STUDY OF SPATIAL AND TEMPORAL VARIABILITY OF DROUGHTS IN THE KRISHNA RIVER BASIN IN MAHARASHTRA, INDIA

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

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D E C L A R A T I O N

By the Ph.D. Research Scholar

I hereby *declare* that the Research Thesis entitled **"Study of Spatial and Temporal Variability of Droughts in the Krishna river Basin in Maharashtra, India."** which is being submitted to the National Institute of Technology Karnataka, Surathkal in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy in the Department of Applied Mechanics and Hydraulics is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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C E R T I F I C A T E

This is to *certify* that the Research Thesis entitled **"Study of Spatial and Temporal Variability of Droughts in the Krishna river Basin in Maharashtra, India."** submitted by **Mahajan Dattatraya Rohidas** (Register Number: 110636 AM11F04) as the record of the research work carried out by him, is *accepted as the Research Thesis submission* in partial fulfilment of the requirements for the award of degree of Doctor of Philosophy.

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Dedicated to

MY FAMILY

AND

BELOVED TEACHERS

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ABSTRACT

Spatial and Temporal Drought Analysis of the Meteorological drought, done by the SPI and PNP at multiple timescales over the 59 stations for the period 1960-2012, in Krishna basin in Maharashtra. The present study explores the usefulness of the SPI and the Run theory in investigating drought characteristics at multiple timescales. The SPI performs better than the PNP in monitoring drought at multiple timescales. In regional drought analysis, the areas affected by the severe drought evolve gradually at every timescale from Moderate to Severe. The Severe drought recedes at successive timescale with a time lag varying from 2-4 months for high-intensity drought (1971-75) and 2-9 months for high-severity drought (2000-07).Sub-Basin Wide Drought Analysis of the Hydrological drought done using Modified SWSI, Metrological drought using SPI and PNP for the five sub-basins for the period of 1972-2008 in the Krishna river basin in the state of Maharashtra, India. From MSWSI analysis, UKE sub-basin is the most droughts prone followed by RB sub-basin, while UB sub-basin is the least droughts prone followed by UKW sub-basin. From SPI analysis it was found that UKE sub-basin is the most droughts prone while UKW sub-basin is the least drought prone. From PNP analysis it was found that UKE and RB sub-basins are most the droughts prone followed by SB and UB sub-basins. UKW is the least drought prone. The spatial and temporal variability in drought trends was observed in the study area. From sub-basin wide drought analysis, the MSWSI drought index is found to be better than the SPI and PNP for the Krishna basin in Maharashtra. It was found that the MSWSI index can be used for a whole year for diverse water resources planning and management as it reflects the real-time availability of water. The SPI and PNP had its own merits as well as demerits. The SPI and PNP indices are most suitable for monsoon season. For local and regional drought analysis, the SPI is a better index than MSWSI and PNP. The study area is susceptible to drought events. Moderate drought month occurs in 80 % of the study area, with one-year return period. Severe drought month occurs for 64 % of the area with 2-year return period. An extreme drought month occurs for 78 % of the area with 5-year return period.

Key words*:* Standardized Precipitation Index (SPI), Percent of Normal Precipitation (PNP), Modified surface water Index (MSWSI), Spatial and Temporal Variability.

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Abbreviation	**Definition**
DI	Drought Index
Γ (α)	Gamma function
a.m.s.l	Above mean sea level
BMDI	Bhalme and Mooley Drought Index
C.V	Coefficient of Variation
CSDI	Crop-Specific Drought Index
Dd	Drought duration
EDI	Effective Drought Index
ETDI	Evapotranspiration Deficit Index
ETDI	Evapotranspiration Deficit Index
EWA	European Water Archive
g	Coefficient of Skewness
G.O.M	Government Of Maharashtra
GIS	Geographic Information System
GRACE	Gravity Recovery and Climate Experiment
ha	Hectare
Id	Drought intensity
IDW	Inverse Distance Weighting
K	Coefficient of Kurtosis
km2	Square Kilometre
LPA	Long Period Average
Max	Maximum
Min	Minimum
MK	Man-Kendall
MSWSI	Modified Surface Water Supply Index
n	number of precipitation observations
NRI	National Rainfall Index
OK	Ordinary Kriging
P	Actual precipitation
P Normal	Normal precipitation
PDF	Probability Distribution
PDSI	Palmer Drought Severity Index
PNP	Percent of Normal Precipitation
Pp	probability
Pt	non-exceedance probability
RAI	Rainfall Anomaly Index
RB	Remaining Bhima
RDI	Reconnaissance Drought Index
RDI	Reclamation Drought Index
SB	Sina-Bori-Benetura
Sd	Drought severity

SMDI	Soil Moisture Drought Index
SMDI	Soil Moisture Deficit Index
SMI	Soil Moisture Index
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
SR	Spearman’s rho
SRI	Standardized Runoff Index
SRI	Standardized Runoff Index
SSI	Standardized Soil moisture Index
SWI	Standardized Wetness Index
SWSI	Surface Water Supply Index
te	Drought termination time
ti	Drought initiation time
TWS	Terrestrial Water Storage
UB	Upper Bhima (Up to Ujjani)
UKE	Upper Krishna (East)
UKW	Upper Krishna (West)
W.R.D	Water Resource Department
WMO	World Meteorological Organization
x	amount of precipitation
Z	standard normal random variable
α	shape factor
β	scale factor
g(x)	Gamma distribution

CHAPTER 1

INTRODUCTION

1.1 General

Drought is acknowledged as a significant natural disaster which leads to food, fodder and water shortages along with the destruction of the vital ecological system. Drought is a phenomenon associated with scarcity of water due to delay in rainy season and/or reduction in "Normal" rainfall. Drought is accompanied with unusually dry weather due to deficiency of rainfall which affects hydrological balance in the area. It brings misery to large sections of the population and habitat.

The occurrence of drought is a normal cycle of climate like other extreme climatic events, which is inevitable (Wilhite, 1993). Confusion among stakeholders exists between drought and aridity as the indications are same. Aridity is a long-lasting climatic feature of an area associated with low rainfall and humidity accompanied by high temperature. On the other hand, drought is a brief climatic feature of the area when water availability is considerably below normal value. Droughts can be experienced anywhere such as areas having little or high rainfall or temperature regime. While considering the drought, it is just not enough to consider total precipitation but the timing of occurrence (delayed starting in principal crop season) and the efficacy (i.e., an intensity of rainfall, an occurrence of rainfall events) of the rains is necessary to be considered.

Drought is an environmental disaster which has a concern for hydrology, environment, ecology, meteorology, geology, and agricultural scientists. The surface as well as groundwater resources are affected by drought and can lead to reduced-productivity as well as crop failure, reduced water supply, declined water quality, reduced power generation, disturbed riparian habitations, suspended entertaining events, and economic as well as social events (Riebsame, Changnon, & Karl, 1991). Drought is a natural hazard having the negative effect on society and environment which is intensified by increasing water demand (Mishra & Singh, 2010). The demand of water has been increased many folds to cater a growing population in developing countries and for maintaining living standards as well as for recreation in the developed countries. The rise in conflicts for water sharing has increased amongst urban population (drinking and domestic use), expansion of agriculture in rural sector (livelihood and food security), generation of power (hydropower and thermal power plants), and industrial sectors (processing and cleaning). The conflicts for water sharing between countries, states, regions, and districts had made people enemy of each other. The situation gets worsened in drought period when limited water resources get depleted faster than rejuvenation. Also, water scarcity is added by factors, such as water contamination, a variation of rainfall pattern due to climate change, etc. Drought assessment with regard to availability of fresh water is critical in the management of water resource which requires understanding different concepts and properties of droughts.

Climate change is acknowledged as the foremost threat in the twenty-first century. The seasonal and inter-annual spatial and temporal variability of rainfall in a changing climate scenario is vital for water resource management in a river basin. Freshwater availability is likely to decrease in many river basins due to climate change (Gosain et al., 2006). A number of studies from all over the world are increasingly paying attention to drought detection, and severe droughts that may have resulted from climate change. The meteorological drought conditions change continuously with seasons depending upon rainfall amount and its spatial distribution.

Precipitation, in any of its form, is the only natural source of receiving moisture on the mainland from the sea and is an important link in the water cycle. Droughts are prolonged periods (months to years) of precipitation deficiency over a given region. Drought persists as long as scarcity of water is observed; the physical effect of drought terminates, once this moisture/ water deficiency is fulfilled.

Streamflow is the prime variable to evaluate droughts and it affects many activities such as irrigation, power generation and recreation. The reservoirs are generally used to control floods, hydropower generation, and assured irrigation. In the tropical country like India, where the rainy season is for meager four months; canal irrigation, streamflow, and groundwater are the sources of moisture during the non-rainy days.

1.2 Drought as a Natural Hazard

Climatic hazards originate with the processes that move air across the Earth's surface due to differential heating and cooling. Droughts occur due to complex hydrological processes (Mishra and Singh, 2010). Drought and famine have plagued urban agricultural societies since civilizations first developed (Bryant, E.A., 1991). Large numbers of people in the world are affected by drought which ranks first in terms of a natural hazard (Obasi 1994, Hewitt 1997, Wilhite 2000a). Drought is different from other natural hazards such as Tsunami, floods, hurricanes, earthquakes, volcanic eruption, fires in forests, and tornadoes, since drought it hard to determine when it begins and when it terminates.

Drought affects only the moisture retaining bodies like soil, vegetation, ponds, lakes and artificial water retaining structures. The physical effect of drought terminates, once this moisture/water deficiency is fulfilled. The deficiency may be fulfilled by groundwater, surface water supply from water surplus areas and finally by precipitation.

1.3 Role of definitions in the understanding of Drought

It is difficult to define drought in a single definition since various sectors are affected by it and also it has diverse temporal and geographical distribution. (Richard – R. Heim Jr, 2002). Due to the absence of precise definition which is widely accepted, confusion persists about the existence of drought and also its severity if it exists.

The drought characteristics differ significantly between regions such as the North American Great Plains, Australia, Southern Africa, Western Europe, and Northwestern India (Wilhite D.A and Buchanan-Smith, 2005). In some parts of the world, such as the North-East United States and Southern England, a drought may have more of an effect on urban water supplies than on agriculture. In tropical areas subject to monsoons, drought conditions occur each summer season. In most of tropical Australia, even in coastal regions, endure a rainless dry season lasting several months. Definitions need to be application specific because drought is largely defined by the user and how it may affect his or her activity or enterprise. The impacts of drought on crop yield may differ greatly for maize, wheat, soybeans, and sorghum because each is planted at a different time during the growing season and has different sensitivities to water and temperature stress at various growth stages (Bryant, E. A., 1991).

Drought is classified into five categories depending upon the hydrological variable used to define it (Mishra and Singh, 2010). Definition of Meteorological drought is the deficiency of precipitation over an area for a certain period. The definition of drought, including the period of rainfall deficit prior to the event, varies worldwide. In southern Canada, a drought is any period where no rain has fallen in 30 days. In Australia, drought is usually defined as a calendar year in which rainfall registers in the lower 10 percent of all the records (Bryant, E.A., 1991). Metrological drought in Britain is defined as precipitation for successive days is less than 1.0 mm. In Russia total rainfall not more than 5 mm for 10 days is considered as drought. In Bali, a period of 6 days without rain and in Libya annual rainfall that is less than 180 mm is considered as drought (Richard – R. Heim Jr., 2002). India receives about 75-90% of annual rainfall in south-west monsoon season. In India, Meteorological drought is considered if seasonal rainfall deficit is more than twice the mean deviation or if rainfall is less than 50 % of normal (Pai. et al., 2011).

Hydrological drought is correlated with an insufficient surface as well as subsurface water resources for water users in a given water resources management system

(Mishra and Singh, 2010). Hydrological drought is a result of reduced groundwater, lakes, reservoirs and stream flow. Precipitation shortfall due to meteorological drought results in the reduced surface as well as sub-surface flow, ultimately resulting into Hydrological drought. (Richard – R. Heim Jr., 2002).

Agricultural drought is a phenomenon related to crop failure due to the reduction of soil moisture below the wilting point. Crop water demand is the function of the growth of a plant, soil properties as well as climatic parameters. Supply of moisture to the soil reduces due to meteorological or hydrological drought, which results in agricultural drought.

Socioeconomic drought links to the reduction in supply against an increase in demand of some economic good like water which originates due to Meteorological, Agricultural and Hydrological drought (AMS, 2004). Socio-economic drought is a consequence a weather-related shortfall in water supply when the demand for an economic good exceeds supply (Mishra and Singh, 2010).

Groundwater drought may be induced due to natural or manmade cause. Due to high evapotranspiration, soil moisture decreases in short of precipitation, which in turn causes lowering of groundwater recharge. Groundwater mining occurs when abstraction exceeds groundwater recharge. A careful balance between groundwater recharge and abstraction is required to avoid such droughts.

Ultimately, for developing drought definitions, the most important factors are the type of drought or nature of the deficit which includes hydrometeorological variables, such as streamflow, precipitation in addition to soil moisture and groundwater levels. Droughts can last from a month to few years, so as called as short term or long term drought. The severity of droughts can be identified using truncation levels such as percentiles, mean and median. On spatial scale droughts can be differentiated as local, regional or even national scale (Mishra and Singh, 2010).

1.4 Drought Impacts

Drought onset is a periodic, slow, and insidious. As a result, communities in drought-prone areas must be constantly prepared to insulate themselves from the probability of drought and finally, when overwhelmed, to ensure survival. The effects of drought go far beyond the immediate crisis years when communities and nations are trying to survive physically, socially and economically. Of all hazards, drought has the greatest impact beyond the period of its occurrence.

Since 1967, 50 percent people are affected by droughts out of the 2.8 billion people, who suffered from all natural disasters together. Total 3.5 million people lost their life by natural disasters, out of which 1.3 million souls were lost due to drought impacts (Obasi, 1994). Nearly 50 percent of the world's most populated areas are highly vulnerable to drought and more importantly, almost all of the major agricultural lands are located there (USDA, 1994).

Drought cannot be viewed solely as a physical phenomenon but it should be considered in relation to its impacts on society. Usually, policymakers' principal interest is the impact on people and the economy and the types of response measures that should be employed to assist the victims of drought. As drought impact doesn't cause structural damage to properties, quantification of the drought impact and the provision for drought relief is difficult for government machinery. Often the assessment of drought impacts and corresponding relief measures may be biased.

The key issue for implementing an efficient drought management strategy consists of identifying in advance measures to mitigate drought impacts on the water supply systems, the productive sectors and the environment.

1.5 Drought Index

It is difficult to identify and monitor droughts. Assessment of drought has been a challenging task among drought investigators and authorities, due to indistinctness of drought definitions. Initially, it was sufficient to consider that drought is just a deficiency in rainfall below the normal, with rainfall as the single variable. With the passage of time and advancement in hydrological applications, it found that rainfall is not strong enough to define the complex drought conditions, and assessment of droughts be augmented by other hydrometeorological variables such as streamflow, reservoir storage and groundwater that play significant roles in a drought incidence.

To quantify drought conditions in a region, drought indices have commonly used around the world. Drought indices provide the outline for evaluating drought parameters of interest. A drought index (DI) is a key variable to evaluate the drought effect and defining drought parameters such as spatial extent, duration, intensity, and severity. It is necessary that a drought variable should quantify the drought for multiple time scales at long-time series. Each region has unique hydroclimatic conditions and catchment characteristics. Indices are region specific as the meteorological conditions that result in drought are highly variable around the world. Reliable meteorological observations were available from 200 years before and from that time, all drought indices and drought definitions included drought variable in single or in combination with other meteorological elements (World Meteorological Organization 1975a).

Indices developed to measure the intensity of meteorological drought, were inadequate for agricultural, hydrological, or other applications. A number of different indices, which are been developed to quantify a drought, each has its own strengths and weaknesses (Mishra and Singh, 2010). Meteorological drought indices consider meteorological variables such as precipitation, temperature and evapotranspiration data, etc. They include Rainfall Anomaly Index (RAI; Van Rooy, 1965), Deciles (Gibbs and Maher, 1967), Bhalme and Mooley Drought Index (BMDI; Bhalme and Mooley, 1980), National Rainfall Index (NRI; Gommes and Petrassi, 1994), Standardized Precipitation Index (SPI; McKee et al., 1993, 1995), Effective Drought Index (EDI) (Byun and Wilhite, 1999), Reconnaissance Drought Index (RDI; Tsakiris et al., 2007) and Standardized Wetness Index (SWI; Liu et al., 2017).

Agricultural drought indices consider soil moisture, evapotranspiration and crop conditions, etc. They include Palmer Drought Severity Index (PDSI; Palmer 1965), Crop Moisture Index (CMI; Palmer, 1968), Soil Moisture Drought Index (SMDI; Hollinger et al., 1993), Crop-Specific Drought Index (CSDI; Meyer and Hubbard, 1995), Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) by Narasimhan and Srinivasan (2005) and Soil Moisture Index (SMI; Hunt et al., 2009).

Hydrological drought indices consider reservoir storage, stream flow and rainfall in combination. They include Surface Water Supply Index (SWSI; Shafer and Dezman, 1982), Standardized Runoff Index (SRI: Shukla and Wood, 2008), Reclamation Drought Index (RDI; Weghorst, 1996) and Regional Streamflow Deficiency Index (RDI; Stahl (2001). The use of an appropriate time step is important along with the type of DI used to quantify drought.

1.5.1 Standardized Precipitation Index (SPI)

McKee et al. 1993 and McKee et al. 1995, the researchers at Colorado State University designed the SPI in 1993, which was applicable to the water supply conditions of Colorado and as an addition to information provided by the PDSI and the Surface Water Supply Index (SWSI) (Hayes, M.J. et. al. 1999). The SPI calculated for a specific period at a certain location. It requires a long time series of monthly precipitation data with 30 years or more. By fitting a function to the observed data, the Probability Distribution Function (PDF) is determined. The cumulative distribution is then transformed using equal probability to a Normal distribution with a mean of zero and standard deviation of one so that the values of the SPI are really in standard deviation (Edwards and McKee, 1997). With the help of SPI, one can determine the drought or a wet event at a particular time scale for that location and is comparable to SPI at another location. Table 1.1 provides a weather classification based on SPI.

Table 1.1: Weather classification based on SPI

SPI values	>2	1.5 to 1.99	1.0 to 1.49	-0.99 to 0.99	-1 to -1.49	-1.5 to -1.99	< -2
Class	Extremely wet	Very wet	Moderately wet	Near normal	Moderately dry	Severely dry	Extremely dry

1.5.2 Surface Water Supply Index (SWSI)

Many indices were valid for certain specific application in that region only because the meteorological conditions that result in a drought vary from region to region. The indices developed to measure the Meteorological drought were inadequate for hydrological, agricultural, or any other applications (R Heim Jr., 2002).

The Surface Water Supply Index (SWSI) was introduced by Shafer and Dezman (1982) to quantify a Hydrological drought. The SWSI is calculated from monthly non-exceedance probability from historical records of streamflow, reservoir storage, precipitation, and snowpack. The SWSI was mainly developed to monitor irregularities in surface water supply resources. It was a worthy measure to monitor the impact of hydrologic droughts on domestic as well as industrial water supplies, irrigation and power generation. There was a certain limitation in using the SWSI. The factor weights used to calculate the SWSI vary with spatial scale as well as temporal scale due to variances in hydroclimatic conditions resulting in the SWSI having different statistical properties (Mishra and Singh, 2010).

1.5.3 Percent of Normal Precipitation (PNP)

The PNP is the simple meteorological index used widespread. Actual precipitation on a monthly, seasonal, annual, or water year period scale is compared to its Long Period Average (LPA) or Normal rainfall. (Wilhite, D.A., 2000). Statistical assessments of drought are based on identifying abnormal deviations from conditions established over a 30 year base period. It is widely assumed that for periods of 30 plus years normality can be accepted (Ormerod, W. E., 1976).

1.6 Spatio-temporal drought analysis

The Spatio-temporal analysis is also termed as Regional drought analysis, depends upon several factors; duration, severity, frequency and area on which impact of drought depends (Mishra and Singh, 2009). Comparisons of drought severity are possible with time and space (Palmer, W. C., 1965).

Spatio-temporal patterns at multiple time scales based on diverse thresholds can classify a region at different severity levels. Information on regional drought characteristics is critical and therefore, the regional or spatial behavior of droughts should be given importance and needs further research (Panu and Sharma, 2002; Rossi et al., 1992).Spatio-temporal drought analysis based on the combination of duration, severity, area and return period is critical for short and long-term water management.

1.6 Drought Trend Analysis

One of the commonly used tools for detecting changes in climatic and hydrologic time series is trend analysis. Trend analysis of the SPI and the PNP time series will reveal the drought trends at a particular station. As rainfall is the only input parameter for Meteorological drought analysis, trend analysis of seasonal and intraseasonal rainfall is essential to detect micro changes in climate change scenario. A number of statistical tests exist to assess the significance of trends in time series. Parametric and non-parametric analysis methods are frequently used for the trend analysis.

1.8 Drought Characteristics

Droughts can be differentiated in terms of their spatial characteristics. Drought characterization is essential for drought management operations (Zargar et.al. 2011). Drought characterization can be done by several hydrological and climatological parameters which should be properly understood to develop measures for mitigating drought impacts. The severely affected drought areas evolve gradually. The spatial pattern of drought severity and intensity vary as per time scales. Drought is a normal part of climate and its recurrence, like other extreme climatic events, is inevitable (Wilhite, 1993). It only concerns when a considerable area in a region is under drought. A regional drought is acknowledged when the sum of the areas affected by drought reaches a selected critical areal threshold. The most common areal threshold is 50 percent of the total area (Paulo and Pereira, 2006). Pai et al. (2011) classified as regional drought when 21 – 40 % of the area is under drought and it is termed as severe regional drought when the area under drought exceeds 40%. Patel et al. (2007) analyzed spatial patterns of meteorological drought and its severity using SPI in Gujarat State, located in western India. They found that the SPI at a 3-month time-scale was effective in capturing seasonal drought patterns over space and time.

The SPI also has certain advantages over the Palmer Drought Severity Index (PDSI). Hughes and Saunders (2002) analyzed extreme drought events for the Europe, based on the SPI values at time scales of 3, 6, 9, 12, 18, and 24 months and the PDSI for the period 1901 to 1999. Their analysis showed that the SPI is better in spatial standardization than the PDSI; also, the SPI is a simple and effective tool for the study of European drought. Paulo & Pereira (2006) distinguished droughts from other water scarcity region of Alentejo, Portugal. Their results showed that drought characterization with the PDSI and the SPI produce coherent information, but adopting the SPI is appropriate as it needs only precipitation data than data intensive PDSI. Understanding the relationships between multiple drought characteristics can be useful in developing measures for reducing the impacts of droughts.

1.9 Basin/sub-basin level drought analysis

The government of Maharashtra adopted the State Water Policy in 2003 as per the recommendations of National Water Policy – 2002 and Maharashtra Water and Irrigation Commission's Report. The objectives of the Maharashtra State Water Policy are to ensure the sustainable development and optimal use and management of the State's water resources, economic and social up gradation of the people of the state of Maharashtra and to maintain significant environmental values within fringe areas of a river system. The Maharashtra state Water Policy mentions that - 'To adopt an integrated and multi-sectoral approach to the water resources planning, development and management on a sustainable basis taking river basin/sub-basin as a unit.' A river basin/sub-basin as a unit should be considered during the water resources planning of the State, adopting the multi-sector approach. (W.R.D, G.O.M., 2005). Out of 308 lakh ha geographical area of the State, the cultivable area is 225 lakh ha. This geographical area is divided into five major river basins of Krishna, Godavari, Narmada, Tapi, and basin groups in Konkan. The Maharashtra Water and Irrigation Commission have proposed delineation of five river basins basically into 25 distinct sub-basins for the planning of water resources development in the State. Natural availability of water is the sole criteria for basin delineation. The sub-basins basic characteristics are governed by the hydrological regime, which is a function of rainfall distribution, draining area and the climate. Therefore, it is necessary to analyze drought at basin/ sub-basin level.

1.10 Scope of the Present Study

The Asian climate is dominated by the southwest monsoon. Indian economy is largely based on agriculture, as approximately 70% of the total population depends on it for their livelihood. About 75%-90% of the rainfall in India occurs during the four monsoon months (June- September) with large spatial and temporal variations over the country. The heavy concentration of rainfall within a short time results in devastating floods while; delayed and sparse rainfall results into drought conditions. The net sown area in the country is about 140 Mha, out of which the 68% of the area is susceptible to drought and 50% area is classified as severe drought-prone (Kamble et al., 2010).

The availability of fresh water for agriculture, drinking and domestic use for the large population, processing industries, and power sector has a significant influence in developing the economy of India, under changed climate scenarios. Food security, employment of human resource and power security are at the great stake due to possible adverse impacts of global climate change on water resources. Therefore, an assessment of water availability at various spatial and temporal scales is essential.

Knowledge of the probability of occurrence of droughts along with duration, intensity, and spatial extent is critical in the planning as well as management of scarce water resources. The comparisons of current droughts with historical droughts in terms of spatial and temporal variation can be done by drought indices and thus provide decision-makers a tool to measure drought events and reduce drought impacts. Assessment of historical droughts in the region with their impacts is of prime importance for water resource planning and their management.

It can be seen from the literature review that several studies have been carried out in India using the Percent of Normal Precipitation (PNP).Very few studies are done using the Standardized Precipitation Index (SPI). The definition of various drought categories based on the PNP does not take in to account the Coefficient of Variation (C.V) of the rainfall. However, the SPI does not have these drawbacks as it is a Normalized drought index, where the rainfall data are transformed into standardized normal distribution.

There is a difference in the drought climatology based on the PNP and the SPI. The PNP is biased by the aridity of the region while the SPI is not biased. The SPI can monitor wet and dry incidences at multiple scales. The main advantage of the SPI is it can compare drought severity at many locations irrespective of climatic differences between them.

With the development of surface water storage potential in areas having heavy rainfall, the water managers tend to use this surface water for drought-affected areas with scanty/below Normal rainfall. The transfer of surface water may be by gravity, lifting water by pumping and combination of pumping and then distribution by gravity. The water transfer may be within the river basin or inter-basin water transfer. The use of groundwater potential to combat drought also reduces the severity of the drought.

There is a rise in conflicts for water sharing between the donor basin/region and recipient basin/region. There is a need to develop a criterion to minimize these conflicts. One of the attempts is to develop Modified Surface Water Supply Index for any region of interest. Shafer and Dezman, (1982) developed the Surface Water Supply Index by calculating monthly non-exceedance probability from existing historical records of snowpack, reservoir storage, precipitation, and streamflow to monitor irregularities in surface water supply sources. In Modified Surface Water Supply Index (MSWSI), the snowpack component is not applicable in the study area. The MSWSI developed for a region can be linked to human and livestock population, cultivable land area, cropping pattern, industrial water demand, etc.

As the SPI is based on only precipitation, it cannot identify regions/areas which are supplied with surface water. The degree of severity of meteorological drought can be significantly reduced with the supply of the surface/groundwater. The drought mitigation measures to be adopted must be based on the actual water supply, to avoid conflicts and optimum utilization of scarce resources. There is a need to study the Spatial and Temporal variability of droughts using MSWSI. *This study will lead to the identification of the extent of water scarcity in the region regarding reservoir storage and streamflow during the drought period*.

1.11 Objectives of the Study

The objectives of this study are:

1. To analyze the Spatial and Temporal variability of droughts by the Standardized Precipitation Index (SPI), the Percent of Normal Precipitation (PNP), and the Modified Surface Water Supply Index (MSWSI) in the Krishna River Basin in Maharashtra.

2. To identify the drought-affected area by the combination of drought indices in the Krishna River Basin in Maharashtra.

3. To evaluate the drought indices for finding suitable and better drought index to detect and monitor droughts in the Krishna River Basin, under different time scales.

1.12 Organisation of the Thesis

The thesis is divided into eight chapters followed by the list of references and publications.

Chapter 1 Introduction; it provides an overview of key issues and rationale of this research and objectives, those form the basis of the study.

Chapter 2 Literature review; this chapter outlines the work carried out by previous researchers. A research gap is presented at the end of this chapter.

Chapter 3 Description of the study area; this chapter describes physiographical features of the study area, location and climate parameters such as rainfall, streamflow, reservoir, etc.

Chapter 4 Spatial and Temporal Drought Analysis**;** this chapter investigates the Meteorological drought, its spatial and temporal variation by the SPI and the PNP at multiple time scales over the Krishna basin in Maharashtra. Also, an attempt is made to find out which of these two indices is better for drought monitoring over the study area. Evaluation of the SPI is done on 1-, 3-, 6-, 9-, 12-, 18-, 24-, 36-, and 48- month time scale computed using long time series (1960-2012) of monthly precipitation data at 59 stations in the study area. The PNP is analyzed using Annual precipitation and Water-Year precipitation of the same time series. In the regional drought analysis, the spatial variations of percentage area under two regional drought events in the study area at multiple time scales are studied.

Chapter 5 Sub-Basin Wide Drought Analysis; this chapter evaluates a Hydrological drought using the Modified SWSI, Metrological drought using the SPI and the PNP for the Krishna river basin in the state of Maharashtra, India. The difference between the Modified SWSI and the original SWSI is to be used hydrological components for evaluating drought condition. The Modified SWSI is calculated with dam inflow, streamflow, and precipitation while the original SWSI is calculated with snowpack, streamflow, precipitation, and reservoir storage. The Krishna basin in Maharashtra was divided into five sub-basins using the climatological factors i.e. precipitation, streamflow and dam inflow. The impact of spatial division (05 sub-basins) and the impact of temporal division (06-time scales) were accomplished.

Chapter 6 Drought Trend Analysis; In this chapter, the drought trend of the Standardized precipitation index (SPI) at 1-, 6-, 12-, 24- and 48- month time scale, the Percent of Normal Precipitation (PNP) at Annual and Water-Year time scale and Seasonal rainfall (winter, pre-monsoon, monsoon and post-monsoon time scale) are computed using long time series (1960-2012) of monthly precipitation data at 59 stations in the study area. Similarly drought trend of the MSWSI and the SPI at 1-, 3-, 6-, 12-, 24- and 48- month time scale, the Percent of Normal Precipitation (PNP) at Annual , Water-Year time scale and Seasonal rainfall (pre-monsoon, monsoon and post-monsoon time scale) are computed using long time series (1972-2008) of monthly precipitation data at 05 sub-basins in the study area. The statistical significance at 95% confidence level as per the Mann-Kendall and the Sen's slope estimator is used for drought trend.

Chapter 7 Summary and conclusions; in this chapter overall summary and conclusions of previous chapters are discussed. The objectives achieved and future scope of work is overviewed.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Drought is the phenomenon related to the complex process of atmospheric circulation. It is a characteristic feature of a particular region which can be understood by studying historical meteorological and hydrological data in that region. Study of droughts for a particular area/region is a multi-dimensional exercise. Drought analysis is the process of quantifying drought at temporal and spatial scale. Attempts have been made to understand aspects of drought such as severity, intensity, spatial coverage, duration, recurrence period, time of occurrence, etc. Various tools and measures are available and being generated to know the drought phenomenon in a better way. Drought indices, trend analysis, the theory of 'Runs', spatial-temporal variability are some of the tools used in the study of drought.

2.2 Drought Index

A drought Index is normally a single value used for representing the severity of a drought, which is more useful than raw data in understanding the drought conditions over an area (Pai et al., 2011). Rainfall is the basic element that is responsible for creating, maintaining or removing drought conditions. Other important factors such as evapotranspiration, soil moisture, etc. are used for computation of various drought indices. The indices based on only rainfall data to compute meteorological indices are simple and outperform the complex drought indices such as the PDSI which requires multiple data and are difficult to generate (Oladipio 1985). Shahabfar & Eitzinger, (2013) assessed spatiotemporal dynamics of droughts in six climatic regions in Iran by evaluating and comparing six meteorological drought indices with remote sensing based drought indices. They concluded that meteorological drought indices show high performance in detecting and measuring drought intensity compared with other remote sensing based drought indices.

2.2.1 Percent of Normal Precipitation (PNP)

Definition of a drought as per the PNP is region specific. The U.S. Weather Bureau identified drought when the rainfall of 21 days or above is less than 30% of the Normal value (Henry, A.J., 1906). Ramdas (1950) defined a drought with reference to south-west monsoon rainfall in India when an area is having weekly rainfall less than or equal to 50 % of the Normal. As per Indian Meteorological Department (IMD), the season rainfall over the country is classified as a) Deficient (rainfall < 90% of LPA) b) Excess (rainfall > 110% of LPA) c) Normal (rainfall 90% to 110% of LPA). District-wide season rainfall is classified as a) Moderate meteorological drought (rainfall 50-74% of LPA) b) Severe meteorological drought (rainfall < 50% of LPA). Nationwide season rainfall is classified as a) Nationwide moderate drought (nationwide seasonal rainfall is deficient, and 21-40% of the area of the country is under drought) b) Nationwide severe drought (nationwide seasonal rainfall is deficient and more than 40% of the area of the country is under drought.). Parthasarathy et al. (1987) used this classification for drought analysis over different meteorological subdivisions of India.

A number of studies carried out in India to estimate the drought by using the PNP. The PNP can be applied to local, district, state/region, basin and national wide basis. Studies using the PNP were performed at the District scale, the Sub-division scale, and the National scale. But as per Pai et al. (2011) classification of areas/regions having similar climatic condition having low C.V for rainfall is useful. Choudhury et al. (1989) scrutinized numerous statistical features of drought incidences in India. Droughts occur more frequently in the arid or semi-arid region (Shanwad et al., 2010). To identify drought-prone areas as well as chronically drought-affected areas, the probabilities of occurrence of droughts in different meteorological sub-divisions have been worked out by Appa Rao G. (1991). He found out that West Rajasthan is most droughts prone with a return period of 30 months followed by Gujarat, the east Rajasthan, the western Uttar Pradesh, Tamil Nadu, Jammu & Kashmir and the Telangana with a return period of 36 months. Banerji and Chabra (1964) studied drought conditions using PNP data on the subdivision scale of the Telangana division in the state of Andhra Pradesh, India. They found that severe drought conditions coincided with the PNP values of less than 50%. Gore and Sinha Ray (2002) made an analysis of the variability of drought incidence during 1901-1998 at the district-wide spatial scale of Maharashtra, India. They identified 26 large scale meteorological droughts and out of them, worst 11 droughts when more than half area of the state was affected by drought.

Attempts were made for probabilistic studies of drought using the PNP. Sinha Ray and Shevale (2001) studied the probability of drought occurrence in the various sub-divisions of India for the period of 1875 to 1998. They found that probability of occurrence of drought to be highest in the Saurashtra & Kutch, followed by the Jammu & Kashmir and the Gujarat region. Guhathakurta P. (2003) studied the probability of droughts of 424 districts covering all meteorological sub-divisions of India for the period of 1988-2001. They showed that the subdivision Saurashtra and Kutch were maximum affected by droughts, where on an average 37.5 % of the districts were affected by drought per year. They also found out that the Rai Bareilly of east U.P., Sangrur of Punjab, Chamba of Himachal Pradesh and the Wynad of Kerala suffered heavily from drought almost every year. Gore et al. (2010) examined the probability of district-wide droughts based on southwest monsoon season by PNP for 319 districts over India, using data for the period of 1901–2000 and found the highest probability of drought over northwestern India and the lowest probability along the west coast and northeast India.

The simplicity and veracity of PNP in drought assessment as per available literature underlines the use PNP in drought assessment and planning of water resources.

2.2.2 Standardized Precipitation Index (SPI)

The SPI is used worldwide to assess and quantify Meteorological drought. All climatic regions can be compared by transforming the distribution of the precipitation record to a normal distribution (Hayes et al., 1999). It is popular since only precipitation data is used and its ability to calculate drought levels for different time scales. Hughes and Saunders (2002) analyzed drought climatology for Europe by the SPI at multiple time scales for the period of 1901–1999. They showed that the SPI is a simple and effective tool in analyzing European drought. Hayes et al. (1999) investigated the US 1996 drought and observed that the SPI has the added advantage of a multiple time scale, which was used for investigating temporal evolution of particular drought event. The SPI can measure drought at multiple timescales, i.e. 1-, 3-, 6-, 9-, 12-, and 48-months, but the interpretations changes according to its timescale. The shorter time scales up to 6 months describes drought events affects agricultural stage, while the longer ones up to 48 months are useful for water resources management (Heim, R., 2002, Mishra and Singh, 2010). The SPI can also be used as a drought indicator due to its lot of advantages over other drought indices and used to quantify the most type of drought (Mishra, A. K., & Desai, V. R. 2005, Cancelliere, A., et al. 2007).

The complexity of drought events underlines the necessity to assess and compare by different drought indices. Comparative studies of various drought incidences done to find out which is the best-suited drought index in that particular region. Hayes et al. (2000) compared the 1996 drought in the southern plains and south-western United States using the SPI and PDSI. The SPI was able to detect the drought, 1 month ahead of PDSI. Ntale and Gan (2003) analyzed the East African droughts by three drought indices: the PDSI, the Bhalme–Mooley Index (BMI) and the SPI. They found that SPI was more appropriate for monitoring East African droughts because it has fewer data requirements, can be computed at multiple time scale and adaptable to the East African climate, and was easy to interpret. Pai et al. (2011) studied the district-wide and nationwide climatology of droughts of different intensities for the S-W Monsoon over India using the PNP and SPI indices. They compared drought based on two drought indices (PNP and SPI), to find out the suitability of these two indices for drought monitoring over India. They found that the PNP and SPI are suitable for the nation-wide drought monitoring whereas the SPI is more suitable for the district-wide drought monitoring during the southwest monsoon season. The performance of two indices, Deciles, and the SPI for drought monitoring in the Hossein Abad Plain was done by Ghasemiet al (2011). They found the ability of the SPI to detect the onset of drought, its spatial and temporal variation consistently and it may be recommended for operational drought monitoring in the country, also the SPI was found to be more responsive to the emerging drought and performed better. Comparative studies of drought using the SPI and the Reconnaissance Drought Index (RDI) were done in Iran. Javad et al. (2010) calculated and compared the SPI and the RDI in the eight coastal stations of Iran. Precipitation, as well as potential evapotranspiration (PET), was used to calculate the RDI. Their results showed that there are very significant correlations (greater than 0.9) between the SPI and RDI in all stations of interest. They concluded that the SPI is enough to monitor meteorological drought in extreme coastal climates of Iran. Their study strongly proposes the SPI for detecting meteorological droughts in the extreme coastal climates of Iran. Zarch et al. (2011) computed SPI and RDI, for 3, 6, 9, 12, 18 and 24-month timescales in 40 meteorological synoptic stations in Iran. Drought severity maps for the SPI and the RDI were also presented in the driest year (1999–2000). Their results showed that the correlation of the SPI and the RDI was more considerable in the 3, 6 and 9 months than longer timescales.

Very often a time lag is observed between meteorological drought and the hydrological drought. Huang et al. (2017) examined the correlations between hydrological and meteorological droughts in the Wei River Basin, a typical arid and semi-arid region in China. They found that the propagation time from meteorological to hydrological drought vary from season to season. In summer is short, whilst that in winter is long. Hydrological features such as soil moisture, streamflow, and groundwater are sensitive to timescales as observed by Szalai et al. (2000). They showed that streamflow is highly correlated with 2- month time scale while for groundwater levels different time scales were correlated. They also concluded that agricultural drought was correlated best with SPI -2 and SPI-3 time scale.

Calculation of SPI for longer time scales (24 months or more) fitting of probability distribution may be biased due to the limitation of records (Mishra and Singh, 2010). Therefore long-term monthly precipitation data of at least 30 years is required for the calculation of SPI (Hayes et al., 1999). The effect of the length of record on the SPI calculation was investigated by Wu, H.et al. (2005) by examining correlation coefficients, the index of agreement, and the consistency of dry/wet event categories between SPI values derived from different precipitation record lengths. Their results showed that SPI values computed from different lengths of record are highly correlated and consistent when the gamma distributions of precipitation over the different time periods are similar. Hughes and Saunders, (2002) found the gamma distribution to provide the best model for describing monthly precipitation over most of Europe.

Using the SPI as a drought-monitoring tool will improve the timely identification of emerging drought conditions that can trigger appropriate state and federal actions (Hayes, et al.1999). The versatility of the SPI in drought analysis has been proved by various researchers for determining drought characteristics, trend analysis and Spatio-temporal analysis.

2.2.3 Surface Water Supply Index (SWSI)

Indices developed to assess meteorological drought were inadequate for the agricultural, hydrological, or other applications (R Heim Jr., 2002). Majority of reservoirs in the study area are located in the Western Ghats, a region with high rainfall. The East flowing rivers carry this water to the regions having low rainfall. The SWSI primarily monitor the abnormalities in the surface water supply sources.

Hence, it is a good measure to monitor the impact of hydrologic droughts on urban and industrial water supplies, irrigation and hydroelectric power generation (Mishra and Singh, 2010). The hydrological component in the SWSI (Shafer and Dezman, 1982) was replaced to modify the SWSI to suit the requirement in that region. The SWSI was modified and used for the drought outlook by Kim et al. (2012) by replacing the snowpack parameter with the groundwater in the Geum River basin in Korea. Kwon and Kim (2010) assessed the hydrological drought in South Korea in a semi-distributed form using an equation modifying the SWSI. Their results showed that more watershed division gives more detailed spatial information for a hydrologic drought of a watershed. In India no studies have been reported using SWSI, an attempt has been made to assess hydrological droughts using Modified Surface Water Supply Index (MSWSI).

2.3 Drought Trend Analysis

Trend analysis of droughts and its spatial and temporal variability in a changing climate is vital to assess climate-induced changes and suggest adequate water resources management strategies for the future. Trend analysis of the hydrologic variables is essential to detect the micro changes in climate change scenario. A number of statistical tests exist to assess the significance of trends in time series. The Parametric and non-parametric analysis methods are frequently used for the trend analysis. The Linear regression is a parametric method while the Man- Kendall Test and the Spearman's rho (SR) are the nonparametric methods. Mann (1945) formulated the Mann-Kendall test as a non-parametric test for trend detection and the test statistic distribution had been given by Kendall (1975) for testing non-linear trend and turning point. A non-parametric test is taken into consideration over the parametric one since it can evade the problem roused by data skew (Smith, 2000). The Parametric methods are powerful than the non-parametric methods, but they require data to be independent and normally distributed. However, the hydrologic variables like rainfall, streamflow and reservoir storage are usually positively (generally) or negatively skewed data with some extreme values. Thus, nonparametric tests are suitable for rainfall data structures (Hamed and Rao 1998). The Man-Kendall (MK) test is superior to the Spearman's rho (SR) test on detection of a trend in hydro-meteorological time series (Yue et al., 2002). The magnitude of the trend in the time series was determined using the Sen's estimator (Sen, 1968). The Sen's estimator was used for determining the magnitude of the trend in hydro-meteorological time series (Lettenmaier et al., 1994, Yue and Hashino, 2003, Partal and Kahya, 2006 and Pingale et al. 2014).

The trend analysis of the hydrologic variables is done by many researchers in various parts of the globe. Logan et al. (2010) examined the trend in SPI for a heavily agricultural region in the central U. S. Their analysis showed that the areas of the basin which receive less than 500 mm of precipitation annually are showing decreasing trends (becoming drier) over the twentieth century. The MK trend test was used by Huang et al. (2015) to analyze the trends of the Dry Spells in Inner Mongolia. They showed that summer is the only season showing strong trends for all the Dry Spells indices i.e. the summer droughts have become increasingly serious in Inner Mongolia. Nury & Hasan (2016) assessed the trend and variability of monthly rainfall, as well as SPI-3, using the MK tests in the northwestern region of Bangladesh, which is the drought-prone area. Their analysis showed no statistically significant monthly rainfall trends in the selected stations, whereas the seasonal rainfall trends showed a declining trend in Bogra, Ishurdi, Rangpur and Sayedpur stations respectively.

Data period plays a crucial role in the trend analysis. The trend of the SPI was investigated by Rahmat et al. (2016) for more than 100 years of data using the MK test to detect wet (increasing) and dry (decreasing) periods across Victoria, Australia. They repeated analysis using recent data from approximately half the data set between 1949 and 2011. Contrasting results from the original full data set analysis were revealed. Their work pointed out the importance of selecting the time series data length in identifying the trends. The SPI was computed at multiple-time steps and the

MK test was applied on monthly SPI time series for trend detection by Khadr, M. (2016) for the 22 meteorological stations in the upper Blue Nile River region. Their analysis showed statistically insignificant trends in SPI time series.

The trend analysis studies can also be done using the SPI at different time scales. Achugbu and Anugwo (2016) carried out the trend analysis using the MK trend test for the Kano, Nigeria, using a long-term 100 years rainfall data. SPI at 3, 6, 9, 12 and 24-month timescale was used to assess the short-term, seasonal, annual and long-term droughts. Since significant trend for the entire study period (1911-2010) was not detected, the 100 years series was sub-divided into 30 years overlapping time period. The period 1951-1980 and 1961-1990 revealed the highest number of the statistically significant downward trend. High slope values were more prevalent in the higher time scales.

Trend analysis studies were done in different regions of China. Yuan et al. (2016) analyzed the spatial distribution of dryness/wetness trends using the Mann-Kendall test in eight regions in China from 1961 to 2014.They indicated that the rainy season SPI was valuable for assessing dryness/wetness spatial and temporal variations. The SPI time series in the northwest and southwest showed increasing trends, while northeast China, south China, and Taiwan showed more than one upward/downward trend during the study period, and the SPI time series in central, east, and north China showed no change in trend.

In India, attempts have been made in the past to determine trends in the rainfall at national and regional scales. Rupa Kumar et al. (1992) analyzed monthly rainfall data for 306 stations distributed across India for change detection study. Out of the 306 stations considered, they found that 171 have shown increasing trends, with 18 of them being significant, and 135 have shown decreasing trends, with 13 of them being significant. Sen and Sinha Ray (1997) detected a declining trend in the drought-affected area over northwest India, central Peninsula and southern parts of the Indian

Peninsula. According to Srivastava et al. (1998), the heavy rainfall events during the southwest monsoon has shown an increasing trend, whereas a decreasing trend has been observed during pre-monsoon, post-monsoon and winter, seasons over certain parts of the country. Dash et al. (2004) found a decreasing trend in winter, pre-monsoon and post-monsoon rainfall over the most parts of India. Pai et al. (2011) examined the long-term trends in the district-wide SPI series (1901–2003) over India. Trend analysis of seasonal and intraseasonal rainfall at regional scales revealed the changing pattern of monsoon rainfall in India. The spatial pattern of the temporal trend in meteorological drought was studied by Das et al. (2016) using monthly gridded standardized precipitation–evapotranspiration index (SPEI) data of 1901–2008. The significant increasing trend of both drought duration and magnitude during the monsoon was found over parts of the eastern, central and north-eastern region of India, whereas the parts of the west coast, arid western region, and north India showed a significantly decreasing trend. The Mann–Kendall test for seasonal trend analysis by Reddy and Ganguli (2013) for droughts in western Rajasthan (India) showed the increase in a number of grids under drought during the study period.

2.4 Drought Characteristics

The identification, monitoring, and characterization of droughts help in the management of scarce water resource, which becomes critical in case of drought events. Drought indices are useful to characterize drought. In order to describe the regional drought phenomenon, three characteristics seem appropriate, namely duration, areal extent, and intensity of the water deficit. The temporal and spatial characteristics of droughts were investigated to provide a framework for sustainable water resources management in a semi-arid region (Kim et.al.2002). Drought characterization is useful for the water resource management in the basin. Drought frequency of short duration will affect the agricultural production in the basin, whereas the drought of high severity with a small duration will affect the hydropower generation. The whole water cycle and consequently the resources in the basin will be affected if high severity drought with longer duration persists in the basin.

The ‘Run theory’ was proposed by Yevjevich (1967) to define the drought characteristics and applied by Sirdas and Sen (2003) for determining the drought characteristics in Turkey. Paulo and Pereira (2006) used the ‘Run theory’ to distinguish droughts from other water scarcity regimes to have a common understanding of the general characteristics of droughts as hazards and disasters. Drought characteristics in the Awash River Basin of Ethiopia based on meteorological and hydrological variables were analyzed by Edossa et al. (2010). The SPI was used for temporal and spatial analyses of meteorological drought and the theory of runs was used to define hydrological drought by considering stream flow as the drought indicator. Analysis of the relationship between meteorological and hydrological drought indices in the basin showed that occurrence of hydrological drought event at Melka Sedi stream gauging station lags meteorological drought event in the Upper Awash on average by 7 months.

The SPI is versatile drought index to quantify most of the climatic conditions. The SPI provides a simple and easy to interpret approach for characterizing drought because it uses a probabilistic scale suitable for spatial comparisons (González and Valdés, 2006). Lana and Burgue~no (1998) characterized spatial and temporal extreme droughts in northeast Spain and concluded that the spatial and temporal characterization of their extreme episodes contributes to a better understanding of drought and its consequences. Masud et al., (2015) characterized drought events in terms of drought severity and duration on the basis of two drought indices, the SPI and the Standardized Precipitation Evapotranspiration Index (SPEI) of the Saskatchewan River Basin (SRB) that spans southern parts of Alberta, Saskatchewan and Manitoba, the three Prairie Provinces of Canada. They found that the areas characterized by higher drought severity are also associated with higher drought duration. The areas characterized by longer drought duration were dominated by more severe droughts, an indication that both drought severity and duration are positively correlated.

Hisdal and Tallaksen (2003) calculated meteorological and hydrological drought characteristics in Denmark, by deriving the probability of an area affected by a drought of a given severity. A comparison of drought characteristics showed that stream flow droughts are less homogeneous over the region, less frequent and last for longer time periods than precipitation droughts. Tallaksen et al. (2009) examined drought propagation at the catchment scale using spatially aggregated drought characteristics using monthly time series covering the period 1961–1997 for the Pang catchment, UK. Three catchment scale drought characteristics were considered in this study: drought duration, average area covered, and an average deficit over the total area. Their study revealed relatively large differences in the spatial and temporal characteristics of drought for the different variables.

Temporal characteristics of meteorological droughts i.e. drought intensity, areal extent and recurrence frequency were analyzed by Kasei et al. (2010) by using the SPI for a time series between 1961 and 2005 from 52 meteorology stations across the Volta basin. Using this analysis the severity of the historical droughts of 1961, 1970, 1983, 1992 and 2001 that occurred in the region was assessed and their intensity, areal extent and return periods were obtained. Santos et al. (2010) analyzed droughts in mainland Portugal based on monthly precipitation data, from September 1910 to October 2004, in 144 rain gauges distributed uniformly over the country. They characterized the drought events by means of the SPI applied to different time scales. Li .et al. (2012) applied SPI to analyze annual drought index in Huaihe River Basin using the precipitation data of nearly 50 years (1961-2010) of 35 meteorological stations. Their results showed that the frequency and areas of drought in Huaihe River Basin reduced along with an increase in the intensity of drought at the beginning of 21st Century. The spatial and temporal characteristics of meteorological droughts were analyzed by Lorenzo-Lacruz and Morán-Tejeda (2016) in the Balearic Islands (Spain) using the SPI of 12 months scale calculated for each of the 50 precipitation series at from 1974 to 2014. Khadr, M. (2016) characterized the temporal and spatial characteristics of meteorological drought in the upper Blue Nile basin to provide a framework for sustainable water resources management. Analysis of historical droughts was undertaken by converting observed monthly precipitation records (1960–2008), for 22 meteorological stations, to the SPI.

2.5 Spatio-temporal drought analysis

The overall impact of a drought depends on several factors; severity, frequency, area, and duration which are essential for Spatio-temporal analysis or in other words regional drought analysis (Mishra and Singh, 2009). In a regional drought analysis, Spatio-temporal patterns were investigated at different scales based on different thresholds and the region classified based on different severity levels. Information on regional drought characteristics is critical and should be incorporated in strategic short as well as long-term water resource management and therefore, one of the areas needing further research is the regional or spatial behavior of droughts (Rossi et al., 1992; Panu and Sharma, 2002). Meteorological drought events occurring in Bangladesh were analyzed by Dash et al. (2012) by calculating SPI and PDSI for the period 1961–1990. They observed that regional drought analysis provide better results as compared to the point analysis. The regional analysis able to detect about 80 % of the drought events occurred during the study period. Shorthouse and Arnell (1997), Tallaksen et al. (1997), Adler et al. (1999), and Stahl and Demuth (1999) have shown that meteorological and hydrological droughts at regional scales were determined by large-scale atmospheric circulation anomalies. Within reasonable limits, time and space comparisons of drought severity are possible (Palmer, W. C., 1965). Bewket and Conway (2007) analyzed rainfall variability in the drought-prone Amhara region of Ethiopia, both in terms of spatial and temporal scale and found high levels of spatial variability at sub-regional scales in Ethiopia.

Sigdel and Ikeda (2011) used monthly mean precipitation data for a period of 33 years to produce the SPI for the spatial pattern and temporal progression of the drought events with the time scale of 3 months (SPI-3) and 12 months (SPI-12) as they are applicable for agriculture and hydrological aspects, respectively. They observed 9 %

of the area covered by moderate drought and 5% of the area covered by severe and extreme drought with respect to SPI-12. They also observed that droughts were more frequent for SPI-3 and of more duration for SPI-12. The spatiotemporal variability and trends of droughts across Bolivia between 1955 and 2012 were investigated by Vicente et al. (2015) using two climate drought indices: the SPI, and the Standardized Precipitation Evapotranspiration Index (SPEI). They found that the average drought conditions across the country showed a temporal behavior mainly characterized by decadal variations.

Droughts of less duration are more frequent, while return period of large duration drought is more. Soule P.T. (1992) examined patterns of drought frequency and duration based on multiple definitions of drought events, using data from three Palmer indices [hydrologic drought index (PHDI), drought severity index (PDSI) and monthly moisture anomaly index] in the contiguous United States. He observed that near-normal events were more persistent in the extreme west/south-west (California and Arizona) than any region of the United States. Min et al (2003) investigated the spatial and temporal relationships of drought occurrence and intensity between Korea and East Asia by the SPI, calculated from monthly precipitation data from 1951 to 1996. They found that the frequency of occurrence of droughts in Korea has significant time intervals of 2–3 and 5–8 years and has been increasing since the 1980s. Hisdal et al. (2001) evaluated Pan-European dataset of more than 600 daily streamflow records from the European Water Archive (EWA) and detected spatial and temporal changes in hydrologic droughts. They concluded that there is no clear indication that stream flow drought conditions in Europe have generally become more severe or frequent in the time periods studied. Livada and Assimakopoulos (2007) used the SPI to detect drought events in spatial and temporal basis using monthly precipitation data from 23 stations well spread over Greece and for a period of 51 years. They concluded from the estimation of the SPI on 3-, 6- and 12-month time scales that the frequency of mild and moderate drought conditions is approximately of the same order of magnitude over the whole Greek territory. Logan et al. (2010)

examined the change in precipitation from 1900 to 2006 on a regional scale over a portion of the Central United States by using the SPI at several time scales ranging from 1 to 12 months. No difference in drought frequency patterns across the region was observed by them. Ndehedehe et al. (2016) employed SPI, Standardized Soil moisture Index (SSI), and Terrestrial Water Storage (TWS) derived from Gravity Recovery and Climate Experiment (GRACE) into spatial and temporal patterns over the Lake Chad basin. Drought analysis with the SPI shows that drought persistence is higher on a longer time scale while on short time scales drought becomes more frequent.

Droughts are the characteristic feature of a region. Spatial and temporal patterns of occurrence of droughts vary with/within a region and due to climate change. Spatial and time behaviors of rainfall shortage and excess were analyzed by Lana et al. (2001) for Catalonia (NE Spain) using a database obtained from 99 rain gauges with monthly totals collected from 1961 to 1990. They concluded that the SPI offers the best picture of monthly rainfall shortage and excess patterns. The differences in spatial patterns of drought over a range of timescales were analyzed by Vicente-Serrano, S. M. (2006) using the SPI calculated over timescales of 1, 3, 6, 12, 24 and 36 months in the Iberian Peninsula. He showed that the spatial patterns and time scales of drought indices may differ greatly and that the spatial behavior of the index, when calculated for long time scales, is not coherent. Six meteorological drought indices including PN, SPI, CZI, MCZI, Z-Score and I were compared and evaluated by Shahabfar and Eitzinger (2013) for assessing spatiotemporal dynamics of droughts in six climatic regions in Iran. Their research concluded that more climatic data including precipitation on a temporal and spatial scale is required to assess the results more accurately.

The study done in the Contiguous United States and the nine climatologically homogeneous regions by Ganguli and Ganguly (2016) found that spatial coverage of extreme meteorological drought in the recent years (post-2010) exceeds that of the iconic droughts of the 1930s (the Dust Bowl era), and the 1950s. Their results were in contrast with trends in spatial variance that does not exhibit any statistically significant trend. Mercado et al (2016) calculated at different time steps the drought indicators: SPI, Standardized Precipitation Evaporation Index (SPEI), Evapotranspiration Deficit Index (ETDI), Standardized Evapotranspiration Deficit Index (SEDI) and Standardized Runoff Index (SRI) of a catchment located in the southeast of Mexico. Their results showed that meteorological drought indicators did not identify all drought events for the time steps of 1 and 3 months. For 3-, 6- and 9-month time steps, meteorological drought indicators tend to identify the onset with a lag. For long-time steps of 12 and 24, the use of agricultural and hydrological droughts indicators was recommended, since these indicators can identify prolonged drought periods. Their results suggested that for a better monitoring of drought in a catchment, use of not only meteorological drought indicators but also hydrological and agricultural ones are important in order to identify drought events and their Spatio-temporal evolution.

In Asia, studies related to spatiotemporal analysis were done. Patel et al. (2007**)** analyzed the spatial patterns of meteorological drought and its severity using the SPI in the Gujarat State, located in western India. They found that the SPI at a 3-month time-scale was effective in capturing seasonal drought patterns over space and time. Parker et al (2009) explored the usefulness of the SPI to spatiotemporal variability in meteorological drought at seasonal scale in arid to semi-arid parts of Gujarat, India. They found that the SPI at a 3-month time-scale was effective in capturing seasonal drought patterns over space and time in Gujarat and further concluded that 3-month SPI of September was a good indicator of an anomaly associated with food grain production particularly in drought-prone areas. However, the 3- month SPI of September has not yielded a true picture of drought risk in Gujarat due to a longer time-scale and short period of rainfall data used to derive the SPI. The spatiotemporal variation and periodic change from 1961 to 2014 in eight regions in China were investigated Yuan et al. (2016). Their results indicated that the rainy season SPI was valuable for assessing dryness/wetness spatial and temporal variations. Mihajlović (2006) analyzed the meteorological drought (March 2003-April 2004) at 32 stations in the Pannonian part of Croatia by means of the SPI, at time-scales of 1, 3, 6, and 12 months. Their study indicates that the drought progression from start to its end can be monitored by SPI at multiple time scales.

A Spatio-temporal drought study was made in Europe. Hughes and Saunders (2002) analyzed extreme drought events for Europe based on SPI values at time scales of 3, 6, 9, 12, 18, and 24 months and PDSI for the period 1901 to 1999. Their analysis showed that the SPI offers a better spatial standardization than the PDSI; also, the SPI was a simple and effective tool for the study of European drought.

Spatial information can be well represented using a Geographic Information System (GIS). The vulnerability of central Iran's Zayandeh-Rood river basin to drought was assessed by Babaei et al. (2013), using multiple indicators such as the SPI, water demand, the PDSI and the Groundwater Balance and SWSI. Indicators' spatial information was categorized in layers prepared in the spatial domain using a GIS.

Various studies have evaluated different interpolation methods used for spatial analysis of droughts. Inverse Distance Weighting (IDW) and Ordinary Kriging (OK) are the most commonly used interpolation methods (Li and Heap, 2011). Carbone et al. (2008) assessed the suitability of interpolations methods for both the SPI and PDSI based on 316 stations in North and South Carolina (~ 12 stations per 10,000 km^2) and concluded that IDW and Kriging had similar accuracy and outperformed other methods. Similar results were obtained by Akhtari et al. (2009) for spatial interpolation at 43 stations in Iran (~22 stations per 10,000km^2) and Ali et al. (2011) for 27 climatic stations in the Boushehr province of Iran (~12 stations per 10,000 km^2). Khadr, M. (2014) used IDW and the Kriging methods for the spatial distribution of the SPI at 40 climatic stations in Germany and found that both methods revealed very close results.

Each interpolation technique has its advantages and disadvantages. The Kriging method assumes that there is a relationship between points that non-random and changes over space. There are issues of non-stationarity in real-world datasets with Kriging method, which may limit its applications (Afzali et al., 2016). The IDW method estimates the values based on their distance from observed data sites (Shepard, 1968). The IDW method gives relatively large weights data to sites close to the interpolation point. IDW is used when the data points are scattered but dense enough to represent local variations (Afzali et al., 2016). It is advantages IDW interpolation method since it is simple, intuitive and also it is fast for computing the interpolated values (Li et al. 2014). Mishra, & Nagarajan, R. (2013) used the IDW method to find out the areal extent of drought in the in Tel river basin, India. Ali et al. (2011) found out that IDW method is more appropriate for the spatial analysis of SPI index. Mozafari et al. (2011) showed that IDW method is more appropriate for the spatial analysis of SPI index in Boushehr province of Iran. Mishra & Desai (2005) used IDW approach for the spatial interpolation of precipitation over the Kansabati River basin. Thus, IDW is a widely used method to interpolate the point data and find out the spatial extent (Hay hoe et al. 2003; Luo et al. 2008; Murphy et al. 2010; Li et al. 2014).

2.6 Literature summary

Studies for drought indices implies that all drought indices use precipitation either singly or in combination with other meteorological elements, such as temperature, local antecedent moisture conditions, streamflow, dam inflow and groundwater levels. There are certain advantages of SPI over other Indices a) it is based on only precipitation b) it is versatile and can be calculated on any time scale, giving the capability to monitor conditions important for both hydrological and agricultural applications. This property helps to identify temporal dynamics of drought, including its progress and weakening, otherwise, it was difficult with other indices. c) For any location and timescale, the frequencies of the extreme and severe drought classifications are consistent. As per literature gamma distribution is best suitable for calculation of SPI at multiple time scales. Hence gamma distribution is used in this study.

A semi-distributed modified SWSI for hydrological drought evaluation based on the component of precipitation, stream flow, dam inflow, and groundwater levels, and is useful to evaluate hydrologic droughts with greater accuracy in terms of time and space.

Trend analysis of droughts and its spatial and temporal variability in a changing climate is vital to assess climate-induced changes and suggest adequate water resources management strategies for the future. Therefore an assessment of future water availability at various spatial and temporal scales is essential.

The characteristics of drought make it possible to identify and quantify drought and its deep impacts on economy, society, and environment. In strategic short as well as long-term water resource management, information on regional drought characteristics should be incorporated. Therefore, the regional or spatial behavior of droughts needs further research.

Spatial and temporal variation of drought at various time scales is essential for the proper assessment of droughts as sees from the literature review. Shorter time scales (up to 6 months) are used to assess agricultural droughts while longer time (up to 48 months) are used for hydrological droughts in water resource management. The IDW method can be used to interpolate the point data and find out the spatial extent. Due to advantages and limitations of each of the drought index, a combination of drought indices is necessary for spatiotemporal drought analysis. PNP, SPI, and MSWSI are supplementary to each other to overcome the limitations.

CHAPTER 3

DESCRIPTION OF STUDY AREA

3.1 Physiographic Description of Study Area

The Krishna river basin comes under semi-arid southern region. It ranks fourth considering annual discharge and fifth largest basin in terms of surface area. The basin lies between 73°17′ to 81°09′ east longitudes and 13°10′ to 19°22′ north latitudes. It extends 701 km in terms of length and 672 km in width. In the Krishna river basin, the predominant land is used for agriculture where the annual Krishna basin occupies eight percent of Indian Territory with a surface area of about 258,948 km^2. The basin area is shared by three states of erstwhile Andhra Pradesh (75,948 km2_ 30%), Karnataka (111,650 km^2_ 44%) and Maharashtra (69,425 km^2_ 26%). Out of total river length of about 1,400 km, Maharashtra shares 306 km while the remaining river flows through Karnataka (483 km) and at last Andhra Pradesh (306 km) (The Krishna basin report, India-WRIS, 2014). The study area under research is a part of the Krishna basin which comes under administrative boundary of the state of Maharashtra as shown in Figure 3.1.

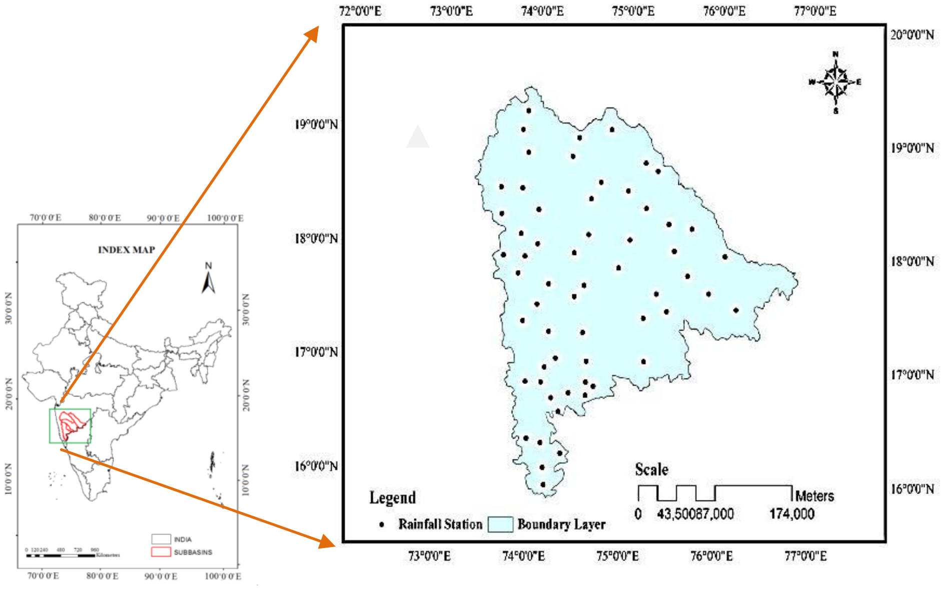


Figure 3.1 Krishna river basin in Maharashtra

3.2 Data and Materials Used

A range of spatially distributed data such as topographic features, hydrologic soil types, land use land cover and the stream network is needed to study hydrological regime. In addition to this, meteorological data such as temperature and hydrological data such as precipitation and stream flows are also necessary. Table 3.1 summarizes the input data.

Table 3.1: Input data and their sources for the Krishna river basin in Maharashtra

Data	**Source**	**Period**
Digital Elevation Model	ASTER GDEM (30m) Resolution	---
Streamflow (daily)	CWC, Hydrology Project, Maharashtra	1972-2008
Rainfall Data	IMD Pune	1960-2012
Reservoir Inflow- Outflow (monthly)	Water Resource Department, Maharashtra.	1972-2008

3.2.1 Digital Elevation Model Data

Digital Elevation Model (DEM) data has been used to delineate the Krishna Basin using 30-meter ASTER DEM available on the website. (http://www.jspacesystems.or.jp/ersdac/GDEM/E/4.html).

3.2.2 Streamflow Data

Monthly streamflow data is compiled from daily streamflow data and used for analysis.

Table 3.2 Gauge discharge station in the Krishna basin of Maharashtra

Sr.No	Gauge discharge Station	River	Sr.No	Gauge discharge Station	River
1	Sarati	Nira	6	Samdoli	Warana
2	Takli	Bhima	7	Arjunwad	Krishna
3	Wadakbal	Sina	8	Kurundwad	Krishna
4	Dhond	Bhima	9	Warunji	Koyna
5	Narasingpur	Bhima	10	Karad	Krishna

3.2.3 Rainfall Data

The monthly rainfall data compiled from the daily rainfall data of 59 rain gauge stations (Table 1: Appendix A) distributed in the study area is used for the analysis.

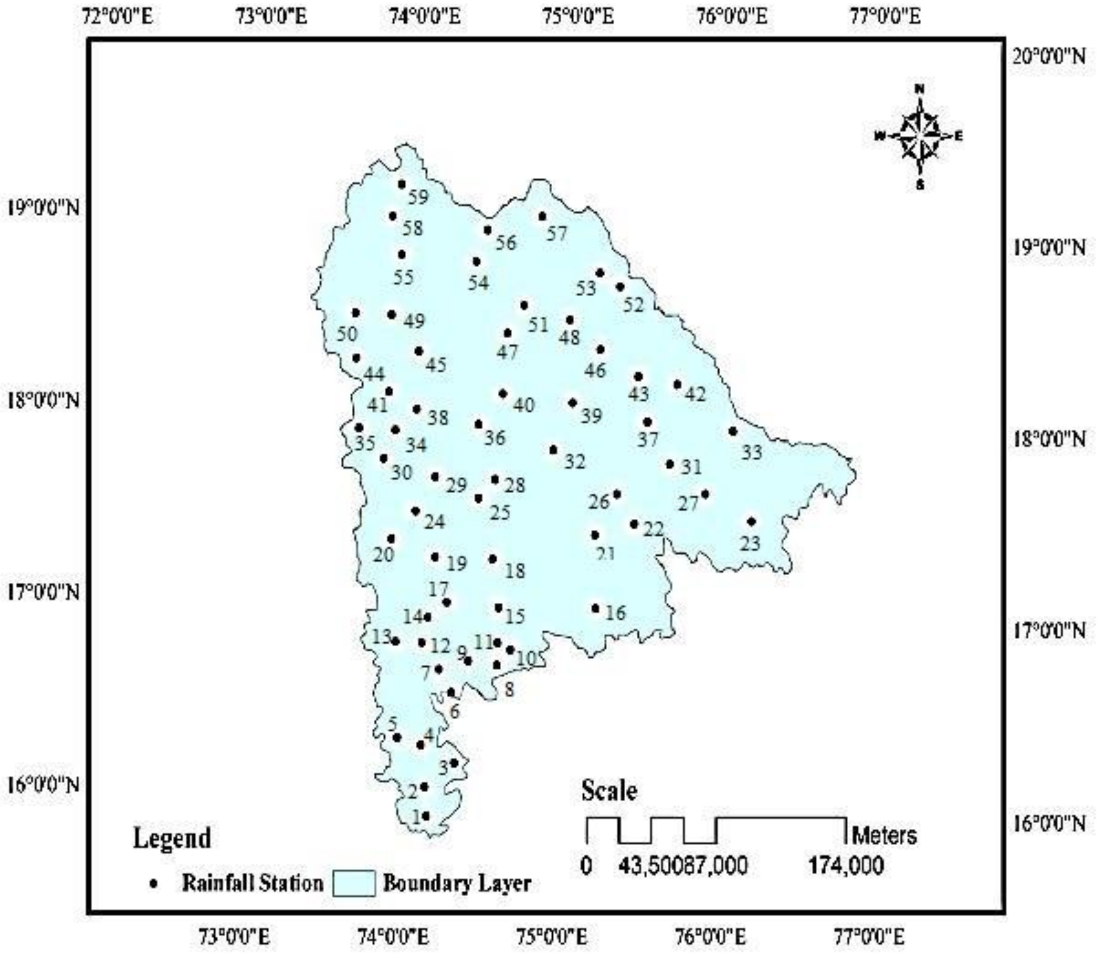


Figure 3.2 Rain gauge stations in the Krishna river basin in Maharashtra

1:Chandgad,2:Ajra,3:Gadhinglaj,4:Gargoti,5:Radhanagari,6:Kagal,7:Kolhapur,8:Shirol, 9:Hatkanangale, 10:Miraj, 11:Sangli, 12:Panhala, 13:Shahuwadi, 14:Shirala, 15:Tasgaon, 16:Jath, 17:Islampur, 18:Vita, 19:Karad, 20:Patan, 21:Sangola, 22:Mangalvedha, 23:Akkalkot, 24: Satara, 25: Vaduj , 26:Pandharpur, 27:Solapur, 28: Koregaon, 29: Dahiwadi Man, 30: Medha Jaoli, 31:Mohol, 32:Malshiras, 33:Tuljapur, 34:Wai, 35: Mahabaleshwar, 36: Phaltan, 37:Madha, 38:Khandala, 39:Indapur, 40:Baramati, 41: Bhor,42:Parenda,43:Barshi,44: Velhe, 45:Saswad,46: Karmala, 47: Dhond,48:Karjat, 49: Pune, 50:Paud,51: Shrigonda,52: Jamkhed, 53:Asti, 54: Shirur,55: Khed 56: Parner,57:Ahmednagar,58: Ghod Ambegaon,59: Junnar.

3.2.3.1 Rainfall Pattern in the Krishna Basin

Normal annual rainfall over the Krishna river basin in Maharashtra is about 859 mm. The S-W Monsoon starts in mid- June and withdraws by the mid- October. Out of 90% of annual rainfall received during the Monsoon months, 70% occurs during July to September. The monthly rainfall data compiled from the daily rainfall data from 59 rainfall stations in the Krishna basin in Maharashtra from 1960 to 2012 is used. The mean rainfall varies from 5610 mm at Mahabaleshwar situated in Western Ghats of Maharashtra where the river originates to 498 mm at Dhond in the plateau.

3.2.4 Reservoir Inflow-out flow

Monthly reservoir inflow-outflow of Major and Minor Irrigation projects is considered.

3.2.4.1 Major Irrigation Projects

Table 3.3 Major Irrigation Projects in the Krishna Basin river basin in Maharashtra

Sr.No.	Project Name	Sr.No.	Project Name	Sr.No.	Project Name
1	Koyna H.E. Project	9	Kadvi	17	Khadakwasla
2	Dhom	10	Dimbhe	18	Panshet
3	Kanher	11	Wadaj	19	Warasgaon
4	Warna,	12	Manikdoh	20	Temghar
5	Radhanagari	13	Yedgaon,	21	Vir
6	Dudhganga	14	Pimpalgaon Joge	22	Bhatghar
7	Patgaon	15	Chaskaman	23	Ghod
8	Kumbhi	16	Pawana	24	Ujjani
				25	Bhama Askhed

3.2.4.2 Medium Irrigation Projects

Table 3.4 Medium Irrigation Projects in the Krishna Basin river basin in Maharashtra

Sr.No.	Project Name	Sr.No.	Project Name	Sr.No.	Project Name
1	Tulshi	5	Jangamhatti	9	Mangi
2	Kasari	6	Mhaswad	10	Sina@ Nimgaon
3	Chikotra	7	Ekrukh	11	Wadivale
4	Chitri	8	Hingani Pangaon	12	Hingani Hatiz
				13	Kurnoor

CHAPTER 4

SPATIAL AND TEMPORAL DROUGHT ANALYSIS

4.1 Introduction

Droughts are regional in nature and often characterized by temporary departures from normal precipitation resulting in severe water shortage (Reddy and Ganguli, 2013). They can be differentiated by three characteristics- intensity, duration, and spatial variation. This chapter investigates the Meteorological drought, its spatial and temporal variation by the SPI and PNP at multiple timescales over the Krishna basin in Maharashtra. Evaluation of the SPI done on 1-, 3-, 6-, 9-, 12-, 18-, 24-, 36-, and 48- month timescales computed using long time series (1960-2012) of monthly precipitation data of 59 stations in the study area. PNP is analyzed using Annual precipitation and Water-Year precipitation of the same time series.

4.2 Methodology

4.2.1 Steps in calculating SPI

The SPI was designed by McKee et al., (1993, and 1995) to compute precipitation excess/deficits on multiple timescales. The brief procedure to calculate the SPI is as follows.

i) To determine the probability density function (PDF).

Computation of the SPI involves fitting a gamma probability density function, to a given frequency distribution of precipitation totals for a station. The alpha and beta parameters of the gamma probability density function are estimated for each station, for each timescale of interest (3 months, 12 months, 48 months, etc.), and for each month of the year.

The gamma distribution defined by its frequency or probability density function:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}} \quad \text{for } x > 0 \tag{4.1}$$

Where α > 0 is a shape factor, β > 0 is a scale factor, and x is the amount of precipitation. Γ (α), is the gamma function which is defined as

$$\Gamma(\alpha) = \int_0^{\infty} y^{\alpha-1} e^{-y}\, dy \tag{4.2}$$

Fitting the distribution to the data requires that α and β be estimated. Edwards and McKee (1997) suggested a method for estimating these parameters using the approximation of Thom (1958) for maximum likelihood as follows:

$$\hat{\alpha} = \frac{1}{4A}\left[1 + \sqrt{1 + \frac{4A}{3}}\right] \quad , \quad \hat{\beta} = \frac{\bar{x}}{\hat{\alpha}} \tag{4.3}$$

Where

$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n}$

n = number of precipitation observations

ii) Cumulative probability of an observed precipitation amount is computed.

The resulting parameters are then used to find the cumulative probability of an observed precipitation event for the given month and timescale for the station in question. The cumulative probability is given by:

$$G(x) = \int_0^x g(x)\, dx = \frac{1}{\hat{\beta}^{\hat{\alpha}}\Gamma(\hat{\alpha})} \int_0^x x^{\hat{\alpha}-1} e^{-x/\hat{\beta}}\, dx \tag{4.4}$$

Let $t = x / \hat{\beta}$, this equation becomes the incomplete gamma function:

$$G(x) = \frac{1}{\Gamma(\hat{\alpha})} \int_0^x t^{\hat{\alpha}-1} e^{-t}\, dt \tag{4.5}$$

Since the gamma function is undefined for x=0 and a precipitation distribution may contain zeros, the cumulative probability becomes:

$$H(x) = q + (1 - q)\,G(x) \qquad (4.6)$$

Where, q is the probability of zero precipitation. For larger timescales (like 3-, 6-, 9-, 12-, 24-month) the probability of monthly null precipitation is zero. So the errors in calculating the parameters α and β due to the monthly null precipitation do not affect the distribution at larger timescales.

iii) The inverse normal (Gaussian) function, applied to the cumulative probability, results in the SPI.

The cumulative probability, H(x), then transform to the standard normal random variable Z with a mean of zero and a variance of one, which is the value of SPI. Following Edwards and McKee (1997) and Hughes and Saunders (2002), the Z or SPI value is obtained computationally using an approximation provided by Abramowitz and Stegun (1965) that converts cumulative probability to the standard normal random variable Z:

$$Z = SPI = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad \text{for} \quad 0 < H(x) \leq 0.5 \qquad (4.7)$$

$$Z = SPI = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad \text{for} \quad 0.5 < H(x) \leq 1.0 \qquad (4.8)$$

Where:

$$t = \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)} \qquad \text{for} \ 0 < H(x) \leq 0.5 \qquad (4.9)$$

$$t = \sqrt{\ln\left(\frac{1}{(1.0 - H(x))^2}\right)} \qquad \text{for} \ 0.5 < H(x) \leq 1.0 \qquad (4.10)$$

$c_0 = 2.515517 \quad c_1 = 0.802853 \quad c_2 = 0.010328$

$d_1 = 1.432788 \quad d_2 = 0.189269 \quad d_3 = 0.001308$

McKee et al. (1993) used a classification system using SPI values as shown in Table 4.1 to define drought intensities

Table 4.1 Classification based on SPI values

SPI values	>2	1.5 to 1.99	1.0 to 1.49	-0.99 to 0.99	-1 to -1.49	-1.5 to -1.99	<-2
Class	Extremely wet	Very wet	Moderately wet	Near normal	Moderately dry	Severely dry	Extremely dry

4.2.2 Steps in calculating PNP

PNP is a modest form of determining the amount of precipitation at any region or location. It is effective when used for rainfall season for the climatologically similar region. It is the ratio of actual precipitation to Normal precipitation determined in percentage. PNP can be computed for a day, week, month, annual year (monthly precipitation totals from January-December), water year (monthly precipitation totals from June-May) and rainfall season. Table 4.2 shows the classification based on PNP.

Table 4.2**:** Classification based on PNP values

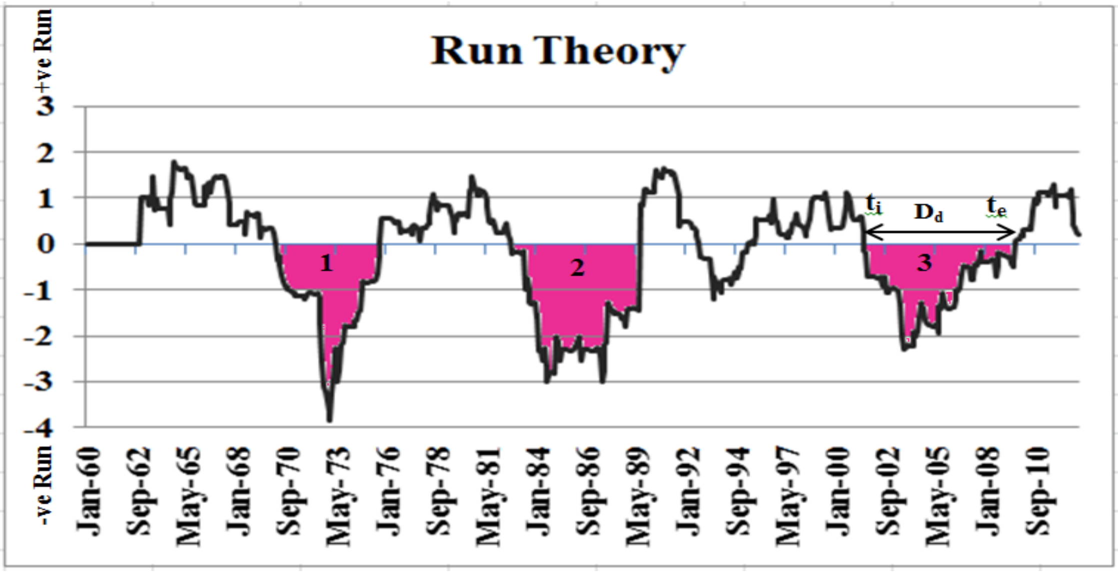
Season rainfall Classification	**Local drought**	**Regional drought**
No drought	>75% of LPA	0-10% of area is under local drought
Mild meteorological drought	----	10-20% of area is under local drought
Moderate meteorological drought	50-74% of LPA	21-40% of area is under local drought
Severe meteorological drought	<50% of LPA	>40% of the area is under local drought

The PNP was calculated by dividing actual rainfall by its long period average (LPA) or normal rainfall and multiplying by 100%.

$$PNP = \frac{P}{P_{Normal}} \times 100 \qquad (4.11)$$

4.2.3 Run theory

For analysis of drought, the information of the drought component is very significant. Historical drought events can be compared w.r.t duration, intensity, severity, spatial coverage etc. within the same or different region. Drought needs to be quantified for providing relief measures, prediction of losses etc. 'Run theory' was proposed by Yevjevich (1967), to identify and characterize drought events. Run Theory can be used along with other drought indices in identifying drought characteristics such as drought intensity, drought duration, and drought severity, as shown in Figure 4.1.



1. Drought with the highest intensity.
2. Drought with the highest severity.
3. Drought with the highest duration.

Figure 4.1: Characteristics of local drought events with the theory of Runs

A run is defined as a part of time series of drought parameter X_t, where all values are either below the selected truncation level of X_o is called either a negative run or vice-versa. According to Yevjevich (1967) and Dracup et al. (1980), a hydrologic drought event has major components listed below. (a) Drought initiation time (t_i): time at which the drought event begins i.e., the starting of the water scarcity. (b) Drought termination time (t_e): time at which the drought event ends i.e., the end of the water scarcity. (c) Drought duration (D_d): It is the time period between the initiation and termination of a drought event. (d) Drought severity (S_d): It indicates a cumulative deficiency of a drought parameter below the critical level. (e) Drought intensity (I_d): It is the average value of a drought parameter below a critical level. It is measured as the drought severity divided by the duration.

4.2.4 Inverse Distance Weighting (IDW)

Interpolation and GIS techniques were used to map the spatial extent of drought characteristics from the point data. IDW weights the influence of each SPI value by a normalized inverse of the distance from the rain gauge station to the interpolated point. It is assumed by IDW method that SPI value has more influence at the rain gauge station and it diminishes with distance. The SPI value of neighboring stations is also considered by the IDW approach. The IDW formula has the effect of giving data points close to the interpolation point relatively large weights whilst those far away exert little influence. The weight used the more influence points close to x_0 are given.

$$\hat{Z}(x0) = \sum_{i=1}^{n} z(xi)dij - r$$

Where x0 is the estimation point and *xi* are the data points within a chosen neighborhood. The weights (r) are related to distance by j which is the distance between the estimation point and the data points.

4.3 Results and Discussion

At different timescales, the SPI shows different weather conditions. Also for the whole year, the weather is not the same. The temporal variability of dry and wet conditions as per month at SPI-1 and SPI-3 are observed. The Run theory is used to obtain drought characteristics from Time series at multiple timescales. Local drought is classified at 59 stations for three major droughts by the SPI and PNP at Annual and

Water-Year timescale. The effect of drought on Kharip and Rabi crops is studied. The regional drought affects more than local drought. The Regional drought classification by the PNP and SPI was done. The Spatial variation of high-intensity drought (1971 to 1975) and high-severity drought (2000 to 2006) is analyzed by the SPI at multiple timescales. The Spatial maps showing the severity of 1972, 2003 and 2012 is prepared for understanding spatial variation of droughts. The Droughts were classified for various return periods from 1 year to 20 years also maps showing the spatial variation of the drought severity for various return periods is displayed. The drought-prone stations were identified and ranking of the stations are done as per the drought severity.

4.3.1 Weather classification at multiple timescales of the SPI

Weather conditions vary with the timescale. Figure 4.2 shows the weather classification in percentage by the SPI at multiple timescales for the Paud station. It is observed that extremely wet and moderately wet conditions are more at SPI-1 timescale. Very wet conditions are more at the SPI-48 timescale. Near normal conditions are more at SPI-3 timescale. The moderately drought conditions are more at SPI-36 timescale. The severely dry and extremely dry conditions are more at SPI-48 timescale. Similar results regarding weather classification were observed for other 58 stations in the study area.

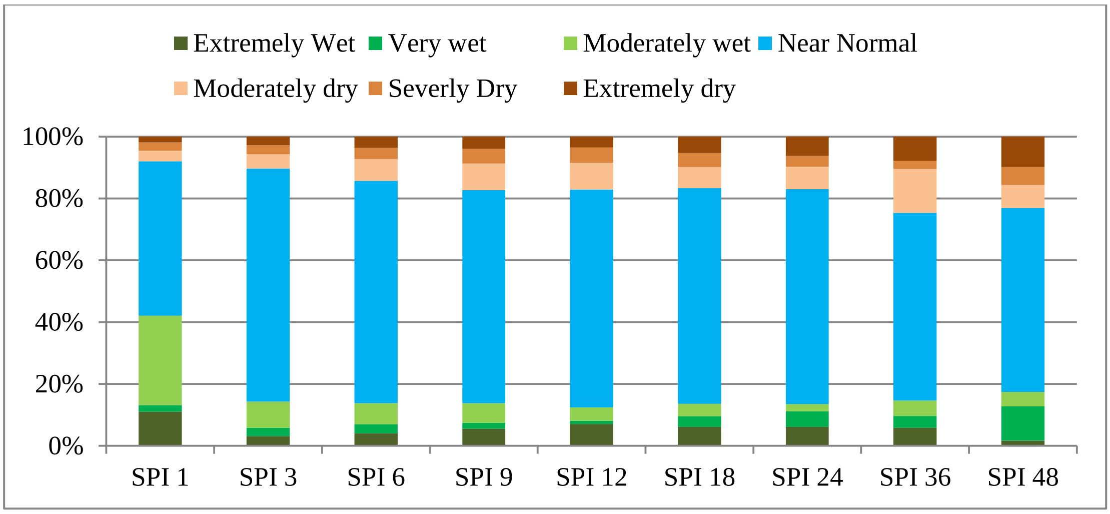


Figure.4.2: Weather classification of Paud station at multiple timescales

4.3.2 Frequency of Dry and Wet Months

The Indian weather can be broadly classified into four seasons: winter (January–February), pre-monsoon (March-May), monsoon (June-September), and post-monsoon (October-December). About 75%-90% rain occurs during monsoon season (June-September) and 10% to 15% during post-monsoon (October-December).The Indian cropping season is classified into two main seasons-(i) Kharif and (ii) Rabi based on the monsoon. The Kharif cropping season is from July-October during the south-west monsoon and the Rabi cropping season is from October-March (winter). The crops grown between March and June are the summer crops. Drought during sowing month or during critical growth periods reduces the yield and quality of the crops. The Month wide weather classification can help in managing water resources during the drought periods.

4.3.2.1 Frequency of Dry and Wet Months at SPI -1 timescale

The cumulative frequency of dry and wet months of the different drought class as per SPI-1 calculated at the Paud station for the period of 1960-2012 shown in Figure 4.3.

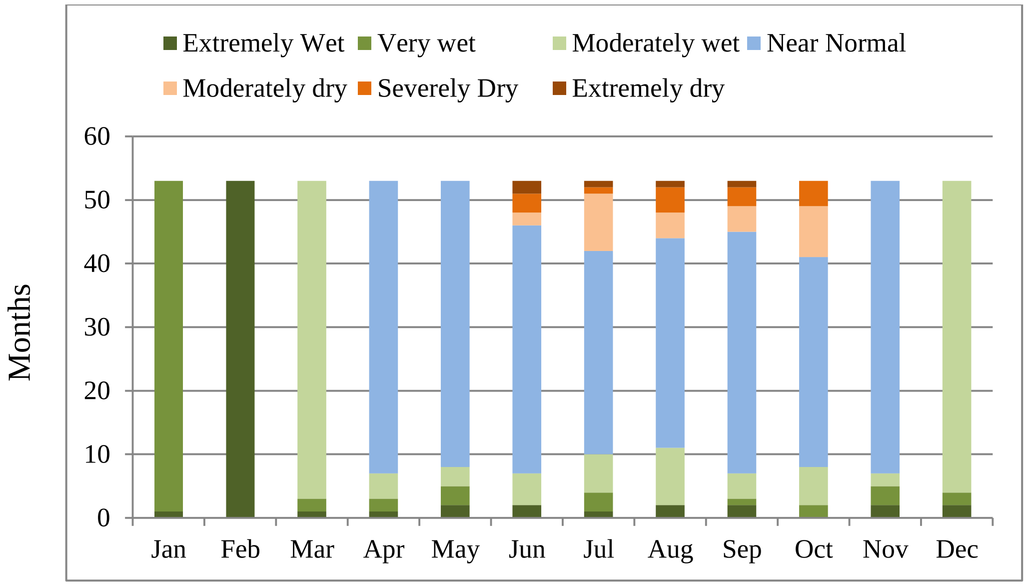


Figure.4.3: Frequency of Dry and Wet Months at Paud station by SPI-1 timescale

The results indicate that there were 47 dry months occurring in the study period, among which moderate dry conditions occurred in 27 months, severe dry conditions occurred in 15 months and extremely dry conditions occurred in 5 months. As for the occurrence of wet conditions in the study area, there were totally 277 wet months in the study period, among which moderate wet conditions occurred in 138 months, very wet conditions occurred in 70 months and extremely wet conditions occurred in 69 months. Figure 4.3 (b) indicates that even though rainfall is very scanty over Dec.-Mar, wet conditions are more as compared to other months. Dry conditions not observed on Jan. - May and Nov. - Dec. Similar results regarding SPI-1 timescale are observed for other 58 stations in the study area.

4.3.2.2 Frequency of Dry and Wet Months at SPI -3 timescale

The cumulative frequency of dry and wet months of different drought class as per SPI-3 calculated at the Paud station for the period of 1960-2012 shown in Figure 4.4.

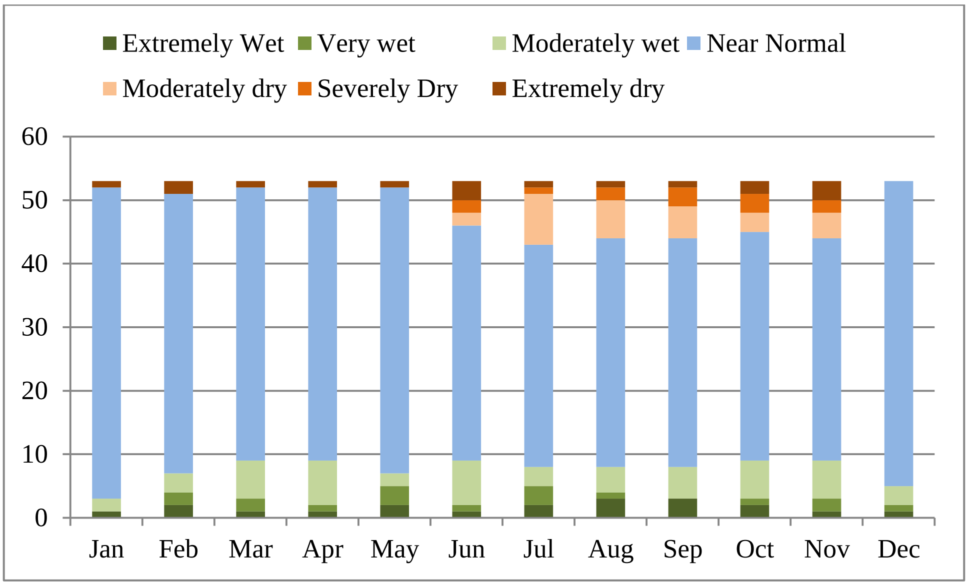
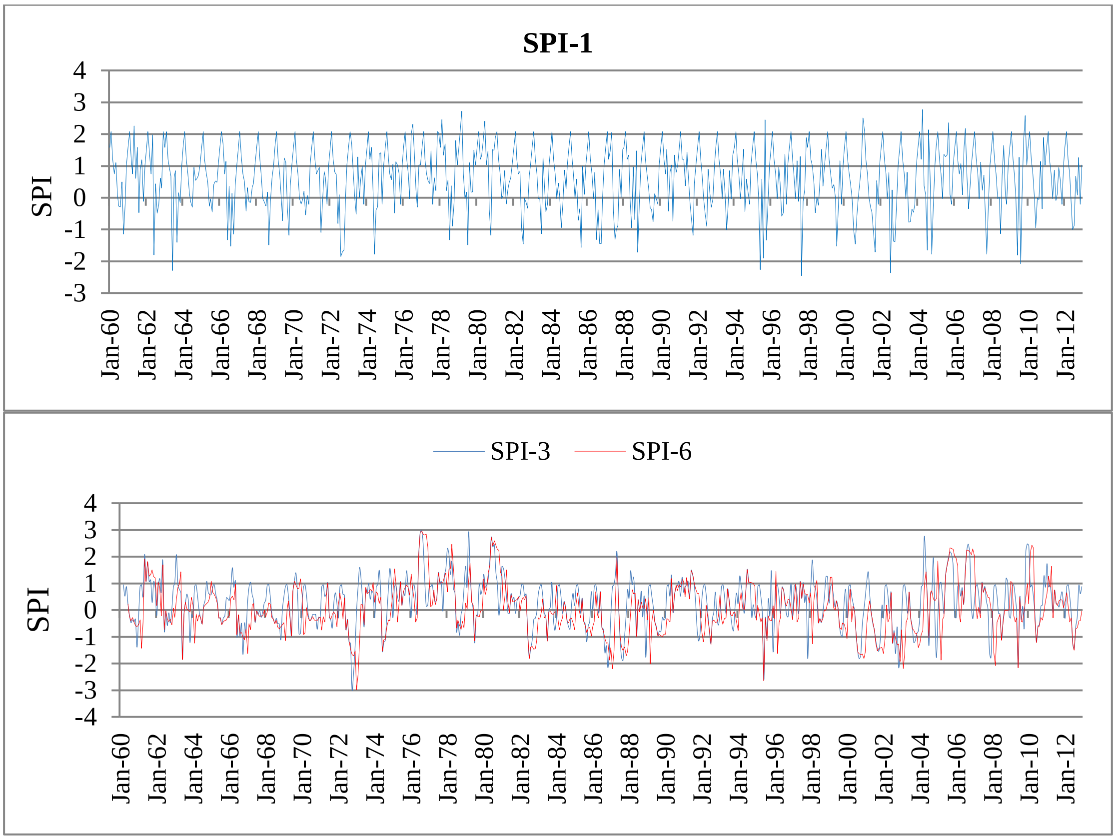


Figure.4.4: Frequency of Dry and Wet Months at Paud station by SPI-3 timescale

Results indicate that there were 66 dry months occurring in the study period, among which moderate dry conditions occurred in 30 months, severe dry conditions occurred in 18 months and extremely dry conditions occurred in 18 months. As for the occurrence of wet conditions in the study area, there were totally 91 wet months in the study period, among which moderate wet conditions occurred in 54 months, very wet conditions occurred in 17 months and extremely wet conditions occurred in 20 months. Results obtained by SPI-3 are consistent with actual conditions, whereas SPI-1 results show exaggerated wet conditions during December to March. Similar results regarding SPI-3 timescale are observed for other 58 stations in the study area.

4.3.3 Time series of the SPI at multiple timescales

A drought event is defined as a period in which the SPI is continuously negative and reaching a value of -1.0 or less (McKee et al., 1993). The event ends when the SPI becomes positive. Time series of SPI at any timescale is used to identify wet, normal and drought conditions at a particular station. The time series graphs on multiple timescales during 1960-2012 for the Paud stations are shown in Figure 4.5.



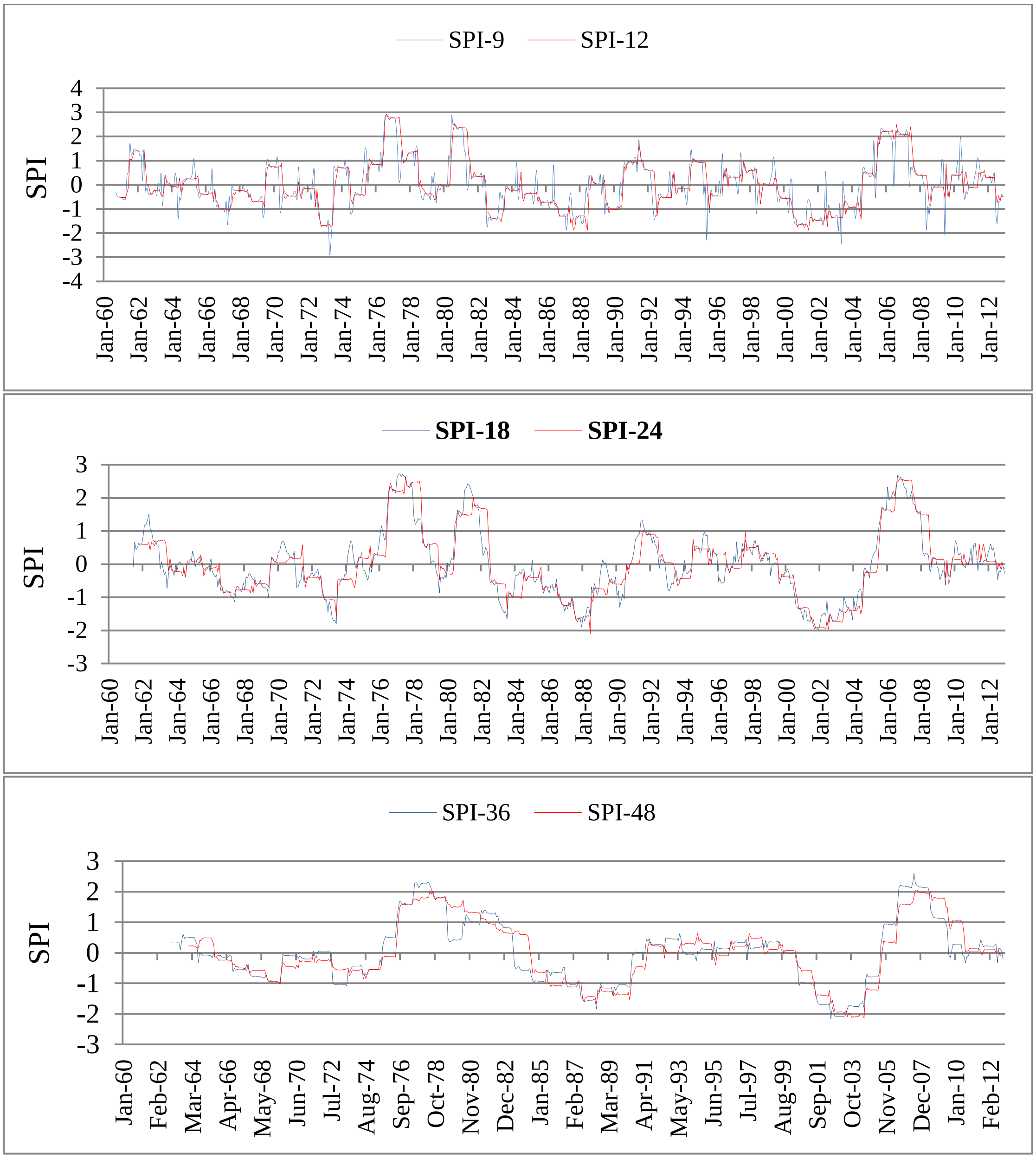


Figure 4.5: SPI time series at the Paud station at multiple timescales

Figure 4.5 shows the SPI time series of the Paud station from 1960 to 2012. On shorter timescales, (1, 3 and 6 months), the wet and dry periods are short and high frequency. These timescales indicate the soil moisture conditions and hence applicable for monitoring agricultural droughts. The SPI-1 of June is useful to monitor soil moisture required for sowing. At SPI-1 timescale, drought conditions observed from July to October. At SPI-3 timescale, drought conditions observed from

June to December. The SPI-3 of August and September indicates moisture conditions during harvesting and can estimate crop yield. The SPI-1 and SPI-3 monitor the Kharif crops while the SPI-6 and SPI-9 monitor the Rabi crops. At SPI-12 to SPI-48, droughts were less frequent but of longer duration. The time lag in drought initiation and termination observed from SPI-1 to SPI-48. Similar results are observed for other 58 stations in the study area. The drought characteristics at the Paud station for multiple timescales during 1960-2012 are shown in Table 4.3 and 4.4.

Table 4.3**:** Drought characteristics at the Paud station at multiple timescales

SPI series	Total drought severity	Number of drought incidences	Drought Duration (months)			Drought Intensity (I_d)			Drought Severity (S_d)		
			Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.
SPI 1	-82	39	5	1	2	-2.4	-0.4	-0.8	-5	-1	-4
SPI 3	-114	29	8	1	5	-1.8	-0.4	-0.8	-10	-2	-4
SPI 6	-178	30	14	1	7	-1.5	-0.3	-0.8	-15	-1	-6
SPI 9	-208	8	49	1	13	-2.1	-0.5	-0.9	-32	-2	-26
SPI 12	-213	8	60	11	32	-1.2	-0.5	-0.8	-71	-6	-27
SPI 18	-209	6	67	17	40	-1.1	-0.6	-0.9	-77	-10	-35
SPI 24	-188	3	99	39	70	-1.2	-0.6	-0.9	-82	-24	-63
SPI 36	-195	3	88	37	65	-1.3	-0.7	-1.0	-87	-25	-65
SPI 48	-232	3	131	62	92	-1.4	-0.5	-0.8	-87	-60	-77

Table 4.4**:** Drought characteristics at the Paud station at multiple timescales

SPI series	Number of drought months	Drought Lead Time (months)			Drought termination time (months)			Drought Return Period (months)		
		Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.
SPI 1	91	3	0	0.5	3	0	1	46	1	14
SPI 3	136	6	0	1.3	3	0	1	57	3	17
SPI 6	212	9	0	1.9	13	0	2	55	1	14
SPI 9	241	16	0	2.3	12	0	3	87	1	22
SPI 12	252	26	0	10.0	25	0	8	107	1	34
SPI 18	242	21	6	13.7	13	1	7	104	1	47
SPI 24	209	14	11	12.7	26	11	17	115	94	105
SPI 36	194	38	2	16.7	25	4	13	115	95	106
SPI 48	277	47	14	25.0	83	2	32	107	19	74

The analysis of different drought characteristics at the Paud station is as follows. i) Total drought Severity: It is low in SPI-1, medium in SPI-3 and high in SPI-6 to SPI-48. ii) Drought months: It is low in SPI-1, medium in SPI-3 and high in SPI-6 to

SPI-48. iii) A number of drought incidences: It is highest for SPI-1 and gradually decreased with increase in a timescale up to SPI-24.iv) Drought duration: Maximum and average drought duration is lowest for SPI-1 and it gradually increased with the timescale and is highest for SPI-48. v) Drought lead time: Maximum and average lead time is lowest for SPI-1 and it gradually increased with the timescale and is highest for SPI-48.vi) Drought termination time: Maximum and average termination time is lowest for SPI-1 and it gradually increased with the timescale and is highest for SPI-48. vii) Drought return period: Maximum, minimum and average drought return period is lowest for SPI-1 and it gradually increased with timescale and is highest for SPI-48 except for SPI-3. viii) Drought intensity: It is maximum for SPI-12 and minimum for SPI-48. Other SPI classes have intermediate values with no specific relation. Similar results are observed for other 58 stations in the study area.

4.3.4 Local drought classification by PNP and SPI

Drought analysis by the PNP was performed under two timescales namely; water year (June to May) and annual year (January to December). The SPI analysis was done using SPI-12 timescale for the month of May and December. The SPI-12 of May resembles water year (June-May) and SPI-12 of December resembles annual year (Jan-Dec) of the PNP index. Three severe droughts in Maharashtra viz., 1972, 2003 and 2012 were analyzed by PNP and SPI and the results are shown in Table 4.5

Table 4.5**:** Local drought classification as per PNP and SPI-12

Drought Classification of rain gauge stations	SPI-12					PNP				
	1972 Dec.	1973 May	2003 Dec.	2004 May	2012 Dec.	1972 Annual	1972-73 Water Year	2003 Annual	2003-04 Water Year	2012 Annual
Moderate	7	6	11	14	17	21	21	32	35	28
Severe	14	12	16	26	15	34	33	21	17	12
Extreme	34	36	24	10	3	--	--	--	--	--
Total stations	55	54	51	50	35	55	54	53	52	40

From table 4.5 it is observed that i) The SPI has 3 classes (moderate, severe, and extreme) of drought as compared to 2 (moderate and severe) classes of PNP. ii) A number of moderate drought locations as per PNP is more than that of SPI-12. iii) For 1972-73 drought, moderate, severe and extreme drought locations as per SPI-12 (Dec.) and SPI-12 (May) analysis, also PNP (annual) and PNP (water year) are almost same, while for 2003-04 drought, moderate and severe drought locations are less for SPI-12 (Dec.) than SPI-12 (May). However, extreme drought locations for SPI-12 (Dec.) greater than SPI-12 (May). v) For 2003-04 drought as per PNP analysis, moderate drought locations for water year greater than annual, while severe drought locations for water year less than annual.vi) For 2012 drought, total drought location by PNP (annual) less than SPI-12 (Dec).

4.3.5 Drought analysis for the Kharif, Rabi and Summer/Hot season crops

Table 4.6 shows the classification of rainfall stations by drought severity as per SPI-12 (December) and PNP (Yearly), similarly Table 4.7 shows the classification of rainfall stations by drought severity as per SPI-12 (May) and PNP (Water-Year) for various drought years. It is observed that in comparison with SPI-12 analysis, PNP analysis shows a high number of stations under drought. By comparing average SPI-12 and PNP from Table 4.6 and Table 4.7, it is observed that drought severity increases for all Water Years at par with antecedent Annual year except 1985-86, 1986-87,1992-93, 2003-04 and 2001-02 where the drought severity is reduced. This is due to non-seasonal rainfall from January to May. The increase in drought severity for water year hampers the summer/hot season crops which are water stressed due to the failure of monsoon and vice versa. Thus SPI-12 (May) and PNP (Water Year) in comparison with SPI-12 (December) and PNP (Yearly), helps to analyze the state of summer/hot season crops. Drought analysis by SPI-12(December) and PNP-Yearly designate the water balance due to south-west monsoon and north- east post-monsoon rains which terminates by the end of December. The rainfall stations under moderate droughts (PNP: 50%-74% and SPI -12: -1.00 to -1.49) for all drought years is witnessed by the failure of the Rabi crops with reduced productivity of the Kharif crops. The rainfall stations under severe droughts (PNP: <50%) and severe/extreme dry conditions (SPI -12: < -1.49) for all drought years is witnessed by a failure of both Kharif as well as Rabi crops.

Table 4.6: Drought classification of rainfall stations as per SPI-12 (December) and PNP (Yearly)

Year	SPI-12 (December)					PNP(Yearly)			
	Extremely dry	Severely Dry	Moderately dry	Total	Average SPI-12	Severe Drought	Moderate Drought	Total	Average PNP (%)
	-2.00 or less	-1.50 to -1.99	-1.00 to -1.49			<50%	50%-74%		
1971	1	1	11	13	-0.50	1	15	16	83.85
1972	34	14	7	55	-2.00	34	21	55	49.48
1982	0	3	12	15	-0.49	0	20	20	84.27
1985	1	5	13	19	-0.78	3	20	23	76.19
2000	0	5	12	17	-0.52	1	18	19	84.79
2002	2	6	13	21	-0.79	3	25	28	76.96
2003	25	15	11	51	-1.82	21	32	53	52.77
2012	3	15	17	35	-1.12	12	28	40	67.19
1966	0	2	4	6	0.04	1	9	10	99.68
1968	2	4	6	12	-0.46	2	16	18	85.80
1978	0	1	2	3	0.12	0	5	21	102.38
1984	0	2	4	6	-0.30	0	11	11	89.21
1986	1	5	13	19	-0.76	2	28	30	75.95
1987	7	1	10	18	-0.27	2	15	17	96.86
1992	0	3	9	12	-0.54	0	24	24	81.83
1994	0	3	13	16	0.22	1	19	20	103.55
1995	0	0	8	8	-0.17	0	8	30	94.07
2001	0	2	16	18	-0.55	0	21	21	83.67
2008	0	0	6	6	-0.15	0	11	26	93.31
2011	0	4	9	13	-0.41	3	17	20	84.29

Table 4.7: Drought classification of rainfall stations as per SPI-12 (May) and PNP (Water-Year)

Year	SPI-12 (May)					PNP(Water-Year)			
	Extremely dry -2.00 or less	Severely Dry -1.50 to -1.99	Moderately dry -1.00 to -1.49	Total	Average SPI-12	Severe drought <50%	Moderate drought 50%-74%	Total	Average PNP (%)
1971-72	3	2	13	18	-0.72	3	22	25	78.11
1972-73	36	12	6	54	-2.03	33	21	54	49.29
1982-83	1	8	17	26	-0.80	1	31	32	76.58
1985-86	2	9	11	22	-0.91	4	23	27	73.09
2000-01	1	3	16	20	-0.56	1	23	24	83.87
2002-03	4	6	17	27	-0.92	4	28	32	74.08
2003-04	10	26	14	50	-1.56	17	35	52	58.08
1966-67	0	3	8	11	-0.32	1	16	17	88.89
1968-69	3	4	9	16	-0.56	3	15	18	83.62
1978-79	0	3	7	10	-0.26	2	12	14	90.96
1984-85	0	1	7	8	-0.30	0	13	13	90.14
1986-87	0	3	8	11	-0.56	1	19	20	81.68
1987-88	7	5	8	20	-0.37	4	16	20	94.28
1992-93	0	1	8	9	-0.45	0	16	16	84.78
1994-95	0	5	11	16	0.21	4	15	19	103.65
1995-96	0	4	5	9	-0.43	1	14	15	86.96
2001-02	0	2	13	15	-0.47	0	20	20	86.44
2008-09	0	0	10	10	-0.26	0	13	13	90.82
2011-12	1	5	10	16	-0.49	3	19	22	82.77

4.3.6 Regional drought classification

Thiessen Polygon tool in Arc GIS 10.2 used to construct polygons corresponding to the area of influence of the 59 rain gauge stations in the study area. Each of the polygons measured in Km^2 and expressed as a percentage of the total study area. The rainfall stations closely spaced assigned less area and vice-versa. Even though some stations may designate drought conditions, a regional drought is acknowledged only when some threshold portion of the total study area is under drought. Regional drought classification as per Table 4.2 is used for SPI and PNP to classify regional droughts in the study area from 1960 to 2012.

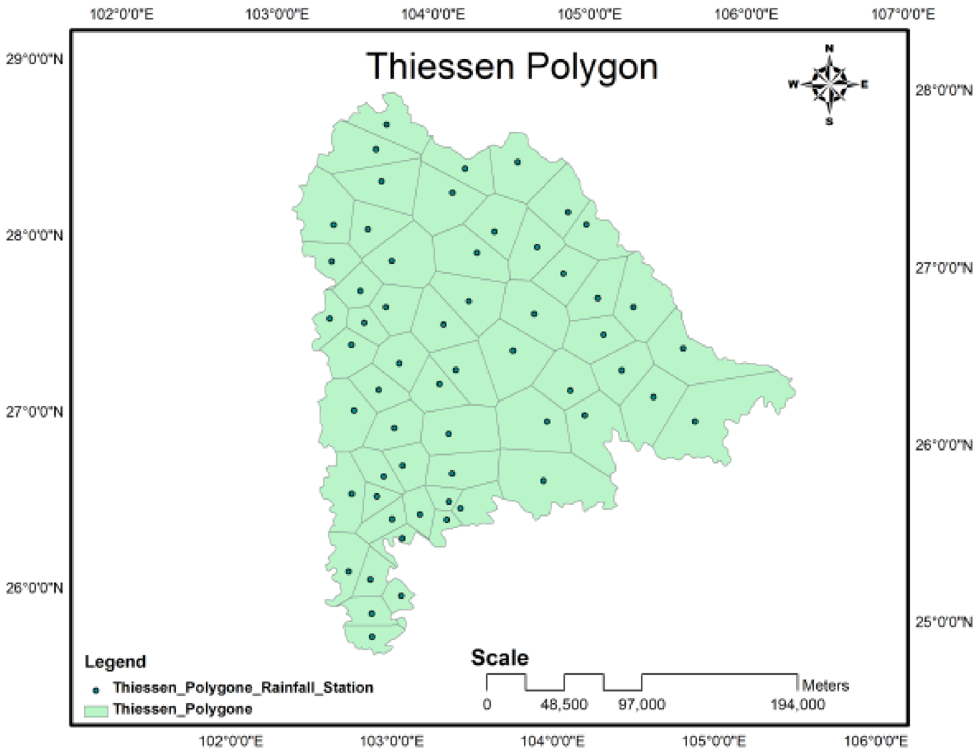


Figure 4.6**:** Thiessen Polygon as per rain gauge stations

Area-wide regional weather classification of every year is performed and the results are tabulated in Table 4.8.

Table 4.8: Area-wide Regional drought classification as per PNP and SPI

Drought Classification	PNP-Yearly	PNP-Water Year	SPI-Dec	SPI - May
Severe (>40 %)	9	7	3	4
Moderate (21 % to 40 %)	12	12	13	7
Mild (10 % to 20 %)	11	10	10	14
Non Drought (< 10 %)	21	23	27	27
Total study Years	53	52	53	52

From Table 4.8 it is observed that a number of severe drought incidences in PNP analysis more as compared SPI. Number of Moderate drought incidences as per PNP water year is more than SPI-May. Number of Mild drought incidences as per SPI-May is more than PNP water year while it is nearly same for SPI-Dec and PNP-Yearly. Severe drought incidences as per PNP-Yearly are more than PNP-Water year, while moderate and mild droughts are nearly same. The area-wide weather classification for the PNP-Water year is performed for all Severe and Moderate drought years. Sr.No. 1-7 are severe droughts while Sr.No. 8-19 are Moderate droughts. The results are tabulated in Table 4.9 and shown in Figure 4.7

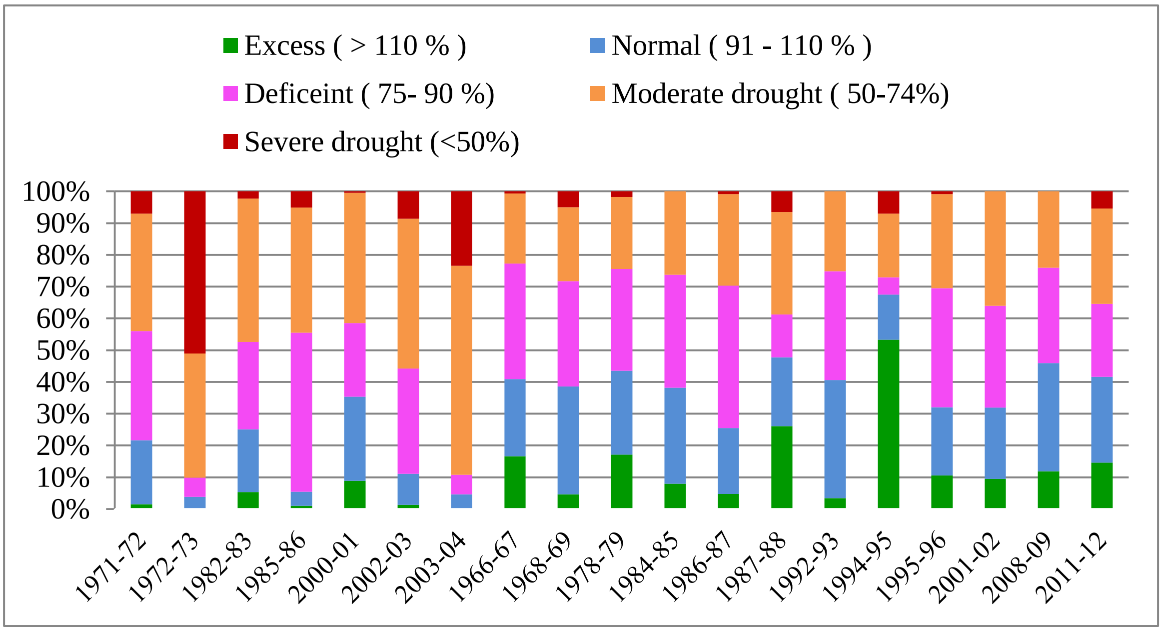


Fig.4.7 Weather classification for PNP-Water year for Severe and Moderate drought years

Table 4.9 shows that the drought year 1972-73 was most severe of all with 51 % of the study area is under severe drought and 39.4% of moderate drought followed by 2003-04, with 23.4 % of study area under severe drought and 65.8% of moderate drought. The Water year 1982-83 and 1985-86 had a subsequent moderate drought with 45.1 and 39.4 % of the area under moderate drought with 2.3 and 5.1 % area under severe drought respectively. The Water year 2002-03 had a moderate drought with 47.2 % of the area under moderate drought with 8.6 % area under severe drought.

Table 4.9 Area wide weather classification for PNP-Water year for Severe and Moderate drought years

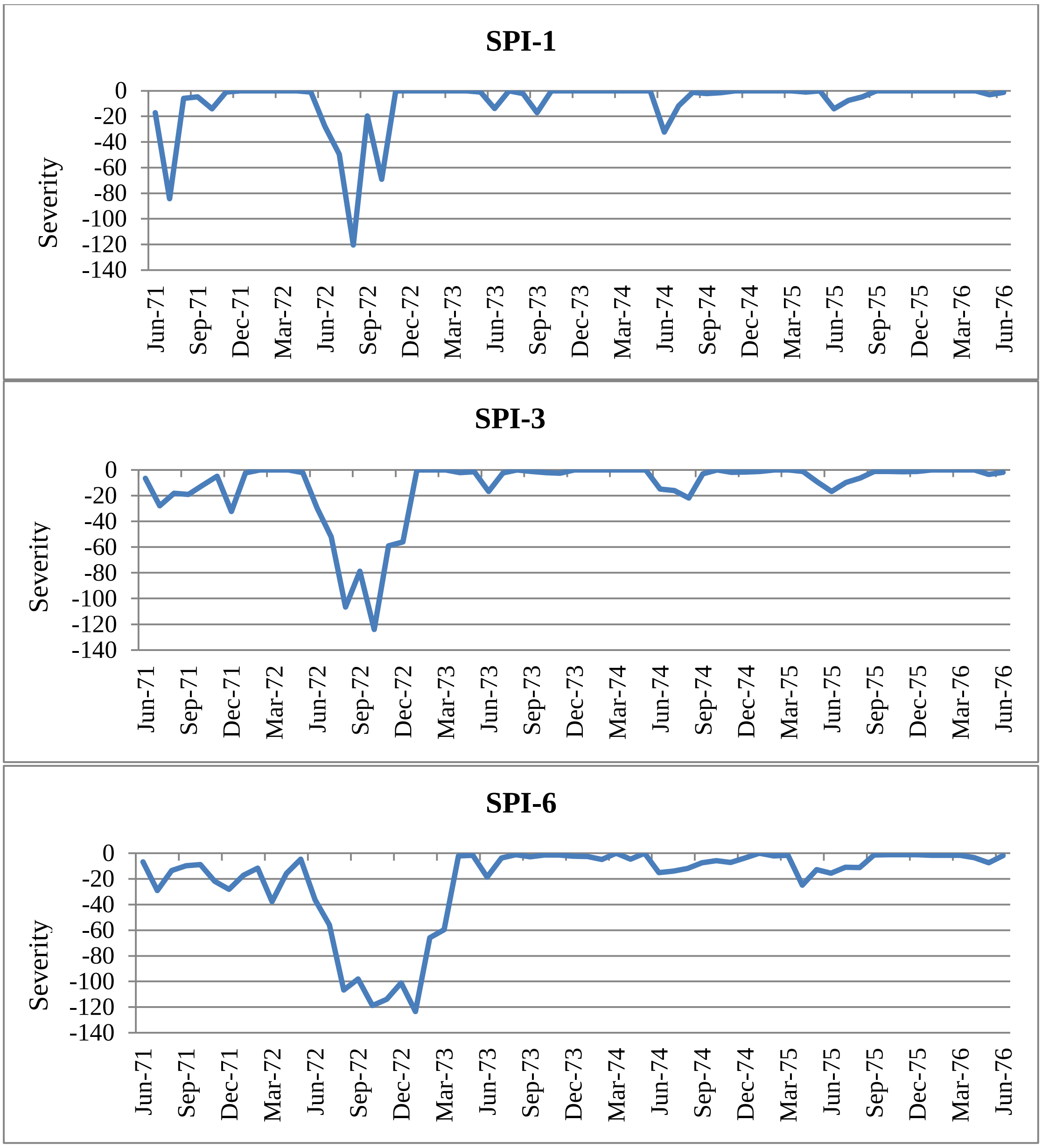
Sr.No.	Drought year	Excess	Normal	Deficient	Moderate drought	Severe drought
		>110 %	91-110 %	75-90 %	50-74 %	<50 %
1	1971-72	1.5	20.1	34.4	37	7
2	1972-73	0	3.8	6.1	39.1	51
3	1982-83	5.3	19.8	27.5	45.1	2.3
4	1985-86	1	4.4	50.1	39.4	5.1
5	2000-01	8.9	26.5	23.1	41	0.5
6	2002-03	1.3	9.8	33.1	47.2	8.6
7	2003-04	0	4.6	6.2	65.8	23.4
8	1966-67	16.6	24.3	36.4	22	0.7
9	1968-69	4.6	34	33.1	23.3	5
10	1978-79	17.1	26.4	32.1	22.6	1.8
11	1984-85	7.9	30.3	35.5	26.3	0
12	1986-87	4.7	20.8	44.8	28.8	0.9
13	1987-88	26.1	21.6	13.5	32.3	6.5
14	1992-93	3.4	37.2	34.2	25.2	0
15	1994-95	53.3	14.2	5.4	20.1	7
16	1995-96	10.6	21.4	37.5	29.6	0.9
17	2001-02	9.5	22.4	32.1	36	0
18	2008-09	11.9	34	30.1	24	0
19	2011-12	14.6	27	23	30	5.4

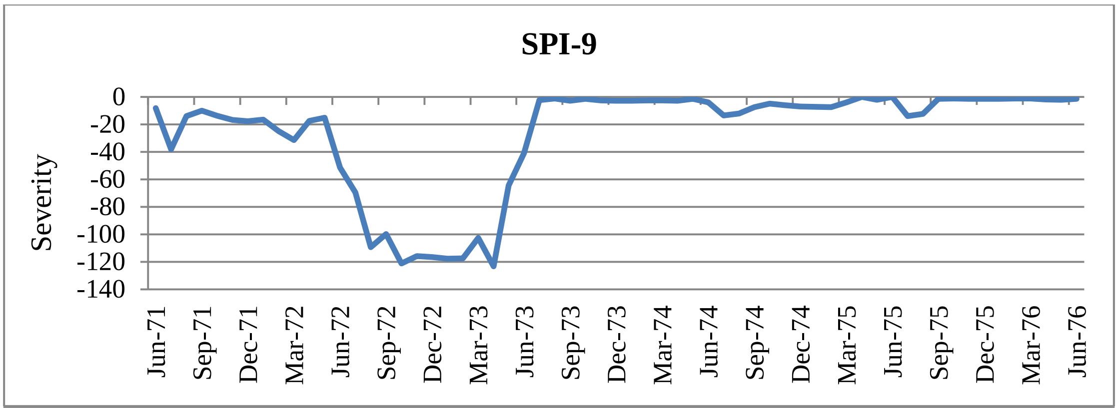
4.3.7 Spatial variation of Regional droughts

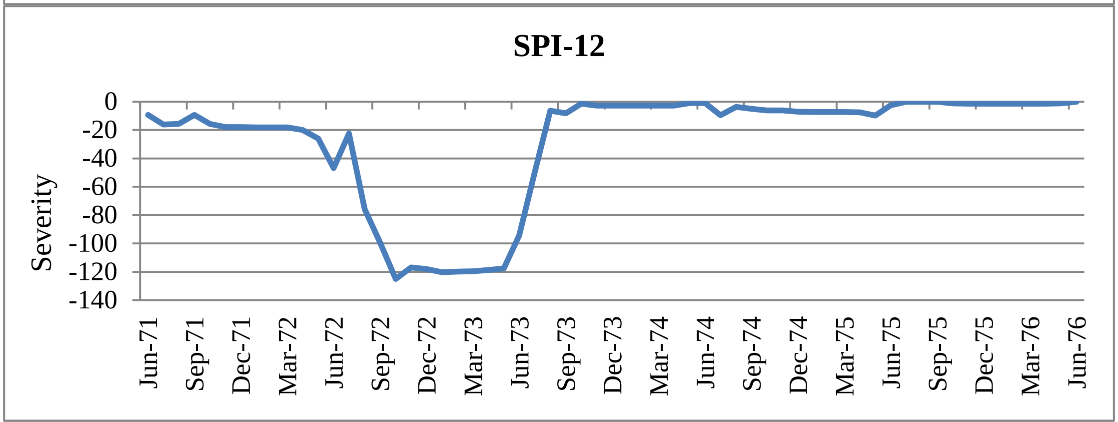
The spatial variations of percentage area under two regional drought events in the study area at multiple timescales are considered for regional drought analysis. The initiation, termination, severity, and duration of drought vary with the timescale. With the increase in timescale, small drought events merge to form a single drought event. The spatial coverage and class of drought vary with the timescale as observed in Figure 4.8, to Figure 4.11.

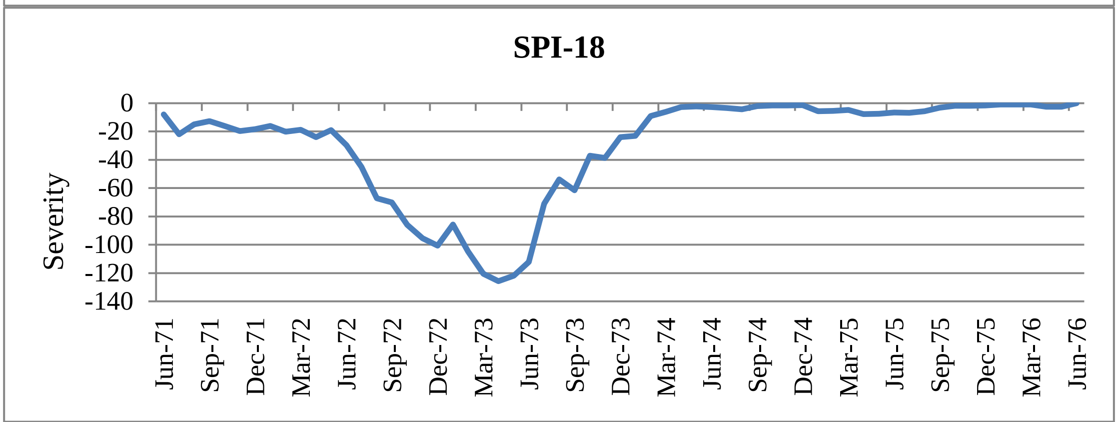
4.3.7.1 Spatial variation of high-intensity Regional drought

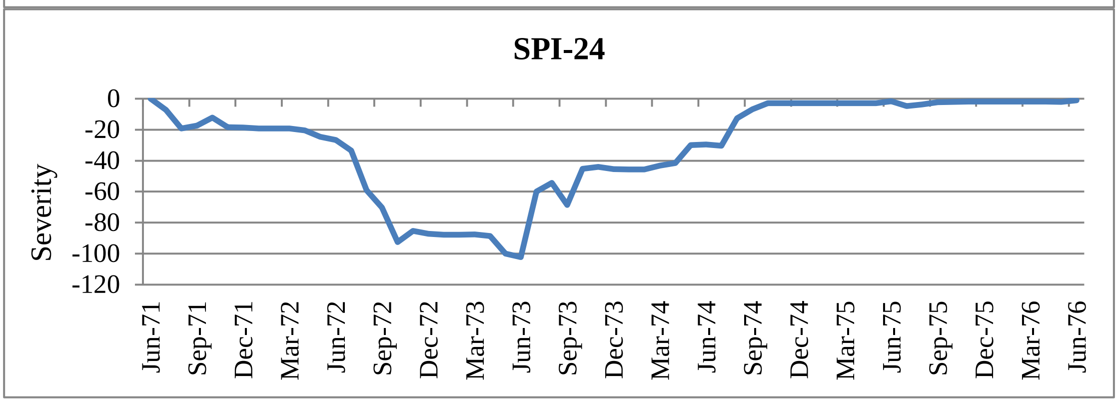
The drought severity time series of a drought event of high-intensity from the period June 1971 to September 1975 as shown in fig. 4.8




SPI-9
Severity
0
-20
-40
-60
-80
-100
-120
-140
Jun-71 Sep-71 Dec-71 Mar-72 Jun-72 Sep-72 Dec-72 Mar-73 Jun-73 Sep-73 Dec-73 Mar-74 Jun-74 Sep-74 Dec-74 Mar-75 Jun-75 Sep-75 Dec-75 Mar-76 Jun-76


SPI-12
Severity
0
-20
-40
-60
-80
-100
-120
-140
Jun-71 Sep-71 Dec-71 Mar-72 Jun-72 Sep-72 Dec-72 Mar-73 Jun-73 Sep-73 Dec-73 Mar-74 Jun-74 Sep-74 Dec-74 Mar-75 Jun-75 Sep-75 Dec-75 Mar-76 Jun-76


SPI-18
Severity
0
-20
-40
-60
-80
-100
-120
-140
Jun-71 Sep-71 Dec-71 Mar-72 Jun-72 Sep-72 Dec-72 Mar-73 Jun-73 Sep-73 Dec-73 Mar-74 Jun-74 Sep-74 Dec-74 Mar-75 Jun-75 Sep-75 Dec-75 Mar-76 Jun-76


SPI-24
Severity
0
-20
-40
-60
-80
-100
-120
Jun-71 Sep-71 Dec-71 Mar-72 Jun-72 Sep-72 Dec-72 Mar-73 Jun-73 Sep-73 Dec-73 Mar-74 Jun-74 Sep-74 Dec-74 Mar-75 Jun-75 Sep-75 Dec-75 Mar-76 Jun-76

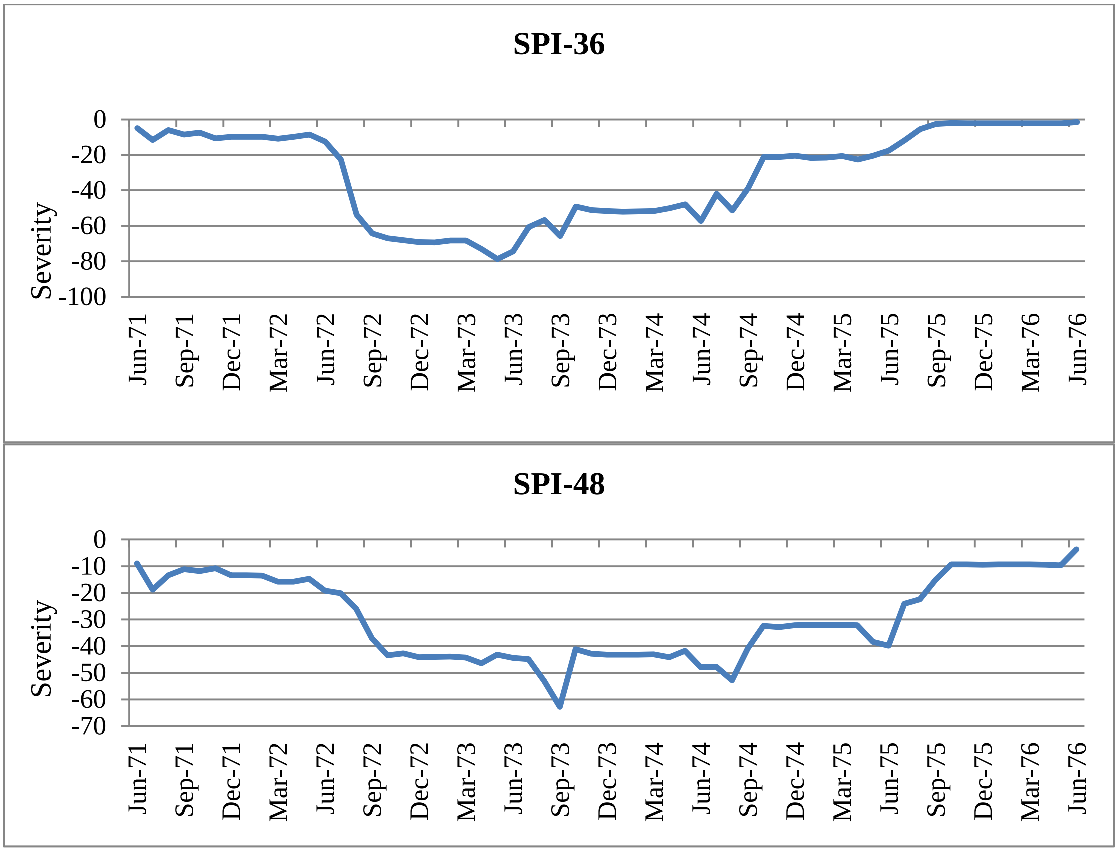
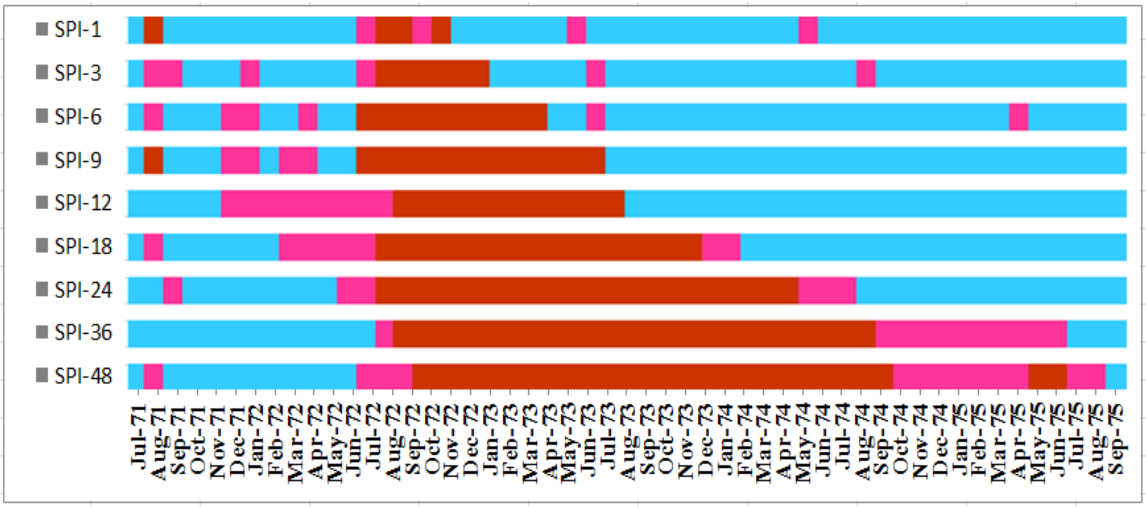


Figure.4.8: Drought severity- time series at multiple timescales of a high-intensity drought event



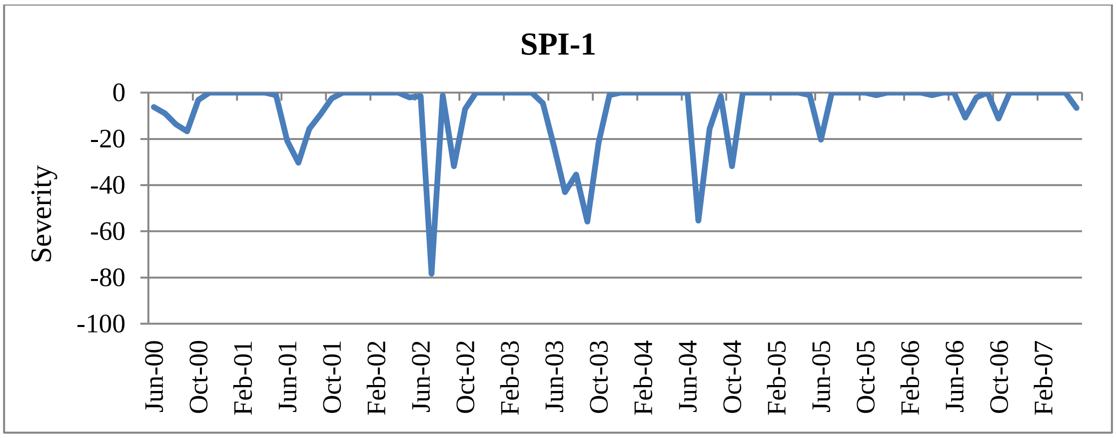
Classification: Normal (0-20%), Moderate drought (21%-40%), Severe drought (> 40%)

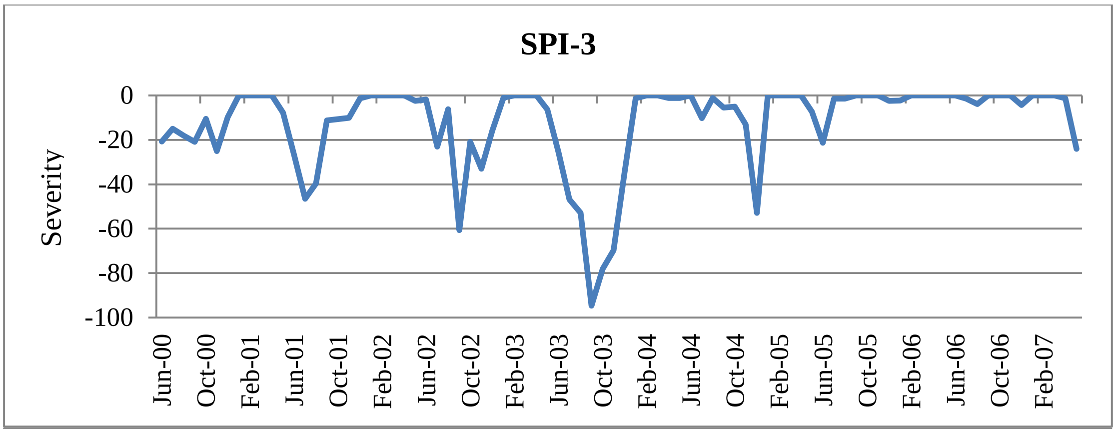
Fig.4.9: Spatial variation of percentage area under a high- intensity drought event

From Figure 4.9, it is observed June 1971 is a Normal month at every timescale (area under drought within 20%). July 1971 faces an extreme shortage of rainfall reflecting severe drought at SPI-1 timescale with 86% of area and SPI-9 with 48% of the area under drought. Simultaneously SPI -3,-6,-18 and -48 reflects Moderate drought with % area under drought within 23% to 33%. The areas affected by severe drought evolve gradually at every timescale from Moderate to Severe except for SPI-6 and SPI-9. June 1972 triggers severe drought at SPI-6 and SPI-9 timescales, while SPI-1, SPI-3,-12,-18,-24 and SPI-48 reflect Moderate drought conditions due to antecedent rainfall as per their respective timescales. The SPI-12 timescale detects initiation of Moderate drought, 3 & 6 months in advance that of SPI-18 & SPI-24 timescales resp. SPI-6 and SPI-9 timescales detect severe drought 1 month in advance that of SPI-1,-9, -18 and SPI-24. August 1972 denotes severe drought conditions at all except SPI-48 timescale, with maximum drought area of 96 % at SPI-1 timescale. October 1972 has a severe drought at every timescale. After November 1972, severe drought recedes at successive timescales with a time lag varying from 2-4 months. While SPI-1 to SPI-12 recedes abruptly from Severe to Normal, SPI-18 to SPI-48 recedes gradually from Severe to Moderate and then to Normal.

4.3.7.2 Spatial variation of high-severity Regional drought

The drought severity time series of high-severity drought from the period July 2000 to August 2006 as shown in Figure 4.10




SPI-3
Severity
0
-20
-40
-60
-80
-100
Jun-00
Oct-00
Feb-01
Jun-01
Oct-01
Feb-02
Jun-02
Oct-02
Feb-03
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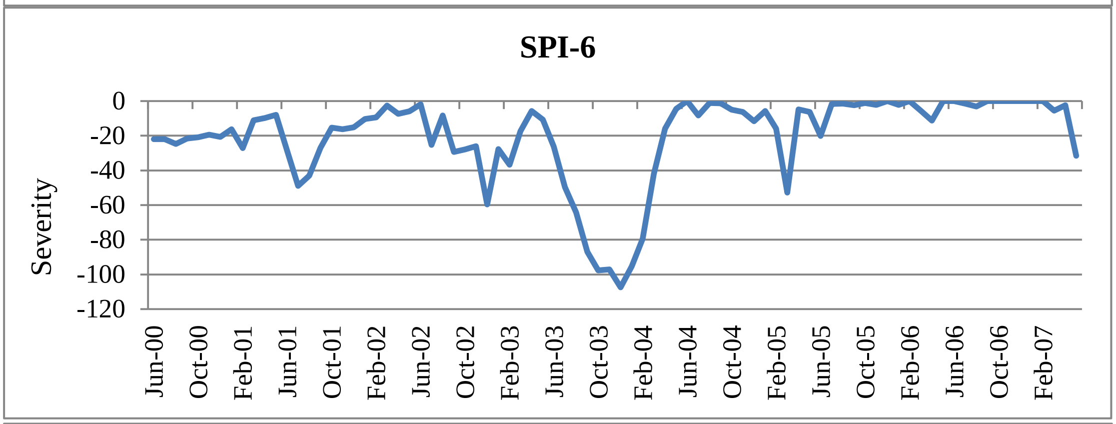
Jun-06
Oct-06
Feb-07


SPI-6
Severity
0
-20
-40
-60
-80
-100
-120
Jun-00
Oct-00
Feb-01
Jun-01
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Feb-02
Jun-02
Oct-02
Feb-03
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Jun-04
Oct-04
Feb-05
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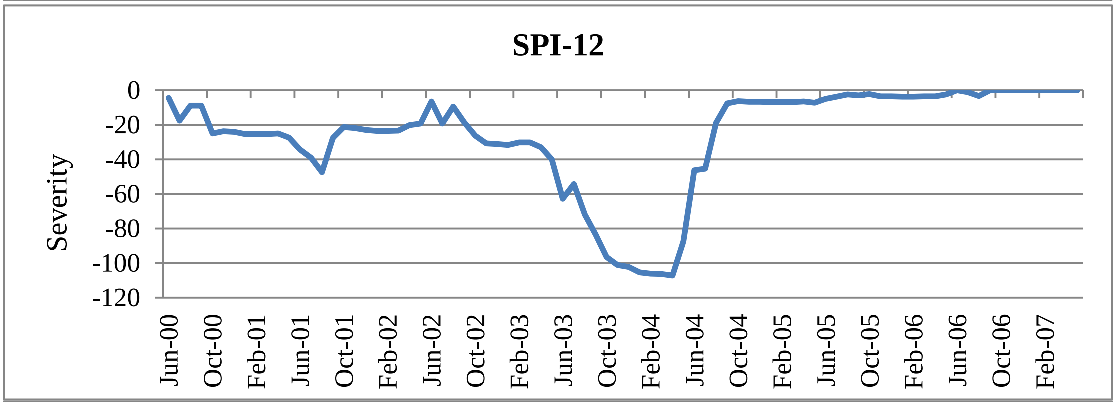
Feb-06
Jun-06
Oct-06
Feb-07


SPI-12
Severity
0
-20
-40
-60
-80
-100
-120
Jun-00
Oct-00
Feb-01
Jun-01
Oct-01
Feb-02
Jun-02
Oct-02
Feb-03
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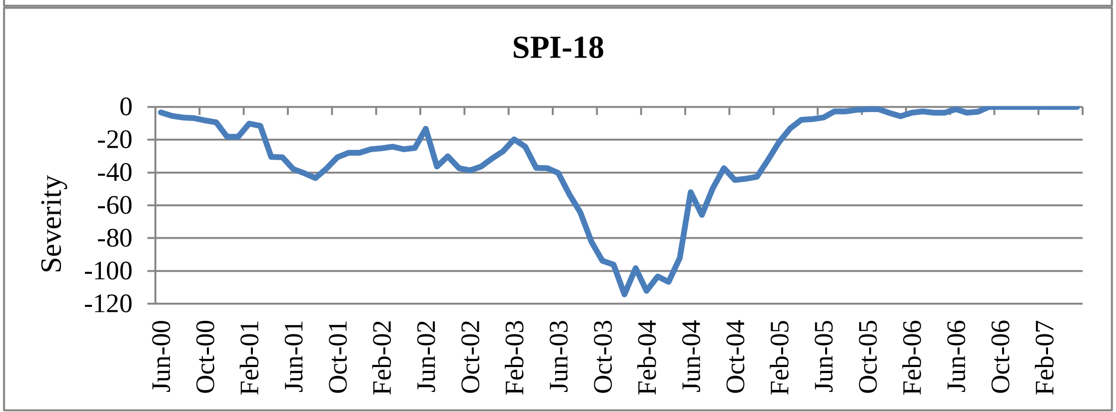
Jun-06
Oct-06
Feb-07


SPI-18
Severity
0
-20
-40
-60
-80
-100
-120
Jun-00
Oct-00
Feb-01
Jun-01
Oct-01
Feb-02
Jun-02
Oct-02
Feb-03
Jun-03
Oct-03
Feb-04
Jun-04
Oct-04
Feb-05
Jun-05
Oct-05
Feb-06
Jun-06
Oct-06
Feb-07

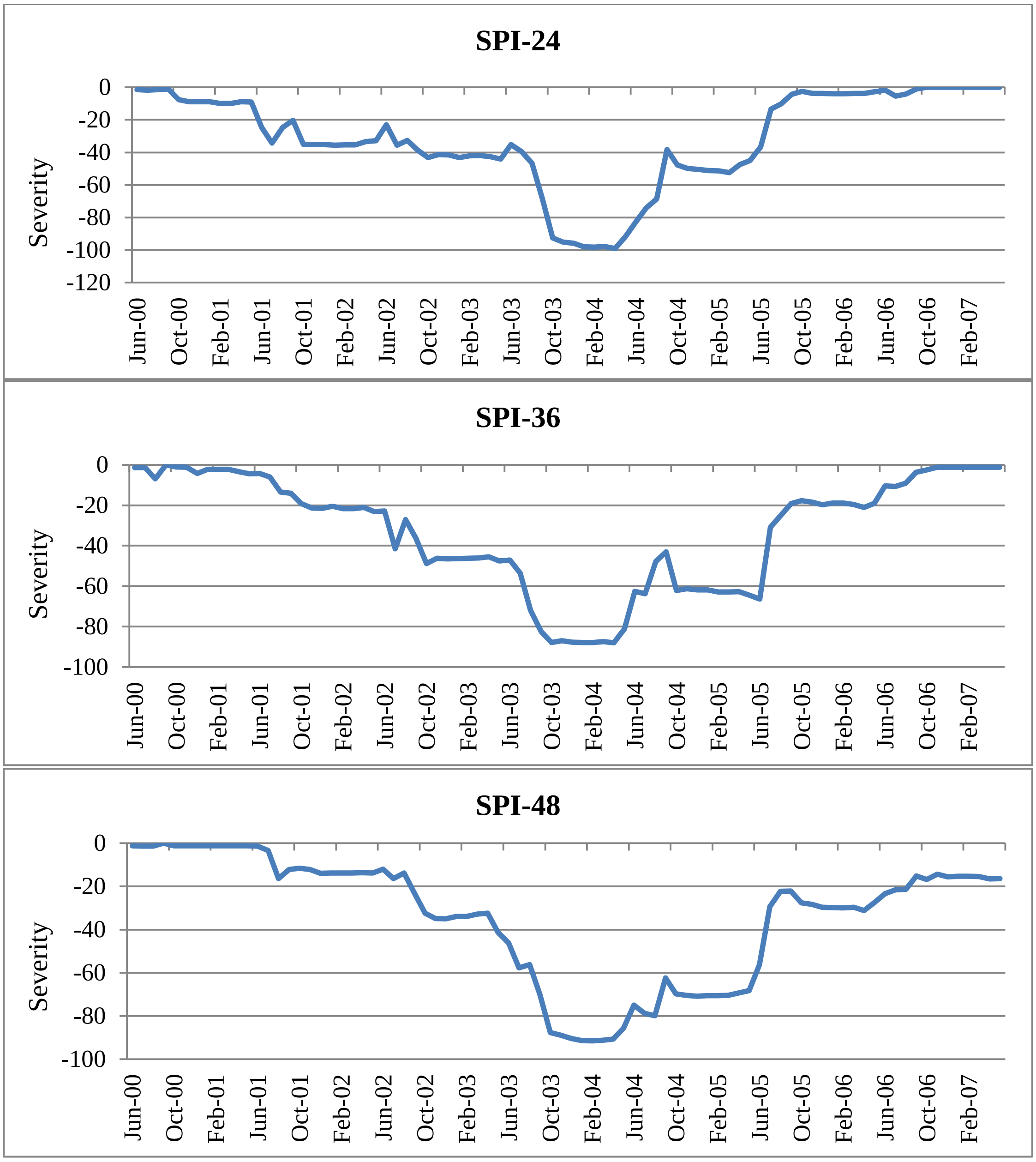
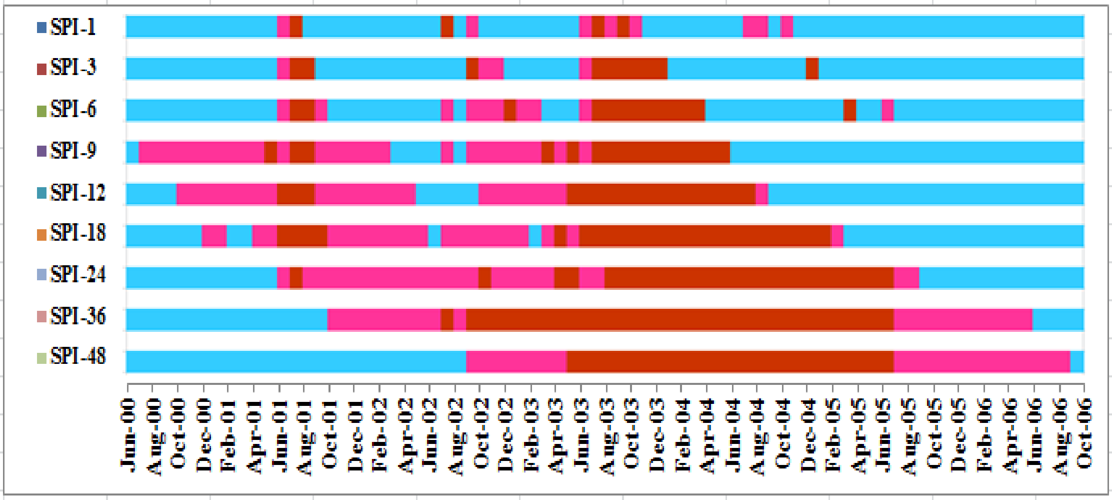


Figure.4.10: Severity time series at multiple timescales of a high severity drought event

From Figure 4.8 and 4.10 it is observed that total severity of drought event increases with increase in timescale. The gradual change in drought class at multiple timescales is shown in Figure 4.11.



Classification: Normal (0-20%), Moderate drought (21%-40%), Severe drought (> 40%)

Figure 4.11: Spatial variation of percentage area under a high severity drought event

From Figure 4.11, it is observed June 2000 is a Normal month on every timescale. Moderate drought is first detected at SPI-6 and SPI-9 timescales from July 2000, at SPI-1 and SPI-3 from September 2000, at SPI-12 from October 2000, at SPI-18 from December 2000, at SPI-24 from June 2001, at SPI-36 from October 2001 and at SPI-48 from September 2002. Severe drought is first detected at SPI-9(45% area under drought) from May 2001, SPI-1, SPI-3, SPI-6 and SPI-24 timescales from July 2001, at SPI-12 and SPI-18 from June 2001, at SPI-36 from July 2002 and at SPI-48 from May 2003. July 2003 denotes severe drought conditions at all except SPI-24 timescale, with maximum drought area of 65 % at SPI-9 timescale. After September 2003, severe drought recedes at successive timescales with a time lag varying from 2-9 months. While SPI-3 to SPI-9 recedes abruptly from Severe to Normal, SPI-1 along with SPI-12 to SPI-48 recedes gradually from Severe to Moderate and then to Normal.

4.3.7.3 Comparison of high-severity and high-intensity Regional drought

The drought characteristics of two regional drought events at multiple timescales are as shown in Table 4.10.

Table 4.10**:** Regional drought characteristics at multiple timescales

SPI series	Drought Severity		Drought months		Drought intensity	
	1971-75	2000-06	1971-75	2000-06	1971-75	2000-06
SPI 1	-417	-480	8	14	-52	-34
SPI 3	-577	-750	12	17	-48	-44
SPI 6	-1040	-1371	16	31	-65	-44
SPI 9	-1379	-1869	18	43	-77	-43
SPI 12	-1480	-1952	21	42	-70	-46
SPI 18	-1579	-2251	25	47	-63	-48
SPI 24	-1636	-2529	28	51	-58	-50
SPI 36	-1742	-2633	36	56	-48	-47
SPI 48	-1538	-2533	39	48	-39	-53

It is observed that drought severity increases with timescales up to SPI-36. The drought severity at SPI-24 and SPI-48 is nearly same. Drought months in both droughts increase with timescales but it decreases after SPI-36 during 2000-06. In 1971-75, maximum drought intensity is at SPI-9 whereas it is found maximum at SPI-48 during 2000-06. Maximum drought intensity is at SPI-48 during 2000-06 than at 1971-75 and it is nearly same for both droughts at SPI-36.

4.3.8 Spatial interpolation of SPI Values

The Inverse Distance Weighting (IDW) method is used for spatial interpolation of SPI Values over the entire study area. The spatial display maps for SPI values were prepared by using Arc GIS 10.2 for severe drought years and are shown in Figure.4.12, 4.13 and 4.14. The 1972 drought was most severe with almost all study area under severe and moderate drought as per Figure 4.12. The 2003 drought had more area under moderate drought than the area under severe drought as seen in Figure 4.13. The 2012 drought had very less area severe drought while the major area under moderate drought and less area under mild drought as per Figure 4.14. In all the three drought years the Western Ghats had less drought intensity as compared to another area.

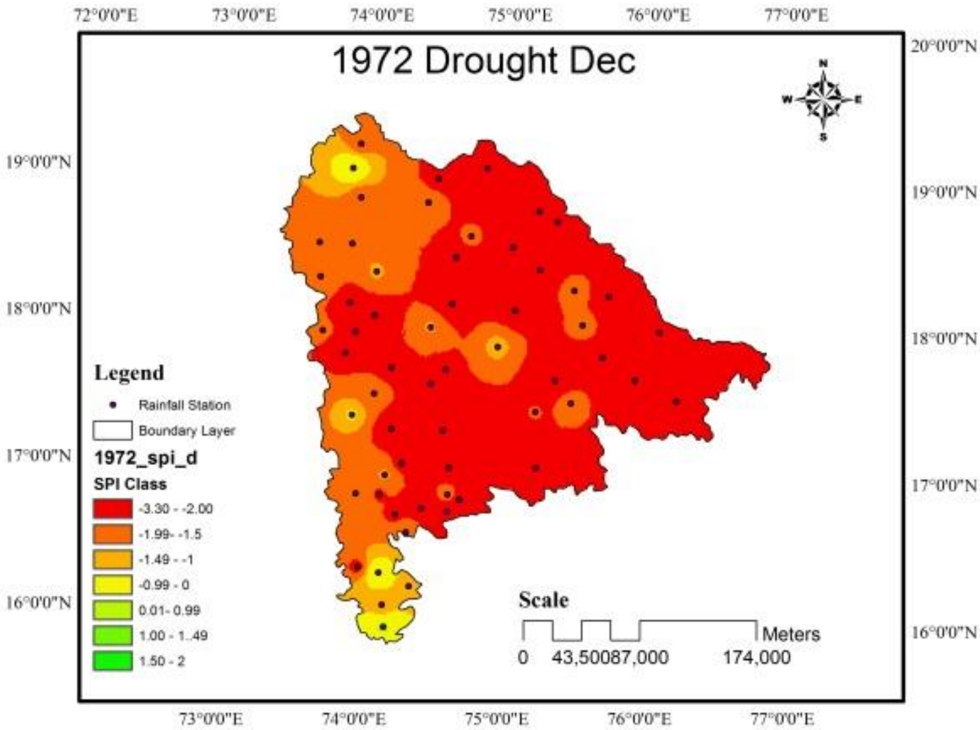


Fig.4.12 Spatial variation of 1972 drought

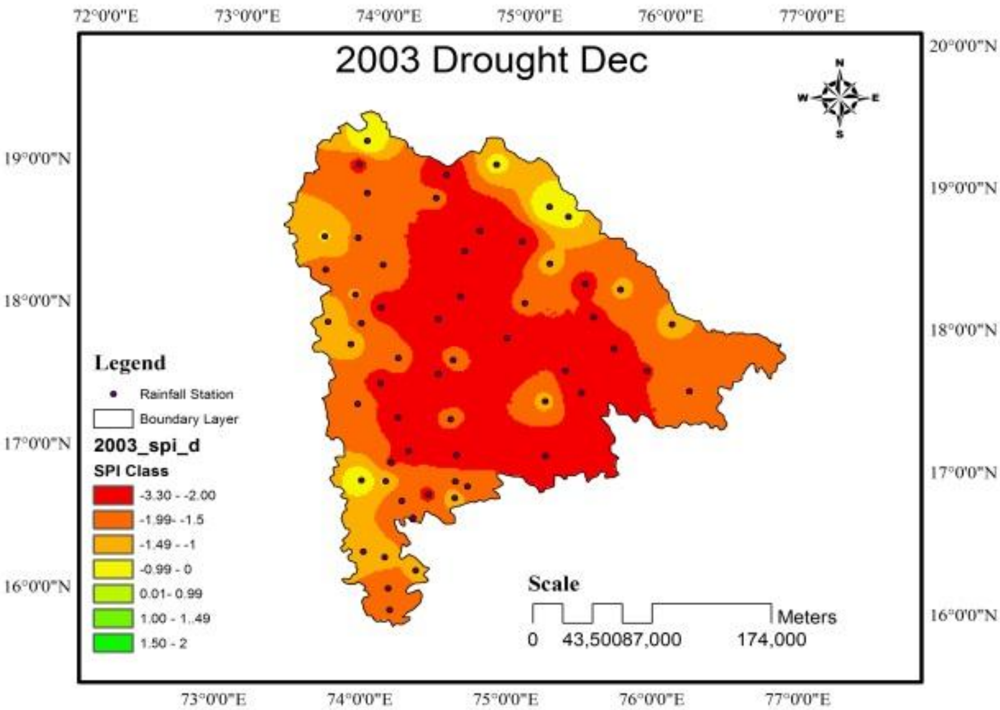


Fig.4.13 Spatial variation of 2003 drought

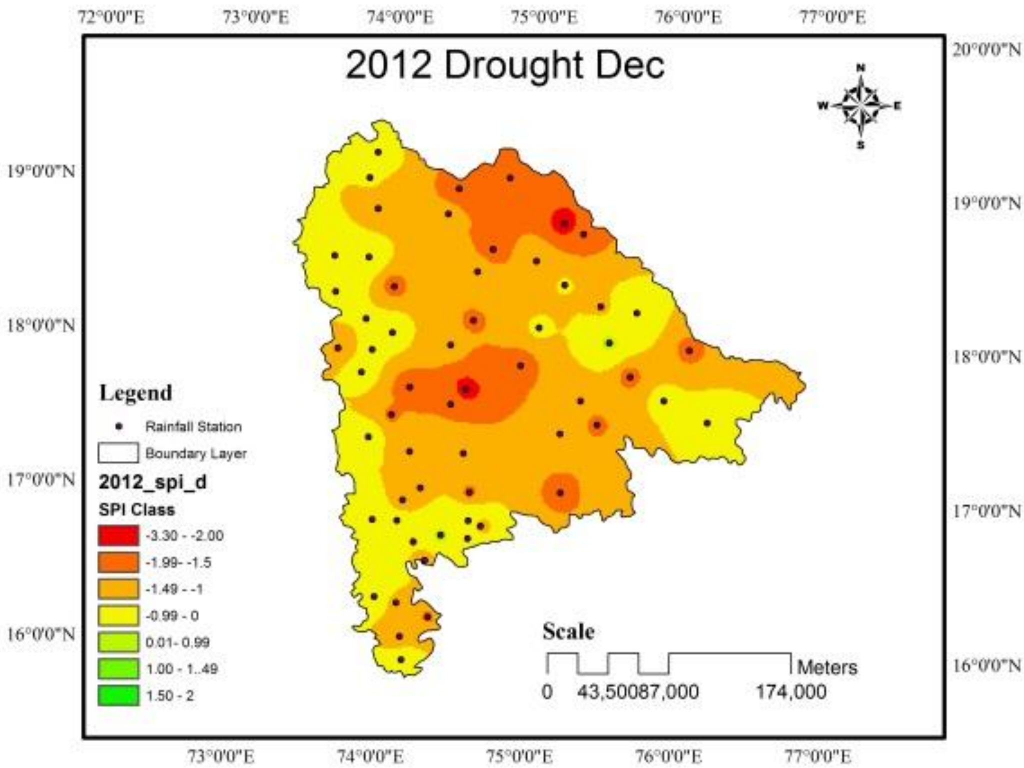


Fig.4.14 Spatial variation of 2012 drought

4.3.9 Drought classification for various return periods

Less severe droughts frequently occur while high severe droughts are rare to occur. Probability analysis for various return periods of different drought severity done for different return periods and the results displayed in Figure 4.15

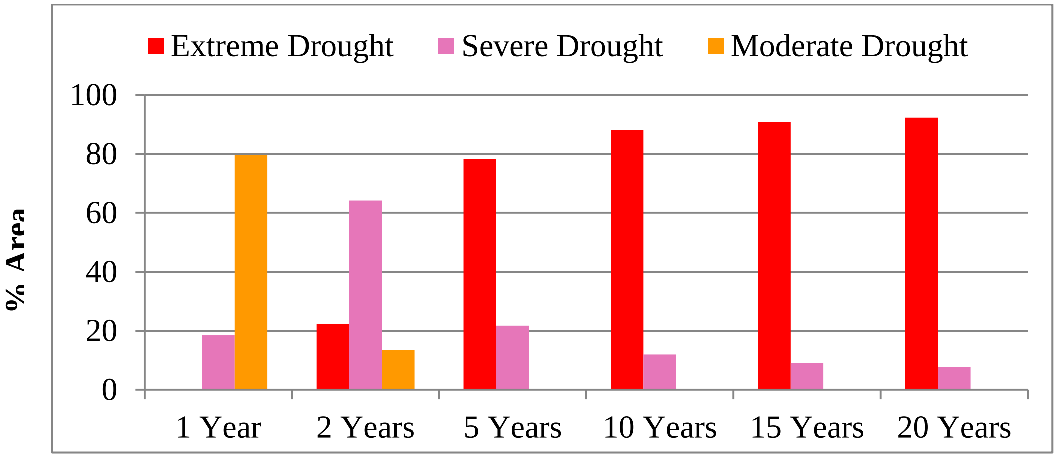
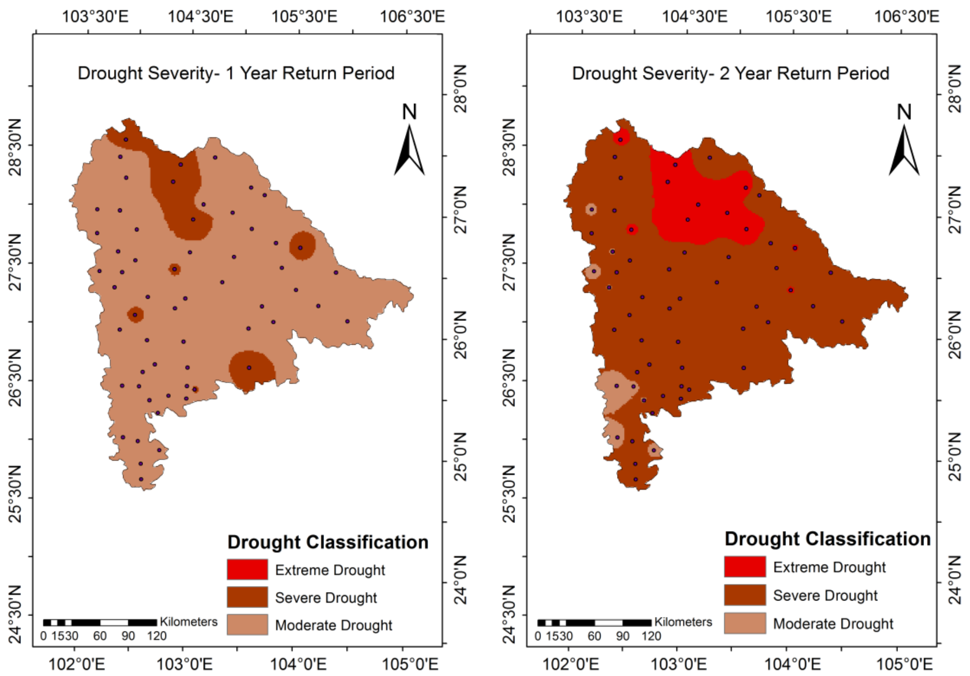


Figure 4.15: Percentage area of Drought severity for various Return Period.

Figure 4.15 indicates that in 80 % of the study area, moderate drought month occurs with one-year return period. Severe drought month occurs for 2-year return period for 64 % of the area. An extreme drought month occurs for 78 % of the area for 5-year return period. It is least at 22% area for 2-year return period and 92 % area for 20-year return period.

4.3.10 Drought severity maps for various return periods

Figure 4.16 shows that at 1-year return period, the maximum area under moderate drought observed, while severe drought for 2-year return period. The area under moderate drought is least for 15-year return period. The area under extreme drought is least at 2-year return period and is highest at 15-year return period. It is observed that a drought is a recurring event. The people in the study area should be ready to face moderate drought month within every year, severe drought months within 2 years. The part of Solapur district along with the Western Ghats excluding area under Satara and Sangli districts faced severe drought month every 5 years. Almost 95 % of the study area faced extreme drought month in every 10 years.



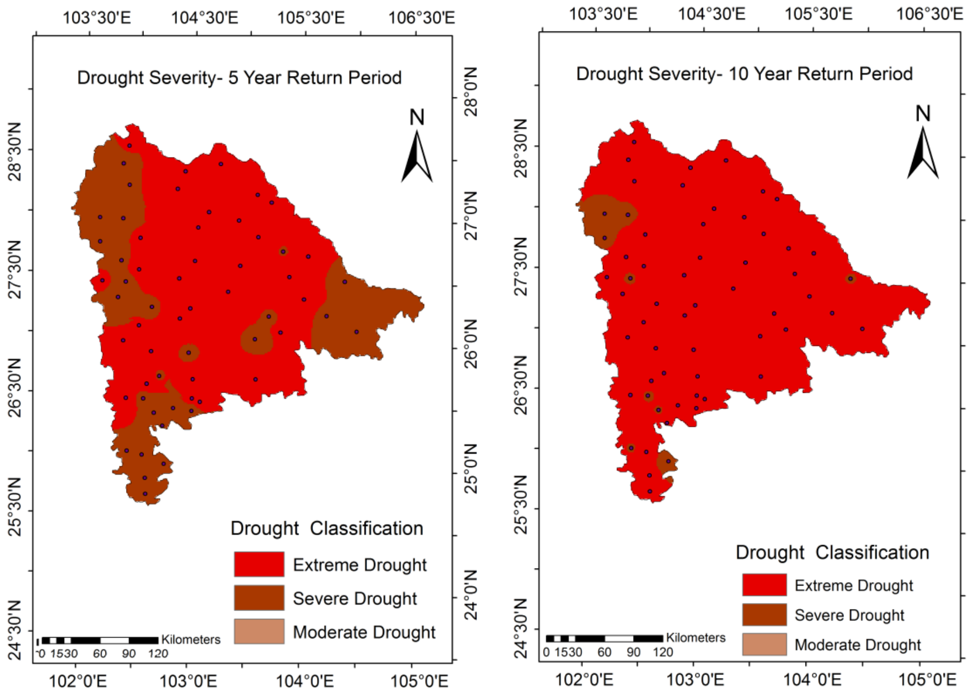


Figure 4.16: Spatial variation of Drought severity for various return periods

4.3.11 Identification of severe drought prone-areas

As per McKee et al., (1993), SPI greater than -2 is classified as Severely Dry. The summation of drought months having SPI value >-2 for all timescales is performed for the 59 stations in the study area .The ratio of the sum for each station to the highest value from all the stations is multiplied by 10. This method will assign rank from 1 to 10. Rank 1 will be the least severe drought-prone area while rank 10 will be the highest severe drought-prone area as per Table 2, Appendix A. It is observed that Gadhinglaj station is least affected by droughts whereas Paud station is most affected by droughts.

4.4 Conclusion

PNP and SPI were used to analyze the spatial and temporal variation of droughts over the Krishna basin in Maharashtra. The PNP and SPI analysis were helpful to identify local and regional droughts. However, there were significant differences in the analysis of local and regional droughts. Drought characteristics of local droughts changes with the timescale. Therefore appropriate timescale should be used for specific water resource management. For example, SPI-3 and SPI-6 suitable for irrigation purpose, while SPI-1 suitable for drinking water supply. SPI-1 should be used with caution since SPI–1 shows exacerbated picture of very wet conditions in January-March and December (Figure 4.3-b), even though rainfall is almost nil during these months. SPI-1 timescale evaluates dry conditions from June- Oct. i.e. S-W monsoon period. Results obtained by SPI-3 are consistent with actual wet/dry conditions. For regional planning higher timescales may be useful. Since SPI is a normalized Index, the variability of SPI is proportional to that of the precipitation change. SPI performs better than PNP in monitoring drought at multiple timescales.

Local drought classification by the SPI and PNP varies with a timescale (Table 4.5). It is observed that the SPI has 3 classes of drought as compared to 2 of PNP. A number of moderate drought locations as per PNP is more than that of SPI-12. Annual and Water-year timescale gives different results for 1972-73 and 2003-04 drought. For 1972-73 drought, moderate, severe and extreme drought locations as per SPI-12 (Dec.) and SPI-12 (May) analysis, also PNP (annual) and PNP (water year) are nearly same, while for 2003-04 drought, moderate and severe drought locations are less for SPI-12 (Dec.) than SPI-12 (May).However, extreme drought locations for SPI-12 (Dec.) is much more than SPI-12 (May). For 2003-04 drought as per PNP analysis, moderate drought locations for water year is more than annual, while severe drought locations for water year is less than annual. For 2012 drought, total drought location by PNP (annual) is less than SPI-12 (Dec).

Yearly drought analysis and Water year drought analysis influences the cropping pattern. Water year drought analysis will have more influence in managing summer crops since we can assess the availability of soil moisture at the end of water year; similarly, Yearly drought analysis will have more influence on managing Kharif and Rabi crops.

The Theissen polygon method to assign influence area to each rain gauge station was suitable for regional drought analysis. The drought class varies as per PNP and SPI (Table 4.8). It is observed that a number of severe drought incidences in PNP analysis are more as compared SPI. Number of Moderate drought incidences as per PNP water year is more than SPI-May. Number of Mild drought incidences as per SPI-May is more than PNP water year while it is nearly same for SPI-Dec and PNP-Yearly. Severe drought incidences as per PNP-Yearly are more than PNP-Water year, while moderate and mild droughts are nearly same.

The drought characteristics of two regional drought events (1971-75 and 2000-06) vary with timescales (Table 4.10). It is observed that drought severity increases with timescale up to SPI-36. The drought severity at SPI-24 and SPI-48 is nearly same. Drought months in both droughts increase with timescale but it decreases after SPI-36 during 2000-06. During 1971-75, maximum drought intensity is at SPI-9 whereas it is found maximum at SPI-48 during 2000-06. Maximum drought intensity is at SPI-48 during 2000-06 than at 1971-75 and it is nearly same for both droughts at SPI-36.

Moderate drought month occurs in 80 % of the study area, with one-year return period (Figure 4.15). Severe drought month occurs for 64 % of the area with 2-year return period. An extreme drought month occurs for 78 % of the area with 5-year return period. Drought severity maps for different return periods can identify areas susceptible to mild, moderate and severe droughts. The spatially interpolated drought maps will help water managers and district administrators for taking measures in drought relief and contingency planning. The ranking of rain gauge stations will help the water managers and administrators to allocate funds and deciding priority for drought mitigation works.

CHAPTER 5

SUB-BASIN WIDE DROUGHT ANALYSIS

5.1 Introduction

Droughts are prolonged periods (months to years) of precipitation deficiency over a given region. Precipitation, in any of its form, is the only natural source of receiving moisture on the mainland from the sea and is an important link in the water cycle. A sub-basin as a unit for managing water resources is important due to same climatological features and is easy for assessment of water resources from different sources such as precipitation, stream flow, groundwater and water stored in reservoirs.

The sub-basin wide drought analysis done by using MSWSI, SPI, and PNP for five sub-basins in the Krishna river basin of Maharashtra, India. The Krishna basin in Maharashtra was divided into five sub-basins using the hydrometeorological variables i.e. precipitation, streamflow, and dam inflow.

5.2 Sub-Basin Wide Planning

The study area was divided into five sub-basins as per hydrological regime as per Table 5.1 and shown in Figure 5.1.

Table 5.1: Sub-basins of the Krishna River in Maharashtra

Sr. No.	River Basin	Names of Sub-basins	Categorization for planning on the basis of availability of natural water
1	Krishna	Upper Krishna (West)	Abundant
2		Upper Krishna (East)	Highly Deficit
3		Upper Bhima (Up to Ujjani)	Normal
4		Remaining Bhima	Normal
5		Sina-Bori-Benetura	Highly Deficit

Source: W.R.D., G.O.M. (2005)

Classification of sub-basins is on basis of naturally available quantum of water as tabulated in Table 5. 2.

Table 5.2: Categorization of sub-basins as per availability of water

Sr. No.	Plan Group	Per ha Availability (m^3)
1	Abundant area	Above 12000
2	Surplus area	8001-12000
3	Normal area	3001-8000
4	Deficit area	1501-3000
5	Highly Deficit Area	Below 1500

Source: W.R.D., G.O.M. (2005)

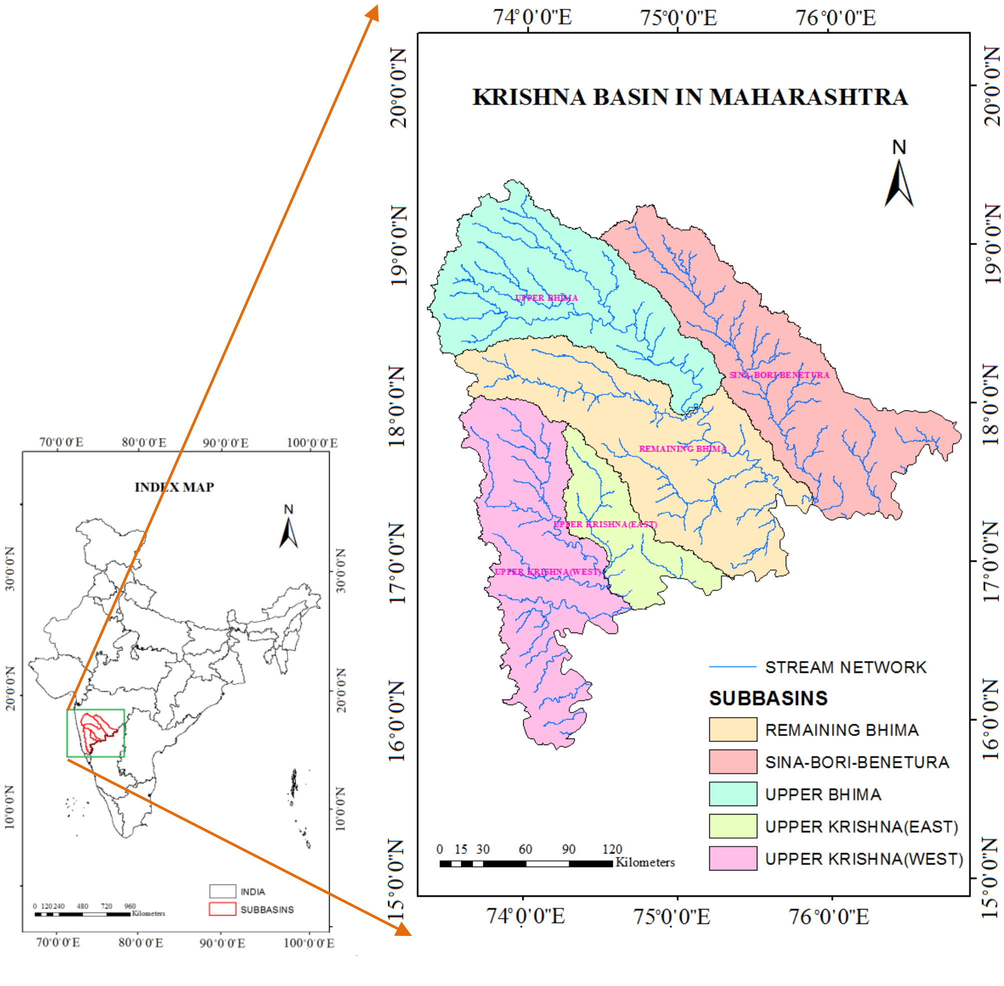


Figure 5.1: Sub-basins of the Krishna River in Maharashtra

5.3 Data Used

Precipitation, Streamflow, and Dam inflow data were used for calculation of the Modified Surface Water Index. The sub-basin wise number of streamflow gauge discharge stations, reservoirs, and rain gauge stations are as shown in Table 5.3. The data period used is from June 1972 to May 2008.

Table 5.3: Details of reservoirs, stream flow and rain gauge stations as per sub-basins

Sr.no.	Sub - Basins	Streamflow Gauge discharge stations	Reservoirs	Rain gauge stations
1	Upper Krishna-West(UKW)	05	14	20
2	Upper Krishna-East(UKE)	00	00	05
3	Upper Bhima (UB)	02	15	11
4	Remaining Bhima (RB)	02	03	11
5	Sina-Bori-Benetura (SB)	01	06	12
Total		10	38	59

5.3.1 Source of Data Used

i) Stream flow and Reservoir storage data- Water Resource Department, Government of Maharashtra,

ii) Rainfall data- Indian Metrological Department, Pune

5.4 Methodology

Shafer and Dezman (1982) introduced Surface Water Supply Index (SWSI) to assess the moisture conditions across the state of Colorado. A basic aim of the SWSI was to express the non-dimensional index. The SWSI is an indicator of surface water conditions. The SWSI allows a comparison of water supply availability for each region containing different variables such as snowpack, precipitation, streamflow, and reservoir storage (Garen, 1993, Wilhite and Glantz 1987, Doesken et al. 1991). However, the index is to be re-calculated when data and management rules are changed for each region.

5.4.1 Modification of the SWSI

The snowpack component in the SWSI developed by Shafer and Dezman (1982) is not applicable in the study area; therefore the mathematical formulation of the Modified Surface Water Supply Index (MSWSI) is given by:

$$MSWSI_t = \frac{[w_1 P_t^{resv} + w_2 P_t^{prec} + w_3 P_t^{strm} - 50]}{12} \quad (5.1)$$

Where

w_1, w_2, and w_3 are the weights for each hydrological component ($w_1 + w_2 + w_3 = 1$); P_t is the non-exceedance probability (in percentage), the superscripts resv, prec and strm and represents the reservoir storage, precipitation, and stream-flow components, respectively at time t.

$$P_t = 1 - P_p \quad (5.2)$$

Where $P_p = \left(\frac{m}{N} + 1\right) * 100$ (5.3)

m = Rank of individual data point

N= Total number of data points

Table 5.4 shows the classification based on MSWSI.

Table 5.4: Classification based on MSWSI

MSWSI values	**Class**
>4	Abundant supply
1 to 4	Surplus
-0.99 to 0.99	Normal
-1.00 to -1.99	Mild Drought
-2 .00 to -2.99	Moderate Drought
-3.00 to -4.00	Severe Drought
<-4	Extreme Drought

5.4.2 Calculation of Weights

Doesken et al. (1991) proposed a method that can reflect the relative contribution of hydrological components to estimate the weights (w_1, w_2, w_3, and w_4). The initial weights of each month for each component was calculated as monthly values divided by the annual total of the component. Garen, D.C. (1993) obtained these weights by a subjective assessment of the impact of each of the components on water availability in the basin in the case of Colorado and Montana. However, in the case of Oregon, the weights were obtained by an objective and arbitrary algorithm. He assessed that in the absence of criterion, there is no way of knowing if the best weights have been found. In this study, the weights were calculated by the area irrigated by each of the hydrologic component namely; the reservoir storage, precipitation, and stream-flow.

5.4.3 MSWSI, SPI, and PNP at Multiple- Timescales

A drought variable should be able to quantify the drought for multiple timescales. The timescale ranges from a month to a few years representing a particular season, number of months, annual, and water-year. In this study MSWSI and SPI determined at 1-, 3-, 6-, 12-, 24- and 48-month time-scales and PNP at Monthly, Yearly and Water-Year time-scales. For calculation of MSWSI, SPI, and PNP at a time-scale, the cumulative value of hydrologic component at that time-scale is considered.

5.5 Results and Discussion

Droughts were identified and their characteristics such as duration, severity, and intensity were determined by MSWSI-12 and SPI-12. Total drought months in the study period classified as per severity by MSWSI-12, SPI-12 and PNP (yearly and water-year). Weather classification of all sub-basins was performed at MSWSI-1, SPI-1, and PNP at monthly timescales. Drought-prone sub-basins were identified by ranking them as per drought severity by MSWSI, SPI, and PNP at multiple timescales. Figure 5.2 shows Time series by MSWSI-12 and SPI-12 at -1,-3,-6,-12,-24 and -48- month timescale.

5.5.1 Time series graph by MSWSI and SPI at Multiple Timescales

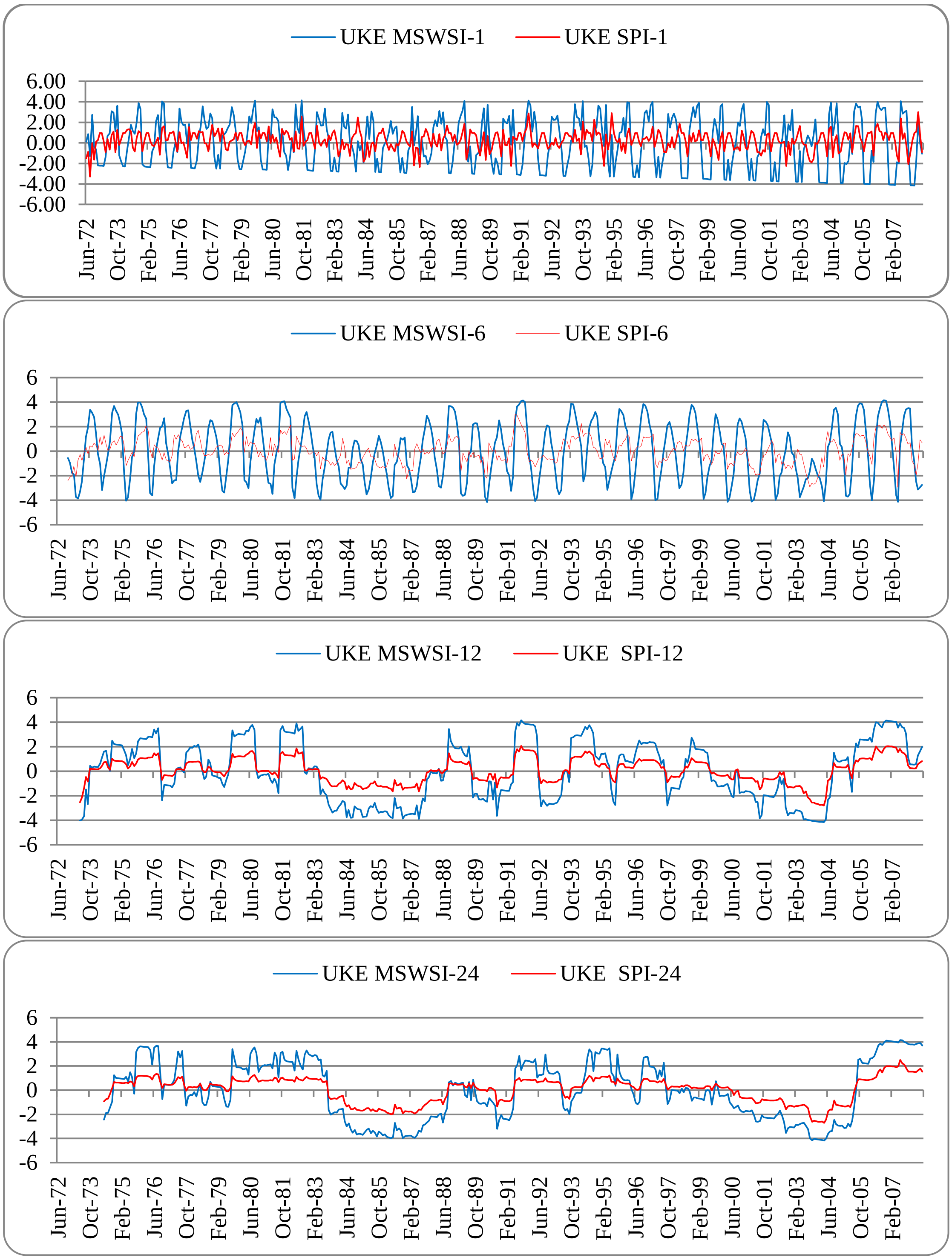


Figure.5.2**:** SPI and MSWSI time series of UKE sub-basin at multiple timescales

Time lag was observed from temporal patterns of MSWSI and SPI time series graphs as per timescale. At MSWSI-1 timescale, droughts were observed in every year from October to May. At SPI-1 timescale, droughts were observed from June to September during drought years and occasionally during other months. At MSWSI-6 timescale, droughts were observed in every year from February to June and during March to May during failure of Monsoon. At MSWSI-12 timescale, droughts were observed in every year from February to June and during March to May during failure of Monsoon. At SPI-12 timescale, droughts were observed from June to March during drought years and occasionally during other months. At 12 and 24-month timescales, both MSWSI and SPI follow the same pattern i.e. start and end of drought periods are nearly same.

5.5.2 Drought identification by MSWSI-12 and SPI-12

Droughts and their characteristics were identified by MSWSI-12 and SPI-12 at the UKE, SB, UB, RB, and UKW sub-basins and the results are as per Table 5.5. It was observed that a number of droughts as per SPI-12 were less as compared to the MSWSI-12 in all sub-basins. As per the MSWSI-12 analysis, it was observed that the UKE sub-basin faced the most severe drought during 1983-88 and the high-intensity drought during 2000-04. The SB sub-basin faced the most severe drought during 2002-06 and the high-intensity drought during 1973 and 1991-93. The UB sub-basin faced the most severe and the high-intensity drought during 1999-2005. The RB sub-basin faced the most severe drought during 2000-05 and the high-intensity drought during 1973. The UKW sub-basin faced the most severe and the high-intensity drought during 2000-2004. A maximum number of droughts (12) were detected at the UKE and SB sub-basins, while least number of droughts (9) was detected at the UKW sub-basin.

Table 5.5: Drought Identification using MSWSI-12 and SPI-12

1: Sr.No.,2: Drought Period, 3: Drought Duration (months), 4: Drought Severity, 5: Drought Intensity										
	MSWSI-12					SPI-12				
	1	2	3	4	5	1	2	3	4	5
Upper Krishna (East)	1	May 1973-Sep. 1973	5	-15.85	-3.17	1	Jun-1972 -Sep-1973	16	-31.1	-1.95
	2	Oct-1976 –Apr. 1977	7	-9.29	-1.33					
	3	Nov 1978-Jul-1979	9	-5.51	-0.61					
	4	Oct. 1980-Aug. 1981	11	-7.1	-0.65					
	5	May 1983-Jul. 1988	63	-167.13	-2.65	2	May-1983-Nov-1987	55	-60.9	-1.11
	6	Sep.1989-May 1991	21	-38.19	-1.82	3	Sep-1989-May-1991	21	-12.1	-0.58
	7	Jun 1992-Jun-1993	13	-29.7	-2.28	4	Jun-1992-Jun-1993	13	-9.7	-0.74
	8	Jun 1995-Aug.1995	3	-6.66	-2.22					
	9	Sep. 1997-Jun-1998	10	-13.54	-1.35					
	10	Aug.1999-Aug.2000	13	-15.27	-1.17					
	11	Oct 2000-Aug.2004	47	-142.84	-3.04	5	Oct-2000-Aug-2004	47	-56.1	-1.19
	12	May 2005-Jun 2005	2	-2.04	-1.02					
Sina Bori	1	May 1973-Sep.1973	5	-12.75	-2.55	1	Jun.1972-Sep-1973	16	-39.4	-2.46
	2	Sep.1976-May 1978	21	-46.44	-2.21	2	Sep-1976-May-1978	21	-20.1	-0.96
	3	June 1979-Aug. 1979	3	-2.70	-0.90					
	4	June 1981-Sept. 1981	4	-4.27	-1.07	3	Jun.1981-Sep-1981	4	-2.2	-0.54
	5	Aug. 1982-July 1983	12	-25.50	-2.12					
	6	Sept. 1984-May 1985	9	-11.12	-1.24	4	Sep.1984-May 1985	9	-5.0	-0.56
	7	July 1985-Oct. 1987	28	-64.84	-2.32	5	Jul.1985-Oct.1987	28	-25.4	-0.91
	8	Oct. 1991-Sept. 1993	24	-60.53	-2.52	6	Oct-1991-Sep-1993	24	-22.8	-0.95
	9	Sept. 1994-July 1996	23	-48.98	-2.13	7	Sep-1994-Sep.1995	13	-13.2	-1.01
	10	Aug. 1997-June 1998	11	-24.11	-2.19	8	Aug-1997-Jun-1998	11	-8.4	-0.76
	11	June 2001-May 2002	12	-18.49	-1.54	9	Jun.2001-May-2002	12	-6.1	-0.51
	12	Aug. 2002-May 2006	46	-97.47	-2.12	10	Sep.2002-Jul-2005	35	-34.3	-0.98
Upper Bhima	1	May 1973-Sep. 1973	5	-11.49	-2.30	1	Jun.1972-Sep.1973	16	-27.4	-1.71
	2	July 1974-May 1975	11	-12.94	-1.18					
	3	Aug. 1977-Oct. 1977	3	-3.41	-1.14					
	4	July 1978-Aug. 1979	14	-18.89	-1.35	2	Jul.1978-Aug.1979	11	-7.9	-0.72
	5	July 1982-Aug. 1983	14	-34.39	-2.46	3	Jul.1982-Jul-1983	13	-15.5	-1.19
	6	July 1985-Aug. 1988	38	-90.16	-2.37	4	Jul.1985-Jun.1988	36	-37.3	-1.04
	7	Sept. 1989-June 1990	10	-7.63	-0.76					
	8	June 1992-April 1994	23	-29.70	-1.29	5	Jun.1992-Nov.1993	18	-10.34	-0.57
	9	July 1995-July 1996	13	-24.51	-1.89	6	Jun.1995-May 1996	12	-8.8	-0.73
	10	Dec. 1999-May 2005	66	-165.96	-2.51	7	Jan-2000-Aug.2004	56	-76.2	-1.36
Remaining Bhima	1	May 1973-Sep. 1973	5	-14.05	-2.81	1	Jun. 1972- Sep. 1973	16	-35	-2.18
	2	July 1977-Jan. 1978	7	-6.12	-0.87					
	3	June 1978-Aug. 1978	3	-1.96	-0.65					
	4	Sept. 1982-Aug. 1983	12	-29.06	-2.42	2	Sep.1982- Aug-1983	12	-9.7	-0.81
	5	Aug. 1984-Nov. 1987	40	-87.01	-2.18	3	Oct.1983-May-85	20	-7.5	-0.37
	6	Sep. 1990-Sep. 1990	1	-1.41	-1.41	4	Sep.1985- Sep.1987	25	-24.6	-0.98
	7	Oct. 1991-Sept. 1993	24	-46.38	-1.93	5	Oct.1991- Sep.1993	24	-18.1	-0.75
	8	Apr.1995-July 1996	16	-29.53	-1.85	6	Oct.1994-Jun.1996	21	-9.9	-0.47
	9	Oct. 1997-June 1998	9	-6.23	-0.69	7	Sep.2000-May.2002	23	-19	-0.82
	10	June 2000-June 2005	61	-152.09	-2.49	8	Sep.2002-Aug.2004	24	-38.6	-1.61
Upper Krishna (West)	1	May 1973-Sep. 1973	5	-11.25	-2.25	1	Jun.1972-Sep.1973	17	-27.5	-1.62
	2	July 1974-May 1975	11	-13.37	-1.22					
	3	July 1981-Aug. 1983	26	-32.66	-1.26					
	4	June 1984-May 1989	60	-124.31	-2.07	2	Aug.1984-Aug.1988	49	-49.7	-1.01
	5	July 1989-July 1990	13	-25.16	-1.94	3	Jul.1989-Mar.1991	21	-13.1	-0.63
	6	July 1992-Mar. 1993	9	-4.28	-0.48					
	7	July 1995-May 1997	23	-36.83	-1.60	4	Jul.1995-May1997	23	-13.5	-0.59
	8	Aug. 1998-May 1999	10	-12.51	-1.25	5	Aug.1998-May.1999	10	-3.5	-0.35
	9	June 2000-July 2004	50	-152.43	-3.05	6	Jun.2000-Aug.2004	51	-63	-1.24

As per the SPI-12 analysis, it was observed that the UKE sub-basin faced the most severe and the high-intensity drought during 1983-87. The SB sub-basin faced the most severe and high-intensity drought during 1972-73.The UB sub-basin faced the most severe drought during 2000-2004 and high-intensity drought during 1972-73. The RB sub-basin faced the most severe drought during 2002-04 and the high-intensity drought during 1972-73. The UKW sub-basin faced the most severe drought during 2000-2004 and the high-intensity during 1972-73. A maximum number of droughts (10) was detected at the SB sub-basin, while least number of droughts (9) was detected at the UKE (5) sub-basin.

5.5.3 Drought months Classification at MSWSI-12 and SPI-12 Time-Scale

5.5.3.1 Drought months Classification at MSWSI-12 Time-Scale

Droughts were classified as per MSWSI-12 timescale for all five sub-basins and the results are shown in Figure 5.3.

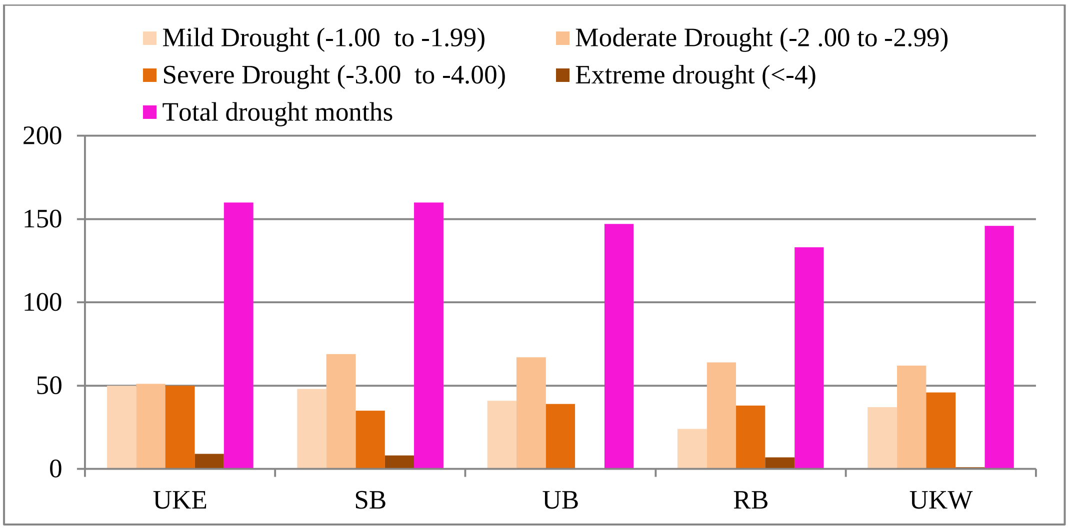


Figure 5.3: Classification of Droughts at MSWSI-12 Time-Scale

It is observed that that total number of drought months was highest (160) at the UKE and SB sub-basin, while it was least (133) for the RB sub-basin. Mild drought months were highest (50) at the UKE sub-basin, while it was least (24) for the RB sub-basin. A number of moderate drought months were highest (69) for the SB sub-basin, while it was least (51) for the UKE sub-basin. A number of severe drought months were highest (50) for the UKE sub-basin, while it was least (35) for the SB sub-basin. A number of extreme drought months were highest (9) for the UKE sub-basin, followed by (8) for the SB sub-basin and (7) for the RB sub-basin.

5.5.3.2 Drought months Classification at SPI-12 Time-Scale

Droughts were classified as per SPI-12 timescale for all five sub-basins and the results are shown in Figure 5.4.

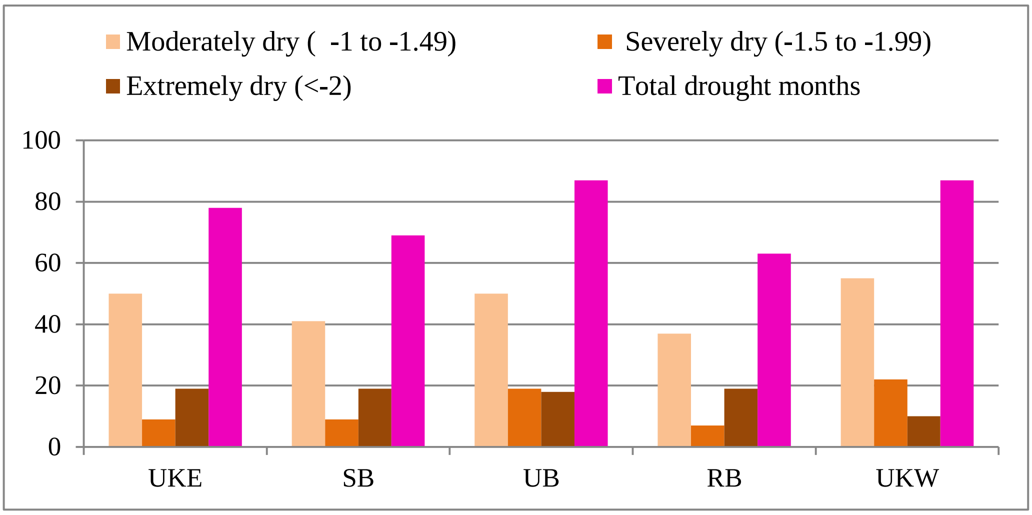


Figure 5.4: Classification of Droughts at SPI-12 Time-Scale

It is observed that total numbers of drought months were highest (87) at the UB and UKW sub-basin, while they were lowest (63) for the RB sub-basin. Moderately dry months were highest (55) at the UKW sub-basin, while they were lowest (37) for the RB sub-basin. Severely dry months were highest (22) for the UKW sub-basin, while they were least (7) for the RB sub-basin. Extremely dry months were least (10) for the UKW sub-basin.

5.5.3.3 Drought years Classification by PNP at Yearly and Water-Year timescale

Droughts were classified at the Yearly basis and Water-Year basis at all sub-basins for the period June 1972 – May 2008 and the results are as per Figure 5.5 and Figure 5.6 resp.

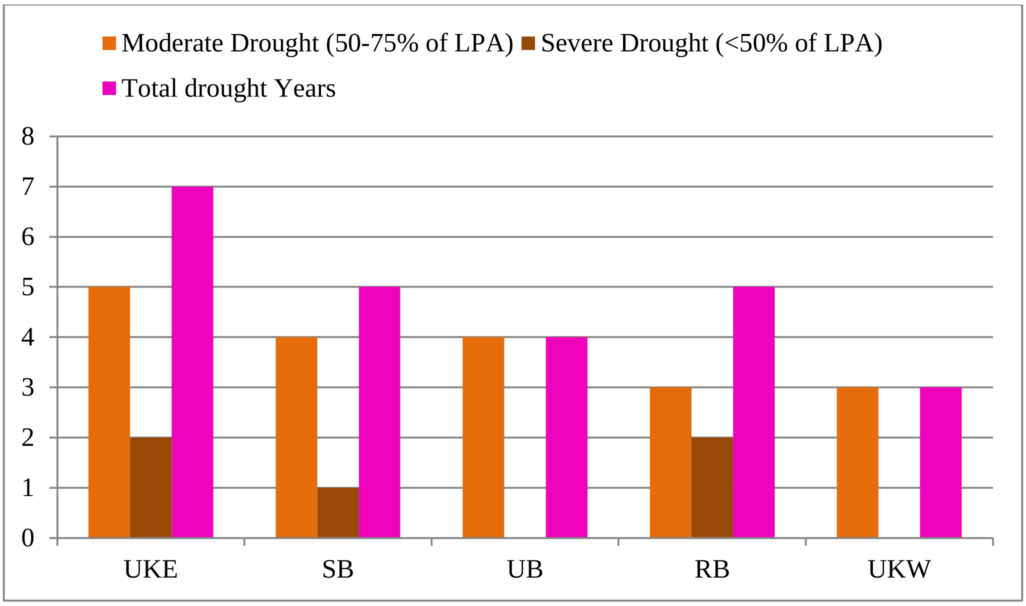


Figure 5.5: Classification of Droughts by PNP at Yearly basis

From Figure 5.5 it is observed that the UKE sub-basin was experiencing the highest number of total, moderate and extreme drought years while the UKW sub-basin was experiencing the least number of Total drought years. The Severe droughts years were not observed at the UB and UKW sub-basin.

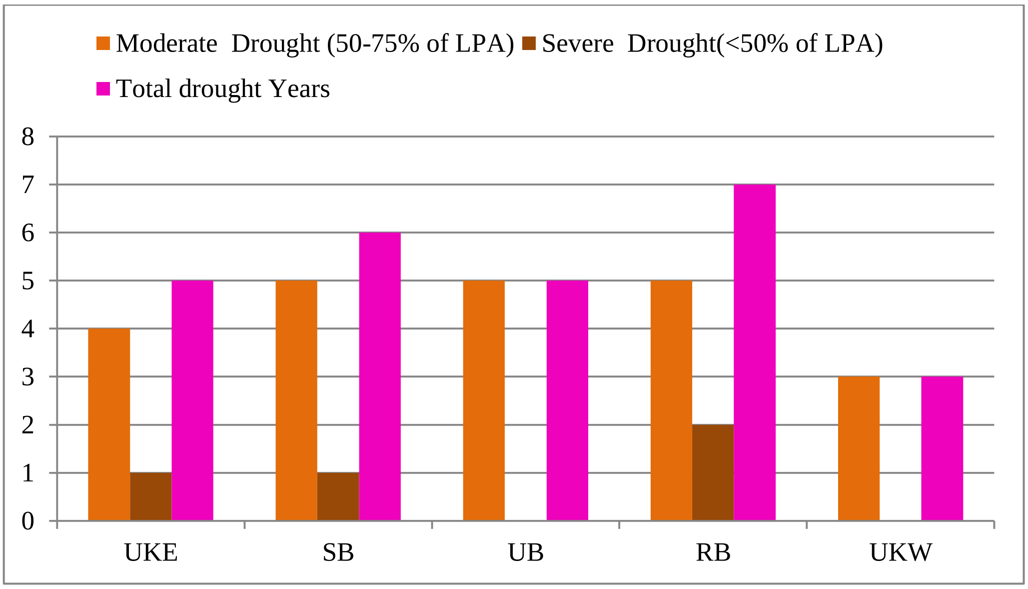
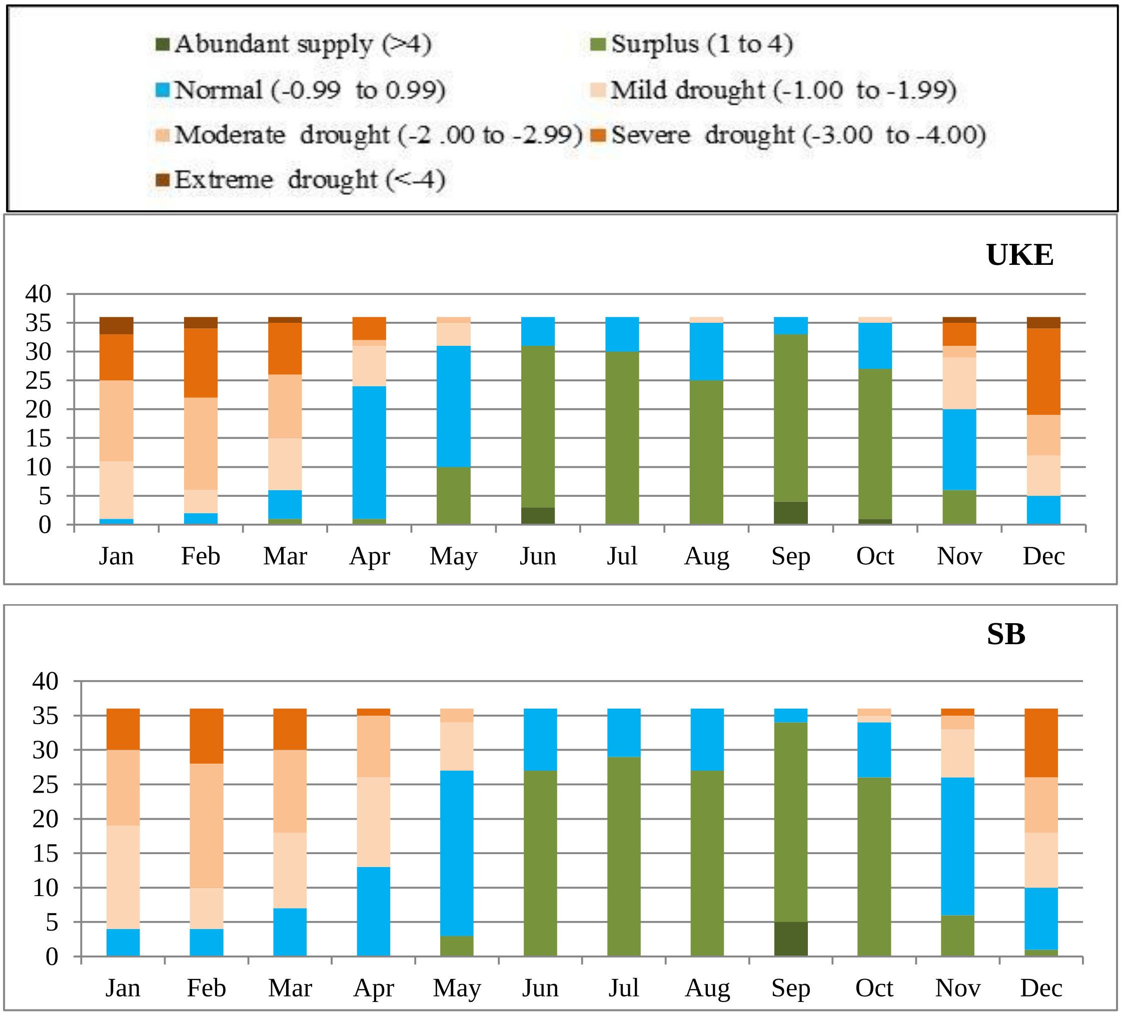


Figure 5.6: Classification of Droughts by PNP at Water-Year basis

From Figure 5.6 it is observed that the RB sub-basin was experiencing the highest number of total, moderate and extreme drought years while the UKW sub-basin was experiencing the least number of Total drought years. The Severe droughts years were not observed at the UB and UKW sub-basin.

5.5.4 Month wide weather classification at MSWSI-1 timescale

Month wide weather classification is done by MSWSI-1 timescale, over the study period and the results are shown in Figure 5.7.



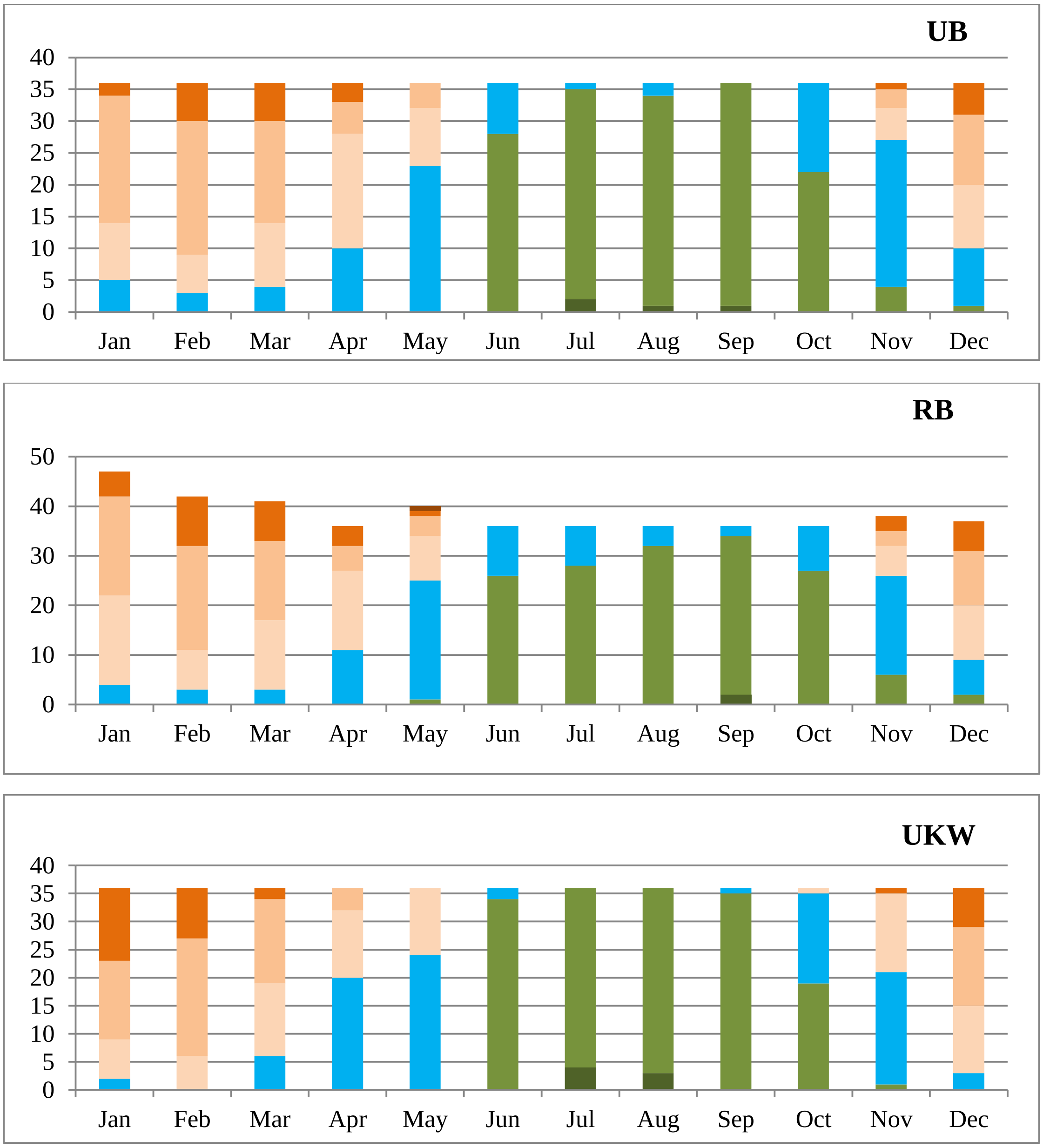


Figure.5.7**:** Month wide weather classification of sub-basins at MSWSI-1 timescale

Weather classification of the UKE sub-basin as per Figure 5.7 revealed that January month was having a maximum number of drought conditions. No drought conditions were observed during June, July, and September months. August and October months were having least number of drought conditions. September month was having a maximum number of wet conditions. No wet conditions were observed during January, February, and December months. December month was having least number of wet conditions. The Extreme drought conditions were not observed during April-October. Abundant supply conditions were highest during September month.

Weather classification of the SB sub-basin revealed that January and February months were having a maximum number of drought conditions. No drought conditions were observed during June – September. October month was having less number of drought conditions. September month was having a maximum number of wet conditions. No wet conditions were observed during January-April. December month was having least number of wet conditions. The Extreme drought conditions were not observed. Abundant supply conditions were observed during September for only 5 months.

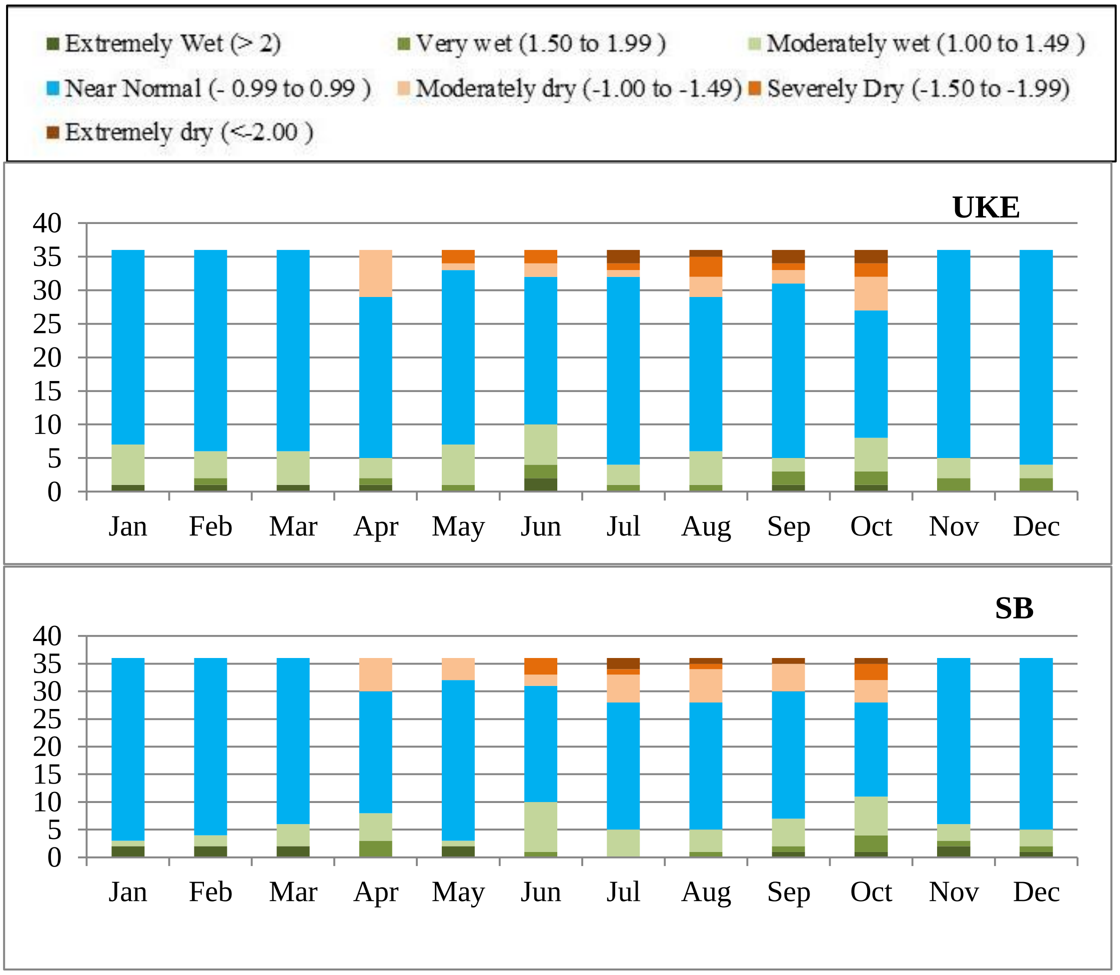
Weather classification of the UB sub-basin revealed that February month was having a maximum number of drought conditions. No drought conditions were observed during June – October. May month was having less number of drought conditions, while July month was having a maximum number of wet conditions. No wet conditions were observed during January-May. December month was having least number of wet conditions. The Extreme drought conditions were not observed. Abundant supply condition was observed during July-September for only 4 months.

Weather classification of the RB sub-basin revealed that February and March months were having a maximum number of drought conditions. No drought conditions were observed during June – October. May month was having less number of drought conditions. September month was having a maximum number of wet conditions. No wet conditions were observed during January-April. May month was having least number of wet conditions. The Extreme drought condition was observed in May for only l month. Abundant supply conditions were observed during September for only 2 months.

Weather classification of the UKW sub-basin revealed that that February month was having a maximum number of drought conditions. No drought conditions were observed during June to September months. October month was having least number of drought conditions. July and August months were having a maximum number of wet conditions. No wet conditions were observed during January to May and December months. November month was having least number of wet conditions. Extreme drought conditions were not observed. The Severe drought conditions were not observed during April to October. Abundant supply condition was highest during July month.

5.5.5 Month wide variation of weather at SPI -1 timescale

Month wide weather variation is done by SPI-1 timescale (Figure 5.8), which resembles average monthly rainfall over the study period and gives a fair picture of monthly rainfall pattern.



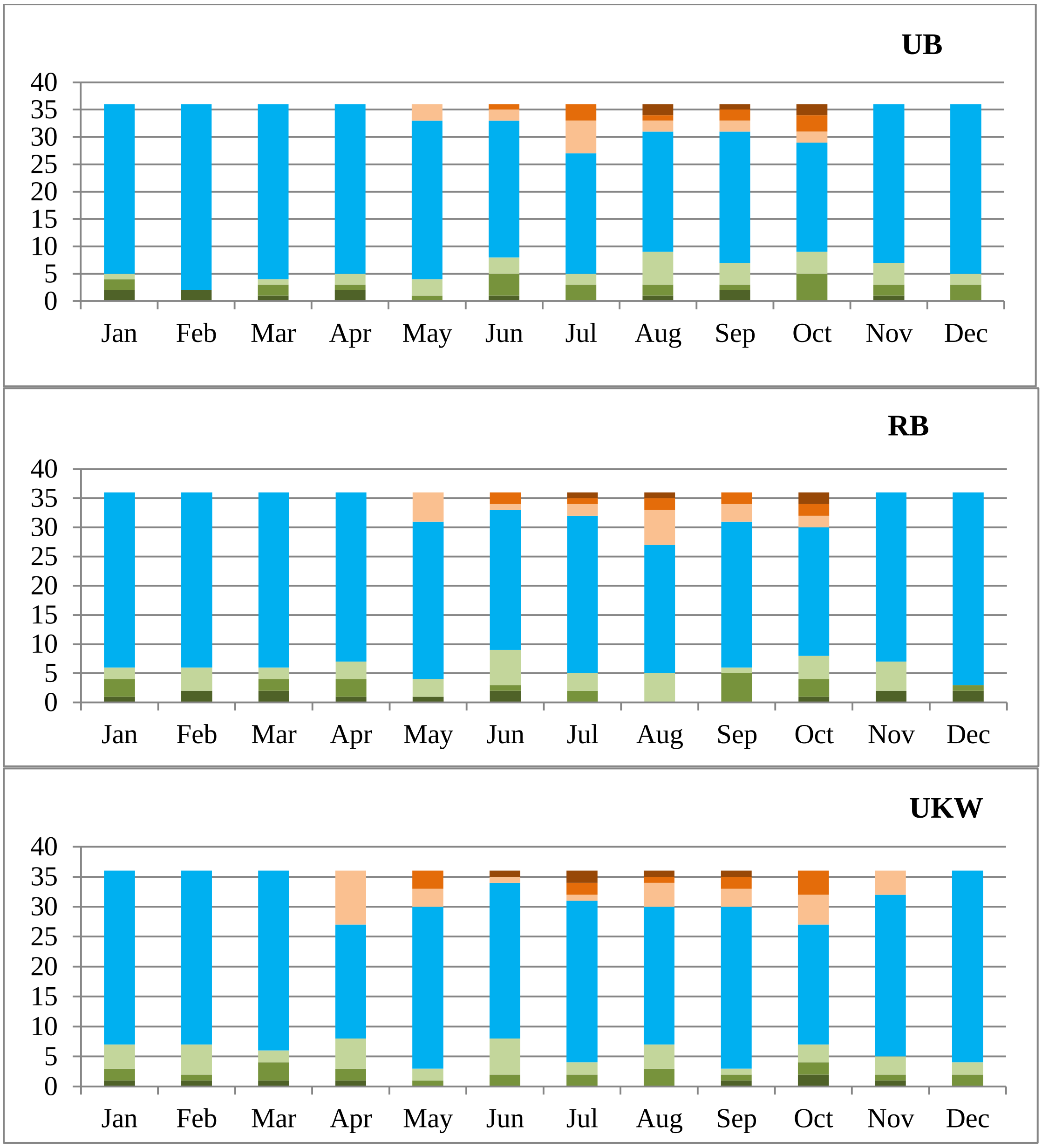


Figure.5.8**:** Month wide weather classification of sub-basins at SPI-1 timescale

Weather classification of the UKE sub-basin revealed that October month was having a maximum number of drought conditions. June was having a maximum number of wet conditions. No drought conditions were observed in Jan.-March and Nov.-Dec. months.

Weather classification of the SB sub-basin revealed that July-August and October months were having a maximum number of drought conditions. June was having a maximum number of moderately wet conditions. No drought conditions were observed in Jan.-March and Nov.-Dec. months.

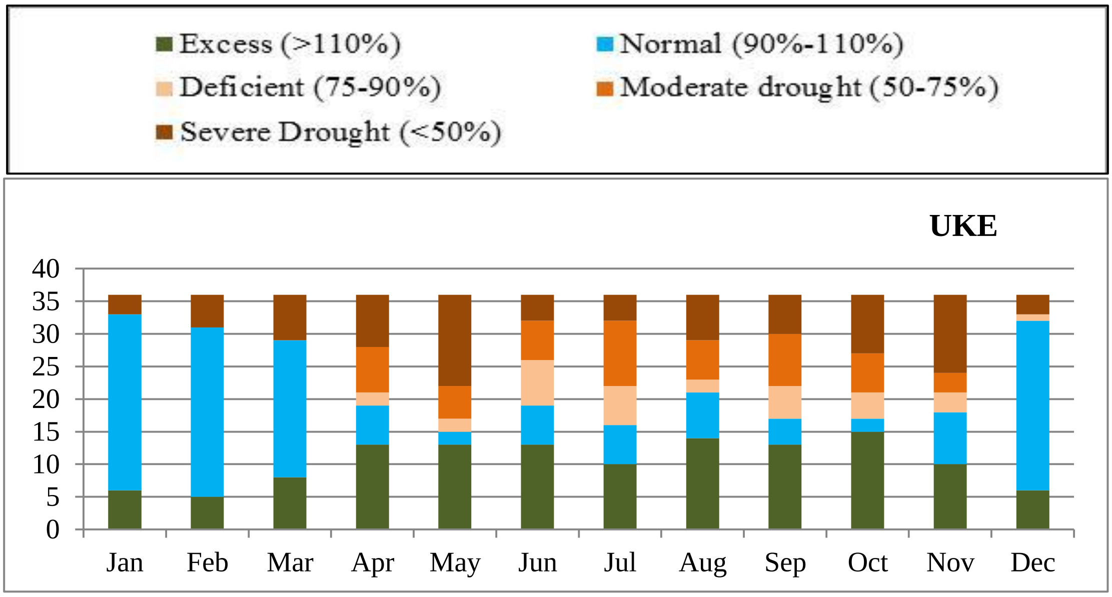
Weather classification of the UB sub-basin revealed that July was having a maximum number of drought months. October was having a maximum number of very wet conditions. No drought conditions were observed in Jan.-April and Nov.-Dec. months.

Weather classification of the RB sub-basin revealed that August was having a maximum number of drought months. September was having a maximum number of very wet conditions. No drought conditions were observed in Jan.-April and Nov.-Dec. months.

Weather classification of the UKW sub-basin revealed that October month was having a maximum number of drought conditions. No drought conditions were observed in Jan.-March and December months.

5.5.6 Month wide variation of weather at PNP Monthly timescale

Month wide weather variation was done by PNP (Figure 5.9), which is average monthly rainfall over the study period and gives a fair picture of monthly rainfall pattern.



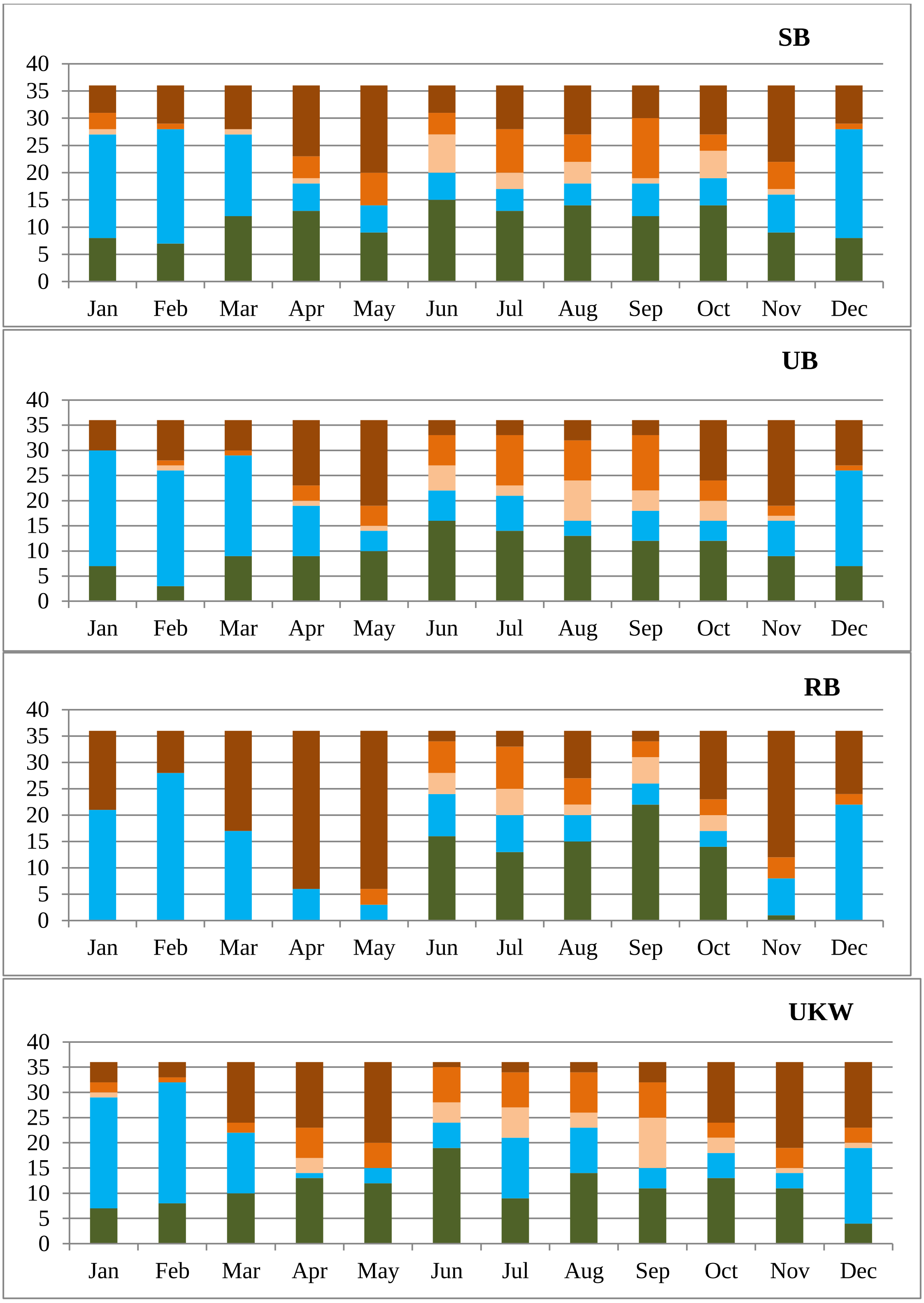


Figure.5.9**:** Weather classification of sub-basins by PNP Monthly timescale

Weather classification of the UKE sub-basin revealed that July was having a maximum number of Moderate drought months, while May was having a maximum number of severe drought months. May was having highest drought months, while January was having least number of drought months. October was having a maximum number of excess rainfall months.

Weather classification of the SB sub-basin revealed that September was having a maximum number of Moderate drought months, while May was having a maximum number of severe drought months. May was having highest drought months, while January-March and December were having least number of drought months. June was having a maximum number of excess rainfall months.

Weather classification of the UB sub-basin revealed that September was having a maximum number of Moderate drought months, while May and November were having a maximum number of severe drought months. May was having highest drought months, while January was having least number of drought months. June was having a maximum number of excess rainfall months.

Weather classification of the RB sub-basin revealed that July was having a maximum number of Moderate drought months, while April and May were having a maximum number of severe drought months. May was having highest drought months, while September was having least number of drought months. September was having a maximum number of excess rainfall months.

Weather classification of the UKW sub-basin revealed that August was having a maximum number of Moderate drought months, while November was having a maximum number of severe drought months. May and November were having highest drought months, while December was having least number of drought months. June was having a maximum number of excess rainfall months.

5.5.7 Drought characteristics by MSWSI and SPI at multiple timescales

Drought characteristics of all sub-basins by MSWSI and SPI at 6 timescales are as per Table 5.6.

Table 5.6 Drought characteristics by MSWSI and SPI at multiple timescales

1: Timescales, 2: Total drought Severity, 3: Drought months, 4: Drought Incidences, 5:Average Drought Intensity 6: Average Drought Severity												
Sub-basins	MSWSI						SPI					
	1	2	3	4	5	6	1	2	3	4	5	6
Upper Krishna (East)	1	-445.7	208	40	-2.1	-11.1	1	-113.06	104	48	-1.21	-2.36
	3	-449.5	214	36	-2.1	-12.5	3	-170.49	203	32	-0.89	-5.33
	6	-446.9	214	35	-2.1	-12.8	6	-220.41	248	25	-0.86	-8.82
	12	-436.6	200	12	-2.2	-36.4	12	-226.45	227	8	-0.90	-28.31
	24	-419.5	186	11	-2.3	-38.1	24	-250.7	226	6	-0.78	-41.78
	48	-391.8	170	2	-2.3	-195.9	48	-244.17	226	3	-1.08	-81.39
Sina Bori	1	-393.5	219	39	-1.8	-10.1	1	-124.48	143	55	-1.01	-2.26
	3	-416.1	210	36	-2.0	-11.6	3	-197.05	223	43	-0.86	-4.58
	6	-413.0	218	35	-1.9	-11.8	6	-236.5	263	35	-0.87	-6.76
	12	-417.2	198	12	-2.1	-34.8	12	-205.51	213	12	-0.86	-17.13
	24	-409.4	199	7	-2.1	-58.5	24	-209.01	200	8	-1.02	-26.13
	48	-368.5	186	8	-2.0	-46.1	48	-182.53	174	4	-1.01	-45.63
Upper Bhima	1	-411.7	231	36	-1.8	-11.4	1	-53.47	75	34	-0.79	-1.57
	3	-417.8	220	36	-1.9	-11.6	3	-88.56	175	34	-0.57	-2.60
	6	-413.0	211	36	-2.0	-11.5	6	-100.67	253	32	-0.34	-3.15
	12	-399.1	197	10	-2.0	-39.9	12	-132.12	240	6	-0.47	-22.02
	24	-386.8	192	8	-2.0	-48.4	24	-145.62	264	4	-0.40	-36.41
	48	-351.9	169	4	-2.1	-88.0	48	-161.64	268	3	-0.62	-53.88
Remaining Bhima	1	-408.5	225	36	-1.8	-11.3	1	-97.01	88	35	-1.21	-2.77
	3	-425.2	220	35	-1.9	-12.1	3	-178.24	201	36	-0.93	-4.95
	6	-423.6	211	35	-2.0	-12.1	6	-221.62	233	29	-0.92	-7.64
	12	-373.8	178	10	-2.1	-37.4	12	-212.1	226	11	-0.86	-19.28
	24	-382.9	176	7	-2.2	-54.7	24	-230.22	230	6	-0.96	-38.37
	48	-356.9	184	4	-1.9	-89.2	48	-230.3	247	4	-0.88	-57.58
Upper Krishna (West)	1	-422.0	231	38	-1.8	-11.1	1	-113.06	104	48	-1.21	-2.36
	3	-431.2	218	36	-2.0	-12.0	3	-170.49	203	32	-0.89	-5.33
	6	-426.6	211	36	-2.0	-11.8	6	-220.41	248	25	-0.86	-8.82
	12	-410.3	196	9	-2.1	-45.6	12	-226.45	227	8	-0.90	-28.31
	24	-403.8	200	6	-2.0	-67.3	24	-250.7	226	6	-0.78	-41.78
	48	-378.1	183	4	-2.1	-94.5	48	-244.17	226	3	-1.08	-81.39

As per MSWSI analysis, it is observed that for all sub-basins, total drought severity was highest for 3-month timescale and gradually decreased as the timescale increased and was least for the 48-month timescale. Total drought month was maximum for 1-month timescale except for the UKE sub-basin and lowest for the 48-month timescale for all sub-basins. The number of drought incidences decreased with increase in timescale for all sub-basins. Average drought intensity was found to be more for higher timescales for all sub-basins. Average drought severity increased with the timescale for all sub-basins.

As per SPI analysis, it is observed that for all sub-basins, total drought severity was least for 1-month timescale and gradually increased with timescale and was highest for 24-month timescale except for the UB sub-basin. Total drought month was highest for 6-month timescale except for the UB and RB sub-basins (48-month timescale) and lowest for the 1-month timescale for all sub-basins. The number of drought incidences decreased with increase in timescale for all sub-basins. Average drought intensity was found to be highest for the 1-month timescale for all sub-basins. Average drought severity increased with the timescale for all sub-basins.

5.5.8 Identification of drought-prone Sub-basins as per MSWSI, SPI and PNP

Due to the geographical location such as rain shadow area, certain areas are always susceptible to droughts. These areas need to be identified and priority to be given in in drought relief and contingency planning. The sub-basin having highest sum is given rank 1 and other sub-basins in descending order of their sum.

5.5.8.1 Identification of drought-prone Sub-basins as per MSWSI

Ranking of sub-basins is done as per drought severity at multiple timescales. Summation of extreme droughts at 6 timescales is performed at each sub-basin and the results are as per Table 5.7. It is found that the UKE sub-basin was the most droughts prone while UB sub-basin was the least drought-prone.

Table 5.7: Ranking of drought-prone Sub-basins as per MSWSI

MSWSI values	Drought Classification	UKE	SB	UB	RB	UKW
<-4	Sum of Extreme drought months at 6 timescales	53	24	1	28	3
Rank		1	3	5	2	4

5.5.8.2 Identification of drought-prone Sub-basins as per SPI

Ranking of sub-basins is done as per drought severity at multiple timescales. Summation of extreme droughts at 6 timescales is performed at each sub-basin and the results are as per Table 5.8. It is found that UKE sub-basin was the most droughts prone while UKW sub-basin was the least drought-prone.

Table 5.8: Ranking of drought-prone Sub-basins as per SPI

SPI values	Drought Classification	UKE	SB	UB	RB	UKW
<-2	Extremely dry	80	61	69	78	48
Rank		1	4	3	2	5

5.5.8.3 Identification of drought-prone Sub-basins as per PNP

To identify drought-prone sub-basins, summation of total drought years of each sub-basin by Yearly and Water- Year is performed as per Table 5.9. It is found that UKE and RB sub-basin were the most droughts prone while UKW sub-basin was the least drought-prone.

Table 5.9: Ranking of drought-prone Sub-basins as per PNP

Total drought years	**UKE**	**SB**	**UB**	**RB**	**UKW**
As per Yearly basis	7	5	4	5	3
As per Water-Year basis	5	6	5	7	3
Total Sum	12	11	9	12	6
Rank	1	2	3	1	4

5.9 Conclusion

Sub-basin wide drought analysis over the Krishna basin in Maharashtra was done using the MSWSI, SPI, and PNP. Classification of sub-basins was done on basis of naturally available quantum of water. Time series graph by the MSWSI and SPI at multiple timescales of all sub-basins were analyzed. During the MSWSI analysis, it was observed that as the timescale increases, the start of drought period is delayed same as the timescale. Drought terminates by June with the start of monsoon for all timescales. Drought period was during the non-monsoon season. At MSWSI-6 and MSWSI-12 timescales, drought period starts in February and ends in June. These two timescales are applicable for water resource management since water availability in streams and reservoirs starts depleting from February and is at lowest at the first week of June. During the failure of monsoon, drought period was extended up to May of next water year for MSWSI-6 and MSWSI-12 timescales. As per SPI analysis, SPI-1 and SPI-3 timescales are applicable to access water availability during monsoon (June to September) and SPI-6 and SPI-12 timescales during monsoon and post-monsoon (June to March). It is observed that drought by MSWSI continues further up to start of next monsoon season even if no drought conditions are shown by SPI. Therefore MSWSI reflects true conditions of water availability.

Severe and high-intensity droughts were identified by MSWSI-12 for all sub-basins. It was found that the UKE sub-basin faced most severe drought during 1983-88 and high-intensity drought during 2000-04. The SB sub-basin faces most severe drought during 2002-06 and high-intensity drought during 1973 and 1991-93. The UB sub-basin faces most severe and high-intensity drought during 1999-2005. The RB sub-basin faced most severe drought during 2000-05 and high-intensity drought during 1973. The UKW sub-basin faces most severe and high-intensity drought during 2000-2004. A maximum number of droughts (12) are detected at the UKE and SB sub-basins, while least number of droughts (9) is detected at UKW sub-basin.

As per the SPI-12 analysis, similarity regarding most severe droughts and high-intensity droughts was observed for the UB, RB and UKW sub-basins. It was observed that the UKE sub-basin faced most severe and high-intensity drought during 1983-87. The SB sub-basin faced most severe and high-intensity drought during 1972-73. The UB, RB and UKW sub-basins faced most severe drought during 2000-04 and high-intensity drought during 1972-73. A maximum number of droughts (10) was detected at the SB sub-basin, while least number of droughts (9) was detected at the UKE (5) sub-basin.

Drought classification of all 5 sub-basins in the study area was performed by MSWSI-12, SPI-12 and PNP drought indices at Yearly and Water-Year time-scales. A number of drought months as per SPI was found to be much less than MSWSI. The RB sub-basin was having least number of total drought months, mild drought months and extreme drought months as per MSWSI-12 analysis; while total drought months, moderate and extreme dry months are least as per SPI-12 analysis. The UKE sub-basin was having the highest number of total drought months, severe drought months and extreme drought months as per MSWSI-12 and total drought months, moderate and extreme drought years as per PNP-Yearly analysis. The UKW sub-basin was having the highest number of total drought months, moderately dry and severely dry months and least number of extremely dry months as per SPI-12 analysis. The UKW sub-basin was experiencing the least number of total drought years as per PNP Yearly and Water- Year analysis. Severe droughts years were not observed at the UB and UKW sub-basin as per PNP Yearly and Water- Year analysis.

Month wide weather variation was analyzed for all sub-basins at MSWSI-1, SPI-1 and PNP- Monthly scale. As per MSWSI-1 analysis, wet conditions were observed at the UB Sub-basin during June to September. September was wettest month and February was the driest month. Wet conditions were observed at the RB sub-basin during May to December. September was the wettest month and February was the driest month. Wet conditions were observed at the SB sub-basin during May to December. September was the wettest month and February was the driest month. Wet conditions were observed at the UKE sub-basin during March to November. September was the wettest month and February was the driest month. Wet conditions were observed at the UKW sub-basin during June to November. July was the wettest month and February was the driest month. Wet conditions were observed during Monsoon period. Drought conditions were observed during Non-Monsoon period. MSWSI -1 reflects true moisture availability at real-time basis. MSWSI-1 is applicable for agriculture drinking water supply planning.

As per SPI-1 analysis, wet conditions were observed at the UB sub-basin during whole year. October was the wettest month and July was having most drought months. Wet conditions were observed at the RB sub-basin during the whole year. June was the wettest month and August was having most drought months. Wet conditions were observed at the SB sub-basin during whole year. June was the wettest month and July was having the most drought months. Wet conditions were observed at the UKE sub-basin during whole year. June was the wettest month and October was having the most drought months. Wet conditions were observed at the UKW sub-basin during whole year. June was the wettest month and October was having the most drought months

As per PNP- Monthly analysis, Wet conditions were observed at the UB sub-basin during whole year. June was the wettest month and May was having the most drought months. Wet conditions were observed at the RB sub-basin during June to November. September was the wettest month and May was having the most drought months. Wet conditions were observed at the SB Sub-basin during whole year. June was the wettest month and May was having the most drought months. Wet conditions were observed at the UKE Sub-basin during whole year. October was the wettest month and May was having the most drought months. Wet conditions were observed at the UKW Sub-basin during whole year. June was the wettest month and November was having the most drought months.

Drought characteristics of sub-basins by MSWSI at multiple times-scale revealed that, for all sub-basins, total drought severity was highest for 3-month timescale and gradually decreased as the timescale increased and was least for 48-month timescale. Total drought month was maximum for 1-month timescale except for the UKE sub-basin and lowest for 48-month timescale for all sub-basins. The number of drought incidences decreased with increase in timescale for all sub-basins. Average drought intensity was found to be more for higher timescales for all sub-basins. Average drought severity increased with timescale for all sub-basins.

Drought characteristics of sub-basins by SPI at multiple time-scale revealed that total drought severity was least for 1-month timescale and gradually increased with timescale and was highest for 24-month timescale except for the UB sub-basin. Total drought month was highest for 6-month timescale except for the UB and RB sub-basins (48-month timescale) and lowest for 1-month timescale for all sub-basins.

Number of drought incidences decreased with increase in timescale for all sub-basins. Average drought intensity was found to be highest for 1-month timescale for all sub-basins. Average drought severity increased with timescale for all sub-basins.

Ranking of sub-basins was done as per drought severity by MSWSI at multiple timescales revealed that the UKE sub-basin was the most drought-prone while the UB sub-basin was the least drought-prone, while that by SPI at multiple timescales revealed that the UKE sub-basin is the most drought-prone while the UKW sub-basin was the least drought-prone.

CHAPTER 6

DROUGHT TREND ANALYSIS

6.1 Introduction

The study of drought trends is extremely important as it is related to food security and management of scarce water resource, which becomes critical in case of drought events. In this chapter, the trend of drought events by Standardized precipitation index (SPI) at 1-, 6-, 12-, 24- and 48- month timescales, Percent of Normal Precipitation (PNP) at Annual and Water-Year timescales and Seasonal rainfall (winter, pre-monsoon, monsoon and post-monsoon timescales) are computed using long time series (1960-2012) of monthly precipitation data at 59 stations in the study area. Similarly drought trend of MSWSI and SPI at 1-, 3-, 6-, 12-, 24- and 48- month timescales, Percent of Normal Precipitation (PNP) at Annual , Water-Year timescales and Seasonal rainfall (pre-monsoon, monsoon and post-monsoon timescales) are computed using long time series (1972-2008) of monthly precipitation data at 05 sub-basins in the study area. The statistical significance at 95% confidence level as per Mann-Kendall and Sen's slope estimator are used for drought trend analysis.

6.2 Methodology

The study of drought trends performed by analyzing the time series of a drought index. SPI and PNP are two drought indices to monitor and quantify Meteorological drought, similarly, MSWSI is used to monitor and quantify Hydrological drought. Trend analysis of SPI, MSWSI and PNP time series revealed the drought trends at the particular station as well as sub-basins. The drought trend of SPI at 1-, 6-, 12-, 24- and 48- month timescales were analyzed in the study area. To investigate the changes in rainfall for different seasons, a year was distributed into four seasons: winter (January-February), pre-monsoon (March-May), monsoon (June-September), and post-monsoon (October-December). SPI-12(Dec), Water Year -Dec, SPI-12(May) and Water Year- May considers the cumulative 12 months precipitation totals at the end of December and May respectively. MSWSI allows a comparison of water supply availability for each region containing different variables such as precipitation, stream flow, and reservoir inflow. The analysis of drought trend of MSWSI at 1-, 3-, 6-, 12-, 24- and 48- month timescales at five sub-basins Upper Bhima (RB), Remaining Bhima (RB), Sina-Bori Benetura (SB), Upper Krishna East (UKE) and Upper Krishna West (UKW) in the study area. Theissen Polygon tool in Arc GIS 10.2 used to construct polygons corresponding to the area of influence of 59 rain gauge stations in the study area. Each of the polygons measured in Km^2 and expressed as a percentage of the total study area.

6.2.1 Mann-Kendall Test

The Mann-Kendall statistic S is given as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{1}$$

The application of trend test is done to a time series xi that is ranked from i = 1, 2 …n-1 and x_j, which is ranked from j = i+1, 2 ….n. Each of the data points x_i is taken as a reference point which is compared with the rest of the data point's x_j so that,

$$\operatorname{Sgn}(x_j - x_i) = \begin{cases} +1, > (x_j - x_i) \\ 0, = (x_j - x_i) \\ -1, > (x_j - x_i) \end{cases} \tag{2}$$

It has been documented that when n ≥ 8, the statistic S is approximately normally distributed with the mean.

$$E(S) = 0 \tag{3}$$

The variance statistic is given as

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(i)(i-1)(2i+5)}{18} \tag{4}$$

Where t_i as considered the number of ties up to sample i. The test statistics Z_c is computed as

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{Var(s)}}, S > 0 \\ 0, \ S = 0 \\ \frac{S-1}{\sqrt{Var(S)}}, S < 0 \end{cases} \quad (5)$$

Here Z_c follows a standard normal distribution. A positive (negative) value of Z_c signifies an upward (downward) trend. The significance level, or a Type I error, α, is the probability of rejecting the null hypothesis when it is true. A significance level α is also utilized for testing either an upward or downward monotonic trend. If Z_c appears greater than Zα/2 where α depicts the significance level, then the trend is considered as significant. Significance levels are normally set quite low at values of 0.01, 0.05 or 0.10. The smaller the value of α, the more is the confidence there is that the null hypothesis is really false when it has been identified as such. From the relationship among power, a slope of the trend, and sample size for the given significance level of 0.05 and coefficient of variation CV = 0.5, the power of the test is an increasing function of both the absolute slope and the sample size. In other words, as the sample size increases, the power of the test increases leading to an increased ability to discern the existence of the trend. (Yue S. et al., 2002). In this study significance level (α) of 0.05 i.e., the confidence level (1-α) of 95% as per Mann-Kendall is used for drought trend analysis over the Upper Krishna basin in Maharashtra.

6.2.2 Sen's Slope Estimator Test

The magnitude of the trend is predicted by the Sen's estimator (Sen, 1968). Here, the slope (T_i) of all data pairs is computed as

$$T_i = \frac{x_j - x_k}{j-k} \quad (6)$$

Where x_j and x_k are considered as data values at time j and k (j>k) correspondingly. The median of these N values of Ti is represented as a Sen's estimator of slope which is given as:

$$Qi = \begin{cases} T_{\frac{N+1}{2}} & \text{N is odd} \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right) & \text{N is even} \end{cases} \quad (7)$$

Sen's estimator is computed as

Q_{med}=T (N+1)/2 if N appears odd, and it is considered as

Q_{med}= [TN/2+T (N+2)/2]/2 if N appears even.

In the end, Q_{med} is computed by a two-sided test at 100 (1-α) % confidence interval and then a true slope can be obtained by the non-parametric test. The Positive value of Qi indicates an upward or increasing trend and a negative value of Qi gives a downward or decreasing trend in the time series.

6.3 Results and Discussions

Trend analysis of droughts and its spatial and temporal variability in a changing climate is vital to assess climate-induced changes and suggest adequate water resources management strategies for the future. Trend analysis is carried out at rainfall station as well as sub-basin level.

6.3.1 Trend analysis of drought events at the rainfall stations

Trends in annual, seasonal and multiple timescales were investigated at 59 rainfall stations in the study area. The data were analyzed using basic statistical properties i.e. maximum, minimum, standard deviation, the coefficient of Skewness 'g' and coefficient of Kurtosis 'K'. The coefficient of skewness measures the skewness of a distribution. A data set skewed to the left is to say that it is negatively skewed. A data set skewed to the right is to say that it is positively skewed. The coefficient of Skewness g is positive for 55 stations and negative for 4 stations. The coefficient of Kurtosis K is more peaked for 8 stations for Annual rainfall series.

The Negative and Positive trend at multiple timescales is as shown in Figure 6.1. Out of 59 rainfall stations, SPI-12(Dec) and Water Year- December (WY-Dec) timescales detect positive trend at 2 stations and negative trend at 3 stations. SPI-12(May) and

Water Year-May (WY-May) timescales detect positive trend at 3 stations and negative trend at 2 stations. SPI-1 timescale detects no positive trend while the negative trend in 4 stations. SPI-6 timescale detects the positive trend in 7 stations and the negative trend in 20 stations. SPI-12 timescale detects the positive trend in 13 stations and the negative trend in 22 stations. SPI-24 timescale detects the positive trend in 25 stations and the negative trend in 22 stations. SPI-48 timescale detects the positive trend in 31 stations and the negative trend in 19 stations. Pre-monsoon timescale detects the negative trend in 41 stations. Post-monsoon and Winter rainfall trend analysis detects no significant trend at all stations.

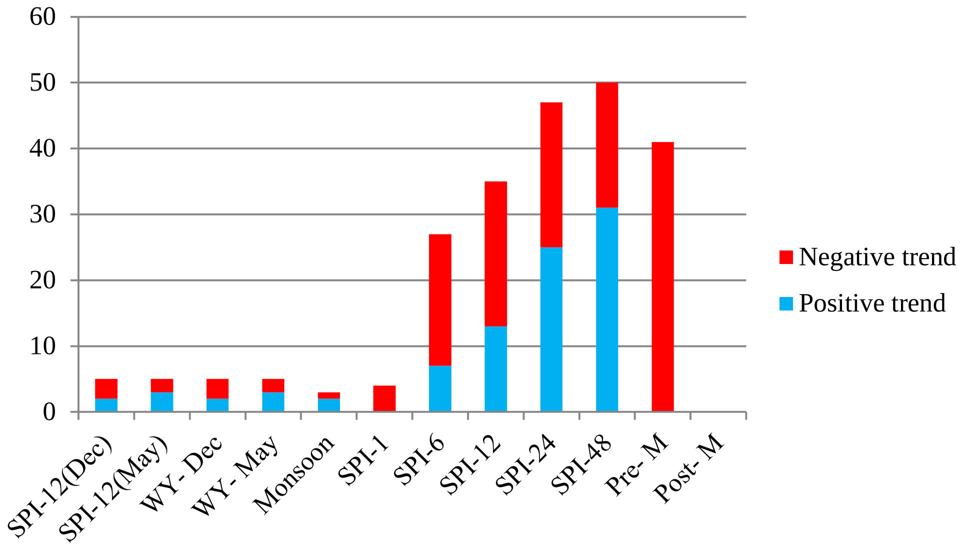


Fig.6.1: Trend analysis at multiple timescales

The magnitude of the trend in the SPI and Pre-monsoon time series, as determined using the Sen's estimator, is as shown in Table no.2, Appendix A. It is observed that magnitude of the trend as per Sen's estimator increases with SPI timescales. Gadhinglaj station from western Maharashtra shows negative trend from SPI-1 to SPI-48, pre & post- monsoon series. Pune station from western Maharashtra shows the positive trend at every timescale excluding pre-monsoon. Tasgaon, Akkalkot stations from the arid region and Gargoti from western Maharashtra, shows the negative trend at every timescale. Wai station shows the positive trend in SPI-

12(May), WY- May, and SPI- 6 to SPI-48 classes. This analysis shows that wet regions are getting wetter while arid regions are getting more arid. The exception is for Gadhinglaj and Gargoti station, which is closer to Western- Ghats is showing the negative trend. SPI-12(Dec), SPI-12(May), Water Year- Dec and Water Year- May shows nearly similar trends.

Table 6.1: Trend Analysis of SPI, PNP, and Seasonal rainfall Timescales

Time Scale	No. of stations having Positive Trend	Study area having Positive Trend (%)	No. of stations having Negative Trend	Study area having Negative Trend (%)	Total percentage of study area having Significant Trend
SPI-12(Dec)	2	2	3	8	10
SPI-12(May)	3	3	2	3	6
WY- Dec	2	2	3	8	10
WY- May	3	3	2	3	6
Monsoon	2	2	1	1	3
Pre-Monsoon	0	0	41	63	63
Post-Monsoon	0	0	0	0	0
SPI-1	0	0	4	10	10
SPI-6	7	10	20	32	42
SPI-12	13	23	22	35	58
SPI-24	25	41	22	37	78
SPI-48	31	51	19	33	84

The results of trend analysis at multiple timescales and the spatial variation of positive and negative trends are as shown in table no.6.1. It is observed that the areas having a significant trend at SPI-12(Dec), SPI-12(May), Water Year -Dec and Water Year- May by SPI increased with timescale.

6.3.2 Trend analysis of drought events at the sub-basin level

Trend analysis at the sub-basin level carried out by the MSWSI, SPI at 1-, 3-, 6-, 12-, 24- and 48- month timescale, and PNP at Annual, Water-Year, Pre-Monsoon, Monsoon and Post-Monsoon timescale.

Table 6.2: Sen's estimator of slope at Sub-basins for MSWSI Timescales

Sub-basins	MSWSI-1 $x10^{-3}$	MSWSI-3 $x10^{-3}$	MSWSI-6 $x10^{-3}$	MSWSI-12 $x10^{-3}$	MSWSI-24 $x10^{-3}$	MSWSI-48 $x10^{-3}$
RB	**-4.12**	**-2.23**	**-1.96**	**-2.95**	**-5.28**	**-8.66**
UB	-1.67	-0.23	0.21	-0.17	-0.46	**-4.69**
SB	**-2.44**	-1.35	-1.12	**-2.22**	**-2.95**	**-4.25**
UKE	-3.03	-0.92	-0.58	-1.01	-3.16	-6.10
UKW	0.05	0.62	0.73	-0.80	-0.82	-2.30

*Bold values indicate statistical significance at 95% confidence level as per the Mann-Kendall test (+ for increasing and - for decreasing).

The results of the MSWSI of 05 sub-basins at multiple timescales are as shown in Table no. 6.2. It is observed that the Remaining Bhima (RB) sub-basin was having the negative trend on every timescale. The Upper Bhima (UB) sub-basin was detecting the negative trend at 48-month timescale only. The Sina–bori (SB) sub-basin was detecting the negative trend at 1-, 12-, 24- and 48-month timescales. The Upper Krishna East (UKE) and Upper Krishna West (UKW) sub-basins do not detect significant trend at any timescale. The maximum Sen's slope was observed at 48-month timescale for all sub-basins.

The results of trend analysis by SPI of 05 sub-basins at multiple timescales are as shown in Table no. 6.3. It is observed that the RB sub-basin was detecting the negative trend at 48-month timescale, while the SB sub-basin was detecting the positive trend at 48-month timescale. The UB sub-basin was detecting the positive trend at 24-month timescale. The UKE and UKW sub-basins do not detect any significant trend.

Table 6.3: Sen's estimator of slope at Sub-basins for SPI Timescales

Sub-basins	SPI-1 x10^{-3}	SPI-3 x10^{-3}	SPI-6 x10^{-3}	SPI-12 x10^{-3}	SPI-24 x10^{-3}	SPI-48 x10^{-3}
RB	-0.23	-0.52	-0.61	-0.73	-0.63	**-1.15**
SB	0.14	0.28	0.34	0.37	0.83	**1.54**
UB	0	-0.14	0.04	0.88	**1.10**	0.52
UKE	0	-0.30	-0.26	0.29	0.07	0
UKW	0	0	0.04	0.08	0.50	0.52

*Bold values indicate statistical significance at 95% confidence level as per the Mann-Kendall test (+ for increasing and - for decreasing).

The results of trend analysis by PNP of 05 sub-basins at Annual, Water-Year, Monsoon, Pre-Monsoon and Post-Monsoon timescale are shown in Table no. 6.4.

Table 6.4: Sen's estimator of slope at Sub-basins for PNP Timescales

Sub-basins	Annual x10^{-2}	Water-Year x10^{-2}	Monsoon x10^{-2}	Pre-Monsoon x10^{-2}	Post-Monsoon x10^{-2}
RB	-0.34	-4.43	11.16	**-150.43**	-11.63
UB	0.37	6.19	3.97	**-252.55**	4.80
SB	-5.73	-7.35	2.99	-98.72	1.82
UKE	-6.02	-0.02	-4.21	**-133.52**	-2.92
UKW	-15.12	-17.27	-12.31	**-160.92**	-15.28

*Bold values indicate statistical significance at 95% confidence level as per the Mann-Kendall test (+ for increasing and - for decreasing).

It is observed that Pre-Monsoon timescale showed the negative trend at the RB, UB, UKE and UKW sub-basins. The SB sub-basin does not detect any significant trend.

6.4 Conclusions

Drought trend analysis was carried out at rainfall station by SPI at 1-, 6-, 12-, 24- and 48- month timescales as well as sub-basin level by SPI and MSWSI at 1-, 3-, 6-, 12-, 24- and 48- month timescale and PNP at Annual, Water-Year, Winter, Pre-Monsoon, Monsoon and Post-Monsoon timescale at both rainfall and sub-basin level. The spatial and temporal variability in drought trends was observed in the study area.

At rain gauge stations, PNP drought trend analysis at both annual and water-year timescale was able to detect significant trend at only five stations out of 59 rainfall stations. The number of stations having a significant trend with SPI increased with timescale. As the SPI-1 timescale is able to detect significant trend at only 4 stations, the number of stations having a significant trend increased as the SPI timescale increased up to SPI-48 at 50 stations. Drought trend of Seasonal rainfall showed different results. Pre-monsoon timescale detects significant negative trend at 41 stations with no significant positive trend at any of the stations. Monsoon timescale detects only 2 positive and 1 negative significant trends at total 59 stations. The Post-monsoon timescale was not able to detect any significant trend at all stations. The results indicate the negative trend of pre-monsoon rainfall at about 63 percent of the area. SPI- 48 timescale was able to detect significant trend at about 84 percent of the area.

At sub-basin level, MSWSI trend analysis the RB sub-basin had the negative trend at every timescale. As per SPI trend analysis, the negative trend observed at the RB sub-basin at 48-month timescale. The positive trend was observed at the SB sub-basin at 48-month timescale and for the UB sub-basin at 24-month timescale. No significant trend observed at the UKE and UKW sub-basins by the MSWSI and the SPI at every timescale. For Pre-Monsoon scale, the negative trend observed at the RB, UB, UKE and UKW sub-basins. No significant trend was observed at Annual, Water-Year, Monsoon and Post-Monsoon timescale for all the sub-basins.

This analysis may be used to solve problems associated with floods, droughts and allocation of water for agriculture, industry, hydro-power generation, domestic and industrial use.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 General

Drought is a phenomenon associated with scarcity of water**.** The demand for water has been increased many folds to cater a growing population in maintaining living standards, recreation, expansion of agriculture, generation of power and industrial sectors. The seasonal and inter-annual spatial and temporal variability of rainfall in a changing climate scenario is vital for water resource management in a river basin. Knowledge of the probability of occurrence of droughts along with duration, intensity, and spatial extent is critical in the planning as well as management of scarce water resources.

The first objective of this study is to analyze the Spatial and Temporal variability of droughts by Percent of Normal Precipitation (PNP), Standardized Precipitation Index (SPI), and Modified Surface Water Supply Index (MSWSI) in the Krishna River Basin in Maharashtra. The second objective is to identify the drought-affected area by the combination of drought indices in the Krishna River Basin in Maharashtra. The last objective is to evaluate the drought indices for finding suitable and better drought index to detect and monitor droughts in the Krishna River Basin in Maharashtra under different timescales.

7.2 Summary and Conclusions

A drought is differentiated by three characteristics- intensity, duration, and spatial variation. Drought climatology over the Krishna basin in Maharashtra is examined at both local and regional level using PNP and SPI. Drought characteristics of local droughts changes with the timescale. Appropriate timescales are useful for specific water resource management. SPI-3 and SPI-6 are suitable for irrigation purpose, while SPI-1 suitable for drinking water supply. SPI-1 should be used with caution since SPI–1 shows exacerbated picture of very wet conditions in January-March and December, even though rainfall is almost nil during these months. The SPI-1 timescale evaluates dry conditions from June- Oct. i.e. S-W monsoon period. Results obtained by the SPI-3 are consistent with actual wet/dry conditions.

Sum of severe and extreme droughts as per the SPI was much more than severe drought as per the PNP, while a number of moderate droughts are more in the PNP. Yearly drought analysis and Water year drought analysis influences the cropping pattern. Water year drought analysis will have more influence in managing summer crops since we can assess the availability of soil moisture at the end of water year; similarly, Yearly drought analysis will have more influence on managing Kharif and Rabi crops.

The present study explores the usefulness of the SPI and the Run theory in investigating drought characteristics at multiple timescales. As for timescale increased, the decrease in a number of drought incidences was accompanied by an increase in drought severity and return period. Increase in drought duration was followed by a decrease in drought intensity, as timescale increases. Time lag was identified from the SPI-9 to SPI-48 in drought initiation and termination. The Maximum and average values of drought duration, severity, lead-time, termination time and return period increased with the timescale. The SPI being a normalized Index, the variability of the SPI is proportional to that of the precipitation change. The SPI performs better than the PNP in monitoring drought at multiple timescales. In regional drought analysis, the areas affected by the severe drought evolve gradually at every timescale from Moderate to Severe except for the SPI-6 and SPI-9 during (1971-75) high-intensity drought. The Severe drought recedes at successive timescale with a time lag varying from 2-4 months for high-intensity drought (1971-75) and 2-9 months for high severity drought (2000-07). For regional planning higher timescales are useful.

The study area is susceptible to drought events. Moderate drought month occurs in 80 percent of the study area, with one-year return period. Severe drought month occurs for 64 percent of the area with 2-year return period. An extreme drought month occurs for 78 percent of the area with 5-year return period. The spatially interpolated drought maps, the drought severity maps for different return periods as well as the ranking of rain gauge stations and sub-basins will help the water managers and administrators in drought monitoring and relief operations.

The Sub-basin wide drought classification by MSWSI at multiple timescales was found to be sensitive to timescales. Extreme drought months are highest for the UKE sub-basin except for the RB sub-basin at 48-month timescales. The UB sub-basin is having least number of extreme droughts at all-timescales followed by the UKW sub-basin. From MSWSI analysis the UKE sub-basin is most droughts prone followed by the RB sub-basin, while the UB sub-basin is least droughts prone followed by the UKW sub-basin. The Sub-basin wide drought classifications done by the SPI are susceptible to multiple timescales. All sub-basins experience highest moderately drought conditions at 12-month timescale. Increase in drought severity class from Moderately dry to Extremely dry was accompanied by a decrease in drought months. This trend was observed for all sub-basins at 1.3,24 and 48-month timescale except for the UKE Sub-basin at 48-month time-scale, where Severely dry conditions are highest. Severely dry months are lowest at 12-month timescale at the UKE, SB, and RB sub-basins. From the SPI analysis, it was found that the UKE sub-basin is most droughts prone while the UKW sub-basin is least drought prone.

From sub-basin wide drought classification by the PNP, it was found that total drought years and Moderate drought years are more for Water-Year basis than the Yearly basis for the SB, UB, and RB Sub-basins. Severe drought years are same as compare to the Yearly and Water-Year basis for all sub-basins except for the UKE sub-basin. From the PNP analysis, it was found that the UKE and RB sub-basins are the most droughts prone followed by the SB and UB sub-basins. The UKW is the least drought prone.

From the time series graph, it was observed that as the timescale increased, the start of drought period is delayed, same as the timescale. During the failure of monsoon, drought period was extended up to May of next water year for the MSWSI-6 and MSWSI-12 timescales. By weather classification at MSWSI-1 timescale, wet conditions were observed at all sub-basins during monsoon season. The September was the wettest month. Drought conditions were observed during the Non-Monsoon period. The February was the driest month. The MSWSI -1 reflects true moisture availability on a real-time basis. The MSWSI-1 is most suitable for the planning of water resources for drinking water. At weather classification at SPI -1 timescale, wet conditions were observed during whole year for all sub-basins. The June was the wettest month for all sub-basins except for the UB Sub-basin, where the October was the wettest month. From Weather classification at PNP Monthly timescale, wet conditions are observed at all Sub-basins during whole year except for the RB Sub-basin during June to November.

Drought characteristics of sub-basins by the SPI at multiple timescales revealed that the number of drought incidences and drought intensity decreased, while drought severity decreased with increase in timescale. Total drought severity for the UKE sub-basin was highest for 1-,3-and 6 month timescale, while it was maximum for SB sub-basin for 12,24, and 48-month time-scale. Drought characteristics of sub-basins by the MSWSI at multiple times scale revealed that total drought severity, the number of drought incidences, drought intensity and the number of drought months decreased with increase in timescale. Total drought severity for the UKE sub-basin was highest for every timescale among all sub-basins. Drought severity was lowest for the 3-month timescale for all sub-basins except for the RB sub-basin, where it was least for the 1-month timescale. The drought characterization will help hydrologists and water managers for a better understanding of drought parameters. The understanding of time lag of droughts by the SPI on multiple timescales will help to establish relations between precipitation, groundwater level, streamflow and accumulation of inflow in natural and artificial water bodies, where often time lag is noticed after precipitation takes place.

Drought trend analysis is carried out at rain gauge stations as well as sub-basin level by the SPI and the MSWSI at multiple timescales. The spatial and temporal variability in drought trends was observed in the study area. At rain gauge station, the PNP drought trend analysis at both annual and water-year timescale was able to detect significant trend at only 5 stations out of 59 rain gauge stations, the SPI based drought trend analysis was found to be more sensitive to multiple timescales. As the SPI-1 timescale was able to detect significant trend at only 4 stations, the number of stations having significant trend increased as the SPI timescale increased up to SPI-48 at 50 stations. Drought trend of Seasonal rainfall time series varies as per the classes. Pre-monsoon timescale detects significant negative trend at 41 stations with no significant positive trend at any of the stations. Monsoon timescale detects only 2 positive and 1 negative significant trends at total 59 stations. The Post-monsoon timescale was not able to detect any significant trend at all stations. The results indicated that there was a negative trend of pre-monsoon rain gauge at over 63 percent of the area. The SPI-48 timescale was able to detect significant trend at over 84 percent of the area. At sub-basin level, the MSWSI trend analysis was able to detect negative trend at the RB sub-basin at every timescale. The UKE and UKW sub-basins did not detect significant trend at every timescale. As per SPI trend analysis, the negative trend was observed at the RB sub-basin at 48-month timescale. The positive trend was observed at the SB sub-basin at 48-month timescale and for the UB sub-basin at 24-month timescale. The UKE and UKW sub-basins did not detect significant trend at every timescale. For Pre-Monsoon scale, the negative trend was observed at the RB, UB, UKE and UKW sub-basins. No significant trend was observed at Annual, Water-Year, Monsoon and Post-Monsoon timescale for all sub-basins. This analysis may be used to solve problems associated with floods, droughts and allocation of water for agriculture, industry, hydro-power generation, domestic and industrial use.

From sub-basin wide drought analysis, the MSWSI drought index is found to be better than the SPI and the PNP for the Krishna basin in Maharashtra. From weather classification, it was found that the MSWSI index can be used for a whole year for diverse water resources planning and management as it reflects the real-time availability of water. The SPI and the PNP have its own merits as well as demerits. The SPI weather classification indicates large positive value during the dry season, which may be misleading to the water managers. The SPI and the PNP indices are most suitable for monsoon season. For local and regional drought analysis, the SPI is a better index than the MSWSI and the PNP. The ranking of stations and sub-basins as per drought severity is possible with SPI and MSWSI respectively. The Spatially interpolated drought maps using the SPI can serve as ready reckoner for drought mitigation and contingency planning.

7.3 Future Scope

- Impact of anthropogenic activities such as recharge and withdrawal of groundwater affects the sustainability of agriculture and drinking water supplies during the drought period. The building of reservoirs and its distribution network is cost and time consuming along with an irrevocable loss to the environment. Accessibility of groundwater, scrutiny of groundwater potential to combat drought needs to be studied.

- Out of five sub-basins in the Krishna River in Maharashtra state, two sub-basins namely Upper Bhima and Upper Krishna (West) are water surplus, while others are a water deficit. Many Inter-sub basin water projects are proposed and some are under construction. Efficacy of such projects needs to be assessed.

Table 1: Rain gauge stations in the Krishna Basin river basin in Maharashtra

Sr. No.	Rainguage stations	Elevation	Annual	Monsoon	Pre-Monsoon	Post-Monsoon
		(m) (a.m.s.l)	Mean (mm)	Mean (mm)	Mean (mm)	Mean (mm)
1	Mahabaleshwar	1382	5610	5348	77	183
2	Radhanagari	610	3687	3488	58	140
3	Changad	701	2889	2622	112	153
4	Velhe	619	2533	2381	28	122
5	Ajra	643	1952	1744	88	119
6	Shahuwadi	557	1874	1683	58	132
7	Patan	610	1747	1567	50	129
8	Paud	662	1687	1549	25	113
9	Panhala	953	1657	1467	55	133
10	Medha Jaoli	683	1637	1442	49	145
11	Gargoti	556	1477	1275	79	123
12	Bhor	610	1118	973	30	114
13	Kolhapur	570	1059	832	84	140
14	Shirala	518	1055	851	75	128
15	Gadhingalaj	518	1028	801	90	135
16	Satara	612	1025	826	60	138
17	Wai	701	907	716	53	136
18	Kagal	554	866	649	74	141
19	Ghod Ambegaon	683	819	684	23	111
20	Pune	559	789	627	46	114
21	Koregaon	682	771	597	55	117
22	Tuljapur	550	767	632	32	101
23	Karad	581	759	585	49	122
24	Hatkanangale	586	746	540	70	133
25	Islampur	551	734	533	59	138
26	Shrigonda	555	534	395	28	108
27	Jamkhed	582	716	574	38	102
28	Akalkot	486	710	548	38	120
29	Junnar	675	707	609	13	85
30	Khed	613	688	552	35	101
31	Barshi	515	660	528	34	95
32	Asti	458	659	531	26	100
33	Pandharpur	460	654	487	32	129

34	Sangola	501	654	467	44	140
35	Sangli	549	642	429	70	140
36	Shirol	610	636	439	69	125
37	Vita	670	632	453	57	119
38	Ahmednagar	657	629	490	25	113
39	Tasgaon	570	627	430	71	123
40	Madha	484	624	468	33	119
41	Miraj	554	622	403	80	134
42	Parenda	506	617	482	29	99
43	Saswad	763	615	475	32	108
44	Jath	583	609	412	59	136
45	Mohol	457	606	458	39	104
46	Karmala	553	605	459	32	111
47	Mangalvedha	465	594	435	32	121
48	Dahiwadi Man	703	587	397	48	139
49	Karjat	549	574	432	36	104
50	Malshiras	522	571	426	20	124
51	Indapur	541	558	420	28	108
52	Khandala	662	545	390	38	115
53	Parner	822	541	411	26	101
54	Vaduj	703	534	380	44	109
55	Solapur	479	725	549	49	117
56	Baramati	551	532	382	25	122
57	Phaltan	571	525	369	33	120
58	Shirur	582	504	377	24	103
59	Dhond	509	498	354	27	116

Table 2: Ranking of rain gauge stations as per drought severity at multiple time scales

Station Name	SPI 1	SPI 3	SPI 6	SPI 9	SPI 12	SPI 18	SPI 24	SPI 36	SPI 48	Total	Rank
Mahabaleshwar	6	12	13	12	14	15	11	0	0	83	3
Radhanagari	8	6	9	11	15	15	13	1	0	78	3
Chandgad	10	9	14	14	11	28	27	39	39	191	7
Velhe	7	5	4	4	1	5	8	12	14	60	2
Ajra	9	11	12	13	12	8	10	14	24	113	4
Shahuwadi	7	10	12	15	13	15	14	12	13	111	4
Patan	8	10	14	14	14	14	12	12	24	122	4
Paud	12	18	23	25	22	33	38	47	58	276	10
Panhala	10	7	9	9	11	7	2	0	0	55	2
Medha	5	9	11	14	15	14	12	1	10	91	3
Gargoti	10	10	12	13	15	18	21	31	29	159	6
Bhor	8	9	17	22	22	22	20	12	5	137	5
Kolhapur	8	10	16	14	10	14	8	17	21	118	4
Shirala	9	11	16	17	21	18	23	31	44	190	7
Gadhinglaj	7	8	7	7	0	0	0	1	2	32	1
Satara	6	13	13	14	20	20	18	10	14	128	5
Wai	4	10	14	17	19	23	20	15	24	146	5
Kagal	9	6	12	14	17	12	1	13	15	99	4
Ambegaon	3	10	11	14	9	8	7	11	2	75	3
Pune	6	8	10	8	7	5	0	0	0	44	2
Koregaon	5	8	12	17	13	14	4	1	1	75	3
Tuljapur	6	11	15	16	14	13	16	14	12	117	4
Karad	5	10	17	27	30	24	21	17	11	162	6
Hatkanangale	9	12	14	20	19	15	7	0	0	96	3
Islampur	10	11	13	19	20	21	19	17	22	152	6
Solapur	6	10	16	18	19	23	18	1	0	111	4
Jamkhed	4	8	18	17	21	16	12	11	10	117	4
Akkalkot	8	12	15	14	12	15	18	10	1	105	4
Junnar	7	12	19	26	29	19	12	0	0	124	4
Khed	7	10	13	13	11	6	0	1	8	69	3
Barshi	3	9	18	24	31	30	28	23	23	189	7

Asti	5	12	22	30	28	23	24	12	7	163	6
Pandharpur	7	6	9	13	16	17	10	8	0	86	3
Sangola	6	9	10	12	9	6	3	0	0	55	2
Sangli	8	6	9	10	9	3	0	0	0	45	2
Shirol	8	7	13	13	11	16	13	22	14	117	4
Vita	5	8	15	16	12	17	10	13	24	120	4
Ahmednagar	4	8	18	17	21	16	12	11	10	117	4
Tasgaon	9	13	19	23	25	27	28	27	27	198	7
Madha	5	9	10	15	14	19	13	2	9	96	3
Miraj	9	8	10	12	12	14	2	4	4	75	3
Parenda	6	6	9	18	20	34	35	23	15	166	6
Saswad	4	7	13	16	19	9	2	0	0	70	3
Jath	11	10	13	14	11	30	34	34	46	203	7
Mohol	4	9	17	27	27	26	26	10	5	151	5
Karmala	5	9	19	28	31	22	13	13	1	141	5
Mangalvedha	6	12	14	17	16	25	35	19	28	172	6
Dahiwadi Man	5	9	12	15	11	17	11	10	11	101	4
Karjat	7	9	21	26	27	21	21	22	8	162	6
Malshiras	7	9	14	19	17	10	8	0	9	93	3
Indapur	4	8	16	17	9	2	0	0	0	56	2
Khandala	7	7	16	23	25	23	30	25	13	169	6
Parner	3	15	24	31	36	29	25	14	22	199	7
Vaduj	5	11	15	15	17	15	10	11	20	119	4
Shrigonda	7	17	20	22	17	21	18	19	10	151	5
Baramati	6	10	18	24	17	16	17	13	2	123	4
Phaltan	5	7	11	12	12	10	11	15	9	92	3
Shirur	10	13	19	18	12	10	9	20	29	140	5
Dhond	5	11	20	26	24	16	11	13	11	137	5

Table 3: Sen's estimator of slope (unit/month) for SPI and Pre-Monsoon rainfall Timescales

Rainfall stations	SPI-1 $x10^{-3}$	SPI-6 $x10^{-3}$	SPI-12 $x10^{-3}$	SPI-24 $x10^{-3}$	SPI-48 $x10^{-3}$	Pre-Monsoon
Mahabaleshwar	-0.06	**-0.50**	**-0.67**	**-0.63**	0.07	**-1.03**
Radhanagari	0.00	0.13	0.41	**0.96**	**1.60**	**-0.90**
Chandgad	-0.02	**-0.50**	**-0.75**	**-0.93**	**-1.10**	**-1.46**
Velhe	0.00	**-0.82**	**-1.10**	**-1.10**	-0.22	**-0.89**
Ajra	0.00	**-0.78**	**-1.10**	**-1.10**	**-0.84**	**-1.19**
Shahuwadi	0.00	**0.49**	**0.57**	**0.72**	**1.50**	0.00
Patan	0.00	**-0.56**	**-0.86**	**-1.10**	**-0.82**	**-0.88**
Paud	0.00	-0.10	0.00	0.07	0.22	**-0.46**
Panhala	0.00	-0.26	-0.10	0.21	1	**-1.21**
Medha Jaoli	0.00	**-0.46**	**-0.45**	-0.35	-0.11	**-0.76**
Gargoti	-0.22	**-1.30**	**-1.80**	**-2.00**	**-1.60**	**-1.20**
Bhor	0.00	0.22	0.40	**0.64**	**1.30**	**-0.28**
Kolhapur	-0.10	**-0.77**	**-1.20**	**-1.30**	**-1.00**	**-1.19**
Shirala	0.00	**-0.65**	**-0.84**	**-1.00**	**-0.64**	**-1.47**
Gadhingalaj	**-0.27**	**-1.10**	**-1.10**	**-1.10**	**-1.00**	**-1.97**
Satara	-0.20	**-0.87**	**-1.10**	**-1.70**	**-1.90**	**-1.10**
Wai	0.00	**0.84**	**1.40**	**2.00**	**3.10**	-0.25
Kagal	-0.19	**-0.79**	**-0.80**	**-1.20**	**-1.20**	**-2.21**
Ambegaon	0.00	0.28	**0.66**	**0.78**	**1.40**	**-0.57**
Pune	0.25	**1.50**	**2.50**	**3.00**	**3.40**	**-0.69**
Koregaon	0.00	-0.41	0.00	0.31	**1.40**	**-1.00**
Tuljapur	0.00	0.04	0.15	**0.51**	**0.86**	0.00
Karad	0.00	0.00	0.39	**0.64**	**1.10**	**-1.32**
Hatkanangale	0.17	**0.96**	**1.60**	**2.20**	**3.00**	**-0.89**
Islampur	0.00	0.35	**0.53**	**0.93**	**1.70**	**-0.80**
Solapur	0.00	-0.35	**-0.56**	**-0.75**	**-1.20**	0.31
Jamkhed	0.00	-0.16	0.00	0.21	**0.58**	0.00
Akalkot	**-0.20**	**-1.10**	**-1.60**	**-2.10**	**-2.50**	-0.42
Junnar	0.00	**0.37**	**0.79**	**1.30**	**2.10**	0.00
Khed	0.00	-0.26	-0.14	0.13	0.51	**-0.64**
Barshi	0.00	-0.22	-0.22	0.08	-0.33	**-0.42**
Asti	0.00	**0.54**	**1.10**	**1.90**	**2.90**	**-0.10**
Pandharpur	-0.11	**-0.55**	**-0.70**	**-0.80**	**-0.69**	-0.15
Sangola	**-0.35**	**-1.10**	**-1.30**	**-1.30**	**-1.70**	**-0.91**
Sangli	0.00	0.08	0.09	**0.46**	**1.10**	-0.52
Shirol	0.00	0.04	0.24	**0.61**	**1.50**	-0.27
Vita	0.00	0.25	**0.93**	**1.60**	**2.20**	**-0.87**
Ahmednagar	0.00	-0.16	0.00	0.21	**0.58**	**-0.53**
Tasgaon	**-0.42**	**-1.50**	**-1.50**	**-1.60**	**-1.90**	**-1.37**
Madha	0.00	-0.07	0.00	**0.54**	**1.10**	-0.08
Miraj	-0.10	**-0.59**	**-0.69**	**-0.67**	-0.45	-0.90
Parenda	0.00	-0.28	**-0.64**	**-0.81**	**-0.99**	0.00
Saswad	0.00	0.00	0.14	**0.65**	**2.00**	**-0.69**
Jath	-0.15	**-0.57**	**-0.62**	**-0.69**	**-1.20**	-0.59
Mohol	0.00	-0.28	-0.06	0.40	0.51	-0.30

Karmala	0.00	-0.32	0.00	**0.68**	**1.10**	**-0.32**
Mangalvedha	0.00	-0.13	-0.09	-0.04	0.00	-0.06
Dahiwadi	-0.12	**-0.80**	**-0.75**	**-0.56**	**-0.78**	**-0.68**
Karjat	0.00	-0.21	0.34	**0.98**	**1.50**	**-0.55**
Malshiras	0.00	-0.23	0.04	0.40	**0.75**	**-0.25**
Indapur	0.00	-0.08	**0.49**	**0.93**	**1.70**	**-0.50**
Khandala	0.00	**0.56**	**1.10**	**1.50**	**1.90**	-0.23
Parner	-0.04	**-0.61**	-0.35	**-0.42**	**-0.84**	**-0.57**
Vaduj	0.00	-0.11	0.25	0.45	**0.77**	**-0.66**
Shrigonda	0.00	-0.14	0.34	**0.78**	**0.82**	**-0.60**
Baramati	0.00	0.15	**0.81**	**1.50**	**2.40**	**-0.16**
Phaltan	0.00	0.16	**0.88**	**1.70**	**3.00**	-0.21
Shirur	0.00	-0.24	0.24	**0.67**	**0.76**	**-0.55**
Dhond	0.00	0.00	**0.48**	**0.89**	**1.70**	**-0.01**

*Bold values indicate statistical significance at 95% confidence level as per the Mann-Kendall test (+ for increasing and - for decreasing).

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List of Publication from Present Research

International Journals

1) Dattatraya R. Mahajan and Basavanand M. Dodamani, (2016). "Spatial and temporal drought analysis in the Krishna river basin of Maharashtra, India," *Cogent Engineering*.DOI/10.1080/23311916.2016.1185926 .

2) Dattatraya R. Mahajan and Basavanand M. Dodamani, (2015). "Trend Analysis of Drought Events Over Upper Krishna Basin in Maharashtra." International conference on water resources, coastal and ocean Engineering (ICWRCOE 2015), *Aquatic Procedia* 4 (2015) 1250 – 1257. doi:10.1016/j.aqpro.2015.02.163

International Conference

1) Dattatraya R. Mahajan and Basavanand M. Dodamani, (2016). "Classification of Droughts in Krishna River Basin in Maharashtra by MSWSI at Multiple Time Scales". *International Conference on Water, Environment, Energy and Society* (ICWEES-2016).

BRIEF RESUME

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