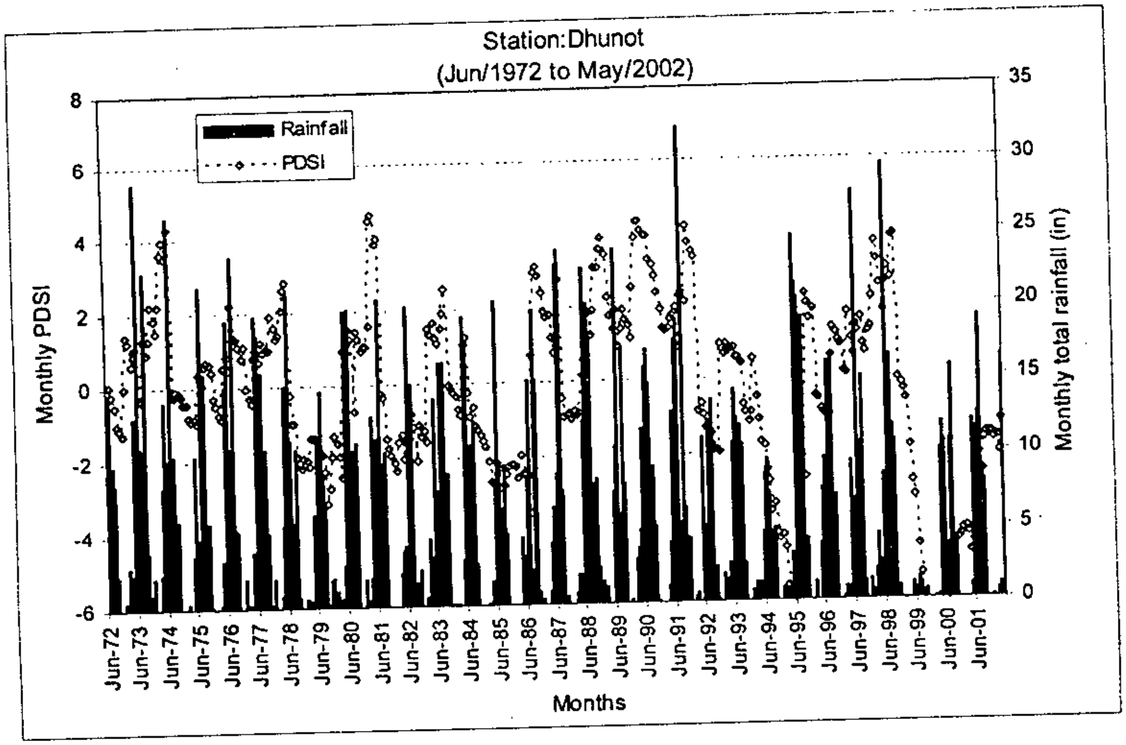


Figure A 5.1 Time series of monthly rainfall and PDSI of NW region



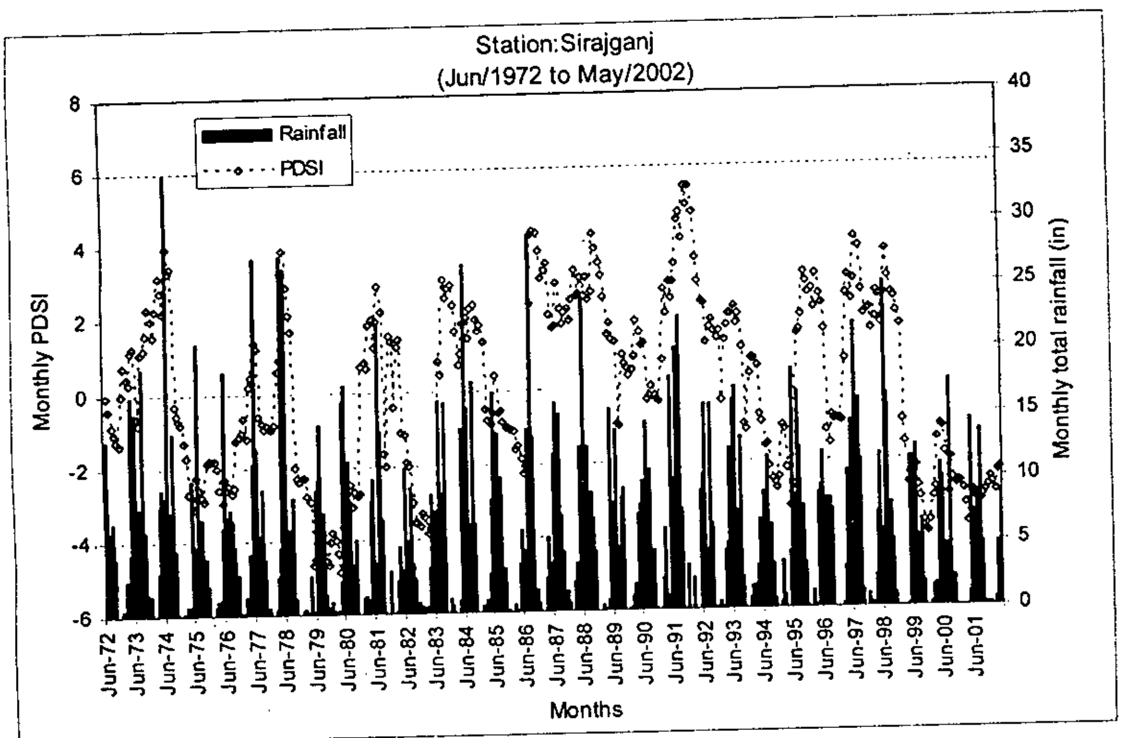
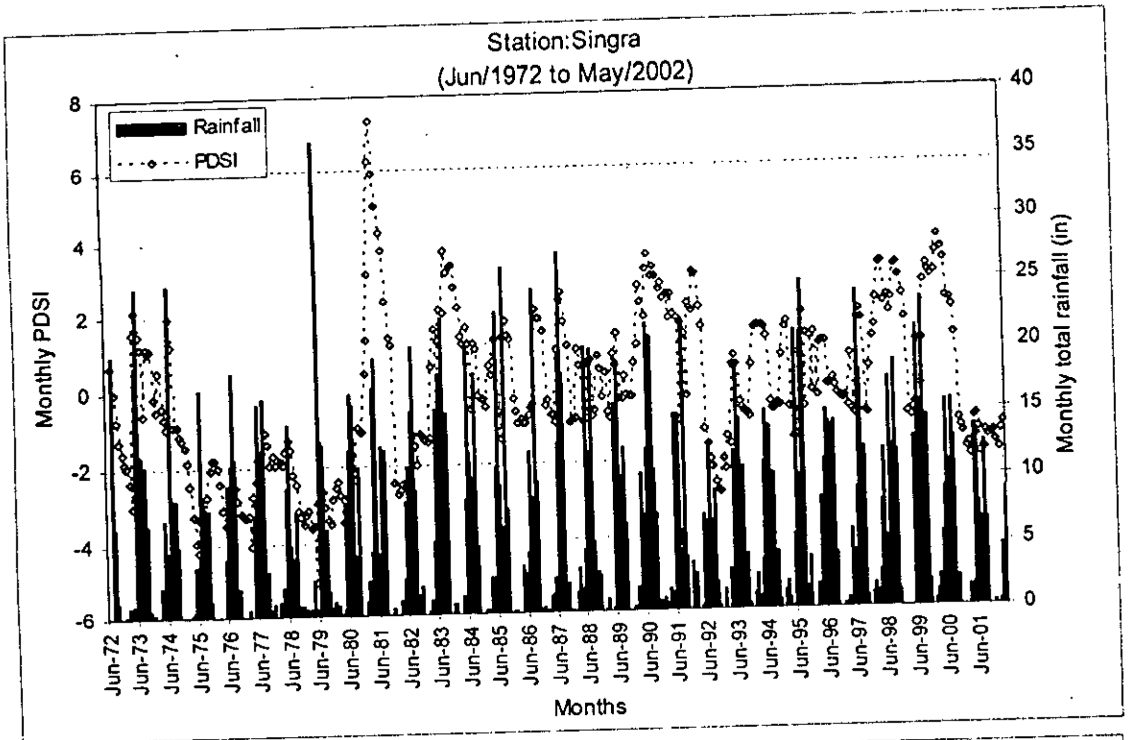


Figure A 5.1 Time series of monthly rainfall and PDSI of NW region (continued)



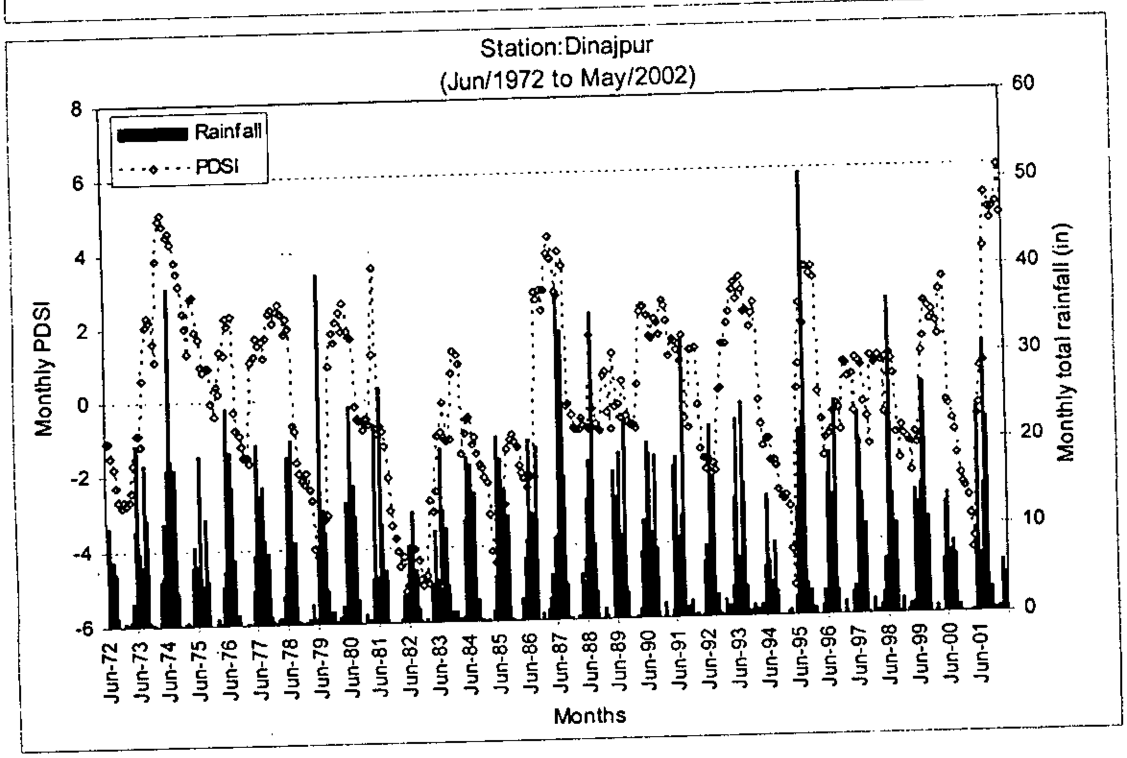


Figure A 5.1 Time series of monthly rainfall and PDSI of NW region (continued)

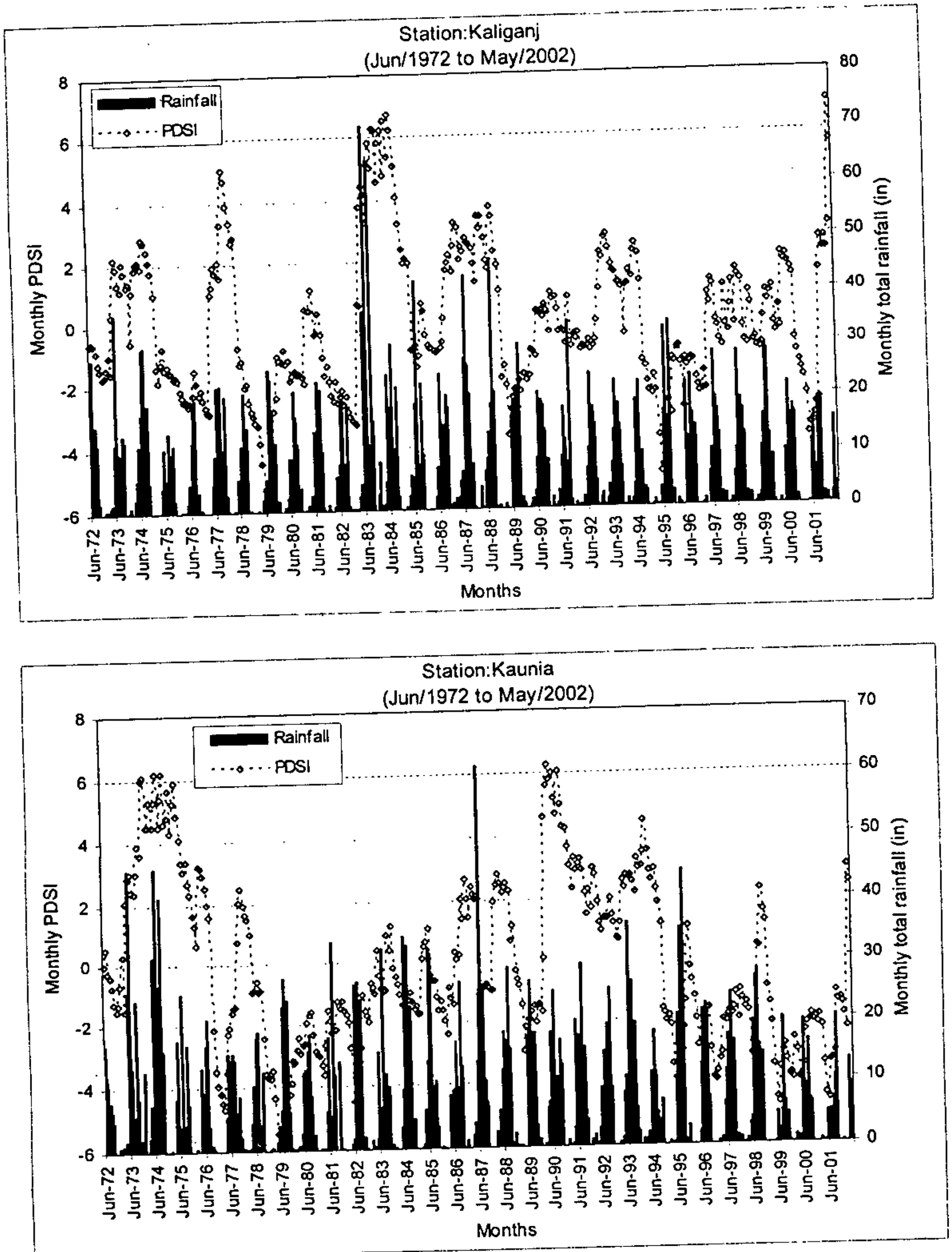
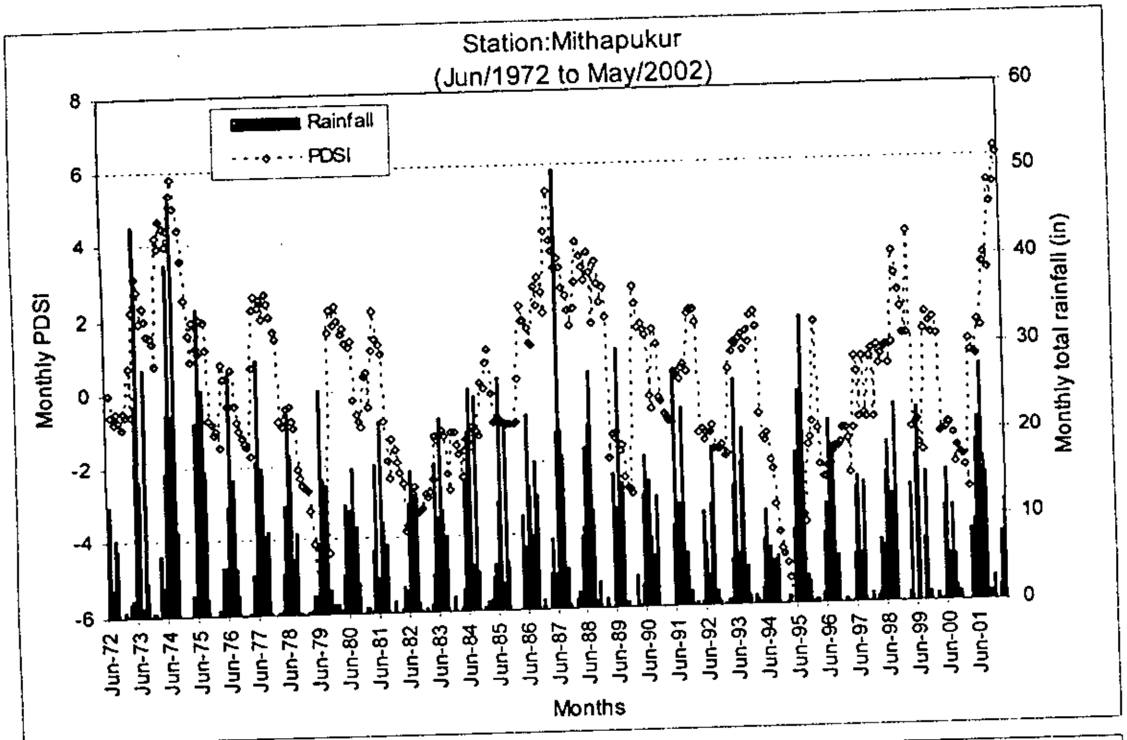


Figure A 5.1 Time series of monthly rainfall and PDSI of NW region (continued)



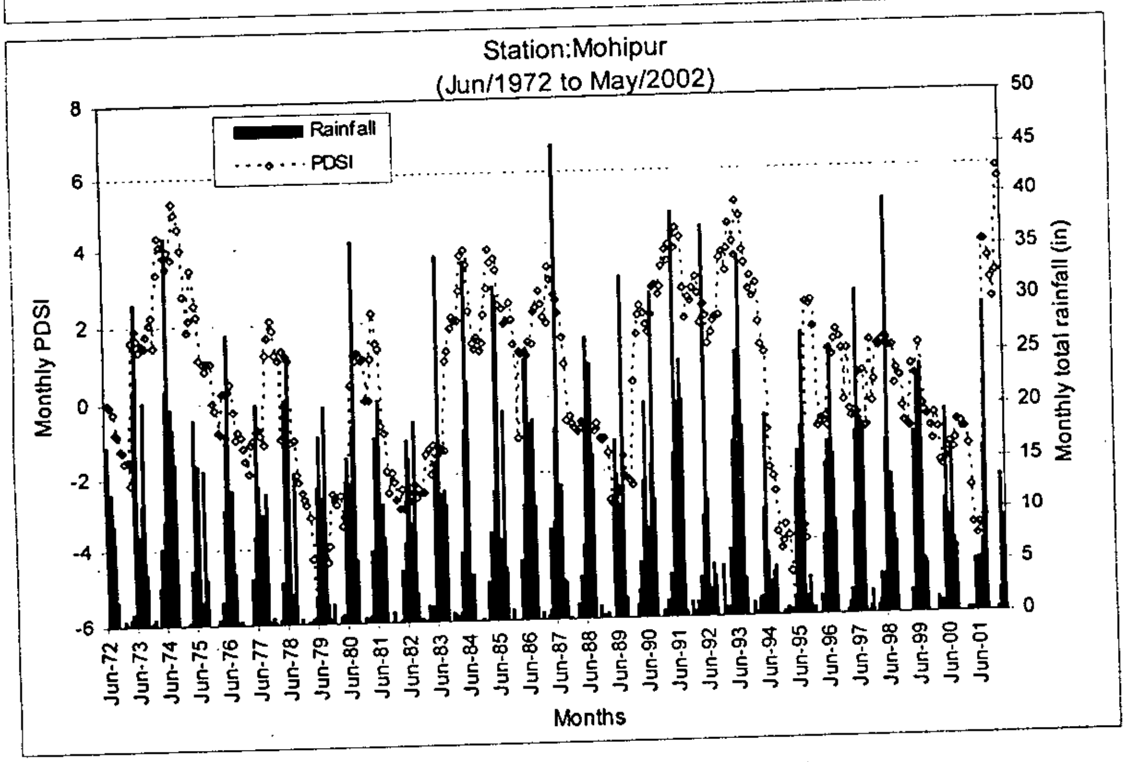
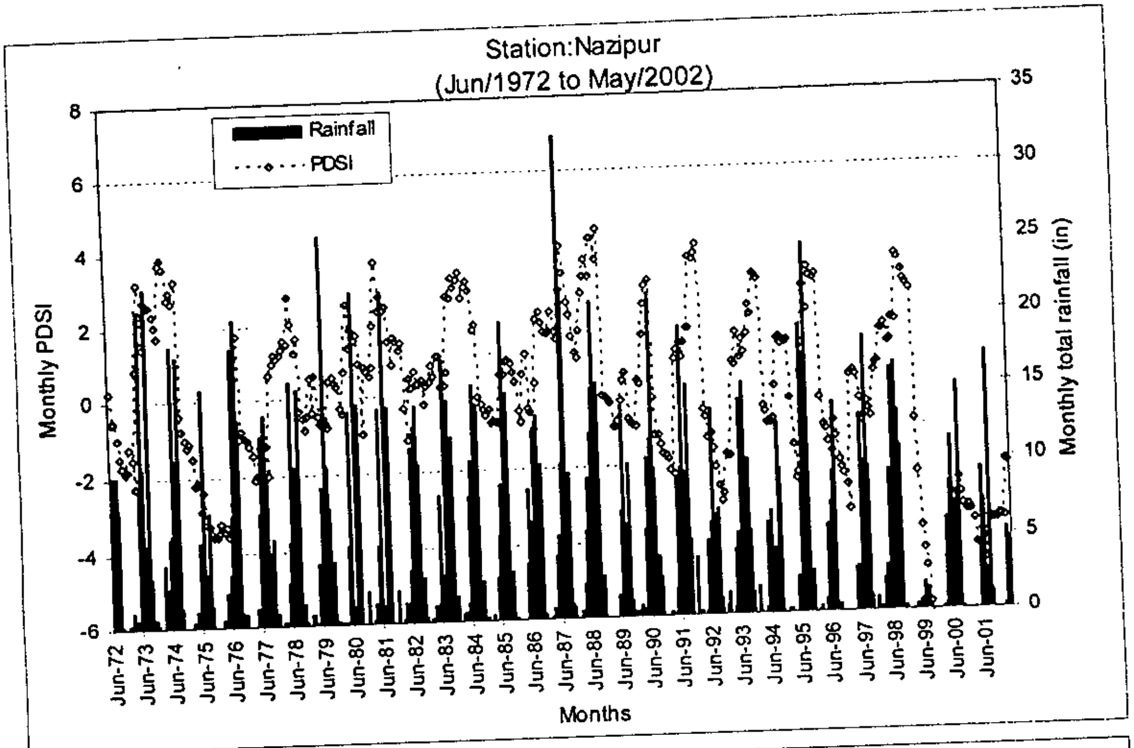


Figure A 5.1 Time series of monthly rainfall and PDSI of NW region (continued)



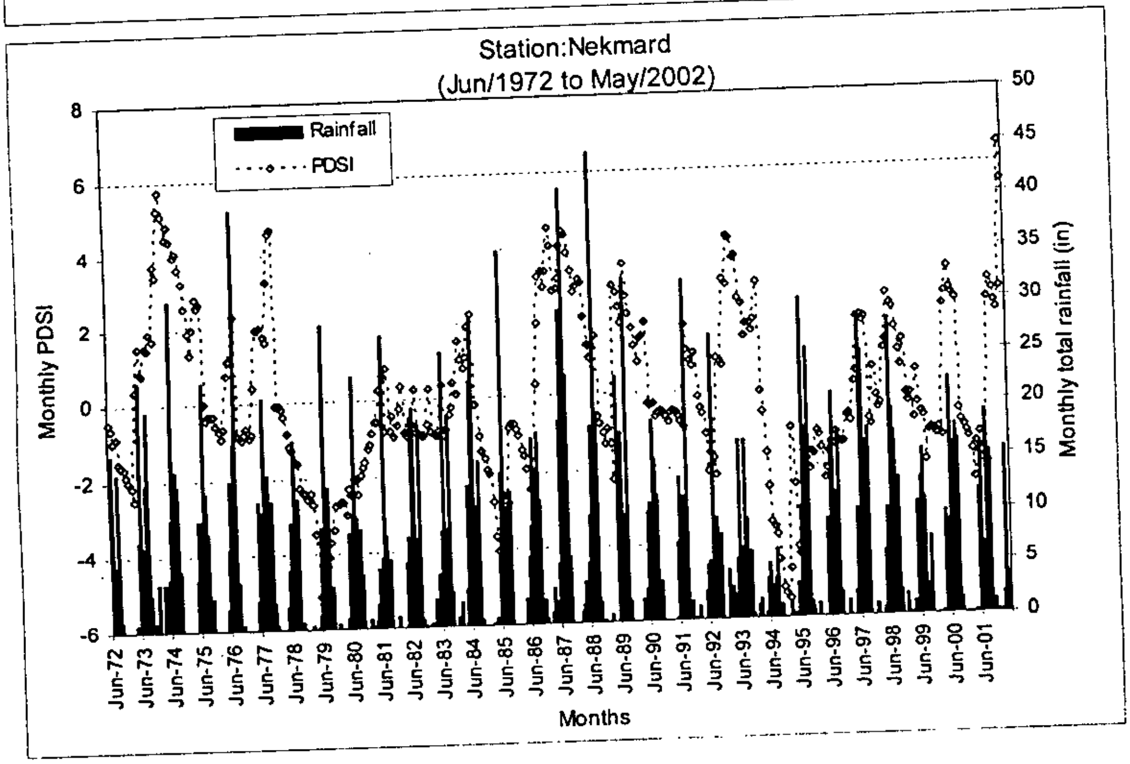
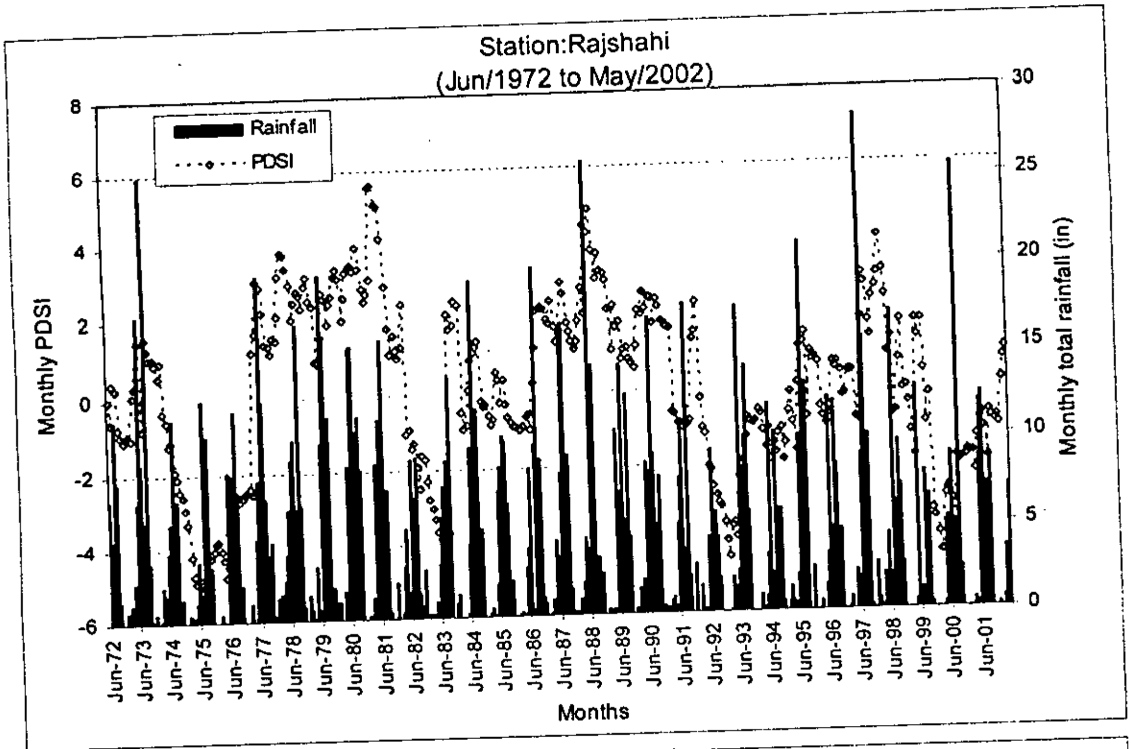


Figure A 5.1 Time series of monthly rainfall and PDSI of NW region (continued)



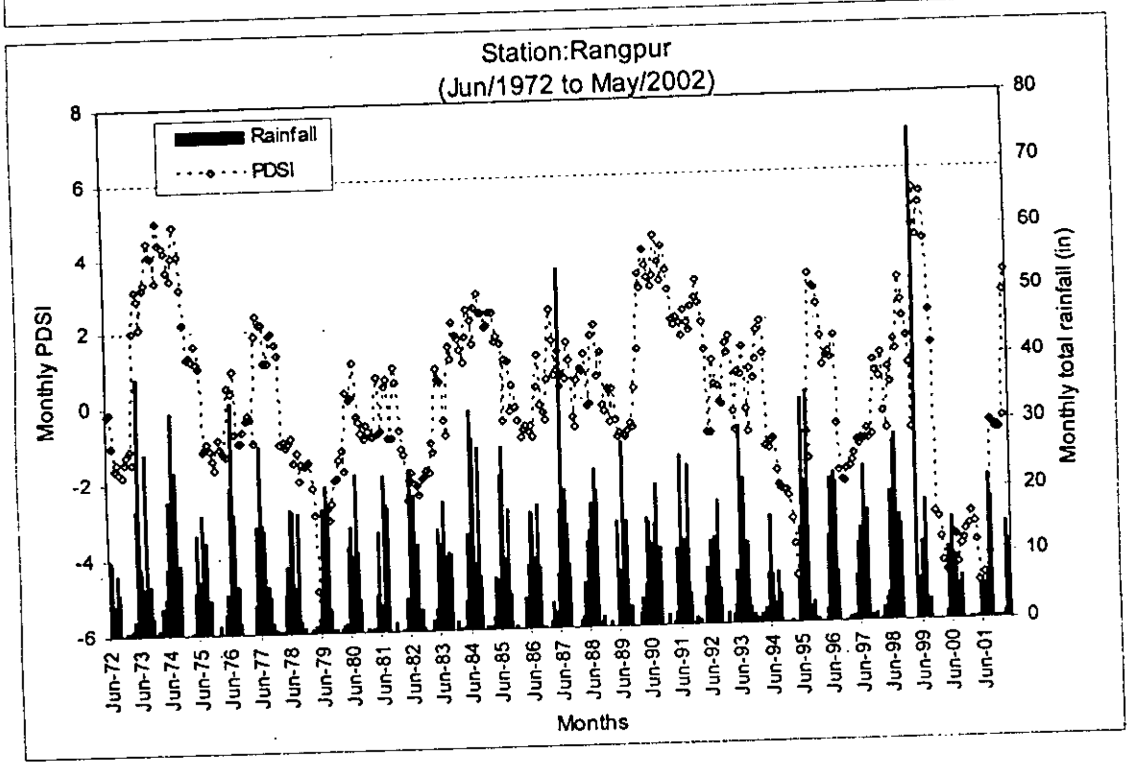


Figure A 5.1 Time series of monthly rainfall and PDSI of NW region (continued)

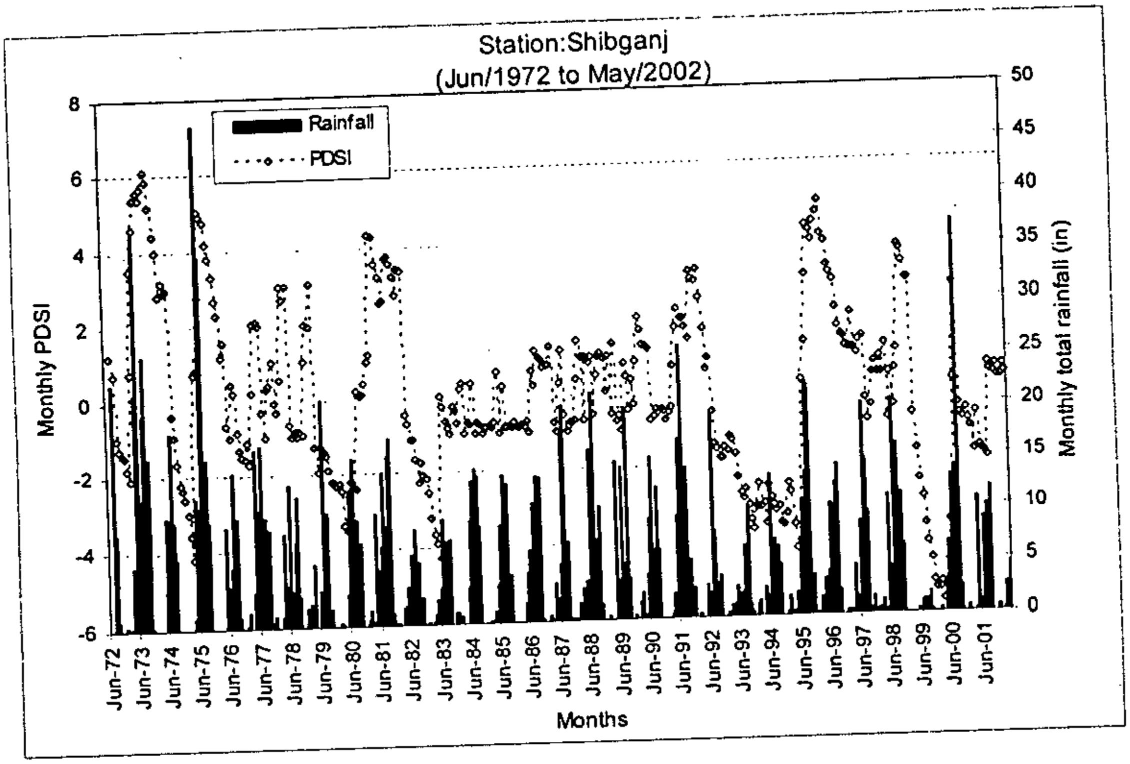


Figure A 5.1 Time series of monthly rainfall and PDSI of NW region (continued)