STUDY OF REGIONAL DROUGHT CHARACTERISTICS AND ENVIRONMENT

Ph.D. THESIS

by

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DEPARTMENT OF WATER RESOURCES DEVELOPMENT & MANAGEMENT
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE - 247 667 (INDIA)
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A THESIS

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ROORKEE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "**STUDY OF REGIONAL DROUGHT CHARACTERISTICS AND ENVIRONMENT"** in partial fulfilment of the requirement for the award of the Degree of Doctor of Philosophy and submitted in the Department of Water Resources Development and Management of the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period from July, 2013 to January, 2018 under the supervision of Dr. S. K. Mishra, Professor, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee and Dr. R. P. Pandey, Scientist-G, National Institute of Hydrology, Roorkee.

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

(KUMAR AMRIT)

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

(S. K. Mishra) Supervisor	(R. P. Pandey) Supervisor

The Ph.D Viva-Voce Examination of Kumar Amrit, Research Scholar, has been held on…………..

Chariman, SRC	**Signature of External Examiner**

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Signature of Supervisor (s)	**Head of the Department**

Dated:

ABSTRACT

Water is regarded as the important natural resource for the well-being of Society and existence of life on the earth. Increasing population and industrialization reduces the water supply for agricultural and domestic purposes. Major reason of reduced water supply is lack of precipitation, which leads to effect the usual social, economic and developmental activities of that region. When there is prolonged shortage of water supply or the occurrence of rainfall lower than the average for a given region then it is said to be drought. Among all the natural hazards droughts are the most severe around the globe, occurring in every region and spreads over lager area than earthquake and floods. The recent studies on hydrologic extremes indicate that even after advancement in technology every region in the world is susceptible to ill-effects of droughts. In India droughts are very frequent which results in loss of about ten millions of lives over the period of 18th, 19th, and 20th centuries. The agriculture in India is heavily dependent on the rainfall especially the rainfall from the south west monsoon. The monsoon failure leads to the reduced water supply and reduction in the crop yield. Keeping this in mind, the study focuses on the behavior of regional meteorological drought characteristics (i.e. frequency, severity and its duration) across the different climatic regions of India and its relationship with the various climatic parameters. In this study, long-term rainfall data of 113 years (1901-2013) of 516 districts of India located in different climatic regions has been used. In India, mean annual rainfall (P) ranges from 100 mm at Jaisalmer in Rajasthan to 4700 mm at Tamenlong in Manipur and the mean potential evapotranspiration varies from 1340 mm in Kottayam, Kerala to 2664 mm at Jaisalmer (in Rajasthan). In India, about 80-90% of the annual rainfall occurs during the monsoon (rainy) season and the deficit during the monsoon season of a year usually continue till the arrival of next monsoon season. Therefore, in this study the seasonal rainfall departure from corresponding long term mean has been used to identify the drought years and its severity. The analysis revealed that the average return period of drought can be described using the climatic parameters in terms of ratio of average annual potential evapotranspiration to average annual rainfall (PET/P). The average return period of drought and its severity have notable related to the PET/P ratio. The average return period of drought increases gradually from dry to wet regions, from 2-3 years in the arid regions ($12 > PET/P \geq 5$), 4-6 years in the semiarid regions ($5 > PET/P \geq 2$) and 6-9 years in the sub-humid regions ($2 > PET/P \geq 3/4$) and 10 years or more in humid regions. The arid and semiarid regions are more vulnerable to severe and frequent drought events than the areas in the sub-humid and humid regions. The areas with PET/P ratio of less than or equal

to 1.5 has much rare chance of occurrence of severe drought events. In the regions with PET/P ratio less than 1.5, the occurrence of extreme droughts are almost none. Further, the more frequent and persistent droughts occur in arid and semi-arid regions than in the other climatic regions. This study can be used as a sensible tool for prediction of regional drought characteristics and to sensitize the drought response system for proactive planning based on long term regional pattern.

The study has been also carried out to explore the relationship of drought frequency and severity with the range of annual temperature variation. From the analysis of a large set of meteorological data in India from various climatic regions, the frequency and severity of meteorological droughts are found to be strongly related with the range of annual normal temperature variation (θ_R). The average drought frequency and severity increase with increase in θ_R, and vice versa. Specifically, parts of Gujarat and of Rajasthan and Gujarat States falling under arid climatic region (where θ_R varies in the range of 40 °C to 35 °C) faced droughts once in every three years and the maximum rainfall deficiency had been 70% or more. The semiarid regions which include central and south-west parts of India where θ_R varies from 35 °C to 30 °C have the average drought frequency of once in 4-6 years with more number of severe drought events. The places with θ_R ranging from 30 to 25 °C and 25 - 20 °C experienced droughts once in 6-9 and 9-14 years with maximum severity in the range of 57% to 45% and 45% to 35%, respectively. Regions $\theta_R < 20$ °C generally experienced moderate droughts once in 14 years or more.

Further, in this study, Standardized Precipitation Index (SPI) popularly known for drought monitoring using rainfall data coupled with Tennant method widely used for describing the environmental flow (EF) condition of a river in terms of percentage of average annual flow (%AAF) using the flow data during low and high flow season. For the conservation of natural and healthy ecosystem, minimum amount of good quality water, also known as environmental flow (EF), has to be preserved in rivers for their survival. For low flow season, the rainfall-runoff data of three catchments of Mahanadi basin (viz. Ghatora, Kurubhata and Salebhata); two catchments of Brahmani-Baitarini basin (Anandpur and Jaraikela); two catchments of the Godavari basin (Hivra and Nandgaon), and four catchments of Narmada basin (viz. Mohegaon, Manot, Hridaynagar and Sher) has been used. For high flow season, the rainfall-runoff data of five catchments of Mahanadi (viz., Salebhata, Ghatora, Kurubhata, Rampur and Simga), nine catchments of Godavari (viz., Hivra, Jagdalpur, Kumhari, Nandgaon, Nowrangpur, Penganga, Ramakona, Sardaput, Satrapur), one catchment of Brahmani-Baitarini basin (i.e. Anandpur), and one catchment of Tapi basin (i.e.

Burhanpur) were used. The analysis reveals the existence of strong relationship between the two enabled EF prediction for even ungauged watersheds using SPI (rather than %AAF) derivable from more easily available rainfall data only. The suggested approach can be used to describe the environmental flow conditions during high and low flow season using easily available rainfall data only, useful for ungauged catchments.

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(Kumar Amrit)

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviation/ Symbol	**Description**
%	Percentage
°	Degree
°C	Degree Centigrade
$	United States Dollar
€	Euro
θ_{Hmax}	Highest value of normal maximum temperature during the year
θ_{Lmin}	Lowest value of normal minimum temperature during the year
θ_{R}	Range of annual normal temperature variation
F	Frequency of drought
T	Average return period of drought
%AAF	Percentage of average annual flow
AAF	Average annual flow
API	Antecedent Precipitation Index
AVHRR	Advanced Very High Resolution Radiometer
AWC	Available water content
BBM	Building Block Method
CMI	Crop Moisture index
CSDI	Crop Specific Drought Index
DECI	Drought exceptional circumstance index
DI	Deciles index
DSIe	Drought Severity Index
DVI	Drought Vulnerability Index
GIS	Geographic Information System
EDI	Effective Drought Index
EF	Environmental flow
EFA	Environmental flow assessment
EFR	Environmental flow requirement
ENSO	El Nino-Southern Oscillation
ESI	Evaporative Stress Index
FDAM	Flow Duration Analysis Method
FDC	Flow duration curve
HSC	Habitat Suitability Criteria

Abbreviation/ Symbol	**Description**
IFIM	Instream Flow Incremental Method
IHA	Indicators of Hydrologic Alterations
IIP	Island of Ireland Precipitation
IMD	India Meteorological Department
IPCC	Intergovernmental Panel on Climate Change
JDI	Joint Deficit Index
MAF	Mean Annual Flow
MAI	Moisture adequacy index
NDVI	Normalised Difference Vegetation Index
P	Mean annual Precipitation
PDI	Perpendicular Drought Index
PDSI	Palmer drought severity index
PEI	Precipitation effectiveness index
PET	Average annual potential evapotranspiration
POF	Percent of Flow
RAI	Rainfall Anomaly Index
RDI	Reconnaissance Drought Index
RS	Remote sensing
RVA	Range of Variability Approach
SDI	Streamflow Drought Index
SPEI	Standardized Precipitation Evapotranspiration Index
SRI	Standardized Runoff Index
SSFI	Standardized Streamflow Index
SST	Sea surface temperatures
SVI	Standardized Vegetation Index
TCI	Temperature Condition Index
VCI	Vegetation Condition Index
VHI	Vegetation Health Index
VSWI	Vegetation Supply Water Index
VTI	Vegetation Temperature Index

CHAPTER 1

INTRODUCTION

1.1 DROUGHT

Drought is a natural calamity occurring due to less than normal rain falling over a given period of time at a given space, and consequently, leading to short-term water deficit and economic loss. Among all the natural hazards droughts are the most severe around the globe, occurring in every region and spreads over lager area than earthquake and floods (Wilhite and Glantz, 1985; Tallaksen and Van Lanen, 2004). The recent studies on hydrologic extremes indicate that even after advancement in technology every region in the world is susceptible to ill-effects of droughts. For instance, the European heat waves in 2003 reduced the agricultural production (Parry, 2007). The severe drought events during 2011-2012 over half of the United States, Korean Peninsula and Eastern Africa have put the region into the disaster zone category (Dutra et al., 2012; Karl et al. 2012; Mosley, 2012; USDA, 2012). Droughts are the most complex climatic hazard, mainly due to difficulty in identifying their onset and termination (Wilhite, 1993). A drought is defined by different people according to their subject of interest. For instance, to a meteorologist it is the absence of rain while to an agriculturist it is the deficiency of soil moisture in the crop root zone to support crop growth and productivity. To a hydrologist it is the lowering of water levels in lakes, reservoirs, etc. while for the city management it may implies the shortage of drinking water availability (Tallaksen and Van Lanen, 2004). A drought is an adverse environmental phenomenon that affects almost all aspects of society. It is a normal feature of climate and its occurrence is inevitable (Wilhite 2000; Rosenberg and Verma, 1978). A drought may significantly affect the crop yield, plants, and animals and create hardship for the society in terms of huge loss of wealth and lives. Droughts also significantly affect the economy of a country. For instance, the damage of 1988 drought on the US economy has been estimated as $40 billion, which is around 2–3 times the estimated loss caused by the 1989 San Francisco earthquake (Riebsame et al., 1990). In addition, drought is a recurring theme in Australia, with the most recent, the so called ‘millennium’ drought, now having lasted for almost a decade (Bond et al., 2008). The drought in year 2006 was very severe. The estimated reduction in national winter cereal crop was 36%, costing rural Australia by around AUD $3.5 billion and putting many farmers in financial crisis (Wong et al., 2009).

The droughts in past few decades in Europe, Australia, United States and Asia have become more severe and frequent due to change in climate (Wilhite and Hayes, 1998; Changnon et al., 2000; Demuth and Stahl, 2001; Bond et al., 2008; Feyen and Dankers, 2009). The recent study done by the Intergovernmental Panel on Climate Change indicates that the increasing deficiency of water, increase in temperature, rising frequency of El Niño events and decrease in rainy days are the major factors which reduces the production of rice, wheat and maize over the major part of Asia in last few decades (Bates et al., 2008). In years 1997, 1999 to 2002 frequent severe droughts were observed, leading to large economic and societal losses in a large area of northern China (Zhang, 2003).

In India, droughts occur frequently and these are mainly confined to the peninsular and western part of the country (Madhusoodanan and Eldho, 2015). Besides there are also some drought prone areas in other parts of the country as well. The drought prone area spread over 300 districts and about 60% of the population of the country gets affected by drought at one or other time in the country.

1.2 ENVIRONMENTAL FLOW

For the conservation of natural and healthy ecosystem, minimum amount of good quality water, also known as environmental flow (EF), has to be preserved in rivers for their survival (Poff et al., 2009). EF is maintained in streams for sustainability of aquatic lives and a lack of it may affect the whole ecosystem (Brisbane Declaration, 2007; Wang and Lu, 2009). Thus, EF is necessary to carry out the needs of animal, vegetation, and aquatic lives which depend on the river water for their sustenance.

The socioeconomic development and climate change have affected the global hydrological cycle, threatening human water security, the health of aquatic environment, and river biodiversity largely during past few decades (Vörösmarty et al., 2010; Jacobsen et al., 2012; Van Vliet et al., 2013). These situations alert for assessment of environmental flow requirement (EFR) and water scarcity (Vörösmarty et al., 2010; Kirby et al., 2014). Thus, EFR is defined as the quality, quantity, and timing of the water flows required for maintaining estuarine ecosystems and human livelihoods and well-being that depend on these ecosystems (Brisbane Declaration, 2007). More than 240 methods are available and being used worldwide to calculate EFR to maintain healthy rivers (Tharme, 2003). These methods can be grouped into four categories: hydrological, hydraulic rating, habitat simulation, and holistic methods.

The long-term data on river flows measured at different points for a stream are often required for application of the simplest hydrological methods. These methods assume a relationship between flow and specific biological parameters. Some of the commonly used hydrological methods for the assessment of EFR are: Tennant (1976) method, BC-Instream flow threshold method (Hatfield et al. 2003), Alberta desktop method, flow duration curve methods, Shifting flow duration curve (FDC) technique etc.

The assessment of Environmental flow is very important for the survival of the healthy ecosystem. All the methods developed for the assessment of environmental flow condition of the catchment required flow data. It is quite difficult to estimate the environmental flow condition in ungauged catchments where flow data is not available. Therefore, some index should be developed which can be used for the assessment of EF condition of catchment using the easily available rainfall data instead of flow data, useful for ungauged catchment.

1.3 MOTIVATION OF THE STUDY

Droughts have a wide range of effects on the masses in a developing country like India. The impact of droughts is specifically conspicuous in view of the tropical monsoon character of the country. Rainfall by the south-west monsoon is notorious for its vagaries. Out of India’s total geographical area about 1.07 million km^2 area is subjected to different degrees of water stress and drought conditions (Mishra et al., 2007).

Meteorological drought adversely affects the recharge of soil moisture, surface runoff and ground water table. Soils dry up, surface runoff is reduced and ground water level is lowered. Rivers, lakes, ponds and reservoirs tend to dry up wells and tube-wells are rendered unserviceable due to lowering of the ground water table. Indian agriculture still largely depends upon monsoon rainfall where about two-thirds of the arable land lack irrigation facilities and is termed as rainfed. The effect is manifested in the shortfalls of agricultural production in drought years. Severe shortage of food-grains had been felt and the country had to resort to import of food-grains to save the poor people from hunger and starvation. The north western and peninsular regions are susceptible to more frequent droughts. The plateau region covers the States of Andhra Pradesh, Bihar, Chhattisgarh, Gujarat, Haryana, Karnataka, Maharashtra, Madhya Pradesh, Orissa, Rajasthan, Tamil Nadu, West Bengal and Uttar Pradesh. In Rajasthan alone, 56% of its area and 33% of population fall under critically drought prone areas. The corresponding figures in Andhra Pradesh are 30% of area and

20% of population, in Gujarat 29% of area and 20% of population and in Karnataka 25% of area and 22% of population.

The drought characteristics vary with climatic conditions. Therefore, a detailed study of drought frequency, severity and duration is needed, to understand their relationship with the common climatic parameters and variation in their behavior in different climatic regions, to cope up with the severe drought impacts.

1.4 OBJECTIVES OF THE STUDY

1. To identify the most important variables affecting the drought characteristics.
2. To analyze the regional meteorological drought characteristics.
3. To study the relationship among climatic factors and regional drought characteristics.
4. To study the relationship among the temperature variation range and frequency and severity of droughts.
5. To relate Standardized Precipitation Index with Tennant method for the prediction of environmental flow condition using rainfall.

1.5 ORGANIZATION OF THESIS

The thesis are arranged as follows

Chapter 1: This chapter describes the subject background and objectives of the study.

Chapter 2: This chapter includes the literature reviewed related to drought assessment, classification, drought characteristics, relation between drought characteristics and climatic parameters, and environmental flow.

Chapter 3: This chapter describes the information related to the study area and the various data used for the accomplishment of the research objectives.

Chapter 4: This chapter deals with detailed study of regional meteorological drought characteristics (i.e. frequency, severity and persistence) and its relationship with climatic parameters in different climatic region. This Chapter may enhance understanding and ability to cope with adverse impacts of droughts on the society.

Chapter 5: This chapter discuss the relationship of temperature variation range during the year with the average frequency of occurrence of drought and magnitude of severity at a given place.

Chapter 6: This chapter explains the coupling of Tennant concept with Standardized Precipitation Index for the prediction of environmental flow condition during low flow season (October-June) using the data of eleven catchments from the four different river basins (viz. Mahanadi, Godavari, Brahmani-Baitarini and Narmada) of India.

Chapter 7: This chapter covers the exploration of SPI based method for environmental flow prediction during high flow season (July-September) using the data of sixteen catchments located in four different river basins (i.e. Mahanadi, Godavari, Brahmani-Baitarini and Tapi)

Chapter 8: This chapter summarises and concludes the study besides incorporating major research contribution and providing scope for future work.


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CHAPTER 2

REVIEW OF LITERATURE

2.1 GENERAL

Drought is a natural phenomenon in which the available water for a region is less than that under usual conditions for an extended period of time and leads to the economic loss (Yadav et al., 2014). The drought may persist for weeks, months and years. The economic loss caused by drought is the relatively more than of any other natural hazards and severely effects farming, water resources, environment and human lives (Anderson et al., 2000; Wilhite, 2000; Bryant, 2005). It may occur in almost every region in the world even in wet and humid climatic regions (Dai, 2011). The studies of past 50 years indicate that there has been significant increase in the affected area and damage during droughts (Zhang et al., 2012).

The severity along with the frequency of the drought events has increased in recent years because of climate changing due to global warming (Dai et al., 2004; Sheffield et al., 2012; IPCC, 2013). The increasing population coupled with the changing climate increases the water demand due to which the frequency and severity of drought events are likely to increase (Smith and Katz, 2013; Trenberth et al., 2014, Trinh et al., 2017). Droughts affect both surface and groundwater resources due to which there is reduction in supply of water, lowering of water quality, failure of crop, reduced range productivity, diminished power generation and also affect the economic and social activities (Riebsame et al., 1991). The change in hydrologic conditions due to fluctuation in climate have the significant effect on the lean season water availability and water chemistry which ultimately reduces the water quality (Webster et al., 1996).

2.2 DROUGHT AROUND THE WORLD

About 50% of earth’s terrestrial land are drought prone which covers the major portion of agricultural land in arid, semi-arid and sub-humid regions (Gol’tsberg 1972; Kogan, 1997). The severe drought events have been experienced over the large area of Europe, Australia, Asia, Africa, Central America, South America, and North America in last few decades (Le Comte, 1995; Le Comte, 1994) and huge social and economic loss leads to increasing the interest of the researchers to droughts (Downing and Bakker, 2000). About 2.8 billion people have been suffered due to natural hazards during 1967-1991, out of which droughts affected half of them (Kogan, 1997). During 1967 to 1991 the direct and indirect effect of droughts led to death of about 1.3 million people (Song et al., 2004).

North America

The increase in the number and severity of drought events significantly increased the ill-effects of droughts in the United States during the years 1980-2000 (Wilhite and Hayes, 1998; Changnon et al., 2000). For instance, the total loss during 1988 drought in the US has been estimated to be $40 billion, which is 2–3 times the total loss caused by the 1989 earthquake in San Francisco (Riebsame et al., 1990). The data available with the National Climatic Data Center, USA (2002), shows that the severe and extreme drought events in the last century affects about 10% of the total land surface of the United States. Out of 58 natural disasters in the United States during the period 1980 to 2003, 10 were due to droughts (Ross and Lott, 2003). Droughts (17.2% of the total) alone accounted for $144 billion (41.2%) of the estimated $349 billion total cost of all weather-related disasters (Ross and Lott, 2003). Economically droughts are the most expensive natural hazards to hit the United States (Cook et al., 2007). The major part of Canada have faced droughts due to high spatial and temporal variation in precipitation. The Canadian Prairies are more susceptible to drought (Environment Canada, 2004). Western Canada has faced about 40 long duration droughts in past two centuries. The persistent drought events were observed during 1890s, 1930s, and 1980s in southern part of Alberta, Saskatchewan, and Manitoba (Phillips, 1990; Wheaton, 2000). In 2001, the aggregate level of the Great Lakes plunged to their lowest points in more than 30 years, with Lake Superior and Lake Huron displaying near record lows (Mitchell, 2002).

Europe

The drought becomes more severe in major part of the Europe (Demuth and Stahl, 2001). For example, Lehner et al. (2006) has done the combined study of probable effects of changing climate on future drought and flood frequencies for particular regions in Europe. The potential of global integrated water model WaterGAP to simulate low and high flow regimes was evaluated and then it was applied to estimate the relative changes in the frequencies of drought and flood. The results indicated large ‘critical regions’ for which significant changes in flood or drought risks might be expected under proposed global change scenarios. The northern to north-Eastern Europe are most susceptible to increase in the frequency of flood, while there is significant increase in the frequency of drought in southern and south eastern part of the Europe. There will be an increase in the average precipitation and its variability is expected to be more for northern regions, suggesting higher flood risks, while less rainfall, prolonged dry spells and increased evaporation may increase the frequency of droughts in southern areas (Watson et al., 1997; EEA, 1999; Voss et al., 2002). Because of their large scale characteristics, droughts should be studied within a regional context (Demuth and Stahl, 2001; Tallaksen, 2000; Mishra and Singh, 2009).

In past 30 years a number of severe drought events have occurred in Europe and most severe events have occurred in in 1976, 1989, 1991 and a long duration drought over the major portion of the Europe in 2003 (Feyen and Dankers, 2009). The average economic loss in 1991 due to drought in Europe has been estimated to be €5.3 billion and the damage of the 2003 drought in Europe costs about €8.7 billion (European Communities, 2007).

Asia

In the recent study of IPCC it has been found that the temperature and frequency of El Niño events increased with less number of rainy days which partly increases the water stress and leads to reduction in the production of wheat, rice and maize in major parts of Asia in last few decades (Bates et al., 2008). For examples, the persistent drought during 1999–2000 affected about 60 million people from Central and Southwest Asia. The severe and frequent droughts in many areas of northern China in 1997, 1999 to 2002 caused huge economic loss (Zhang, 2003). The total agricultural land affected by droughts were estimated to be more than 40 million hectares in 2000. The rural and urban area both are affected by water shortage, desertification and dust storms due to the droughts. For example, there were 20 years during which the Yellow River experienced zero flow (drying up) during the period of 1972–1997, since in early 1990s the onset and longer periods of the drying up have become more frequent. The longest drying up period of 226 days have been observed with no flow in the Yellow River during severe drought event of 1997 in northern China. The increase in global warming increases both temperature and drying in late 1970s which leads to the increased risk of droughts (Zou et al., 2005; Dai et al., 2004). India is one of the most vulnerable country to drought in the world; in India over the past five decades average frequency of drought has been reported to be once in three years. What is of concern is its increasing frequency. Since the mid-nineties, prolonged and widespread droughts have occurred in consecutive years, while the frequency of droughts has also increased in recent times (FAO, 2002).

Australia

In Australia droughts are normal recurring phenomenon as the variability in hydroclimatic condition of Australia is very high (McMahon et al., 1992; Love, 2005; Kirono et al., 2011; Stone, 2014). Gibbs and Maher (1967) suggested that the estimation of total rainfall to be the best drought indicator for Australia. The Federation drought (1895-1902), the World War II drought (1937-1945) and the recent drought (before 1995) are considered among the major drought events, and significantly affect the environment (Humphries and Baldwin, 2003; Bond et al., 2008) and economical condition of Australia (Productivity Commission, 2008; Kirono et al., 2011). For instance, there was loss of about 30 million sheep during the World War II drought (1942-1945) (BoM, 2009) and the reduction of about 30% was observed in agricultural production of southeast Australia during droughts during years 1994, 2002 and 2006 (ABARE, 2008). The most recent drought, called 'millennium' drought, (2001-2009) have lasted for almost a decade (Bond et al., 2008). Since European settlement this is the worst drought that has affected major portion of Eastern and Southern Australia (Murphy and Timbal, 2007), with very low flows in many rivers during this period and sometimes flow becomes below 40% than previous records (Murray-Darling Basin Commission, 2007). There were reduction in the cereal crop by 36% during 2006 drought and the loss estimated by the Australian Bureau of Agriculture and Resource Economics was about AUD $3.5 billion which creates financial crisis to most of the farmers (Wong et al., 2009).

According to the Bureau of Meteorology, the future rainfall is likely to reduce by 3-5% over Australia (CSIRO, BoM, 2007). In addition to this, the temperature is supposed to increase by one degree Celsius which subsequently raise the potential evaporation for 2-6 percent by 2030. The drought in 2002-2003 shows that the drought event can be more severe not because of low rainfall, likely due to the increase in temperature (Nicholls, 2004), leading to the inference that severity of drought event in future will be more due to the relatively warm climate.

Africa

In West Africa, the Sahel—a semiarid region between the Guinea coast rainforest and Sahara desert has faced a drought of extraordinary severity in the late 1960s. The devastating effect of drought events on this region was a major reason for the establishment of the United Nations Convention on Combating Desertification and Drought (Zeng, 2003). The drought frequency at the end of 19th century have increased in the region. Three long duration drought events significantly affect the society and environment of the Sahel nations. The severe droughts were followed by Famine in the 1910s, the 1940s, and the 1960s, 1970s and 1980s, although a partial recovery occurred during 1975–1980. Since the 1600s at least one severe drought must occurred in each century, the recent drought in Sahel becomes more severe and frequent. It also caused great damage in terms of more permanent social and economic disorganisation and migration on a massive scale to towns or other regions, an increased dependency on foreign aid and food relief. At the peak of the crisis, in April-June, 1974, there were some 2,00,000 people entirely dependent on food distribution in Niger (Batterbury and Warren, 2001).

2.3 DEFINITIONS OF DROUGHT

In literature drought has defined in many ways. Drought has no single definition which could be accepted everywhere (Wilhite, 1993; Kavvas and Anderson, 1996; Ponce et. al. 2000, Zhang et al., 2012). The definitions of drought can be classified into conceptual and operational definitions (Wilhite and Glantz, 1985). Conceptual definitions describes drought and its effects in relative to normal conditions, it does not give information about onset, termination and severity of drought events. The operational definitions of drought facilitate to identify the onset, severity and termination of drought events. The various drought definitions discussed in literature are as follow: Hoyt (1938) defined the drought for humid and semi humid regions as the year with the annual rainfall less than 85% of the mean annual rainfall. Ramdas and Malik (1948) said a month to be drought month if it receives less than or equal to 50% of the normal rainfall. Drought is defined as the period with low rainfall, low relative humidity, high temperature and strong wind (Condra 1944). Palmer (1965) defined an event to be drought event as circumstances when the actual rainfall is lower than the rainfall necessary for the existing climatic conditions. The period with less than the average rainfall is drought (National Commission on Agriculture 1965). When there is deficiency of more than 25% of average rainfall in consecutive 4 weeks during the period of May to October is classified as meteorological drought (National Commission on Agriculture 1976). A period of fifteen consecutive days without 2.54 mm of rainfall is said to be absolute drought (Herbst et al. 1966). Yevjevich (1967) defined the droughts as the departure of rainfall from the mean.

A period of fourteen consecutive days with lowest average flow at a particular measuring point in a streamflow through a climatic year (starts on 1st April) is said to be drought (Joseph, 1970). Dracup (1980) discussed the drought as the shortage of streamflow from its long term median flow. The reduction in the soil moisture for a specific crop is defined as drought (World Meteorological Organization 1975). Van Bavel and Verlinden (1956) defined the drought as a day on which the soil moisture is less than the available soil moisture capacity. Drought is defined as the condition when there is lowering of soil moisture in such a way that there is no longer the absorption of water by the plants from soil (Shantz 1970).

2.4 DROUGHT CLASSIFICATION

In general, droughts are classified into four categories (Dracup et al. 1980; Wilhite and Glantz, 1985; American Meteorological Society, 2004; Mishra and Singh 2010; Zhang et al. 2013) which are as follow:

2.4.1 Meteorological drought: A drought is said to be meteorological drought if there is significant reduction of rainfall from normal over an area for a period of time (Santos, 1983; Eltahir, 1992; Mishra and Singh 2010; Zhang et al. 2013). Several studies have been carried out using the monthly precipitation data assuming drought as a deficiency of rainfall corresponding to its long-term mean (Pinkeye,1966; Gibbs, 1975; Chang, 1991; Vrochidou et al. 2013).

2.4.2 Hydrological drought: Meteorological drought, if prolonged, results in hydrological drought with marked depletion of surface water and consequent drying up of inland water bodies such as lakes, reservoirs, streams and rivers and depletion in water table. The identification and quantification of hydrological drought can be done using the flow data (Sen, 1980; Chang and Stenson, 1990; Mohan and Rangacharya, 1991; Zhang et al. 2012; Choi et al. 2013).

2.4.3 Agricultural drought: It occurs when soil moisture and rainfall are inadequate to support crop growth to maturity and cause extreme crop stress leading to the loss of yield.

2.4.4 Socio-economic drought: A Socio-Economic drought is associated with a deficiency of water needed to meet the demand of industrial and urban activities because of weather-related shortfall in water supply that directly affects the economy of the area.

In recent years a new category of drought is being discussed in literature, i.e. **“Environmental Drought”.** It is associated with a deficiency of water which effect sustenance of regional eco-system.

2.5 ASSESSMENT OF DROUGHT

Drought assessment involves analysis of spatial and temporal water related data. Several methods were developed to assess the drought quantitatively. Basically, droughts are assessed with reference to nature of water deficit, averaging period, truncation level and regionalization approach (Dracup et al 1980). Over the years, various indices have been developed to detect and monitor droughts and quantification of severity. The effects of drought often accumulate slowly over a considerable period of time; they may linger for several years after the drought period ends. As a result, the onset and termination of a drought are difficult to determine precisely and that is why a drought is often referred to as a creeping phenomenon (Mishra et al 2007).

2.6 DROUGHT INDICES

The information regarding the areal extent, severity and duration of a drought events are important factor to consider for proactive planning and mitigation strategies (Mishra and Singh, 2011). However, due to multiplicity of definitions discussed in previous section, it is difficult to arrive at unanimous acceptance of answer about the onset, duration and severity of drought (National Drought Mitigation Center, Nebraska, USA, 2000). Wilhite and Glantz, (1985) described another category of drought definition as operational definitions; these definitions identify the onset, termination, areal extent and severity of a drought. These definitions are based on scientific reasoning and are often region-specific, requiring the analysis of certain hydro-meteorological information. Operational definitions are formulated in terms of drought indices. These indices are useful for formulating the drought policies, systems for drought monitoring, drought awareness and mitigation plan. Depending upon the type of drought to be studies viz. meteorological, hydrological or agricultural drought, the indices are also classified as meteorological, hydrological and agricultural drought indices. The meteorological drought indices are based on the deficiency of rainfall or other climatic parameter, hydrological drought indices are based on the deficit streamflow in rivers and lakes/reservoirs and agricultural drought indices are based on the deficiency of soil moisture in the root zone.

In the early decade of the past century drought indices are focussed mainly on the region specific drought characterization. Munger (1916) developed the Index to monitor the forest fire risk from year to year in US. He considered the duration of drought as the number of consecutive days without

24-h rainfall of 1.27 mm. Marcovitch (1930) incorporated temperature along with precipitation to compute drought index. He defined the drought index as:

$$\text{Drought index} = {}^{1}/_{2}(N/R)^{2} \qquad (2.1)$$

Where, N is the total number of two or more consecutive days above 32.2°C (90°F), and R is the total summer rainfall for the same months.

Thornthwaite (1931) developed the precipitation effectiveness index (PEI), based on the principal that soil moisture availability depends upon the evaporation. Thornthwaite (1931) defined the PEI as the sum of the 12 monthly precipitation effectiveness ratios, where the ratio of monthly precipitation to monthly evaporation is said to the monthly effectiveness ratio.

Thornthwaite (1948) further suggested a drought index as the difference between precipitation and evapotranspiration. Antecedent Precipitation Index (API) (McQuigg, 1954) was originally derived to estimate soil moisture content for use in flood forecasting, computed on daily basis by multiplying the index for the previous day by a factor (0.90). Later on duration and amount of rainfall was introduced into API to be used as drought index. Later with the development of water budget accounting methods, it was possible to track the soil moisture availability in the soil profile. It was thought that agricultural drought begins only with the moisture inadequacies in the soil profile and not when the rainfall ceases. To address the idea of moisture adequacy, McGuire and Palmer (1957) developed the moisture adequacy index (MAI), as an outgrowth from the concept of potential evapotranspiration, comparing a location's moisture need to the actual moisture supply (rainfall plus available soil moisture). The moisture adequacy index is expressed as a percentage ratio of the actual moisture supply to the moisture need, where 100% indicates the supply is sufficient to meet the requirements.

Most of the above indices are developed on the basis of simplistic theory of region specific rainfall deficiencies occurred during the first half of the past century and these laid the foundation for more sophisticated techniques in the field of drought characterization during the later half of the past century. The advanced indices thus developed are subject specific, categorised as meteorological, hydrological and agricultural drought indices, based on the consequences of drought in different sectors.

2.6.1 Meteorological Drought Indices

Several studies have been carried out using precipitation as one of the climatic input for drought monitoring. Literature indicates that, many studies have been carried for drought monitoring, assuming drought as the deficiency of rainfall (daily, monthly, seasonal and annual) from the corresponding long term mean (Pinkeye, 1966; Santos, 1983; Chang, 1991; Eltahir, 1992; Sinha et al., 1992; Sant et al., 2015). Many studies have also been carried out using cumulative precipitation shortages to analyse drought duration and intensity (Chang and Kleopa, 1991; Estrela et al., 2000; Banik et al., 2015). A number of drought indices have been developed using precipitation singly or in combination with any other climatic parameter viz. Temperature, potential evapotranspiration etc. (WMO, 1975).

The various meteorological drought indices are: Palmer drought severity index (PDSI) (Palmer, 1965), Rainfall Anomaly Index (RAI) (Van Rooy, 1965), Decile Index (Gibbs and Maher, 1967), Bhalme and Mooly Drought Index (BMDI) (Bhalme and Mooley, 1980), Standardized Precipitation Index (SPI) (McKee et al., 1993), National Rainfall Index (NRI) (Gommes and Petrassi, 1994), Effective Drought Index (EDI) (Byun and Wilhite, 1999), China - Z Index (CZI) (Wu et al., 2001), Reconnaissance Drought Index (RDI) (Tsakiris and Vangelis, 2005), Drought Vulnerability Index (DVI) (Pandey et al., 2010), Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) etc.

Palmer drought severity index (PDSI; Palmer, 1965) is perhaps the first operational drought index, which was practically applied for monitoring drought in various drought watch systems in USA. It uses a soil moisture algorithm based on precipitation, temperature data and local available water content (AWC) of the soil. The PDSI was the first comprehensive effort for monitoring standardized moisture conditions over an area. It also allows comparison of estimates of moisture status between locations and different time periods.

Several applications of PDSI have been reported in literature for assessment of onset, severity and areal extent of drought events (Palmer, 1967; Karl and Quayle, 1981; Szinell et al., 1998; Kim et al., 2003; Van der Schrier et al., 2007; Dupuis, 2010; Zahradníček et al., 2015). PDSI has also been widely used for the spatio-temporal analysis of drought characteristics (Lawson et al., 1971; Karl and Koscielny, 1982; Diaz, 1983; Soule, 1993; Briffa et al., 1994; Jones et al., 1996; Loukas et al., 2002; González and Valdés 2003), monitoring hydrologic trends, crop forecasts, and assessing potential fire severity (Heddinghaus and Sahol, 1991; Makra et al., 2002; Mika et al., 2005; Horváth et al., 2010; Liu et al., 2012), droughts over large geographic areas (Johnson and Kohne, 1993), and drought forecasting (Kim and Valdes, 2003; Özger et al., 2009). In addition to these applications, some of the researchers modified PDSI for practical application in the field of water supply monitoring (Karl, 1986; Heddinghaus and Sahol, 1991). The detailed procedure for calculations of PDSI may be found in Palmer (1965) and in many subsequent publications (e.g., Alley 1984; Kim et al. 2002).

Gibbs and Maher (1967) developed rainfall deciles based drought index (RDDI) for investigating rainfall deficiency as per criteria set by the Australian Bureau of Meteorology. Deciles are computed from actual precipitation series. Initially, the rainfall values of each calendar month (or sum of rainfall values for a group of months for multiple time steps) are arranged in ascending order with the rank associated to each value and a cumulative frequency distribution is fitted. The distribution is then divided into 10 deciles (10% slices), where the wettest and driest months in the series are indicated by the first and last decile respectively. Deciles have been used in many drought indices evaluation studies (e.g., Keyantash and Dracup, 2002; Morid et al., 2006; Smakhtin and Hughes, 2007; Mpelasoka et al., 2008; Pandey et al., 2008; Dogan et al., 2012). The use of decile is advantageous due to simplicity in its computation. The applicability of deciles index indicated that it does not provide acceptable assessment of drought in India (Pandey et al., 2008).

McKee et al. (1993) developed Standardized precipitation index (SPI) to cater the need of monitoring drought in a variety of climatic conditions. This is the most widely used drought index and gained world-wide popularity during the past three decades. It is primarily a meteorological drought index and can be calculated for practically any time step i.e. 1-, 3-, 6-, 9-, 12-, 24-months etc. Because of its capability of calculating for multiple steps it is capable of addressing a variety of drought related phenomenon ranging from short term soil moisture deficiency to multi-monthly and multi-year water shortages leading to meteorological, hydrological and groundwater drought instances. This versatility of SPI makes it useful for varied climatic conditions. Various researchers used SPI for forecasting of drought (Mishra and Desai, 2005a; Mishra et al. 2007), frequency analysis (Mishra et al. 2009; Moradi et al., 2011; Yan-jun et al., 2012; Zhang et al., 2012; Piccarreta et al. 2004), spatio-temporal analysis (Bonaccorso et al. 2003; Edossa et al. 2010; Mishra and Singh, 2009; Masud et al., 2015). Bonaccorso et al. (2003) investigated the spatial variability of drought for the period of

70 years (1926-1996) using SPI, in Sicily. The results indicated that the drought characteristics varies across the Island with multi-year fluctuations and, 1970s onwards the Island experienced more severe and frequent drought.

Byun and Wilhite (1999) developed Effective Drought Index (EDI) to overcome the weaknesses of previously developed drought indices. EDI addressed the variety of issues like precise detection of onset and termination of drought. Based on the concept of effective precipitation this index considers the aggravating effects of runoff and evapotranspiration. Initially it is designed to calculate drought severity on daily time step. This enables rapid detection of drought and precise assessment of short-term drought. Also, it can be applied to compute monthly drought severity. Unlike other indices, it is based on time-dependent reduction factor. While other indices are based on deviation from central tendencies. EDI had effectively been applied in several studies across the globe (Yamaguchi and Shinoda, 2002; Papaioannou et al., 2005; Usman et al., 2005; Morid et al., 2006; Pandey et al., 2008; Ajayi and Olufayo, 2007; Smakhtin and Hughes, 2007; Marinaki et al., 2007; Akhtari et al., 2009; Kim et al., 2011; Dogan et al., 2012; Deo and Sahin, 2015). Pandey et al. (2008) demonstrated that the EDI could be used to monitor droughts conditions of India more effectively than other drought indices, including the SPI.

The indices viz. deciles index (DI), China-Z index (CZI), modified CZI (MCZI), percent of normal (PN), Z-Score, standard precipitation index (SPI) and effective drought index (EDI) were compared for drought monitoring in Iran using the data of 32 years. The comparison of the above indices shows that there is similar performance of SPI, CZI and Z-Score in drought identification and also respond slowly to drought onset Morid et. al. (2006). In addition, there are several other indices (Penman, 1948; Thornthwaite, 1948; and 1963; Bhalme and Mooley, 1980; Van Rooy, 1965; Keetch and Byram, 1968; Wu et al., 2001; Tsakiris and Vangelis, 2005; Pandey et al., 2010 etc.) which have been used in certain applications in different parts of the world.

2.6.2 Hydrological drought Indices

Hydrological drought is generally considered as the period during which surface and subsurface water supplies are inadequate to meet established demands under a given water-management system (Linsely et al., 1975). For hydrologic drought analysis generally streamflow data is used. Several studies have been carried out using streamflow data for the analysis of hydrological drought (Yevjevich, 1967; Gupta and Duckstein, 1975; Dracup et al., 1980; Sen, 1980; Shafer and Dezman, 1982; Zelenhasic and Salvai, 1987; Ben-Zvi 1987; Chang, 1987; Chang and Stenson, 1990; Frick et al., 1990; Mohan and Rangacharya, 1991; Clausen and Pearson, 1995; Hisdal and Tallaksen, 2003; Tallaksen and Van Lanen, 2004; Beersma and Buishand, 2004; Pandey et al., 2008; Shukla and Wood, 2008; Nalbantis and Tsakiris, 2009; Vasiliades and Loukas, 2009; Edossa et al. 2010; Hannaford et al. 2011; Lorenzo-Lacruz et al. 2010; Vidal et al. 2010).

Yevjevich (1967) proposed theory of runs for assessment of hydrological drought on the basis of deficiency of streamflow with respect to the long term mean value as the truncation level. The excess or deficit for a month is the difference between the actual streamflow of a month and the long term mean value for that month. In this method, the streamflow data is plotted as a continuous time series. The truncation level (long term mean value) will separate the excess and deficit periods. The run length is defined as the distance between two successive points on the truncation line where the series switch from one side to other. The run length between two successive downcross and upcross is termed as the duration of drought. The run sum is defined as the sum of the negative deviations, which is the drought severity. Several studies have been done using the run theory for the analysis of local and regional characteristics of drought (Guerrero-Salazar, 1975; Paulo et al., 2003) and for drought prediction (Moye et al., 1988; Sen, 1989). The run theory have been also used for the drought characterisation in Mediterranean regions (Santos, 1983; Rossi et al. 1992; Henriques and Santos, 1999; Cancelliere and Rossi, 2002). Dracup (1980) applied the theory of runs for assessment of hydrological drought based on the deficiency of streamflow with the long term median value as the truncation level. The excess or deficit for a month is the difference between the actual streamflow of a month and the long term median value for that month. The months with deficit values are assessed as hydrologic drought periods. The severity of a drought event is the cumulative streamflow deficits occurring continuously.

Modarres (2007) used the Standardized Streamflow Index (SSFI), statistically similar to SPI (McKee et al., 1993) for hydrological drought assessment. The SSFI for a given period is defined as the difference of streamflow from mean divided by standard deviation as shown in Eq. 2.2.

$$SSFI = \frac{F_i - \overline{F}}{\sigma} \tag{2.2}$$

Where, F_i is the flow rate in time interval i, $\overline{F}$ is the mean of the series and σ is the standard deviation of the series.

Shukla and Wood (2008) proposed the Standardized Runoff Index (SRI) for hydrologic drought analysis on a similar concept as that of SPI for meteorological drought assessment. A suitable probability distribution is fitted to the sample represented by the time series values. Cumulative probability is estimated from the probability distribution. Then this cumulative probability is converted to a standard normal deviate (with zero mean and unit variance). SRI has more applicability than SPI as it incorporates hydrologic and meteorological processes that influence the volume and timing of streamflow. The drought duration is defined as the number of months for which the SRI value is below zero and the severity is the cumulative sum of the SRI values for that particular drought event.

Pandey et al. (2008) developed the Drought Severity Index (DSIe) for assessment of streamflow drought severity. They defined the DSIe as a function of the ratios of (1) deficit flow volume to corresponding volume of the truncation level and (2) duration of deficit flow to the maximum possible duration of the independent streamflow drought event (= 365 days). The DSIe can be described using Eq. 2.3.

$$DSIe = \frac{V_d}{V_{TL}} X \frac{d_e}{d_m} \qquad (2.3)$$

Where, V_d is the deficit streamflow volume for the duration of drought event, V_{TL} is the expected streamflow volume at truncation level flow for the duration of drought event, d_e is the duration of independent drought event, and d_m is the maximum duration of an independent drought event. The hydrologic droughts severity can be categorised as mild, moderate, severe or extreme depending upon the value of DSIe.

Nalbantis and Tsakiris (2009) developed Streamflow Drought Index (SDI) for computation of streamflow drought severity. The SDI has the same theoretical background as that of SRI (Shukla and Wood, 2007) because they derive the hydrological drought index by transforming monthly streamflows into z-scores.

2.6.3 Agricultural drought indices

The soil moisture is very sensitive parameter for agricultural crops. Therefore, the soil moisture in the root zone is generally estimated for the monitoring of agricultural drought. The soil moisture deficit can cause crop failure without support of surface water resources. There have been significant impact on the yield due to the deficiency in soil moisture at different growth stages of the crop (Narasimhan and Srinivasan, 2005). The yield can be reduced by 25%, if the deficiency in water during the pollination stage of corn becomes 10% (Hane and Pumphrey, 1984). A decline of soil moisture depends on several meteorological and hydrological factors including differences between actual evapotranspiration and potential evapotranspiration. However, plant water requirements depend on prevailing weather conditions and biological characteristics of the specific plant and soil.

In India, the India Meteorological Department (IMD) used Aridity Anomaly Index (I_a) as an indicator for monitoring of agricultural drought. Aridity index is based on the Thronthwaite's approach to describe water deficiency experienced by plants and is estimated as the percentage ration of annual water deficit to annual potential evapotranspiration (Thronthwaite and Mather, 1955). Aridity Anomaly Index is the deviation of value of aridity index from normal expressed as percentage. If the value of I_a is upto 25% it is termed as mild drought and if value exceeds 50% it is referred as severe drought condition and in between 26% to 50% it is called moderate drought Based on the values of I_a weekly aridity anomaly maps are published by IMD. These aridity anomaly maps are useful in monitoring of agricultural drought and the deficit of moisture faced by the rising plants.

The various agricultural drought indices used for drought monitoring are: Crop Moisture index (CMI) (Palmer, 1968), Soil Moisture Drought Index (Hollinger et al., 1993), Crop Specific Drought Index (CSDI) (Meyer and Hubbard, 1995), Vegetation Condition Index (VCI) (Liu and Kogan, 1996), Soil Moisture Deficit Index (Narsimhan and Srinivasan, 2005) etc. Sohrabi et al. (2015) developed a Soil Moisture Drought Index (SODI) for drought characterization. The results indicated that SODI can detect and quantify the extended severe droughts associated with climate variability and change. Many researchers have used the agricultural drought indices for drought characterization (Palmer, 1968; Meyer and Pulliam, 1992; Narasimhan, 2004; Narasimhan and Srinivasan 2005; Penalba et al., 2007; Dutra et al. 2008; Hunt et al. 2009; Dorigo et al., 2012; Llano et al., 2012;Todisco and Mannocchi 2013; Sohrabi et al. 2015)

2.6.4 Drought indices based on remote sensing

Prediction and strength to deal with natural hazards is an important part of natural resource management and sustainable development. For long term planning to mitigate the adverse impact of drought, it is needed to monitor drought at finer spatial and temporal scales. This needs water related information frequently over a larger region. With the advent of Geographic Information System (GIS) and Remote sensing (RS) technology, it is now possible to monitor larger areas at much finer time periods (Pandey et al., 2009). The important data required for macro level studies can be captured frequently by remote sensing upto large areal extent. GIS can be used as a tool for handling the spatial data and spreading the information among the users. Various researchers have used the capabilities of RS and GIS for monitoring vegetation condition to assess drought.

The advent of Earth observation satellites from the 1980s facilitated the use of optical sensors for drought monitoring and detection. This sophisticated satellite data driven technology paved the way for derivation of truly spatial information at global or regional scale and at a high repetition rate. Several indices were developed to describe the state of the land surface, mainly of vegetation, with the potential to detect and monitor anomalies such as droughts (Gray and McCrary 1981; Tarpley et al. 1984; Justice et al. 1985; Tucker and Sellers 1986; Tucker et al. 1987; Liu and Kogan, 1996; Pandey et al., 2003). It is considered that satellites provide timely and better coverage of spatial information arising out of the drought conditions. There are several indices which have been developed based on satellite data.

Various important information related to present drought situation can be extracted by the spatial interpolation of values of drought index. There may be high variability in values, as the interpolation process affected by many factors. Therefore, the use of remote sensing for the monitoring of drought, by extracting meteorological and biophysical characteristics of terrestrial surfaces, has attained more attention (Rhee et al., 2010). Remote sensing is particularly useful for monitoring of drought in the areas where there is inadequate sampling gauges. It provides alternate approach for drought monitoring over a large region. The remote sensing methods used to monitor moisture condition of soil and vegetation stress rather than the precipitation, which makes this method different from most of the existing methods (Choi et al., 2013).

The various remote sensing based drought indices are: Normalised Difference Vegetation Index (NDVI; Tucker, 1979), Vegetation Health Index (VHI; Kogan, 1997), Vegetation Supply Water

Index (VSWI; Carlson et al., 1990), Vegetation Condition Index (VCI; Kogan, 2002), Evaporative Stress Index (ESI; Anderson et al., 2007) Perpendicular Drought Index (PDI; Ghulam et al., 2008) etc.

Normalized Difference Vegetation Index (NDVI; Tucker, 1979) is the most prominent satellite data based index for drought monitoring. NDVI is calculated as:

$$NDVI = \frac{(NIR - \mathrm{Re}\,d)}{NIR + \mathrm{Re}\,d} \qquad ....$$

Where, NIR and R represents reflectance in near infrared and red regions of an electromagnetic spectrum. The values of NDVI vary between -1 to +1. The higher NDVI value corresponds to the regions having higher rates of evapotranspiration that represent dense vegetation, permeable soil and considerable soil moisture. The smaller NDVI value represents the regions having less evapotranspiration rates which signifies the region with bare ground or less vegetative cover, relatively impermeable soils and low soil moisture (Nagarajan 2003).

Tarpley et al. (1984) computed the normalized vegetation index using the Advanced Very High Resolution Radiometer (AVHRR) on NOAA-7 for monitoring the vegetation condition. Tucker and Choudhury (1987) applied NDVI for drought monitoring. This triggered the development of several other drought indices such as Vegetation Condition Index (VCI; Kogan, 1990, 1995), the anomaly of the NDVI called NDVIA (Anyamba et al., 2001), or the Standardized Vegetation Index SVI (Peters et al., 2002).

In addition to the information derived from the optical domain, the thermal channels of Landsat Thematic Mapper (TM) and the Advanced Very High Resolution Radiometer (AVHRR) sensors were also exploited, resulting in the retrieval of land surface temperature estimates (LST). Applying the thermal channels to drought monitoring, Kogan (1995) proposed the Temperature Condition Index (TCI). Most promising was the final combination of optical and thermal information into the Vegetation Temperature Index (VTI) or Vegetation Health Index (VHI) by Kogan (1997, 2000).

Sancho et al. (1981) done the statistical analysis of historical droughts to characterize the drought behaviour in Mexico. The drought events during the period from 1500 B.C. to 1978 were analysed. A statistical analysis for rainfall is also presented. Annual data were analyzed for 1-, 2-, 3-, and 5-yr. periods.

Hisdal and Tallaksen (2003) done a case study in Denmark for regional meteorological and hydrological drought characteristics. A new approach was proposed to find the possibility of a specific region to get affected by a drought of given magnitude of deficit and its efficacy was checked to find both the meteorological and hydrological droughts. The comparison of drought characteristics indicates that hydrological droughts are less homogeneous over the area, less frequent and its duration is longer than meteorological droughts. Edossa et al. (2010) analysed the characteristics of drought using the hydro-meteorological parameters in Awash River basin of Ethiopia. The spatio-temporal analysis of meteorological drought has been done using SPI, and hydrological drought was defined by the run theory using runoff as an indicator. The analysis indicated that in Middle and Lower Awash River Basin droughts were very frequent and severe.

Wilhite et al. (2007) studied the hazardous impacts of drought, an important factor to enhance the preparedness and its mitigation. The study shows that, this is very important information to convince policy and other decision makers of the need for additional investments in drought monitoring and prediction, mitigation, and preparedness. Kalamaras et al. (2010) used the daily rainfall data of several station located at different places in Greece for the assessment of drought. In order to detect the drought at these stations, a series of drought indices were computed. The results indicated that the severity of drought in the region has an increasing trend.

Mihajlovic (2006) analyzed the meteorological drought using SPI at four different timescales (i.e. 1, 3, 6 and 12 months) during 2003-2004 at 32 stations in Pannonian part of Croatia. The results indicated that SPI at multiple timescales can be used to identify onset and termination of drought events in Pannonian part of Croatia. Moradi et. al. (2011) investigated the characteristics of meteorological drought for Fars province in Iran. In this study effort has been made to predict the frequency, magnitude of deficit, duration and its extent in the Fars province using Standardized Precipitation Index at 5 time scales of 3, 6, 12, 24 and 48 months from 26 stations within and outside of the province. The maps of extent of drought in the province were prepared with the help of Geographic Information System (GIS). The analysis indicated that the southern part of the province has higher intensity drought and it lasts longer than anywhere also in the province while the effects of drought were not significant in northern region.

Yan-jun et. al (2012) studied drought evolvement characteristics based on standardized precipitation index (SPI) in the Huaihe river basin. They analyzed the annual drought index for the year 1961-

2010 using SPI. The data used in the research was the precipitation data obtained from the 35 meteorological station in the basin. The study indicated that in beginning of 21st century the severity and frequency of a drought event get increased with subsequent decrease in area affected by drought. In addition to this, the frequency of mild and moderate droughts in the basin are relatively more than severe drought events.

Mirabbasi et. al. (2013) analyzed meteorological drought in northwest Iran using the Joint Deficit Index (JDI). The JDI was calculated using the precipitation data for the period from 1970 to 2007 for the study. The analysis revealed that complete assessment of drought can be done by using JDI. The amount of precipitation needed to attain the usual condition of the place can be determined by using JDI. In addition to above the JDI is also capable of estimating probability of exceedance of the precipitation data required to achieve the normal condition. The analysis shows that the onset of drought can be predicted with more accuracy.

2.7 DROUGHT FREQUENCY

Drought is most hazardous natural disaster (Wilhite, 2000; Bryant, 2005) which effect both human lives and natural environment, leading the water managers to be concerned about the estimation of frequency and probabilities of occurrence (Mirakbari et al., 2010). The hydrological extremes are generally expressed in terms of their return period (Kim et al., 2003). Haan (1977) defined return period of drought, as the average time between the events of certain magnitude or less. In literature, several methods are discussed for the computation of return period of droughts (Chung and Salas 2000; Pandey et al., 2001; Kim et al., 2003). Fernandez and Salas (1999a,b) estimated the return periods and assorted chance of failure of hydrologic events linked to meteorological droughts, annual maximum floods, low flows, and hydrological droughts, which are either dependent or independent. The probabilities of occurrence and return periods, and risks of drought events for dependent hydrologic processes were studied (Chung and Salas, 2000; Kim et al., 2003). A realistic approach for analysing the frequency of multilayer drought duration of annual flow series was developed (Lee et al., 1986; Kim et al., 2003). A large number of studies have been done on the definition, return period and climatic impacts of drought events (Smakhtin 2001; Kim et al., 2003).

For investigating the variability of droughts (spatial and temporal) regional frequency analysis of annual maximum streamflow drought has been done for three different regions of New Zealand (Clausen, and Pearson, 1995). Lee et al. (1986) suggested an approach for the return period of multiyear drought of annual streamflow series. The suggested methodology was tested on the historic droughts of Feather River, California. The result shows that the observed nine-year drought of Feather River has the return period of 360 years. The monthly precipitation data for the period of 46 years (1951-1996) has been used for the analyzing the spatiotemporal relationship of occurrence of droughts and its severity over Korea and East Asia. The study indicated that in Korea during 1980s the frequency of drought get increased, and it ranges between 2-3 and 5-8 years (Min et al., 2003). Kim et al. (2003) estimated the return period of droughts by conducting the drought frequency analysis for Conchos River Basin in Mexico. This analysis revealed that the return periods of the severe drought events occurring in the 1990s are 100 years or higher for univariate analysis, and 50 years for bivariate analysis. Mirakbari et al. (2010) suggested the regional bivariate frequency analysis of meteorological drought in Khuzestan province, southwest of Iran using the monthly rainfall data of 41 stations. In this study, Khuzestan province was regionalized based on the bivariate risk of drought events. The suggested approach is applicable to regional analysis of agricultural and hydrological droughts .

2.8 DROUGHT SEVERITY

Drought events are natural phenomenon which can be classified by its severity (i.e. magnitude of deficit) and duration. The severity of drought events can be estimated by hydro-meteorological data (i.e. precipitation, streamflow and groundwater) using the deviation from the long term mean. The proactive planning and mitigation strategies for a drought event rely on the information related to its areal coverage, degree of deficiency (i.e. severity) and duration it lasts (Dogan et al. 2012; Mishra and Singh, 2011). Hayes et al., (2010) suggested that the severity of the drought event is one of its important feature since, it is directly associated to hazardous effects of drought. The severity of drought events can be estimated in many ways. The various standardized drought indices used for drought monitoring describes the severity of drought events as the standard deviations from mean (Mishra et al., 2009; Vicente-Serrano et al., 2009; Bloomfield and Marchant, 2013; Joetzjer et al., 2013; Loon and Laaha, 2015). The severity and duration of hydrological drought are linked, as the deficit accumulates during the period for which drought event lasts (Woo and Tariiule, 1994; Shiau and Shen, 2001; Kim et al., 2003; Hisdal et al., 2004; Wong et al., 2013; Loon and Laaha, 2015). Van Loon et al. (2014) have found a non linear relation between duration and severity of drought event which depends on its propagation and related strongly to watershed and climate characteristics

(Van Lanen et al., 2013; Loon and Laaha, 2015). Loon and Laaha (2015) explained the severity of hydrological drought on the basis of climate and watershed characteristics. This study was carried out to investigate the controls on severity of drought using hydro-meteorological data and physiographic characteristics of 44 watersheds of around 50 years. The analysis indicated that the duration of the drought event is controlled by the storage and duration of dry spells, while the degree of deficit is primarily governed by the average wetness of watershed and elevation. In other words, it can be said that the both severity and duration of the drought events are governed by the watershed and climate characteristics in a different way.

Stephens (1998) assessed the drought severity using the modeling approach through its significant impact in wheat growing areas of Australia. In this study, a drought exceptional circumstance index (DECI) was formed which integrates severity and duration of drought events using the long term rainfall records to directly rank dry cropping years. The approach used in this study highlights the frequency of severe drought events across the different regions. In literature, many studies have been done using the modeling approach, the characteristics of drought were extracted from rainfall data (Shiau, 2006; Modarres, 2009; Mirakbari et al., 2010; Song and Singh, 2010; Ganguli and Reddy, 2012; Mirabbasi et al., 2012; Reddy and Ganguli, 2012; Chen et al., 2013; Lee et al., 2013; Ma et al., 2013; Yoo et al., 2013; Yusof et al., 2013; Zin et al., 2013; Rauf and Zeephongsekul, 2014; Tosunoglu and Can, 2016) and in some studies the streamflow data has been used for the joint modeling of drought characteristics. Among these, the bivariate copula functions has been used by Shiau et al. (2007) in Yellow River basin, China, to make joint distributions series for drought severity and duration obtained from the monthly streamflow data.

Shin and Salas (2000) suggested a methodology based on annual rainfall for analysis and quantification of spatio-temporal patterns of meteorological droughts. By using a neural network algorithm, they determined the posterior probabilities of drought severity and assigned a Bayesian drought index for a site, which is useful for constructing drought severity maps that display the spatial variability of drought severity on a yearly basis. The several studies has been done on the spatio-temporal variation in drought severity across the globe (Mihajlovic, 2006; Vicente-Serrano, 2006; Blenkinsop and Fowler, 2007; Elagib, 2009; Santos et al., 2010; Gallant et al., 2013; Rahmat et al., 2015; Li et al., 2016; Khadr, 2017). Kleppe et al. (2011) studied the severity and duration of drought events during medieval times in Lake Tahoe Basin. The estimation of severity (i.e.

magnitude of deficit) and duration of drought events northern Sierra Nevada carried out by using hydroclimatic conditions in Fallen Leaf Lake, California. The water balance calculations indicated that the annual rainfall departed by more than 60% of normal (from late 10th century to early 13th century AD), leads to the lowering of lake's shoreline by 40-60 m from its modern elevation.

Masud et al. (2015) analyzed the meteorological drought events in terms of severity of events (i.e. magnitude of deficit) and its duration using the standardized precipitation index (SPI) and standardized evapotranspiration index (SPEI) over the Saskatchewan Basin, Canada. The results indicated that the duration of the drought events are higher in the regions experiencing higher magnitude of deficit. Many researchers have used SPI for the analysis of meteorological droughts (Hayes et al. 1999; Wu et al., 2001; Huges and Saunders 2002; Mishra and Desai 2005; Pandey et al., 2008; Edossa et al. 2010; Mishra and Singh, 2009; Khalili et al., 2011; Dogan et al., 2012; Yan-jun et al., 2012; Zhang et al., 2012; Nam et al., 2015; Li et al., 2016; Dayal et al., 2017; Spinoni et al., 2017).

Dogan et al. (2012) compares the various drought severity indices based on precipitation in semi arid Konya (closed basin), Turkey. In this study the comparison of drought indices has been done on various time step (1 month-48 months) using the monthly rainfall data of 12 spatially scattered stations. The analysis revealed that for the studies of long term drought events the drought indices should be used for the time steps 6, 9, and 12 months, and for the quantification of drought severity (i.e. magnitude of deficit) use of a suitable time step is as important as the type of drought index. Gallant et al. (2013) investigated the drought characteristics on seasonal scale over Australia, for the period of 1911-2009 using four different indices. The change in the frequency, intensity and duration of drought events were estimated across Australia for the above said period (1911-2009). The analysis shows that average duration of droughts statistically significantly increased in Southeast Australia since 1911. Several studies (Guttman, 1998; Morid et al., 2006; Pandey et al., 2008; Paulo and Pereira, 2006; Smakhtin and Hughes, 2007; Wu et al., 2001) have indicated that there is an advantage in considering more than one DI for drought studies.

2.9 DROUGHT PERSISTENCE

Drought is most hazardous climatic phenomenon whose impacts becomes more severe as it lasts for a longer duration. The persistence of drought event creates worst condition for the society. A persistent drought event is defined as the occurrence of two or more consecutive drought years, such as 2-, 3- and 4- consecutive years. The worst impacts draw the attention of many researchers towards the persistent drought events (Karl, 1983; Stahle and Cleaveland, 1992; Woodhouse and Overpeck, 1998; Cole et al., 2002; Zaidman et al., 2002; Fye et al., 2003; Huang et al., 2005; Herweijer *et al*., 2006; Van der Schrier et al., 2006; Marsh et al., 2007; Manuel, 2008; Demuth, 2009; Maxwell and Soule, 2009; Seager et al., 2009)

Karl (1983) investigated the spatial characteristics of drought in United States using the Palmer Drought Severity Index (PDSI). The analysis indicated that compared to the coastal region in east and west the interior of the United States have longer drought persistency. Further, Ford and Labosier (2014) examined the persistence of a drought event in Southeast United States by identifying the spatial pattern of frequency and persistency of seasonal drought, computing the probability persistence of drought from one season to next by using logistic regression, and examining the effects of El Nino-Southern Oscillation (ENSO) (Enfield et al., 2001; McCabe and Muller, 2002; McCabe et al., 2004; Curtis, 2006; Senkbeil et al., 2012, Daradur et al., 2016). The analysis revealed that the seasonal drought in Southeast US are difficult to forecasts due to the rare persistence of drought. The desertification of Semiarid Savanna in west-central Texas, United States has increased due to persistence of severe droughts (Wonkka et al. 2016).

Parry et al. (2012) analyzed the development and causes of the multi year drought in Europe using a critical objective classification of regional hydrological drought. In this study, the spatial and temporal characteristics of drought and synoptic climatic parameters of multi-year droughts during 1962–64, 1975–76 and 1995–97, were investigated on a European scale. The analysis shows that for effective planning and mitigation strategies, the important factors to consider are the clear understanding of spatio-temporal characteristics of multi-year drought. During the second of the twentieth century the drought event persisted for 2-, 3- and 4- or more consecutive years (1962–64, 1975–76, 1988-1992 and 1995–97) in UK (Marsh et al., 2007). Meng et al. (2017) analyzed the persistence of drought using logistic regression in eastern part of China. The probability of occurrence of drought of current season was calculated using SPI, Southern Oscillation Index and the drought persistency of preceding season. The results indicated that the summer season have more significant persistence of drought than other. Wilby et al. (201) investigated the properties (spatial and temporal) of persistent meteorological drought using the homogeneous Island of Ireland

Precipitation (IIP) network. The analysis revealed that drought during 1850s persisted for 5 years at sites in southeast and east Ireland, or 3 years across the whole network.

In literature, many studies have been documented on the drought persistency by number of researchers around globe (Karl, 1983; Mechoso and Iribarren, 1992; Zaidman et al., 2002; Scian and Donnari, 1997; Robertson and Mechoso, 1998; Woodhouse and Overpeck, 1998; Compagnucci *et al*., 2002; Zou et al., 2005; Marsh et al., 2007; Herweijer and seager, 2008; Maxwell and Soule, 2009; Seager et al., 2009; Ortegren et al., 2011; Parry et al., 2012; Leng et al., 2015; Meng et al., 2017). Pandey et al. (2013) studied the drought characteristics in India and found that the persistent drought events for 2- and 3- consecutive years are more common in arid and semi-arid rgions as compared to sub-humid and humid regions.

2.10 RELATION BETWEEN DROUGHT CHARACTERISTICS AND CLIMATIC PARAMETERS

Droughts occur around the globe in most of the climatic regions (Dai, 2004; Dai, 2011; Sheffield et al., 2012, Xu et al., 2015). The occurrence of drought events are related to the regional climatic parameters (Dracup et al.,1980; Ponce et al., 2000; Pandey and Ramasastri, 2001). The drought characteristics (i.e. frequency, severity and duration) varies cross the climatic regions (Gregory, 1989; Ponce et al., 2000; Pandey and Ramasastri, 2002). The change in the behavior of the drought event in different climatic region is one of the important factor to be considered in planning and management strategies (Singh et al., 2002; Mishra and Singh, 2010; Xu et al., 2015). The various indices used for drought monitoring are based on different climatic and hydro-meteorologic parameters (Precipitation, temperature, evapotranspiration, streamflow). The calculated values of the indices represents the severity (i.e. magnitude of deficit) of drought (Hayes et al., 2011; Hao and Singh, 2015). The water demand around the world has been significantly increased due to increase in areal extent of arid climate. The areal extent of arid climate has been pronounced in last 15 years of twentieth century in most of the part of the world when there is rapid increase in global warming (Fraedrich et al. 2001; Beck et al., 2006; Son and Bae, 2015). The frequency and severity of drought events has been increased significantly in the recent years because of changing climate (Sheffield et al., 2012; Intergovernmental Panel on Climate Change (IPCC), 2013; Nam et al., 2015). Many researchers have used the precipitation and potential evapotranspiration as the main indicator to define climate (UNEP, 1992; Le Houérou, 1996; Ponce etal., 2000; Pandey and Ramasastri, 2001, 2002; Brunetti et al., 2004).

For drought characterization in mid-latitudinal regions a new climatic classification was proposed by Pandey and Ramasastri (2002) based on the ratio of mean annual potential evapotranspiration (Ep) to the mean annual precipitation (Pa). Ponce et al., (2000) classified the climatic regions into eight types from super arid to super humid based on the ratio of mean annual precipitation (P_{ma}) to annual global terrestrial precipitation (P_{agt}). The study indicated that the average drought return period varies between 2 years in extremely dry regions (i.e. super and hyper arid) and 100 years in extremely wet regions (i.e. hyper and super humid regions). The analysis revealed that the droughts are very frequent and severe in hyper arid and arid regions with average return period of 2-3 years, the drought frequency varies from once in 5 years in semiarid to once in 6 years in sub humid regions and in humid and hyper humid regions drought events are very rare with average return period of more than 15 years. Similar study has been done by Pandey and Ramasastri (2001) considering the average annual precipitation and average annual evapotranspiration as the parameters which defines climate. The mid-climatic regions of India are classified as arid, semiarid, subhumid and humid regions based on mean annual potential evapotranspiration/ precipitation ratio (PET/P). In this study, a relationship has been developed between average return period of drought and the ratio of mean annual potential evapotranspiration to mean annual precipitation (PET/P). the analysis revealed that the average drought frequency (expressed in terms of return period) varies from 2 to 3 years in arid regions (with $12 > PET/P \geq 5$), 4 to 5 years in semiarid regions (with $5 > PET/P \geq 2$), 6 to 10 years in subhumid regions (with $2 > PET/P \geq 3/4$) and 10 years or more in humid regions. Elagib (2009) assessed the drought on the basis of changes occurred in the ratio of precipitation and potential evpotranspiration (dryness ratio) during 1941-2005 in Central Sudan. The monthly and annual dryness ratio of 8 stations were checked, indicating a trend towards severe and more frequent droughts. The trend is significant in arid regions and increase in areal extent of drought has been observed. Feng et al. (2014) analyzed the potential evapotranspiration and meteorological data of 93 stations for the period of 50 years (1961-2010) to assess the effect of climatic parameters on potential evapotranspiration during droughts in North China. A notable increasing trend has been observed in the annual potential evapotranspiration with the worse condition of drought. The analysis revealed that the climatic parameters (viz. temperature and sunshine hours) had positive effects on the change in potential evapotranspiration during periods of drought, while other parameters (i.e. effective precipitation, vapor pressure, wind speed, relative humidity) had negative impacts on potential evapotranspiration.

Liu et al. (2016) in eastern Hulun Buir steppe, China studied the drought reconstruction and its relation to the sea surface temperatures in the Pacific Ocean. In the analysis, a significant correlation was found between sea surface temperatures (SST) in North Pacific Ocean and drought variations. The spatiotemporal change in summer precipitation has been explained by regional SST in Yellow river basin of China (Yuan et al., 2016). Nam et al. (2015) assessed the impacts of drought hazards in climate change perspective for South Korea by checking the change in the trends of drought. The analysis revealed that at various time scales, substantial increase in drought severity has been observed for each indicators of drought. Sun and Ma (2015) explored the effects of non-linear precipitation and temperature trends on drought events over the Loess Plateau during 1961-2010 using the monthly rainfall and temperature records of 53 meteorological stations. The analysis revealed that the drought become more frequent in Loess Plateau due to partial lowering of rainfall and rise in observed temperature. The results shows that the affects of temperature trends on drought events are more significant than precipitation trends.

Zhang and He (2016) estimated the water demand over arid and semiarid regions for the identification of drought. The precipitation and potential evapotranspiration are the main drought indicators for quntification of water demand for monitoring of drought over dry regions (arid and semi arid). The results indicated that the places with average annual rainfall of less than 300 mm, potential evapotranspiration would be used as the water demand indicator for the quantification of drought. The variation in the characteristics of drought due to shift of various climate (i.e. tropical, warm temperate, cold and polar) to arid climate over the monsoon regions of Asia were investigated (Son and Bae, 2015). A decrease of about 12.1% and 27.3% has been observed in annual rainfall and streamflow respectively, and the mean annual temperature was increased by 0.5 ℃. The results shows that change in temperature of arid climate zones influences the characteristics of drought.

Livsey et al., (2016) found that in last 3,000 years drought events along the northwestern Gulf of Mexico are regulated by North Atlantic sea surface temperature. The effect of Pacific sea surface temperature on Texas drought cannot be neglected. This study indicates that over southern Texas the Atlantic Multidecadal Oscillation was a major factor which modulated the frequency of drought. Liu et al. (2016) analyzed the spatial and temporal characteristics of multiscalar drought for the period 1957-2012 across the Loess Plateau of China. The SPI and SPEI at various time scales (1-, 3-, 6-, 12- and 24) were computed using the climate data obtained from 54 weather stations. The analysis revealed that for the monitoring of regional drought under the condition of changing climate, SPEI should be preferred because of its multiscalar nature and capacity to discover the effects of temperature on drought situation. Thus, several studies have been done to relate the climatic parameters with the drought characteristics (Ponce et al., 2000; Pandey and Ramasastri, 2001, 2002; Wei et al., 2003; Burke et al., 2006; Ju et al., 2006; Rong et al., 2007;Yang et al.,2012; Sen, 2014; Son and Bae, 2015; Xu et al., 2015).

2.11 ENVIRONMENTAL FLOW REQUIREMENT

The most important natural resource for the well being of human and the environment on the earth is fresh water (Gleick, 1993). There is increase in water demand globally due to the lack of water supply which is coupled with increasing population and industrialization. This leads to scarcity of fresh water resource on the earth (Wang and Lu, 2009). Water has to be sustained in rivers for conservation of natural ecosystem, and therefore, the minimum amount of water flow required for river's survival is called environmental flow (EF). For the maintenance of structure, function and form of the river, environmental flow is very essential (Poff et al., 2009). Environmental flow was promoted as a key element of the integrated water resources management by The World Conservation Union (Dyson et al., 2003).

The dynamics of runoff are regulated by different mechanisms, which act on a range of spatial and temporal scale (Sivakumar et al., 2001). The health of river ecosystem can be determined by many factors such as flow, channel structure and riparian zone, quality of water, exploitation level and macrophyte cutting and dredging (Norris and Thoms, 1999). Initially, it was believed that all the problems related to health of the river are associated with low flows and that the river ecosystem will be conserved till a minimum flow is maintained in the river, but as time lapses people become more aware about importance of all the other elements of flow regimes such as floods, medium and low flows (Poff et al., 1997; Hill et al., 1991).

The increase in global water demand made the researcher to think about the assessment of flow requirement. Various studies have been done across the globe to formulate, implement and adapt different methods of environmental flow assessment (EFA). The various methods of EFA have been often reviewed critically in a number of studies (Stalnaker and Arnette 1976, Jowett 1997, Dunbar et al. 1998, Annear et al. 2002, Arthington 2012, Hatfield et al. 2013, Linnansaari et al. 2013).

Initially EFA methods were developed to estimate the instream flow needs of fish below the irrigation and hydroelectric dams on large rivers (Trihey and Stalnaker 1985; Kumar et al., 2007) with aim to set the flow required during low flow seasons (Leathe and Nelson 1986). A broad-based conference to discuss the social, biological and legal aspects of the instream flow problems was organised by The American Fisheries Society in Idaho and Proceedings was published (Orsborn and Allman 1976). It was observed that the EFA methods developed show the gaps in practice and knowledge of environmental flow in developing countries as these methods were developed in the perspective of developed countries (Tharme and Smakhtin 2003).

2.12 CLASSIFICATION OF EFA METHODS

The methods for environmental flow assessment have been categorized in a number of ways by various researchers (Stalnaker 1990; Dunbar et al. 1998; Dyson et al. 2003; King et al., 2003; Tharme and Smakhtin 2003). The methods were categorized as Standard setting and Incremental (Stalnaker 1990). The standard setting method are used to generate a flow values upto certain level required for the maintenance of aquatic ecosystem. The incremental method was defined as the organized and repeatable processes which includes the transformation of the hydrology of the stream and fishery habitat stream flow relation into a baseline habitat time series, simulation of water management alternatives and compare with the baseline, and project rules are negotiated. Further, Dunbar et al. (1998) followed the same categories but they used the term Empirical methods instead of Incremental Methodologies. They believed that desktop methods (Standard Setting Methods) are used for the prediction of suitable schedule of instream flow requirements which is done by doing some exercise in office using the available information. The determination of schedule of flow requirements in Empirical Methods make use of data (biological and physical) which are collected in the field. The flow regime requirements can be assessed by combining easily obtained information with detailed site-specific studies. Various management alternatives can be assessed using an incremental approach in place of the standard setting method (Dunbar et al. 1998).

Tharme (2003) and Tharme and Smakhtin (2003) classified the methods of environmental flow assessment into four different groups viz. hydrological, hydraulic rating, habitat-simulation and holistic approach. Hydrological methods are based on analysis of historic (existing or simulated) streamflow data, do not operate at a species-specific level, and provide an overall flow level that aims to conserve the biotic integrity of a stream. This is based on the general assumption that more water provides the best insurance for river biota (to a point), and sustaining some low threshold reduces risk to the biota.

2.12.1 Hydrologic methods

This method estimates the various flow statistics based on the observed or simulated data of daily streamflow. Hydrologic models are generally used to simulate flow records and to create natural flow conditions before changes in flow regime are expected because of anthropogenic activities like urbanization or land use changes. Tennant Method, the Flow Duration Analysis Method (FDAM), the Range of Variability Approach (RVA) and the Percent of Flow (POF) approach are some of the examples of hydrologic methods (Richter et al. 2012, Tharme 2003).

Tennant method:

In this method, the various streamflow conditions are classified using Average Annual Flow (AAF). This method uses percentages for classification of conditions (Table 2.1). This method is a globally accepted for the assessment of environmental flow. Tennant Method relates AAF percentage on a seasonal basis to flows that uphold geomorphic function (flushing flows) and flows that preserve instream habitat condition (Table 2.1). The flow condition are grouped into seven classes based on the average annual flow (AAF)

Table 2.1 Flow conditions based on percentage of AAF (Tennant, 1975)

Flow Condition	October-March	April-September
Flushing flow	200% AAF	200% AAF
Optimum range of flow	60-100% AAF	60-100% AAF
Outstanding	40% AAF	60% AAF
Excellent	30% AAF	50% AAF
Good	20% AAF	40% AAF
Fair or Degrading	10% AAF	30% AAF
Poor or Minimum	10% AAF	10% AAF
Severe Degradation	10% AAF to zero flow	10% AAF to zero flow

Flow duration analysis method

The FDAM uses various exceedance percentiles on the flow duration curve (FDC) as flow indicators. The strong link between the streamflow and the ecosystem at a site is the base for this approach. A FDC displays the percentage of time a given discharge is equaled or exceeded. The major demerits of the flow duration curve analysis are that in this method timing, rate of change and duration of flow are not considered, as these are main factors for assessment of environmental flow.

Range variability approach (RVA):

There are 32 variables classified in 5 different groups used in Range variability approach known as Indicators of Hydrologic Alterations (IHA). Results of ecological monitoring program and the re-calculation of IHA statistics help in the adaptive management of the system and redefining targets for the following years (King et al. 1999, Richter et al. 1997).

Percentage of flow approach:

This method utilizes the percentage departure of flow from the natural flow regime is set as the upper and lower limits for Environmental Flows Requirement (EFR). The approach suggested in this method is simple and it always sets the environmental flow requirement to mimic the natural flow regime.

The assessment of environmental flow using hydrologic methods are simple, inexpensive and can be done quickly. In several management situations multiple stakeholders with opposing interests are involved. In some other cases, management of rare and endangered aquatic or riparian biota becomes the main concern. The other methods based on multidisciplinary approach can be used in such situations for assessment of environmental flow. It is quite difficult to apply the hydrologic methods in the places where data is insufficient and information regarding natural conditions cannot be easily generated.

2.12.2 Hydraulic methods

These methods relate health and sustainability of ecosystems to hydraulic variables such as maximum depth, wetted perimeter, velocity, longitudinal connectivity, etc. Hydraulic methods assumes that for a certain discharge at different cross sections there is a direct relationship between ecosystem health and specific value of a hydraulic variable.

These methods are simple, inexpensive and relate streamflow and ecology, considering the physical habitat conditions. In hydraulic approach timing, duration, frequency and rate of change of flow are not taken into account during analysis which is major disadvantage of this method. As the analysis is limited to cross sections of streams so riparian vegetation is also not taken into consideration in the analysis.

2.12.3 Habitat simulation methods

Habitat simulation methods are extension of hydraulic methods described earlier. Models are used for target groups of aquatic species to arrive at the sustainability of habitats for varying discharge conditions. Most of the models under this category consider two components (i) hydraulic simulation component, and (ii) habitat simulation component. Habitat simulation programs use the output from the hydraulic simulation models to link the simulated physical conditions - depth and velocity - to the conditions required by the target species at various stages of its life history called Habitat Suitability Criteria (HSC). The HSC is calculated for each cell and at each time step of the model. The main advantage of the habitat simulation methods is that it provides a relatively scientific and defensible flow assessment by enabling the evaluation of multiple scenarios for various species and life stages. These models are data intensive and may be difficult to apply in data scarce regions. Special expertise for data interpretation and analysis is also required to extract meaningful results.

2.12.4 Holistic methods

The Holistic approach includes all or some of the methodology described earlier to estimate the environmental flow requirement. The Australian Holistic Approach and South African Building Block Method (BBM) were the first models developed under this category. Instream Flow Incremental Method (IFIM) is another holistic method developed in early 1980s. This is a decision support system which allows assessment of impacts on management decisions of habitats. The major concern of the holistic approach is sustainability of natural ecosystem while depending upon the expert suggestion is main drawback of this approach (King et al. 1999, Tharme 2003). These models requires huge and various data viz. ecological, social, water quality parameters and geomorphologic. Love et al. (2006) used the rapid result approach for the computation of environmental flow requirement (EFR) for the Rusape River (tributary of Save River) in Zimbabwe. For the estimation of EFR in terms of mean monthly flow the building block method (BMM) was used. The study revealed that the proposed environmental flow requirement can be attained within observed average monthly flows. Shiau et al. (2004) used RVA to study impact of construction of a weir on Chou-Shai Creek. One standard deviation from the mean of pre-construction period for each of the thirty two parameters analyzed was set as the management target range. The model results showed that increasing instream flow releases or reducing diversions could improve the conditions downstream, and the average attainment rate was much closer to the pre-project condition.

Iyer (2005) proposed the terminology such as “environmental flows” or “water for nature” which means that in addition to the different uses water must be allocated for nature to sustain the healthy ecosystem. Since water comes from the nature itself therefore, it seems to inappropriate principle to allocate water to nature. Therefore, the highest priority for using the water should be given to the aquatic ecosystem.

Kashaigili et al. (2005) explored the challenges and options for the allocation of environmental flow in the Great Ruaha River catchment in Tanzania. The analysis indicated that during the dry season the flow of Great Ruaha River should be in the range of 0.5–1 m^3/s which pass through the Ruaha National Park, so as the environment in the park can be sustained. The challenges identified in the study are: (i) environmental flows is still new concept (ii) limited data and lack of understanding of the ecological and hydrologic relations, (iii) insufficient knowledge and support, (iv) lack of storage reservoirs to control environmental water discharge, and (v) there are contradicting policies and institutions on environmental issues. The options to meet the allocation of EF are: (i) creating awareness among communities, government officials and decision makers on EF, (ii) capacity building in EF (iii) local institutions should be developed with legislative support, (iv) storage and water harvesting structures should be designed to store water for the environment, and (v) the water for the environment can be ensured by making alteration in policies of water utilization and water rights.

Kashaigili et al. (2007) conducted a hydrological study for the estimation of environmental flow requirement in the Great Ruaha River Catchment, Tanzania using the desktop reserve model. The results indicate that about 21.6% (i.e. 635.3 Mm^3/a) of mean annual runoff is required to sustain the basic ecological operations of the river. The study revealed that the hydrological indices can be used to provide a first estimate of environmental water requirements, if the ecological information are not available. Mazvimavi et al. (2007) estimated the environmental flow requirement (EFR) in 151 sub basins of Zimbabwe using the desktop hydrological method. The study revealed that in areas with perennial rivers the EFR should be in the range of 30-60% of the average annual flow (AAF) to maintain modified to natural habitat, while in the regions with non perennial rivers the EFR should be 20–30% of AAF.

Gupta (2008) studied about the implication of EF in management of river basin. The approaches for the assessment of environmental flow are evaluated in perspective of flow characteristics of river. The study revealed that EF can be integrated in the mainstream of operation of infrastructure (such as dams and pumps) to modulate the flow of water for the aquatic and other environment in the basins having regulated flows.

Yang et al. (2009) estimated the EFR for integrated water resources allocation by quantification of consumption of artificial and natural water in the Yellow River Basin. The analysis suggested that the minimum annual EFR should be about 54.76% of the natural river flows to maintain the healthy ecosystem, while for the integrated water resources allocation the EFR was estimated to be 45.25% of the natural river flows. The determination of EFR for integrated water resources allocation in a river basin is based on the downstream river water requirements.

Andrew (2012) used IHA framework for characterization of natural streamflow at gauging sites and wetlands. Potential ecological responses to the hydrologic alterations were hypothesized for the different types of alterations experienced at each site. Overall ecosystem health and specific ecological objectives were the two targets set for the analysis. The overall ecosystem health targets and the ecosystem objective targets were integrated into a flow regime for each site. The study proposed a method for applying the targets to support decision making.

Meijer et al. (2012) suggested an approach to include EF requirement in water allocation modeling. In their study, they propose ‘RIBASIM’ (water resources planning package) used for sensible allocation of particularly the high flow pulses and large and small floods that are part of an environmental flow requirement.

Yin and Yang (2012) correlated the change in river morphology, approved EF regimes, and the rivers ability to supply water. The research suggested an approach to find the reasonable EF and prescribed morphology. The pertinence of proposed method was tested on Tanghe River in China, which leads to the inference that for the reservoir operations and to direct the supply of water the proposed method is very useful.

Peñas et al. (2013) developed a methodology based on the numerical modelling of salinity and also considers the hydro-meteorology of the catchment to estimate the EFR in well-mixed estuaries in Spain. The proposed methodology was tested on 5 estuaries located along the northern coast of Spain showing the significance of considering the hydrological variability. The approach suggested can be applied to large scales, even in the less availability of biological and physical data.

Solis and McKinney (2014) estimated the maximum availability of water for environmental flows which does not affect water requirements of natural ecosystem, and flood risk in Presidio-Ojinaga may not increase. The proposed environmental flows are based on the analysis of the prior reservoir alteration hydrology of the river (Rio Grande). About 66% of water of reservoir alteration conditions should be supplied to environment to reduce the flood risk and improves human water supply.

Nia et al. (2016) estimated the environmental flow of Kashkan River in Iran. Several methods (viz. Tennant, aquatic base flow (ABF), ABF of Maine, Hoppe, Arkansas and flow duration curve) were applied to estimate the environmental flow requirement of Kashkan River. The analysis shows that for the estimation of the lowest flow that should be allocated to EF, Tennant method is more suitable.

Yang et al. (2016) estimated the ungauged natural flow regime using back propagation 42 hydrological station of Taiwan. About 31 Indicators of Hydrologic Alteration (IHA) and daily discharge data of 20 years were used in the analysis for the quantification of natural flow regime. The model presented in this study exhibit excellent correlation coefficient of more than 0.7, represents the efficacy of the model to estimate the natural flow regime in ungauged chatchments.

Freeman et al. (2001) studied impacts of flow regime changes due to water resources development on stream communities which depend much on habitat integrity. Their studies show the IFIM is useful in analyzing impacts of incremental changes in flow regime on instream habitat for target species. The study shows the advantage of IFIM to quantify tradeoffs between habitat and flow modification over standard-setting approaches.

2.13 RESEARCH GAP

Droughts are regional in nature and their characteristics are governed by regional climatic parameters (Dracup et al., 1980a; Ponce et al. 2000; Pandey and Ramasastri 2001, 2002). The most common climatic elements which govern regional drought characteristics are precipitation, temperature and humidity, and hence the evapotranspiration. In literature, various studies have been done to relate the climatic parameter with regional drought characteristics. Pandey and Ramasastri (2001) showed the significant relation between average return period of drought and the ratio of mean annual potential evapotranspiration to mean annual precipitation in midlatitudinal regions of India considering the data of 101 raingauge stations located in drought prone regions of India. India has very wide climatic spectrum from hyper arid to hyper humid so there is need to relate climatic parameters with various drought characteristics (i.e. frequency, severity and persistence) in all climatic regions covering almost whole India which will be helpful for prediction of regional drought characteristics and proactive mitigation based on long term regional pattern.

Temperature is one of the important parameter of climate and its variation over the year also describes the climatic condition of a place. In literature, a number of studies have been carried out for drought monitoring using the temperature data but none of them discussed the relationship of drought characteristics (i.e. frequency and severity) and range of annual temperature variation. Therefore, there is a room for exploring a relation between drought characteristics and range of annual temperature variation.

There exist a large number of EF methods, none of them has the efficacy to predict EF for ungauged watersheds, i.e. using rainfall only. On the other hand, SPI has the efficacy to describe a similar dry or wet situation, based on rainfall data only. Thus, there exists a possibility to explore for a relationship between these two, for EF prediction from rainfall, useful for ungauged watersheds.

2.14 SUMMARY

Literature pertaining to understand the concept of drought, its effect around the globe, drought assessment, drought characteristics (i.e. frequency, severity and persistence) and its relationship with climatic parameters, and environmental flow requirement and its assessment were reviewed in this chapter. It is believed that the literature reviewed, will help to understand the problems related to drought, leading to the proactive planning for drought mitigation.

CHAPTER 3

STUDY AREA AND DATA USED

This chapter presents the description of study area and the data required for the analysis. This chapter deals with the geography and climate of the areas over which the various studies have been done. The study on the regional meteorological drought characteristics has been conducted for districts in different climatic regions covering whole India. The relationship between SPI and Tennant method have been proposed for low and high flow seasons using the data of various watersheds from different river basins of India.

3.1 REGIONAL METEOROLOGICAL DROUGHT CHARACTERISTICS

For the long-term regional meteorological drought characteristics, the study was carried out over the 516 districts located in different states of India. The climate varies across the country and various regions of India have different climatic conditions.

The north western part of India includes the states of Punjab, Haryana, Rajasthan and Gujarat covering 91 districts of the country. These regions comes under arid climatic condition in west and semi arid in eastern part. The rainfall in the region is much less than the mean annual rainfall of the country and erratic with high inter annual variability. The average annual rainfall in the region varies from less than 100 mm in Jaisalmer, Rajasthan to 1000 mm in Yamunanagar, Haryana.

The state of Punjab covers an area of 50,362 km^2 of north-western part of India. Rainfall ranges from 900 mm in the mountain foothills to 400 mm in plains. Haryana state has an area of 44,212 km^2. Rainfall ranges from 300 mm to 800 mm, and is unevenly distributed. Rajasthan with an area of 342,239 km^2 becomes the largest state of India. The mean annual precipitation in the state range from 100 mm in Jaisalmer to 900mm in the Jhalawar district. The state of Gujarat has an area of 196,204 km^2. The mean annual precipitation in the state typically ranges from 400 mm to 800 mm. The north western region involves the climatic variability throughout the year. The region experiences extreme hot to extreme cold climatic condition. The summer in this region starts from April and extends up to June. The months of May and June are extremely hot with the temperature varies from 32 °C to 45 °C and sometimes reaches up to 49 °C. The months from July to September are the monsoon season in which the region receives nearly 80% of the annual rainfall. In winters the temperature falls as low as 0 °C which leads to the extreme cold condition in the region.

The central region covers 103 districts located in the states of Maharashtra, Madhya Pradesh, Chhattisgarh and a part of Uttar Pradesh. The region comes under semi arid to dry sub humid climatic condition. There is huge diversity of rainfall in different parts of the region. The state of Maharashtra extends over western and central India covering the area of 307,710 km^2. The major part of the state receives the average annual rainfall between 600-900 mm accept the coastal region where the average annual rainfall is found to be more than 2000 mm. Madhya Pradesh is the state located in the central India encompassing the area of 308,245 km^2 and is also known as the "heart of India" because of its geographical location. The state has subtropical climate with hot and dry summer and cold winter. The eastern part receives heavy rainfall during monsoon (July to September) with annual mean of 1500 mm. The average annual rainfall increases on moving from west to east as the monsoon wind moves from east to west in the state. The rainfall in the south-east part of the state is highest. Chhattisgarh was formerly part of Madhya Pradesh which comes into recognition as an independent state in year 2000 covering the area of 135,194.5 km^2. The state has tropical climate with mean annual rainfall of 1300 mm.

The central region receives 70% of the annual rainfall during monsoon season (July-September). The region has very hot and dry summer days with temperature range between 30 °C to 45 °C. The winter in the region starts from November and extends up to January. The region has tropical climate.

The southern region includes 91 districts covering 5 states of southern India viz. Karnataka, Andhra Pradesh, Telangana, Tamil Nadu and Kerala. The region has exceptional diversity in the climate. The hilly and plateau regions show similar climatic behavior while the plains presents comparatively warmer atmosphere. The southern, north western and the western parts are hilly and rich in vegetation. There is huge diversity in the annual rainfall in the region. The coastal region of Karnataka and the state of Kerala have the average annual rainfall in the range of 2500 mm to 4000 mm. The central part of the region receives the mean annual rainfall of 500 mm to 900 mm while the parts of Andhra Pradesh and Tamil Nadu located along the sea receives the annual rainfall of 1000 mm to 1300 mm. The Eastern and Western Ghats meet at Nilgiri hills. The Western Ghats produce hindrance for south-west monsoon to enter the state of Tamil Nadu. Tamil Nadu is mostly dependent on monsoon leads to the acute water deficit in the state. There have been large variation in the climate of the region. Summer starts in March and lasts till May with temperature range of 30 °C to 40 °C. Major part of the rainfall is received during the southwest monsoon, only one third of the total rainfall is received during northeast monsoon. Winters are very pleasant, due to large coastal belt winters are not very cold and the temperature ranges between 12°C to 30°C.

The eastern region covers the states of Bihar, Jharkhand, Odisha, West Bengal and eastern part of Uttar Pradesh. The climatic condition in the region varies from semi arid in eastern Uttar Pradesh to sub humid in the coastal areas of Odisha. The state of Bihar located in east India covering the area of about 94,163 km^2 and recognised as the 13th largest state of the country according to area. The state is located between 24° 20'10'' N - 27° 31'15'' N latitude and between 83° 19' 50'' E -88° 17' 40'' E longitude. The state has sub tropical climate and receives the average annual rainfall of 1200 mm. The area has hot summers and cold winters with the average temperature of 27 °C. Jharkhand is the state of India which came into existence in 2000 when it was divided from Bihar covering the area of 79,710 km^2. Major part of the state located in the plateau of Chota Nagpur, which is the source of the Damodar, Koel, Kharkai, Brahmani, and Subarnarekha rivers, whose upper watersheds lie within Jharkhand. Most of the part of the state covered with forest. The average annual rainfall of the state is 1300 mm. Odisha is the state located in eastern part of India covering the area of 155,707 km^2 with the coastline of 450 km. The coastal plain lies in the eastern part of the Odisha. It extends from the River Subarnarekha in the north to the Rushikulya river in the south. The region become fertile due to the deposition of silt by the Subarnrekha, Brahmani, Rushikulya, Baitarani, Budhabalanga and Mahanadi rivers flowing into Bay of Bengal. About three-fourth part of the state covered with the forest and hills. Most of the part of the state includes the hills and mountains of Eastern Ghats. Major portion of the state comes under the sub humid region with average annual rainfall of 1450 mm. West Bengal is the state located in eastern part of India extending from Himalayas in north to Bay of Bengal in south covering the area of about 88,752 km^2. The average annual rainfall in West Bengal is 1500 mm except the northern part which includes Darjeeling, Jalpaigudi and Cooch Behar districts which receives heavy rainfall of more than 3000 mm. The climate varies from tropical savanna in south to humid subtropical in the north part of the state. The eastern Uttar Pradesh located in eastern part of India includes the districts of the proposed Purvanchal state. The region receives the average annual rainfall of 1000 mm.

The eastern India receives 80% of the annual rainfall during monsoon season. The region has diverse physiography. The region experiences hot summer and cold winter with average temperature in the range of 27 °C to 30 °C.

The northern region covers the state of Jammu and Kashmir, Himachal Pradesh, Uttarakhand and central and western Uttar Pradesh. This region has huge diversity in the climatic condition from semi arid in UP west to sub humid in Himachal Pradesh. There is huge diversity in climatic condition in Himachal Pradesh and Uttarakhand due to high variation in the altitudes. The climate varies from hot and subhumid tropical in the southern tracts to, land with high elevation, cold, alpine, and glacial in the northern and eastern mountain ranges. Major portion of these states covered with mountains and forests. There is huge variation in the annual rainfall in the region. The region receives average annual rainfall of 800 mm in UP west to around 1500 mm in the state of Himachal Pradesh. The summer in the region have significant variations in the temperature as moving from the plains of western Uttar Pradesh to the hilly region of Himachal Pradesh.

The North eastern part of the country includes the states of Assam, Sikkim, Arunachal Pradesh, Mizoram, Manipur, Nagaland, Meghalaya and Tripura. This region has humid climatic condition with average annual rainfall ranging from 1538 mm in Dimapur, Nagaland to 6161 mm in East Khasi hills in Meghalaya. Figure 3.1 showing the States of India whose annual/seasonal and monthly rainfall data were used for the study of regional meteorological drought characteristics.

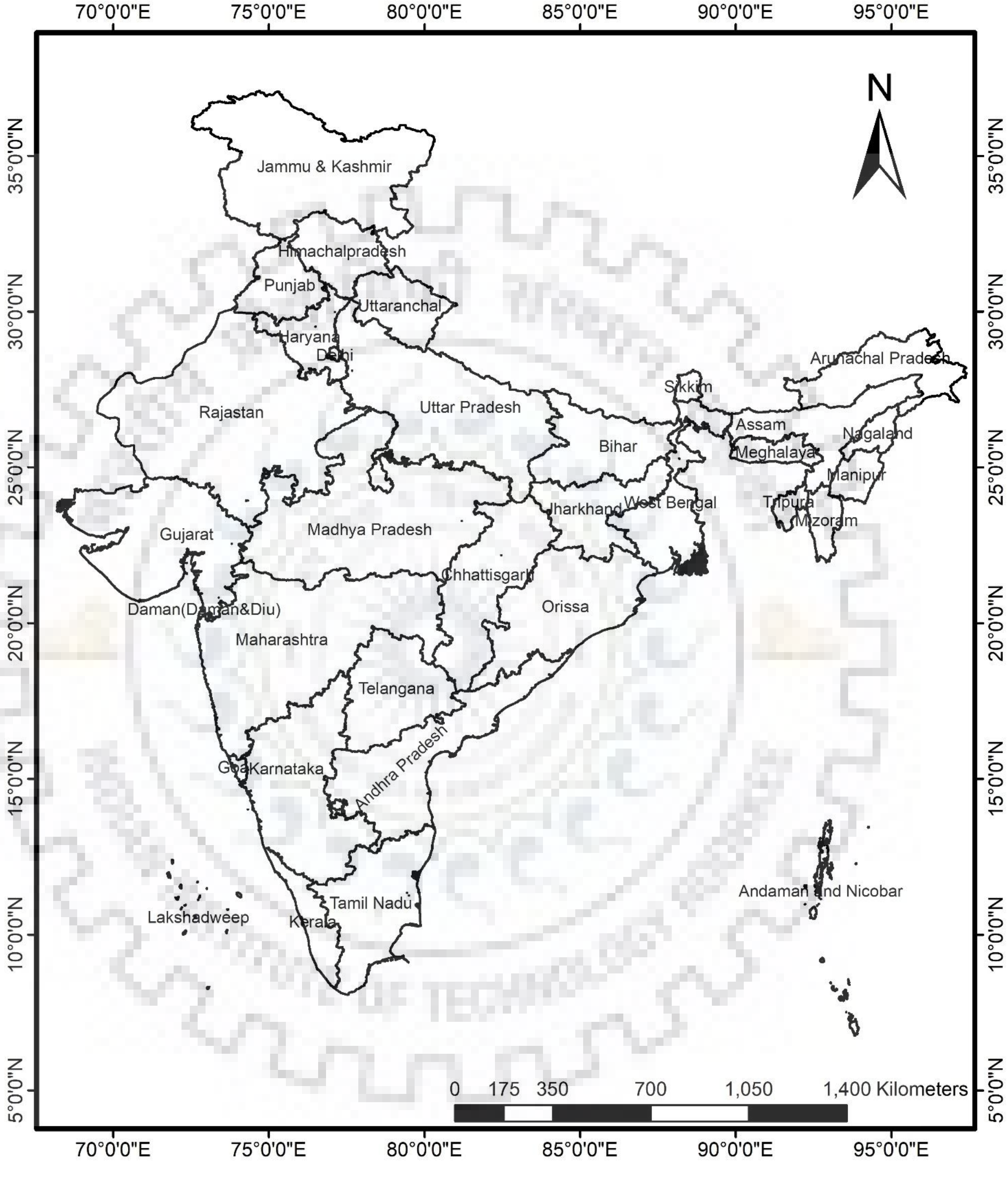


Figure 3.1 Index map representing the study area

3.2 RELATIONSHIP AMONG DROUGHT CHARACTERISTICS AND TEMPERATURE VARIATION RANGE

To explore the relationship of drought characteristics (i.e. frequency and severity) and range of annual temperature variation, the study area covering 256 districts/stations from different climatic regions of India has been considered in this analysis. The location of meteorological stations across the climatic regions in India is shown in Fig. 3.2.

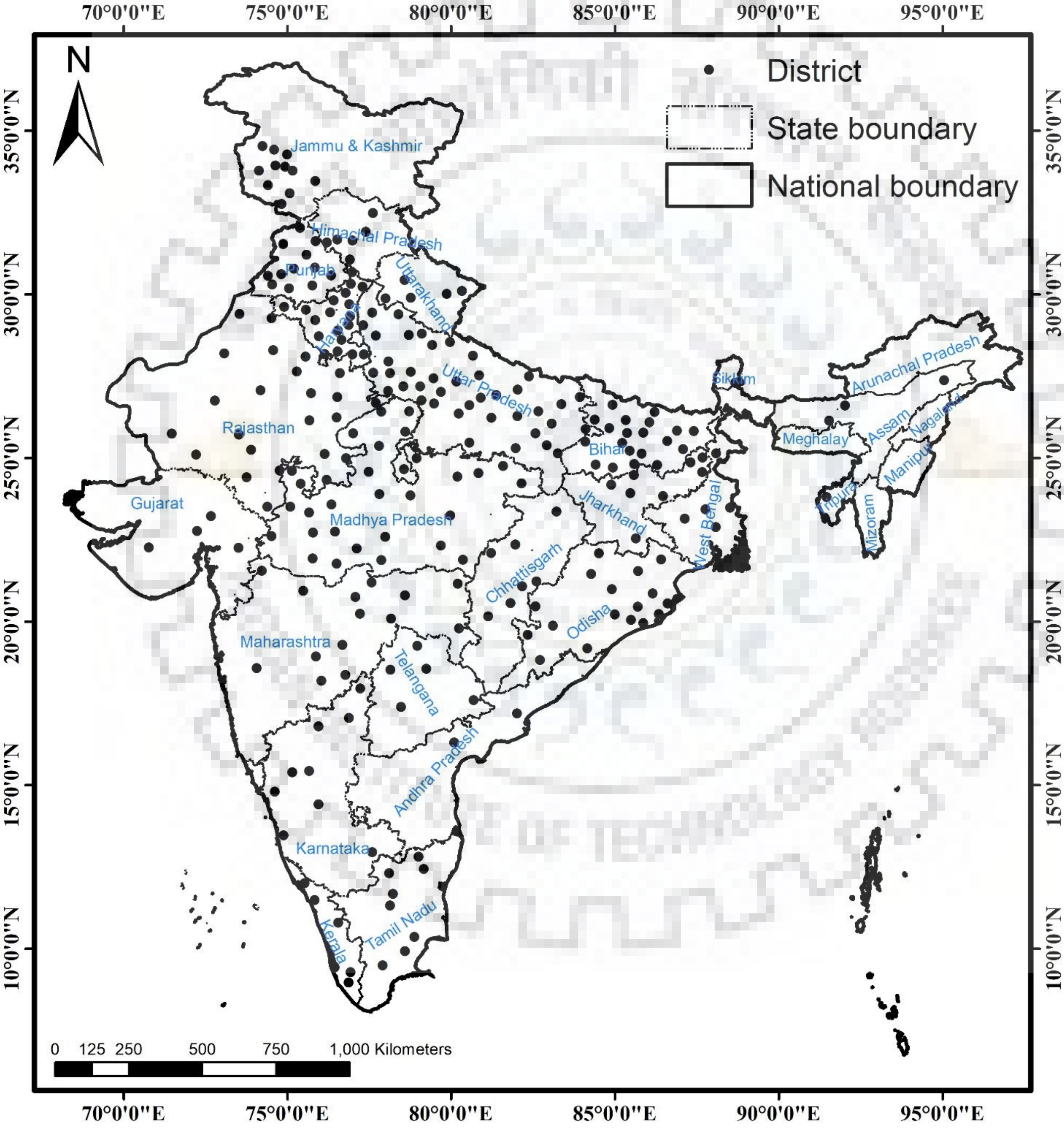


Figure 3.2 Location of districts/stations of temperature data used in the study.

3.3 COUPLING OF SPI AND TENNANT CONCEPT

By coupling the Standardized Precipitation Index (SPI), frequently used as a meteorological drought index, with the Tennant concept, popularly used in environmental flow (EF) assessment, this study attempts to predict EF condition of a catchment using easily available rainfall data only, useful for ungauged catchments. Its application has been demonstrated using the data of different catchments from the various river basins in India during low and high flow seasons.

3.3.1 Low flow Season

The study area for exploring the relationship between SPI and EF during the low flow season (October to June) includes the eleven catchments from the four major river basins (viz. Mahanadi, Brahmani-Baitarni, Godavari and Narmada). The study has been done using the data of three catchments of Mahanadi basin (viz. Ghatora, Kurubhata and Salebhata); two catchments of Brahmani-Baitarini basin (Anandpur and Jaraikela); two catchments of the Godavari basin (Hivra and Nandgaon), and four catchments of Narmada basin (viz. Mohegaon, Manot, Hridaynagar and Sher) falling in sub-tropical, and sub-humid climatic regions of India. The detailed description of the catchments are discussed further in this chapter.

Ghatora

Arpa River rises in the Plateau of Pendra-Lormi located in Khodri ranges near Bilaspur in Chhattisgarh, India. The river flows through Balod Bazar and merges with the Seonath River near the place Thakur Deva, which is a tributary of Mahanadi River. Arpa River flows the length of 147 km when it merge into the Seonath River. The Watershed lies between 22^0 2’ to 22^0 46’ latitudes north and 81^0 36’ to 82^0 26’ east longitudes. The drainage area of the watershed is about 3035 km^2. The elevation at the Ghatora gauging site is 246 m. The climate of the region is sub-tropical and sub humid with average annual rainfall of 1320 mm. The catchment area comprises both flat and undulating lands covered with forest and cultivated lands. The drainage network of the watershed is presented in Figure 3.2.

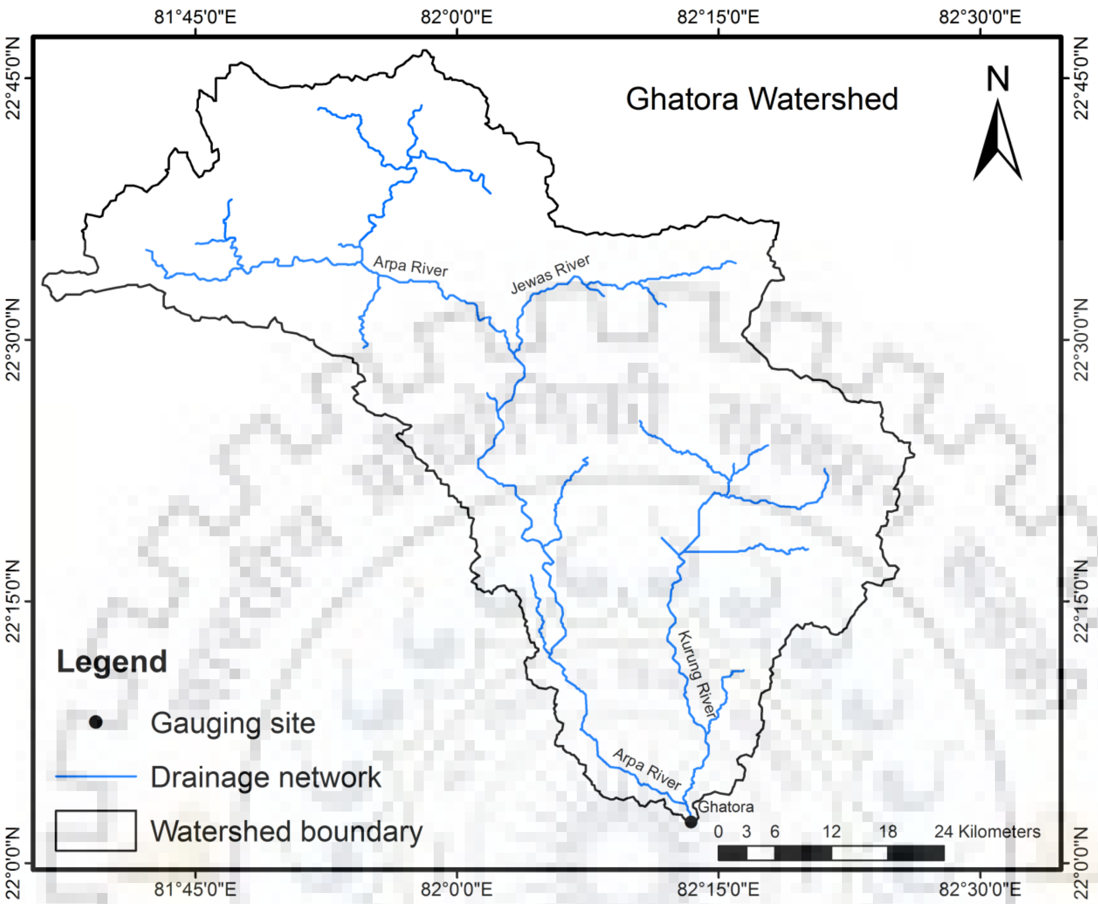


Figure 3.3 Drainage network of Ghatora watershed

Kurubhata

Mand River originates in Surguja district of Chhattisgarh at an elevation of 686 m. The river is the tributary of Mahanadi River. The Mand River flows through a total length of 241 km. It drains the area of about 4625 km^2. The catchment lies between 21^0 58’ to 23^0 05’ latitudes north and 82^0 50’ to 83^0 34’ east longitudes. The elevation of the watershed drops to 215 m at Kurubhata gauging site. The major portion of the watershed in Raigarh district and some part of the watershed also located in the Surguja and Korba districts. The watershed receives average annual rainfall of 1309 mm. About 80% of the annual rainfall is received during monsoon season. The climate of the region is sub tropical and sub humid. The catchment area consist of both flat and undulating lands covered with forest and cultivated lands. The drainage network of the watershed is presented in Figure 3.4.

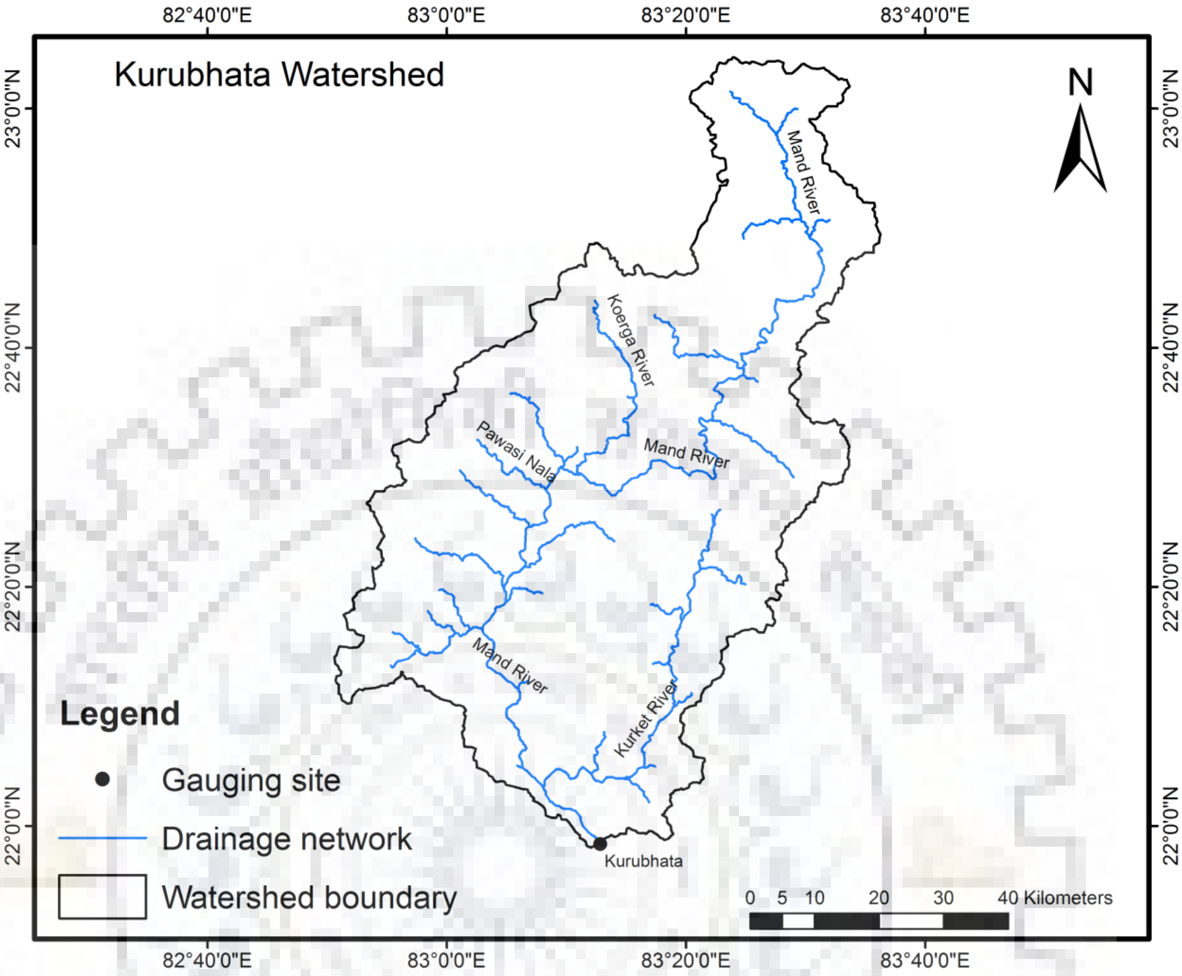


Figure 3.4 Drainage network of Kurubhata watershed

Salebhata

Ong River is the tributary of Mahanadi and originates at an elevation of 457 m. The river flows across Odisha and it travels 204 km before it merges to Mahanadi. The catchment lies between 20° 40’N to 21^0 28’ N latitude and longitude between 82^0 33’E to 83^0 34’E. The drainage area of the Salebhata is about 4650 km^2. The region receives the mean annual rainfall of 1300 mm. About 80% of total annual rainfall received during the monsoon season. The elevation at Salebhata gauging site drops to 140 m. The region experience hot and dry summer followed by humid monsoon and severe cold. The potential evapotranspiration varies from 5 mm/day to 8.5 mm/day. Major crops of the region are non–paddy crops like pulses, oil seeds, maize & cottons. The drainage network of the watershed is presented in Figure 3.5.

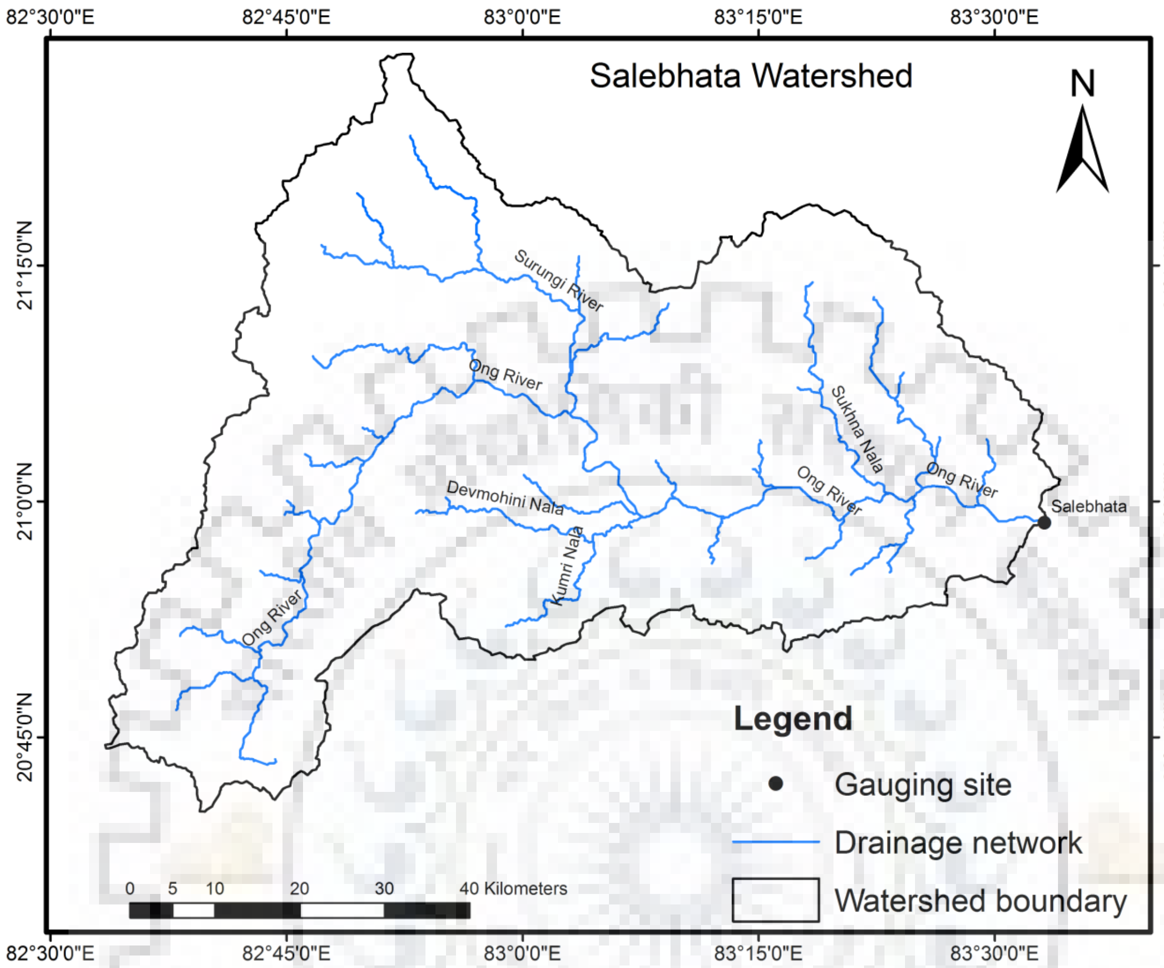


Figure 3.5 Drainage network of Salebhata watershed

Anandpur

Baitarni River rises in Guptaganga hills in Orissa, India. The flows through the total length of 360 km. The Anandpur watershed lies between 21° 12’N to 22^0 15’ N latitude and longitude between 85^0 09’E to 86^0 22’E. The elevation range between 480 m in the upper portion of watershed to 45 m at Anandpur gauging site. The drainage area of the watershed is approximately 8570 km^2. The major portion of the watershed is located in Keonjhar and Mayurbhanj district of Orissa while a small part of it is in Paschim Singhbhum district of Jharkhand. The watershed receives the average annual rainfall of 1441 mm. The potential evapotranspiration varies between 5mm/day to 8mm/day. The climate of the region is characterized as sub humid with hot and humid summer. The major crops used to cultivate in the region are Paddy, Maize, Niger, Arhar etc. The drainage network of the watershed is presented in Figure 3.6.

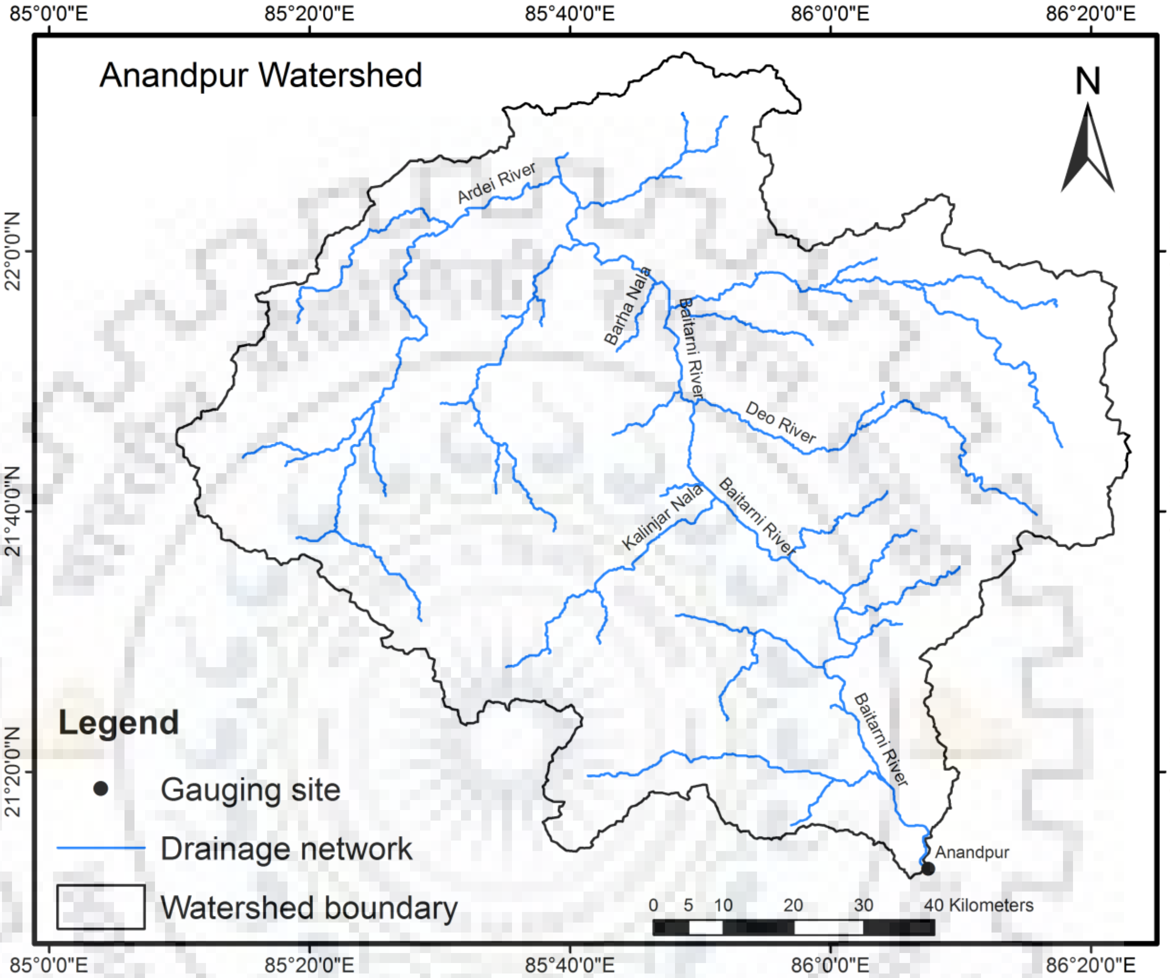


Figure 3.6 Drainage network of Anandpur watershed

Jaraikela

Koel River rises near Palamu Tiger Reserve in Jharkhand. It is tributary of Brahmani River. The catchment area extends between 21° 50’N to 23^0 36’ N latitude and longitude between 84^0 29’E to 85^0 49’E. The elevation varies from 185 m at Jaraikela gauging site to 640 m in the upper part of the watershed. The drainage area of the watershed is about 9160 km^2. The major portion of the watershed spreads over the Lohardagga, Gumla, Ranchi and Paschim Singhbhum districts of Jharkhand and some part is located in Sundergarh district of Orissa. The average annual rainfall of the region is 1000 mm out of 80% of which is received during monsoon season. The climate is classified as sub humid. The topography of the catchment is flat and undulating covered with deep forest and cultivated lands. The drainage network of the watershed is presented in Figure 3.7.

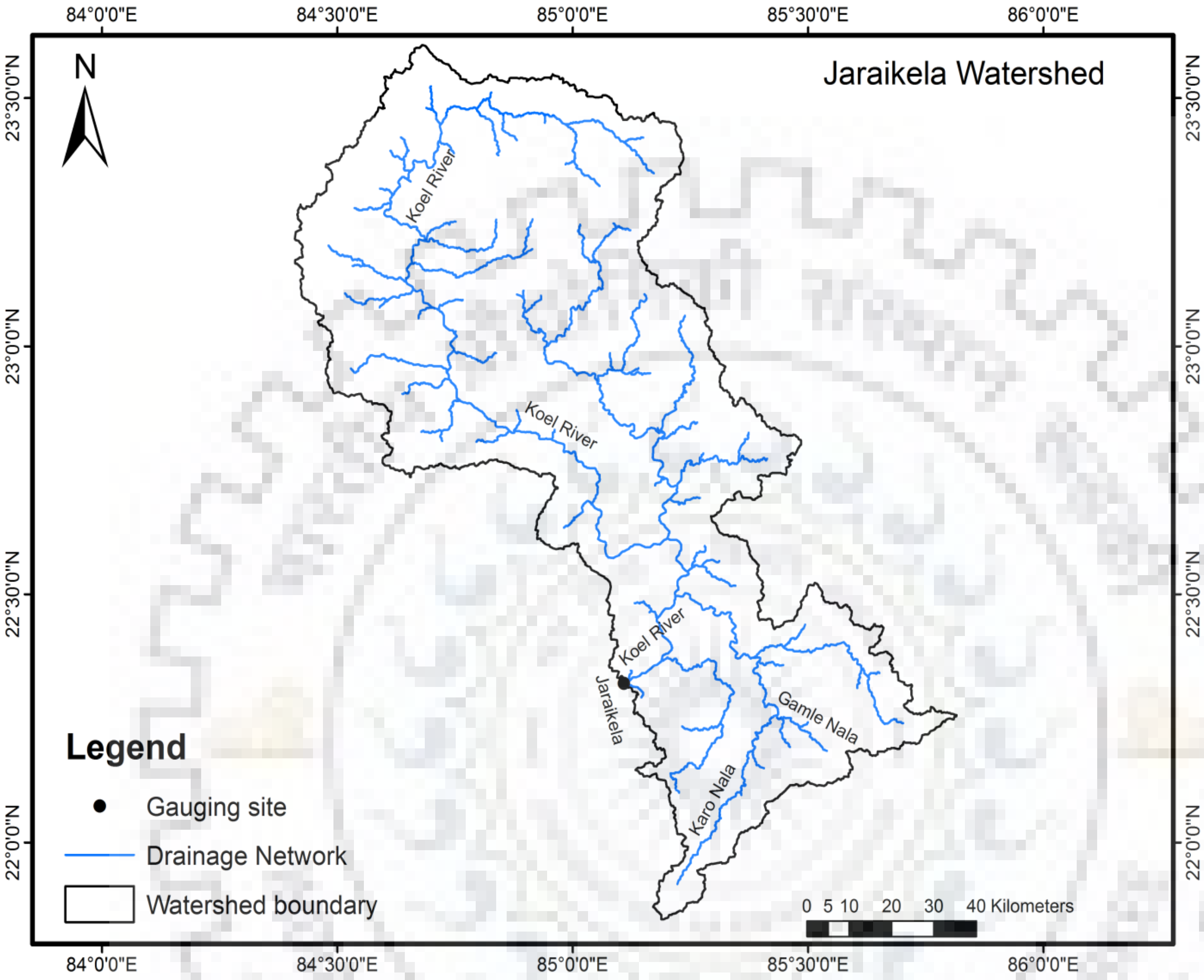


Figure 3.7 Drainage network of Jaraikela watershed

Hivra Catchment

Wardha River, sub tributary of Godavari River, originates in Satpura range at an elevation of 777 m in village khairwani located in Betul district of Madhya Pradesh. Its catchment at Hivra (elevation = 230 m) lies between 20^0 21’ & 21^0 52’ latitudes north and 77^0 25’ & 78^0 45’ east longitudes covers the drainage area of about 10240 km^2. The climate of the region is tropical with average annual rainfall of 1020 mm. The major portion of the watershed spreads over Amravati, Wardha, and Nagpur districts of Maharashtra and some part is located in Betul district of Madhya Pradesh. The catchment area comprises both flat and undulating lands covered with forest and cultivated lands. The drainage network of the watershed is shown in Figure 3.8.

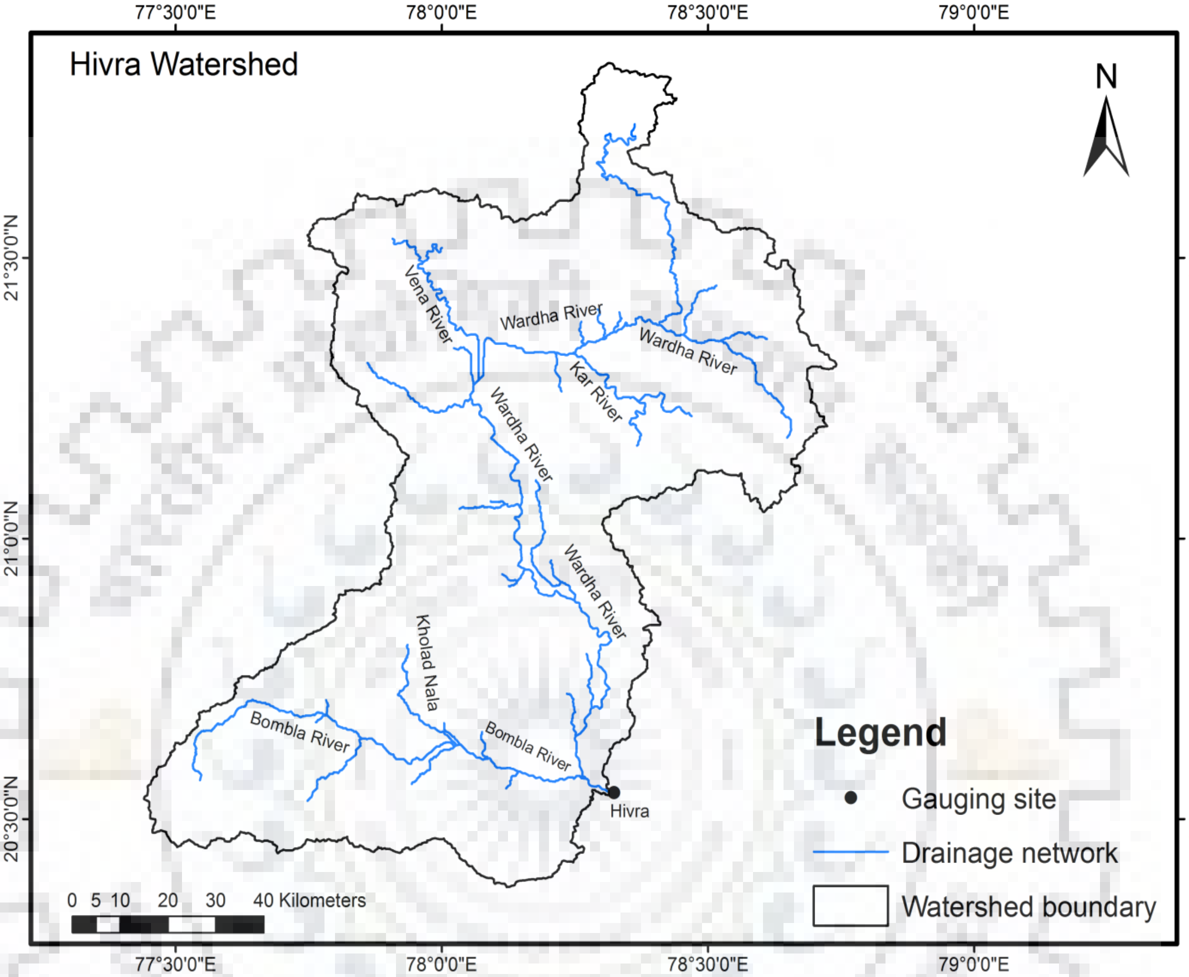


Figure 3.8 Drainage network of Hivra watershed

Nandgaon Catchment

Wunna River originates in Wardha district of Maharashtra at an elevation of 496 m. The river is the sub tributary of Godavari River. The Wunna river traverse through a total length of 110 km before reaching to the Nandgaon gauging site (elevation=198 m). The catchment lies between 21^0 58’ & 23^0 05’ latitudes north and 82^0 50’ & 83^0 34’ east longitudes, draining the area of about 4580 km^2. The region has tropical climate, and it receives average annual rainfall of 1060 mm. The half portion of watershed lies in Wardha and remaining half is located in Nagpur district of Maharashtra. The catchment area comprises both flat and undulating lands covered with forest and cultivated lands. The drainage network of the watershed is shown in Figure 3.9.

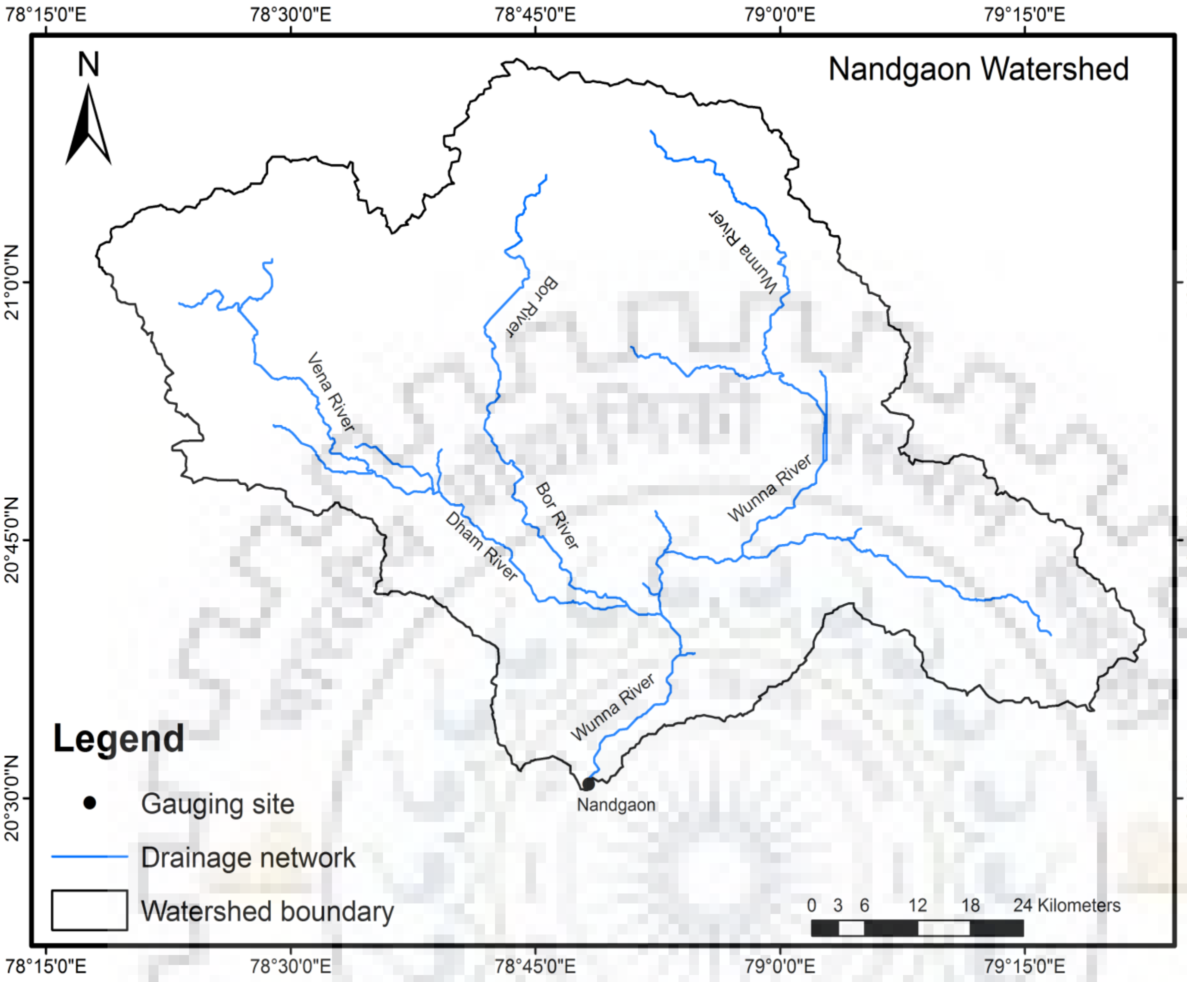


Figure 3.9 Drainage network of Nandgaon watershed

Mohegaon catchment: Burhner River rises in the Maikala range, south-east of Gwara village in the Mandla district. The catchment lies between 22^0 06' to 22^0 55'N latitude and 80^0 33' to 81^0 23'E longitude at an elevation of about 900 m and covers the area of about 3978 km^2. The river has high flow during month of June to October, medium flow from November to February and there is very low or no flow in the months of March to May. The elevation at Mohgaon gauging site drops to 509 m. Its climate is classified as sub-tropical and sub-humid with average annual rainfall of 1,547 mm. The catchment area comprises both flat and undulating lands covered with forest and cultivated lands. Soils are mainly red and yellow silty loam and silty clay loam. Forest and agricultural lands share nearly 58% and 42% of the catchment area, respectively. The drainage network of the watershed is presented in Figure 3.10.

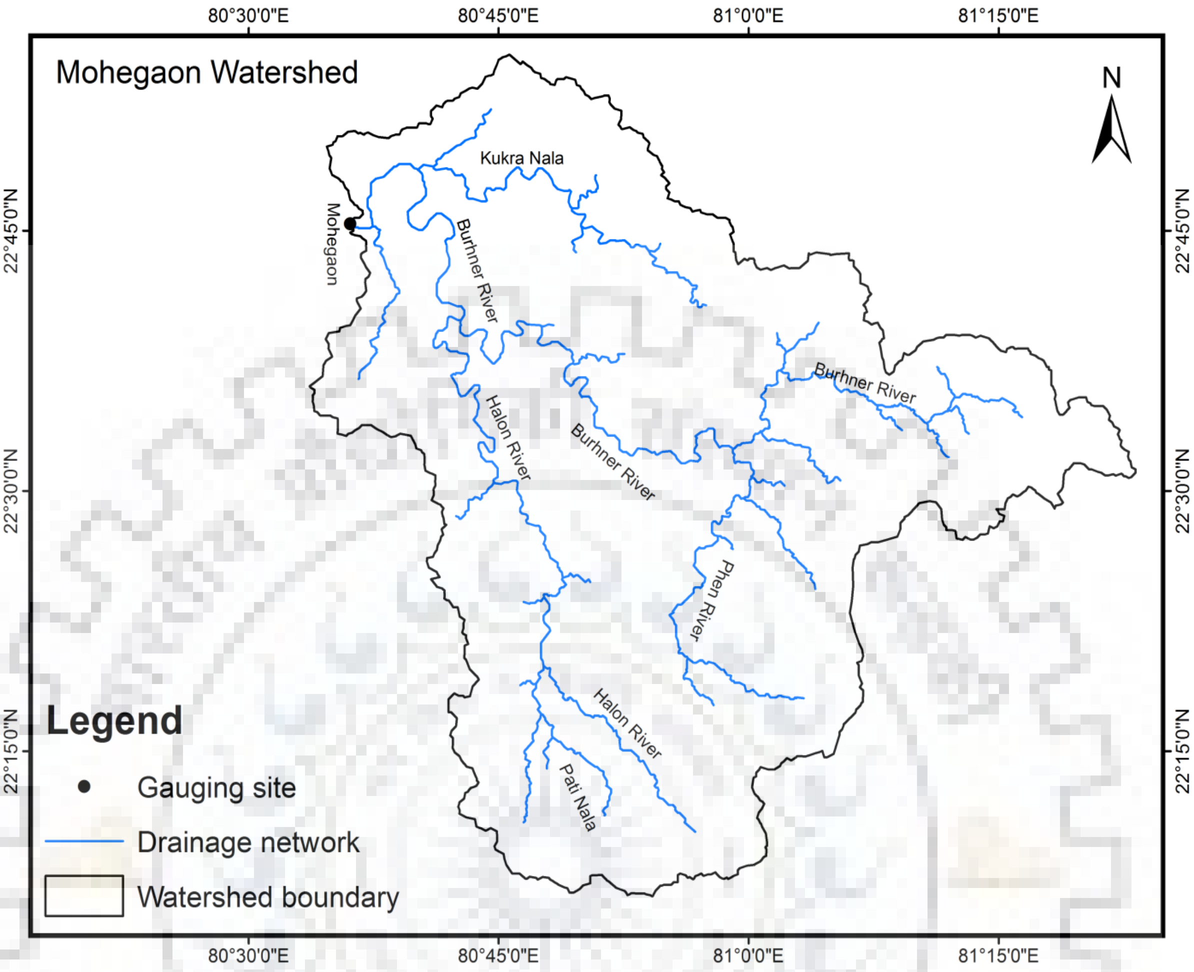


Figure 3.10 Drainage network of Mohegaon watershed

Manot catchment: It lies between 22^0 26' to 23^0 18' latitudes north and 80^0 24' to 81^0 47' east longitudes. The sub-basins cover the drainage area of 4884 km^2. Its elevation ranges from 450 m near Manot site to 1,110 m in the upper part of the catchment. The river is perennial and has some flow throughout the year. Flow data were available from 1982 to 1989, in which the year 1987 had high flow since in this year the sub-basin received the rainfall more than the mean annual rainfall. The climate of this region is classified as sub-tropical and sub-humid with average annual rainfall of 1273 mm. The summer is very hot and winter is quite cold. In major parts of the catchment, soils are red, yellow, and medium black with shallow to very shallow depth. The catchment is covered by forest and its topography is hilly. Approximately, 52% of the catchment area is under cultivation, about 35% under forest, and 13% under wasteland. The drainage network of the watershed is presented in Figure 3.11.

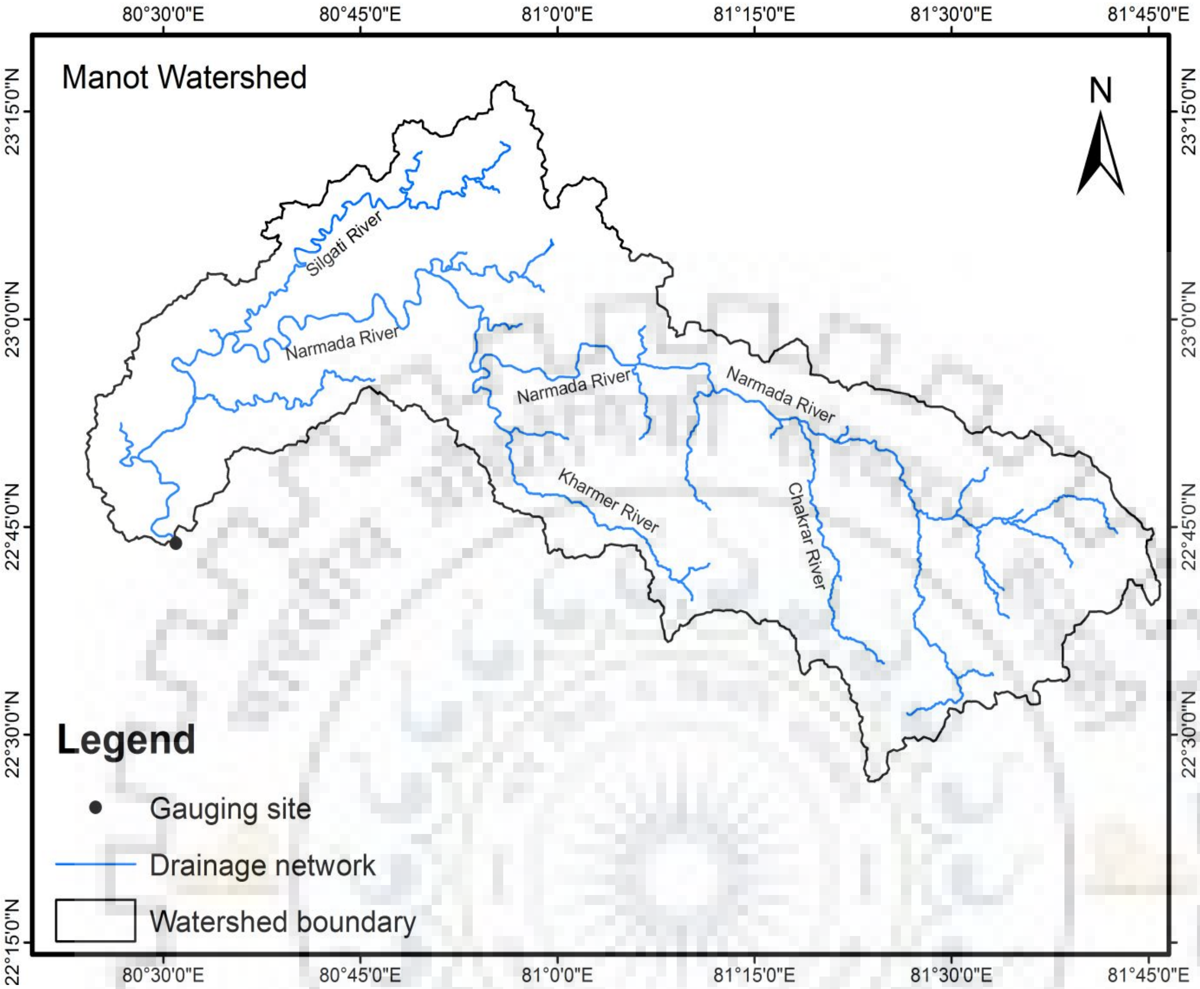


Figure 3.11 Drainage network of Manot watershed

Hridaynagar catchment: River Banjar rises from the Satpura range in Durg district and it is a tributary of River Narmada. It is an intermittent river; it has flow during June to February, and it runs dry during the rest of the months. Flow data of 1981-1989 were available; the river has low flow in 1987 since the annual rainfall in this year departed by about 34% than the mean annual rainfall. Hridaynagar is located at 21°42’ N latitude and 80° 50’ E longitude at an elevation of 600 m. The drainage area is about 3,370 km^2 and the elevation drops from 600 to 372 m at Hridaynagar gauging site. It receives the mean annual rainfall of 1,428 mm. About 90% of the annual rainfall is received during monsoon season. It has sub-tropical and sub-humid climate. Evapotranspiration varies from 4 mm/day in winter to 10 mm/day in summer. The area comprises of both flat and undulating lands covered with timber, grasses, and cultivated land. Soils vary from black to mixed red soils. The forests cover about 65% of the catchment area, about 29% of the area is used to grow agricultural crops, and the remaining part falls under water bodies and degraded lands. The drainage network of the watershed is presented in Figure 3.12.

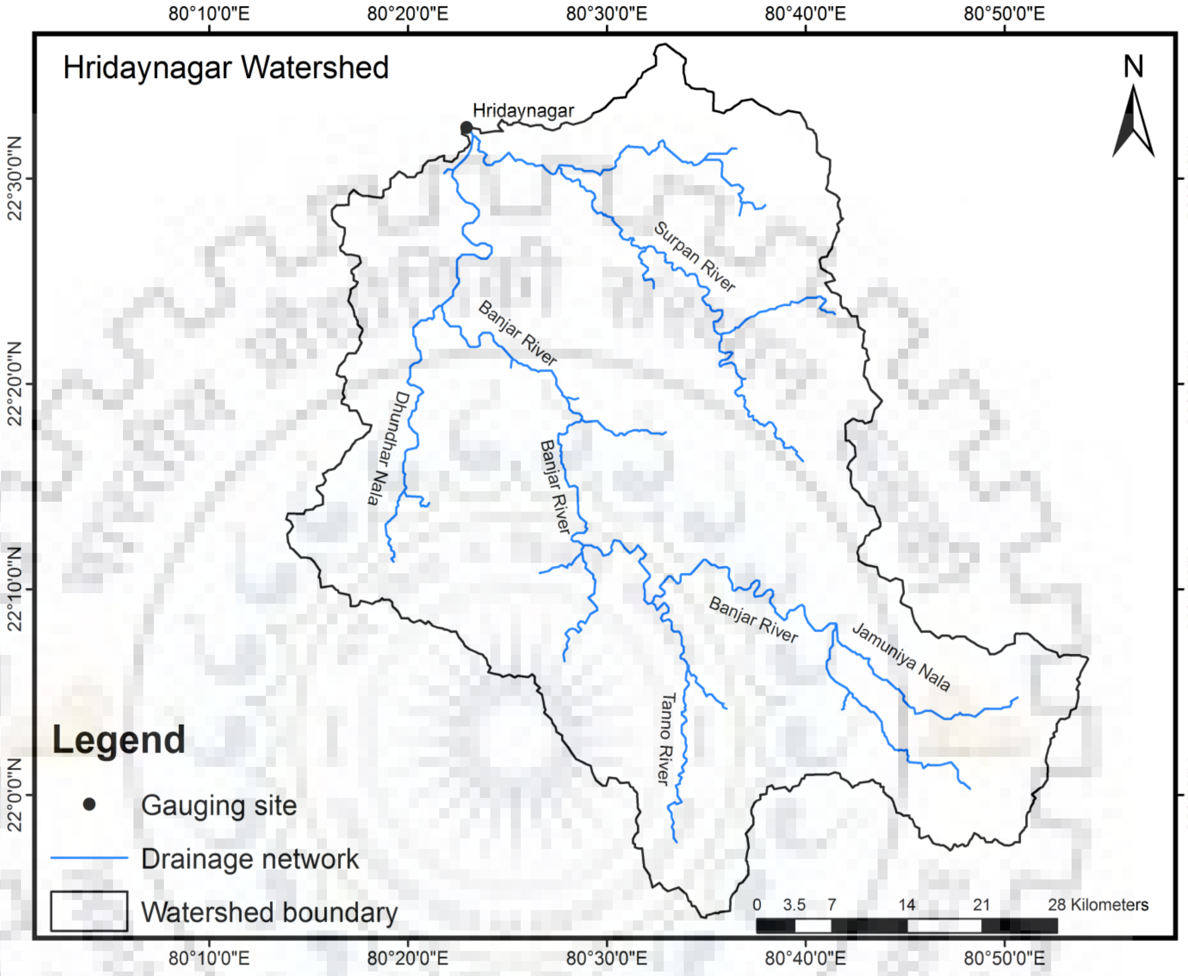


Figure 3.12 Drainage network of Hridaynagar watershed

Sher catchment: It lies between 22° 15'N to 23^{0} 05' N latitude and longitude between 79^{0} 00'E to 79^{0} 45'E. It rises in the southern Satpura range in the Seoni district at an elevation of 600 m (Jain et al. 2007, Deshmukh et al. 2010). Sher River has some flow throughout the year. It has good flow from June to February and low flow during March to May. Its catchment covers the area of 2901 km^{2} with the mean annual rainfall of 1042 mm, and receives 90% of the annual rainfall during south-west monsoon. Climate in this region is sub-tropical and sub-humid. The region consists of both flat and undulated lands. Soils in this region are mainly black soil. The drainage network of the watershed is presented in Figure 3.13.

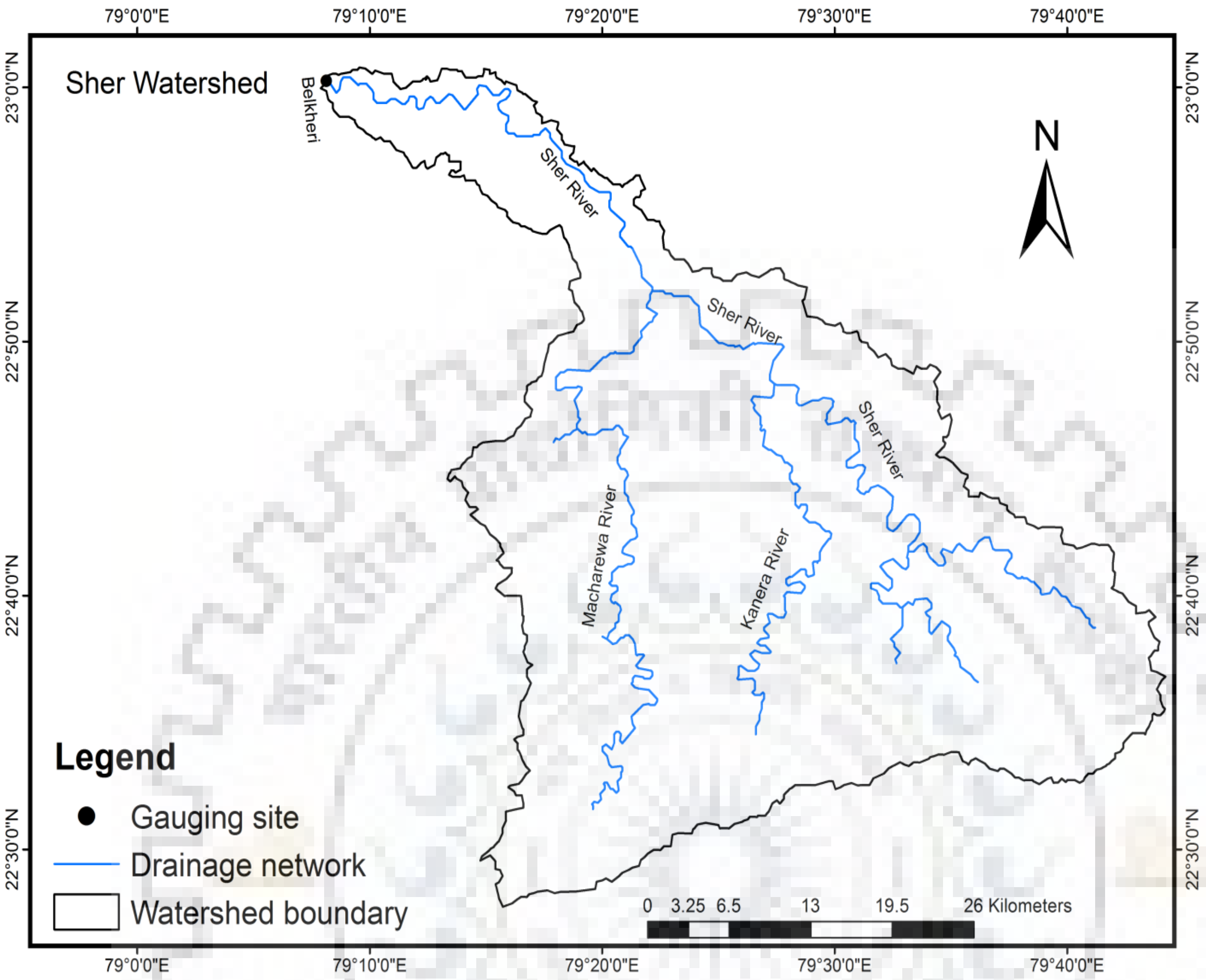


Figure 3.13 Drainage network of Sher catchment

3.2.2 High flow season

The study for the high flow season (July to September) utilizes the streamflow data of sixteen catchments located in different river basins viz. Mahanadi, Godavari, Brahmani-Baitarni and Tapi. The study area includes five catchments of Mahanadi basin (viz., Salebhata, Ghatora, Kurubhata, Rampur and Simga), nine catchments of Godavari basin (viz., Hivra, Jagdalpur, Kumhari, Nandgaon, Nowrangpur, Penganga, Ramakona, Sardaput, Satrapur), one catchment of Brahmani-Baitarini basin (i.e. Anandpur), and one catchment of Tapi basin (i.e. Burhanpur). The description of Salebhata, Ghatora, Kurubhata, Rampur, Hivra, Nandgaon and Anandpur catchments were discussed earlier in this chapter, the description of the remaining catchments are given a below:

Rampur Catchment: Jonk River, tributary of Mahanadi River, originates in Sundabeda plateau and enters Maraguda valley located in Naupada district in Odisha, India. The river flows through the Raipur district and traverse a length of 588 km before it joins Mahanadi at Sheorinarayan. The elevation varies from 231 m at Rampur gauging site to 700 m in the upper part of the watershed. The drainage area of catchment is about 2920 km^2. The climate of the region is sub-humid with mean annual rainfall of 1160 mm. The region consists of tropical vegetation. The drainage network of the watershed is presented in Figure 3.14.

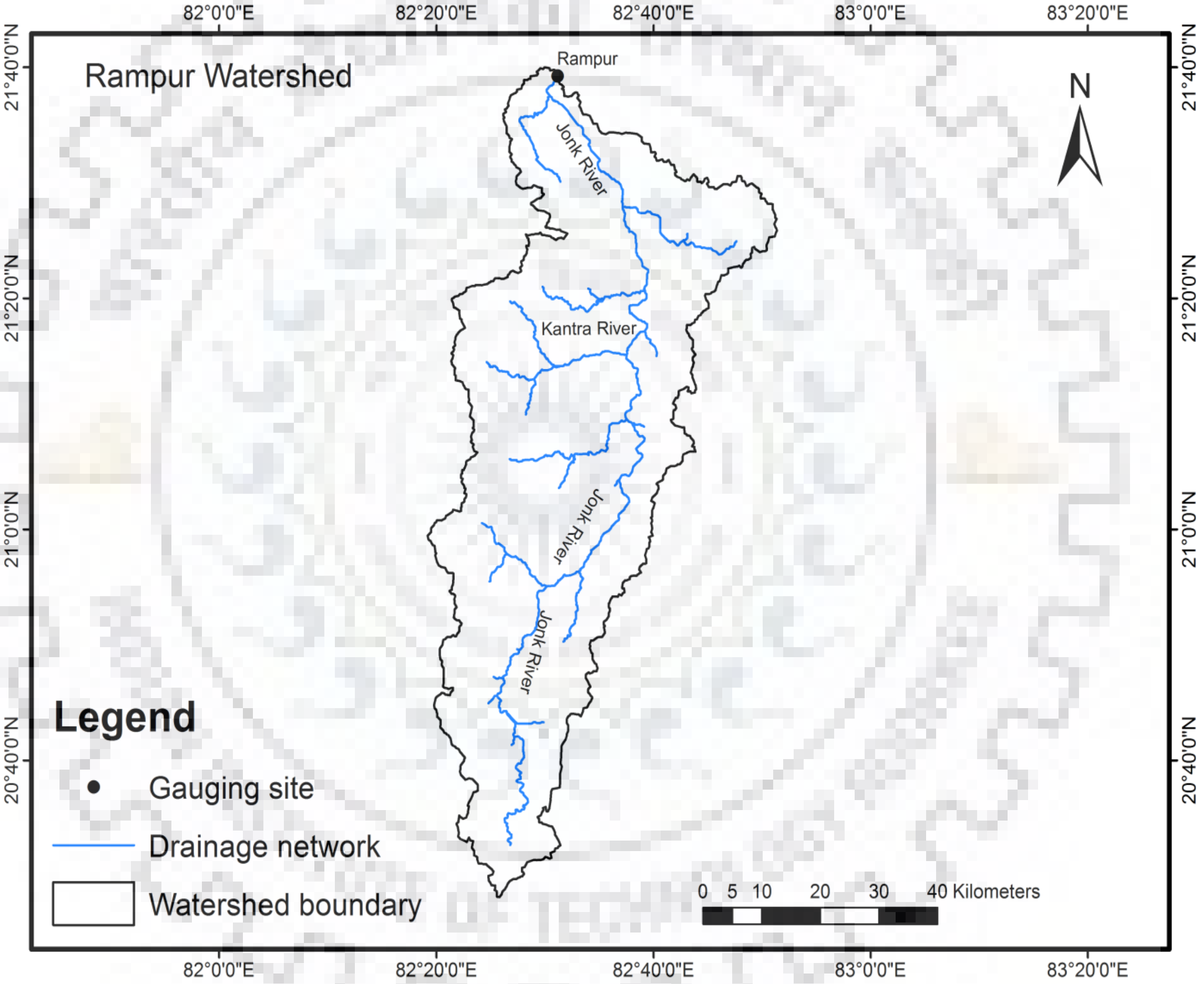


Figure 3.14 Drainage network of Rampur watershed

Simga Catchment: The Seonath River is major tributary of Mahanadi River originates near village Panabaras (Rajnandgaon, Chhattisgarh). The catchment (area = 30,761km^2) is located between latitude 20^0 16' N to 22^0 41' N and Longitude 80^0 25' E to 82^{0}35' E and flows through the length of

722 Km before it confluence with the Mahanadi River at Simga. The elevation of the catchment range from 745 m in upstream and drops to 219 m at Sigma gauging site. Kharun, Tandula, Hamp, Arpa, Agar and Maniyari Rivers are the main sub tributaries of Seonath River. The region has sub tropical climate with mean annual rainfall of 1170 mm. The drainage network of the watershed is presented in Figure 3.15.

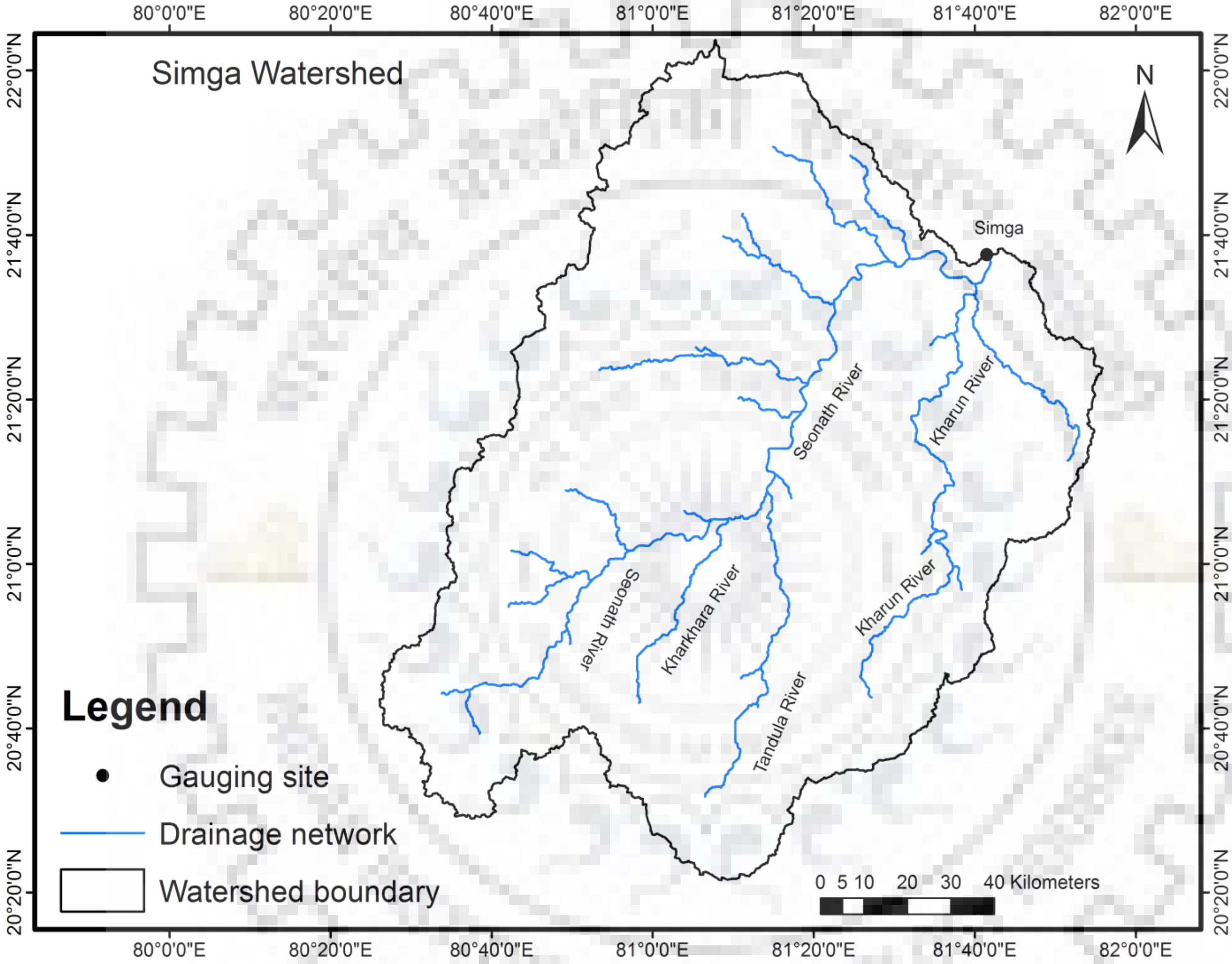


Figure 3.15 Drainage network of Simga watershed

Jagdalpur Catchment: The River Indravathi, tributary of Godavari River, rises in Dhandakaranya range at an elevation of 914 meters located in Kalahandi district of Odisha. It traverse the length of 166 km up to Jagdalpur gauging site located in Chhattisgarh (elevation=543 m) and covers the drainage area of 7380 km^2. The region has tropical climate with average annual rainfall of 1220 mm. The catchment has potential evapotranpiration rate in the order of 5-7.5 mm/day. The major part of the watershed is located in Nabarangpur, Koraput and Rayagada districts of Orissa and only few part lies in Bastar district of Chhattisgarh. The catchment is covered with both forest and cultivated lands. The drainage network of the watershed is presented in Figure 3.16.

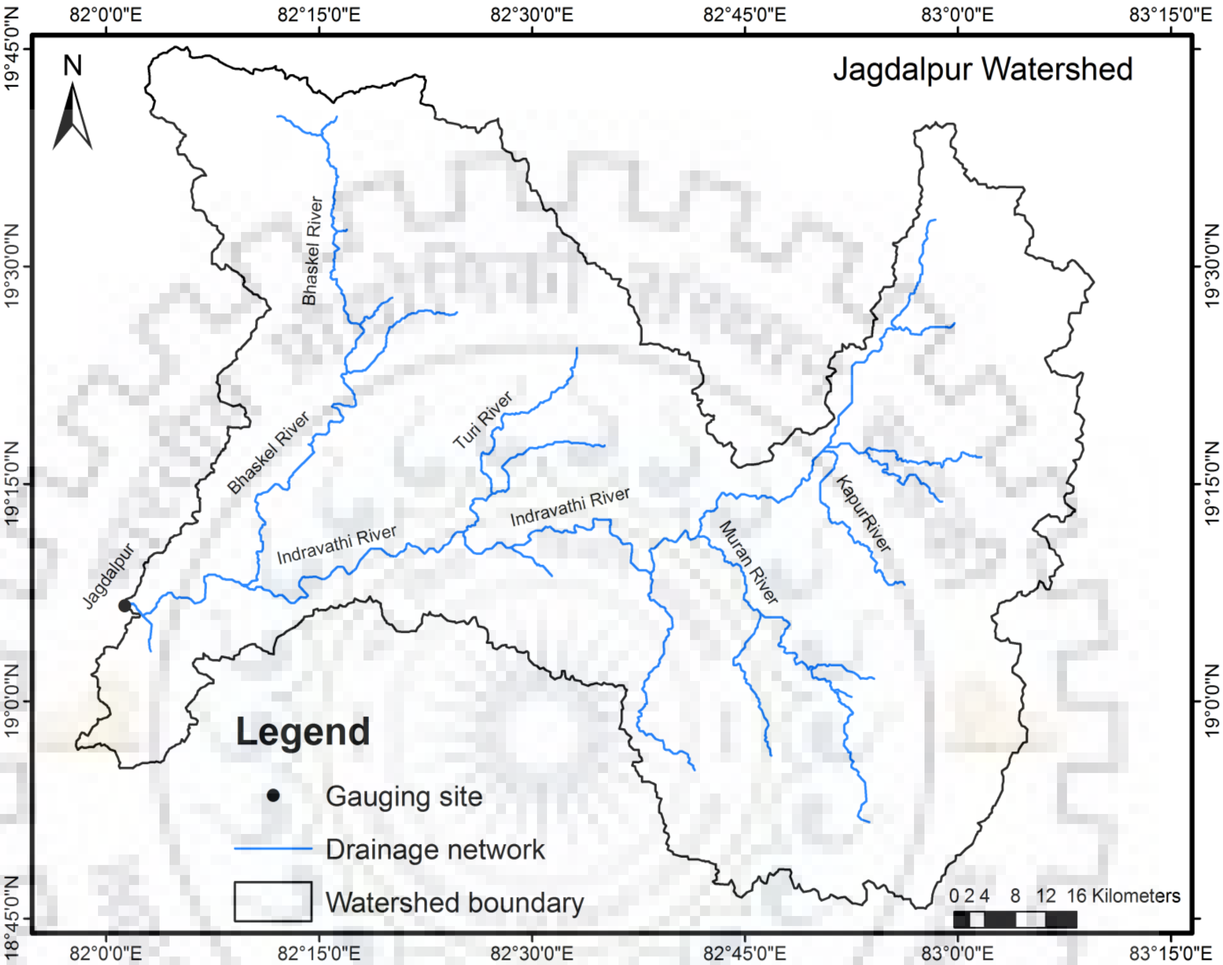


Figure 3.16 Drainage network of Jagdalpur watershed

Kumhari Catchment: The River Wainganga, sub-tributary of Godavari River originates in southern slopes of Satpura range at an elevation of 1048 m, in Mundara village located in Seoni district of Madhya Pradesh, India. Its gauging site at Kumhari covers the catchment area of 8070 km^2. The elevation of the watershed range from 289-860 m. The region has sub-tropical and sub-humid climate with average annual rainfall of 1280 mm and potential evapotranspiration between 5.5mm/day and 8.6 mm/day. The catchment area consist of both flat and undulating lands covered with forests and cultivated lands. The area is rich in black cotton soil. Wheat, millets, cotton, oil-seeds, pulses and rice are the major crops used to grow in the region. Major area of the watershed falls in Seoni and very few part is spread over the Mandla and Balaghat districts of Madhya Pradesh. The drainage network of the watershed is presented in Figure 3.17.

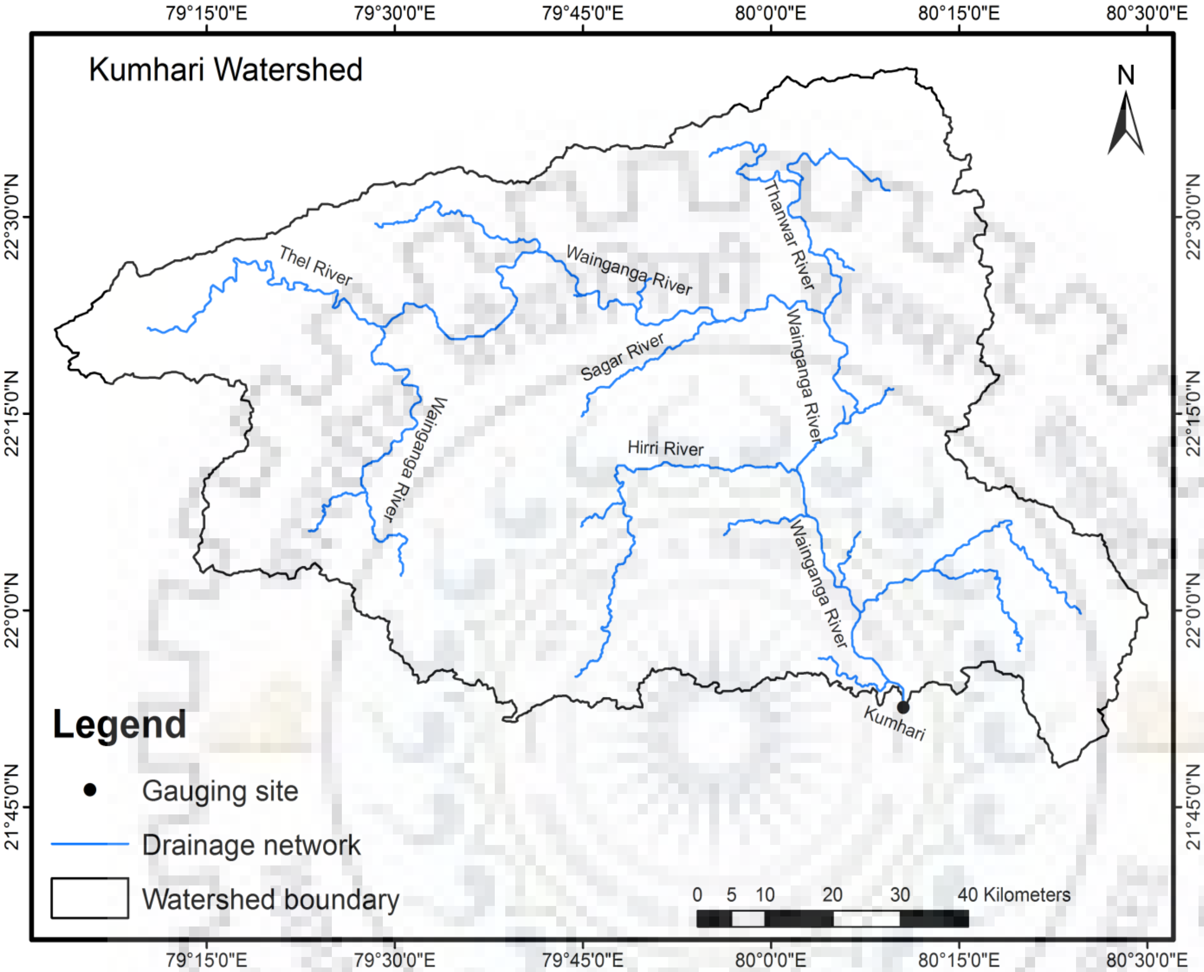


Figure 3.17 Drainage network of Kumhari watershed

Nowrangpur Catchment: The River Indravathi, tributary of Godavari River, rises in Dhandakaranya range at an elevation of 914 meters located in Kalahandi district of Odisha. It traverse the length of 94 km up to Nowrangpur gauging site (elevation=560 m) and covers the drainage area of 3545 km^2. Major portion of watershed area falls in Koraput and Rayagada districts while small part is located in Kalahandi and Nabarangpur districts of Orissa. The region has tropical climate with average annual rainfall of 1560 mm and potential evapotranspiration range from 5-7.5 mm/day. The catchment is covered with both forest and cultivated lands. Paddy and Maze are the major crops of this region. The drainage network of the watershed is presented in Figure 3.18.

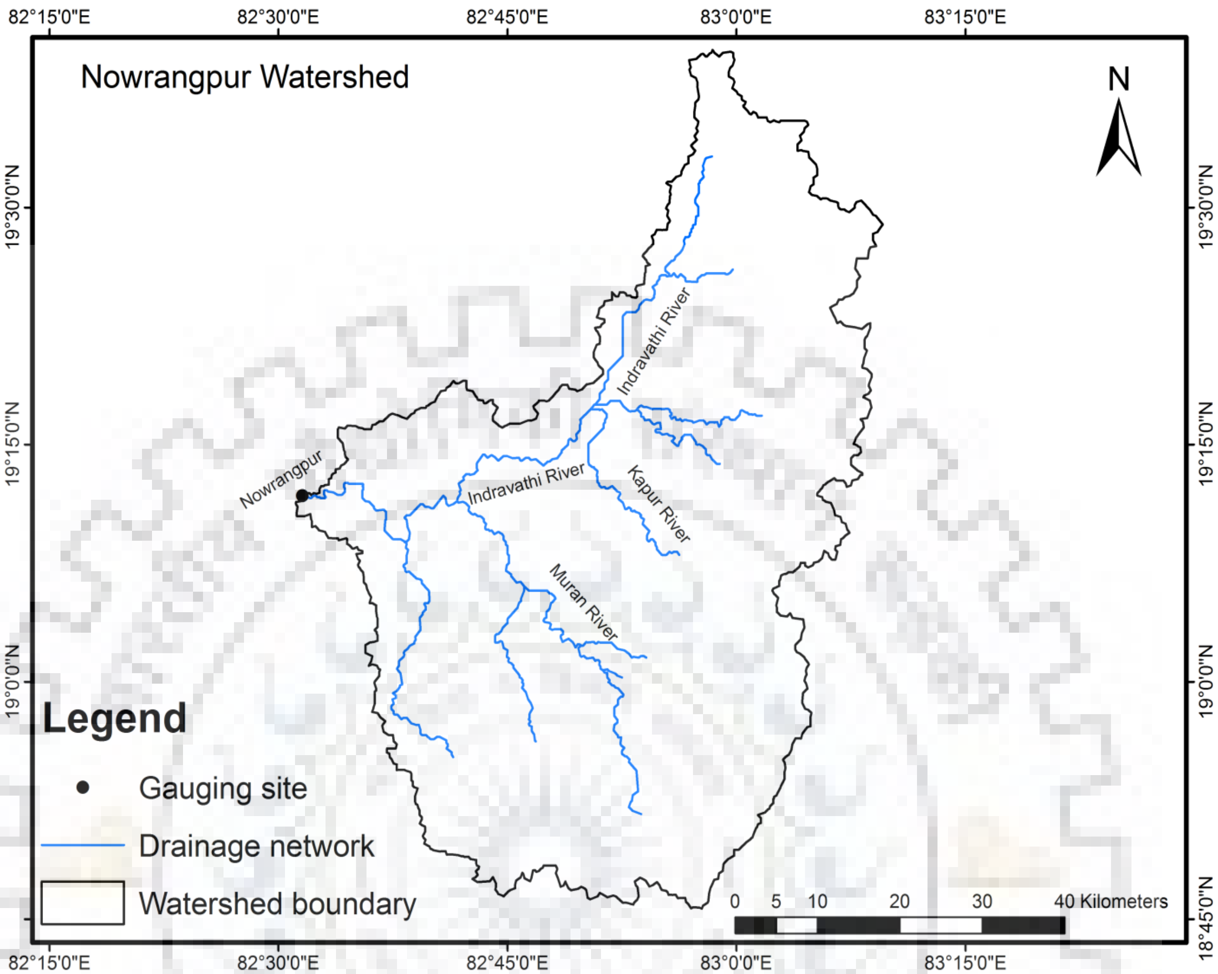


Figure 3.18 Drainage network of Nowrangpur watershed

Penganga Catchment: Penganga River, sub-tributary of Godavari River rises in Ajantha ranges in Aurangabad district of Maharashtra. It is the major river of Yavatmal district. The river covers the drainage area of 18441km^2 up to P.G. Bridge gauging site. The elevation in upper part of watershed is 650 m and drops to 229 m at P.G. Bridge gauging site. The region has sub-tropical climate with mean annual precipitation of 1015 mm. Potential evapotranspiration in the catchment range from 5.3 mm/day to 8.8 mm/day. The region has good cultivation of cotton and wheat. The watershed is spread over Yavatmal, Washim, Buldana and Hingoli districts of Maharashtra. The drainage network of the watershed is presented in Figure 3.19.

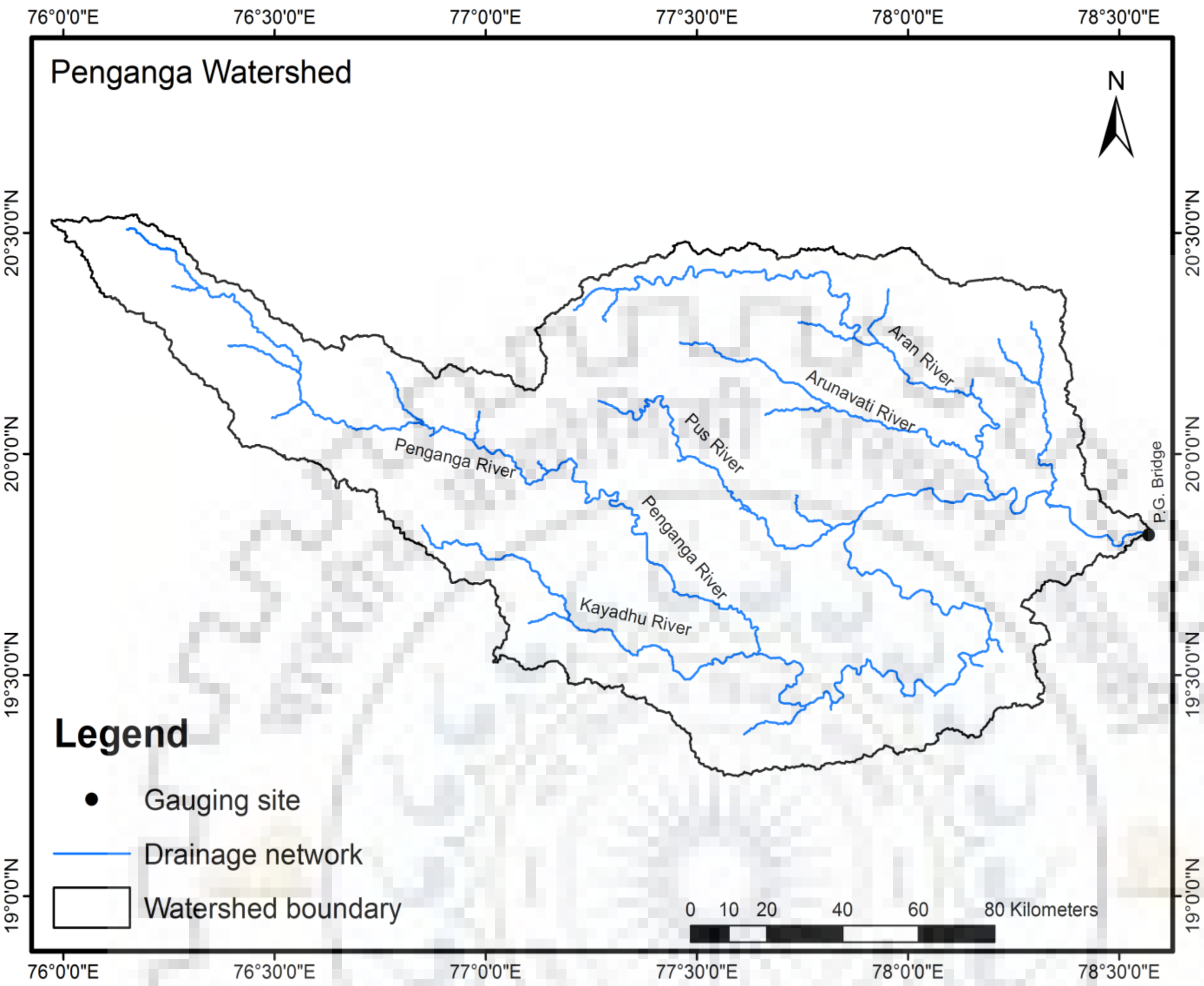


Figure 3.19 Drainage network of Penganga watershed

Ramakona Catchment: Kanhan River is tributary of Wainganga River and sub-tributary of Godavari River, rises in Satpura range near Chindwara district, Madhya Pradesh. The catchment area of the river at Ramakona gauging site is 2500 km^2. The elevation in upper part of the catchment is 1045 m and drops to 336 m at the gauging site. The region has subtropical and tropical wet and dry climate with average annual rainfall of 1080 mm and potential evapotranspiration is range from 4.8-8.6 mm/day. Most of the part located in Chhindwara and remaining portion of the watershed falls in Betul district of Madhya Pradesh. The catchment is covered with both forest and cultivated lands. Major commercially harvested trees are bamboo, teak, saalbee, harra and tendu patta. The drainage network of the watershed is presented in Figure 3.20.

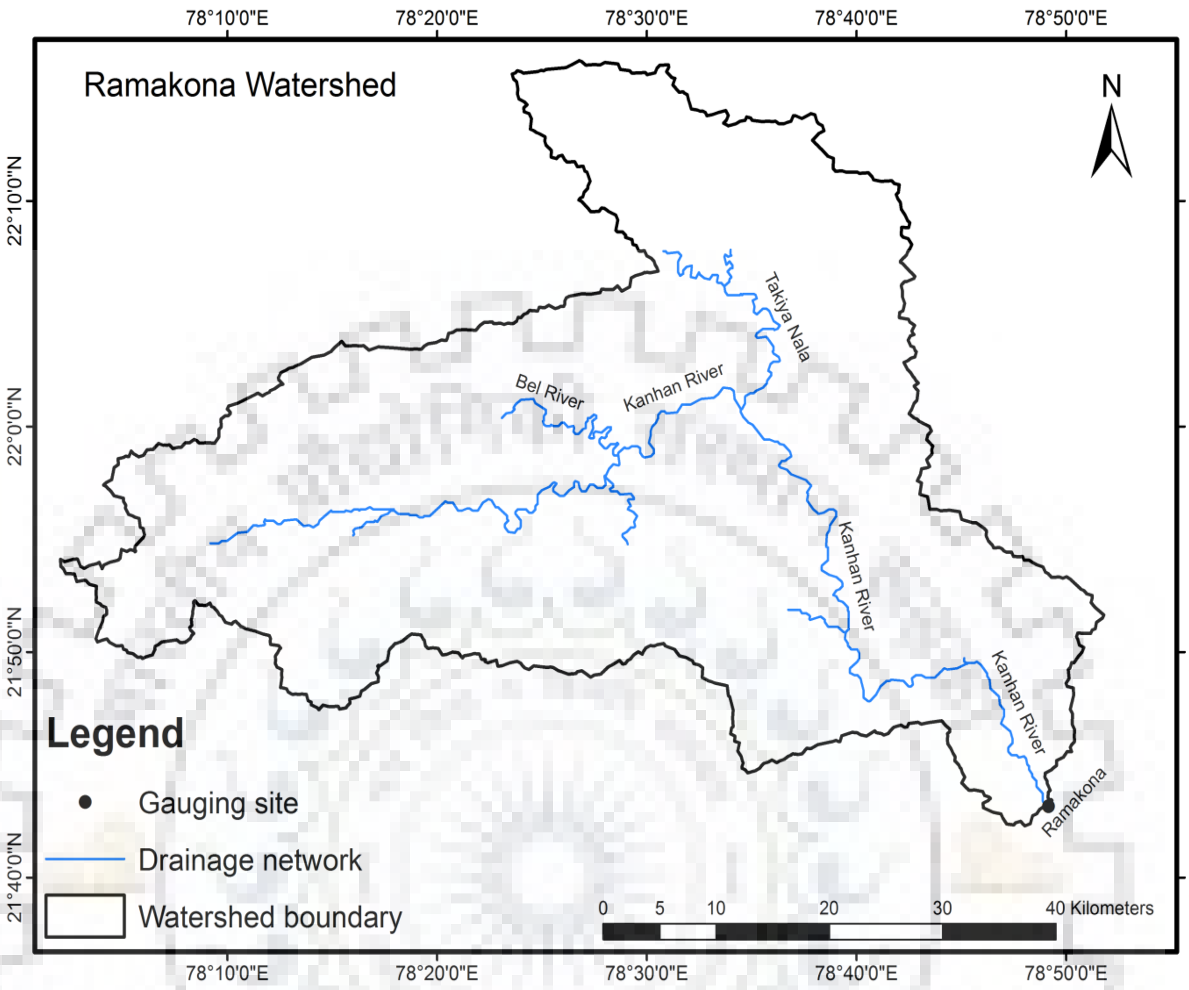


Figure 3.20 Drainage network of Ramakona watershed

Sardaput Catchment: Sabari River is the main tributary of Godavari River, rises in Sinkaram hills at an elevation of 1370 m in Kunavaram, Andhra Pradesh. The river traverse through the length of 185 km up to Sardaput (elevation=240 m) gauging site, covering the catchment area of 3047 km^2. The region receives the average annual rainfall of 1320 mm, and have sub tropical humid climate. The potential evapotranspiration in the region varies from 5 mm/day to 7.6 mm/day. The catchment comprises of both forest and cultivated lands. Soils are mostly red mixed with organic matter and the major crops in the region are paddy, ragi, maize etc. Around 90% of the catchment area lies in Koraput district of Orissa and only 10% of the area is located in Bastar district of Chhattisgarh. The drainage network of the watershed is presented in Figure 3.21.

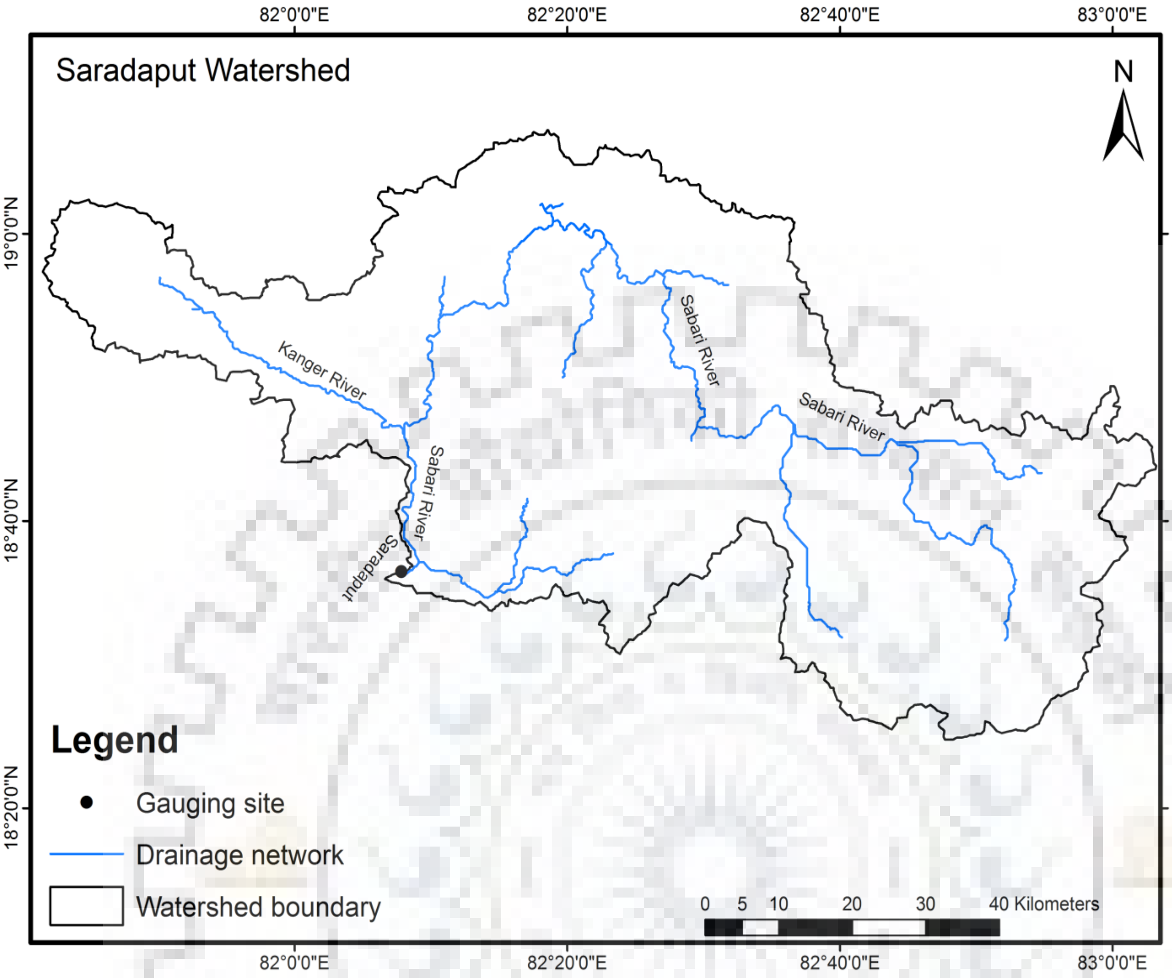


Figure 3.21 Drainage network of Saradaput watershed

Satrapur Catchment: Kanhan River is tributary of Wainganga River and sub-tributary of Godavari River, rises in Satpura range near Chhindwara district, Madhya Pradesh. The catchment area of the river at Satrapur gauging site is 11100 km^2. The highest elevation of the catchment is 990 m in the upper part and lowest of 290 m at the gauging site. The region has tropical savannah climate with average annual rainfall of 1110 mm and potential evapotranspiration between 5 mm/day to 8.8 mm/day. The major portion of watershed spreads over Chhindwara (Madhya Pradesh) and Nagpur (Maharashtra), very small part falls in Betul and Seoni districts of Madhya Pradesh. The catchment comprises of both flat and undulating lands in which major part is covered with forest. The drainage network of the watershed is presented in Figure 3.22.

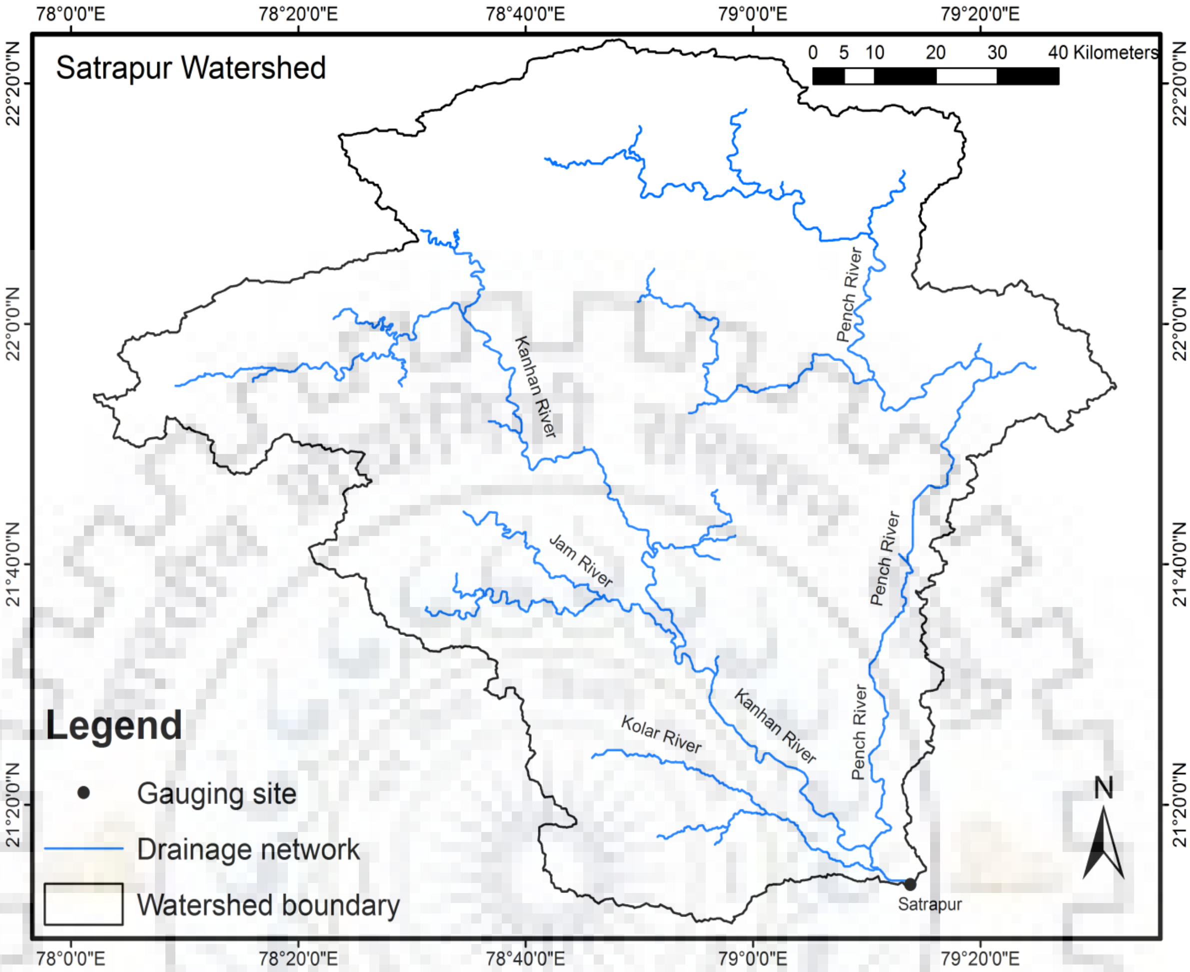


Figure 3.22 Drainage network of Satrapur watershed

Burhanpur Catchment: River Tapi is one of the major rivers in India. The river rises in Gawilgarh hills of Deccan plateau at an elevation of 752 m. The river flows through the state of Madhya Pradesh, Maharashtra and Gujarat, traversing a length of 724 km. Its catchment at Burhanpur covers the area of 8487 km^2. The catchment has elevation maximum of 890 m and lowest of 220 m. The region has sub-tropical climate with average annual rainfall of 840 mm. Potential evapotranspiration in the catchment varies from 5.2 mm/day to 8.8 mm/day. Watershed area spreads over Betul and East Nimar districts of Madhya Pradesh, and Nagpur (Maharashtra). The catchment comprises of both flat and undulating lands covered with timber, grasses and cultivated lands. The drainage network of the watershed is presented in Figure 3.23.

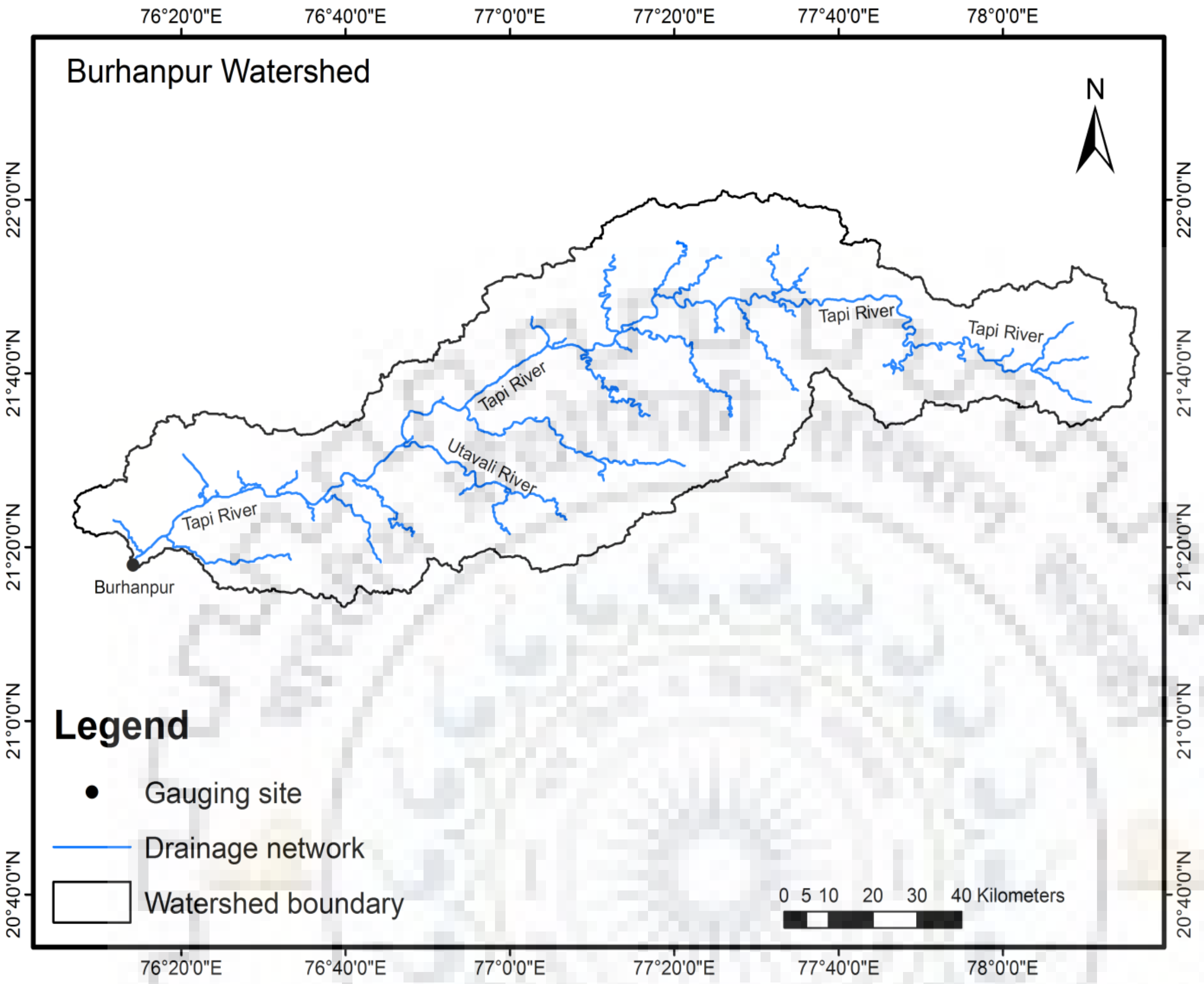


Figure 3.23 Drainage network of Burhanpur watershed

3.4 DATA USED

Various kind of meteorological and hydrological data sets have been used for the accomplishment of different type of analysis for given objectives. The data used during the study are rainfall, discharge, potential evapotranspiration and temperature.

3.4.1 Rainfall

The district wise monthly rainfall for the period of 113 years (1901-2013) of 516 districts located in the different climatic regions of India has been used to analyse the drought characteristics (i.e. frequency, severity and persistence) across the country. The data for the above period has been obtained from India Meteorological Department, Pune. The missing data has been filled by taking the average of the rainfall of the surrounding districts. The location of the of all 516 district raingauge stations whose data has been used in the study is presented in Fig. 3.24.

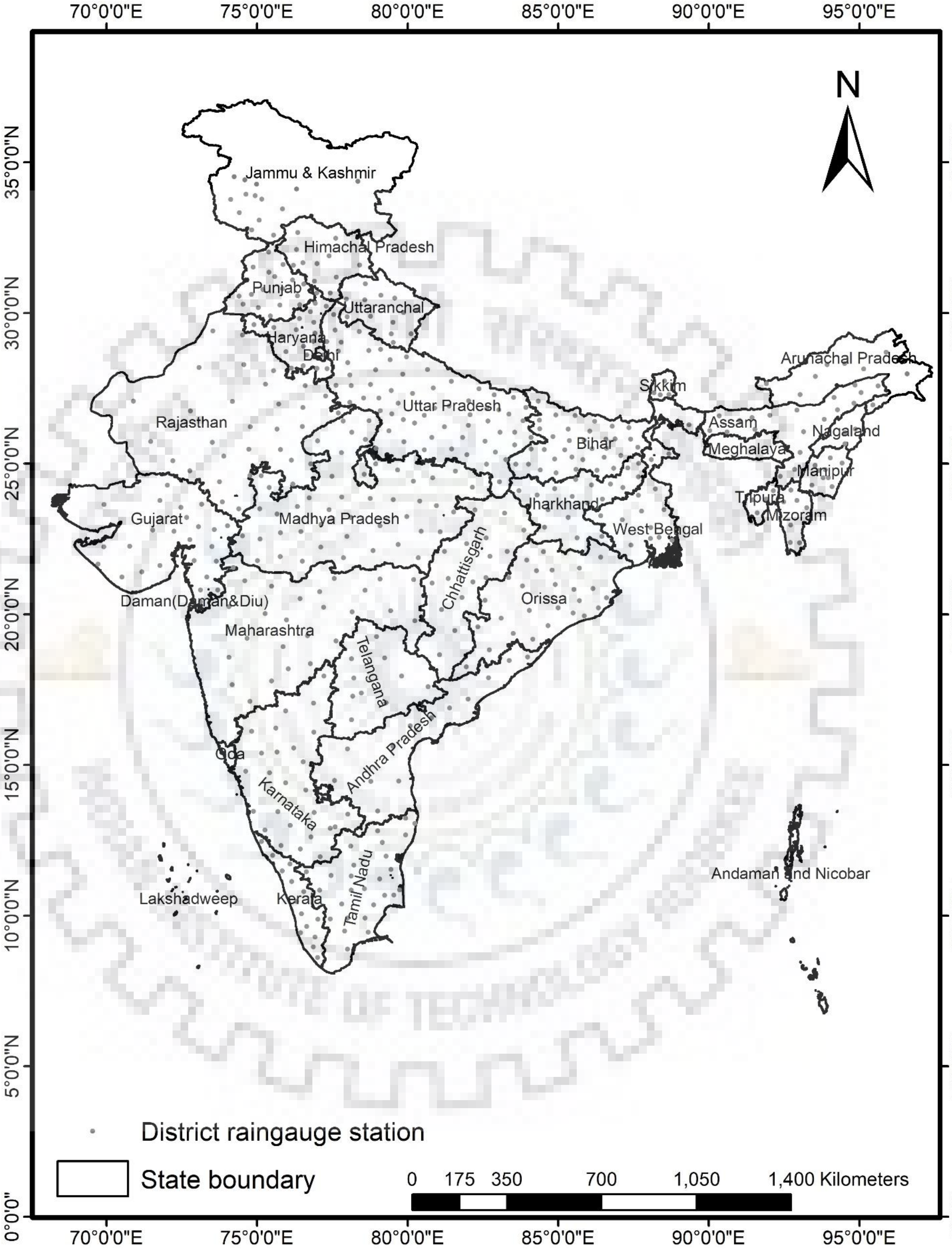


Figure 3.24 Location of district rain gauge station

3.4.2 Potential evapotranpiration

The average annual potential evpotranspiration data for the different districts used in the study have been obtained from the website of India Water Portal. The ratio of mean annual potential to mean annual rainfall are used to describe the variation in drought characteristics in different climatic regions.

3.4.3 Temperature

The daily normals of maximum and minimum temperature of 256 districts for 44 years period (1970 to 2013) located in different climatic regions of India has been obtained India Meteorological Department, Pune. These data were used to relate the frequency and severity of drought events with the range of annual temperature variation.

3.4.4 Discharge

The discharge data for the different periods of the above discussed watersheds has been obtained from the website of India WRIS, a joint venture of the Central Water Commission (CWC), Ministry of Water Resources, River Development & Ganga Rejuvenation, Government of India and Indian Space Research Organization (ISRO), Department of Space, Government of India. The rainfall and discharge data of the catchments were used to explore the relationship between SPI and environmental flow condition. The data length of the different watersheds used in the study are summarized in Table 3.1.

Table 3.1 Data length of the watersheds used in the study

Sr. No.	Watershed	Data length (monthly)	Sr. No.	Watershed	Data length (monthly)
1	Ghatora	1991-2007	12	Rampur	1991-2007
2	Kurubhata	1991-2007	13	Simga	1991-2007
3	Salebhata	1991-2007	14	Jagdalpur	1990-2007
4	Anandpur	1991-2007	15	Kumhari	1990-2007
5	Jaraikela	1991-2006	16	Nowrangpur	1990-2007
6	Hivra	1990-2007	17	Penganga	1980-1997
7	Nandgaon	1990-2007	18	Ramakona	1990-2007
8	Mohegaon	1981-1990	19	Saradaput	1990-2007
9	Manot	1981-1990	20	Satrapur	1990-2007
10	Hridaynagar	1981-1990	21	Burhanpur	1990-2007
11	Sher	1978-1986			

CHAPTER 4

REGIONAL CLIMATIC PARAMETERS AND DROUGHT CHARACTERISTICS

4.1 INTRODUCTION

Drought is a natural phenomenon caused by the occurrence of less than the average rainfall for longer duration (Wilhite et al., 2000; Pandey and Ramasastri, 2001; Tallaksen et al., 2004; Mishra and Singh, 2010; Dai, 2013; Van Loon and Van Lanen, 2012). The drought characteristics changes with the change in climatic conditions. It is important to understand the change in the behavior of various drought characteristics across the different climatic regions. The frequency, severity and duration of the event are referred as drought characteristics and these characteristics vary across the different climatic regions (Dracup *et al.*, 1980; Gregory, 1989; Ponce *et al.*, 2000; Pandey & Ramasastri, 2001, 2002). The global warming is one of the major reason of the increased severity and frequency of drought events in the recent decades (Cook et al., 2004; Trenberth et al., 2004; Vicente-Serrano et al., 2010; Dai, 2011; IPCC, 2013; Liu et al., 2016). The development in agriculture practices leads to significant increase in the water requirement in the semiarid areas all over the world (Dalezios and Bartzokas, 1993, 1995; Dalezios et al., 2000). Further, the variation and change in climate increases variability in distribution and amount of rainfall which leads to the occurrence of frequent droughts (Dalezios et al, 1991; Dalezios et al., 2000; Mishra and Singh, 2010). An year is said to be drought year if it receives the less than 75% of mean annual precipitation. The duration of drought events may lasts for one or more consecutive years. The number of years that a drought event of a particular severity likely to recur is said to be drought frequency (*F*); for example, once in 5 years. The return period (T) is the inverse of the frequency which also called recurrence interval (T=1/F). In general both frequency and return period are often used synonymously.

The primary purpose of this chapter is to present the relationship of common climatic parameters with drought characteristics in different climatic regions. It is hoped that this study may enhance understanding and ability to cope with adverse impacts of droughts on the society.

4.2 CLIMATIC CLASSIFICATION

Many classifications of climate have been proposed from time to time by various researchers based on the characteristics of plant or vegetation and temperature. During the nineteenth century biologists were initially thought about the climatic classification of living cover of the earth (Koppen, 1931; Thornthwaite 1948). They initially considered plant/vegetation characteristics and natural landscape to describe global climate classes.

4.2.1 Historical Climatic Classification

Köppen and Geiger, (1939) on the basis of certain critical values of precipitation and temperature divides the earth's surface into five great climatic zones. These five climatic zones were described as dry, tropical rainy, temperate rainy, cold snowy forest, and polar climate. For a certain region less precipitation than the evaporation is the basis to indicate the dryness of the climate. These can be determined from the average annual precipitation and average annual temperature. The average temperature of at least 18°C in the coldest month distinguished the climate as tropical rainy. The mean temperature of below 10°C in hottest month and below -3°C in coldest month describes the climate as polar climates and cold snowy forest respectively. Rest of the climates was said to be temperate rainy. On the basis of differences in the seasonal distribution of precipitation and temperature these climatic groups were further sub divided (Köppen 1931; Köppen and Geiger, 1939).

Köppen and Geiger (1928) used many formulae to find this critical value of rainfall (R), and lastly concluded to the relationship $R = 0.44(T-k)$ for the estimation of the value of critical rainfall, where T represents the mean annual temperature, and the value of the constant k may be estimated by the seasonal concentration of rainfall. The regions with rainfall more than R were thus classified as humid while the regions where rainfall is less than R were said to be dry. In spite of the wider acceptance of the Köppen's climatic classification, Trewartha (1943) noted that Köppen's classification was criticized from various drawbacks (Ackerman 1941; Jones and Weymouth 1997).

The various studies have been done on the classification of climatic regions for many years by various researchers' leads to think that like any other variable quantities the world can also be classified into different climatic groups. The climatic classification was proposed on the basis of balance between moisture and incoming and outgoing heat at the earth's surface (Thornthwaite, 1948). To define climatic regions precipitation (P) and potential evapotranspiration (PE) were used as important climatic factors (Pandey and Ramasastri, 2001). The relative moistness and aridity of the climate was expressed by comparing the potential evapotranspiration with the precipitation and the periods of excess (S) and moisture deficiency (D) using a simple water balance concept. Finally, an annual/seasonal moisture adequacy index, I_m, was derived from the following relationships (Eqs. 4.1 & 4.2).

$$I_m = \frac{100(S - D)}{PE} \qquad (4.1)$$

If the soil moisture is assumed to be constant, the equation is simplified to:

$$I_m = 100(\frac{P}{PE} - 1) \qquad (4.2)$$

Based on I_m, the earth's climatic system was categorized into nine classes (Table 4.1).

Table 4.1: A rational classification of climate by Thornthwaite (1948)

Sl No.	Climate Type	Climate code	Moisture index, I_m
1	Perhumid	A	100 and above
2	Humid	B_4	80 to 99.9
3	Humid	B_3	60 to 79 9
4	Humid	B_2	40 to 59.9
5	Humid	B_1	20 to 39.9
6	Moist subhumid	C_2	0 to 19.9
7	Dry subhumid	C_1	-19.9 to 0
8	Semiarid	D	-39.9 to - 20
9	Arid	E	-60 to - 40

The climatic regions were also classified on the basis of aridity index. The United Nations Environment Programme (UNEP) adopted the aridity index and defined as:

$$\mathrm{AI} = \frac{\mathrm{P}}{\mathrm{PET}}$$

Where PET is the potential evapotranspiration and P is the average annual precipitation (UNEP, 1992). Here also, PET and P must be expressed in the same units, e.g., in millimetres. The climatic classification based on the aridity index (UNEP, 1992) is given in table 4.2.

Table 4.2 UNEP classification of aridity index

Classification	**Aridity Index**
Hyper arid	AI<0.05
Arid	0.05<AI<0.20
Semi-arid	0.20<AI<0.50
Dry sub humid	0.50<AI<0.65

Ponce et al. (2000) proposed a classification based on the ratio of mean annual precipitation (P_{ma}) to annual global terrestrial precipitation (P_{agt}). The moisture stored in atmosphere is different in different climatic regions. In polar and arid regions it varies from 2-15 mm while in humid regions the stored moisture is in the range of 45-50 mm. The value of 25 mm was assumed as global terrestrial mean to calculate annual global terrestrial precipitation. On an average the atmospheric moisture recycle at every 11 days which becomes 33 cycles in one year (L'vovich, 1979), so the annual global terrestrial precipitation comes out to be 825 mm but for calculation purpose it was rounded off to 800 mm. The range of mean annual terrestrial precipitation lies between 100-6400 mm. Ponce et al. (2000) classified the climate into eight classes as given in Table 4.3.

Table 4.3 Classification of climate by Ponce et al. 2000

S. No.	**Climate class**	**P_{ma} /P_{agt} ratio**
1	Superarid	$P_{ma}/P_{agt} < 0.125$
2	Hyperarid	$0.125 \leq P_{ma}/P_{agt} < 0.25$
3	Arid	$0.25 \leq P_{ma}/P_{agt} < 0.5$
4	Semiarid	$0.5 \leq P_{ma}/P_{agt} < 1$
5	Subhumid	$1 \leq P_{ma}/P_{agt} < 2$
6	Humid	$2 \leq P_{ma}/P_{agt} < 4$
7	Hyperhumid	$4 \leq P_{ma}/P_{agt} < 8$
8	Superhumid	$P_{ma}/P_{agt} \geq 8$

The above classification was subsequently revised by Pandey and Ramasastri (2002) for drought characterization in mid-latitudinal regions. The climatic spectrum has been classified on the basis of ratio of mean annual potential evapotranspiration to mean annual precipitation (PET/P), and length of wet season which has been utilized in this study. The climatic classification proposed by Pandey and Ramasastri (2002) is presented in Fig. 4.1.

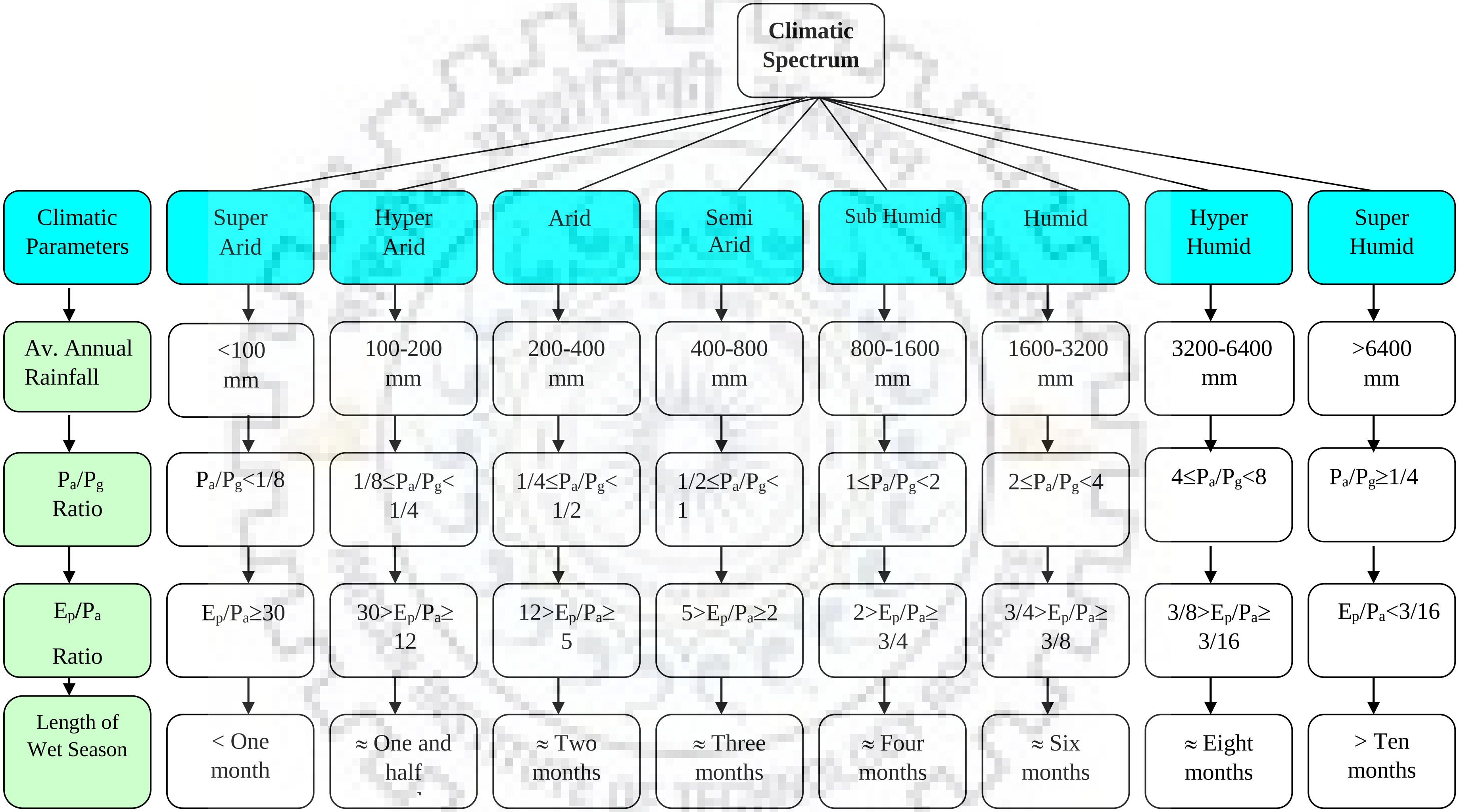


Figure 4.1 Classification of Mid-climatic regions (Pandey and Ramasastri, 2001)

The various climatic region of India is presented in Figure 4.2.

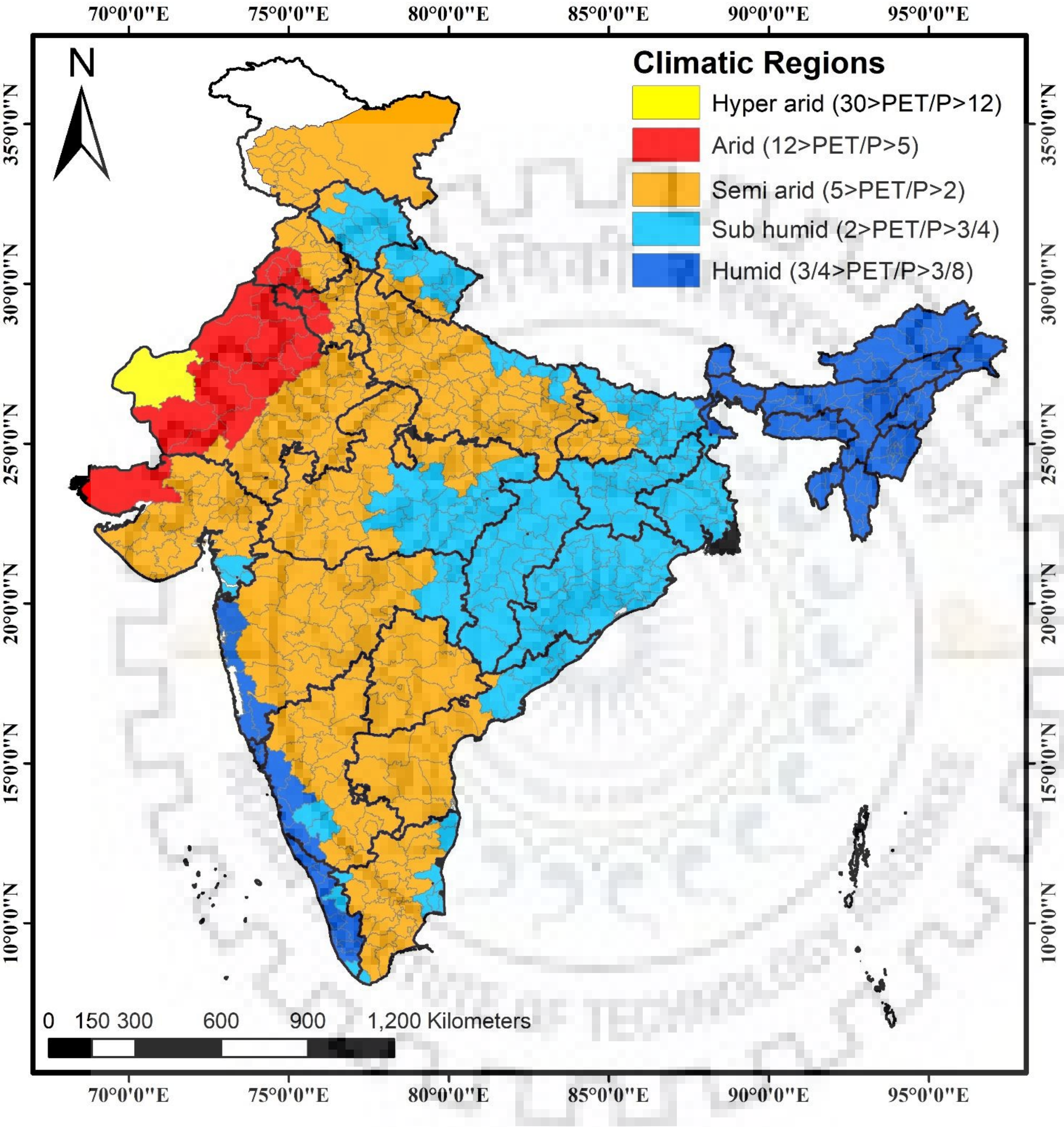


Figure 4.2. Spatial distribution of climatic regions in India

4.3 APPROACH AND DATA USED IN THE STUDY

In the present analysis, the seasonal rainfall of 516 districts covering the different climatic regions of India for the period from 1901-2013 (113 years) were analyzed. The percentage departure of seasonal rainfall series from the corresponding long term mean were estimated for each of the 516 stations for the identification of drought events and drought years. In India, about 80-90% of the annual rainfall occurs during the monsoon (rainy) season and the deficit during the monsoon season of a year usually continue till the arrival of next monsoon season. Therefore, in this study the seasonal rainfall departure from corresponding long term mean has been used to identify the drought years and its severity.

The IMD defines, the drought as the season/year when the deficiency of rainfall is more than 25% of corresponding mean (Yadav et al., 2015; Amrit et al., 2017). The percentage of seasonal rainfall departure from the long term mean were plotted for the identification of drought years. The sample plot of seasonal rainfall departure for Ahmadabad station in Gujarat is presented in figure 4.3.

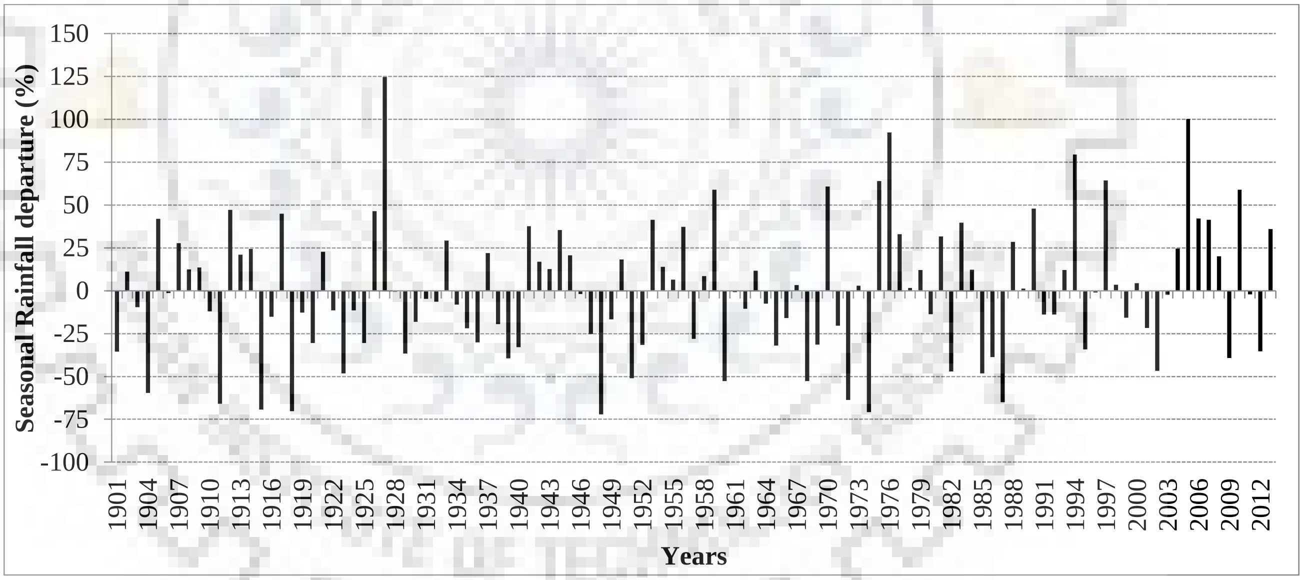


Figure 4.3. Plot of percentage seasonal rainfall departure from mean for Ahmadabad, Gujarat

The mean annual potential evapotranspiration of 516 districts obtained from the website of India Water Portal. Scrutiny of long-term rainfall records from 516 stations in India indicated that the mean annual rainfall (P) ranges from 100 mm at Jaisalmer in Rajasthan to 4700 mm at Tamenlong in Manipur and the mean potential evapotranspiration varies from 1340 mm in Kottayam, Kerala to 2664 mm at Jaisalmer (in Rajasthan).

4.4 DROUGHT CHARACTERISTICS AND CLIMATIC PARAMETERS

There is a growing need to improve the understanding and capability to analysis of drought characteristics in different climatic regions. The changeability of the climate is an integral part of a general weather in any region (Daradur and Nedealkova 2000). The drought characteristics refer to the frequency, severity and the duration (or persistence) of events over a given region. These characteristics vary across the climatic regions (Gregory, 1989; Ponce et al., 2000; Pandey and Ramasastri, 2001; 2002; Mishra and Singh, 2010). The main climatic parameters used in this study are average annual precipitation and average annual potential evapotranspiration.

The major indicator used in the analysis of drought characteristics in most of the studies are long term precipitation record (Herbst et al., 1966; Mohan & Rangarcharya, 1991; Dalezios et al., 2000; Ponce et al., 2000; Wilhite, 2000; Pandey & Ramasastri 2001 and 2002; Mishra and Singh, 2010; Dogan et al., 2012; Pandey et al., 2014; Moorhead et al, 2015). Therefore, the most widely used perception of drought is as meteorological phenomenon that occurs due to the less than the average rainfall at a particular place over a given period of time. The drought occurs when the occurrence of annual or seasonal rainfall is less than 75% of the corresponding mean while others might consider it to occur at or below 60 or 50% of normal (Glantz 1994). The climatic parameters are defined in terms of the ratio of average annual potential evapotranspiration (PET) and average annual precipitation (P). It is hoped that the relationships between the PET/P ratio and the drought characteristics sensitize the drought mitigation system for proactive planning based on long term regional pattern.

4.5 RETURN PERIOD

The average return period of drought for each of the 516 station was calculated by dividing the total number of years of data analysed by the total number of years with rainfall deficit more than 25%.

$$\text{Average return period of drought} = \frac{\text{Total number of years of data analysed}}{\text{Total number of drought years}}$$

Similarly, the return periods of severe and extreme drought events were computed as the total number of years of record analyzed divided by the number of severe/extreme drought events in each district. The average return period of drought in the different districts of India is shown in Fig. 4.4.

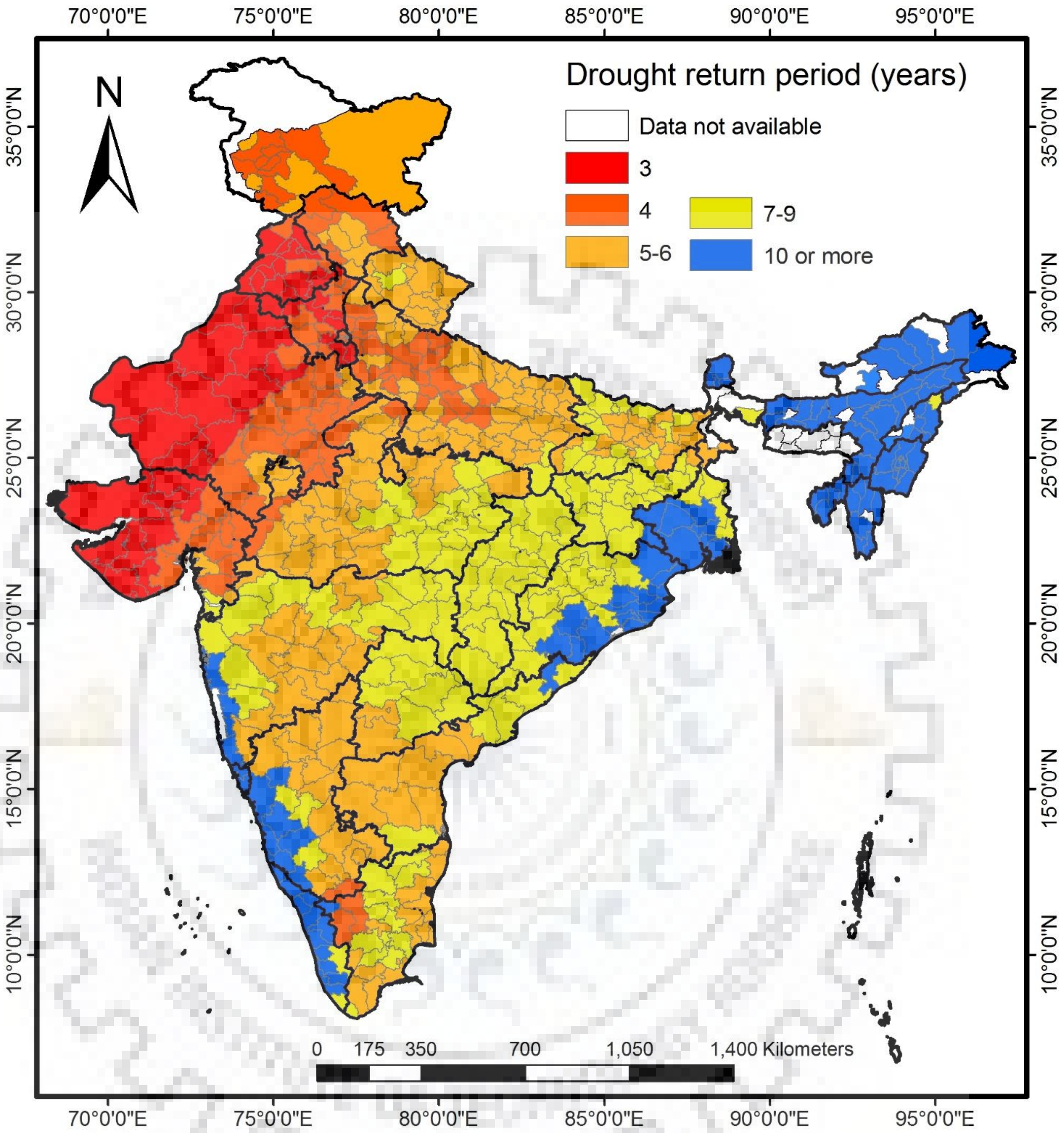


Figure 4.4. The average return period of drought in different districts of India

It is clear from Fig. 4.4 that the north western part of India which covers the states of Rajasthan, Gujarat, Haryana and Punjab are very susceptible to drought having the average drought frequency between once in 3 years to once in 4 years. The states of Uttarakhand, western Madhya Pradesh, Karnataka, southern Maharashtra and eastern Uttar Pradesh has the average drought return period of 5-6 years. The average return period of drought has been estimated to be in the range of 7-9 years in the states of Chhattisgarh, Jharkhand, eastern Madhya Pradesh, eastern Maharashtra, northern Andhra Pradesh and western Orissa. The coastal regions of Maharashtra, Karnataka, Kerala Orissa has the average drought frequency of once in 10 years or more. The north eastern states of the country has the average drought return period of more than 10 years. It can be seen from the Fig.4.3 that as moving from west to east (i.e. arid to humid) part of the country the drought becomes less frequent.

4.5.1 Relationship of PET/P Ratio and Drought Return Period

Regressions have been applied to explore the relationships between the PET/P ratio and average return period of drought. The inferences for drought frequency (F) have been drawn in relation to the PET/P ratio. A comparison of results of this study with various literature on drought experience in the other parts of the world shows that they are in good agreement which represents the significance of the study. The exponential and power type regressions have been applied in order to relate the PET/P ratio with the average return period of drought, as the ratio of average annual potential evapotranspiration to average annual precipitation (PET/P) may never be zero.

The coefficient of determination ($R^2 = 0.711$) in power type regression (Figure 4.5) showed very good correlation than that of the exponential or logarithmic type regression. It is evident from Figure 4.5 that the average return period of meteorological droughts has notable relationship with the PET/P ratio. Figure 4.5 reveals that the average return period decreases with increase in the PET/P ratio. Average drought frequency (expressed in terms of return period) varies from 2 to 3 years in arid regions (with $12 > PET/P \geq 5$), 4 to 6 years in semiarid regions (with $5 > PET/P \geq 2$), 6 to 10 years in subhumid regions (with $2 > PET/P \geq 3/4$) and 10 years or more in humid regions.

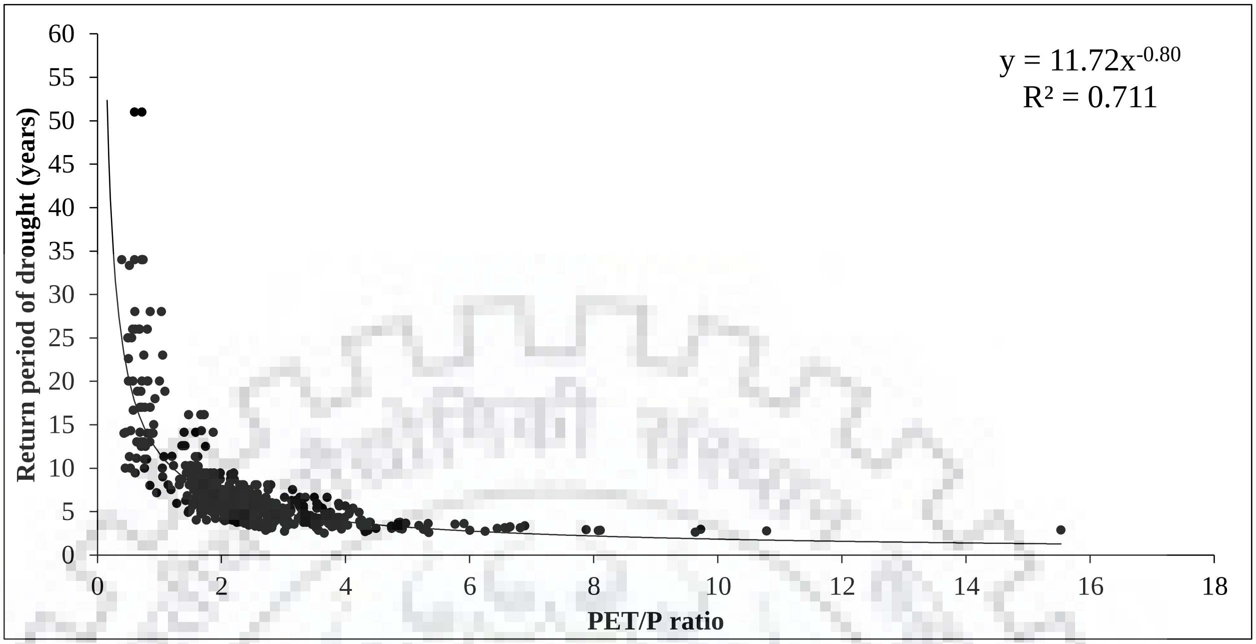


Figure 4.5. Relationship of drought return period with PET/P Ratio

From the relationship presented in Figure 4.5, it can be stated that the arid regions where the average annual potential evapotranspiration is more than five times the amount of average annual precipitation has the average drought frequency of once in every 2 years to once in 3 years. For instance, Barmer, Bikaner, Jodhpur, Jalore in Rajasthan; Kutch in Gujarat; Sirsa, Hisar, Bhiwani, Fatehabad in Haryana; and Bhatinda, Faridkot, Moga in Punjab having the PET/P ratio value more than 5 experienced frequent droughts once in every 3 years. In the semiarid regions, the mean annual potential evapotranspiration is two to five times the total amount of mean annual rainfall, the drought occurs once in every 4-6 years on an average. Further, in the regions, where the mean annual potential evapotranspiration is of the order of about twice of the total annual rainfall (i.e. PET/P ≈ 2), the droughts reoccurs with the average return period of 5 years (Figure 4.5).The average return period of droughts are in the range of 4-5 and 5-6 years, in the places where the PET/P ratios are between 3.0–5.0 and 2.0–3.0, respectively. For example, Alwar, Bhilwara, Bundi in Rajasthan; Ahmadabad, Anand, Bhavnagar in Gujarat; Faridabad, Karnal, Kurukshetra in Haryana; Bhind, Datia, Jhabua in Madhya Pradesh; Farukhabad, Agra, Mathura, Muzaffarnagar in Uttar Pradesh; faced the drought once in 4 years with the PET/P ratios values of 3.0–5.0, while the districts Betul, Bhopal, Indore, Ujjain in Madhya Pradesh; Amravati, Nanded in Maharashtra; Guntur, Krishna, Nellore in Andhra Pradesh; Belgam, Bidar in Karnataka; Buxar, Patna, Seikhpura in Bihar; Allahabad, Azamgarh, Lucknow in Uttar Pradesh have the average return period of 5-6 years with

PET/P ratios values of 2.0–3.0. Also, this may be clearly seen in Figure 4.5 that the drought frequency decreases exponentially with the increase of wetness. The spatial variation in drought return period in different climatic regions of India are shown in Figure 4.6.

In sub-humid areas ($0.75 \leq PET/P < 2$), the average drought return period is in the range of 6-10 years (Figure 4.5).The PET/P ratios found to be 1.0-2.0 in the districts Balaghat, Jabalpur, Narsinghpur in Madhya Pradesh; Bastar, Durg, Koriya in Chhattisgarh; Surguja, Gadchiroli, Gondiya in Maharashtra; Bhagalpur, Madhepura, Madhubani in Bihar; Chatra, Deoghar, Dhanbad in Jharkhand; Angul, Debgarh, Nawpara in Orissa have the average drought frequency of once in 7 years to once in 9 years. In areas where average annual precipitation is nearly equal to average annual potential evapotranspiration (i.e. $PET/P \approx 1$), the drought return period is more than 10 years. Further, if the area belongs to the further wet side of the climatic spectrum, (i.e. $0.5 \leq PET/P < 1$), the drought frequency vary in the order of once in 11 years to once in 16 years. The humid region covering the coastal regions of Maharashtra and Karnataka, state of Kerala and north-eastern States of the India experienced less frequent drought once in 14 years on an average. However, it can also be seen from analysis (Figure 4.5) that a few stations in sub-humid regions, namely, Satara in Maharashtra, Vizyanagaram in Andhra Pradesh, Kandhamal and Khurda in Orissa and Hooghly in West Bengal State, where mean annual rainfall nearly equals the local mean annual potential evapotranspiration, experienced less frequent droughts. The average frequency of drought at these stations was once in every 16, 14, 16, 14 and 13 years, respectively. There might be some other factors (physical/regional/morphological factors) particularly in respect of the presence of orographic barrier also affecting the drought characteristics at these places and restricts the value of correlation coefficient of above relationships to moderately significant level (i.e., $R^2 = 0.711$).

The inferences drawn in this study found to be rationally comparable with the results documented in literature from the studies done in the other parts of the world. For example, the PET/P ratio for Sarido in Brazil having the arid climate is nearly equal to 5.8, has the drought return period of 3 years on an average (Kogan 1997; Pandey and Ramasastri, 2001), while the drought recurs once in 5 years in semiarid (PET/P lies between 2.2 - 4.8) Saritao and Caatinga (Pandey and Ramasastri, 2001). The average drought frequency of once in 8 years and once in 12 years have been figured out in sub-humid regions of Agreste (PET/P in the order of 1.3 - 2.0) and Mata (PET/P in the order of 0.7-1.1) respectively (Magalhaes & Magee 1994; Pandey and Ramasastri, 2001).

The analysis of long-term rainfall for the period of 112 years (1874-1985) in semi arid Georgetown (average annual rainfall = 475 mm), Australia, shows the average return period of drought in the region to be 5 years (French, 1987). The upper midwest United States having sub-humid climatic condition, experienced the droughts once in 10 years (Klugman, 1978; Pandey and Ramasastri, 2001) and receives the average annual precipitation of about 1500 mm (NOAA, 1980). Swearingen (1994) analyzed the rainfall of semiarid Morroco for the period of 94 years (1901-1994). The analysis revealed that out of total number of years of data analyzed, 25 years are observed to be drought years, leads to the inference that the place has the average drought frequency of once in 4 years. Thus, the relationship presented here, is in good agreement with the behavior of the drought frequency in similar climatic regions around the globe. It is believed that the study will be very useful for understanding drought characteristics in different climatic conditions on the earth.

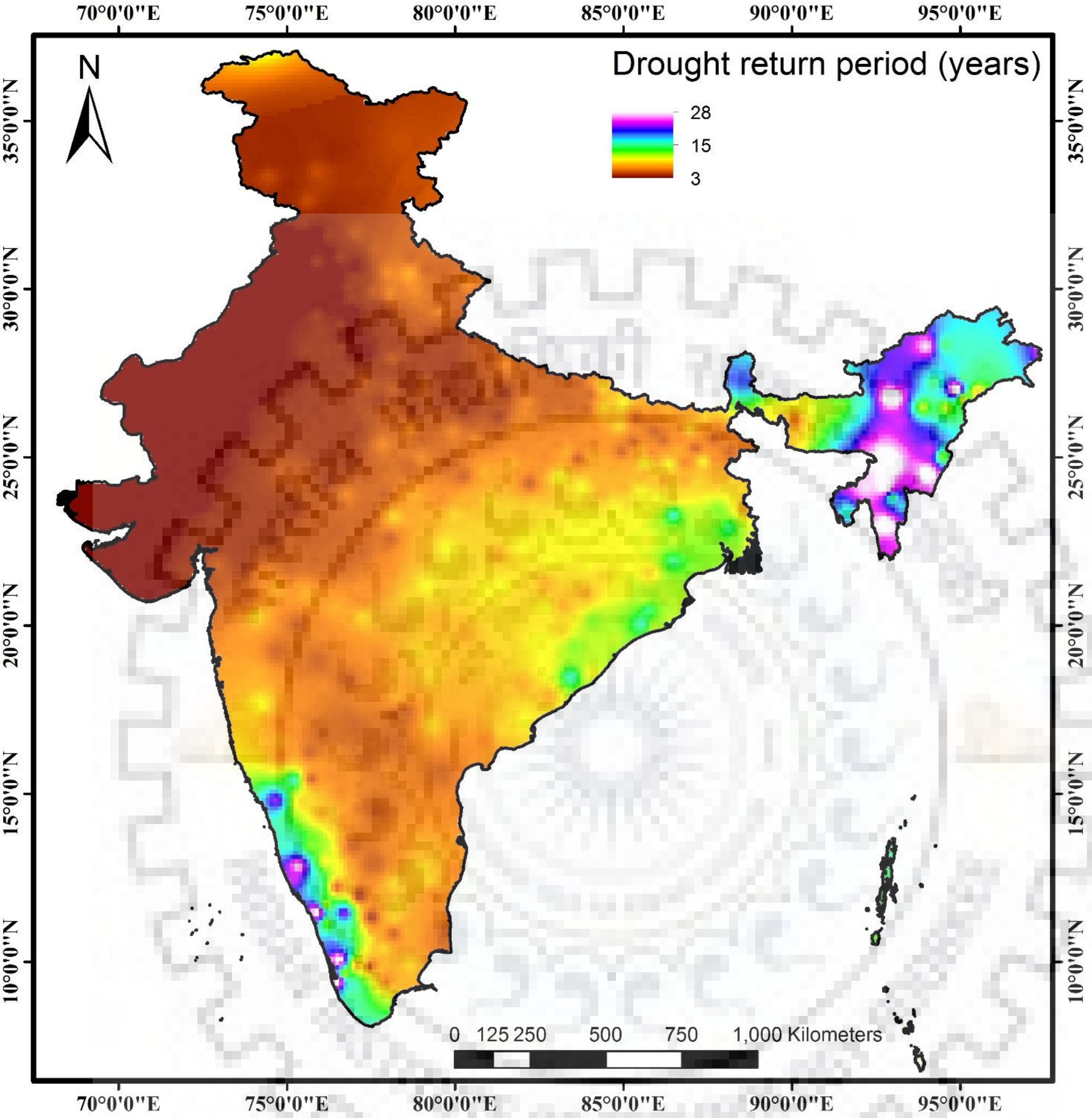


Figure 4.6 Spatial variation of drought return period in different climatic regions of India

4.6 DROUGHT SEVERITY

The severity of drought events refers to the magnitude of rainfall deficit from its long term mean. Based on the percentage departure from mean, the annual and seasonal droughts can be classified as moderate, severe, and extreme as per the limiting values of percentage of rainfall departure given in Table-4.4.

Table 4.4 Classification of drought based % departure of rainfall from mean **(**Pandey et al. 2008)

Percentage departure from mean (%)	**Type of Drought**
< -25 to -45	Moderate
< -45 to -60	Severe
< -60 or less	Extreme

The rainfall departure or magnitude of deficit expressed in percentage of long term average rainfall can be computed using the equation 4.3 as follow:

$$S = \frac{\langle P - P_m \rangle \times 100}{P_m} \tag{4.3}$$

Where, S is the magnitude of deficit, P is the amount of rainfall received during a season/year and P_m is the average seasonal/annual rainfall.

The maximum rainfall departure over the period of 113 years (1901-2013) for each of the 516 districts were estimated. The range of maximum rainfall departure (i.e. magnitude of severity) in each district is shown in Fig. 4.7. The Fig.4.7 clearly shows that the maximum deficiency of rainfall has been found in the north western India, which is of the order of 75-95% of its long term average. This region of India is relatively more susceptible to severe and extreme drought events. The central part of India experienced the maximum rainfall deficiency in the range of 55-75% over the period of 113 years, while the maximum magnitude of deficit has been estimated to be in between 40-55% in eastern and southern India. The state of Kerala and North eastern states of India had experienced relatively less severe droughts of magnitude of severity less than 40%.

The analysis revealed that the maximum rainfall deficit of 95% from long term mean had been observed in hyper arid in Jaisalmer having mean annual rainfall of 100 mm and mean annual potential evapotranspiration of 2663 mm. In arid regions the maximum deficiency of rainfall experienced in the range of 80% to 95%. For instance, Ganganagar in Rajasthan; Sirsa in Hayana; Faridkot in Punjab having PET/P values of 10.8, 7.9 and 6.6 experienced the maximum severity (i.e. magnitude of deficit) of 93%, 82% and 80% respectively over the period of 113 years. However, the semi arid areas with average annual rainfall (P) and average annual potential evapotranspiration (PET) ranges between 400-1100 mm and 1800-2400 mm respectively, have faced the maximum amount of rainfall deficit in the order of 55-80%. For example, Jhajjar in Haryana; Baghpat in Uttar Pradesh; Jhabua in Madhya Pradesh; Gopalganj in Bihar; have the PET/P ratio 4.9, 3.8, 3.0 and 2.1, faced the maximum rainfall deficiency of 79% 72.1%, 62.9% and 52.2% respectively. Further, the maximum severity range from 40-60% have been found in the districts located in sub humid regions of India. It is evident from the analysis that the maximum amount of rainfall departure in humid regions are in the order of 40% or less of long term mean.

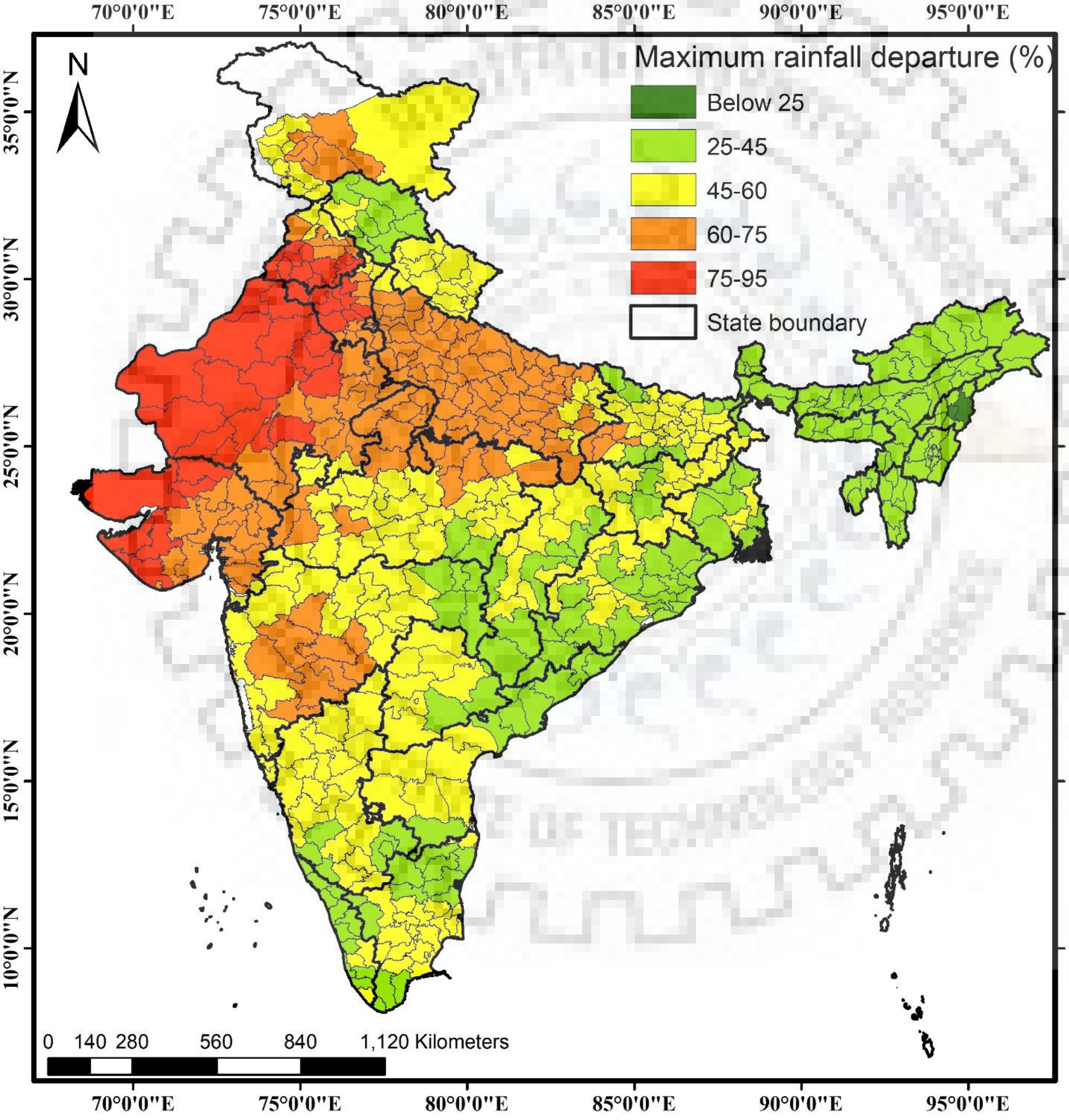


Figure 4.7. Spatial distribution of maximum rainfall departure across India

4.6.1 Relationship of PET/P Ratio and magnitude of drought severity:

The classification of drought severity presented in Table 4.4 has been employed for the further analysis of severity of drought in this study. The probability of occurrence of droughts of different severity (i.e. moderate, severe and extreme) at a particular place have been computed in terms of percentage of the total number of drought events occurred at that place. Being a percentage, it is purely qualitative and descriptive in nature which is used to express the magnitude of severity of drought in terms of rainfall deficiency. The drought events of different severity have been identified on the basis of the magnitude of deficit and leads to the computation of the probabilities of their occurrence.

The various regressions have been employed to relate the PET/P ratio and probabilities of occurrence of moderate, severe and extreme drought events. The better correlation ($R^2 = 0.594$) has been observed in logarithmic type than power and exponential type regressions. Thus, it is clear from Fig. 4.8 that the severity of meteorological drought events are indicatively related to the PET/P ratio.

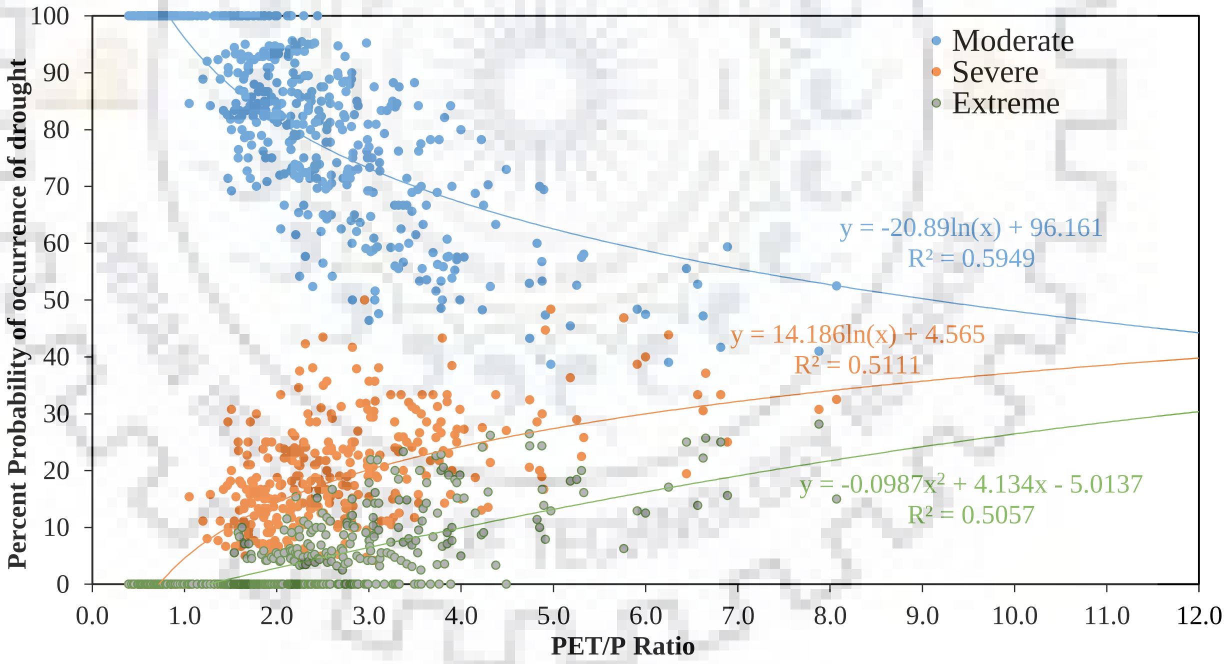


Figure 4.8 Relationship of PET/P ratio with percent probability of occurrence of drought events of different severity

It can be seen from Fig.4.8 that the occurrence probability of severe and extreme droughts from sub-humid to arid regions gradually increases; however, there is reduction in the probability of occurrence of moderate drought events for the same region. For instance, the regions with PET/P value of 1.5 has the probabilities of occurrence of 90% and 10% for moderate and severe drought respectively. In these regions, the extreme drought events are very rare and their probability of occurrence is nearly zero. The places where PET/P value is about 4 (i.e. semiarid regions) the percent probabilities of occurrence of moderate, severe and extreme drought events are 68%, 25% and 7% respectively; however in arid regions with PET/P value of 7.0 occurrence probabilities are 55%, 31% and 14% respectively. Therefore, the places falls in arid and semi arid regions are more susceptible to relatively more frequent severe and extreme drought events than the places located in sub humid climatic conditions. The relationship presented in Fig. 4.8 clearly shows that there is no occurrence of extreme drought events in the regions having PET/P value less than 1.5. Further, it can be seen from Fig.4.8 the severe droughts are rare or negligible in the areas where the average annual potential evapotranspiration is less than the average annual rainfall (PET/P<1). The above discussed pattern of probability of occurrence reveals that the regions with a lesser PET/P ratio are less vulnerable for severe and extreme meteorological drought events. The above results are in very good agrements with the reported work of Lugo and Morris (1982), Gol'tsberg (1972), and Gregory (1989), stating that the climatic regions with less mean annual deficit (PET-P) face less severe droughts. For instance, Sertao having semi arid climatic condition located in Brazillian Northeast found to be faced more severe droughts than Agreste having sub-humid climatic condition (Magalhaes and Magee 1994; Ponce, 1995). Further, the study done by Kendrew (1961) supports the results, indicating that the arid and semiarid regions of Australia where the mean annual precipitation varies from 250 mm to 750 mm, experienced more frequent and severe droughts. The Upper Blue Nile River Basis (UBNRB) in western Ethiopia with average annual rainfall and potential evapotranspiration of 1224 mm and 1448 mm respectively (Ayalew, 2010), i.e. PET/P=1.18 experienced less severe droughts (Khadr, 2017). Thus, it can be stated that the arid and semiarid regions are more susceptible to severe and extreme droughts than those of sub-humid regions in India.

4.7 DROUGHT PERSISTENCE IN SUCCESSIVE YEARS

The duration of a drought event is one of the important factor among the various drought characteristics to consider for planning of drought risk management strategies for a particular climatic region. Sometimes a drought event may continue for more than one year. The tendency of drought events for more than one successive year is termed as drought persistence. For example, a drought event lasts for two years, is a persistent drought of 2 years.

In this study, the maximum duration of the persistent drought over 113 years (1901-2013) for each of 516 districts have been analyzed. Further, an effort has been made to relate the events with maximum persistency of drought with climatic parameters in different climatic regions of India. The persistency of drought events vary from 2- consecutive years to 5- consecutive years in the different climatic regions of India. The analysis indicated that arid and semi arid regions are more vulnerable to the persistent drought events than sub humid regions. The places with PET/P ratio varying from 3.0 to 10.0 have experienced relatively more number of persistent drought events. For instance, Barmer (PET/P=9.7) in Rajasthan; Bhatinda (PET/P=6.0) in Punjab; Kaithal (PET/P=4.9) in Haryana have experienced 11, 8 and 6 number of persistent drought events respectively, during the period from 1901-2013. The drought persisted hardly for 3 consecutive years or more in sub humid regions.

The investigation of data spread sheet, shows that the drought events for 5 consecutive years are much rare. Hanumangarh (2000-2004), Ganganagar (1934-1938), Alwar (1937-1941), Dausa (1937-1941) and Jhunjhunu (2002-2006) in the State of Rajasthan, are only five districts where drought persisted for maximum of 5- consecutive years. The percent probabilities of occurrence of drought events of 2-, 3- and 4- consecutive years are plotted (not shown) against PET/P ratio. The plots are scattered having low coefficient of correlation does not shows any significant relation. However, it can be expressed that the arid and semi arid regions have relatively more chances of occurrence of drought events of more than one year duration. The spatial variation in the maximum persistency of drought over 113 years across the different climatic regions of India is presented in Fig. 4.9 It can be clearly seen from the Fig. 4.9 that the north western India comprising of the states of Punjab, Haryana, Rajasthan and Gujarat are very susceptible to frequent and persistent drought of 3 to 4 consecutive years. The persistent event for maximum of 4 consecutive years are unique feature of this region.

For the purpose of clarity, the duration of drought events have been separately examined from spreadsheet for arid, semi arid, sub humid and humid regions. The probability of occurrence of drought of 4 consecutive years are relatively more in the regions with PET/P ratio greater than 6.0 than the other regions. Further, the persistent drought for maximum of 3 consecutive years have greater probability of occurrence in the areas with PET/P ratio between 3.0 and 6.0. The sub humid regions rarely experienced the persistent event of 3 years or more. The regions with PET/P ratio range from 2.0 to 1.1 have faced the persistent drought for the maximum of 2 consecutive years only. There had been no persistency of a drought event observed in the regions with PET/P ratio equal to or less than 1.0. It is clear from the Fig.4.9 that the humid regions includes the coastal region of Maharashtra, Karnataka, Kerala, and the north eastern part of India have never faced any persistent drought event. Further, it can also be seen from the Fig.4.9 that the States of Rajasthan, Gujarat, Haryana, Punjab, western Uttar Pradesh, western Madhya Pradesh, some parts of Karnataka and Andhra Pradesh have faced the maximum drought persistency of 3-4 years. The inferences drawn in this study are in very good agreement with the study of Rasool (1984) which concludes that the duration of a drought event can approach to as long as 4-5 years because of higher inter-annual variability in rainfall. Karl (1983) studied the tendency of an event to persist, and it was observed that there is higher tendency of drought event to be persistent in the central part of the United States than in eastern and western part, with duration of droughts ranging from 3 to 5 years. Further, Johnson and Kohne (1993) have documented that the arid and semi arid regions of United States, covering the states of Colorado, Montana, North Dakota, and Wyoming have the greater persistence of drought, which also supports the results observed of this study.

4.8 SUMMARY

Among the various natural hazards droughts have most damaging effect on the environment and economy on which human depends. The major impacts of drought are reduced crop production, reduction in the availability of drinking water, hydropower production, and may leads to poverty and regional conflicts. The effects are very serious leading to loss of live and migration in developing countries. The impacts are devastating and likely to increase with the time as the water demand in the society increases. The average return period of drought can be described using the climatic parameters in terms of ratio of average annual potential evapotranspiration to average annual rainfall (PET/P). The important observations of the analysis are:

1. The north western India (Rajasthan, Gujarat, Haryana and Punjab) experienced the frequent drought with return period of 3-4 years. The states of Uttarakhand, western Madhya Pradesh, Karnataka, southern Maharashtra and eastern Uttar Pradesh has the average drought return period of 5-6 years.

2. The coastal regions and north eastern states of the country has the average drought frequency of once in 10 years or more.
3. The coefficient of determination ($R^2 = 0.711$) shows that the return period is significantly related to PET/P ratio.
4. The average return period of drought increases gradually from dry to wet regions, from 2-3 years in the arid regions ($12 > PET/P \geq 5$), 4-6 years in the semiarid regions ($5 > PET/P \geq 2$) and 6-9 years in the sub-humid regions ($2 > PET/P \geq 3/4$) and 10 years or more in humid regions.
5. The maximum rainfall deficit of 95% from long term mean had been observed in hyper arid in Jaisalmer, Rajasthan.
6. North western India is very susceptible to severe and extreme droughts with maximum rainfall deficiencies in range of 75-95% of long term mean rainfall.
7. The arid and semiarid regions are more vulnerable to severe and frequent drought events than the areas in the sub-humid and humid regions.
8. The areas with PET/P ratio of less than or equal to 1.5 has much rare chance of occurrence of severe drought events. In the regions with PET/P ratio less than 1.5, the occurrence of extreme droughts are almost none.
9. The more frequent and persistent droughts occur in arid and semi-arid regions than in the other climatic regions.

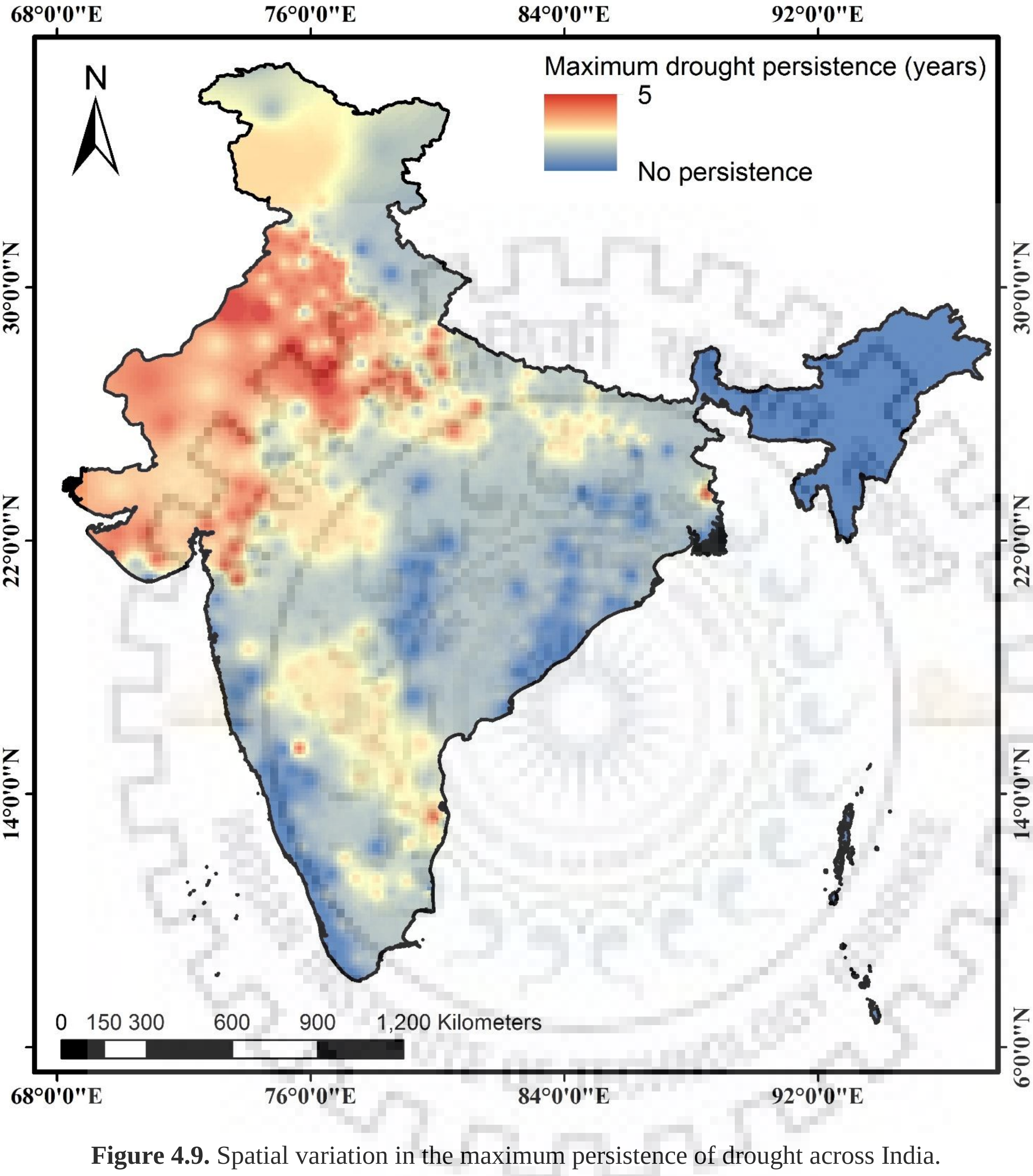


Figure 4.9. Spatial variation in the maximum persistence of drought across India.

The relations presented in this chapter can be used as a sensible tool for prediction of regional drought characteristics and to sensitize the drought response system for proactive planning based on long term regional pattern.

CHAPTER 5

RELATIONSHIP OF DROUGHT FREQUENCY AND SEVERITY WITH RANGE OF ANNUAL TEMPERATURE VARIATION

5.1 INTRODUCTION

The changing climate around the globe is one of the main factor which affects the hydrologic cycle (IPCC, 2007). Any change in temperature affects the atmospheric moisture, precipitation and circulation pattern of the atmosphere, e.g. changes in the rate of evaporation affects the hydrological cycle. The inconsistency in components which characterize the process of hydrologic cycle is responsible for occurrence of hydrologic extremes (Ponce et al., 2000). The increase in occurrence of hydrologic extremes have grown human concerns towards the increase in frequency and severity of droughts in recent decades (Peterson et al., 2013; Wilhite et al., 2014; Pandey et al., 2010). The water deficit condition for a longer duration may have the damaging effect on regional economy, energy production, public health, urban water supply, agriculture and ecosystem services. The estimated loss caused by drought is of the order of 6–8 billion dollars every year which is much more than the loss caused by any other natural hazards (Wilhite, 2000). The lack of precipitation is the primary cause of the occurrence of drought but its severity also depends on the amount of water that infiltrates into the ground, evaporates from land surface and transpires from plants (Trenberth et al., 2014). The drought frequency and severity are expected to increase due to change in climate (Zhang et al., 2012). This invites attention of researchers and scientists to study the relationship of drought frequency and severity with regional climatic parameters, viz., precipitation, temperature, and evapotranpiration particularly under changing climate (Hu and Willson, 2000; Zou et al., 2005; Easterling et al., 2007; Zhang et al., 2012; Dai, 2013).

In literature drought is defined in different ways (Zhang et al., 2012). Most commonly a drought is defined as a relative deficit in a given area compared to its average or usual water availability, either in the form of rainfall, river flow, surface/ground water storages or due to combination of these for certain period of time. Thus, drought is a temporary phenomenon. A drought event refers to its occurrence over a period of one or more consecutive years (Dracup et al, 1980; Ponce et al, 2000; Pandey and Ramasastri, 2002).

Liu et al. (2015) in eastern Hulun Buir steppe, China studied the drought reconstruction and its relation to the sea surface temperatures in the Pacific Ocean. In the analysis a significant correlation was found between sea surface temperatures in North Pacific Ocean and drought variations. North Atlantic sea surface temperature regulated drought along the northwestern Gulf of Mexico in last 3,000 years. The effect of Pacific sea surface temperature on Texas drought have been studied and the analysis indicated that over southern Texas the Atlantic Multidecadal Oscillation was a major factor which modulated the frequency of drought (Livsey et al., 2016). Pandey and Ramasastri (2001) explored relationship between the average drought return period with the ratio of evapotranspiration and precipitation in arid, semiarid and sub humid regions of India using the data of 95 stations. These relationships are very vital in understanding the regional drought characteristics. Since the average drought return period is related to the evapotranspiration which, in turn, is a function of temperature, it is in order to determine relationship of the range of temperature variation in a year (θ_R) with the return period/frequency and severity of droughts.

The objective of this study is to relate the average drought return period and severity with historical range of temperature variation (θ_R) at a place. The present analysis has been carried out for 256 districts/stations located in different parts of India as shown in Figure 3.2. It will help provide improved understanding of regional drought characteristics in different climatic regions simply based on quite easily available long term historical maxima and minima of temperature values observed at a place.

5.2 METHODOLOGY

The drought is most commonly perceived as a ‘meteorological phenomenon’ characterized by deficiency of rainfall with respect to normal rainfall over a given period of time. For some, a drought occurs when rainfall is below 75% of long-term mean (Glantz, 1994) whereas others might consider it to occur at 60 or 50% of normal. The percentage departures of annual and seasonal rainfall from corresponding long term mean have been computed for identification of drought season or drought year using IMD approach and quantification of their degree of severity in each of the 256 districts. IMD defines drought as a period of year or season when the deficiency of rainfall is more than 25% of its mean. The percent departure from mean enables to classify droughts as moderate, severe, and extreme, as described in Table 4.4 (Chapter 4).

The average return period of drought is computed by dividing the total number of years of data analyzed by the total number of years with rainfall deficit more than 25%.

$$\mathbf{T} = \frac{\mathbf{N}}{\mathbf{n}} \tag{5.1}$$

where T = Average return period of drought, N = Total number of years of rainfall records analysed, and n = Total number of drought years identified from N number of years of record. Mathematically, the return period (T) is reciprocal of frequency (F), i.e. $F = \frac{1}{T}$.

The historical range of temperature variation (θ_R) at a place is computed by subtracting the lowest value of normal (or historical) minimum temperature from the highest value of normal (or historical) maximum temperature:

$$\theta_R = \theta_{H\max} - \theta_{L\min} \tag{5.2}$$

where θ_{Hmax} = Highest value of normal maximum temperature during the year and θ_{Lmin} = Lowest value of normal minimum temperature during the year.

5.3 RESULTS AND DISCUSSION

The geographical area of India encompasses different climatic regions starting from hyper arid to hyper humid. The mean annual rainfall across these regions varies from 100 mm in hyper arid to more than 6400 mm in north eastern parts having hyper humid climate. The long-term annual and seasonal rainfall records were analysed to identify the historical droughts and determine their return periods during the period 1901-2013 using IMD approach.

Fig. 5.1 shows the spatial variation of θ_R (Eq. 5.2) for each station/district in different regions of the country. As seen, the north western part of Rajasthan and in parts of Haryana have θ_R in range of 40 ^oC to 35 ^oC. The southern Rajasthan, Madhya Pradesh, Uttar Pradesh, part of Bihar and northern Chhattisgarh have θ_R in range of 35 ^oC to 30 ^oC. θ_R lies between 30 ^oC and 25 ^oC in southern Chhattisgarh, west and south west Maharashtra, south Orissa and in some part of Bihar and Jharkhand. In the States of West Bengal, southern Jharkhand, north Orissa, Andhra Pradesh and western Karnataka, θ_R is of the order of 20 - 25 ^oC. The coastal region which includes the Kokan region, States of Kerala and Tamil Nadu exhibits $\theta_R < 20$ ^oC.

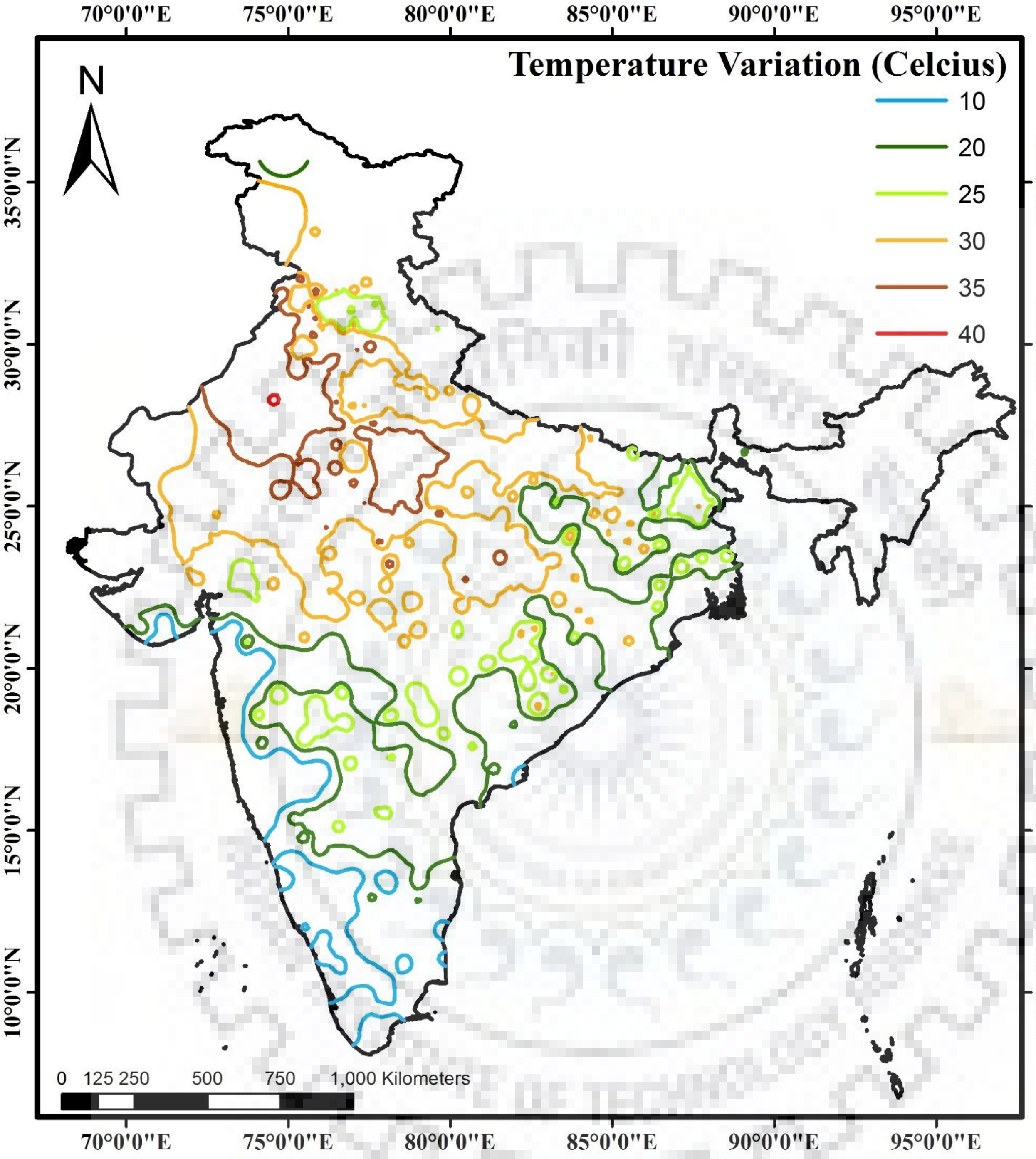


Figure 5.1 θ_R (°C) variation in different regions of India

The spatial distribution of average drought frequency over various climatic regions of India is shown in Fig. 5.2. A comparison of Figs. 5.1 and 5.2 indicates that the average frequency of drought is more in regions with higher θ_R, and vice-versa.

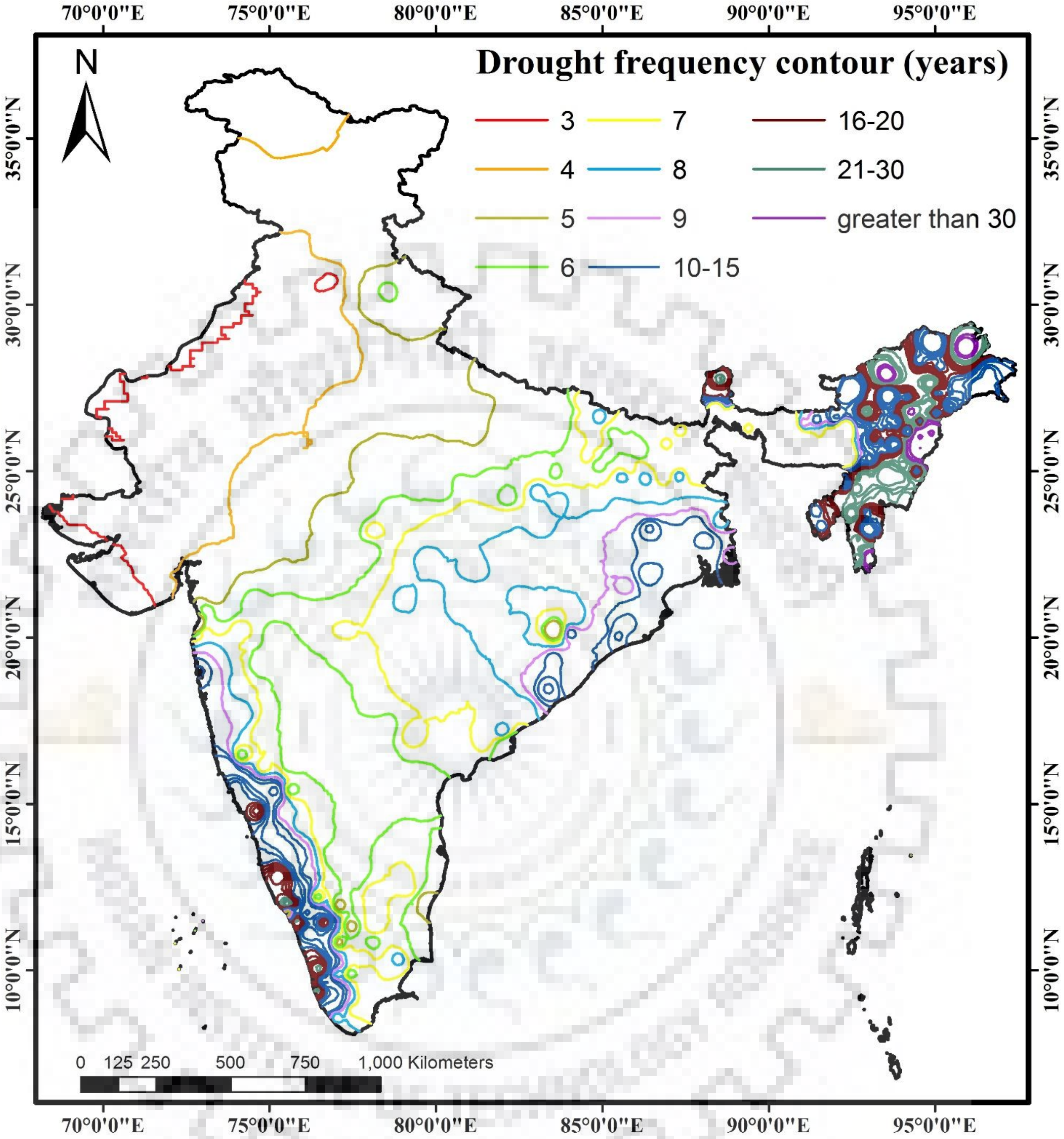


Figure 5.2 Contour plots of drought return period in different climatic regions of India

5.3.1 Relationship between θ_R and return period

For exploring a relationship between drought frequency (F) and θ_R, a polynomial type relationship (Figure 5.3) was fitted with coefficient of determination (R^2) = 0.702, implying that the frequency (F) or return period (T) of meteorological droughts is (directly or inversely) related with θ_R. In other words, the average return period decreases with increase of θ_R, i.e. the places exhibiting larger range of temperature variation would face droughts with higher frequency or with shorter return period, and vice versa.

As seen from Figure 5.3, the average return period varies from 3 to 4 years where θ_R is in the range of 40 °C to 35 °C. For instance, the meteorological stations at Churu & Nagaur in the State of Rajasthan; and Bhatinda & Jalandhar in the State of Punjab face droughts once in every 3 years and θ_R ranges from 40 - 35 °C. Furthermore, Jhalawar, Bhilwara, and Tonk districts in Rajasthan; Rewari & Hisar in Haryana; Ludhiana in Punjab have θ_R in the range of 40 - 35 °C and the droughts are experienced with an average frequency of once in 4 years.

The places where θ_R varies from 35 - 30 °C, average drought return period lies between 4 to 6 years, and 6 to 9 years in the regions where $30\ ^{o}C > \theta_R > 25\ ^{o}C$. The districts Satna, Jodhpur, Gonda, Rajasmand among others having θ_R of order of 35 - 30 °C have the return period between 5-6 years. The return period is of the order of 9 to 14 years where θ_R varies between 25 °C to 20 °C and greater than 14 years at places with lowest θ_R, i.e. 20 - 10 °C. Thus, drought events are relatively less frequent at places where $\theta_R < 20\ ^{o}C$.

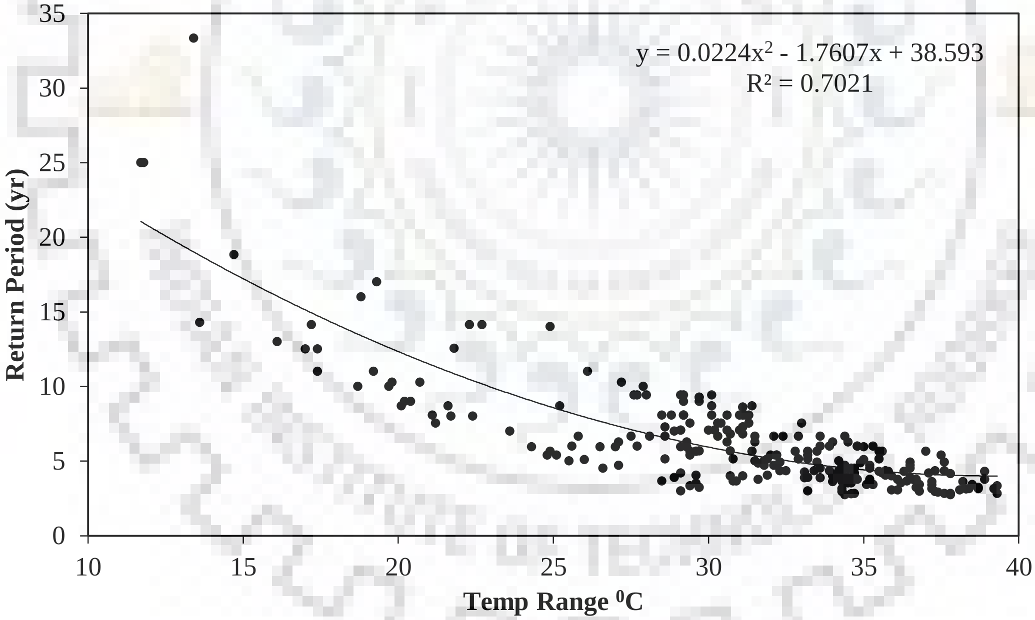


Figure 5.3 Average drought return period corresponding to temperature variation

The above results can also be verified with the drought events documented for other countries in literature, for example, Kazakistan, Ukraine, Brazil, Africa and Australia. In Kazakhstan of Russia that falls in arid region, the air temperature is lowest in January ranging from -18.5 °C to -1.8 °C and highest in July ranging from 19.4 °C to 28.4 °C (Karatayev and Clarke. 2016). The average return period of drought is 3 years, for it has faced 35 droughts in 100 years (Kogan 1997). The semi arid Ukraine where the average minimum and maximum temperatures are -9 ^oC and 25 ^oC have the average drought frequency of once in 4 – 5 years (Kogan 1997). The average return period of drought in Morroco in Africa is 3 years (Swearingen 1994) where the average high temperature range between 32 ^oC to 36 ^oC in summers and minimum temperature lies between -10 ^oC and -8 ^oC (Wikipedia). Agreste in Brazil have the average maximum and minimum temperatures 32 ^oC and 13 ^oC respectively, experienced the drought events once in 8-12 years (Magalhaes and Magee 1994; Ponce,1995). In Georgetown, a semi arid region of Australia has drought frequency once in 5 years (French 1987) and the mean maximum and minimum temperature in Georgetown are 36.6 ^oC and 12 ^oC (i.e. $\theta_R \approx 25^oC$), respectively (Bureau of Meteorology, Government of Australia, 2009). These are consistent with the relationship presented in this study (Figure 5.3).

5.3.2 Relationship between θ_R and severity

As also mentioned, the drought severity refers to the magnitude of rainfall deficit with reference to normal rainfall. The exponential type regression (Figure 5.4) is fitted with $R^2 = 0.730$. It can be seen that the maximum severity increases with increase in θ_R, and vice versa. As an example, the places where θ_R is in the range of 40 ^oC to 35 ^oC, the values of maximum deficit, i.e. severity, has been more than 70% of the long term mean rainfall. Ganganagar district in Rajasthan has mean annual precipitation 235 mm, mean annual potential evapotranspiration 2500 mm, and θ_R of 38 ^oC, and it experienced the maximum rainfall departure of the order of 93% (extreme drought event) from long term annual mean. Faridabad ($\theta_R = 35.1^oC$) in Haryana with average annual rainfall 580 mm faced maximum rainfall deficiency of 75%. The places where θ_R varies from 35 - 30 ^oC have experienced severe to extreme drought events with the maximum rainfall departure in the order of 55% to 70%. Furthermore, the places with θ_R ranging from 30 ^oC - 25 ^oC faced severe droughts with maximum rainfall departure of the order of 45% to 57%. Indore ($\theta_R = 32.2^oC$) in Madhya Pradesh and Dhanbad ($\theta_R = 28.8$ ^oC) in Jharkhand having mean annual rainfall 1314 mm experienced the maximum deficiency of rainfall by about 57.8% and 48.4%, respectively. The maximum deficiency of rainfall ranged from 45% to 35% where 25 $^oC > \theta_R >$ 20 ^oC and less than 35% in places where θ_R varied from 20 ^oC to 10 ^oC. The maximum rainfall deficiency in Khurda district of Orissa was 37% where $\theta_R = 22.3$ ^oC. The severity of drought events was largely moderate at places where $\theta_R <$ 20 ^oC.

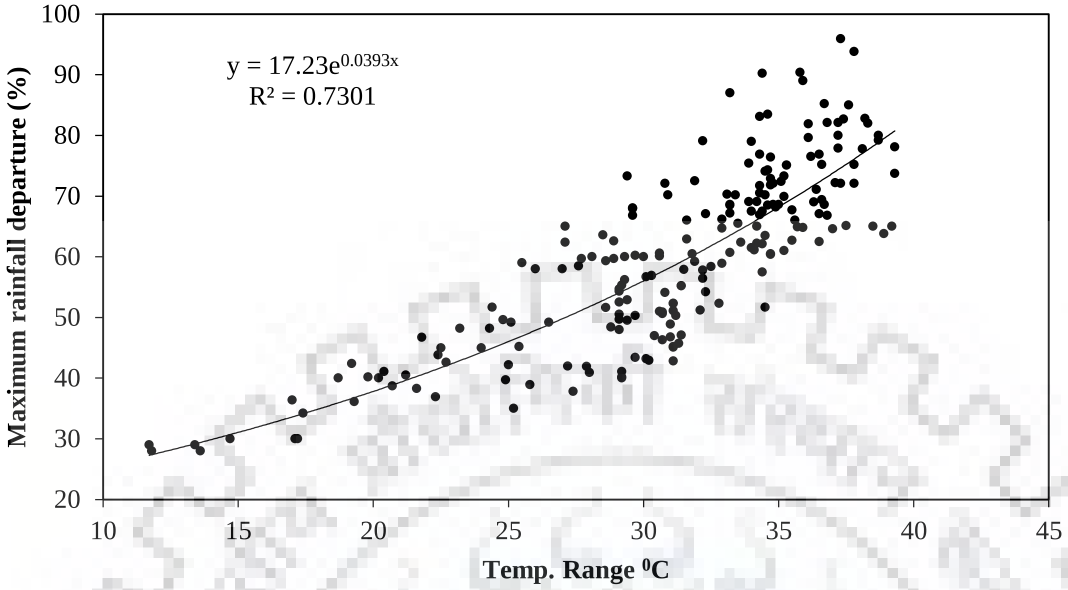


Figure 5.4 Maximum rainfall departures corresponding to θ_R

The spatial variation in the maximum rainfall departure (i.e. magnitude of severity) in different regions of India is presented in Fig. 5.5. It is clear from Fig. 5.5 that the north western India covering the states of Rajasthan, Gujrat and Haryana are more susceptible to severe and extreme drought events. The magnitude of severity of drought events decrease from west to east in India. The north eastern and coastal region of India experienced drought events with less magnitude of severity. A comparison of Fig. 5.1 and Fig. 5.5 shows that the regions with higher θ_R face higher deficiency of rainfall and vice-versa. Thus, it can be inferred that the places/regions where θ_R is relatively higher face more frequent and more severe drought events, and vice versa.

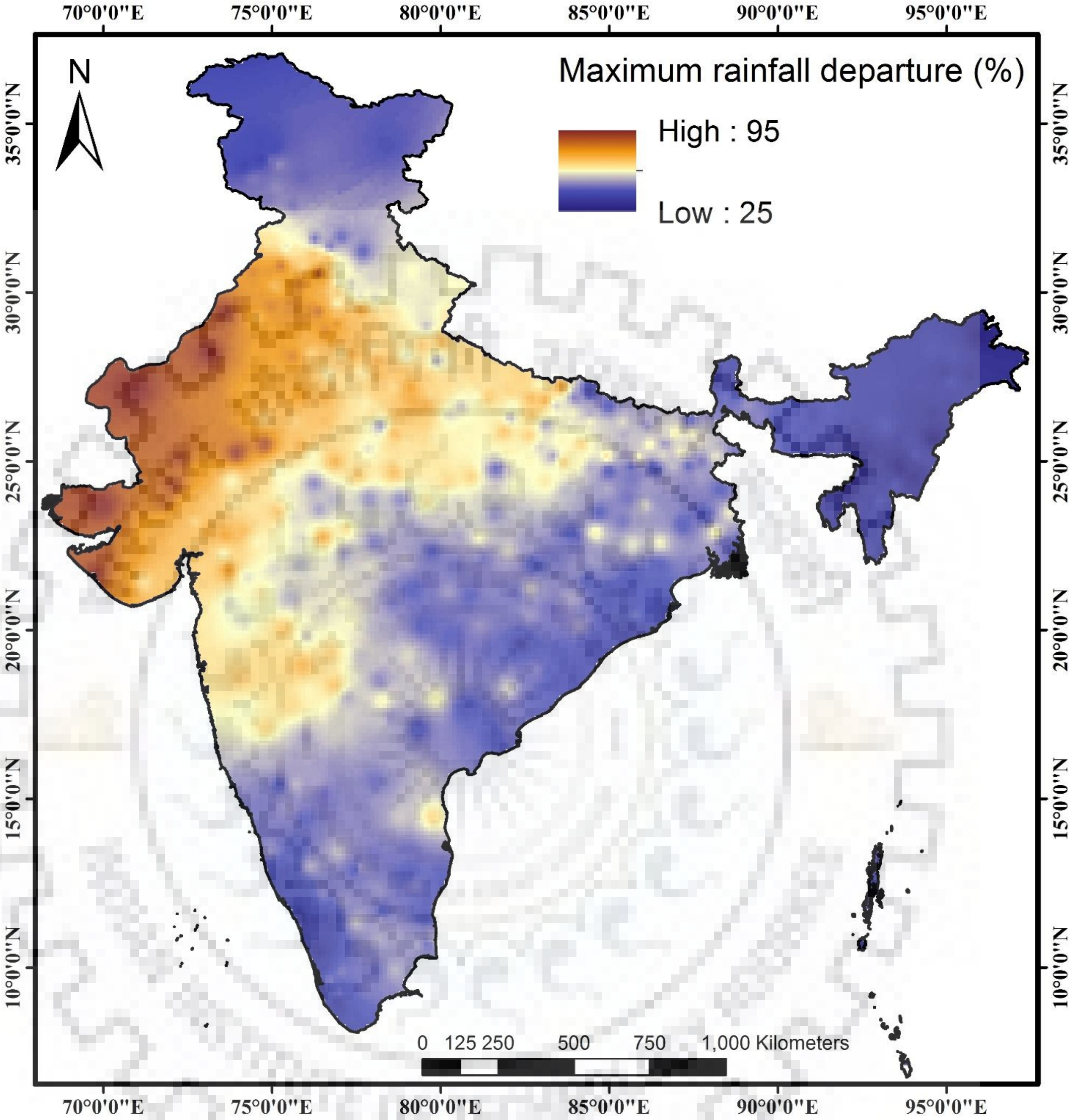


Figure 5.5 Spatial variation in maximum rainfall departure in different climatic regions of India

5.4 SUMMARY

From the analysis of a large set of meteorological data in India from various climatic regions, the frequency and severity of meteorological droughts are found to be strongly related with the range of annual normal temperature variation (θ_R). The average drought frequency and severity increase with increase in θ_R, and vice versa. The following conclusions are drawn from the study:

1. The coefficient of determination shows that frequency (R^2= 0.702) and severity (R^2= 0.730) are strongly related to the range of annual temperature variation.
2. Specifically, parts of Gujarat and of Rajasthan States falling under arid climatic region (where θ_R varies in the range of 40 °C to 35 °C) faced droughts once in every three years and the maximum rainfall deficiency had been 70% or more.
3. The semiarid regions which include central and south-west parts of India where θ_R varies from 35 °C to 30 °C have the average drought frequency of once in 4-6 years with more number of severe drought events.
4. The places with θ_R ranging from 30 to 25 °C and 25 - 20 °C experienced droughts once in 6-9 and 9-14 years with maximum severity in the range of 57% to 45% and 45% to 35%, respectively. Regions θ_R < 20 °C generally experienced moderate droughts once in 14 years or more.

CHAPTER 6

COUPLING OF TENNANT CONCEPT WITH SPI FOR EF PREDICTION DURING LOW FLOW SEASON

6.1 INTRODUCTION

For the conservation of natural and healthy ecosystem, minimum amount of good quality water, also known as environmental flow (EF), has to be preserved in rivers for their survival (Poff et al., 2009). EF is maintained in streams for sustainability of aquatic lives and a lack of it may influence the whole ecosystem (Brisbane Declaration, 2007; Wang and Lu, 2009). Thus, EF is necessary to carry out the needs of animal, vegetation, and aquatic lives which depend on the river water for their sustenance.

The socio-economic development and climate change has affected the global hydrological cycle, threatening human water security, the health of aquatic environments, and river biodiversity largely during past few decades (Vörösmarty et al., 2010; Jacobsen et al., 2012; Van Vlietet al., 2013). These situations alert for assessment of EF requirement (EFR) and water scarcity (Vörösmarty et al., 2010; Kirby et al., 2014). Thus, EFR is defined as the quality, quantity, and timing of the water flows required for maintaining estuarine ecosystems and human livelihoods and well-being that depend on these ecosystems (Brisbane Declaration, 2007).More than 240 methods are available and being used worldwide to calculate EFR to maintain healthy rivers (Tharme, 2003).These methods can be grouped into four categories: hydrological, hydraulic rating, habitat simulation, and holistic methods.

The long-term data on river flows measured at different points for a stream are often required for application of the simplest hydrological methods. These methods assume a relationship between flow and specific biological parameters. Some of the commonly used hydrological methods for the assessment of EFR are: Tennant (1976) method, BC-Instream flow threshold method (Hatfield et al. 2003), Alberta desktop method, flow duration curve methods, shifting flow duration curve (FDC) technique etc. Using desktop hydrological method, Mazvimavi et al. (2007) estimated EFR as 30-60% and 20-30% of mean annual runoff (MAR) for perennial and non-perennial rivers, respectively. On the other hand, drought is a natural calamity, resulting from the occurrence of less than average rainfall over a given period of time at a given space which consequently leads to stream flow reduction and short-term water deficit. Further, the droughts cause lowering of water levels in lakes, reservoirs, and tanks etc. There exist in literature various drought indices based on different parameters, useful for drought monitoring. Some of the common indices used to assess for meteorological droughts in India are Standardized Precipitation Index (SPI) (McKee et. al., 1993), Effective Drought Index (EDI) (Byun and Wilhite, 1999); percentage departure of annual and seasonal rainfall from corresponding mean are applied for identification of onset, termination, and quantification of severity of drought events.

Hydrological methods, such as Tennant method, are used for the environmental flow assessment based on the assumption that there exists a close relationship between flow alteration and specific ecological responses. In general, Tennant method is used to recommend instream flows and the Standardized Precipitation Index (SPI) is used to quantify the dry and wet conditions at regional scales. Though both the concepts imply levels of water supply for human activities or natural ecosystems, they deal with the issue at different spatial and temporal scales in hydrological processes.

As above, SPI is used to quantify the dry and wet conditions based on rainfall whereas Tennant method is used to describe the EF condition of a river from severe degradation to flushing flow i.e. whether the river runs dry or has maximum flow based on the flow data. Since both SPI and Tennant Method are used to describe similarly the range of dry and wet conditions based on rainfall and flow data, respectively, their coupling may lead to the existence of a relationship between these two methods/concepts.

Despite the fact there exist a large number of EF methods, none of them has the efficacy to predict EF for ungauged watersheds, i.e. using rainfall only. On the other hand, SPI has the efficacy to describe a similar dry or wet situation, but in terms of drought. Thus, there exists a possibility to explore for a relationship between these two, for EF prediction from rainfall, useful for ungauged watersheds, which forms the primary objective of this study.

The application of this study has been demonstrated on 11 catchments. The detail description and drainage network of all the catchments are presented in chapter 3. The summary characteristics of the study catchments are summarize in Table 6.1.

Table 6.1 Summary characteristics of study catchments

S. No.	Catchment	River	Major River Basin	Area (Km^2)	Data Length	Latitude(N)	Longitude (E)	Average annual rainfall	Elevation Range (m)	Climatic region
1	Ghatora	Arpa	Mahanadi	3035	1991-2006	22^0 2’ to 22^0 46’	81^0 36’ to 82^0 26’	1320	270-740	Sub-humid
2	Kurubhata	Mand	Mahanadi	4625	1991-2006	21^0 58’ to 23^0 05’	82^0 50’ to 83^0 34	1309	256-1025	Sub-humid
3	Salebhata	Ong	Mahanadi	4650	1991-2006	20° 40’ to 21^0 28’	82^0 33’ to 83^0 34’	1300	145-800	Sub-humid
4	Anandpur	Baitarni	Brahmani-Baitarni	8570	1991-2006	$21^0$12’ to 22^0 15’	85^0 09’ to 86^0 22’	1441	50-950	Sub-humid
5	Jaraikela	Koel	Brahmani-Baitarni	9160	1991-2006	21° 50’ to 23^0 36’	84^0 29’ to 85^0 49’	1000	221-830	Sub-humid
6	Hivra	Wardha	Godavari	10240	1990-2007	20^0 21’ to 21^0 52’	77^0 25’ to 78^0 45’	1020	242-800	Semi-arid
7	Nandgaon	Wunna	Godavari	4580	1990-2007	21^0 58’ to 23^0 05’	82^0 50’ to 83^0 34’	1060	217-500	Semi-arid
8	Mohegaon	Burhner	Narmada	3978	1981-1990	22^0 05’ to 23^0 02’	80^0 35’ to 81^0 25’	1547	509-990	Sub-humid
9	Manot	Narmada	Narmada	4884	1981-1990	22^0 26’ to 23^0 18’	80^0 24’ to 81^0 47’	1273	450-1080	Sub-humid
10	Hridaynagar	Banjar	Narmada	3370	1981-1990	21^0 45’ to 22^0 50’	80^0 15’ to 81^0 10’	1428	372-845	Sub-humid
11	Sher	Sher	Narmada	2901	1978-1986	$22^0$15’ to 23^0 05’	79^0 00’ to 79^0 45’	1042	353-840	Sub-humid

6.2 METHODOLOGY

6.2.1 Tennant method

This method was developed by Donald Tennant in Montana region of USA (Tennant 1975, 1976 a,b), also called as Montana approach, primarily for the needs of fish. It used 58 cross-sections and 38 different flows of 11 streams in Wyoming, Montana, and Nebraska (Mann, 2006).A relationship was established between aquatic habitat suitability and flow using subjective assessment of habitat quality and empirical hydraulic data obtained from cross-channel transects. This method is based on the assumption that, to uphold good stream environment, some percentage of average flow is required. For short-term survival, the average depth and velocity of flow should be at least 0.3m and 0.25m/s, respectively and the depth between 0.45 to 0.6m and velocity ranging from 0.45 to 0.6m/s was taken as optimal for the survival of fish. These conditions corresponded to 10% and 30% of average annual flow (AAF), respectively, in different streams under study. Different flow conditions described based on percentage of AAF for low (October-March) flow periods (Tennant, 1975) are given in Table 6.2.

Table 6.2 Flow conditions based on percentage of AAF for low flow season (Tennant, 1975)

Flow Condition	October-March
Flushing flow	200% AAF
Optimum range of flow	60-100% AAF
Outstanding	40% AAF
Excellent	30% AAF
Good	20% AAF
Fair or Degrading	10% AAF
Poor or Minimum	10% AAF
Severe Degradation	10% AAF to zero flow

6.2.2 Standardized Precipitation Index (SPI)

SPI is widely used for drought monitoring; it is computed from the long-term precipitation record for a location for a desired period. In practice, this long-term record is fitted to a probability distribution, preferably gamma distribution, and then normalized such that the mean SPI for the location and desired period are equal to zero (McKee et al., 1993; Edwards and McKee, 1997).

Estimation of SPI includes fitting a gamma probability density function (pdf) (Thom 1958) to the precipitation time series:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \text{ for } x > 0 \qquad (6.1)$$

Where x is the amount of precipitation and α, $\beta > 0$, α is shape and β is scale parameter,

$$\Gamma(\alpha) = \int_{0}^{\infty} y^{\alpha-1} e^{-y} \qquad (6.2)$$

$\Gamma(\alpha)$ is the gamma function.The parameters α and β of the gamma pdf are estimated for each station, for each time scale of interest (viz., 3 months, 6 months, 9 months, 12 months, 48 months, etc.), and for each month of the year using Thom's (1958) approach as follows:

$$\hat{\alpha} = \frac{1}{4A}\left[1 + \sqrt{1 + \frac{4A}{3}}\right] \qquad (6.3)$$

$$\hat{\beta} = \frac{\overline{x}}{\hat{\alpha}} \qquad (6.4)$$

$$A = \ln(\overline{x}) - \frac{\sum \ln(x)}{n} \qquad (6.5)$$

where n is the no. of precipitation observations.

The cumulative probability distribution function (cdf) of an observedprecipitation event can be estimated using these parameters for the given month and time scale. cdf is given by

$$G(x) = \int_{0}^{x} g(x)dx = \frac{1}{\hat{\beta}^{\hat{\alpha}}\Gamma(\hat{\alpha})}\int_{0}^{x} x^{\hat{\alpha}-1} e^{-x/\hat{\beta}} dx \qquad (6.6)$$

Let x/β = t then eq. 6 becomes the incomplete gamma function:

$$G(x) = \frac{1}{\Gamma(\hat{\alpha})}\int_{0}^{x} t^{\hat{\alpha}-1} e^{-t} dt \qquad (6.7)$$

Since the gamma function is undefined for x=0 and a precipitation time series may contain zeros, the cumulative probability ($H(x)$) is defined as:

$$H(x) = q + (1-q)G(x) \qquad (6.8)$$

Where *q* is the probability of a zero. If *m* is the number of zeros in a precipitation time series, Thom (1958) states that *q* can be estimated by *m*/*n*. Thom (1958) uses tables of the incomplete gamma function to determine the cumulative probability G(x).*H*(*x*) is then transformed to the standard normal random variable Z with mean 0 and variance 1, which is the value of SPI. Thus, SPI is a normalized index representing the occurrence of an observed rainfall when compared with the average rainfall of a particular location over a long reference period. Alternatively, SPI values represent the deviation of rainfall from its long-term mean. Its values describe watershed conditions ranging from extremely wet to extremely dry condition. Negative SPI values represent the deficiency in rainfall while positive values of SPI show the surplus rainfall. The former are used to classify the severity of drought event; the higher the absolute (negative) SPI value, more severe the drought event, and vice versa. Table 3 represents different conditions classified on the basis of SPI values (McKee, 1993).SPI has advantages over other indices, as for example, it requires only precipitation/rainfall data and enables drought monitoring over different time scales, viz., 1 month, 3 months, 6 months, 9 months, 12 months, 24 months etc.

Table 6.3 Drought conditions classified on the basis of SPI (McKee, 1993)

SPI	**Condition**
2.0 or more	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
-2 or less	Extremely Dry

6.3 COUPLING OF TENNANT CONCEPT WITH SPI

As seen from Tables 6.2 and 6.3, SPI and %AAF appear to be correlated with each other for describing various drought and flow conditions. For a particular catchment, drought indicates the deficiency of water in that sub-basin whereas EF is important for sustainability of the river ecosystem. In other words, this is the problem of correlating meteorology of a basin with its river ecology. With little manipulation, it is possible to derive Table 6.4 from Tables 6.2 and 6.3 for low flow season, showing the existence of such a relation between SPI and %AAF.

Table 6.4 Proposed coupling of Tennant and SPI concepts for low flow season.

Tennant		SPI	
Flow Condition	**Criteria**	**Criteria**	**Drought condition**
Flushing flow	200% AAF	2.0 or more	Extremely wet
Optimum range of flow	60-100% AAF	1.5 to 1.99	Very wet
Outstanding	40% AAF	1.0 to 1.49	Moderately wet
Excellent	30% AAF	-0.99 to 0.99	Near Normal
Good	20% AAF	-1.0 to -1.49	Moderately Dry
Fair or Degrading	10% AAF	-1.5 to -1.99	Severely Dry
Poor or Minimum	10% AAF or less	-2 or less	Extremely Dry

The existence of such a correlation between SPI and %AAF can also be established mathematically, as follows. SPI represents the deviation of rainfall from its long term average for a location. Assuming the rainfall series to follow a normal distribution, SPI represents the normal deviate:

$$SPI = (x - \mu)/\sigma = Z$$

Where x is the rainfall; μ and σ are the mean and standard deviation of the rainfall series, respectively; and Z is the standard normal variate of normal distribution. The environmental flow conditions are described on the basis of %AAF. Here, average annual flow (AAF) represents the mean of the annual flow series, i.e. μ, and %AAF of a flow, say x, represents the normalized fraction of the corresponding annual mean flow, i.e. 100x/μ. Thus,

$$SPI = [AAF/(100\sigma)]\,[\%AAF - 100] \qquad (6.9)$$

or

$$SPI = [1/(100\,Cv)]\,[\%AAF - 100]$$

Since AAF (or μ), σ, and Cv = coefficient of variation are the characteristic of rainfall series, SPI is in direct correlation with %AAF. Thus, SPI depends on both %AAF and Cv and these vary from region to region depending on the rainfall. Thus, Table 6.4 will be different for different climatic regions and seasons, implying that it will hold for a particular type of region and season. It is of common experience that, in perennial streams, Cv is generally high in monsoon season, and low in non-monsoon season. In this study, based on the relationship derived, such tables are proposed for different watersheds/regions.

6.4 ANALYSIS AND DISCUSSION OF RESULTS

The analysis is carried out for different catchments to explore the relationship between %AAF (describes EF condition in Tennant (1976) approach) and SPI derived at 9-month scale (non-monsoon season from October-June). The following two cases are considered:

Case 1: Relationship derived between SPI and %AAF is calibrated and validated for each of the eleven catchments using split datasets.

Case 2: A general relationship between SPI and %AAF is derived using the calibration dataset of all the watersheds, and tested on the (validation) data used for prediction of EF in case 1.

Case 1

Relationship derived between SPI and %AAF is calibrated and validated for each of the eleven catchments using split datasets, as follows.

Ghatora catchment: The rainfall and runoff data of 1991-2006 were used. The average flow of 9 months (October-June) for each year was computed to estimate AAF and then %AAF to describe different flow conditions of the catchment. Similarly, SPI was computed for the same 9 months for each year for the month of June at 9-month scale using rainfall data of the same period. A plot between %AAF and SPI for the split data is shown in Fig. 6.1(a) for the period of 1991-2000. It is seen that, as SPI increases, %AAF also increases, and vice versa. The value of R^2 is 0.744, which shows a very good fit. Further, the remaining data of the same period (2001-2006) were used for validation of the derived relationship. The observed and computed %AAF of the corresponding SPI values when plotted in Fig. 6.1(b) show the observed and computed %AAF values to be generally close to the line of perfect fit (LPF), indicating a satisfactory fit. The existence of such a relationship is in accordance with Eq. 9.

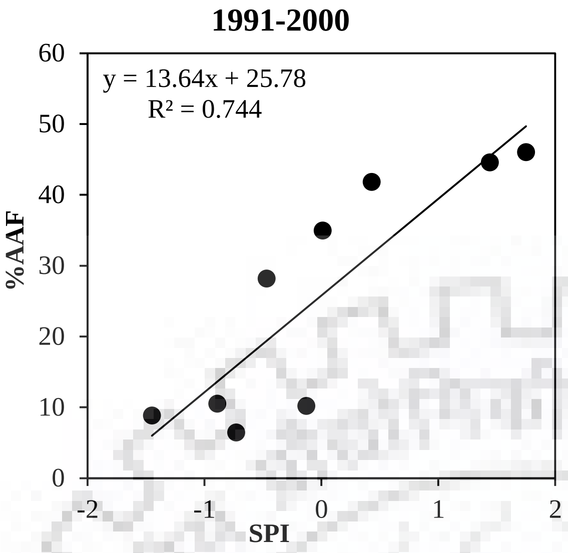


Figure 6.1(a) %AAF versus SPI values for Ghatora catchment

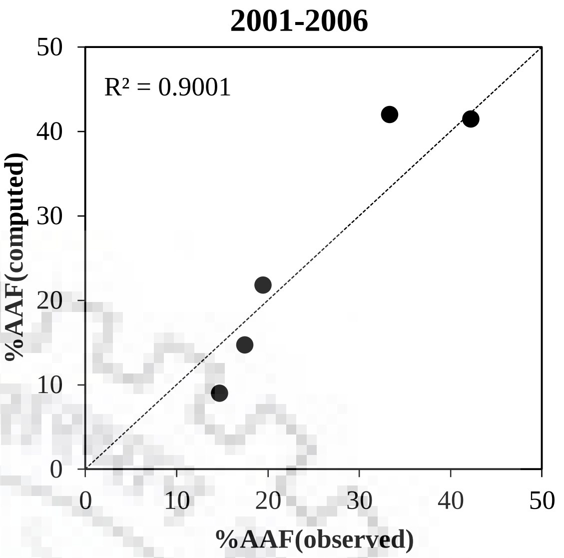


Figure 6.1(b) Observed and computed %AAF for Ghatora catchment.

Kurubhata catchment: The rainfall and flow data of 16 years (1991-2006) were used. Following the similar procedure, as above, the derived %AAF is plotted against the corresponding SPI for Kurubhata catchment in Fig. 6.2(a) with R^2 = 0.886, exhibiting an excellent relationship between %AAF and the corresponding SPI. Thus, EF condition for this catchment can be ascertained using SPI. Further, %AAF has been computed for the period 2001-2006 and plot of observed and computed %AAF is shown in Fig. 6.2(b), leading to similar inference as above.

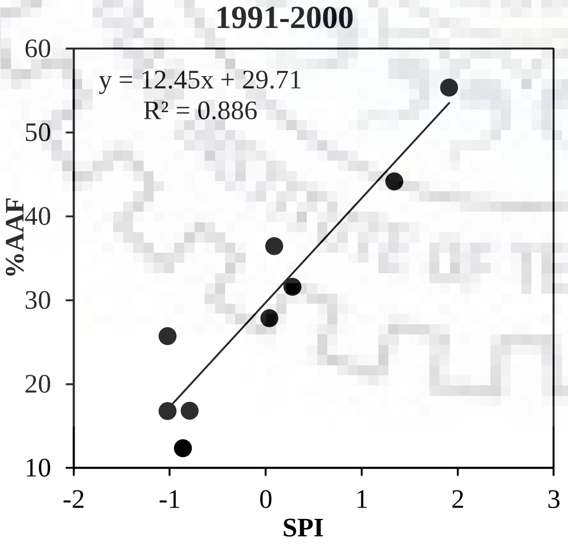


Figure 6.2(a) %AAF versus SPI values for Kurubhata catchment

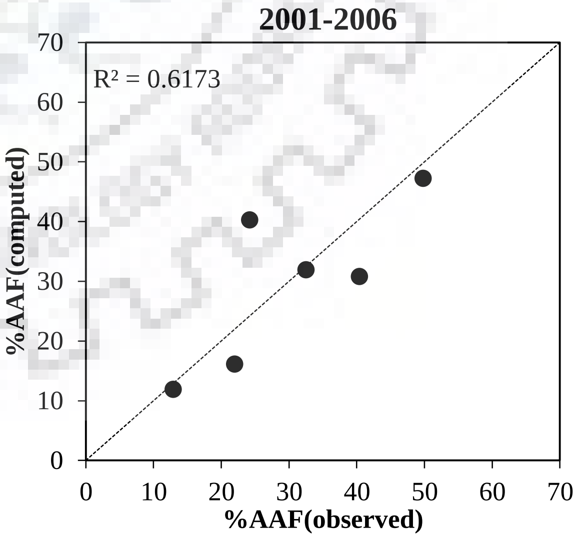


Figure 6.2(b) Observed and computed %AAF for Kurubhata catchment

Salebhata Catchment: The data of 16 years (1991-2006) were used, and the requisite plot using the data of 10 years (1991-2000) is shown in Fig.6.3(a), again indicating a very good fit ($R^2 = 0.791$). The observed and computed values of %AAF for the period 2001-2006 are seen to be in good agreement (Fig. 6.3b).

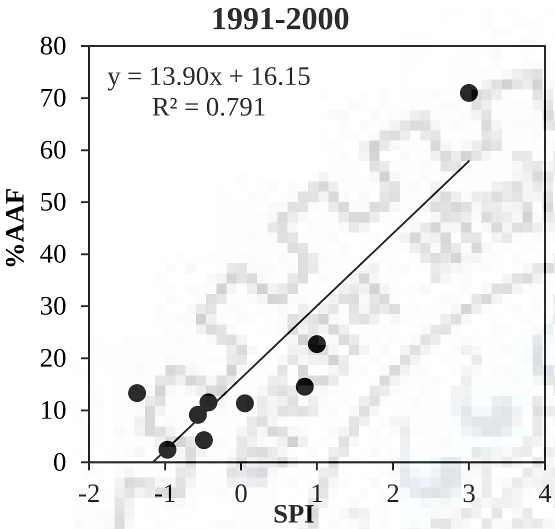


Figure 6.3(a) %AAF versus SPI values for Salebhata catchment

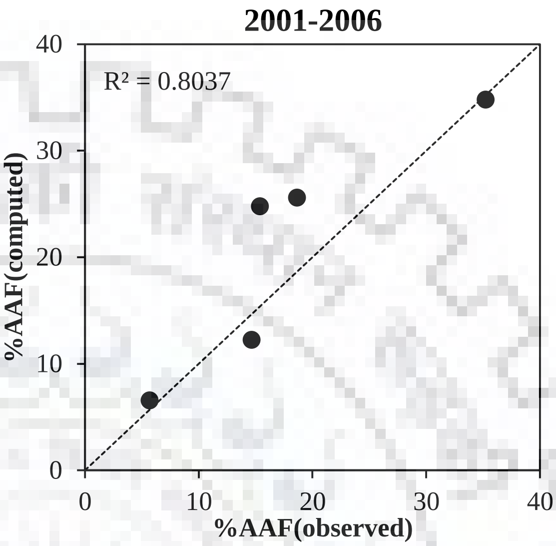


Figure 6.3(b) Observed and computed %AAF for Salebhata catchment

Anandpur Catchment: The rainfall and flow data of 16 years (1991-2006) were used. Following the similar procedure, as above, the derived %AAF for the period 1991-2000 is plotted against the corresponding SPI for Anandpur catchment in Fig. 6.4(a) with $R^2 = 0.704$, exhibiting a very good %AAF - SPI relationship. Thus, EF condition for this catchment can be ascertained using SPI. The observed and computed %AAF (for the period 2001-2006) of the corresponding SPI values were plotted in Fig. 6.4(b), which shows the observed and computed %AAF values to be generally close to LPF.

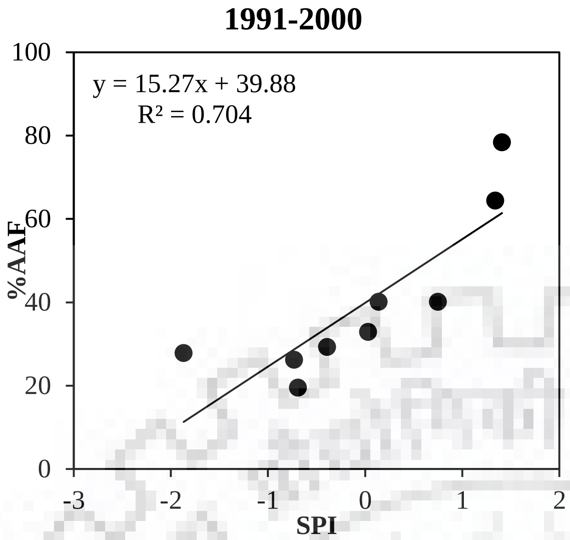


Figure 6.4(a) %AAF versus SPI values for Anandpur catchment

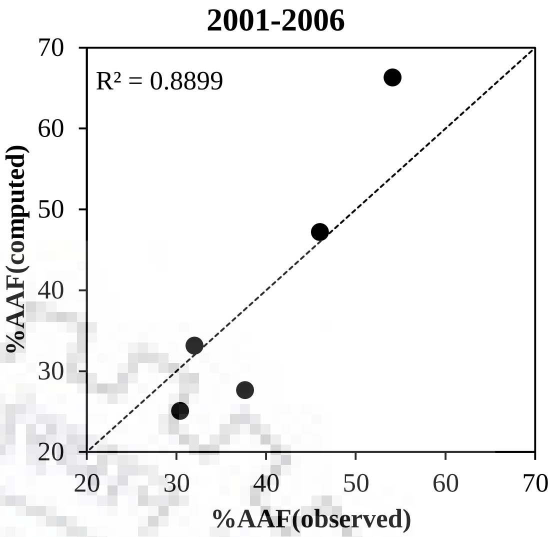


Figure 6.4(b) Observed and computed %AAF for Anandpur catchment

Jaraikela Catchment: The data of 16 years (1991-2006) were used, and the requisite plot using the data of 10 years (1991-2000) is shown in Fig. 6.5(a), again indicating a very good fit (R^2 = 0.767). Further, %AAF has been computed for the period 2001-2006 and plot between observed and computed %AAF is presented in Fig. 6.5(b), leading to similar inference as above.

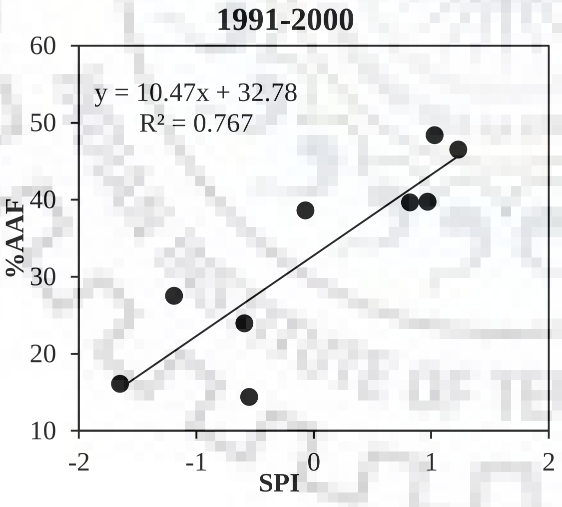


Figure 6.5(a) %AAF versus SPI values for Jaraikela catchment

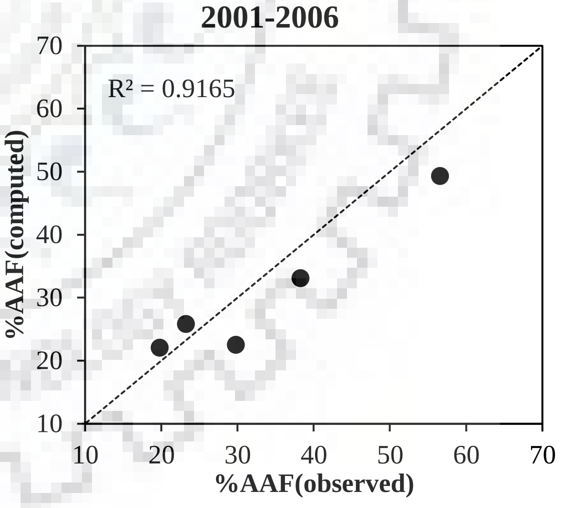


Figure 6.5(b) Observed and computed %AAF for Jaraikela catchment.

Hivra Catchment: The rainfall-runoff data of 17 years (1990-2006) were used. Following the similar procedure, the derived %AAF for the period 1990-2000 is plotted against the corresponding SPI for Hivra catchment in Fig. 6.6(a) with R^2 = 0.745, exhibiting a very good relationship. Thus, EF condition for this catchment can be ascertained using SPI. The observed and computed %AAF (for the period 2001-2006) of the corresponding SPI values were plotted in Fig. 6.6(b), which shows the observed and computed %AAF values to be generally close to LPF.

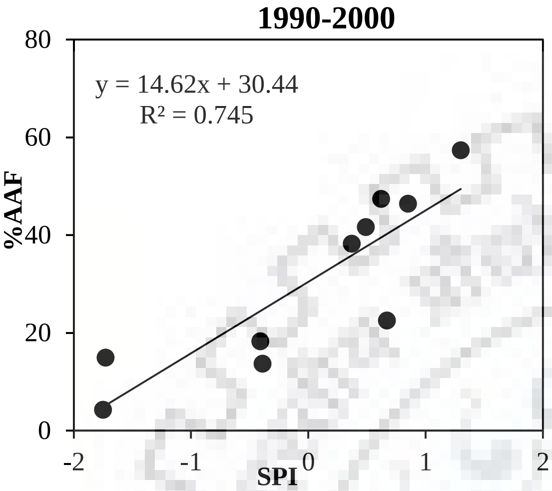


Figure 6.6(a) %AAF versus SPI values for Hivra catchment

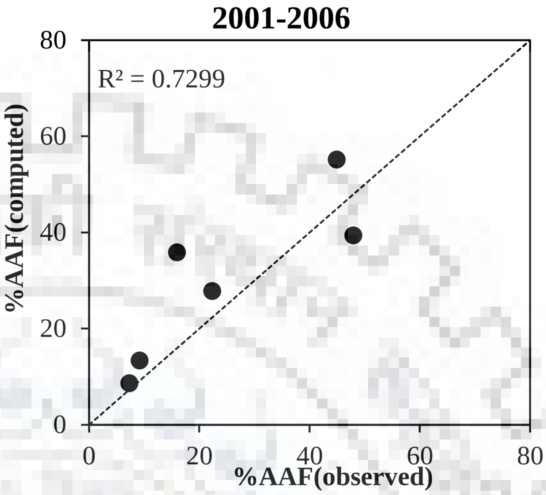


Figure 6.6(b) Observed and computed %AAF for Hivra catchment

Nandgaon Catchment: The data of 17 years (1990-2006) were used, and the requisite plot using the data of 11 years (1990-2000) is shown in Fig. 6.7(a) (R^2 = 0.549). Further, %AAF has been computed for the period 2001-2006 and plot between observed and computed %AAF is presented in Fig. 6.7(b) leading to similar inference as above.

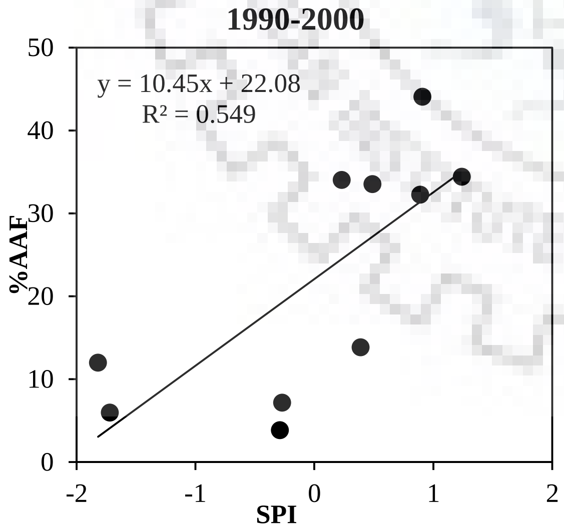


Figure 6.7(a) %AAF versus SPI values for Nandgaon catchment

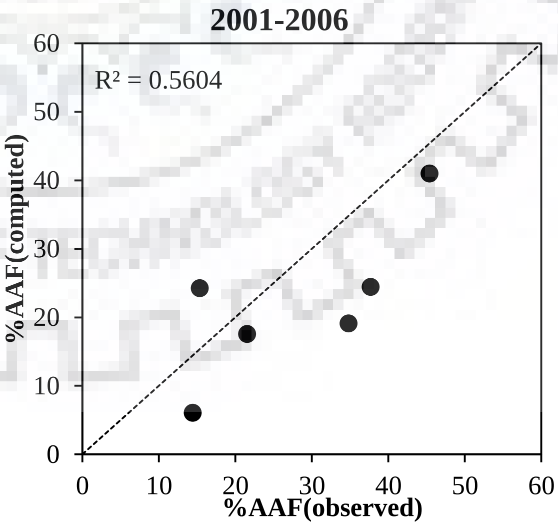


Figure 6.7(b) Observed and computed %AAF for Nandgaon catchment

Mohegaon catchment: The rainfall and runoff data of 1981-1990 were used. The average flow of 9 months (October-June) for each year was computed to estimate AAF, and %AAF to describe different flow conditions of the catchment. Similarly, SPI on 9-month time scale for the month of June was computed for each year using rainfall data of the same period. A plot between %AAF and SPI for the calibration data (1981-1985) is shown in Fig. 6.8(a). The value of R^2 is 0.856 shows a very good fit. Further, the remaining data (1986-1990) were used for validation of the relationship. The observed and computed %AAF of the corresponding SPI values when plotted in Fig. 6.8(b) show the observed and computed %AAF values to be generally close to LPF, indicating a satisfactory fit.

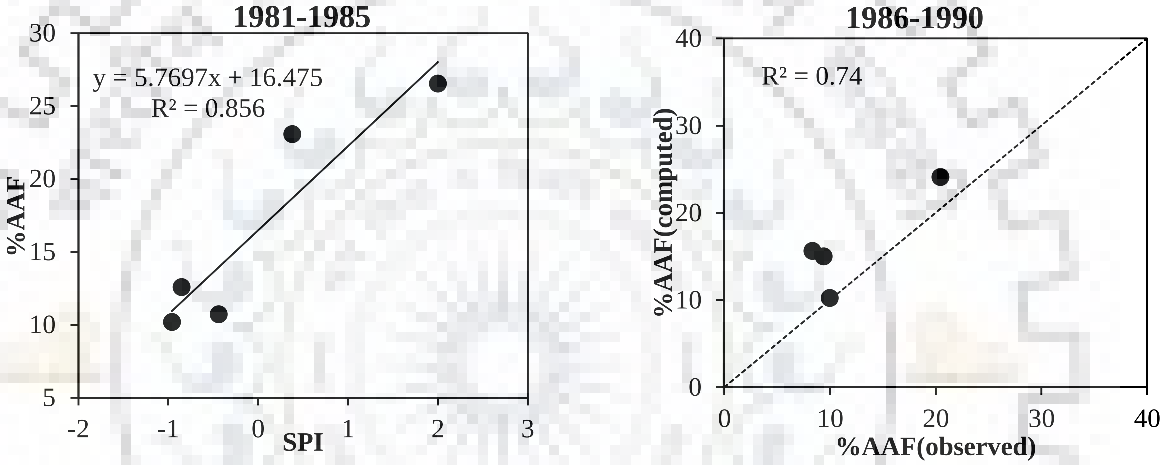


Figure 6.8(a) %AAF versus SPI values for Mohegaon catchment

Figure 6.8(b) Observed and computed %AAF for Mohegaon catchment

Hridaynagar catchment: The rainfall and flow data of 10 years (1981-1990) were used. The derived %AAF is plotted against the corresponding SPI for this catchment in Fig. 6.9(a) for the period of 1981-1985 with R^2= 0.757, exhibiting a good relationship between %AAF and SPI. The observed and computed %AAF for 1986-1990 data plotted in Fig. 6.9(b) are generally close to LPF.

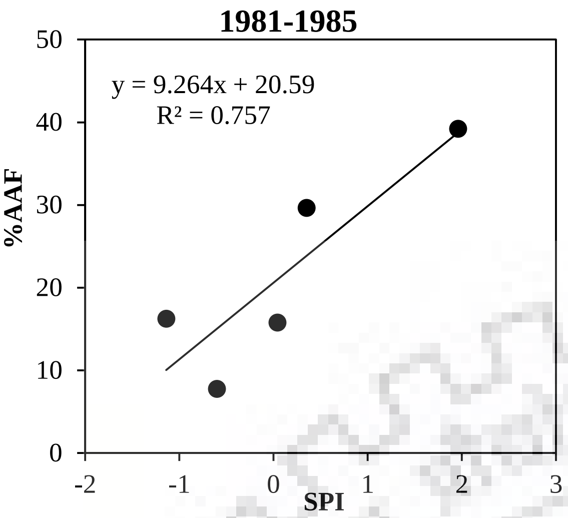


Figure 6.9(a) %AAF versus SPI values for Hridaynagar catchment

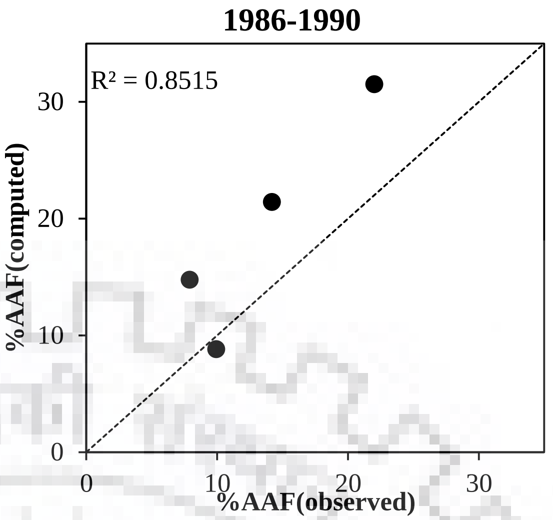


Figure 6.9(b) Observed and computed %AAF for Hridaynagar catchment

Manot Catchment: The data of 10 years (1981 – 1990) were used, and the requisite calibration plot for the period of 1981-1985 is shown in Fig. 6.10(a), fitting with R^2 = 0.771. The validation plot (Fig. 6.10b) from 1986-1990 imply similar inferences as above.

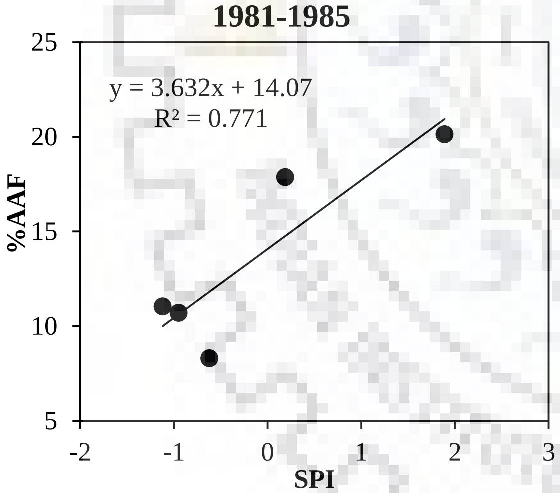


Figure 6.10(a) %AAF versus SPI values for Manot catchment

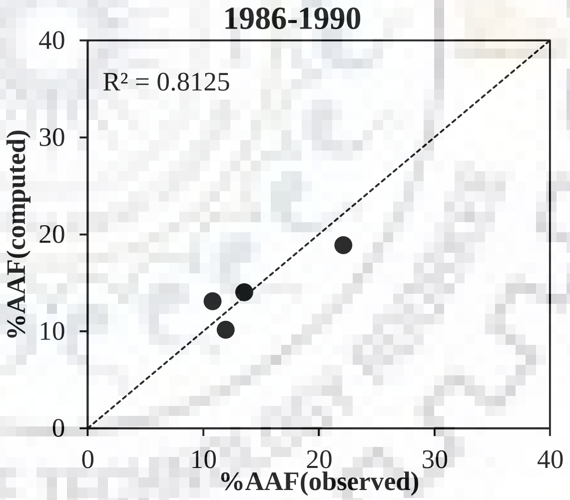


Figure 6.10(b) Observed and computed %AAF for Manot catchment

Sher Catchment: Fig. 6.11(a) shows an excellent (R^2= 0.988) %AAF-SPI relation from 1978-1982 data. The observed and computed %AAF for 1983-1986 data points are close to LPF, as shown in Fig. 6.11 (b).

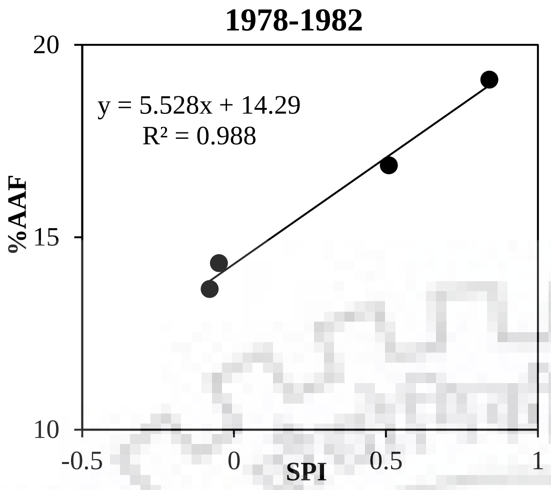


Figure 6.11(a) %AAF versus SPI values for Sher catchment

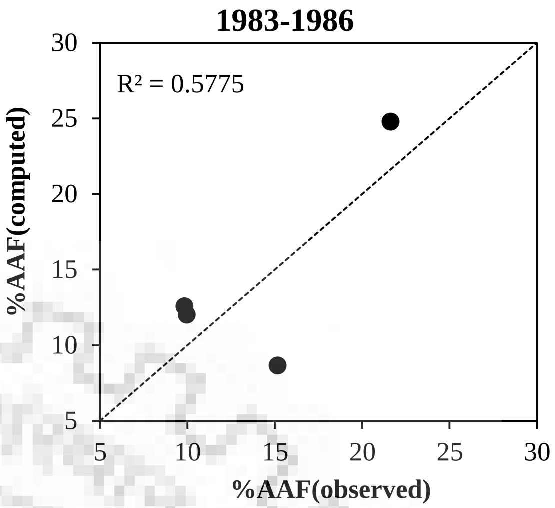


Figure 6.11(b) Observed and computed %AAF for Sher catchment

It can be seen from the above that %AAF (of the non-monsoon season from October-June) is significantly related with SPI derived on 9-month time scale (for the month of June) from the corresponding rainfall data for all the catchments. The summary of the results of all the catchments are presented in Table 6.5

Table 6.5 Summary of application results for Case 1

Catchment	Rainfall		Runoff		Calibration (y=mx+c*)					Validation		
	μ (mm)	σ	μ (cumec)	σ	No. of events	'm'	'c'	R^2	Bias	No. of events	R^2	Bias
Ghatora	311.5	143.2	36.8	20.2	10	13.64	25.78	0.744	0.0	7	0.900	1.9
Kurubhata	308.7	132.9	86.1	35.0	10	12.45	29.71	0.886	-0.05	7	0.617	0.6
Salebhata	336.9	80.4	50.4	36.0	10	13.90	16.15	0.791	-0.06	7	0.803	14.36
Anandpur	570.4	100.5	168.6	64.4	10	15.27	39.88	0.704	-0.1	7	0.889	-0.7
Jaraikela	406.2	99.9	163.3	57.5	10	10.47	32.78	0.767	0.0	7	0.916	-14.7
Hivra	280.9	71.8	52.2	34.5	11	14.62	30.44	0.745	-0.1	7	0.729	32.3
Nandgaon	325.0	106.4	31.0	20.1	11	10.45	22.08	0.549	-0.05	7	0.560	-36.7
Mohegaon	289.8	122.8	64.9	17.4	5	5.769	16.47	0.856	0.0	5	0.740	16.8
Hridaynagar	377.9	147.2	37.7	15.81	5	9.26	20.59	0.757	-0.01	5	0.851	6.0
Manot	335.4	142.0	92.8	27.9	5	3.632	14.07	0.771	0.0	5	0.812	-2.2
Sher	279.2	104.2	22.2	9.1	5	5.528	14.29	0.988	0.0	4	0.577	1.5

*y= %AAF, x = SPI.

It is further seen from Table 6.5 that the number of data points used in calibration is fairly large, varying from 5-11 years in calibration, and 4-7 in validation. The coefficient of determination (R^2) is fairly high (> 0.7) and ranges up to 0.988 in calibration, except for one Nandgaon catchment for which it is 0.549 in calibration and 0.56 in validation. These show the fits to be reasonably satisfactory to excellent ranging from 0.56 (Nandgaon catchment) to 0.90 (Ghatora catchment), respectively. The negative and positive values of 'Bias' in Table 6.5 show that %AAF values are under- and over-predicted, respectively.

In the derived linear SPI - %AAF relationship of the form y=mx+c (Eq. 6.9), where y = %AAF, x = SPI, m = 100Cv SPI and c = 100. From Table 6.5, the m-values range from 10.45 to 13.90 for the first seven catchments and Hridaynagar catchment for which it is 9.26. The other three catchments Mohegaon, Manot, and Sher exhibit m-values in the range (3.632, 5.769). Notably all the latter catchments belong to Narmada basin. The variation of m-values can be explained in terms of μ- and σ-dependent Cv and SPI.

Various trials were attempted for exploring the existence of a relationship for μ- and σ-dependent m using the data of Table 6.5. When plotted (not shown), the μ-m relations for both rainfall and runoff showed the rising trends whereas m-C_v (= σ/μ) relations showed falling and rising trends for rainfall (Fig. 6.12) and runoff (Fig. 6.13), respectively. Thus, it is clear that there exists a definite relationship between m and μ or σ and/or any combination. The roots might appear in the above assumed y = mx relationship used in derivation of Eq. 6.9. To this end, the mean values of both rainfall and runoff of all catchments (Table 6.5) were plotted as shown in Fig. 6.14. As seen, there exists a good relationship between mean rainfall and mean runoff values, indicating the above assumption not to be far from reality. However, the relationship shows that when mean rainfall < 190 mm, mean runoff becomes unreasonably negative. Thus, Eq. 6.9 is subject to further refinement by employing non-linear or other suitable type of rainfall-runoff relationship.

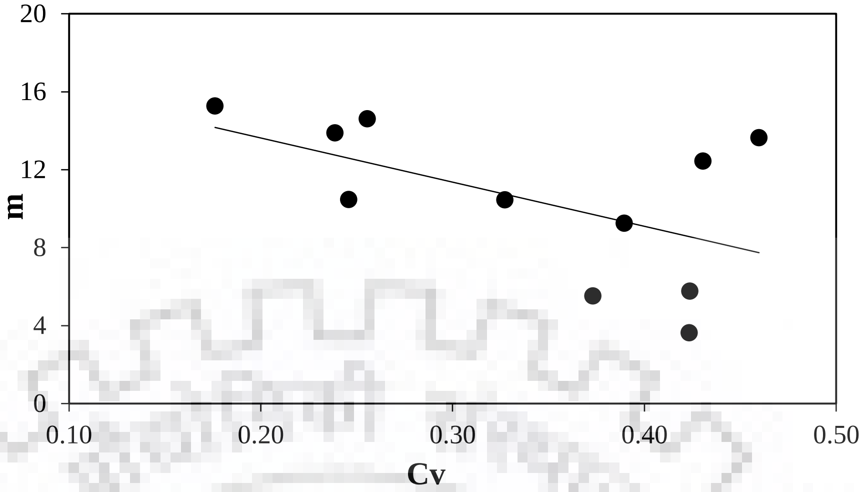


Figure 6.12 Cv (non-dimensional) Vs m (non-dimensional) relationship for rainfall data.

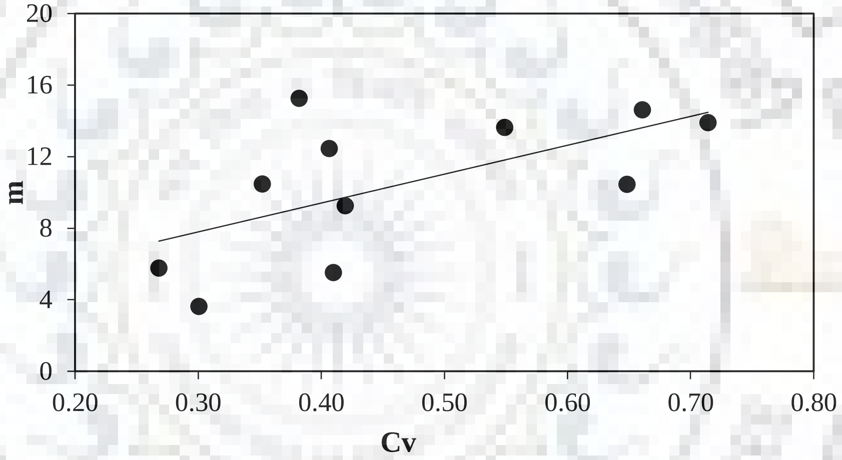


Figure 6.13 Cv (non-dimensional) Vs m (non-dimensional) relationship for runoff data.

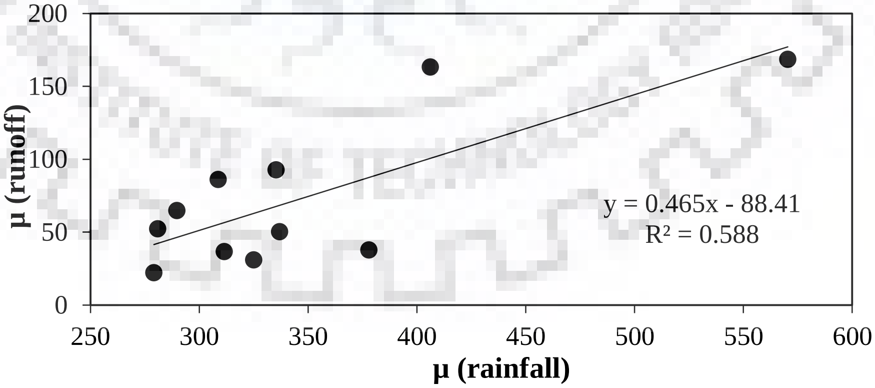


Figure 6.14 μ (runoff in cumec) Vs. μ (rainfall in mm) for verification of the assumed linear relationship (valid for mean rainfall > 191 mm).

Similarly, the 'c' values for all catchments in calibration are seen to vary from 14.07 to 39.88. Note, these are the critical %AAF values when SPI = 0, indicating Excellent or Normal catchment condition (Table 6.4). Thus, these represent the critical values for a catchment, a deviation from which either makes the EF condition of the catchments either dry (SPI < 0) or wet (SPI>0). The former condition is indicative of the available rain or runoff water in a catchment in a year being larger than that available normally, and reverse is true for the latter. Further, while exploring for dependency, c versus μ or σ and/or their combinations were attempted, and the results plotted in Fig. 6.15 and Fig. 6.16 for rainfall and runoff, respectively. As seen, μ of both rainfall and runoff show rising trends. On the other hand, μ versus c plots for both rainfall and runoff showed (not shown) falling trends. It thus further supports the assertion that Eq. 6.9 is close to physical reality, but since both m and c parameters are μ or σ dependent, Eq. 6.9 needs further refinement.

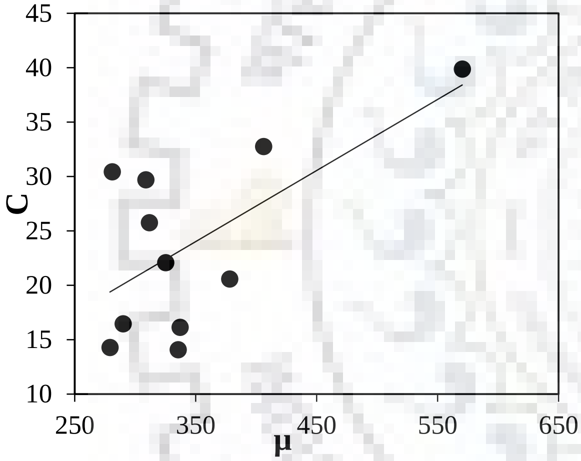


Figure 6.15 μ (mm) Vs. c (non-dimensional) relationship for rainfall.

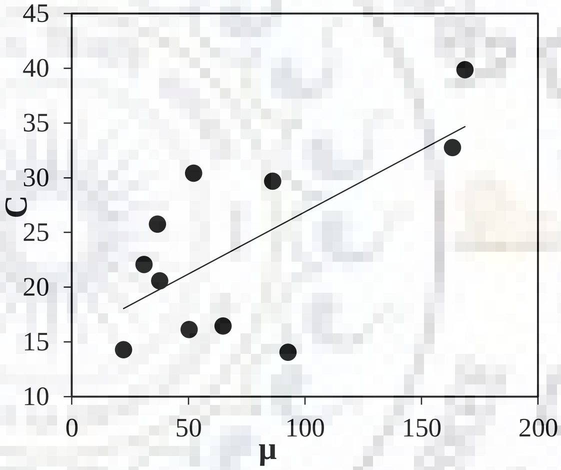


Figure 6.16 μ (cumec) Vs. c (non-dimensional) relationship for runoff

Case 2

The calibration datasets of each of eleven watersheds were taken together for deriving a general relationship between SPI and %AAF, as shown in Fig. 6.17 (R^2 = 0.649), and then tested on the combined validation data of these watersheds. As shown in Fig. 6.18, the observed and computed %AAF values are generally close to LPF, implying that there exists a relationship between SPI and %AAF, and SPI can be used for derivation of %AAF for describing the EF condition of a watershed during low flow season (October-June) based on SPI values, as shown in Table 6.6 derived from the results of Fig. 6.17. Here, it is worth emphasizing that the approach suggested in this study involves all the limitations of Tennant method.

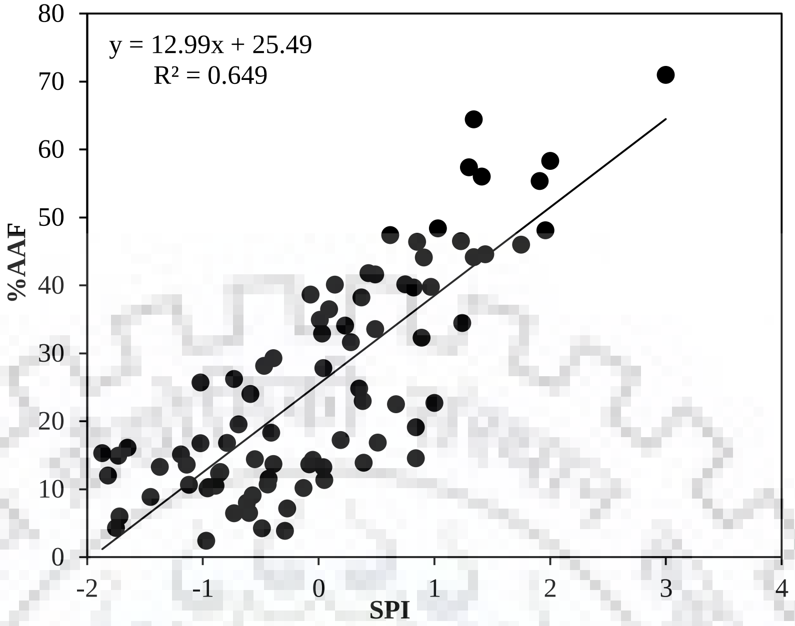


Figure 6.17 %AAF versus SPI values for all the catchments used in the study

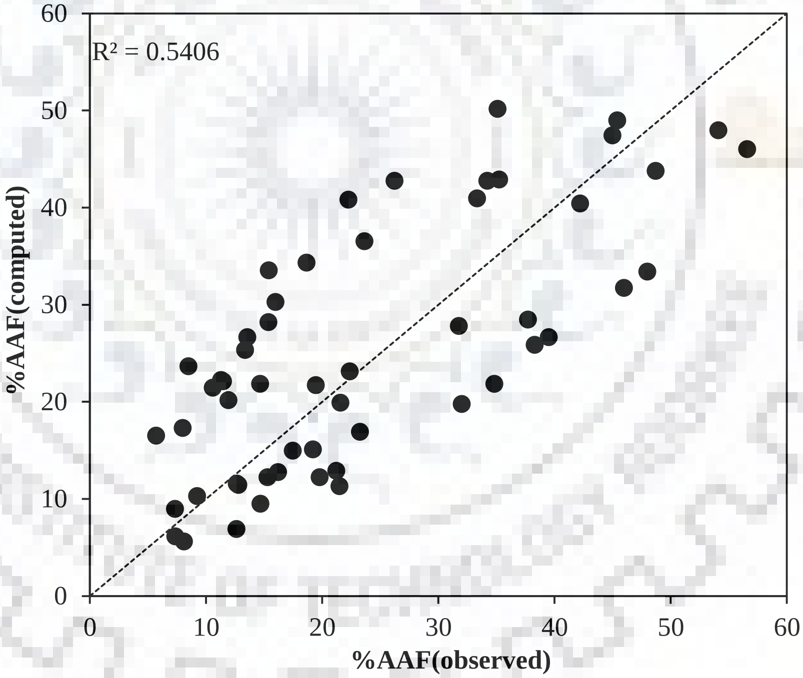


Figure 6.18 Observed and computed %AAF for all catchments used in the analysis.

Table 6.6 Description of flow condition based on %AAF or SPI during low flow season

Flow Condition	**%AAF**	**SPI**
Flushing flow	200%	greater than 13.4
Optimum range of flow	60-100%	2.7 to 5.7
Outstanding	40%	1.1 to 2.6
Excellent	30%	0.3 to 1.0
Good	20%	-0.4 to 0.2
Fair or Degrading	10%	-1.1 to -0.3
Poor or Minimum	10% or less	-1.2 or less

6.5 SUMMARY

The study was carried out using the long-term rainfall-runoff data of eleven catchments, viz., Ghatora, Kurubhata, Salebhata of Mahanadi basin; Anandpur, Jaraikela in Brahmani-Baitaini basin; Hivra, Nandgaon in Godavari basin and Mohegaon, Manot, Hridaynagar, Sher of Narmada basin. SPI at 9 month time scale for the month of June and the percentage of average annual flow (%AAF) were calculated for the same period for each of the catchments. Following conclusions can be drawn from this study:

1. In each of the eleven catchments, %AAF is seen to increase linearly with increase in SPI, and vice versa. R^2 greater than 0.7 for 10 (out of 11) catchments reveal the existence of excellent correlation between SPI and %AAF.
2. The existence of remarkable %AAF-SPI relationship in all catchments underlines the significance of the study, for the EF condition of these catchments can be ascertained using 9-month (October-June) scale SPI (derivable from easily available rainfall data) during low flow season.
3. Since the proposed approach inheres all limitations of the Tennant method, it is not applicable to catchments severely disturbed by anthropogenic activities.

CHAPTER 7

A SIMPLE SPI-BASED ENVIRONMENTAL FLOW PREDICTION DURING HIGH FLOW SEASON

7.1 INTRODUCTION

River habitat, water quality, and biotic interaction are greatly affected by the large variation in quantum of flow (i.e. discharge), flow length etc. around the globe (Naiman et al., 2002).Since the degrading ecosystem leads to both social and economic loss which affect the large number of poor people around the world, it is important to understand the value of the ecosystem services to maintain livelihoods in future for sustainable development (Dysonet al., 2003; Millennium Ecosystem Assessment, 2005; Pearce et al., 2007). It is of common experience that most of the rivers around the globe are fragmented by hydrological changes, causing deterioration of aquatic ecosystem (Millennium Ecosystem Assessment,2005; Poff et al., 1997; Postel and Richter, 2003; Revenga et al., 2005).Alternatively, minimum amount of good quality water, also known as environmental flow (EF),be preserved in rivers for survival and conservation of the natural ecosystem (Poff et al., 2009) involving sustainability of aquatic lives (Brisbane Declaration, 2007; Wang and Lu, 2009; Mathews and Richter, 2007).

The rapid socioeconomic development and change in climate during the past few decades have greatly influenced the global hydrologic cycle up to the extent of putting a threat to water security, wellness of aquatic ecosystem, and river biodiversity (Vörösmarty et al., 2010; Jacobsen et al., 2012; Van Vlietet al., 2013; Amrit et al., 2017). These situations alarm for assessment of EF requirement (EFR) and water scarcity (Vörösmarty et al., 2010; Kirby et al., 2014). Initially, EF assessment methods were developed to estimate the instream flow needs of fish below the irrigation and hydroelectric dams on large rivers (Trihey and Stalnaker 1985) with aim to set the flow required during low flow season (Leathe and Nelson 1986). Presently, more than 240 methods are available and being used worldwide to calculate EFR to maintain rivers in healthy condition (Tharme, 2003) during both low and high flow seasons. These methods can be grouped into four categories- hydrological, hydraulic rating, habitat simulation, and holistic methods.

The simplest hydrological methods require flow data of rivers for EF assessment. These methods assume a relationship between flow and specific biological parameters. The most commonly used hydrological methods are Tennant (1976) method, BC-Instream flow threshold method (Hatfield et al. 2003), Alberta desktop method, flow duration curve methods, shifting flow duration curve (FDC) technique etc. Haghighi and Klove (2017) suggested release of environmental flow in areas where irrigation demand is high. Yang et al. (2016) suggested strategies for management of environmental flow based on the integration of quality and quantity of water for Baiyangdian Wetland, China, and suggested to increase the discharge by 2 m^3/s to prevent further deterioration of its ecosystem. Smakhtin and Masse (2000) proposed a method for the generation of time series of daily flow data using the observed daily precipitation in a watershed. The application of the approach suggested was demonstrated on the various watersheds located in South Africa, and is very useful for the ungauged or poorly gauged sites. Yang et al. (2016) using the daily flow data of 20 years period of 42 flow stations located in upper reaches of Taiwan estimated the ungauged natural flow regime considering 31 Indicators of Hydrologic Alteration. The study reveals that the suggested model estimates the ungauged natural flow regime more accurately for the management of environmental flow.

On the other hand, drought is distinguished to be a natural phenomenon in which the available water for a region is less than that required under usual conditions for a longer period, leading to economic loss. It may persist for weeks, months, and years, and therefore, the economic loss caused by it is higher than any other natural hazard, affecting severely the farming, water resources, environment and human lives (Wilhite, 2000; Bryant, 2005).It can occur in any region anywhere including wet and humid climatic regions (Dai, 2011). There exist a number of drought indices in literature useful for drought monitoring, such as Standardized Precipitation Index (SPI) (McKee et. al., 1993), Effective Drought Index (EDI) (Byun and Wilhite, 1999); percentage departure of annual and seasonal rainfall from corresponding mean. These are applied for identification of onset, termination, and quantification of severity of drought events.

Thus, in literature, SPI has been used to monitor dry and wet events using the rainfall whereas Tennant method has been used to indicate the environmental flow condition of a river ranging from flushing flow to severe degradation, i.e. whether the river has high flow or runs dry based on the flow data. Since both SPI and Tennant methods describe the moisture conditions ranging from dry to wet based on rainfall and flow data, respectively, their correspondence may lead to the proposition of an SPI-based methodology for predicting environmental flow condition during high flow season, employing more easily available rainfall data rather than flow data that are not available in ungauged watersheds and it is the primary objective of this study.

7.2 METHODOLOGY

Tennant method

This has been discussed in section 6.2.1 (Chapter 6). Different flow conditions described using percentage of AAF for high (April-September) flow periods are given in Table 7.1(Tennant, 1975).

Table 7.1 Tenant method for EFR assessment for high flow season (Tennant 1975)

Flow Condition	April-September
Flushing flow	200% AAF
Optimum range of flow	60-100% AAF
Outstanding	60% AAF
Excellent	50% AAF
Good	40% AAF
Fair or Degrading	30% AAF
Poor or Minimum	10% AAF
Severe Degradation	10% AAF to zero flow

Standardized Precipitation Index (SPI)

The detailed description of SPI has been discussed in section 6.2.2 (Chapter 6).

7.3 INTEGRATION OF TENNANT CONCEPT WITH SPI

As seen from Tables 7.1 and 6.3, SPI and %AAF appear to be correlated with each other for describing various drought and flow conditions. For a particular catchment, drought indicates the deficiency of water in that sub-basin whereas EF is important for sustainability of the river ecosystem. In other words, meteorology of a basin is correlated with its river ecology. With little manipulation which includes trial and error, the different conditions of environmental flow (i.e. from flushing flow to poor or minimum flow) described by the %AAF are matched with various moisture conditions (i.e. from extremely wet to extremely dry) defined by SPI values. Therefore, it is possible to derive Table 7.2 from Tables 7.1 and 6.3 for high flow season, showing the existence of a relationship between SPI and %AAF.

Table 7.2 Proposed coupling of Tennant and SPI concepts for high flow season.

Tennant		SPI	
Flow Condition	**Criteria**	**Criteria**	**Drought condition**
Flushing flow	200% AAF	2.0 or more	Extremely wet
Optimum range of flow	60-100% AAF	1.5 to 1.99	Very wet
Outstanding	60% AAF	1.0 to 1.49	Moderately wet
Excellent	50% AAF	-0.99 to 0.99	Near Normal
Good	40% AAF	-1.0 to -1.49	Moderately Dry
Fair or Degrading	30% AAF	-1.5 to -1.99	Severely Dry
Poor or Minimum	10% AAF	-2 or less	Extremely Dry

Such a correspondence between SPI and %AAF can also be established mathematically, as follows. SPI represents the deviation of rainfall from its long term average for a location. Assuming the rainfall series to follow a normal distribution, SPI represents the normal deviate defined as: SPI = $(x-\mu)/\sigma = Z$, where x is the rainfall; μ and σ are the mean and standard deviation of the rainfall series, respectively; and Z is the standard normal variate of normal distribution. The environmental flow conditions are described on the basis of %AAF. Considering a linear rainfall-runoff relation (say, runoff or flow= m x rainfall) for a catchment for simplicity reasons, the average annual flow (AAF) will represent the mean of the annual flow series (i.e. $\mu_f = m\mu_r$), and %AAF of a flow (say $x_f = m\, x_r$) the normalized fraction of the corresponding annual mean flow, i.e. $100x_f/\mu_f=100x_r/\mu_r$). Here, subscripts ‘f’ & ‘r’ correspond to flow and rainfall, respectively. Thus,

$$\text{SPI} = [\text{AAF}/(100\sigma)]\,[\%\text{AAF} - 100] \quad \text{or SPI} = [1/(100\, C_v)]\,[\%\text{AAF} - 100] \qquad (7.1\ a,b)$$

Since AAF (or μ), σ, and Cv = coefficient of variation (= σ/μ) are the characteristic of runoff/rainfall series, SPI is in direct correlation with %AAF. Thus, SPI depends on both %AAF and Cv and these vary from region to region depending on the rainfall and its variation. Here, it is worth emphasizing that the seasonal and/or annual rainfall-runoff series generally exhibit a linear correlation, and therefore, the assumption of linear correlation is not beyond reality. Thus, Eq. 7.1 represents fairly reasonable SPI - %AAF relationship.

From Eq. 7.1, it is easy to infer that the SPI-values and their corresponding %AAF values in Table 7.2 will be different for different climatic regions and seasons, implying that it will hold for a particular type of region and season. In this study, based on the relationship derived, such tables are proposed for different catchments/regions during high flow season.

Table 7.3 Summary characteristics of study catchments

S. No.	Catchment	River	Major River Basin	Area (Km^2)	Latitude(N)	Longitude (E)	Average annual rainfall (mm)	Elevation Range (m)	Climatic region	Data Length	Major Land cover
1	Salebhata	Ong	Mahanadi	4650	20° 40’ to 21^0 28’	82^0 33’ to 83^0 34’	1300	145-800	Sub-humid	1991-2007	Forest, Agriculture, Settlement
2	Ghatora	Arpa	Mahanadi	3035	22^0 2’ to 22^0 46’	81^0 36’ to 82^0 26’	1320	270-740	Sub-humid	1991-2007	Forest, Agriculture
3	Kurubhata	Mand	Mahanadi	4625	21^0 58’ to 23^0 05’	82^0 50’ to 83^0 34	1309	256-1025	Sub-humid	1991-2007	Forest, Agriculture
4	Rampur	Jonk	Mahanadi	2920	20° 28’ to 21^{0}41’	82^{0}21’ to 82^{0}51’	1160	240-700	Sub-humid	1991-2007	Forest, Agriculture
5	Simga	Seonath	Mahanadi	30,761	20^0 21' to 22^0 3'	80^0 26' to 81^{0}55'	1170	267-745	Sub-humid	1991-2007	Forest, Agriculture, Settlement
6	Hivra	Wardha	Godavari	10240	20^0 21’ to 21^0 52’	77^0 25’ to 78^0 45’	1020	242-800	Semi-arid	1990-2007	Forest, Agriculture, Settlement
7	Jagdalpur	Indravathi	Godavari	7380	18^{0}45’ to 19^{0}45’	81^{0}57’ to 83^{0}9’	1220	562-1230	Sub-humid	1990-2007	Forest, Agriculture
8	Kumhari	Wainganga	Godavari	8070	21^{0}41’ to 21^{0}48’	79^{0}2’ to 80^{0}30’	1280	310-860	Dry sub-humid	1990-2007	Forest, Agriculture, Settlement
9	Nandgaon	Wunna	Godavari	4580	21^0 58’ to 23^0 05’	82^0 50’ to 83^0 34’	1060	217-500	Semi-arid	1990-2007	Agriculture, Settlement
10	Nowrangpur	Indravathi	Godavari	3545	18^0 45’ to 19^{0}39’	82^{0}31’ to 83^{0}9’	1560	561-1054	Sub-humid	1990-2007	Forest, Agriculture
11	Penganga	Penganga	Godavari	18441	18^0 45’ to 19^{0}39’	82^{0}31’ to 83^{0}9’	1015	229-650	Semi-arid	1980-1997	Agriculture, Forest, Settlement
12	Ramakona	Kanhan	Godavari	2500	21^0 51’ to 21^{0}53’	78^{0}22’ to78^{0}48’	1080	344-1025	Dry sub-humid	1990-2007	Forest, Agriculture
13	Saradaput	Sabri	Godavari	3047	18^0 24’ to 19^{0}7’	81^{0}41’ to83^{0}3’	1320	271-1320	Sub-humid	1990-2007	Forest, Agriculture, Settlement
14	Satrapur	Kanhan	Godavari	11100	21^0 12’ to 22^{0}23’	78^{0}4’ to79^{0}32’	1110	290-990	Sub-humid	1990-2007	Forest, Agriculture
15	Anandpur	Baitarni	Brahmani-Baitarni	8570	21^{0}12’ to 22^0 15’	85^0 09’ to 86^0 22’	1441	50-950	Sub-humid	1991-2007	Forest, Agriculture
16	Burhanpur	Tapi	Tapi	8487	21^{0}15’ to 22^0 2’	76^0 05’ to 78^{0}18’	840	220-890	Semi-arid	1990-2007	Forest, Agriculture, Settlement

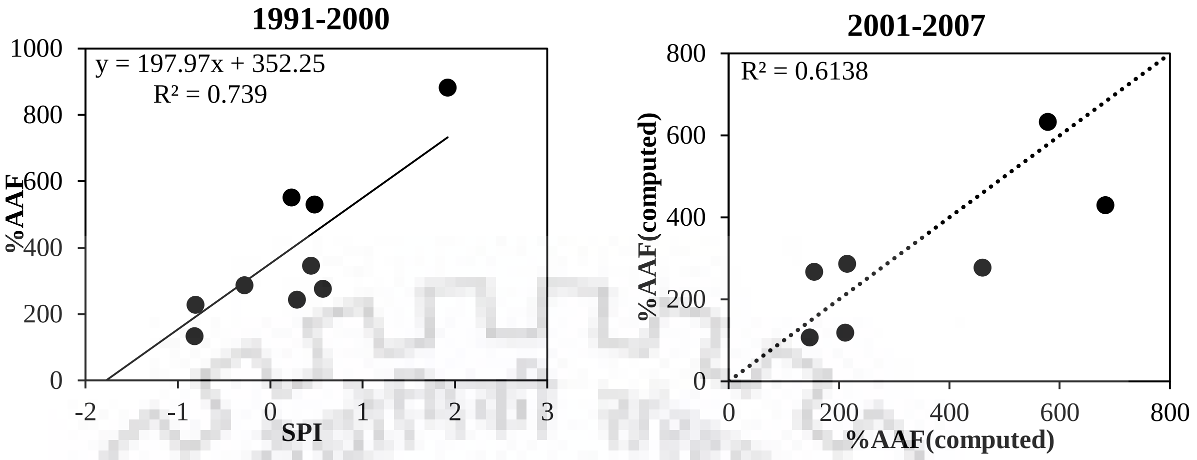
7.4 ANALYSIS AND DISCUSSION OF RESULTS

The description of the study catchments provided in Table 7.3 shows that a variety of catchments have been considered for derivation of the relation between %AAF and SPI as suggested in Eq. 7.1. The use of Tennant (1976) approach to describe EF condition based on %AAF necessitates the availability of long-term runoff/discharge data, and thus, it is suitable for gauged catchments only. On the other hand, SPI describes the drought (moisture deficit) condition of a catchment utilizing the more easily available rainfall data, and therefore, it is applicable to ungauged catchments too. The existence of %AAF – SPI relationship will enable only rainfall-based EF description of even ungauged catchments.

For derivation of %AAF – SPI relationship, SPI-values were derived at 3-month scale (monsoon or high flow season from July-September). Two cases are considered. Case 1explores the existence of %AAF - SPI relationship separately for each of 16 catchments and Case 2 simply derives a general %AAF - SPI relationship based on these data points for all catchments, to ascertain EF condition of all 16 catchments (area ranging from 2500-30761 sq. km, as shown in Table 7.3). In Case 1, relationships derived are calibrated and validated for each of the sixteen catchments using split datasets. In Case 2, a relationship derived from all calibration %AAF - SPI data-points is tested on the whole validation datasets of all the catchments.

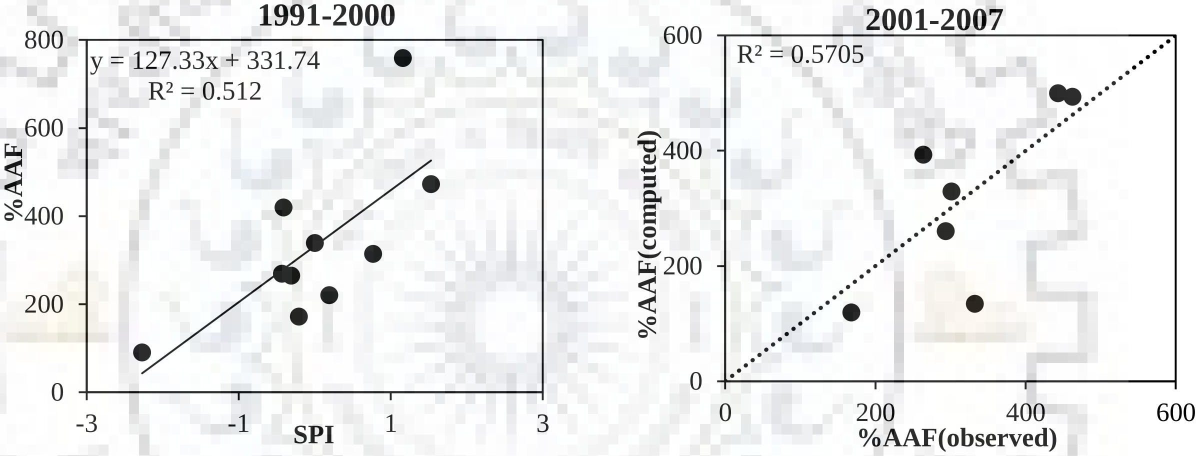
Case 1

The derivation of SPI - %AAF relationship for all the catchments for both cases is summarized in Table 7.4. As an example, the rainfall and runoff data of 1991-2007 were used for Salebhata catchment. The average flow of 3 months (July-September) for each year was computed to estimate AAF and then %AAF to describe different flow conditions of the catchment. Similarly, SPI was computed for the same 3 months for each year for September month at 3-month scale using rainfall data of the same period. A plot between %AAF and SPI for the split data is shown in Fig. 7.1(a) for the period of 1991-2000. It is seen that, as SPI increases, %AAF also increases, and vice versa. The value of R^2 is 0.739, which shows a very good fit. Further, the remaining data of the same period (2001-2007) were used for validation of the derived relationship. The observed and computed %AAF of the corresponding SPI values when plotted in Fig. 7.1(b) show the observed and computed %AAF values to be generally close to the line of perfect fit (LPF), indicating a satisfactory fit. The existence of such a relationship is in accordance with Eq. 7.1. Similarly, the results of the other catchments can be explained from Table 7.4.



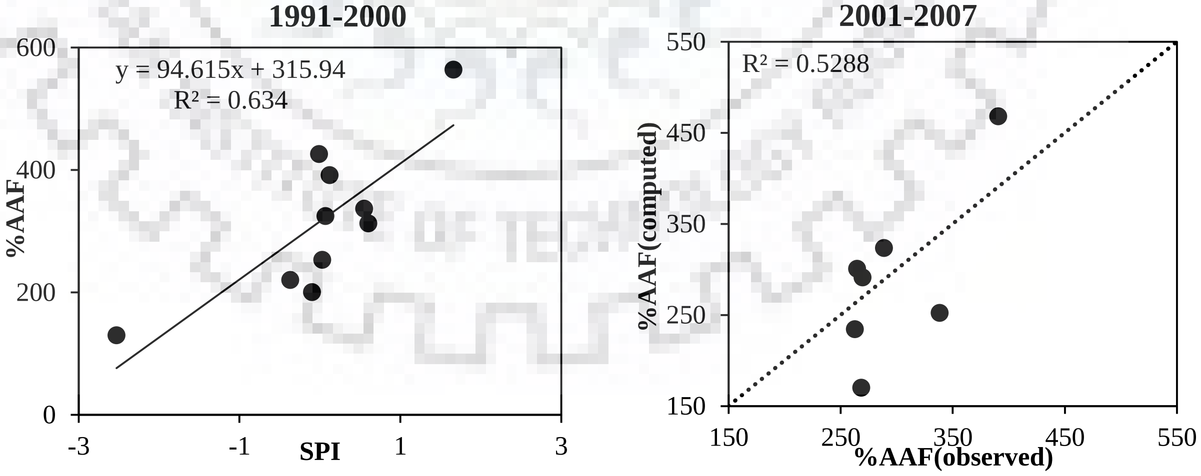
(a) Calibration (b) Validation

(i) Salebhata Catchment



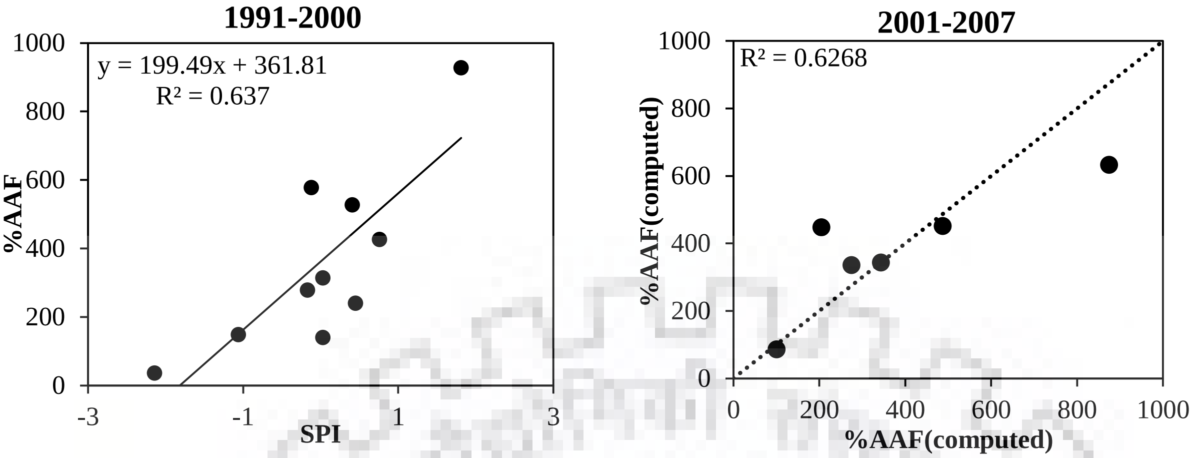
(a) Calibration (b) Validation

(ii) Ghatora Catchment



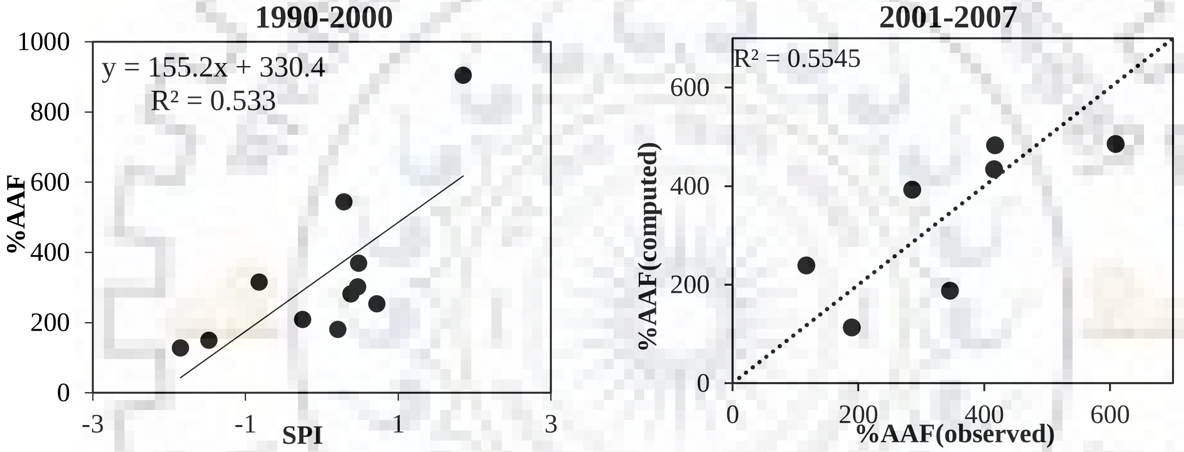
(a) Calibration (b) Validation

(iii) Kurubhata Catchment



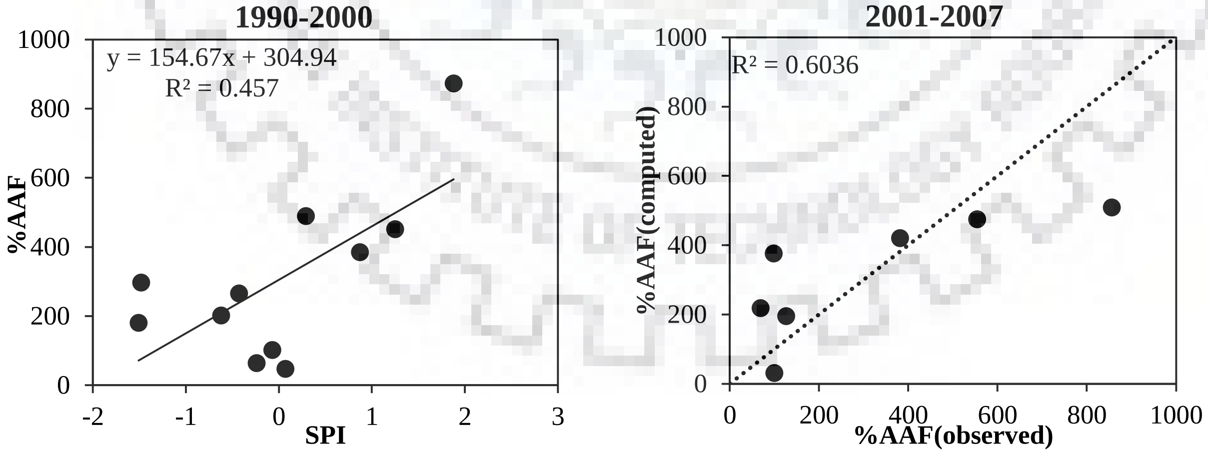
(a) Calibration (b) Validation

(iv) Rampur Catchment



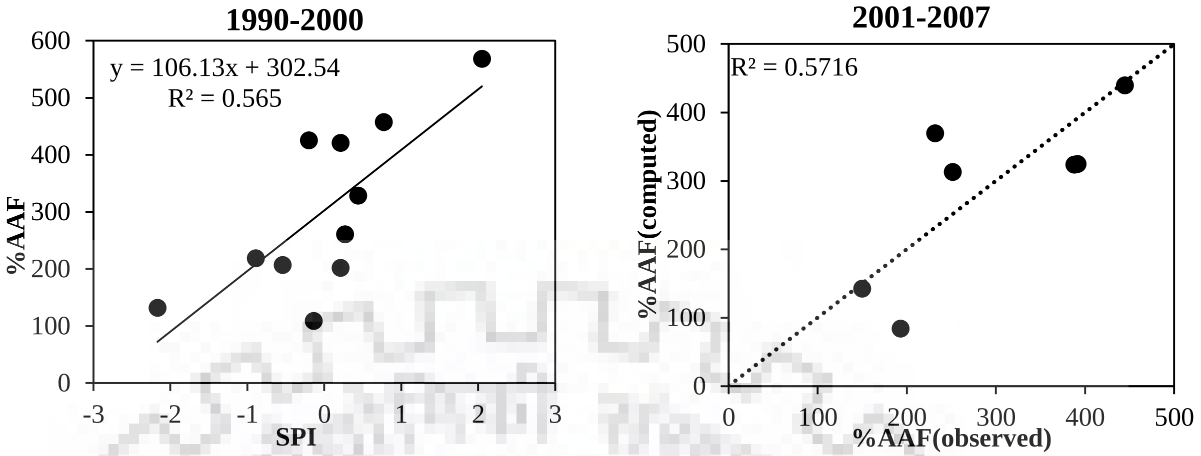
(a) Calibration (b) Validation

(v) Simga Catchment



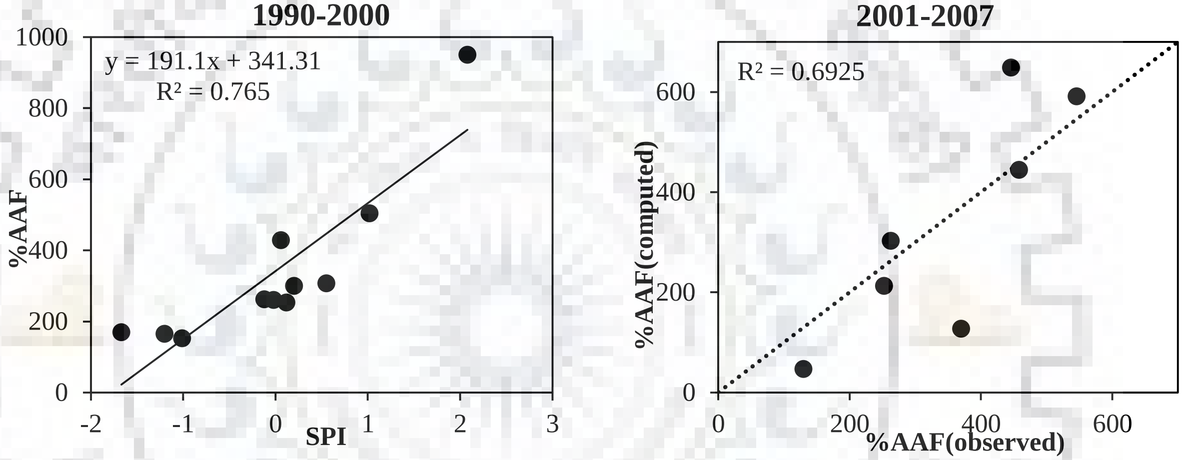
(a) Calibration (b) Validation

(vi) Hivra Catchment



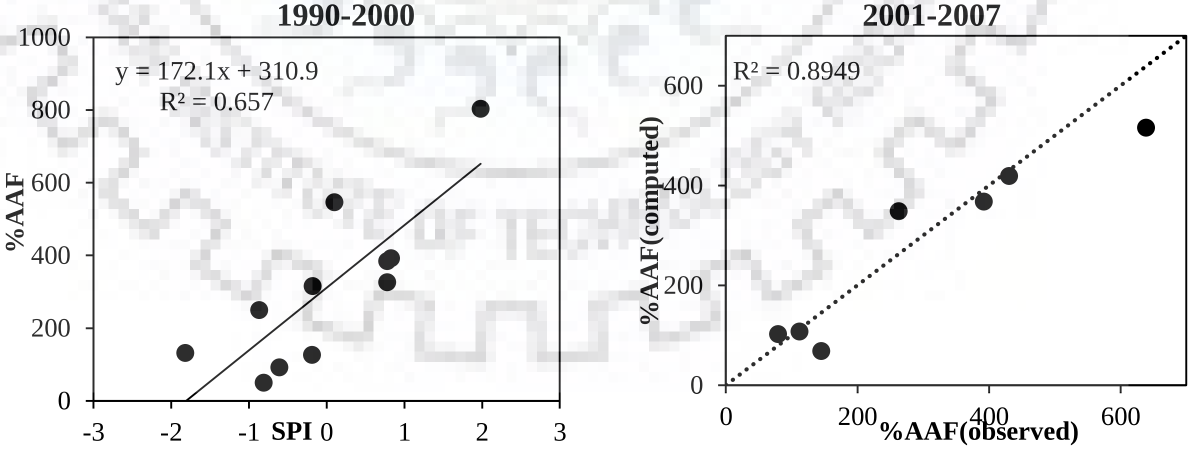
(a) Calibration (b) Validation

(vii) Jagdalpur Catchment



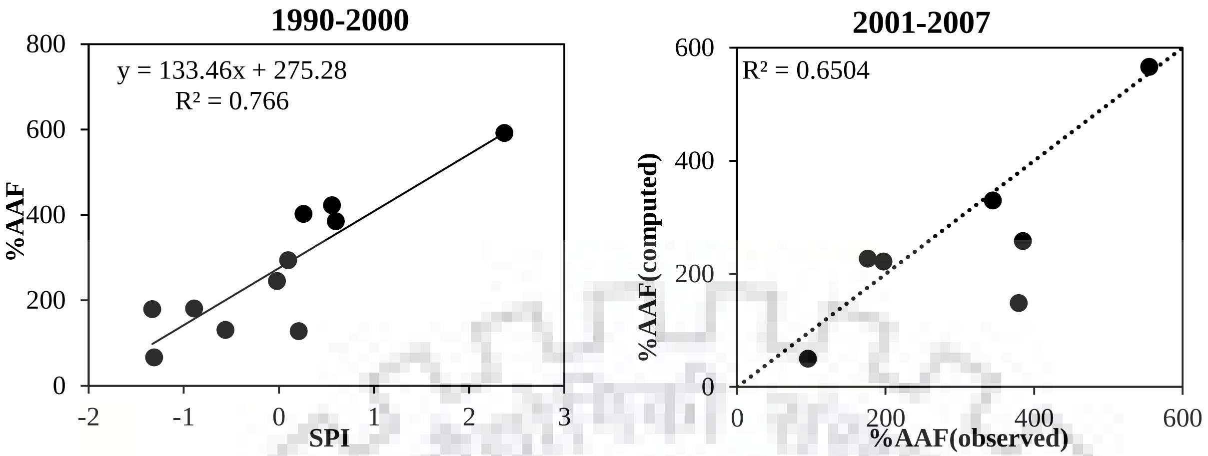
(a) Calibration (b) Validation

(viii) Kumhari Catchment



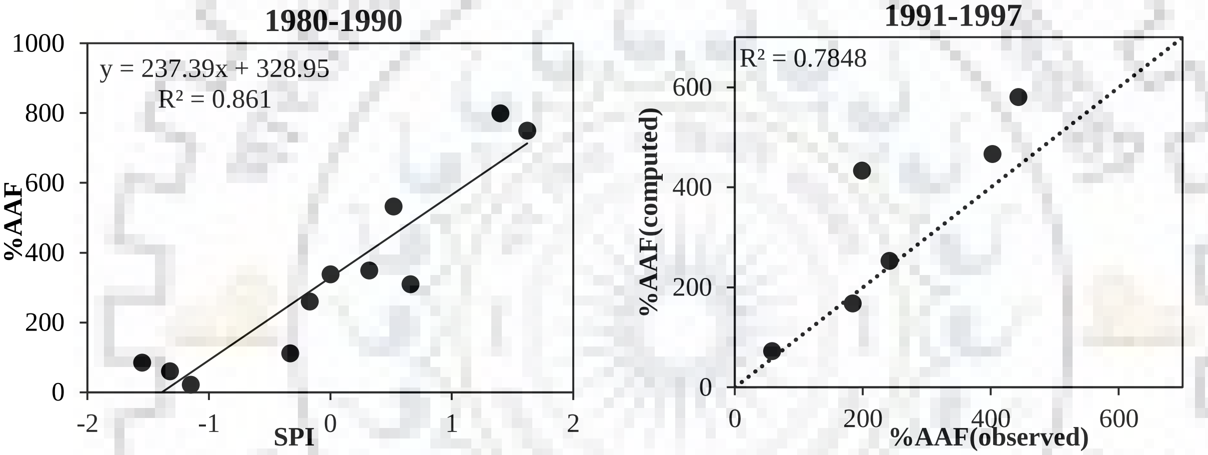
(a) Calibration (b) Validation

(ix) Nandgaon Catchment



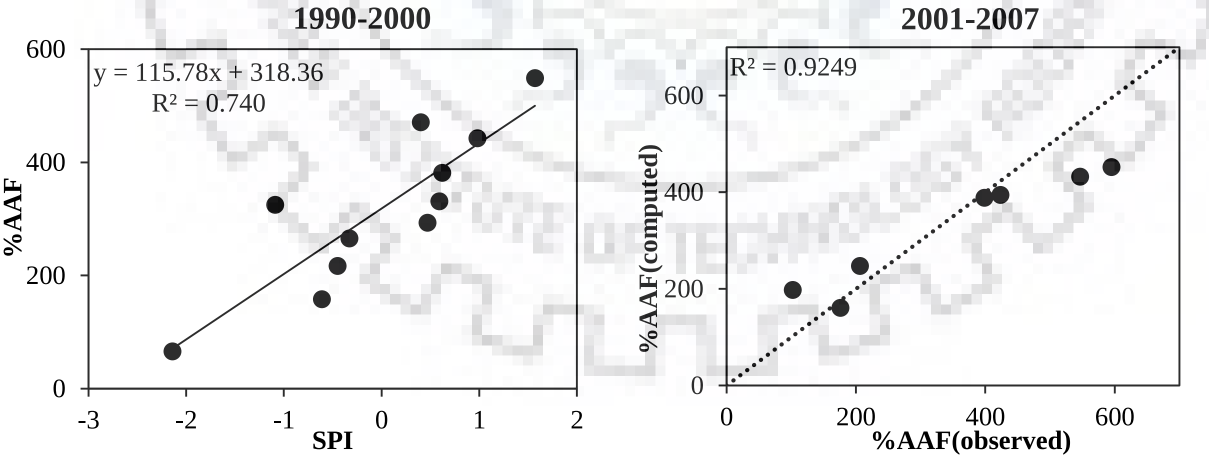
(a) Calibration (b) Validation

(x) Nowrangpur Catchment



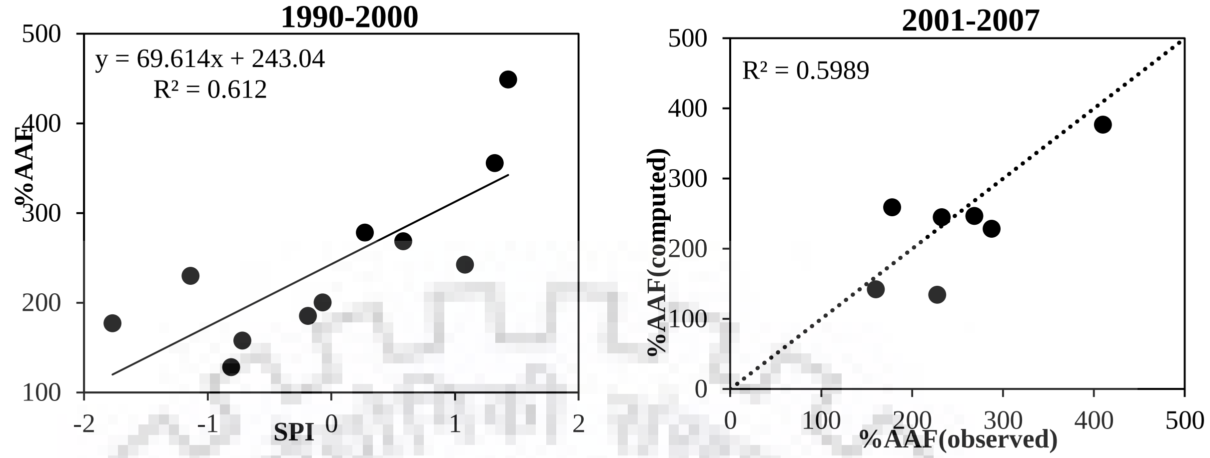
(a) Calibration (b) Validation

(xi) Penganga Catchment



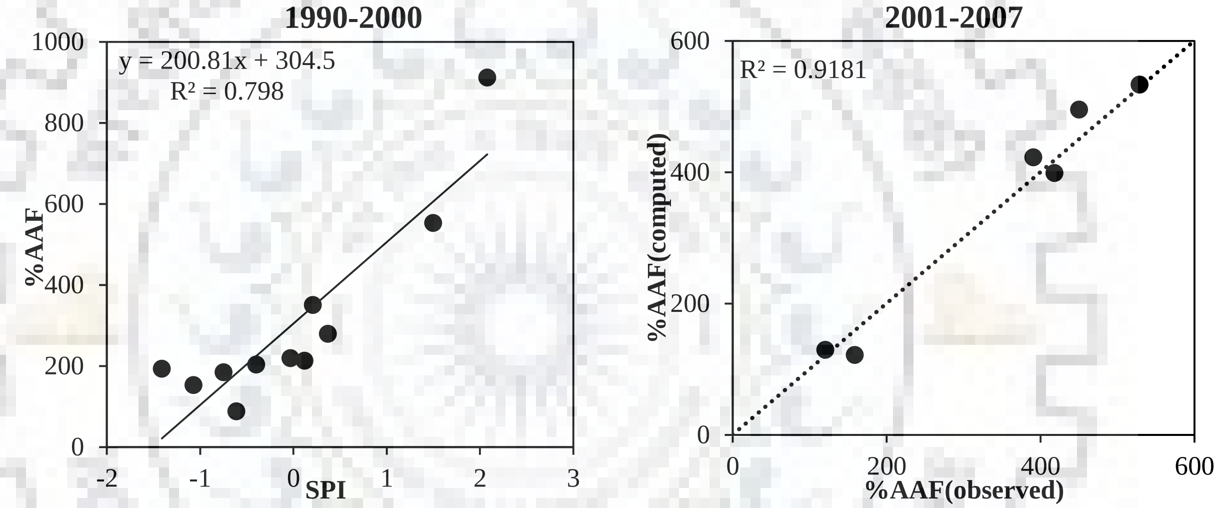
(a) Calibration (b) Validation

(xii) Ramakona Catchment



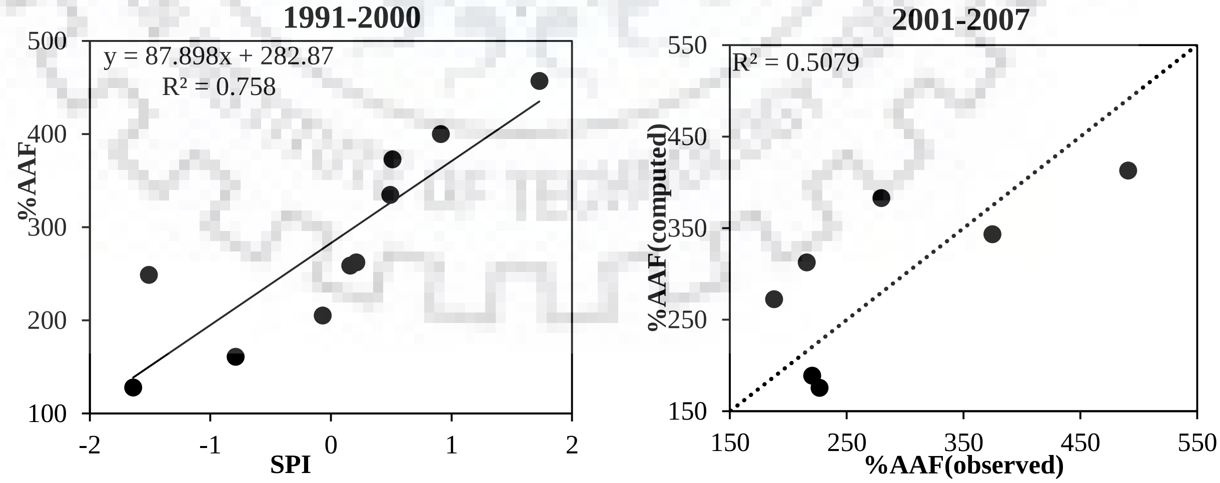
(a) Calibration (b) Validation

(xiii) Sardaput Catchment



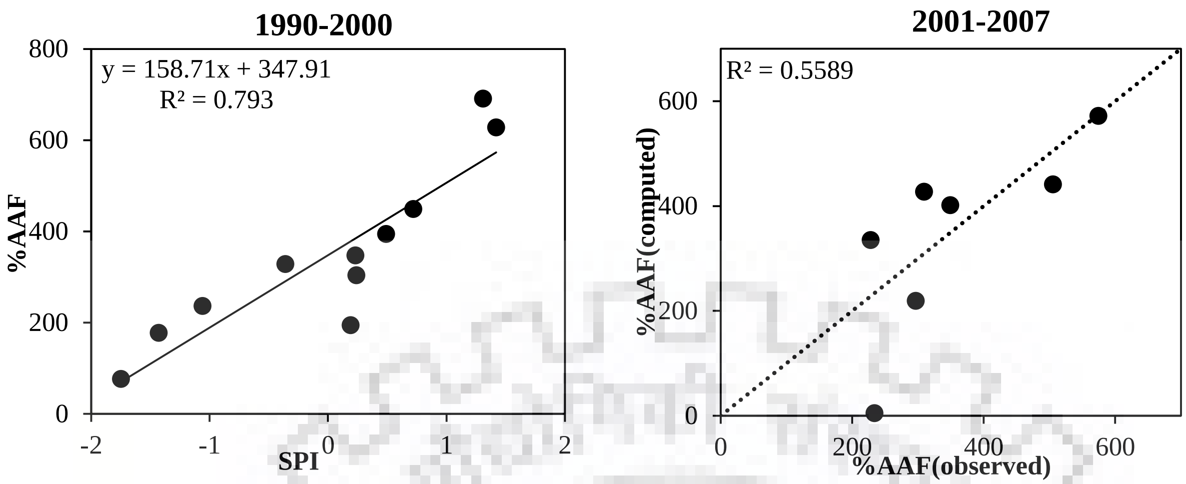
(a) Calibration (b) Validation

(xiv) Satrapur Catchment



(a) Calibration (b) Validation

(xv) Anandpur Catchment



(a) Calibration (b) Validation

(xvi) Burhanpur Catchment

Figure 7.1 Calibration (a) and validation (b) of %AAF - SPI relation for 16 study catchments

Table 7.4 Summary of results for Case 1 during high flow season.

Catchment	**Rainfall**		**Runoff**		**Calibration (y=mx+c*)**					**Validation**		
	μ (mm)	σ	μ (cumec)	σ	**No. of events**	**‘m’**	**‘c’**	**R^2**	**Bias**	**No. of events**	**R^2**	**Bias**
Salebhata	903.1	192.5	50.4	36.0	10	197.9	352.2	0.739	-0.5	7	0.613	-328.7
Ghatora	905.6	142.6	38.7	21.5	10	127.3	331.7	0.512	-0.4	7	0.570	89.4
Kurubhata	939.3	144.7	86.1	35.0	10	94.61	315.9	0.634	-0.4	7	0.528	-41.0
Rampur	860.6	159.6	38.6	28.3	10	199.4	361.8	0.637	-0.1	7	0.626	-201.4
Simga	856.3	140.6	161.8	106.3	10	155.2	330.4	0.533	-0.9	7	0.554	-47.9
Hivra	734.5	152.2	52.8	35.5	11	154.6	304.9	0.457	-0.5	7	0.603	38.7
Jagdalpur	923.3	186.6	115.0	56.24	11	106.1	302.5	0.565	-0.4	7	0.571	-53.3
Kumhari	602.3	201.1	120.8	75.6	11	191.1	341.3	0.765	-1.9	7	0.692	-86.6
Nandgaon	744.4	189.8	31.4	20.7	11	172.1	310.9	0.657	0	7	0.894	-127.7
Nowrangpur	1026.8	212.8	99.4	50.6	11	133.4	275.2	0.766	-0.9	7	0.650	-332.5
Penganga	738.3	255.5	183.0	140.0	11	237.3	328.9	0.861	-0.5	7	0.784	256.5
Ramakona	888.1	245.0	29.4	13.7	11	115.7	318.3	0.740	-0.6	7	0.924	-174.7
Sardaput	935.0	205.4	173.0	53.5	11	69.61	243	0.612	-0.5	7	0.598	-131
Satrapur	834.0	167.2	81.2	53.5	11	200.8	304.5	0.798	0	7	0.918	-151.6
Anandpur	853.6	150	168.6	64.4	10	87.89	282.8	0.758	-0.7	7	0.507	93.2
Burhanpur	639.6	160.1	180.0	95.2	11	158.7	347.9	0.793	-0.1	7	0.558	-96.2

*y= %AAF, x = SPI.

Here, bias represents the deviation of %AAF, and therefore, non-dimensional. It is evident from Table 7.4 that the number of data points used in calibration is fairly large, ranging from 10-11 years in calibration, and 7 in validation. The coefficient of determination (R^2) ranges from 0.512 to 0.861

in calibration, except Hivra catchment for which it is 0.457 in calibration and 0.603 in validation. These show the fits to be reasonably satisfactory to excellent ranging from 0.457 (Hivra catchment) to 0.861 (Penganga catchment), respectively. The negative and positive values of 'Bias' in Table 7.4 show that %AAF values are under- and over-predicted, respectively.

In the derived linear SPI - %AAF relationship of the form y=mx+c (Eq. 7.1), where y = %AAF, x = SPI, m = 100Cv SPI and c = 100. From Table 7.4 and Figs. 7.2- 7.3, the m-values range from 69.61 to 237.3. The variation of m-values can be explained in terms of μ- and σ-dependent Cv and SPI. Various trials were attempted for deriving the existence of a relationship for μ- and σ-dependent m using the data of Table 7.4. When plotted (not shown), the μ-m relations for both rainfall and runoff showed the falling trends whereas m-C_v (= σ/μ) relations showed rising trends for rainfall (Fig. 7.2) and runoff (Fig. 7.3). Thus, it is clear that there exists a definite relationship between m and μ or σ and/or any combination. The genesis might appear to lie in the above assumed y = mx relationship (Eq.7.1). It is further to note that both μ and σ represent the characteristics of both rainfall of and runoff from a catchment, either of the two can be employed in derivation of parameter 'm'; the latter from the concept of homogeneous regions (Singh et al., 2001). It is further to emphasize that conversion tables similar to Table 7.2 can be prepared for each catchment employing the %AAF – SPI relations shown in Table 7.4 and Fig. 7.4, as also shown for Case 2 later.

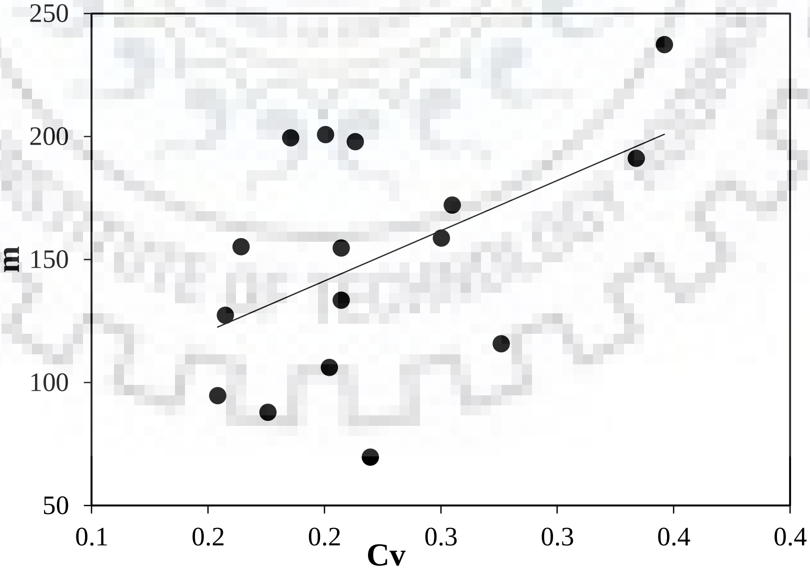


Figure 7.2 Cv (non-dimensional) Vs m (non-dimensional) relationship for rainfall data.

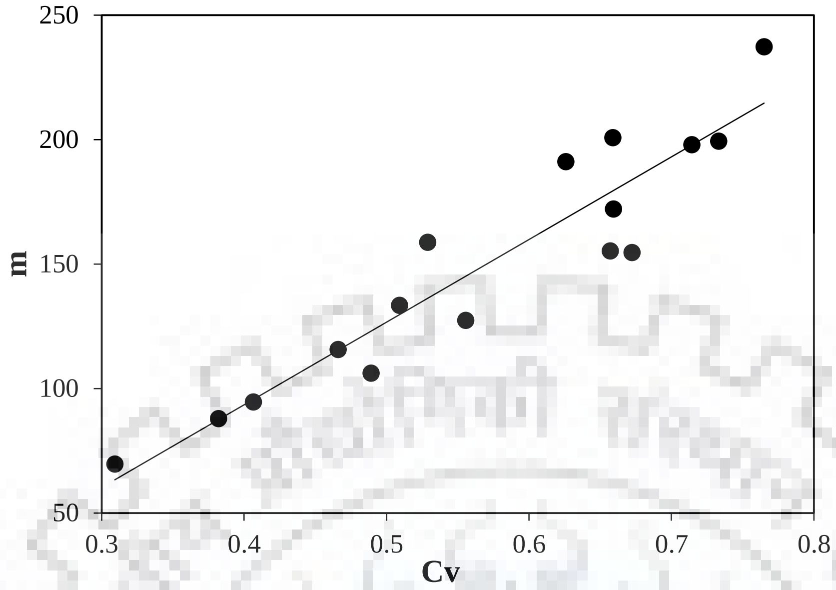
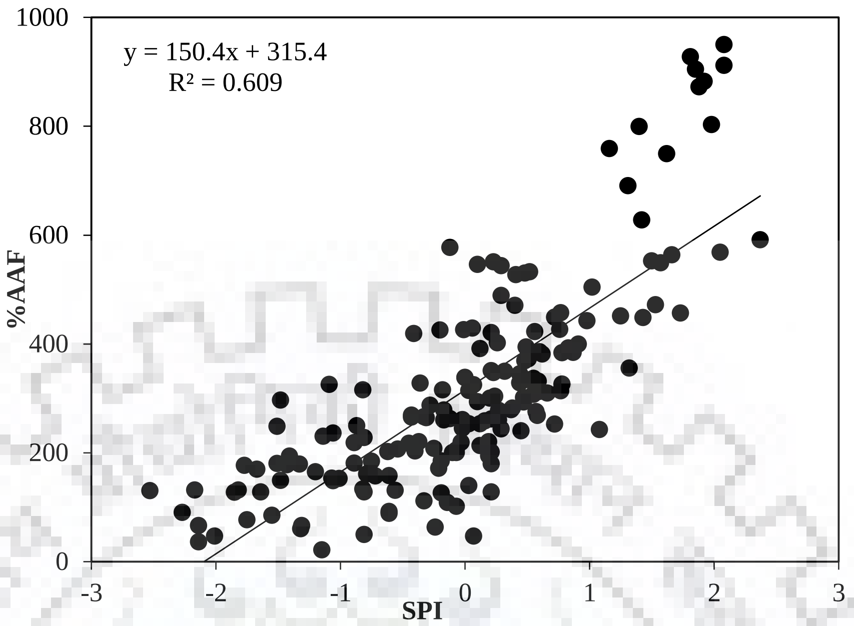


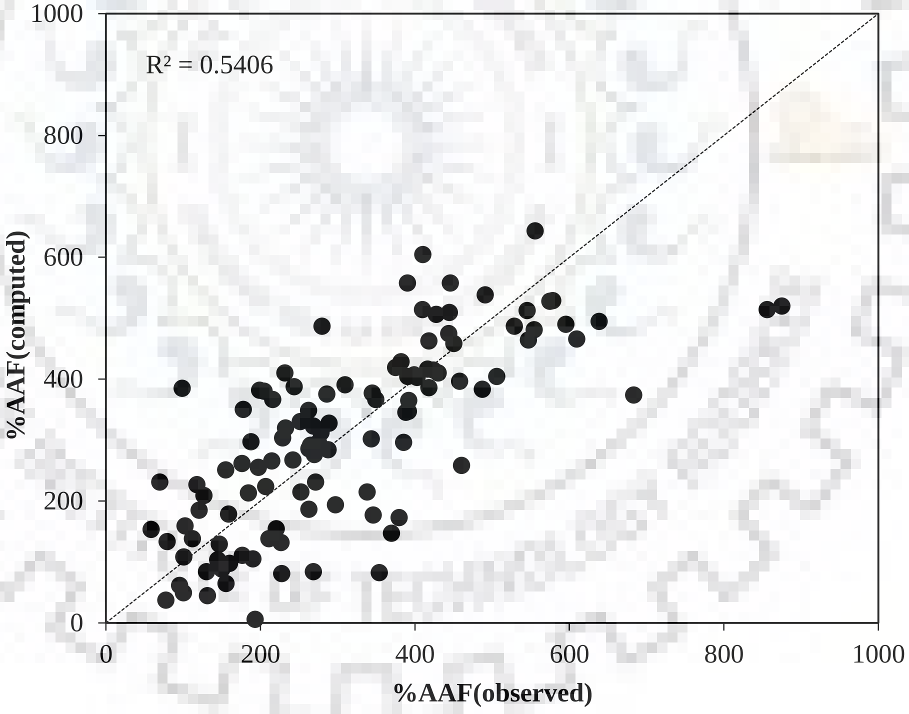
Figure 7.3 Cv (non-dimensional) Vs m (non-dimensional) relationship for runoff data.

Case 2

In this case, a more general relationship is derived simply by considering SPI and corresponding %AAF values used in calibration for all catchments, as shown in Fig. 7.4(a). The resulting R^2 value of 0.609 is lowered because of the inclusion of poorly performing Hivra, Ghatora, and Simga catchment data. Therefore, for the same reasons, similar results are visible in validation (R^2=0.540). As shown in Fig. 7.4 (b), the observed and computed %AAF values appear to be fairly close to LPF, implying that there exists a relationship between SPI and %AAF, and SPI can be used for derivation of %AAF for describing the EF condition of a catchment during high flow season (July-September), as shown in Table 7.5 derived from the results of Fig. 7.4.



(a) Calibration



(b) Validation

Figure 7.4 Calibration (a) and validation (b) of %AAF - SPI relation using respective calibration and validation data of all catchments.

Table 7.5 Description of flow condition based on %AAF or SPI during high flow season

Flow Condition	**%AAF**	**SPI**
Flushing flow	200%	greater than -0.77
Optimum range of flow	60-100%	-1.43 to -1.7
Outstanding	60%	-1.7
Excellent	50%	-1.7 to -1.76
Good	40%	-1.76 to -1.82
Fair or Degrading	30%	-1.83 to -1.90
Poor or Minimum	10%	-1.9 to -2.03

7.5 SUMMARY

The study was carried out using the long-term high flow season rainfall-runoff data of 16 catchments derived from Mahanadi, Godavari, Brahmani-Baitaini, Tapi basins. SPI values at 3 month time-scale for the month of September and %AAF were calculated for the same period for each of the catchments. The following conclusions can be derived from the present study:

1. In each of the sixteen catchments, %AAF is seen to increase linearly with increase in SPI, and vice versa. R^2 greater than 0.63 for 11 (out of 16) catchments reveal the existence of very good correlation between SPI and %AAF.
2. The above relationship in all catchments enables description of the EF condition of these catchments using 3-month (monsoon or high flow season, July-September) scale SPI that is derivable from easily available rainfall data.
3. The suggested approach cannot be applied to catchments severely disturbed by anthropogenic activities, as it includes all limitations of the Tennant method.

CHAPTER 8

SUMMARY AND CONCLUSIONS

Water is necessary for life and it is regarded an important natural resource for the well-being of Society and existence of life on the earth. The rapidly growing population and industrialization cause reduction in the water supply for the agricultural and domestic purposes around the globe. The reduced water supply in a region effects the usual social, economic and developmental activities of that region. The lack of precipitation from the normal is one of the major reason of the reduced water supply. When there is prolonged shortage of water supply or the occurrence of rainfall lower than the average for a given region then it is said to be drought. Drought is insidious natural menace which has serious impacts on agriculture, ecosystem and economy of region. In different region the impacts of drought events are different. The drought characteristics varies across different climatic regions. In other words, drought originates from a deficiency of precipitation over prolonged period of time usually season/year leads to the reduction in the water supply for the society and environment. In India droughts are very frequent which results in loss of about ten millions of lives over the period of 18th, 19th, and 20th centuries. The agriculture in India is heavily dependent on the rainfall especially the rainfall from the south west monsoon. The monsoon failure leads to the reduced water supply and reduction in the crop yield. The major drought prone regions of India covers the State of Rajasthan, Gujarat, Haryana, Telangana, Andhra Pradesh, Odisha, Karnataka and eastern and southern Maharashtra.

Further, the reduction in the rainfall from the average also reduces the flow of river, streams etc. The decreasing flow of the river cause the serious impacts on the aquatic ecosystem. The minimum supply of water is maintained in the streams called EF requirement which helps in sustainability of aquatic lives and other natural ecosystem. The change in the river flow draws the attention of various researchers for the assessment of environmental flow requirement. More than 240 methods of EF requirement are available but none of them has the efficacy to describe the EF condition of ungauged catchment (i.e. all methods require flow data). There exist a need of method which can describe the EF condition of the catchment based on easily available rainfall data.

In the light of above the study has been carried out with following specific objectives; (a) to identify the most important variables affecting the drought characteristics, (b) to analyze the regional meteorological drought characteristics, (c) to study the relationship among climatic factors and regional drought characteristics, (d) to study the relationship among the temperature variation range and frequency and severity of droughts, and (e) to relate Standardized Precipitation Index with Tennant method for the prediction of environmental flow condition using rainfall. A summary of research work and conclusions arrived at are presented below.

8.1 SUMMARY

The drought characteristics refers to the frequency, severity and persistence of the drought event. In this study the drought characteristics of 516 districts covering almost whole India using the data of more than 100 years have been analyzed. The districtwise details of drought attributes are presented in Appendix-I. In India the drought characteristics changes across the different regions. The average drought frequency varies from once in 3 years in north western region to once in 30 years or more in some parts of the north eastern region of the country. The different regions experience the moderate, severe and extreme drought events. The north eastern region hardly faced severe drought events. The maximum magnitude of deficit varies from 95% of annual mean in western Rajasthan to less than 25% in Zuhenboto in Nagaland. The one of the important characteristic of a drought event is its duration. The duration of the drought also varies across the country. The drought persisted for the maximum of 2-, 3-, 4-, and 5- or more consecutive years in different parts of India.

The average return period of drought can be described significantly using the climatic parameters in terms of ratio of average annual potential evapotranspiration to average annual rainfall (PET/P). The average return period of drought and its severity are significantly related to the PET/P ratio. The arid and semiarid regions are more vulnerable to severe and frequent drought events than the areas in the sub-humid and humid regions. The areas with PET/P ratio of less than or equal to 1.5 has rare chance of occurrence of severe drought events. Further, the more frequent and persistent droughts occur in arid and semi-arid regions than in the other climatic regions.

The different climatic region has different temperature variation range. In India the annual temperature variation ranges from 10 ^{0}C in humid region to 40 ^{0}C in arid regions. The range of annual temperature variation has significant relation with the frequency and severity of drought. The areas with the value of annual temperature variation in the range of 30 to 40 ^{0}C are susceptible to more frequent severe drought events. The places with less than 20 ^{0}C of temperature variation over the year faced less frequent droughts with moderate severity.

The water demand is increasing day by day which exceeds the water supply due to increasing water demand for growing population and industrialization. For the conservation of natural ecosystem water has to be preserved in the rivers and it should be clean so that a healthy ecosystem can be maintained. The minimum amount of water required for the survival of rivers is known as Environmental flow (EF). For a healthy ecosystem environmental flows are one of the important factors. There are more than 240 methods are available to describe the environmental flow condition based on flow data only. Tennant method is widely used hydrological method to describe the EF condition of river from severe degradation to flushing flow. SPI also describes the dry and wet condition based on precipitation. Since SPI and Tennant method both describes the dry and wet condition based on different parameters so, an effort has been made to establish a relationship between these two methods which helps to describe the EF condition using the easily available rainfall data only, useful for ungauged catchment. The data of various catchments have been used to describe the EF condition of the catchment based on SPI during low and high flow seasons.

8.2 CONCLUSIONS

The major conclusions of the study are:

1. The north western part of India which covers the states of Rajasthan, Gujarat, Haryana and Punjab are very susceptible to drought having the average drought frequency between once in 3 years to once in 4 years.
2. The states of Uttarakhand, western Madhya Pradesh, Karnataka, southern Maharashtra and eastern Uttar Pradesh has the average drought return period of 5-6 years.
3. The average return period of drought has been estimated to be in the range of 7-9 years in the states of Chhattisgarh, Jharkhand, eastern Madhya Pradesh, eastern Maharashtra, northern Andhra Pradesh and western Orissa.
4. The coastal regions of Maharashtra, Karnataka, Kerala Orissa has the average drought frequency of once in 10 years or more. The north eastern states of the country has the average drought return period of more than 10 years.
5. The coefficient of determination ($R^2 = 0.711$) showed very good correlation with average return period of meteorological droughts and PET/P ratio.
6. The average return period decreases with increase in the PET/P ratio. Average drought frequency (expressed in terms of return period) varies from 2 to 3 years in arid regions (with

$12 > PET/P \geq 5$), 4 to 6 years in semiarid regions (with $5 > PET/P \geq 2$), 6 to 10 years in subhumid regions (with $2 > PET/P \geq 3/4$) and 10 years or more in humid regions.

7. The maximum deficiency of rainfall has been found in the north western India, which is of the order of 75-95% of its long term average. This region of India is relatively more susceptible to severe and extreme drought events.
8. The central part of India experienced the maximum rainfall deficiency in the range of 55-75% over the period of 113 years, while the maximum magnitude of deficit has been estimated to be in between 40-55% in eastern and southern India. The state of Kerala and North eastern states of India had experienced relatively less severe droughts of magnitude of severity less than 40%.
9. The maximum rainfall deficit of 95% from long term mean had been observed in hyper arid in Jaisalmer having mean annual rainfall of 100 mm and mean annual potential evapotranspiration of 2663 mm.
10. The regions with PET/P value of 1.5 has the probabilities of occurrence of 90% and 10% for moderate and severe drought respectively. In these regions, the extreme drought events are very rare and their probability of occurrence is nearly zero.
11. The places where PET/P value is about 4 (i.e. semiarid regions) the percent probabilities of occurrence of moderate, severe and extreme drought events are 68%, 25% and 7% respectively; however in arid regions with PET/P value of 7.0 occurrence probabilities are 55%, 31% and 14% respectively.
12. The north western India comprising of the states of Punjab, Haryana, Rajasthan and Gujarat are very susceptible to frequent and persistent drought of 3 to 4 consecutive years. The persistent event for maximum of 4 consecutive years are unique feature of this region.
13. Hanumangarh (2000-2004), Ganganagar (1934-1938), Alwar (1937-1941), Dausa (1937-1941) and Jhunjhunu (2002-2006) in the State of Rajasthan, are only five districts where drought persisted for maximum of 5- consecutive years.
14. The coefficient of determination (R^2) = 0.702, implying that the frequency (F) or return period (T) of meteorological droughts is significantly related with θ_R.
15. The average return period varies from 3 to 4 years where θ_R is in the range of 40 °C to 35 °C. The places where θ_R varies from 35 - 30 °C, average drought return period lies between 4 to 6 years, and 6 to 9 years in the regions where $30\ ^{o}C > \theta_R > 25\ ^{o}C$.

16. The return period is of the order of 9 to 14 years where θ_R varies between 25 °C to 20 °C and greater than 14 years at places with lowest θ_R, i.e. 20 - 10 °C. Thus, drought events are relatively less frequent at places where $\theta_R < 20$ °C.
17. The places where θ_R is in the range of 40 °C to 35 °C, the values of maximum deficit, i.e. severity, has been more than 70% of the long term mean rainfall. The places where θ_R varies from 35 - 30 °C have experienced severe to extreme drought events with the maximum rainfall departure in the order of 55% to 70%. Furthermore, the places with θ_R ranging from 30 °C - 25 °C faced severe droughts with maximum rainfall departure of the order of 45% to 57%.
18. The maximum deficiency of rainfall ranged from 45% to 35% where 25 °C > θ_R > 20 °C and less than 35% in places where θ_R varied from 20 °C to 10 °C.
19. The existence of remarkable %AAF-SPI relationship with R^2 greater than 0.7 for 10 (out of 11) catchments underlines the significance of the study, for the EF condition of these catchments can be ascertained using 9-month (October-June) scale SPI (derivable from easily available rainfall data) during low flow season.
20. The EF condition of the sixteen study catchments can be ascertained using 3-month (April - September) scale SPI during high flow sason, as the correlation coefficient of R^2=0.63 represents good %AAF-SPI relationship.

8.3 MAJOR RESEARCH CONTRIBUTIONS

The following are the major contributions of the study:

1. The detailed study of meteorological drought characteristics (i.e. frequency, severity and persistence) of 516 districts located in different climatic region using the data of 113 years (1901-2013) has been done.
2. The relationship of drought characteristics and climatic parameters of 516 districts has been established, to check the variation in drought characteristics in different climatic regions.
3. The relationship among drought frequency and severity, and range of annual temperature variation has been explored for 256 districts from the different climatic conditions.
4. A simple SPI based method for the prediction of environmental flow condition using the data of 11 and 16 catchments located in different river basins, has been proposed for low and high

flow season respectively. The proposed method is useful for ungauged catchments as it requires easily available rainfall data only.

8.4 LIMITATIONS

The suggested approach for thr prediction of environmental flow from rainfall inheres all the limitations of the Tennant's method. The EF and the rainfall can be coupled for the catchment where human activities do not affect much hydrological processes. The proposed method might be used carefully when the flow is significantly governed by hydrological engineers, diversion canals, as well as other anthropogenic activities, as the μ and σ characteristics of both rainfall and runoff series are severely affected by these disturbances.

8.5 SCOPE FOR FUTURE RESEARCH

The behavior of drought persistence does not show any significant relation with PET/P ratio and the annual temperature variation, there might be some effect of physiographic and other climatic factors and this may form a scope for future research work. The proposed approach based on SPI for the prediction of environmental flow can be further verified for applicability to hydrometeorologically homogeneous regions. Such a validation would enhance the suitability potential of the proposed approach to the environmental/ecological study of ungauged virgin watersheds unexplored for water resources development.

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APPENDIX-I

District wise details of rainfall, potential evapotranspiration and drought attributes

S. No.	State	District	Mean annual potential evapotranspiration (mm)	Mean Annual precipitation (mm)	Maximum Rainfall deficit (%)	Maximum deficit Year	Drought return period (years)	Maximum drought persistence (years)
1	Andhra Pradesh	Adilabad	2421.03	1026.1	57.4	1920	8	0
2	Andhra Pradesh	Anantpur	2300.8	566.1	48.8	1934	5	3
3	Andhra Pradesh	Chittor	2289.05	888.0	47	1951	7	3
4	Andhra Pradesh	Cuddapah	2328.2	701.2	55.2	1904	6	3
5	Andhra Pradesh	East godavari	2150.09	1140.7	45	1905	9	2
6	Andhra Pradesh	Guntur	2305.15	864.4	48.2	1904	6	2
7	Andhra Pradesh	Hyderabad	2401.47	802.8	49.2	1922	5	3
8	Andhra Pradesh	Karimnagar	2378.78	934.3	55.3	1920	8	0
9	Andhra Pradesh	Khammam	2378.78	1122.5	38.9	1920	7	2
10	Andhra Pradesh	Krishna	2207.58	993.8	44	1905	6	2
11	Andhra Pradesh	Kurnool	2396.87	646.9	45.2	1952	7	3
12	Andhra Pradesh	Mahbubnagar	2422.98	728.0	51.7	1918	5	3
13	Andhra Pradesh	Medak	2383.78	876.9	60	1920	7	2
14	Andhra Pradesh	Nellore	2301.7	1043.6	42	1904	6	2
15	Andhra Pradesh	Nizamabad	2382.82	1034.6	59.6	1971	7	2
16	Andhra Pradesh	Prakasm	2344.52	785.2	48	1952	5	3
17	Andhra Pradesh	Rangareddy	2407.58	809.6	55.6	1920	5	3
18	Andhra Pradesh	Srikakulam	1926.35	1116.9	54.3	1907	9	0
19	Andhra Pradesh	Nalgonda	2363.7	750.6	41.2	1941	8	0
20	Andhra Pradesh	Visakhapatnam	2149.23	1065.9	44.2	1911	7	0
21	Andhra Pradesh	Vizyanagaram	2104.75	1127.6	40.4	1920	14	0
22	Andhra Pradesh	Warangal	2350.53	1002.6	59	1918	7	2

23	Andhra Pradesh	West Godavari	2190.3	1090.5	41	1920	8	2
24	Arunachal Pradesh	Dibang Valley	1878.5	3116	29.3	1967	51	0
25	Arunachal Pradesh	East Kameng	1929.6	2076	41.1	1978	18	0
26	Arunachal Pradesh	East Siang	1893.1	4408.5	39	1967	14	0
27	Arunachal Pradesh	Lohit	1875.6	2714.1	40	1967	15	0
28	Arunachal Pradesh	Lower Subansiri	1849.9	1884	25.6	1967	51	0
29	Arunachal Pradesh	Tawang	1818.9	2139	44.6	2009	15	0
30	Arunachal Pradesh	Tirap	1791.2	2686.5	37.6	1967	15	0
31	Arunachal Pradesh	Upper Subansiri	1799.5	1709	43.7	1974	23	0
32	Arunachal Pradesh	West Siang	1816.8	2846.8	39.4	1967	15	0
33	Assam	CACHAR	1921.02	3170.5	37.4	1994	28	0
34	Assam	Darrang	1881.8	2090.2	42.2	1981	14	0
35	Assam	Golpara	1865	2933.1	43	2011	10	0
36	Assam	Kamrup	1811.4	2132.9	44.6	2006	10	0
37	Assam	Lakhimpur	1922	2990.3	37.8	1967	13	0
38	Assam	NC Hills	1860.5	2788.7	41.2	1984	10	0
39	Assam	Nowgong	1774	1685	56	2009	10	0
40	Assam	Sibsagar	1870	2188.2	36.9	2006	28	0
41	Assam	Barpeta	1856	2435.4	37	1950	10	0
42	Assam	Dubhri	1944.3	2614.3	40	2013	10	0
43	Assam	Dibrugarh	1884.1	2509.2	35	1978	13	0
44	Assam	Jorhat	1887.7	2138.2	32.4	2009	38	0
45	Assam	Kabri Anglong	1811.6	3145	41.3	1955	20	0
46	Assam	Karimganj	1987.5	3725.2	56	2008	10	0
47	Assam	Kokrajhar	1901.7	3242.1	45.5	1971	10	0
48	Assam	Sonitpur	1930.1	1870.2	37.1	2006	28	0
49	Assam	Nalbari	1871.05	2348.6	42	2011	11	0
50	Assam	Golaghat	1885.4	1801.6	35.7	1951	10	0
51	Assam	Tinsukia	1847.9	2587.6	35.9	1994	13	0

52	Assam	Dhemaji	1910.9	2634	33.4	1998	34	0
53	Bihar	Araria	2163.33	1636.6	43.8	1908	8	2
54	Bihar	Aurangabad	2354.7	1091.3	52.6	1966	7	3
55	Bihar	Banka	2205.17	1143.7	54.6	1966	6	2
56	Bihar	Begusarai	2207.64	1135.5	59.1	1966	5	3
57	Bihar	Bhabhua	2346.1	1055.7	68.4	1951	5	3
58	Bihar	Bhagalpur	2207.04	1185.3	60	1923	5	2
59	Bihar	Bhojpur	2327.94	1008.0	74	1972	8	3
60	Bihar	Buxar	2339.49	969.4	68.6	2012	6	3
61	Bihar	Champaran East	2255.6425	1285.8	41.1	1990	9	3
62	Bihar	Champaran West	2294.58	1448.6	35.5	1907	8	2
63	Bihar	Darbhanga	2190.34	1146.5	49.7	1966	6	2
64	Bihar	Gaya	2311.46	1070.5	40.7	2013	7	2
65	Bihar	Gopalganj	2294.25	1108.1	52.2	2005	8	2
66	Bihar	Jahanabad	2320.6	1014.9	71.7	1966	5	2
67	Bihar	Jamui	2197.28	1175.5	36.9	1970	9	0
68	Bihar	Katihar	2197.57	1314.0	57.6	1908	5	2
69	Bihar	Khagaria	2199.44	1149.8	49.2	1966	6	2
70	Bihar	Madhepura	2187.31	1287.2	63.6	1908	8	2
71	Bihar	Madhubani	2178.25	1222.1	52.5	2010	7	2
72	Bihar	Munger	2205.54	1171.6	57	1966	7	3
73	Bihar	Muzaffarpur	2232.34	1175.9	57.3	1966	5	2
74	Bihar	Nawada	2243.5	1041.9	43.4	1927	9	2
75	Bihar	Nalanda	2276.5	1006.1	51.6	1908	7	2
76	Bihar	Patna	2285.6	1005.0	54.1	1966	5	3
77	Bihar	Purnea	2189.07	1538.1	60	1908	6	2
78	Bihar	Rohtas	2348.55	1080.6	62.6	1966	7	3
79	Bihar	Saharsa	2191.84	1334.4	56.7	1908	6	2
80	Bihar	Samastipur	2212.2	1160.6	54.7	1908	5	2

81	Bihar	Saran	2293.02	1056.3	56.9	2005	8	3
82	Bihar	Seikhpura	2244.77	1076.6	60.2	1901	6	3
83	Bihar	Sitamarhi	2202.96	1261.5	51.9	2010	7	2
84	Bihar	Siwan	2303.02	1073.9	60	2009	7	2
85	Bihar	Supaul	2170.66	1303.0	74.5	1973	5	2
86	Bihar	Vaishali	2259.97	1037.1	52.9	1966	6	3
87	Chhattisgarh	Bastar	2324.43	1495.9	44.2	1923	8	2
88	Chhattisgarh	Bilaspur	2326.16	1235.4	56.7	2001	9	2
89	Chhattisgarh	Dhamtari	2319.61	1231.9	47	1979	8	2
90	Chhattisgarh	Durg	2345.29	1182.8	47.2	1974	9	2
91	Chhattisgarh	Janjgir	2308.45	1360.5	39.7	1902	9	2
92	Chhattisgarh	Jashpur	2294.77	1597.2	42.4	2006	9	2
93	Chhattisgarh	Kanker	2355.21	1392.8	49.5	2008	8	2
94	Chhattisgarh	Korba	2307.58	1442.3	50.2	1979	9	2
95	Chhattisgarh	Koriya	2267.12	1258.7	54.3	1979	8	2
96	Chhattisgarh	Kawardha	2331.8	1078.5	46.7	2009	7	2
97	Chhattisgarh	Mahasmund	2304	1293.3	55.2	1965	6	2
98	Chhattisgarh	Raigarh	2302.46	1437.9	45	1979	9	2
99	Chhattisgarh	Raipur	2317.62	1250.9	45	1965	8	2
100	Chhattisgarh	Rajnandgaon	2373.23	1197.6	42.9	1902	9	2
101	Chhattisgarh	Surguja	2281.17	1437.5	58.9	2010	7	2
102	Gujrat	Ahmedabad	2473.04	663.71	72.1	1948	4	3
103	Gujrat	Amreli	1826.17	598.88	66.5	1918	3	4
104	Gujrat	Aanand	2453.98	817.1880142	70.9	1974	4	4
105	Gujrat	Banskantha	2575.1	596.47	90.7	1987	3	3
106	Gujrat	Baroda	2455.1	989.4	62.6	1974	4	3
107	Gujrat	Bhavnagar	2279.24	602.5	71.2	1918	4	3
108	Gujrat	Baroach	2329.74	825.2	68.3	1948	5	3
109	Gujrat	Dangs	2356.5	1887.55	58.3	1974	5	4

110	Gujrat	Dahod	2494.26	884	73.2	1985	4	4
111	Gujrat	Gandhinagar	2522.38	695.09	67.9	1918	4	3
112	Gujrat	Kheda	2494.8	806.6	76.5	1918	4	3
113	Gujrat	Kutch	2006.9	375.5	94	1987	3	3
114	Gujrat	Mehsana	2535.9	670.46	74.2	1987	3	3
115	Gujrat	Narmada	2423.97	1078.1	79.1	1918	4	4
116	Gujrat	Panchmahal	2490.95	978.7	77.1	1911	4	4
117	Gujrat	Patan	2560.03	539.4	85.6	1987	3	3
118	Gujrat	Porbandar	2175.295	594.6	94.3	1918	3	4
119	Gujrat	Rajkot	2291.67	601.8	80.1	1987	3	4
120	Gujrat	Sabarnkantha	2516.03	820.1	70	1974	4	3
121	Gujrat	Surendranagar	2466.94	520.3	75.8	1911	3	3
122	Gujrat	Junagarh	2058.92	787.6	81.8	1918	3	2
123	Gujrat	Jamnagar	2233.4825	511.7	89.3	1911	3	4
124	Haryana	Ambala	2331.01	958.1	59.5	2002	4	4
125	Haryana	Bhiwani	2387.95	414.3	76.5	1979	4	4
126	Haryana	Faridabad	2356.21	584	74.9	1918	3	3
127	Haryana	Fatehabad	2408.01	363.4	82.1	1968	3	4
128	Haryana	Gurgaon	2357.2	555.5	66.8	1928	3	4
129	Haryana	Hisar	2397.54	405.7	80	1987	4	2
130	Haryana	Jhajjar	2353.11	482.6	74	1905	3	4
131	Haryana	Jind	2368.57	491.1	85.2	1987	3	4
132	Haryana	Kaithal	2360.45	481.9	76.9	1982	3	3
133	Haryana	Karnal	2334.83	684.5	62.2	1979	4	4
134	Haryana	Kurukshetra	2336.76	624.1	68.5	2012	4	4
135	Haryana	Mahendragarh	2374.05	486.5	69.6	1979	4	3
136	Haryana	Panchkula	2337.53	861.5	59.1	1918	3	4
137	Haryana	Panipat	2338.06	591.0	72.4	1938	3	3
138	Haryana	Rewari	2359.14	474.3	71.1	1918	4	3

139	Haryana	Rohtak	2361.39	536.7	74.2	1987	4	4
140	Haryana	Sirsa	2445.34	310.3	82.7	1979	3	3
141	Haryana	Sonepat	2341.65	595.3	81	1947	3	4
142	Haryana	Yamunanagar	2322.5	1004.9	57.6	1974	4	2
143	Himachal Pradesh	Chamba	2103.6	854.0	42	1952	4	3
144	Himachal Pradesh	Hamirpur	2279.3	1357	53	1952	5	2
145	Himachal Pradesh	Kangra	2244.1	2084	50.1	1918	4	2
146	Himachal Pradesh	Kinnaur	1698.1	966.0	41.1	1987	4	2
147	Himachal Pradesh	Kullu	1955.7	1031	39.2	1987	5	2
148	Himachal Pradesh	Lahul & Spiti	1512.0	1001.7	40	1982	4	2
149	Himachal Pradesh	Mandi	2211.4	863.0	44.1	1982	5	2
150	Himachal Pradesh	Shimla	2105.0	1229.4	40.3	1987	5	0
151	Himachal Pradesh	Sirmaur	2308.3	1563.1	43.1	1987	5	2
152	Himachal Pradesh	Solan	2326.7	1456.8	44.6	1918	4	2
153	Himachal Pradesh	Una	2321.8	1069.3	51.1	1918	4	2
154	Jammu and Kashmir	Anantnag	1887.2	839	70.3	1963	4	3
155	Jammu and Kashmir	Badgam	2065.6	932	58.8	1963	4	3
156	Jammu and Kashmir	Baramula	1896.4	923	55.2	1939	4	3
157	Jammu and Kashmir	Doda	1931.9	808	66	1963	5	3
158	Jammu and Kashmir	Jammu	2314.5	730	56.4	1963	4	3
159	Jammu and Kashmir	Kargil	1349.0	588	70.7	1963	4	3
160	Jammu and Kashmir	Kathua	2282.6	786	60.2	1952	5	3
161	Jammu and Kashmir	Kupwara	1290.9	515	59.2	1946	5	3
162	Jammu and Kashmir	Leh	863.5	278	60	1982	5	2
163	Jammu and Kashmir	Pulwama	1885.5	859	67.5	1963	4	3
164	Jammu and Kashmir	Punch	2243.2	946	57.4	1934	4	3
165	Jammu and Kashmir	Rajauri	2315.9	803	54.5	1920	5	3
166	Jammu and Kashmir	Srinagar	1675.8	824	66.9	1963	4	3
167	Jammu and Kashmir	Udhampur	2285.8	823	59	1963	4	3

168	Jharkhand	Bokaro	2200.68	1245.1	56	1913	9	2
169	Jharkhand	Chatra	2274.58	1231.5	52.3	1966	7	2
170	Jharkhand	Deoghar	2220.34	1225.5	50.7	1966	7	2
171	Jharkhand	Dhanbad	2219.53	1314.0	48.4	2005	8	2
172	Jharkhand	Dumka	2229.41	1430.0	47.9	1982	8	2
173	Jharkhand	Gharwa	2301.84	1194.7	53.6	1966	9	2
174	Jharkhand	Giridih	2202.67	1212.4	50.1	1966	7	2
175	Jharkhand	Godda	2218.54	1154.7	46.1	1927	9	0
176	Jharkhand	Gumla	2288.16	1409.1	59.5	1979	9	2
177	Jharkhand	Hazaribagh	2213.91	1260.3	44	2010	9	2
178	Jharkhand	Jamtara	2223.09333	1369.5	45.6	1982	7	2
179	Jharkhand	Koderma	2214.93	1134.6	45	1927	7	2
180	Jharkhand	Latehar	2279.814	1326.4	46.6	1966	7	2
181	Jharkhand	Lohardagga	2258.22	1293.7	42.7	1992	9	0
182	Jharkhand	Pakur	2232.23	1539.6	50.6	1927	7	2
183	Jharkhand	Palamu	2276.27	1185.0	51.7	2010	7	2
184	Jharkhand	Ranchi	2251.17	1351.3	44.1	2010	9	0
185	Jharkhand	Sahebganj	2219.77	1440.8	46.3	1966	6	2
186	Jharkhand	Saraikela	2239.65667	1325.4	46.3	1979	9	2
187	Jharkhand	East Singhbhum	2209.4	1394.7	58	2010	10	0
188	Jharkhand	West Singhbhum	2258.4	1335.0	58.5	2008	9	2
189	Karnataka	Bagalkote	2303.08	567.9	51.2	1942	5	2
190	Karnataka	Bangalore Rural	2228.4	786.5	41.7	1908	5	2
191	Karnataka	Bangalore Urban	2223.3	835.5	50.8	1957	5	2
192	Karnataka	Belgaum	2146.95	930.6	53.1	1918	6	2
193	Karnataka	Bellary	2276.22	585.5	45.8	1976	6	2
194	Karnataka	Bidar	2447.69	869.2	53.4	1929	6	3
195	Karnataka	Bijapur	2390.51	580.3	51.5	1972	5	3
196	Karnataka	Chamarajanagar	2113.09	771.9	49.9	1904	4	3

197	Karnataka	Chikmaglur	2059.87	1917.3	41.6	1918	11	2
198	Karnataka	Chitradurga	2198.19	549.9	59	1976	6	2
199	Karnataka	Devangre	2148.32	640.2	43.8	1908	7	0
200	Karnataka	Dharwad	2104.33	778.4	42.6	1905	14	0
201	Karnataka	Gadag	2213.66	588.6	53.9	1990	5	4
202	Karnataka	Gulbarga	2442.33	743.2	56.8	1972	5	3
203	Karnataka	Hassan	2040.6	1137.6	52.1	2012	9	2
204	Karnataka	Haveri	2107.78	768.4	49	1905	8	0
205	Karnataka	Kodagu	1858.78	2698.8	40.1	2001	14	2
206	Karnataka	Kolar	2262.58	694.0	45.5	1923	6	2
207	Karnataka	Kopal	2296.92	649.3	51.5	1985	6	2
208	Karnataka	Mandya	2118.32	701.8	59.5	1965	6	2
209	Karnataka	Mysore	2019.23	804.6	47.7	1990	5	2
210	Karnataka	Raichur	2395.84	627.0	58.1	1926	5	3
211	Karnataka	Tumkur	2208.32	665.1	54.6	1923	5	2
212	Karnataka	Udupi	1870.365	4075.1	49	1918	14	0
213	Karnataka	Uttar Kannada	1998.0025	2841.3	46	1918	19	0
214	Karnataka	Dakshin Kannada	1986.41667	3972.7	38	1918	23	0
215	Kerala	Alpuzha	1600.9	2900	33.4	1986	25	0
216	Kerala	Cannur	1770.6	3416	39.4	1987	33	0
217	Kerala	Ernakulam	1600.2	3241	37	1986	25	0
218	Kerala	Kottayam	1424.1	3163	47.9	1987	10	0
219	Kerala	Kozhikode	1780	3550	32	2000	25	0
220	Kerala	Palakkad	1777.2	2289	36.4	1987	13	2
221	Kerala	Thiruvanantpuram	1777	1856	53.5	1983	7	0
222	Kerala	Idukki	1600	2504	47	1965	7	2
223	Kerala	Mallapuram	1778.1	2827	37	1987	11	0
224	Kerala	Wayanad	1776.2	3343	41.2	1982	10	0
225	Kerala	Kasaragod	1777.8	3550	37.9	1987	20	0

226	Kerala	Thrissur	1776.3	3063	32.8	1952	17	0
227	Kerala	Pathanmitha	1600.9	2975	44	1986	14	0
228	Kerala	Kollam	1777.8	2504	34.2	1982	13	0
229	Maharashtra	Ahmednagar	2436.52	577.4	67.8	1918	5	2
230	Maharashtra	Akola	2490.35	794.7	59.5	1918	6	2
231	Maharashtra	Amravati	2470.56	926.3	56.2	1920	6	2
232	Maharashtra	Aurangabad	2532.75	715.3	70.8	1918	5	2
233	Maharashtra	Beed	2512.11	693.2	73.3	1912	5	2
234	Maharashtra	Buldana	2512.52	769.4	57.8	1918	7	2
235	Maharashtra	Chandrapur	2419.75	1294.3	42.4	1920	7	0
236	Maharashtra	Dhulie	2487.44	598.5	59.1	1918	7	2
237	Maharashtra	Gadchiroli	2385.36	1427.8	42.9	1920	7	2
238	Maharashtra	Gondia	2399.08	1385.9	45	1920	8	2
239	Maharashtra	Jalgaon	2545.65	728.0	53.7	1918	7	2
240	Maharashtra	Jalna	2535.01	710.5	57.4	1920	6	2
241	Maharashtra	Latur	2478.61	810.7	70.1	1986	5	3
242	Maharashtra	Nagpur	2423.72	1127.6	42.7	1972	9	0
243	Maharashtra	Nanded	2444.24	913.8	54.1	1972	6	3
244	Maharashtra	Nandurbar	2463.96	854.1	58	1918	6	2
245	Maharashtra	Nasik	2369.87	994.5	58.5	1918	8	2
246	Maharashtra	Osmanabad	2486.91	777.7	62.4	1972	6	3
247	Maharashtra	Parbhani	2498.59	869.8	68	1920	6	2
248	Maharashtra	Pune	2227.77	1035.1	69.3	1918	7	3
249	Maharashtra	Sangli	2238.38	690.4	67.5	1918	6	3
250	Maharashtra	Satara	2183.05	1272.8	59.9	1918	9	0
251	Maharashtra	Sholapur	2411.49	618.3	67.1	1972	6	3
252	Maharashtra	Wardha	2434.39	1041	46.8	1920	8	2
253	Maharashtra	Washim	2487.32	888.9	58.6	1920	8	2
254	Maharashtra	Yeotmal	2451.77	985.8	52.6	1920	7	2

255	Manipur	Bishnupur	1786.4	2216.9	41.3	1957	26	0
256	Manipur	Chandel	1754.4	2176.4	47.8	1958	20	0
257	Manipur	Churachandpur	1791.4	1789.2	43.5	1982	20	0
258	Manipur	Imphal East	1812.4	2542	26.2	1971	34	0
259	Manipur	Imphal West	1884.3	3128	30.4	1971	34	0
260	Manipur	Senapati	1813.1	2222.1	39.7	1967	20	0
261	Manipur	Tamenlong	1861.9	4702.9	27.7	1971	34	0
262	Manipur	Thaoubal	1785.2	2620	28.8	1966	26	0
263	Manipur	Ukhrul	1807.2	2375	36.3	1972	11	0
264	Mizoram	Aizwal	1897.8	2699.8	35	1972	13	0
265	Mizoram	Champhai	1848.8	2036.5	39	1966	15	0
266	Mizoram	Kolasib	1912.9	2849.1	36	1966	26	0
267	Mizoram	Lawngtlai	1841.6	2557.4	29.6	1971	20	0
268	Mizoram	Lunglei	1869.5	3060.4	30.5	1971	26	0
269	Mizoram	Mamit	1905.8	2567.6	32.2	1966	34	0
270	Mizoram	Saiha	1846.9	2563.4	28.4	1972	51	0
271	Madhya Pradesh	Balaghat	2378.21	1471.5	44.5	1965	8	0
272	Madhya Pradesh	Barwani	2535.32	690.8	57.1	1901	5	2
273	Madhya Pradesh	Betul	2420.97	1075.9	57.9	1918	6	3
274	Madhya Pradesh	Bhind	2403.38	712.2	72.2	1905	4	3
275	Madhya Pradesh	Bhopal	2420.99	1085.5	57.5	1979	5	3
276	Madhya Pradesh	Chattarpur	2377.44	1060.4	64.7	1905	5	2
277	Madhya Pradesh	Chindwara	2350.51	1173.6	52.4	2004	7	2
278	Madhya Pradesh	Damoh	2345.4	1174.3	64.9	1979	6	0
279	Madhya Pradesh	Datia	2400.12	799.1	72.1	1905	6	3
280	Madhya Pradesh	Dewas	2495.89	977.6	75.4	1904	5	3
281	Madhya Pradesh	Dhar	2509.44333	827.2	62.9	1911	5	3
282	Madhya Pradesh	Dindori	2308.52	1397.9	60.7	2009	8	2
283	Madhya Pradesh	Guna	2395.6	1020.5	69.9	1979	5	2

284	Madhya Pradesh	Gwalior	2390.8	802.3	62.1	1941	5	2
285	Madhya Pradesh	Harda	2487.55	1104.7	51.2	1902	5	3
286	Madhya Pradesh	Hosangabad	2394.56	1409.4	46.4	1979	5	3
287	Madhya Pradesh	Indore	2508.96	934.5	57.8	1965	5	3
288	Madhya Pradesh	Jabalpur	2329.73	1256.2	55.2	1979	8	2
289	Madhya Pradesh	Jhabua	2484.05	825.2	62.9	1985	4	2
290	Madhya Pradesh	Katni	2352.98	1144.4	57.5	1986	7	2
291	Madhya Pradesh	Khandwa	2491.72	876.6	54.2	2000	5	3
292	Madhya Pradesh	Khargone	2513.39	760.9	58.4	1918	4	3
293	Madhya Pradesh	Mandla	2346.43	1424.4	51.2	1979	8	2
294	Madhya Pradesh	Mandsaur	2421.65	819.5	59.2	1915	5	3
295	Madhya Pradesh	Morena	2397.64	730.6	65.1	1913	5	2
296	Madhya Pradesh	Narsinghpur	2297.64	1233.5	50.2	1965	7	2
297	Madhya Pradesh	Neemuch	2404.48	805.0	58.2	1951	5	2
298	Madhya Pradesh	Panna	2366.05	1157.6	67.5	2007	5	2
299	Madhya Pradesh	Raisen	2390.78	1211.7	56.9	1979	8	2
300	Madhya Pradesh	Rajgarh	2419.63	997.5	53.2	1951	6	2
301	Madhya Pradesh	Ratlam	2456.07	925.9	70.2	1918	4	3
302	Madhya Pradesh	Rewa	2345.04	1096.8	58.1	1979	7	2
303	Madhya Pradesh	Sagar	2351.81	1170.9	48.9	1913	7	2
304	Madhya Pradesh	Satna	2354.91	1059.4	68.6	1979	7	2
305	Madhya Pradesh	Sehore	2456.38	1120.8	59.2	1914	5	3
306	Madhya Pradesh	Seoni	2347.81	1281.3	43.2	1987	9	2
307	Madhya Pradesh	Sahdol	2287.98	1187.6	49.2	1979	8	2
308	Madhya Pradesh	Shajapur	2436.25	957.4	51.7	1965	5	3
309	Madhya Pradesh	Sheopur	2416.2	745.8	66	1918	4	4
310	Madhya Pradesh	Shivpuri	2390.5	846.2	61.2	1913	6	2
311	Madhya Pradesh	Sidhi	2303.83	1223.0	61	1965	5	2
312	Madhya Pradesh	Tikamgarh	2383.62	980.9	64.6	1905	6	2

313	Madhya Pradesh	Ujjain	2455.36	878.9	57.3	1918	5	3
314	Madhya Pradesh	Umaria	2328.09	1221.3	57.1	1979	8	2
315	Madhya Pradesh	Vidisha	2385.26	1099.6	49.4	1979	5	2
316	Nagaland	Kohima	1214	2161.0	36		18	0
317	Orissa	Angul	2193.62	1394.8	40.9	1979	9	2
318	Orissa	Bolangir	2267.42	1367.0	44.1	1974	7	2
319	Orissa	Cuttak	2043.65	1471.5	45	1996	13	2
320	Orissa	Debgarh	2267.25	1420.3	59	1979	9	2
321	Orissa	Dhenkanal	2165.07	1448.1	42.8	1918	10	2
322	Orissa	Gajapati	2087.76	1386.7	40.2	2002	10	0
323	Orissa	Ganjam	2054.04	1284.6	41.3	1907	10	2
324	Orissa	Jagatsinghpur	1887.68	1587.7	40.5	1996	10	2
325	Orissa	Jajpur	2123.13	1495.0	42	2000	10	0
326	Orissa	Jharsuguda	2298.74	1450.0	48.3	1979	9	0
327	Orissa	Kalahandi	2243.56	1432.5	45	1901	8	2
328	Orissa	Kandhamal	2161.67	1469.1	50.2	1974	11	0
329	Orissa	Kendrapara	1998.37	1504.7	38.3	1901	10	2
330	Orissa	Kendujhargarh	2255.83	1468.6	40	1948	8	2
331	Orissa	Khurda	2006.45	1435.0	36.9	1987	14	0
332	Orissa	Koraput	2205.55	1615.5	43.1	1981	9	2
333	Orissa	Malkangiri	2234.61	1490.2	44.4	1974	7	2
334	Orissa	Mayurbhanj	2200.18	1616.6	41.9	1950	13	2
335	Orissa	Nawpara	2285.88	1252.5	50.5	1974	9	0
336	Orissa	Nayagarh	2073.6	1371.2	58.2	1982	9	2
337	Orissa	Nawrangpur	2292.1	1579.7	34.3	1923	9	2
338	Orissa	Puri	1718.64	1395.4	38.7	1996	10	0
339	Orissa	Rayagada	2161.48	1253.4	43.1	1920	11	0
340	Orissa	Sambalpur	2276.23	1533.5	42.8	2010	8	0
341	Orissa	Sonepur	2252.04	1364.2	51.9	1987	7	2

342	Orissa	Sundergarh	2298.64	1454.1	50.3	1979	9	2
343	Punjab	Amritsar	2359.35	613	65	1904	3	4
344	Punjab	Bhatinda	2418.07	403	76.1	1999	3	4
345	Punjab	Faridkot	2422.77	369	80	2004	3	4
346	Punjab	Fatehgarh Sahib	2361.89	550	89	2012	3	4
347	Punjab	Ferozepur	2433.23	357	82	2012	3	4
348	Punjab	Gurdaspur	2311.32	1032	59.1	1918	4	2
349	Punjab	Hosiarpur	2328.15	828	59.3	1918	3	4
350	Punjab	Jalandhar	2361.89	669	65	1915	3	4
351	Punjab	Kapurthala	2362.21	526	59	1935	3	4
352	Punjab	Ludhiana	2377.22	543	68.6	1987	4	2
353	Punjab	Moga	2403.85	453	85	1968	3	3
354	Punjab	Muktesar	2441.04	367	79.2	2012	3	3
355	Punjab	Nawanshar	2354.47	852	71.7	1918	3	4
356	Punjab	Patiala	2352.94	660	78.8	1987	3	4
357	Punjab	Roopnagar	2349.18	857	73.1	1918	4	4
358	Punjab	Sangrur	2383.83	485	75.6	2007	3	4
359	Rajasthan	Ajmer	2417.07	498.1	69.5	1915	4	3
360	Rajasthan	Alwar	2384.15	619.1	64.8	1905	4	5
361	Rajasthan	Banswara	2476.78	916.4	66.8	1915	4	4
362	Rajasthan	Barmer	2607.45	270.6	87	1918	3	4
363	Rajasthan	Bharatpur	2387.32	645.7	66.5	1979	5	3
364	Rajasthan	Bhilwara	2380.24	615.7	90.4	1998	4	2
365	Rajasthan	Bikaner	2575.78	264.8	94.5	2002	3	3
366	Rajasthan	Bundi	2394.5	720.5	74.8	2000	4	3
367	Rajasthan	Chittorgarh	2402.68	786.6	68.2	1915	5	2
368	Rajasthan	Churu	2487.19	361.0	78.1	1918	3	3
369	Rajasthan	Dausa	2419.44	620.1	75.7	1905	4	5
370	Rajasthan	Dholpur	2401.11	684.3	63.8	1979	4	4

371	Rajasthan	Dungarpur	2488.82	718.1	65.7	1915	4	4
372	Rajasthan	Ganganagar	2523.49	233.9	93.8	1915	3	5
373	Rajasthan	Jaipur	2417.4	567	79	1905	4	4
374	Rajasthan	Jaisalmer	2663.89	100.0	94.5	1918	3	4
375	Rajasthan	Jalore	2563.75	410.1	90.2	1974	3	3
376	Rajasthan	Jhalawar	2414.04	934.4	48.6	1905	4	3
377	Rajasthan	Jhunjhunu	2412.1	452.5	82.8	2002	4	5
378	Rajasthan	Jodhpur	2563.69	317.6	83.5	1918	3	3
379	Rajasthan	Kota	2401.99	770.7	61.5	1905	4	3
380	Rajasthan	Pali	2457.4	467.7	83.1	2002	3	4
381	Rajasthan	Sawaimadhopur	2419.49	726.5	72.1	1905	4	4
382	Rajasthan	Sikar	2435.67	469.7	77.9	1999	3	4
383	Rajasthan	Sirohi	2520.05	834.5	78.6	1974	3	3
384	Rajasthan	Tonk	2408.17	603.7	69	2002	4	2
385	Rajasthan	Udaipur	2429.47	649.2	62.4	1915	4	3
386	Rajasthan	Nagaur	2495.7	387.3	77.8	1918	3	4
387	Rajasthan	Rajasmand	2349.41	555.3	93.4	1919	4	4
388	Rajasthan	Baran	2411.91	859.2	74.1	1977	4	2
389	Rajasthan	Hanumangarh	2471.1	304.9	75.2	1951	3	5
390	Sikkim	East Sikkim	1910.5	2774.4	36.1	1957	17	0
391	Sikkim	North Sikkim	1614.6	2832.8	42.4	1957	26	0
392	Sikkim	South Sikkim	1927.9	2696.4	38	1957	17	0
393	Sikkim	West Sikkim	1899.4	2222.8	35.7	1957	17	0
394	Tamil Nadu	Ariyalur	2071.65	1063.2	54.3	1927	6	2
395	Tamil Nadu	Chennai	2221.68	1285.9	59.2	1904	5	2
396	Tamil Nadu	Cuddalore	2101.02	1217.0	40.8	1974	6	2
397	Tamil Nadu	Dharmapuri	2253.31	875.9	45	1923	8	0
398	Tamil Nadu	Dindigul	1971.96	975.5	47.5	2013	8	2
399	Tamil Nadu	Erode	2109.9	765.0	54.4	1923	4	3

400	Tamil Nadu	Kanchipuram	2204.04	1222.2	43.7	1904	6	3
401	Tamil Nadu	Karur	2037.74	661.8	52.9	1923	5	3
402	Tamil Nadu	Madurai	1937.67	894.8	45.4	1974	7	2
403	Tamil Nadu	Naggapatinum	2002.1	1366.3	52.1	1909	5	3
404	Tamil Nadu	Namakkal	2172.23	788.6	50.3	1923	8	3
405	Tamil Nadu	Nilgiri	2007.9	1845.9	36.6	1952	19	0
406	Tamil Nadu	Peramblur	2119.75	906.2	59.3	1988	6	3
407	Tamil Nadu	Pudukotai	1963.33	893.7	57.7	1974	9	2
408	Tamil Nadu	Ramnathpuram	1838.86	828.9	58.3	1974	5	2
409	Tamil Nadu	Salem	2221.58	967.3	42.4	1923	8	2
410	Tamil Nadu	Sivaganga	1930.84	905.7	53.5	1974	8	2
411	Tamil Nadu	Thanjavur	1982.15	1027.3	51.5	1908	6	2
412	Tamil Nadu	Theni	1923.91	797.9	46	1904	5	2
413	Tamil Nadu	thiruvallur	2263.1	1141.1	59.5	1904	6	4
414	Tamil Nadu	Thiruvarur	1980.62	1169.2	45.6	1980	5	2
415	Tamil Nadu	Trichy	2068.74	833.3	51.5	2012	7	2
416	Tamil Nadu	Thirupur	2031.49	650.9	62	1904	5	2
417	Tamil Nadu	Thiruvannamalai	2250.49	1057.8	47.1	1950	8	3
418	Tamil Nadu	Vellore	2278.87	932.2	41.1	1980	8	2
419	Tamil Nadu	Villupuram	2191.39	1075.8	44.8	1982	6	2
420	Tamil Nadu	Virudunagar	1909.68	814.7	47.3	1926	6	2
421	Tripura	Dhalai	1902.2	2493.3	40	1980	17	0
422	Tripura	North Tripura	1924.2	2568.2	35.8	1979	23	0
423	Tripura	South Tripura	1866.7	2311.5	38	1967	14	0
424	Tripura	West Tripura	1889.3	2180.6	39.7	1972	14	0
425	Uttar Pradesh	Banda	2298.11	886.1	62.7	1979	6	4
426	Uttar Pradesh	Hamirpur	2326.6	818.2	63	1918	6	3
427	Uttar Pradesh	Jalaun	2376.42	800.9	69.3	1905	5	2
428	Uttar Pradesh	Jhansi	2373	841.9	65.6	1913	6	3

429	Uttar Pradesh	Lalitpur	2294.9	991.4	72.9	1976	4	2
430	Uttar Pradesh	Allahabad	2358.89	930	63.5	1997	5	2
431	Uttar Pradesh	Ambedkar nagar	2354.56	943	70.5	1997	5	3
432	Uttar Pradesh	Azamgarh	2354.8	1007	52.3	1997	6	3
433	Uttar Pradesh	Bahraich	2307.21	1143	65.7	1907	6	2
434	Uttar Pradesh	Balia	2333.72	939	58	1998	6	3
435	Uttar Pradesh	Balrampur	2298.11	1168	68.6	1907	5	2
436	Uttar Pradesh	Barabanki	2344.19	970	70.2	1998	4	2
437	Uttar Pradesh	Basti	2336.93	1087	73.5	1973	5	3
438	Uttar Pradesh	Chandauli	2348.8	971	51	2012	7	2
439	Uttar Pradesh	Deoria	2319.52	1056	57.2	2009	5	2
440	Uttar Pradesh	Faizabad	2346.7	1049	60.6	1918	6	2
441	Uttar Pradesh	Farukhabad	2400.39	788	69.1	1918	4	2
442	Uttar Pradesh	Fatehpur	2397.7	881	62.1	1997	5	3
443	Uttar Pradesh	Ghazipur	2352.24	987	62.1	2004	6	3
444	Uttar Pradesh	Gonda	2328.29	1117	68.5	1998	5	2
445	Uttar Pradesh	Gorakhpur	2326.58	1255	56.4	1997	5	2
446	Uttar Pradesh	Hardoi	2377.24	859	67.2	1979	4	4
447	Uttar Pradesh	Jaunpur	2373	914	69.1	1998	6	2
448	Uttar Pradesh	Kannauj	2408.14	800	67.1	1918	4	2
449	Uttar Pradesh	Kanpur Nagar	2404	804	60.1	1918	4	2
450	Uttar Pradesh	Kanpur Dehat	2412.2	776	74.1	1997	5	3
451	Uttar Pradesh	Kaushambi	2372.02	869	74	1997	5	3
452	Uttar Pradesh	Kushinagar	2294.91	1126	47.8	1907	5	2
453	Uttar Pradesh	Kheri	2325.64	1080	67.7	1907	5	2
454	Uttar Pradesh	Lucknow	2363.64	911	60.4	1979	5	2
455	Uttar Pradesh	Mau	2344.1	989	88.4	1998	5	2
456	Uttar Pradesh	Maharajganj	2291.64	1315	76.6	1997	5	2
457	Uttar Pradesh	Mirzapur	2345.45	990	62.4	2009	6	2

458	Uttar Pradesh	Pratapgarh	2397.7	928	71.9	1997	6	2
459	Uttar Pradesh	Rae Breilly	2384.7	843	62.1	1997	4	4
460	Uttar Pradesh	Sant Kabir Nagar	2327.2	1103	73.2	1997	4	2
461	Uttar Pradesh	Sidhartnagar	2303.82	1284	74.1	1973	5	3
462	Uttar Pradesh	Sitapur	2339.23	955	64.7	1979	5	2
463	Uttar Pradesh	Sultanpur	2371	964	60.1	1997	6	2
464	Uttar Pradesh	Sonebhadra	2311.01	1047	64.7	1997	9	2
465	Uttar Pradesh	Unnao	2383.1	827	56.9	1997	4	3
466	Uttar Pradesh	Varanasi	2355.2	992	56.1	2009	6	2
467	Uttar Pradesh	Agra	2394.19	667	69.4	1913	5	4
468	Uttar Pradesh	Aligarh	2362.83	688	74.3	1918	5	3
469	Uttar Pradesh	Auraiya	2412.9	726	75	1905	4	4
470	Uttar Pradesh	Baghpat	2324.9	612	72.1	1997	4	3
471	Uttar Pradesh	Bareilly	2344.67	1026	70.2	1979	4	2
472	Uttar Pradesh	Bijnor	2305.13	1066	66.2	1987	5	2
473	Uttar Pradesh	Budaun	2366.18	825	59.6	1979	4	3
474	Uttar Pradesh	Bulandhahar	2344.68	687	66.6	1905	4	3
475	Uttar Pradesh	Etah	2385.85	667	71.8	1918	4	2
476	Uttar Pradesh	Etawah	2410.53	734	72.3	1997	5	4
477	Uttar Pradesh	Firozabad	2396.4	691	67.1	1913	4	4
478	Uttar Pradesh	Ghaziabad	2323.5	689	71.7	1987	4	4
479	Uttar Pradesh	Hathras	2376.42	669	73.3	1997	4	4
480	Uttar Pradesh	J Phule Nagar	2324.7	953	74.4	1987	5	3
481	Uttar Pradesh	Mainpuri	2405.82	718	62.5	1918	5	4
482	Uttar Pradesh	Mathura	2372.81	600	64.9	1918	4	2
483	Uttar Pradesh	Meerut	2314.48	793	70	1918	4	4
484	Uttar Pradesh	Moradabad	2329.87	919	65.5	1987	5	3
485	Uttar Pradesh	Muzaffarnagar	2315.2	755	71.6	1987	4	4
486	Uttar Pradesh	Pilibhit	2325.8	1109	72.5	1987	4	4

487	Uttar Pradesh	Shahjahanpur	2366.15	961	61.1	1987	4	4
488	Uttar Pradesh	Saharanpur	2316.3	926	58	1987	5	2
489	Uttar Pradesh	Rampur	2325.3	893	73.6	1972	5	3
490	Uttarakhand	Almora	2244.97	1132	58	1987	5	2
491	Uttarakhand	Bageshwar	2093.92	1220	59	1991	5	2
492	Uttarakhand	Chamoli	1907.47	1131	58.4	1987	5	2
493	Uttarakhand	Champawat	2277.96	1240	59.1	1991	5	2
494	Uttarakhand	Dehradun	2299.75	894	56.8	1987	6	2
495	Uttarakhand	Garhwal	2273.09	995	59.7	1987	6	2
496	Uttarakhand	Haridwar	2308.35	821	58.8	1987	6	2
497	Uttarakhand	Nainital	2290.46	1071	58.3	1991	6	2
498	Uttarakhand	Pithoragarh	1920.44	1244	58.2	1991	6	2
499	Uttarakhand	Rudraprayag	1910.08	1110	58.6	1987	5	2
500	Uttarakhand	Tehri Garhwal	2210.04	1021	59.7	1987	7	0
501	Uttarakhand	U. S. Nagar	2305.29	1004	55.7	1987	5	2
502	Uttarakhand	Uttarkashi	1884.18	1009	58	1987	5	2
503	West Bengal	Bankura	2208.54	1360	41	1902	10	2
504	West Bengal	Birbhum	2223.3	1376	44.2	1940	9	2
505	West Bengal	Burdwan	2181.9	1345	40.2	1982	11	2
506	West Bengal	Cooch Behar	1994.14	3272	43	1994	9	0
507	West Bengal	Darjeeling	2001.5	3092	44	2001	19	0
508	West Bengal	Dinajpur South	2118.39	1654	46.1	2000	6	2
509	West Bengal	Hoogly	2070.1	1464	59	1982	13	2
510	West Bengal	Jalpaigudi	1996.98	3855	44.6	2001	11	0
511	West Bengal	Murshidabad	2212.09	1401	42.4	1982	8	2
512	West Bengal	Nadia	2143.79	1323	59.3	1979	7	4
513	West Bengal	24 Prangans North	1827.6	1602	38.8	1935	8	0
514	West Bengal	Kolkata	2001.03	1665	45	1935	11	2
515	West Bengal	Malda	2189.66	1483	58	1979	5	2
516	West Bengal	Purulia	2227.13	1329	43.6	1966	14	0

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1. **Amrit, K.,** Mishra, S. K., & Pandey, R. P. (2017). Tennant Concept Coupled with Standardized Precipitation Index for Environmental Flow Prediction from Rainfall. *Journal of Hydrologic Engineering*, (ASCE), *23*(2), 05017031.
2. **Amrit K.,** Pandey R. P., Mishra S. K., Daradur M., (2018). "Relationship of Drought Frequency and Severity with Range of Annual Temperature Variation". *Natural Hazards*, Springer (DOI: 10.1007/s11069-018-3247-6).
3. **Amrit, K.,** Pandey, R. P., & Mishra, S. K. (2017). Assessment of meteorological drought characteristics over Central India. *Sustainable Water Resources Management*, Springer, 1-12 (DOI: 10.1007/s40899-017-0205-5).
4. **Amrit, K.,** Pandey, R. P., & Mishra, S. K., "Long-Term Meteorological Drought Characteristics in Southern India". In *World Environmental and Water Resources Congress (ASCE) 2018* (pp. 207-215).
5. **Amrit, K.,** Mishra, S. K., & Pandey, R. P., Prediction of Environmental Flow Condition Using the Standardized Precipitation Index in Mahanadi Basin, India. In *World Environmental and Water Resources Congress (ASCE) 2017* (pp. 294-301).
6. **Amrit, K.,** Mishra, S. K., & Pandey, R. P. (2018). Coupling of Tennant Concept with Standardized Precipitation Index (SPI) for the Prediction of Environmental Flow Condition from Rainfall in Upper Narmada Basin. In *Climate Change Impacts* (pp. 265-272). Springer, Singapore **(Book Chapter).**
7. **Amrit, K.,** Pandey, R. P., & Mishra, S. K., (2018) "Characteristics of Meteorological Droughts in North-Western India", Natural Hazards, Springer **(First revision submited).**
8. **Amrit, K.,** Mishra, S. K., & Pandey, R. P., (2017). "A Simple SPI-Based Prediction of Environmental Flow Condition", *Water Resources Management*, *Springer* **(Under review).**