CHARACTERIZATION OF HISTORICAL AND FUTURE HYDROMETEOROLOGICAL DROUGHTS IN AN INDIAN TROPICAL RIVER BASIN

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

ABHISHEK A PATHAK

DEPARTMENT OF APPLIED MECHANICS AND HYDRAULICS

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,

SURATHKAL, MANGALORE – 575025

FEBRUARY 2020

CHARACTERIZATION OF HISTORICAL AND FUTURE HYDROMETEOROLOGICAL DROUGHTS IN AN INDIAN TROPICAL RIVER BASIN

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

ABHISHEK A PATHAK

Under the guidance of

Dr. B M DODAMANI

Professor
Dept. of Applied Mechanics & Hydraulics
NITK, Surathkal

DEPARTMENT OF APPLIED MECHANICS AND HYDRAULICS

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,

SURATHKAL, MANGALORE – 575 025

FEBRUARY 2020

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 '***Characterization Of Historical and Future Hydrometeorological Droughts in an Indian Tropical River Basin'*****,** 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 **Applied Mechanics and Hydraulics Department** 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.

155115AM15F01, ABHISHEK A PATHAK

(Register Number, Name & Signature of the Research Scholar)

Department of Applied Mechanics and Hydraulics

Place: NITK-Surathkal

Date:

C E R T I F I C A T E

This is to *certify* that the Research Thesis entitled '**Characterization of Historical and Future Hydrometeorological Droughts in an Indian Tropical River Basin',** submitted by ABHISHEK A PATHAK (Register Number: 155115AM15F01) 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**.

Prof. B M Dodamani
Research Guide
(Name and Signature with Date and Seal)

Chairman - DRPC
(Signature with Date and Seal)

ACKNOWLEDGEMENTS

With deep sense of gratitude, I express my heartfelt thanks to the eminent Professor from the Department of Applied Mechanics and Hydraulics, NITK, Surathkal, Dr. B M Dodamani, for doing a marvelous job at supervising my research work. His logical and tactical suggestions have been very valuable and encouraging during the development of this research.

I am grateful to Research Progress Committee members, Prof. Lakshman Nandagiri and Prof. Subhash C Yaragal, for their critical evaluation and useful suggestions during the progress of the work.

I am greatly indebted to Prof. Amai Mahesha and Prof. Dwarakish G S, the former Head of the Department of Applied Mechanics and Hydraulics, NITK, Surathkal, and Prof. Amba Shetty., the present Head of the Department, for financial assistance and granting me the permission to use the departmental computing facilities available for necessary research work to the maximum extent, which was very vital for the completion of the computational aspects relevant to this research.

I thank the Director of the NITK, Surathkal, Prof. Karanam Uma Maheshwar Rao, for granting me the permission to use the institutional infrastructure facilities, without which this research work would have been impossible.

I sincerely acknowledge the help and support rendered by all the Faculties, staffs and Research scholars of Department of Applied Mechanics & Hydraulics.

I express heartfelt gratitude to authors of all those research publications which have been referred in this thesis and also like to thank all the Government Departments and Organizations for providing required data.

Finally, I wish to express gratitude, love and affection to my beloved family members for their encouragement and moral support on the road to the completion of my research.

Abhishek A Pathak

ABSTRACT

Drought is acknowledged as a significant natural disaster which leads to food, fodder, and water shortages along with destruction of vital ecological system. Drought is a transient recurring sinister disaster, which originates from the lack of precipitation and further creeps into different subdivisions of hydrological cycle causing adverse effects on agricultural and its allied sector. Combination of these leads to economic losses and several damage to living organisms. Identifying and quantifying drought characteristics of a region is must to understand the behavior of drought and its profound impacts on society, economy, and environment. Along with the historical knowledge, comprehensive overview of future drought projections is a vital step in ensuring future water and food security. The present study focuses on characterizing different hydrometeorological droughts in the historical and future climate of an agrarian Indian river basin. The specific objectives of the study are 1) To investigate annual and seasonal trends of hydro meteorological variables, over the study area. 2) Assessment and comparison of Meteorological, Hydrological and Agricultural drought characteristics with multiple indices 3) To explore the applicability of copulas theory for joint modeling of drought characteristics 4) Characterization of future hydro-climatic droughts. The study was implemented in the Ghataprabha river basin, being one among the potential lands for agriculture in the basin of river Krishna. Firstly, the basin has been categorized in to humid, sub humid and semiarid region based on Aridity Index. Similarly, groundwater well of the study area are grouped in to different clusters using hierarchical and non-hierarchical clustering methods

The annual and seasonal trend analysis of different hydrometeorological variables are carried out using Mann-Kendall trend test and the magnitude of the trend was estimated using the Sen's Slope Estimator. A non-significant decreasing trends in both rainfall and rainy days was observed in semiarid region during monsoon period. Significant increasing trend in mean temperature was observed for all the stations and for all the seasons with the average magnitude of 0.2^{o} C per decade. Along with the mean temperature, annual and

seasonal PET trends were also increasing for all the stations but are significant only in semiarid region with the average increase of 3.5mm per decade. The trends in annual streamflow of the basin are decreasing with magnitude of 574.25 cumecs/year, whereas, no significant trends were observed in the reservoir levels. The trend analysis of the groundwater levels of different clusters, revealed that annual water level in the 81% of the wells of cluster 2 and 47% of the total wells of the study area are significantly declining.

The hydrometeorological droughts assessment with different indices portrayed significant number of droughts in the past. The RDI and SPI are behaving similarly in all the stations whereas, significant discrepancies was observed between SPI/RDI and SPEI. The hydrological drought assessed with SDI followed similar pattern with SRSI whereas it showed significant divergence with meteorological droughts. Similarly, Agricultural drought derived through VCI followed similar pattern of SPI-6 in comparison with SPI-3. A teleconnection between meteorological drought and groundwater drought was observed along with the crucial role of underlying hydrogeological characteristics.

Joint modelling of hydrometeorological drought characteristics and regional bivariate frequency analysis was carried out by employing Archimedean copula. An attempt has also been made to characterize drought in multivariate perspective by developing Standardized Hydro Meteorological drought Index. From the results of bivariate frequency analysis of meteorological drought, it was observed that, droughts of high severity with prolonged duration are frequent in semiarid region compared to humid and sub-humid regions. The joint probability of hydrological drought conveyed drought of smaller duration or severity are more prominent in the basin whereas joint return periods of groundwater drought is high in the well of cluster 2. The developed SHMI considers combined effects of precipitation and streamflow to picturize a near realistic drought scenario of the basin.

The future hydrometeorological drought characteristics were assessed by different RCMs. The different bias correction methods were applied to rainfall and temperature to raw RCMs and observed that CNRM-CM5 with LS bias correction method performed better for correcting the rainfall and VS is proved to be superior for correcting the temperature projections. The trend analysis carried out for the future hydrometeorological variable showed significant decreasing trends in annual and post monsoon season whereas temperature trend is increasing significantly with the rise of 0.15^{0} C per decade. The future hydro-meteorological drought characteristics revealed that the basin will experience more number of droughts compared to the past and it can be attributed to decreasing rainfall trend and significant rise in temperature of the basin. In this study, an attempt has been made to characterize future and historical hydrometeorological droughts comprehensively. The outcome of the study will be helpful to design proactive drought mitigation and preparedness strategies for upcoming drought and it also provides a framework to evaluate the drought risks at other parts of the world.

Key words: Mann–Kendall; Sen’s slope; Copula; Regional Climate Model (RCM); Drought propagation; Joint return periods; Bias correction; Drought Severity, Drought Duration; Trend analysis;

CONTENTS

Page No

List of Tables

List of Figures

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Water is the essential component of life. Unless it is in balanced quantity, any deficit or excess, may cause physiographic imbalance. Similarly, for an entire region, too, deficit or excess of the normal requirement of water may cause imbalance in the regions physical, social, or economic situation. Floods and Droughts have affected human activity throughout the world. Historical records shows that floods and droughts are effected in almost every part of the world at some time or other.

Drought is the most complex and least understood of all natural hazards, affecting more people than any other hazard. Drought affects virtually all climatic regions (Wilhite, 2000a) and more than one half of the earth is susceptible to drought each year (Kogan, 1997). According to Hewitt (1997) drought ranks first among natural disasters in number of persons directly affected. Drought may begin at any time, attain many degrees of severity and last indefinitely. Drought is a "creeping phenomenon" (Gillette, 1950), because of its slow and progressive nature. Drought is a transient recurring natural disaster, which originates from the lack of precipitation and impacts severe economic losses and several damage to living organisms. The effects of drought accumulate slowly over a considerable period of time and sometimes it discontinued suddenly. There is no precise and universally accepted definition of drought because the quantification of impacts of drought is a very difficult task. Ultimately drought affects economic and social sectors, and due to this several drought definitions have been developed by a variety of disciplines for some or other purposes. Drought is a sinister hazard of nature. Although it has number of definitions, it originates from a deficiency of precipitation over an extended period of time, usually a season or more.

1.2 DROUGHT DEFINITIONS AND TYPES

The term drought is used differently by different persons depending upon the context and purpose. Many authors have defined the drought concept and more than 150 definitions of drought are available in the literature (Yevjevich et al., 1983; Easterling, 1988; Rossi et al., 1992; Wilhite, 2000; Gibbs, 1975; Krishnan, 1979; Dracup et al., 1980; Wilhite and Glantz, 1987). In general, drought as a lack of rainfall which adversely affect human activities of the region (Warrick, 1965). Different countries defined drought as per their rainfall pattern (IMD report, 2005). The BRO (British Rainfall Organization) defines "absolute drought" as the period in which an area receives rainfall less than 0.25mm for at least fifteen consecutive days and "partial drought" when mean rainfall does not exceed 0.25 mm per day for at least twenty-nine days. In U.S.A., "a period of 20 consecutive days or more without 6.4 mm or more of precipitation in 24 hours during the season March to September, is considered as a drought situation" Conrad (1944),. In Australia, according to Gibbs and Maher (1967), the rainfall deciles is the best single index of drought which demonstrates temporal and spatial distribution.

The Indian Meteorological Department (IMD) defines "Drought in any area when the rainfall deficiency in that area is ≥ 26% of its long term normal. It is further classified into moderate and severe drought depending upon whether the deficiency is between 26 to 50% and more than 50% respectively". For the country as a whole, When the rainfall deficiency exceeds 10% and when the area under drought exceeds 20% of the total area of the plains in the country (which is 32, 87,782 km2), such a situation is considered as drought for the country as a whole.

Drought has categorized into four types namely, meteorological drought, hydrological drought, agricultural drought and socioeconomic drought (Wilhite and Glantz,1985; American Meteorological Society,1997).

Meteorological Drought: Meteorological Drought is defined as a shortage of precipitation over a period in a region. Precipitation has been commonly used for meteorological drought analysis.

Hydrological drought: Hydrological drought related to a period with inadequate surface and subsurface water resources Hydrological drought is the occurrence of below expected natural water availability in rivers, lakes, groundwater level etc over large areas. It implies reduced levels of surface water (rivers, lakes) and of groundwater. Streamflow has been widely used for hydrological drought analysis.

Agricultural drought: Agricultural drought is a period with reduction in soil moisture that leads to reduction in crop yield. Generally, it refers to situations in which the moisture in the soil fails to meet the needs of the crops growing in the area. It mainly concerns with water deficit in crops due to lack of water supply in the soil.

Socioeconomic drought: Socioeconomic drought is connected with failure of entire water resource systems to meet the water demand and thus this shortages start to affect the society directly or indirectly. Socioeconomic drought occurs when the demand for an economic good exceeds supply due to the result of a weather related shortfall in water supply.

1.3 DROUGHTS IN INDIA

The Indian sub-continent is primarily characterized by a tropical monsoon climate and the entire country is distinguished mainly by the variation in rainfall distribution as well as quantity. India has been facing a several drought events (Vyas SS. et.al, 2015) and it is the most vulnerable drought prone country ((Mishra, A.K., Singh, V.P., 2010). Drought frequency in the country is once in every 2 to 3 years (Parasuraman et al., 2000). In India rainfall is seasonal in nature, and agriculture is mainly depends on rainfall and rainy season. More than 70% of Indian population is depending on agriculture and it is backbone for country’s economic status in India and 44% of the total crop production is contributed by Rain fed agriculture (Vittal et al., 2005).

Agriculture in rain fed area is continued to be a gamble because farmers in rain fed regions faces many uncertainties. 50% of loss in agricultural had been taken place during 1957-1958 drought and around 25% and 16% of yield reduction of rice and oilseeds respectively during the drought year of 2002 (Sharma K and Singh .H.P, 2005). India faced extreme drought during1972-1973 due to -35% departure of rainfall and 200 million people were affected. The area covered by this drought is around 47 % of the country. Recently, in 2009, 2012 and 2014 Indian agricultural production agonized from drought (Vyas SS. et.al,2015). In the drought year 2009, the kharif crop production showed a drop of 8% and paddy crop is most affected with 11.62 million ton of reduction in yield as compared to previous years (Anon, 2010). In 2012, drought reduction in the yield of kharif crop was about 5% (Anon, 2013). Thus, droughts are not only affecting the food security of the country but also it effects nation’s economy also.

1.4 IMPORTANCE OF MULTIVARIATE /COMBINED DROUGHT INDICES

Drought indices are the numerical expressions based on different climatic and hydrological variables or combination of them, used to describe physical characteristics of a drought like duration, severity, frequency and spatial extent (Steinemann et al., 2005; Hayes et al., 2012). However, it is tedious to segregate different types of drought (Mo, 2008), because they may occur at the same time or consecutive and variables which are used in drought studies are interrelated. In reality, drought conditions are associated with multiple variables (Wilhite, 2005) therefore single drought index may be insufficient to characterize the complicated drought phenomenon and its broad impacts. In India, drought studies are limited to single variable based indices. To assess the drought characteristics for Indian basins comprehensively, combination of different drought indices may be best choice than a single-index approach. But this has been very challenging because of non-availability of long term regional climatic data (at least 30 years).

1.5 SCOPE OF THE WORK

India has been facing enormous water related natural hazards whereas frequencies of droughts are more compared to floods and other disasters (Dhanya and Kumar, 2009). However, the probability of drought in India varies from once in 2 years in Western Rajasthan to once in 15 years in Assam (NDMA). In India, more than 68% people are dependent on agriculture. About 16% of India's total area is drought-prone and about 50 million people are annually affected by drought. (Dutta D. et al., (2015).

According to IMD, most of the area which lies in the Krishna river basin is having deficient rainfall (-20% to -59%) or scanty (-60% to -99%). In terms of area prone to drought, Karnataka ranks second in India after Rajasthan (KSAPCC, 2012). Within the Karnataka state, Northern Karnataka is more vulnerable (recurrence period of 3 year) to severe drought (KSNDMC, 2017).

Keeping this in view, the present research is proposed to study different drought characteristics and their return periods in a tropical sub basin of river Krishna. For the study Ghataprabha river basin was considered to understand various drought characteristics in the past and future climate.

1.6 OBJECTIVES OF THE STUDY

1. To investigate annual and seasonal trends of hydro meteorological variables, over the study area.
2. Assessment and comparison of Meteorological, Hydrological and Agricultural drought characteristics with multiple indices.
3. To explore the applicability of copulas theory for joint modeling of drought characteristics.
4. Characterization of future hydro-climatic droughts

1.7 ORGANIZATION OF THE THESIS

The thesis report comprises of eight chapters as listed below

- Chapter 1 (Introduction) presents the overview of drought types and definitions of droughts, historical droughts in India.
- Chapter 2 (Literature Review) deals with a critical review of current understanding of work related to different droughts and their joint modelling.
- Chapter 3 (Study Area) presents the details of the study area and data products used in the study.
- Chapter 4 (Trend analysis) deals with the trend analysis of hydrometeorological variables in the study area.
- Chapter 5 (Drought assessment) deals with assessing different droughts and their comparison.
- Chapter 6 (Bivariate analysis) consist of joint modelling of drought characteristics using copula theory.
- Chapter 7 (Future droughts) deals with characterization of future droughts
- Chapter 8 (Conclusions) presents conclusions of the research limitations and future scope of the research work.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Floods and droughts are commonly occurring natural extremities. Among these, Droughts are very complex phenomena both in terms of definition and causes. Compared to other natural hazards, such as floods and hurricanes, the spatial extent of droughts is usually much greater, as well the impacts of droughts are generally non-structural and difficult to quantify. Drought is a temporary, recurring natural disaster, which originates from the lack of precipitation and brings significant economic losses. It is not possible to avoid droughts. But drought preparedness can be developed and drought impacts can be managed. The success of both depends, amongst the others, on how well the droughts are defined and drought characteristics are quantified (Smakhtin. et al., 2004).

2.2 WORKS DONE ON METEOROLOGICAL DROUGHT

In 1965, Palmar developed Palmar Drought Severity Index (PDSI) to measure the severity of drought. This index is widely used in US. It requires rainfall, temperature and available water content data of soil in that region. It is the most popular regional drought index used for drought monitoring (Mishra and Singh, 2010). Palmar characterize PDSI as meteorological index but it mainly points out towards agricultural and hydrological drought. The methodology used to normalize the PDSI values can give good results for weekly analysis on statistical background (William and Alley 1984). Mckee et.al., (1993) developed standardize precipitation index (SPI) which uses only rainfall as input. SPI shows slow changes to precipitation for longer time scale and calculated that frequency of drought decreases inversely and duration increases linearly with time scale. Guttman (1999), compared PDSI and SPI from one month to forty eight month time scale and he concluded that SPI can be used as the primary drought index to identify drought risk and to take decision in the management of water resources because of its simplicity, probabilistic approach and spatial consistency. It visualizes wet and dry events better than PDSI. He also fitted six different distributions to rainfall and obtained different SPI values from that he concluded that Pearson type III distribution gives best SPI values and time scale more than 24 month is unreliable.

Louks and Vasiliades (2004) analyzed the spatial temporal characteristic of meteorological drought using SPI in Thessaly, Greece. They have used measured rainfall data from 50 stations for 33 hydrological years then spatial distributed over study area. Different probability distributions are fitted to drought severity and best fitted distribution is selected using Chi square and KS tests. They constructed drought severity-area-frequency curves based on monthly time scale. Similar type of work is also carried out by Mishra and Desai (2010).

A new regional drought index is proposed together with Declines method and SPI (Tsakiras et al., 2006). In this index along with rainfall, potential evapotranspiration is also used. He suggested that RDI is more sensitive index than the indices which are using only precipitation data. He concluded that RDI responds similar to SPI and it is more effective in changing climatic environment.

Comparison of SPI with actual rainfall deviation is carried out by Naresh Kumar et.al. (2009) and observed that sensitivity of SPI to low rainfall is less. They concluded with suggestion that dryness and wetness are caused by rainfall at its extremities were underestimated therefore, use of other statistical distributions are need to check before computation of SPI.

Since there are more number of meteorological indices available, comparisons of these indices have been carried out by Saeid et.al (2006), by considering seven meteorological data indices that are SPI, DI, PN, SZI, MSZI, Z score and EDI. They have compared all seven indices with SPI using Pearson coefficient of correlation. Correlation value between SZI and SPI is varying between 0.84 to 0.96 and with Z Score it is varying with 0.74 to 0.89 but correlation coefficient between SPI and MCZI, SPI and EDI is almost is zero. They also observed that EDI is more sensitive with Precipitation than compared to SPI. While comparing DI with SPI they found that magnitude of the SPI at normal period is more as compared to DI. PN is showing extreme drought higher than normal. They recommended to use SPI or EDI efficiently to monitor meteorological drought in the study area. In 2009, we can say new era in drought studies is started because in the beginning and after 2009 many studies have taken place in drought domain.

Vicente-serrano et al. (2009) proposed Standardize Precipitation Evaporation Index (SPEI) and compared with SPI and PDSI. It has an advantage over the previous drought indices because calculation procedure involves both temperature and precipitation and thus it becomes multi scalar drought index. It uses differences between precipitation and evapotranspiration. For the calculation of PET, they have used temperature based Thronthwaite equation. From the study they observed that strong correlation exists between SPI and SPEI for different periods. But this correlation decreases with longer time scale. PDSI provides good correlation of 0.856 with SPEI. They recommend that SPEI can be used efficiently over PDSI and SPI because SPI does not account climatic water demand i.e. PET and calculation of PDSI is complicated has compared to SPEI.

Comparison of SPI and RDI was conducted by Zarch et.al, (2011) in different climatic condition in Iran using rainfall data of forty meteorological from 1975 to 2005. They have seen that correlation coefficient between RDI and SPI is low with increase in time scale and RMSE value between RDI and SPI is also in drier climatic condition than the humid areas. Average value of RMSE is increased from arid region to humid region, spatial variation is observed by drawing severity-area extent curve. From that, they observe 29% of the area is suffered from extreme drought and around 60-80% of the area effected by moderate drought. With this they inferred that difference between RDI and SPI were high in sub humid and humid area of Iran.

Among all drought indices SPI is most widely used because of its simple calculations and less data demand nature. But while calculation of SPI, generally gamma distribution is used. Angelidis et.al, (2012) tries to calculate SPI with normal and log normal distributions using 76 years precipitation data for 19 stations in Portugal for 1,3,6,9 and 12 month scale. scale is used to check best fit distribution and concluded that gamma distribution fits good only for smaller scale but for longer time scale log normal distribution gives similar results has compared to gamma distribution. SPI value calculated with normal distribution slightly over estimates SPI values and log normal distribution slightly under estimates SPI values as compared to SPI values obtained from gamma distribution.

Patel et al. 2007. used SPI to analyse spatial variability of meteorological drought in Gujarat state using monthly rainfall data from 160 station (1981 to 2003). They used 3 month time scale SPI to analyze seasonal variation of precipitation. They found that many districts shows a good correlation between 3 month SPI for September month and food grain anomaly. They concluded that 3-month SPI is effective to identify drought patterns in study area and it is good indicators of anomalies of food grain production.

Exhaustive comparisons of drought indices were carried out by Dogan et al. (2012) they compared 5 drought indices SPI, Percent of Normal (PN), Rainfall Decile based Drought Index (RDDI), China-Z Index (CZI) and Z score. With EDI to know the effect of time step in selecting proper time scale and selection of drought indices in Konya basin, Turkey for 18 different time steps. By correlation analysis, they found that median time scale drought values have good correlation with other time scale of drought values. They have also observed that Z score, SPI and CZI gives same results. They also recommended not to use PN and RDDI for drought monitoring. EDI is recommended for the use of comparison studies because it is free from time step and having good correlation with other drought which are used in their study. They suggested that 6, 9 and 12 month time steps are very much important to identify drought and one month time step is not useful for comparison and monitoring purpose of drought.

Pandey et,al (2008), used geographical based SPATSIM (SPatial Time Series Information Model) and DWRAM (Daily Weather Resources Assessment Model) to characterize drought. SPATISM uses SPI and EDI whereas DWRAM uses only EDI. Ratio of annual precipitation to potential evapotranspiration compared with EDI and found that when the ratio is less than 0.6 EDI shows drought. They suggested that DI is not suitable for study area but EDI suits well and frequency of the drought in the study area is 3-4 years. Byun and Kim (2010) also compared SPI and EDI in Korea using 200 years of (1807 -2007) and concluded that EDI is superior to SPI.

Mishra and Nagarajan (2010) analyzed spatio-temporal variation of SPI with GIS in Odisha district and observed that most of the study area suffered from drought in 2002 and highest value of SPI was observed (-3.06) in July 2002 for 9 month time scale.

Pai et.al, (2011) carried out District wise drought studies during southwest monsoon season using PNP and SPI for 458 districts using long time series of rainfall data (1901-2003) in India. This studies observed that SPI and PNP gives similar results. PNP gives unfair result in arid region while SPI is not. These study shows that severe drought occurred 6 times and extreme drought occurs at 4 times in entire study period. Moderate and above incensed drought was observed from Northwest region to central and interior parts of southern peninsula and probability of occurrence of severe drought is observed in west side, and some portion in eastern side of India. Conclusion drawn from this study are that SPI is better than PNP to analyze district wide drought because SPI is having good correlation with SW monsoon.

Comparison of drought indices derived from remote sensing techniques that are Microwave Integrated Drought Index (MIDI) and Vegetation Health Index (VHI) were compared with SPI by Zang (2013), Wang (2014) respectively. Study reveals that MIDI and VHI are best correlated with SPI at shorter time scale (1 month, 3 month) and conclude that, for shorter time scale drought studies, remotely sensed drought indices will give appreciated results than SPI.

5 different drought indices (SPI, Z score, CZI, RD, and RDDI) were compared with EDI at different time steps by Jain et al. (2014) for Ken river basin in India. In this study EDI is showing good correlation with other indices and highest correlation was obtained with 9 month time scale. Results obtained by this study are very supportive to the results obtained by Dogan et al (2012). Regional drought analysis were carried out by Yildiz (2014) using SPI in Turkey using precipitation data from 1953 to 2004. Intensity area frequency curves are plotted and they observed that aerial extant of drought decrease with increase in drought severity and high frequency. Along with this many studies are carried out to analyze spatiotemporal variation of meteorological drought using SPI (Bonaccors 2014; Battafuoco et al., 2014; Wambua et al., 2015; Dahal et al., 2015), Aridity index (Su et al., 2005), RDI (Cai et al., 2015) and SPEI (Liu et al., 2015). Mahajan and Dodamani (2015) and Su et al.

(2015) carried out trend analysis of meteorological drought using SPI and aridity index respectively. Su et al.,(2015) concluded that yearly Eto and precipitation had increasing trend with slope of 0.672 and 0.459 respectively, but no significant trend were observed in over all the station and the also observed that AI shows –ve trend in winter are showing more significant than other season.

Mahajan and Dodamani (2015) observed that as SPI time scale increases, the stations having significant trends also increases. Out of 59 stations only 2 stations shows + ve and 1 –ve significant trends. They conclude that over all –ve trends were observed at pre monsoon rainfall over 63 % of study area.

Mosadi et al., (2015) tested RDI with different distribution functions for four station in Iran using 50 years of data (1960- 2010). The fitted different distribution to RDI value instead of conventional log normal distribution, KS test were implemented to found out best fit distribution. From Nash-Sutcliffe coefficient value it was observed that there is a much difference between best fit and log normal RDI value in smaller time scale. A study conclude that RDI value may change if best fit distribution is used and it may lead to change the drought severity in RDI calculation.

Integrated approach for identification of drought vulnerability areas is carried out by Thomas et al., (2016) in Bundalkhand, India. Other used 3 month SPI, 6month SPI, ground water index, land use, soil type, water utilization and surface water drought index as parameters to assess the drought vulnerability. Different weights are assigned to the different sub classes of each parameter based on experience and assumptions. Summation of all weights gives total drought vulnerability of the area.

Meteorological drought is studied by Murthy et al., (2016) using CPC rainfall data of 12 years (2001-2012) for entire India, based on IMD criteria. They have used % of deviation of rainfall and rainy days for their studies and prepared drought map based on combination of deviation of rainfall and rainy days. They have observed that 5 drought years (2002, 2004, 2009, 2011 and 2012) in the study period. Rajasthan and Gujarat were affected by scanty and deficit rainfall leading to severe drought and moderate drought were found in western parts of Maharashtra, Karnataka, eastern Andhra and Tamilnadu. Study conclude that for drought assessment both rain fall and rainy days are need to be considered and rainfall distribution is also a key variable in drought with intensity of rainfall.

2.3 WORKS ON HYDROLOGICAL DROUGHT

Hydrological drought is deficiency of water on the surface of the earth (yevjevich1969). Linsley et al (1975) stated that when streamflow fails to supply water for established uses under water management plan. Tallak sen and van lanen (2004) defines hydrological drought is certain period in which water availability is below normal mainly this type of drought is significant decrease in availability of water in all its forms appearing in the land phase of hydrological cycle.

Since Palmar drought index is concentrating or using soil moisture as a major component and it is not considering snowfall and melting into overcome that Shafer and Dezmon (1982) developed a new index to address the limitations of PDSI by considering the components of snow precipitation streamflow and reservoir storage. Modified SWSI is proposed by Garen (1993) to overcome conceptual drawbacks of SWSI.

Chang (1990) used 18 streamflow gauge data to study the effects of droughts on streamflow in Scioto river basin in Ohio river basin. They have studied drought characteristics using truncation level and observed that flow ratios are significantly reducing while truncation level deceases in drought they concluded that estimation of flow based on drainage area ratio is unrealistic during low flow period.

Reliability resiliency vulnerability study and drought risk analysis were carried out by Jinno Kenji et al (1995) for the Fukuoka city in Japan by considering water supply and demand. Tallaksen and Hisdal (1997) used threshold method approach to study hydrological analysis using daily streamflow data of 56 station of 60 years (1931-1990) 70and 90 percentile of the annual seasonal FDC study area were grouped into winter or summer drought sequent peak algorithm used to generate partial duration on series they have also attempted to index the hydrological drought spatially by maximum runoff index Application of extreme value.

Engeland et al., 2004 using generalized extreme value distribution and generalized extreme distribution for Houghland river basin south-west Norway. They conducted 10 day moving average and streamflow is applied and 70 percentile of flow is used to select the best fit distribution. They conclude that irrigation is having more impact on drought but there is a small influence of river regulation on drought.

Peters, et al., (2004, 2005) attempted to analyze Ground water drought using 37 years data of 10 stations, using that 1000 years of discharge and recharge data are generated using nearest neighbor resampling method. Attempt had made to simulate hydraulic head and compared with recharge and discharge drought. They have also tried to combine drought severity and duration to study the impact of drought on ground water. Results shows that more severe drought are likely to happen at downstream as compared to upstream area.

Before 2007 hydrological drought was analyzed using threshold method only. Shukla and Wood (2007) introduces new index called Standardized Runoff Index (SRI) which uses similar procedure of SPI but runoff as input. SRI and SPI vales were compared and found good correlation between them at higher time scale. They conclude that in the absence of meteorological data SRI can be used for drought studies effectively.

Trend analysis for streamflow droughts are carried out by Hong Wu, et al,. (2007) using 69 years (1932-2001) monthly streamflow data of 9 stations in Nebraska, U S. Initially correlation between drought parameters are tested and then Mann- Kendal test is conducted. Results shows that there is significant correlation exist between severity with both duration and magnitude and duration is highly correlated with magnitude. Out of 9 stations 5 to 6 station shows -ve trend on drought parameters. The work concludes that severity and frequency of streamflow drought varies with time scale.

Pandey et al,. (2007) analyzed streamflow drought severity in the sub basin of river Yamuna using 10 day streamflow data of 42 years, from 5 stations. This study proposes severity index based on deficit flow and corresponding volume at truncation level. Results of the study shows that upper part of the river course is more drought prone as compared to lower reaches. These Results were contradictory for the results obtained by Peters et al., (2004).

Groundwater Resource Index is proposed and compared with different time scale of SPI with different time lag of GRI by Mendicino et al., (2008). Results of the study shows high correlation between SPI and GRI during summer. They have tried to forecast the summer drought using GRI and found that correlation coefficient 0.6 and 0.77 with observed runoff and NDVI respectively.

An attempt has been made to draw relationship between meteorological drought and hydrological drought by (Edossa et al., (2009) in Ethiopia using 13 years of (1987 - 2000) streamflow and rainfall data. SPI is used to calculate meteorological drought and truncation level (90%) is used to determine hydrological drought. 2 Month SPI is used to determine lag between meteorological and hydrological droughts. The results shows that there is average of 7 month lag between hydrological and meteorological drought in the study area. Linear relationship is observed between duration and magnitude of meteorological and hydrological drought with R2 of 0.87 and 0.58 respectively. Study conclude that there is no meaningful relation exist between both droughts in terms of intensity.

Groundwater drought studies are conducted by Shahid and Hazarika (2009) using 5 years (1998-2002) monthly groundwater level data and 39 years of (1964 - 2002) monthly rainfall data in northwest states of Bangladesh. To analyze groundwater drought cumulative approach is used. Compression of groundwater levels with SPI 6 and SPI 12 was carried out with in the window of 1985-2002. Time lag between groundwater levels and precipitation is observed. Results of the study shows that correlation coefficient of 0.14 between 1year SPI and minimum groundwater level was observed in the month of April at 95% confidence level. The study concludes that deficit in the rainfall is not solely reason for decrease in groundwater levels.

Nikbakht et al., (2012) attempted to define hydrological drought using Percent of Normal Index (PNI) in northwest Iran using streamflow data of 14 stations from1975-2009. Temporal trends are studied using parametric and non-parametric tests. Results indicates that worst streamflow drought is occurred in 1999-2000 and 2000-2001 for most of the stations. 12 Out of 14 stations shows -ve trend in streamflow drought by non-parametric tests and parametric tests shows no significant trend in the stations.

Different distributions are fitted for streamflow data to study Standardize streamflow Index by Vicente-Serrano et al., (2012) using 60 years of (1945-2005) discharge data of 98 gauging stations in Ebro basin, North-West Spain. The Results of SSI shows that Pearson type III distribution over estimates -ve anomalies and there is no much difference in the drought characters obtained from lognormal, GEV and log- logistic distributions. The study concludes that for calculation of SSI unique probability distribution is not to be used. In other hands the study recommends use of best fit distribution to characterize drought using SSI give reliable results.

Karimi and Shahedi (2013) carried out variable threshold method to study hydrological drought using daily discharge data of 13 stations in Iran. Frequency analysis of drought parameters were studied using generalized Pareto distribution and Weibull distribution. The study concludes that drought intensity is higher in lower catchment as compare to higher.

Nalbantis and Tsakiris (2008) developed a streamflow drought index to define hydrological drought for a basin in central Greece using 30 years of monthly streamflow data. They also tried to define SDI for an ungauged basin using SPI and established linear regression between and SDI and SPI, with and without lag. Results show that highest R2 value of 0.8944 and 0.8835 for with and without lag. Nalbantis (2008) is also tested the proposed method using data from two other basins and got good results as they obtained for the basin in the central Greece. Tabri et al., (2001) also used SDI in the mountainous region of Iran. Regional analysis of drought is carried out by Byzedi et al., (2014) carried by considering physiographic, geo climatic and vegetation factors in Iran. Drought deficit, drought duration values are calculated using run theory. Cluster analysis is used for grouping the similar area which are affected by hydrological drought. Results showed that deficit value per area is increasing from upstream to downstream. From factor analysis, they come to know that watershed elevation, drainage density, watershed area, the percentage of area with NDVI <0.1, rainfall during December to February and percentage of the convex area are the most influencing factors for hydrological drought. Multivariate regression is established using above mentioned 6 factors because they explains 89.2% of variations.

The study concludes that 6 factors are good correlating with hydrological drought deficit volume.

Climate change effects on streamflow drought are studied in South Taiwan by Shan Yupao (2014) 6 GSA models along with 2 climate change emission scenario were used to project temperature and rainfall for the period of 2010-2045 and 2081-2100 from the predicted temperature and rainfall future streamflows are stimulated using HBV hydrological model. Threshold method was used to analyses streamflow drought. This study observes that future streamflow trend decreases in the month of January and February and in an increase in March and April. From frequency analysis study concludes that occurrence of the probability of severe streamflow drought tends to decrease along with magnitude and duration.

Streamflow drought severity-duration and frequency curve are drawn by considering daily, monthly, fixed and desired yield threshold by Sung and Chung (2013) in south western Korea this study considers Q70 as threshold derived from flow duration curve. They observed that yield level is higher than any other threshold level. The desired yield shows higher water deficit for a longer duration. Reservoirs which are present along the river also takes part in the streamflow drought.

Zang et al., (2014) consider two cascade reservoirs for their impact on hydrological drought. For this work they have obtained standardize streamflow indices for inflow and outflow of the reservoirs and standardize reservoirs storage indices. Comparison between SPI with SSI and SRSI is carried out. Results shows that SSI obtained for upper catchment reservoir using inflow is correlating with precipitation at 1 month lag (R=0.55) and SSI obtained from outflow is correlating with precipitation with a lag of 7 to 8 months (R=0.35). They have also observed that severe streamflow droughts are reduced as compared with precipitation droughts this study concludes that streamflow drought severity at the downstream reservoir is increased with duration and increase in outflow magnitude.

Zhao et al., (2014) tried to fit relationship between meteorological drought and streamflow drought using SPI and SRI in Zinghi river basin China. They found that 3 severe streamflow drought and 11 meteorological droughts in between 1972-1990. Correlation between streamflow drought and meteorological drought is carried out and observed that 4 month SPI is good correlating with SRI, therefore, it is used to identify lag between SRI and SPI. Different time lag between 6 month SRI and 11 month SPI is varying from 2-256. This study concludes that frequency of streamflow droughts are less as compared meteorological droughts. In the study area, streamflow drought is lagged on an average 127 days by meteorological drought.

Saghafian and Hama (2015) developed rainfall drought index model to give early warning to hydrological drought using different rainfall thresholds. They sorted out rainfall values which are coming under different severity classes of streamflow drought after that probabilities of rainfall threshold which are falling in each category are calculated. They found that rainfall threshold of 50 % is giving god alarm to streamflow drought. This study concludes that if smaller threshold value of rainfall the number of alarms are less as compared to higher threshold value.

Meteorological and catchment characteristics are considered to study hydrological drought severity by Lan Van and Laaha. in Austria (2015) using 31 catchment characteristics and climatic variables withy drought characteristics to study correlation heat map they used linear models, multiple regression models to develop relationship between most affected climatic and catchment characteristics with drought characteristics. Results shows that average duration of discharge drought is highly correlating with base flow index. Streamflow drought deficit shows good correlation with catchment characteristics along with climatic variables. This study concludes that higher the catchment area more the precipitation, larger drought deficit volume.

Chin and Li (2016) attempted to differentiate drought and water scarcity in Luanihe river basin in China. They proposed concept watershed drought, watershed scarcity and streamflow water scarcity. They define scarcity is shortage of water caused by human action and drought. SWAT model is used for steam flow generation along with human interface. Results shows that 7 severe droughts in the study period and 5 streamflow water scarcity they concluded that streamflow water scarcity was less than watershed water scarcity and watershed drought is 2 times greater than streamflow water scarcity.

Sreedhar et al., (2016) used standardize groundwater index to identify ground water drought prone zones in some tributaries of Krishna river basin India. They used seasonal ground water level from 18 observation wells from 1988-2011. Meteorological droughts are calculated using percentile rainfall deviation by using rainfall data of 20 meteorological stations. This study observed that huge lag time between meteorological and ground water drought.

Gao and Zang (2016) used 53 years of rainfall and runoff from 19 hydrological and 15 metrological stations respectively. To analyze spatio-temporal variation SDI and SPI in arid areas of North West china. To characterize drought Mann-Kendal trend test and wavelet transform techniques are used. They found SDI is having significant upward trend in the study area. From wavelet analysis they observed that variation in the SDI value between different segments of study period. They conclude that nonoccurrence of SDI before 1990 in north part of the study area is shifts towards eastern parts after 1990.

2.4 WORKS ON AGRICULTURAL DROUGHT

In agricultural drought soil moisture is key variable and it interns depends on the physical/chemical properties of the particular soil, weather environments (such as temperature, relative humidity), its bio-chemical composition and different types of irrigation practices. Therefore to provide good definition for agricultural drought all the parameters/ variables which effects negatively to crop yield is need to be consider.

Agricultural drought starts with or succeed of meteorological drought, but it occurs previous to hydrological drought. Agricultural drought can be studied based different indices which uses precipitation shortages, differences between potential and actual evapotranspiration, reduced reservoir levels/ground water or combination of them as input. Different indices have been developed to quantify agricultural drought, each of them are having its own strengths and weaknesses. Most of the agricultural drought indices are relay on soil moisture and remote sensing data alone, some indices also considered crop yield and evapotranspiration to address the agricultural drought.

The “Moisture Adequacy Index” (MAI) (McGuire and Palmer, 1957) is the basic Agricultural drought index to implement the concept of potential evapotranspiration. Palmar C (1965) attempted to derive Crop Moisture Index (CMI) to monitor agricultural drought using short term (weekly) temperature precipitation data. Bergman et al. (1988) developed Soil Moisture Anomaly Index (SMAI). Jakson (1988) developed Crop Water Stress Index (CWSI) by considering field evapotranspiration along with soil moisture.

Drawback of CWSI is that it is not considering crop water requirement of different crop at different periods of growing session. To overcome this Meyer et.al (1993) proposed Crop Specific Drought Index (CSDI). He studied CSDI for corn using soil and crop phenology information in addition to climatological data at daily time scale. Kogan.(1990) developed NDVI based drought index called Vegetation Condition Index (VCI) it is remote sensing based index. It is the ratio of NDVI of given period to NDVI of several periods of record. In India most of the farms are rain fed and there is no agriculture in these areas during summer therefore use of VCI during summer is not preferred.

Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) was developed by Narasimhan and Srinivasan (2005) to monitor agricultural drought using simulated short term (weekly) soil moisture deficit and evapotranspiration data using SWAT model. Soil Moisture Index (SMI) was developed by Sridhar et al (2009) to quantify soil water stress, based on the observed actual soil water content and known field capacity and wilting point. Author says that it can be applied universally if there is an observed values of soil water and known values of welting point and field capacity. Limitation of the index is to get spatially measured soil water for entire study area for a long period. Along with these there are many indices and indicators which have been used to monitor agricultural drought with the aid of remote sensing and can be widely used to monitor agricultural drought viz Standardized Vegetation Index (SVI), Normalized Deference Vegetation Index (NDVI), Vegetation Temperature Condition Index (VTCI) and many more.in this paper remotely sensed agricultural drought indices are concentrated little more.

Application of satellite-based remote sensing for drought monitoring began in the1980s with the application of NDVI data from the operational NOAA AVHRR instrument

(Tucker et al., 1986, 1991; Hutchinson, 1991; Eidenshink and Hass, 1992). Various vegetation indices derived from satellite data enables to identify the areas affected by agricultural droughts (Kogan, 1995, 1998; McVicar and Jupp, 1998) and also Crop yields can be predicted using the techniques of remote sensing (Ungani and Kogen, 1998). A large number of indices obtained from remote sensing are available for agricultural drought assessment and prediction. Many of them are based on vegetation indices (Martínez-Fernándezet al., 2016).

Normalized Difference Vegetation Index (NDVI) is popular index to identify and monitor agricultural drought in regional scale (Tucker and Choudhury, 1987; Kogan, 1997; Bhuiyan et al., 2006; Bayarjargal et al., 2006). Tucker (1979) introduced NDVI as an index of vegetation health and density. It is calculated by taking the difference between the visible and infrared light reflections and then normalized by dividing it by the sum of them. Tucker et al. (1991) demonstrated that inter comparisons of extended time series of NDVI data can provide useful information for drought monitoring. William et al (1994) used NDVI to study drought characteristics in the South American region. Vegetation response to drought was analyzed by examine the spatiotemporal drought maps, obtained from NDVI values.

Kogan (1991) developed NDVI based drought index called Vegetation Condition Index (VCI) and it is the ratio of NDVI of given period to NDVI of several periods of record. This index was used in South America, North America, Asia, Europe and Africa for assessment of drought impact on regional agricultural production (Anyamba et al., 2006). Average VCI values for each week of the growing season were calculated and compared with yields of crops. Strong correlation between VIC and yield is observed particularly in critical periods of crop growth. Dutta et al., (2015) used VCI to assess the agricultural drought in Rajasthan, India. Results shows that occurrence of drought related crop stress during the year 2002. He also validated the VCI by comparing VCI and yield of major rain-fed crops and found that strong positive correlation (0.75) between them.

Since NDVI value depends only on area of green leaf and biomass and it shows delay response to drought (Wang et al., 2001) due to antecedent moisture stored in the soil. Many studies have shown that there is a lag relationship up to 3 months between NDVI and precipitation (Justice et al., 1986; Wang 2000). The lag time is mainly dependent on whether the area is rain fed area, fully/partially irrigated. If the area is purely rain fed then the lag time between NDVI and precipitation is less. NDVI itself does not reflect drought or non-drought conditions. But the severity of a drought can be recognized by deviation of NDVI from its long-term mean. Due to these reasons it is difficult to analyze agricultural drought using vegetation data alone. Therefore, along with NDVI, temperature based, soil moisture based and evapotranspiration based indices or combination of them are derived to analyze agricultural drought comprehensively (Kogan, 1995; Sandholt et al., 2002; Sivakumar et al., 2011).

A study in India found that the utility of the VCI for drought monitoring was improved when used in conjunction with the Temperature Condition Index (TCI) (Singh et al., 2003). Liu and Kogan (1996) also observed that performance of the TCI (Temperature Condition Index) is better than NDVI and VCI, in the high soil moisture regions. In such conditions, NDVI and VCI values are too low, which represents “fake” drought situation. To address this VHI (Vegetation Health Index) was introduced by Kogan (1995a), by combining VCI and TCI. The VHI concept assumes an inverse relationship between NDVI and BT. This is due to the fact that higher land surface temperatures (LSTs) leads to decrease in NDVI, which can be indicative of a drought stress signal because of reduced evapotranspiration (ET). The assessment of drought probability for agricultural areas in Africa have been well shown by Rojas et al. (2011) by coarse resolution NDVI and VHI from NOAA AVHRR. Wang H et.al (2014) calculated Vegetation Health Index (VHI) using multi temporal Normalized Difference Vegetation Index and land surface temperature from 2001 to 2010 to assess the relationship between VHI and SPI in China. Results of VHI shows severe drought during March 2010 and maximum correlation between 3-month SPI and VHI ($r = 0.87$ $p < 0.01$). To quantify Agricultural drought risk in Ukrain, Skakun et al., (2015) used time series of vegetation health index (VHI) obtained from the NOAA satellites (National Oceanic and Atmospheric Administration) and estimated Damage rate by comparing with crop yield data.

VHI has limitation in elevated regions where LST and NDVI shows a positive relationship and areas where water was the primary limiting factor of vegetation growth (Karnieli et al., 2006, 2010). The uncertainty in the relationship between NDVI–temperature for different climatic zones and land cover types makes difficult to monitor regional drought VHI.

Evaporative Stress Index (ESI) was developed by Anderson et al. (2007) for the United States, which uses an energy balance approach to estimate Eta. The energy balance approaches requires vegetation and temperature inputs and it avoids assumptions of the soil profile. Vegetation Drought Response Index (VegDRI), a hybrid geospatial drought monitoring tool developed by Brown et al., (2008) in seven north-central states of the United States. To produce a near real-time 1 km resolution map of drought conditions.

Rhee et al., (2010) proposed Scaled Drought Condition Index (SDCI), to monitor agricultural drought in arid and humid regions. To derive SDCI, LST (Land Surface Temperature) data and the NDVI (Normalized Difference Vegetation Index) data from MODIS (Moderate Resolution Imaging Spectroradiometer) sensor, and precipitation data from TRMM (Tropical Rainfall Measuring Mission) satellite were combined. Limitations of this study is that the categories of SDCI maps were randomly classified and weightages which are used for different components (LST, NDVI and rainfall) are not optimized.

Dalezios N.R et.al (2012) conducted a study to quantify the drought using remotely sensed Reconnaissance Drought Index (RDI). Precipitation and potential evapotranspiration are the inputs required for calculation of RDI (Tsakiris and Vangelis, 2005; Tsakiris et al., 2007). They used 10-day Brightness Temperature (BT) images and 10-day Normalized Difference Vegetation Index (NDVI) provided by NOAA are used to calculate potential evapotranspiration and local precipitation data have been used to calculate RDI. Evaporative Stress Index (ESI) was put forth by Otkin et al. (2013) to calculate ETo (Evapotranspiration) using remotely sensed thermal infrared imagery, and observed that ESI anomalies can give primary warning for agricultural drought. Padhee et al., (2014) also used combination of meteorological observations and soil moisture distribution to assess and predict agricultural drought in irrigated and rain-fed agricultural regions in Bundelkhand, India. Keshavarz et al., (2014) presented the Soil Wetness Deficit Index (SWDI), which is calculated from the LST (Land Surface Temperature) along with NDVI resulting from the MODIS (Moderate Resolution Imaging Spectroradiometer) satellite. Li and Tsubo (2014) also compared CMI with anomalies of NDVI derived from MODIS, to evaluate agricultural drought in the northeast part of China.

The launch of SMOS (Soil Moisture and Ocean Salinity) and SMAP (Soil Moisture Active and Passive) satellites enhanced the application of soil moisture in drought studies. Martínez-Fernández et al., (2015) validated Soil Water Deficit Index (SWDI) derived from SMOS Soil Moisture data over measured soil moisture data. Results obtained from SMOS Soil Moisture data are matching with results obtained from in situ soil moisture data.

Vyas et al., (2015) developed Combined Deficit Index (CDI) by combining remotely sensed NDVI and observed rainfall for three states of India. One of the disadvantage of CDI is the weightages which are given for both NDVI and rainfall is illogical, optimized weights are need to be provide before comparison with other indices. Sánchez et al., (2016) merged NDVI and LST from MODIS (Moderate Resolution Imaging Spectroradiometer) and Surface Soil Moisture obtained from SMOS satellites to derive Soil Moisture Agricultural Drought Index (SMADI). Results of SMDI are validated with the results of CMI, SWDI and SPI calculated from measured soil moisture and measured rainfall data respectively.

2.5 MULTIVARIATE/ COMBINED DROUGHT INDICES

Drought indices are the numerical expressions based on different climatic and hydrological variables or combination of them, used to describe physical characteristics of a drought like duration, severity, frequency and spatial extent (Steinemann et al, 2005; Hayes et al, 2012). However, it is tedious to segregate different types of drought (Mo, 2008), because they may occur at the same time or consecutive and variables which are used in drought studies are interrelated. In reality, drought conditions are associated with multiple variables (Wilhite, 2005) therefore drought index derived from single variable may insufficient to characterize the complicated drought phenomenon and its broad impacts.

Considering the variables related to all types of droughts, Keyantosh and Dracup (2004) developed Aggregate Drought Index (ADI). It considers precipitation, ET, streamflow, reservoir storage, snow and soil moisture as its input. They have not considered of groundwater because they states that groundwater response very slowly to drought and not synchronize with other variables of ADI. Dragota et al. (2009) used combination of SPI climatic water deficit to study drought in Romania. They defined water deficit of the difference between precipitation and ET. They conclude that combined used of SPI and WD characterized drying of a region better than one factor alone.

Researchers from different regions used different combination of variables to produce combined drought indices. While combining the variables, some used linear combinations techniques (Rhee et al., 2010; Zhang and Jia, 2013; Hao et al., 2015), some are used statistical techniques Joint probability, PCA and Multiple regression (Brown et al., 2008; Kao and Govindraju, 2010; Rajashekhar et al, 2014; Rad et al, 2018). The limitations combined drought indices which are developed by combining different variables linearly are, they may not characterize the nonlinear relation (or dependence) among the different variables, and it is difficult to determine the weights used to combine the variables. Limitations of joint probability is that it is only comparable with other multivariate probabilities with the same sets of marginal. Multivariate drought indices are not always superior to univariate drought indices and they will not replace any univariate drought index currently being used (Hao and Singh, 2015). Moreover, similar to the univariate drought index, there is not a significantly preferable or universally accepted multivariate drought index.

2.6 APPLICATION OF COPULAS FOR DROUGHT ANALYSIS

Drought are stochastic in nature, numerous studies have been reported analyzing droughts using probabilistic theories (Gupta and Duckstein, 1975; Kendall and Dracup, 1992; Rossi et al., 1992; Vangelis et al., 2011; Bonaccorso et al., 2015). In bivariate drought studies, there is an assumption that severity and duration are from the same distributions mostly normal distribution but many studies showed that severity, in most cases, expected to follow a gamma, a lognormal distribution or a Gumbel distribution, whereas the duration (as a continuous variable) commonly followed an exponential distribution (Zelenhastic and Salvai, 1987), or a geometric distribution if it is treated as a discrete variable (Kendall and

Dracup, 1992). Therefore to model the drought events, the severity and duration can be modelled by different distributions, and it is difficult to find the appropriate joint severity-duration distribution. To overcome this problem the copulas can be applied. Copulas are functions joining univariate distribution functions from any distribution into a single multivariate distribution function. From the first introduction of copulas by Sklar (1959), several works have been published with applications in various fields, among which is also hydrology. In recent years, copulas have been used for multivariate hydrological analysis. Copulas are widely used to investigate multivariate analysis for drought. Ganguli (2013) modelled drought characteristics in Marathwada region of Maharashtra with the applications of Archimedean copulas and observed that joint modelling showed increase in drought risk in the region as compared to univariate analysis. Xu et al., (2015) used copulas to develop a regional drought frequency model by considering drought duration, severity and the affected areas. Archimedean, extreme value, placket and elliptical copula families were considered for assessing hydrological droughts return period for Texas by Rajshekar et al. (2014). Tosunoglu and Can (2016) modelled joint probability distributions of meteorological droughts of Turkey using copulas. Frank, Clayton, Gumbel–Hougaard and Ali–Mikhail–Haq copula were used to model the joint probabilities of drought characteristics for all homogenous regions.

2.7 DROUGHTS IN FUTURE CLIMATE

There are many investigations are ongoing to understand the droughts considering future climate change (Kwak et al., 2014). To overcome the future water stress, sustainable water resources management is essential from the regional to national scales (Shrestha and Htut, 2016; Vu et al., 2016). Further, changes in climate events and weather extremes have had a significant impact on natural water resources. Many studies on climate model projections suggest that in future climates, frequency of droughts is likely to increase globally (Wetherald and Manabe, 2002). Wander et al., (2014) considered Five General Circulation Models (GCMs) and four emission scenarios (RCPs), was considered to study droughts in future. The results showed nonsignificant impact of different emission scenarios on future drought characteristic. Ahmadalipour et al., (2014) observed intensity and duration of hydrological droughts are expected to increase in the future compared to historical droughts in Willamette River Basin.

2.8 SUMMARY OF LITERATURE

There is extensive literature available for different types of drought. Many studies had been carried out through out the word with different drought indices for quantifying characteristics of meteorological drought, hydrological drought and agricultural drought. However, none of the drought indices has been accepted globally for any climatic region. Different drought indices have their own limitation and all are not fit for all types of climatic regions. Because each region characterized by its own climatic condition which fabricates drought as regional climatic phenomenon. Every region has its prevailing climatic variable/s which plays crucial role in the regional hydrological cycle. Every drought index may not capture these critical climatic parameters effectively, while estimating drought characteristics. Numerous drought indices were developed by the various researcher to quantify meteorological drought. Whereas only few studies were evaluated the compatibility of drought indices for different climatic regions. In Indian context, only countable researches incorporated joint modelling of drought characteristics with the help of copula and no study has been reported application of copula to groundwater drought.

CHAPTER 3

STUDY AREA AND DATA USED

3.1 INTRODUCTION

Krishna river is the second largest river in peninsular India, rises in the Mahadev range of the western ghats 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 of India. The major tributaries of river krishna are Ghataprabha, Bhima, Malaprabha, Tungabhadra, Musi,Palleru and Muneru. Among these, Ghatapraba river basin has been facing a severe water shortage problem for both irrigation and domestic purposes over the past few decades oweing to deficit rainfall (GOK, 2008). The ghataprabha river basin spredes its major portion in North Karnataka vulnerable severe drought (KSNDMC, 2017). The Ghataprabha river basin being a drought prone area, where groundwater levels are depleting continuously and Central Ground Water Board (CGWB) of India is also demarcated the semi-critical or overexploited groundwater areas in the major portion of the basin (CGWB 2011). Keeping points as reference, Ghataprabha river basin is selected for the study.

3.2 DESCRIPTION OF THE STUDY AREA

The Ghataprabha river basin is a sub-basin of the river Krishna and is positioned between 15°45′ and 16°25′N latitudes and 70°00′ and 75°55′E longitudes of (Fig. 3.1). It originates in the Western Ghats at an altitude of 884 m and flows eastward through Sindhudurg and Kolhapur Districts of Maharashtra and Belgaum and Bagalkot districts of Karnataka. The major tributaries of the Ghataprbha river basin are Tambrapani, Hiranyakeshi and Markandeya. The total length of the Ghataprabha River is about 260 km, and total catchment area of the basin is 8829 km^2 out of which 77.2% lies in Karnataka and rest falls in Maharashtra.

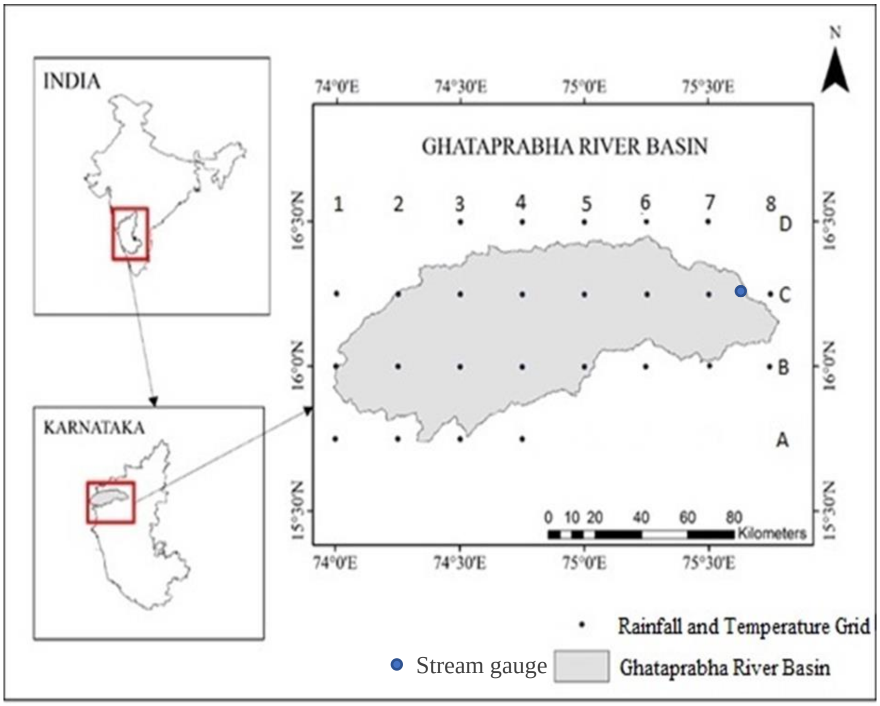


Fig. 3.1 Geographic location of Ghataprabha river basin

The climate of the sub basin is marked by a hot summer and mild winter. The monsoon sets early in June and continues to the end of October. The study area is a semiarid region where rainfall is confined to monsoon season from June to October, and normal rainfall varies from 5000 mm (in a small portion of Westside, which covers the Western Ghats) to less than 600 mm at the eastern part.

The annual mean temperature of the basin varies from 25.1 to 26.6 °C. May is generally the hottest and December is generally the coldest month with the mean daily maximum and minimum temperature being 29.3^{0}C and 13.9^{0}C respectively. The main land use of the area is agriculture, and it is the main occupation of the population of the area. The study area covers three major aquifer systems (Figure 3.2), namely Basalt, Limestone and Schist (CGWB 2012); basalt covers most of the area. The Ghataprabha river basin, being a drought-prone area, encompasses semi-critical or overexploited groundwater areas in the major portion of the basin (CGWB 2011).

3.3 DATA USED IN THE STUDY AND THEIR SOURCES

In the study, gridded daily rainfall data of 0.25-degree resolution, from 1970 to 2013 was obtained from India Meteorological Department (IMD), Pune. Daily maximum and minimum temperature data of 0.25-degree resolution, from 1970 to 2013 was secured from recently developed NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) data sets (Thrasher et al. 2013). To develop NEX-GDDP data sets, initially the Bias-Correction Spatial Disaggregation (BCSD) method was employed to downscale CMIP5 GCMs, latter these data sets were bias corrected using Quantile mapping technique with the aid of climatic data sets of Global Meteorological Forcing Dataset (GMFD). Further spatial disaggregation methods were applied to get finer resolution (0.25 X 0.25 degree) of NEX-GDDP data sets (Thilakarathne and Sridhar, 2017). Twenty-five grid points of rainfall and temperature which covers the Ghataprabha River basin were considered and named from A1 to D7 (Figure 3.1).

The monthly streamflow data measured at Bagalkot from 1970 to 2000 and monthly reservoir levels and reservoir out flows of Hidakal dam from 1983 to 2013 are obtained from India Water Resource Information System (https://www.indiawris. nrsc.gov.in/wris.html) and from the Water Resources Development Organization (WRDO), Govt. of Karnataka, India. In the study, monthly groundwater-level data of 70 wells situated in and around the study area were obtained from the Mines and Geology department Karnataka, India. The procured data were checked for sufficient volume of data availability with continuous observations. The wells with less than 25 years of data were excluded from the study. Finally, groundwater-level data from 59 wells (Figure 3.3), spanning not less than 25 years, were considered for the analysis. The multi temporal Normalized Difference Vegetation Index (NDVI) of 16-day composite with resolution of 250m from 2000-2013 was collected from Terra MODIS Vegetation Indices Product (MOD13Q1) (modis.gsfc.nasa.gov).

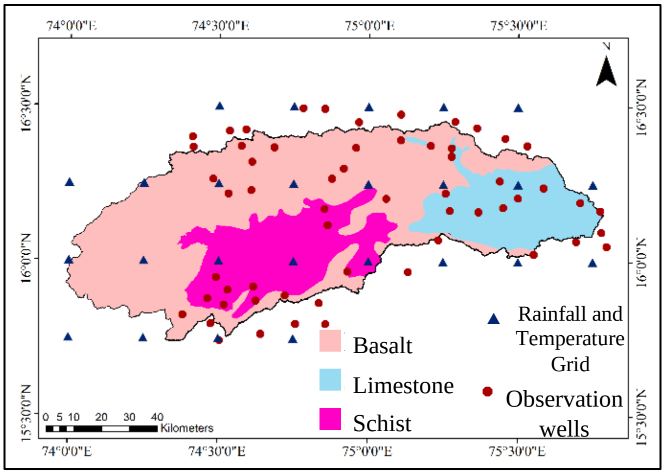


Fig. 3.2. Location of observational wells overlaid on aquifer map

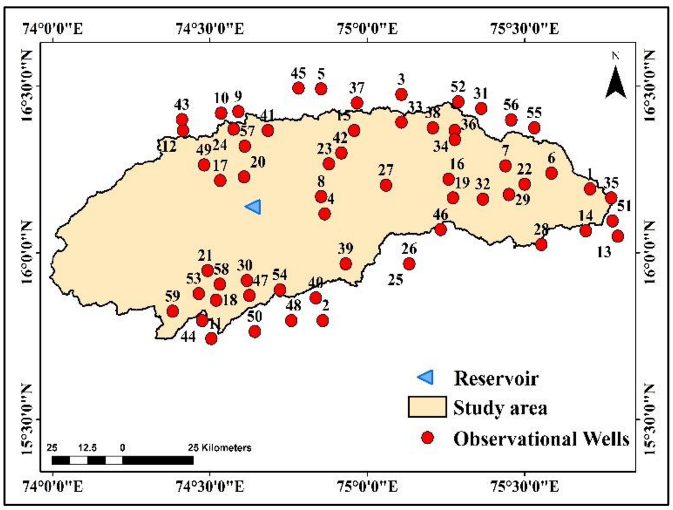


Fig. 3.3. Location of observation wells with reservoir

The RCM-simulated precipitation and temperature from the COordinated Regional climate Downscaling EXperiment (CORDEX) was downloaded for the historic (1970–2005) and future projections (2006–2100) from Earth System Grid Federation (ESGF) (https://esg dn1.nsc.liu.se). The RCP 4.5 scenario describing the medium stabilization after the year 2100 without overshoot pathway to 4.5 W/m^2 was used in this study. The RCP 4.5 assumes a significant role of renewable energy (such as nuclear, hydropower and solar) in the future. Rainfall and temperature projections from four climate models CNRM-CM5, HadCM3, SHMI-RCA4 and REMO for RCP4.5 were used in the study used. The land use and land cover (LULC) data used in the present study was of 100-m spatial resolution at decadal intervals for 1995 and 2005 (Figure 3.4) obtained from “daac.ornl.gov” website.

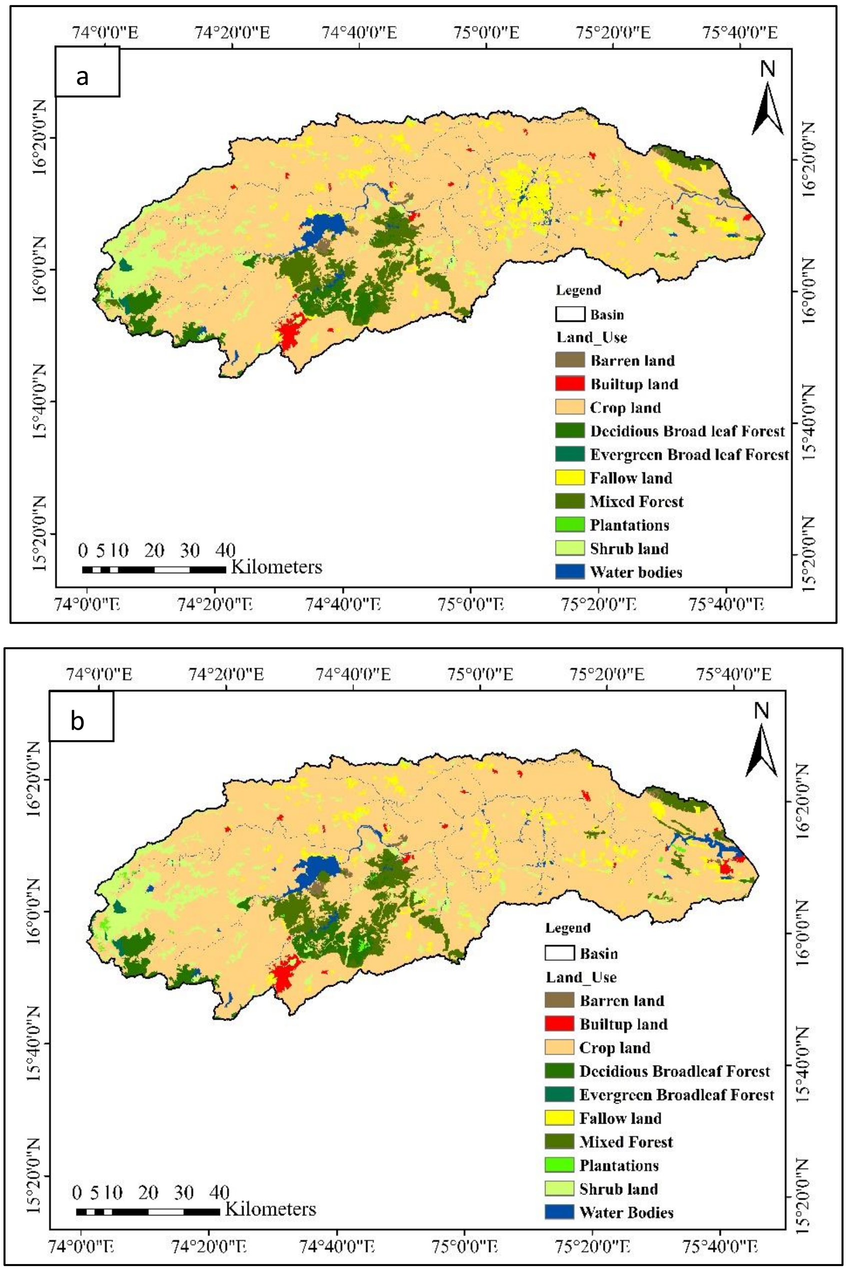


Fig. 3.6. Land use land cover map of the study area for a) 1995 b) 2005

CHAPTER 4

TREND ANALYSIS OF HYDROMETEOROLOGICAL VARIABLES

4.1 INTRODUCTION

The climate of a region plays a pivotal role in building a healthy ecohydrological system in an area and it also has implicit effects on land productivity, agriculture, food security, water quantity and economic status of a region. The temporal or spatial variation of climatic has profound impact on hydrological factors, such as streamflow, base flows, and groundwater levels. Therefore, information on variation/ trends of hydro-meteorological variables at different time scales is a vital prerequisite to facilitate enhanced water resources management practise and strategies.

Rainfall and temperature are the two most effective meteorological drivers which have potential to cause drastic impact on streamflow, reservoir storages, groundwater levels and crop yield in the form of droughts and floods. Thus, the analysis of rainfall and temperature trends is of great concern in the water resources sector and they also help to understand the variation of underlying pattern with the association of climate change. Hence, this chapter looks in to variation and probable changes in the pattern of hydrometeorological time series in the Ghataprabha river basin.

In the Indian subcontinent many researchers (Sarker & Thapliyal, 1988; Lal, 2001; Dash et al. 2007; Kumar and Jain 2012; Raju and Nandagiri, 2017) analyzed trends in hydro meteorological variables in different regions of the country. The Krishna River being one of the large river basin consisting the study area possessed decreasing trend in the annual rainfall and increasing trend in annual rainy days, which indicates that droughts may become more recurrent in Krishna basin. Impact of decreasing trends in the meteorological variables are expected to have considerable consequences on surface and groundwater resource.

Groundwater being one of the prominent entity of the hydrosphere can provide resilience to early-stage agricultural drought (Hughes et al., 2012; Mussá et al. 2015). In recent years, groundwater resources are also depleting significantly due to increased demand and frequent severe droughts (Fishman et al. 2011). In this concern, monitoring and assessing groundwater and surface water trends are also equally important particularly in arid and semiarid regions (Goodarzi et al. 2016).

Trend in the time series is a study increase or decrease of a data points over a longer period of time. The trend analysis often refers to techniques for extracting an underlying pattern of a time series which would otherwise be partly or nearly completely hidden noise (non-periodic undulation). Trend in the time series of hydro-meteorological data can be detected using parametric or non-parametric methods. The parametric test assumes that, the parameters of the population distribution(s) from which data is drawn are normally distributed, while in non-parametric methods no such assumptions were involved. Since many of hydroclimatic variables are not normally distributed, non-parametric test is preferred over parametric test.

In this study, a popularly used non parametric Mann-Kendell trend test is considered to identify trends. This test is commonly employed to detect monotonic trends in environmental, climatic and hydrological time series (Wu et al. 2008; Tabari et al. 2012; Ganguli and Reddy, 2014, Leelaruban et al. 2017). The Mann-Kendell test can be applied to variety of time steps such as daily, weekly, seasonal or annual and spatial scales ranging from a single station to a River basin. The magnitudes of these trends were estimated by Sen's-Slop method. The Mann-Kendell and Sen's slop tests are employed at 95% confidence level to assess trends in hydrometeorological variables (rainfall, rainy day, temperature, potential evapotranspiration, groundwater levels, streamflows and reservoir levels) of Ghataprabha river basin at monsoon (June to September), post-monsoon (October to December), winter (January to February), pre-monsoon (March to May) and annual scale.

4.2 METHODOLOGY

4.2.1 Identifying climatic zones of the study area

The study area spreads over from hilly region (elevation of 1054 m) to flat terrain (elevation of 500 m) and the climatic variables behave differently in each of these regions with respect to elevation. To understand the climatic variability of the study area, the Ghataprabha river basin has been categorized in to humid, sub humid and semiarid region based on UNEP Aridity Index (AI) (UNEP. 1992). The aridity index can be defined as the ratio of average annual Precipitation (P) to the average annual potential evapotranspiration (PET) over the prolonged period of time. The AI can be understood as a degree of balance between atmospheric water supply (mainly precipitation) and demand of water (mainly potential evapotranspiration) on the land surface. In this study, temperature-based Penman-Monteith PET has been calculated in monthly scale for each station (Allen et al. 1998; Paulo et al. 2012; Pandey and Pandey, 2016) and same has been used for calculation of AI. The steps and equations followed in the calculation of temperature-based Penman-Monteith PET has been clearly described by Pandey and Pandey (2016). The AI has been calculated for all the stations of the basin and classified according to the UNEP classification, which classifies the area as humid, sub humid, and semiarid if the value of $P/PET > 0.75$, $0.5 < P/PET \leq 0.75$ and $0.2 < P/PET \leq 0.5$ respectively (UNEP. 1992; Paulo et al. 2012).

4.2.2 Mann–Kendall test for trend analysis

Trend analysis helps to understand the pattern of a time series data. Mann Kendall (MK) test is a non-parametric test extensively used for the trend analysis of hydrological and climatic variables (Wu et al. 2008; Tabari et al. 2012; Ganguli and Reddy 2014). Mann Kendall test received more popularity among other trend analysis methods (Spearman’s Rho test, Student’s t test) because it does not require the data to be normally distributed and it has less influenced by raw and skewed data (Yue S. et al. 2002). The only caution has to be taken before applying the MK test is that, the data should not possess lag l autocorrelation at 95 % confidence level. If such autocorrelation exists, that has to be removed by prewhitening (Thomas et al. 2015).

The MK test was proposed by Mann (1945) as non-parametric test for trend detection and Kendall (1975) formulated the test statistic. According to the test let X_1, X_2, X_3,…….Xn be a time series data, the null hypothesis, Ho assumes that there is no trend will tested against the alternate hypothesis H1 which assumes the trend existing. The test statistics S was determined using the relation

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{4.1}$$

where n is the length of the data and X_j and X_i are the data values in time series i and j (j>i), respectively. The application of trend test is done to a time series x_i that is ranked from i=1, 2. . . n. Each of the data point x_i is taken as reference point which is compared with the rest of the data points so that

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} +1, > \operatorname{sgn}(x_j - x_i) \\ 0, = \operatorname{sgn}(x_j - x_i) \\ -1, < \operatorname{sgn}(x_j - x_i) \end{cases} \tag{4.2}$$

The statistic, S counts the number of adjacent data pairs in which the first value is smaller than the second and subtracts the number of data pairs in which the first value is larger than the second. It has been documented that when n > 10, the statistic S is approximately normally distributed with the mean. The variance of this distribution depends on whether all the values are distinct, or if some are repeated values. The variance of S is given by

$$Var\ (S) = \frac{n\ (n-1)\ (2n+5)\ - \sum_{m=1}^{n} t_m (m-1)\ (2m+5)}{18} \tag{4.3}$$

Where, n = Number of data, m = Number of tied groups and t_m = Number of data points in the m group. Then the MK test statistics Z is computed as

$$Z = \begin{cases} \dfrac{s-1}{\sqrt{\text{var}(s)}}, s > 0 \\ 0, s = 0 \\ \dfrac{s+1}{\sqrt{\text{var}(s)}}, S < 0 \end{cases} \tag{4.4}$$

The presence of a statistically significant trend is evaluated using the Z value. Significance level α is used for testing either an upward or downward monotonic trend (a two-tailed test). If Z appears greater than $Z_{\alpha/2}$ where depicts the significance level, then the trend is considered as significant. The value for $Z_{\alpha/2}$ is obtained from the standard normal cumulative distribution tables for the significance levels (α) 0.001, 0.01, 0.05 and 0.1 (Timo et al. 2002). In the study, the Mann-Kendall nonparametric test is applied at a significance level of α= 0.05, to evaluate the regional trend of rainfall, rainy days, temperature, streamflow, groundwater levels and reservoir levels of the study area. Along with the Mann-Kendell test, Sen's (1968) method was employed to quantify the magnitude of the trend.

4.2.3 Magnitude of Trend Using the Sen's Slope Estimator

Sen's slope estimator test is used to determine the magnitude of trend line. The Sen's slope estimator has been widely used for finding change in slope per unit time in the time series. The method proceeds by calculating the slopes as a change in the measurement per change in time. The approach involves computing slopes for all the pairs of ordinal time points using the median of these slopes as an estimate of the overall slopes.

In this method the slope (Q_i) of all data pairs is first calculated using the equation.

$$Q_i = \frac{x_j - x_k}{j - k} \quad \text{for i = 1,2,3,\ldots.., N} \tag{4.5}$$

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 Q_i is represented as Sen's slope which is given as:

$$Q = \begin{cases} Q_{\left[\frac{N+1}{2}\right]} & if \quad N \text{ is odd} \\ Q = \frac{1}{2}\left(Q_{\left[\frac{N}{2}\right]} + Q_{\left[\frac{N+2}{2}\right]} \right) & if \quad N \text{ is even} \end{cases} \tag{4.6}$$

A positive value of Q indicates an increasing trend and a negative value indicates a decreasing trend in time series.

4.2.4 Regional Classification of observation wells using cluster analysis

Since the aquifer properties of the wells vary from place to place, and it is necessary to identify the wells which show similarities in the groundwater level fluctuation under the influence different aquifer zones, and it is also difficult to analyze the groundwater hydrographs for each well of the aquifer. Hence, the regional classification of the wells was done using hierarchical and non-hierarchical clustering methods to classify the observation wells into different clusters. To begin with cluster analysis, the agglomerative hierarchical clustering with Ward's linkage method (Ward 1963) was performed to identify the homogeneous wells based on groundwater level hydrographs. The measure of similarities between the wells was obtained by Squared Euclidean Distance (SED) measure given as

$$SED_{(x,y)} = \sum (x_i - y_i)^2 \tag{4.7}$$

Where x_i, y_i are the monthly groundwater levels of well x and y respectively.

In the hierarchical clustering method, initially the distance matrix based on the groundwater levels is calculated, and each well is considered as a separate group. Later, these groups are merged with the nearest groups based on the Ward's linkage method (Mirzavand and

Ghazavi 2015). The Ward's method works with the objective function such that it joins the two clusters considering minimum increment in the Sum of Squared Errors (SSE) given as

$$I_{AB} = \frac{n_A n_B}{n_A + n_B} \left\| m_A - m_B \right\|^2 \tag{4.8}$$

Where, I_{AB} is the Increment in SSE after merging clusters A and B

n_A and n_B are number of observations in cluster A and cluster B respectively

m_A and m_B are the centroid of cluster A and B respectively

For non-hierarchical clustering, a widely used K-means algorithm (Hartigan and Wong 1979) was considered to identify the position of each well in each cluster, and it differs from hierarchical clustering in the way that it requires predefined cluster centers to initiate the algorithm. The objective of the K-means algorithm is to split n observations into k clusters in such a way that the distance between cluster center and each observation belongs to the cluster is minimized (Ghosh and Srinivasan 2016).

In the study, optimum clusters obtained through hierarchical clustering is considered as the initial cluster centers for the K-means algorithm and SED is used to identify the distance between cluster mean to the individual observations. Since both, the clustering methods are not producing the same clusters by their own, and this will be an issue while selecting the optimum number of clusters from both the methods. To overcome this, "Elbow method", Average silhouette method (Rousseeuw 1987) and Gap statistics (Tibshirani et al. 2001) were employed. In the Elbow method, an optimum number of the clusters are selected by identifying the bend (Elbow) corresponding to the number of clusters in the Within Sum of Square (WSS) curve.

Average silhouette method measures the ratio of the difference between the distance to elements in the same cluster with the average distance to elements in other clusters to the maximum distance (Amorim and Hennig 2015). The value of the silhouette coefficient can vary between −1 and 1. The silhouette coefficient closer to 1 specifies the wells are clustered appropriately, if it is close to zero indicates the individual lies between two clusters and a negative value show that the individual may be located in the wrong cluster. The average silhouette coefficient of a cluster can be computed by taking the average of the silhouette coefficients belonging to the cluster. A high average silhouette coefficient indicates a good clustering and the optimal number of clusters is the one that has maximum average silhouette over a different range of the clusters (Kaufman and Rousseeuw 1990). The gap statistics was developed by Tibshirani et al. (2001) to identify optimum number of clusters. The gap statistics compares the variation of the total within sum of squares for different number of clusters with their expected values under null reference distribution of data. Variation of gap statistics is typically plotted for different number of clusters k, and the appropriate number of clusters is selected. The optimum number of clusters is obtained based on the corresponding gap statistics in such a way that the rate of increment of the gap statistics from those clusters is insignificant.

4.3 RESULTS AND DISCUSSION

4.3.1 Classification of climatic zones with Aridity Index

Aridity index is calculated as the ratio of average annual precipitation to the average annual PET for all the stations. The values of Aridity index ranges from 0.41(for station D7) to 3.43 (for station D1). Based on the Aridity index, the basin was classified into three zones (Figure 4.1). The values of the aridity index for the stations are given in the Table 4.1 Humid climate was observed in the western side of the basin while semiarid condition in the eastern part. A layer of transition zone was observed between humid and semiarid zones, and that was classified as sub humid zone, which clearly differentiates between humid and semiarid zones. Average annual rainfall varies spatially between 5000 mm at the humid region to 626 mm at semiarid region (Figure 4.2). Annual PET of the basin (Figure 4.3) varies from 1088 mm to 1360 mm from humid region to semiarid region respectively. Eastern portion of the basin, being the semiarid region, characterized by low rainfall and high PET forces the area to become more susceptible to frequent droughts.

Table.4.1 Aridity index values for climatic grids of the basin

Station ID	Aridity Index	Type of Climate	Station ID	Aridity Index	Type of Climate
A1	3.43	Humid	C2	0.88	Humid
A2	2.44	Humid	C3	0.6	Sub humid
A3	1	Humid	C4	0.43	Semiarid
A4	0.61	Sub humid	C5	0.42	Semiarid
B1	1.68	Humid	C6	0.42	Semiarid
B2	1.74	Humid	C7	0.45	Semiarid
B3	0.81	Humid	C8	0.43	Semiarid
B4	0.57	Sub humid	D3	0.51	Sub humid
B5	0.46	Semiarid	D4	0.43	Semiarid
B6	0.45	Semiarid	D5	0.44	Semiarid
B7	0.47	Semiarid	D6	0.44	Semiarid
B8	0.47	Semiarid	D7	0.41	Semiarid
C1	1.48	Humid			

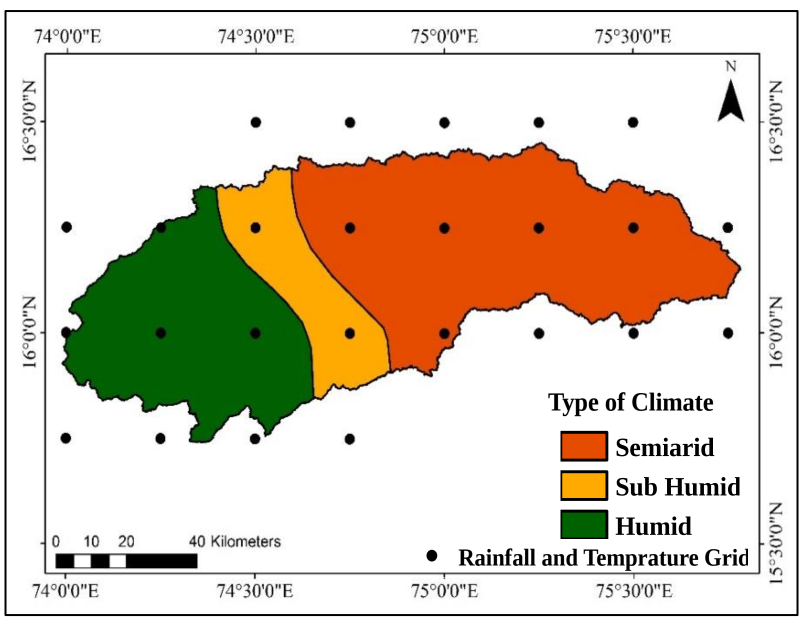


Fig 4.1. Climatic zones of the study area obtained by Aridity Index

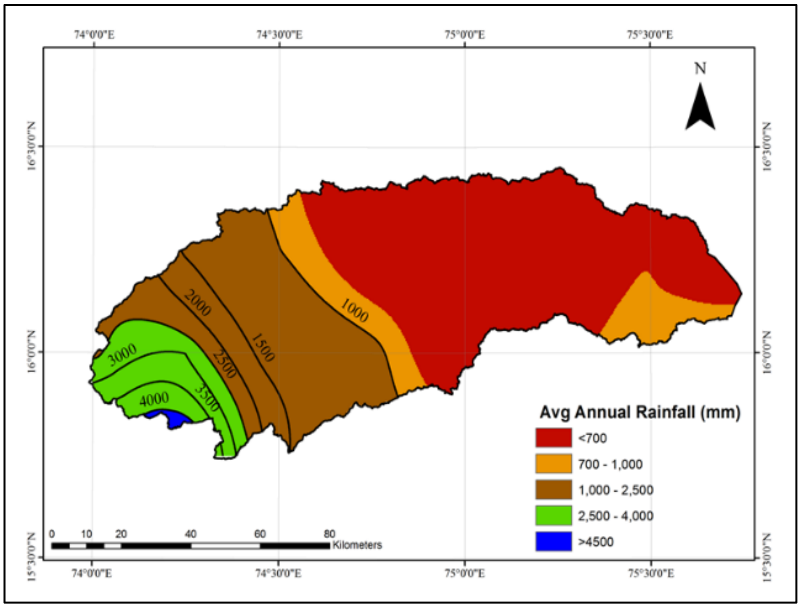


Fig.4.2 Spatial variation of Average annual rainfall of the basin

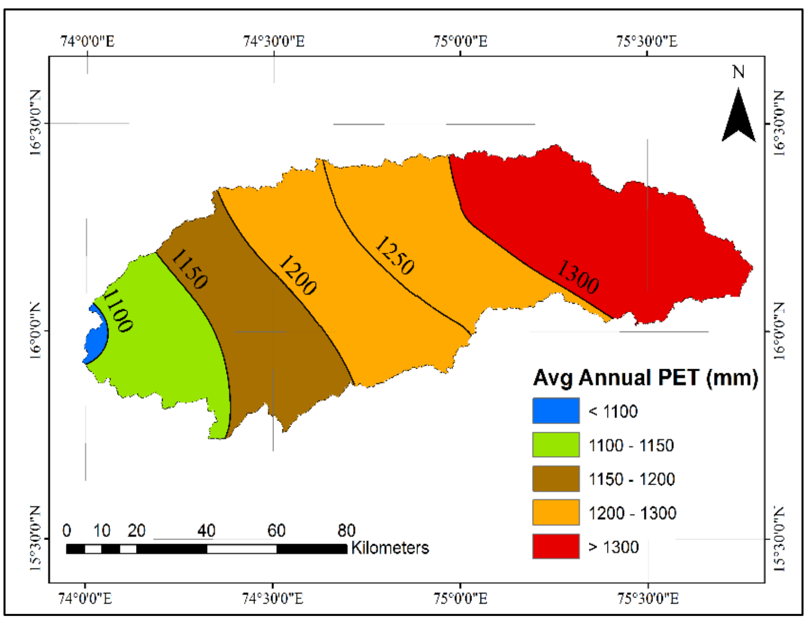


Fig.4.3 Spatial variation of Average annual PET of the basin

4.3.2 Trend Analysis of meteorological variables

Prior to Mann- Kendell trend test, meteorological datasets are tested for serial correlation with 95% confidence level. Annual and seasonal Rainfall and Rainy days do not possess any serial correlation whereas, Temperature and PET showed significant autocorrelation at lag-1. To address the effect of serial correlation of annual temperature, the Modified Mann-Kendell (MMK) test based on the variance correction approach (Hamed and Rao 1998) was employed. The results of MMK did not diverge from the decision of the MK test. Therefore, the MK test along with the Sen's slope test was performed for the original data sets of rainfall, mean temperature and PET for all the stations.

From the results of annual and seasonal rainfall trend, it was observed that most of the stations portrayed decreasing trend during pre-monsoon season (Figure 4.4 A), among them three stations of humid region and one station of sub humid region are significant with the average decrease of 27.5 mm per decade (Table 4.2). During monsoon season (Figure 4.4 B), increasing trends are observed for most of the stations and only few stations showed decreasing trend in the eastern part of the basin however, only A4 and B4 stations were having significant increasing trend. Out of twenty-five stations, 13 stations were having decreasing trend and twelve stations were having increasing trend during post monsoon season (Figure 4.4 C) while, increasing trend was observed in all the stations during winter (Figure 4.4 D). Decreasing trend in the annual rainfall (Figure 4.4.E) can be observed in the stations of eastern portion of the basin.

Out of all stations, increasing trend in the annual rainfall was observed in the four stations (A1, A2, B3 and C2) of humid region, three stations (A4, B4 and D3) of sub humid region and five stations (B6, B7, C5, D4 and D5) of semiarid region with the average increase of 46.4, 35.33 and 18.94 mm per decade respectively. Whereas negative rainfall trends were conveyed by three stations (A3, B2, C1) of humid region, eight stations (B5, B8, C4, C6, C7, C8, D6, D7) of semiarid region and one station (C3) of sub humid region with the average decrease of 35.1, 14.126 and 45.6 mm per decade respectively. The station B1 of the humid region had no trend in precipitation. Analysis of annual rainfall trend, conveyed that 60% of the stations in the semiarid region, 37% of the stations in the humid region and 25% of the stations in the sub humid region showed negative trend in annual rainfall but no stations passed the significance test at 95% confidence.

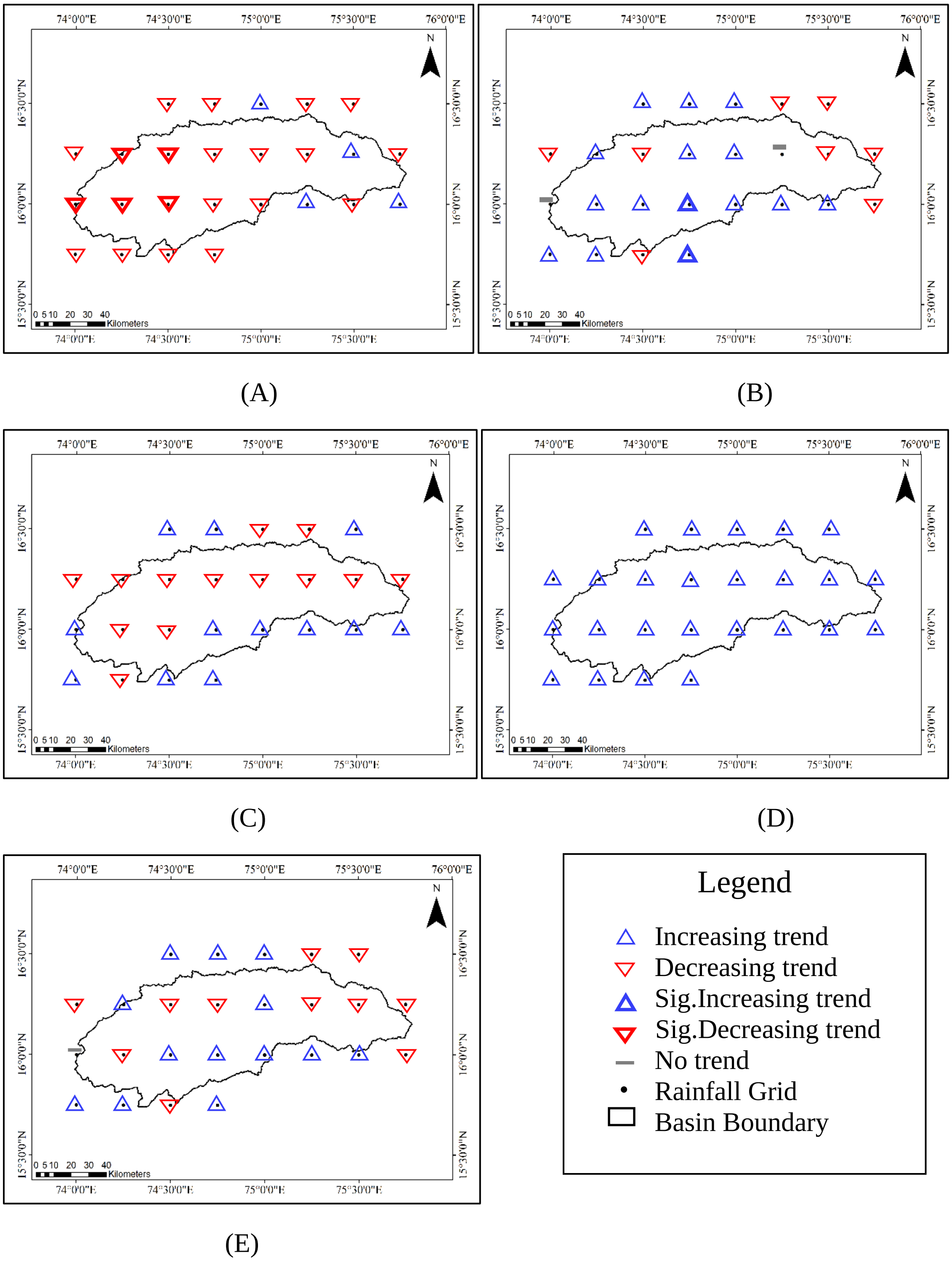


Fig 4.4. Rainfall trend for A) Pre-monsoon B) Monsoon (C) Post-monsoon (D) Winter (E) Annual time scale

Table 4.2 Trend analysis of seasonal and annual rainfall

Station ID	Winter		Pre Monsoon		Monsoon		Post Monsoon		Annual	
	p value	Sen slope	p value	Sen slope	p value	Sen slope	p value	Sen slope	p value	Sen slope
A1	0.08	1.41	0.72	-0.36	0.78	2.81	0.17	1.92	0.72	4.45
A2	0.51	0.23	0.08	-0.80	0.40	13.69	0.83	-0.24	0.52	10.14
A3	0.72	1.03	0.20	-1.01	0.18	-3.99	0.75	0.26	0.25	-3.73
A4	0.27	0.63	0.49	-0.54	**0.04**	**4.68**	0.39	0.73	0.06	5.49
B1	0.11	0.44	**0.03**	**-1.42**	1.00	-0.01	0.88	0.08	1.00	0.04
B2	0.11	0.29	**0.01**	**-1.70**	0.78	1.68	0.65	-0.54	0.75	-2.24
B3	0.56	0.13	**0.01**	**-1.69**	0.83	0.74	0.98	-0.07	0.94	0.28
B4	0.46	1.41	0.06	-0.94	**0.03**	**4.20**	0.99	0.01	0.07	3.65
B5	0.32	0.23	0.44	-0.41	0.37	2.35	0.54	0.67	0.12	3.40
B6	0.18	0.71	0.82	0.12	0.72	0.49	0.08	1.33	0.17	3.14
B7	0.40	0.77	0.78	-0.24	0.66	0.62	0.37	0.66	0.19	2.91
B8	0.26	0.84	0.99	0.03	0.50	-1.27	0.78	0.21	0.78	-0.82
C1	0.24	0.51	0.24	-0.74	0.82	-1.57	0.93	-0.11	0.39	-4.56
C2	0.23	1.41	**0.00**	**-1.70**	0.08	4.47	0.83	-0.20	0.20	3.69
C3	0.22	0.30	**0.00**	**-1.93**	0.80	-0.64	0.09	-1.48	0.10	-4.56
C4	0.27	0.41	0.07	-0.97	0.69	0.59	0.61	-0.39	0.90	-0.27
C5	0.42	0.09	0.75	-0.19	0.75	0.34	0.91	-0.07	0.99	0.03
C6	0.37	0.07	0.32	-0.66	1.00	0.01	0.94	-0.05	0.66	-1.02
C7	0.13	1.23	0.96	0.04	0.47	-1.68	0.90	-0.06	0.54	-1.31
C8	0.12	1.38	0.52	-0.41	0.41	-1.80	0.66	-0.47	0.26	-3.13
D3	0.32	0.91	0.12	-0.85	0.05	2.80	0.52	0.58	0.13	3.14
D4	0.48	0.98	0.21	-0.58	0.53	0.80	0.77	0.25	0.59	1.04
D5	0.30	1.05	0.36	0.43	0.34	1.37	0.88	-0.23	0.28	2.35
D6	0.26	1.12	0.37	-0.45	0.94	-0.11	0.75	-0.39	0.55	-1.04
D7	0.73	0.19	0.53	-0.30	0.54	-1.16	0.94	0.08	0.82	-0.82

Note: Bold values indicate significant trend at 95% confidence level

Along with rainfall trend, annual and seasonal rainy day trends were also studied which intern helps to understand the trends in the rainfall distribution over basin. The definition of a rainy day is adapted from India Meteorological Department (IMD) which classifies the rainy day when a rainfall of a day is more than or equal to 2.5 mm (Murthy et al. 2016). Trend analysis for rainy days is carried out for all the stations and the results indicated that most of the stations exhibits decreasing trend during the pre-monsoon season (Table 4.3). Among them seven stations (A3, B1, B2, B3, C1, C2 and D3) of humid region (Figure 4.5 A) portrayed significant decreasing trend with the average decline of 14 days per decade. Similarly, rainy days in two stations of semiarid (C4 and C8) and sub humid (B4 and D3) are also decreasing significantly with the average fall of 11 and 10 days per decade respectively. The only station (B6) of the semiarid region showed non-significant increasing rainy day trend during pre-monsoon season.

The rainy day trends during monsoon (Figure 4.5 B) and winter (Figure 4.5 D) seasons are increasing except few stations (D7, C8, A3, B2) however only station (A3) of humid region depicted significant decreasing trend. The results of annual rainy day trend (Figure 4.5 E), highlights five stations of humid region and three stations near semiarid edge of the basin possessed decreasing trend and remaining fifteen stations of the basin exhibited increasing trend with the three stations being significant. The two stations of semiarid region (B7 and B8) were having no trends in annual rainy days.

From the results of rainfall and rainy days trends it is important to note that both annual rainfall and annual rainy day trends are decreasing in six stations (A3, B2, C8, C1, D6, and D7) which indicates that the stations may suffer acute shortage of rainfall leading to frequent drought episodes in upcoming years. Eleven stations (A2, A4, B3, B4, B5, B6, C2, C5, D3, D4, and D5) showed an increasing trend in both the annual rainfall and in the annual rainy days. Scanty rainfall can expect in the future for the stations C3, C4, C6, and C7 because these stations were having decreasing annual rainfall trend but increasing trend for annual rainy days.

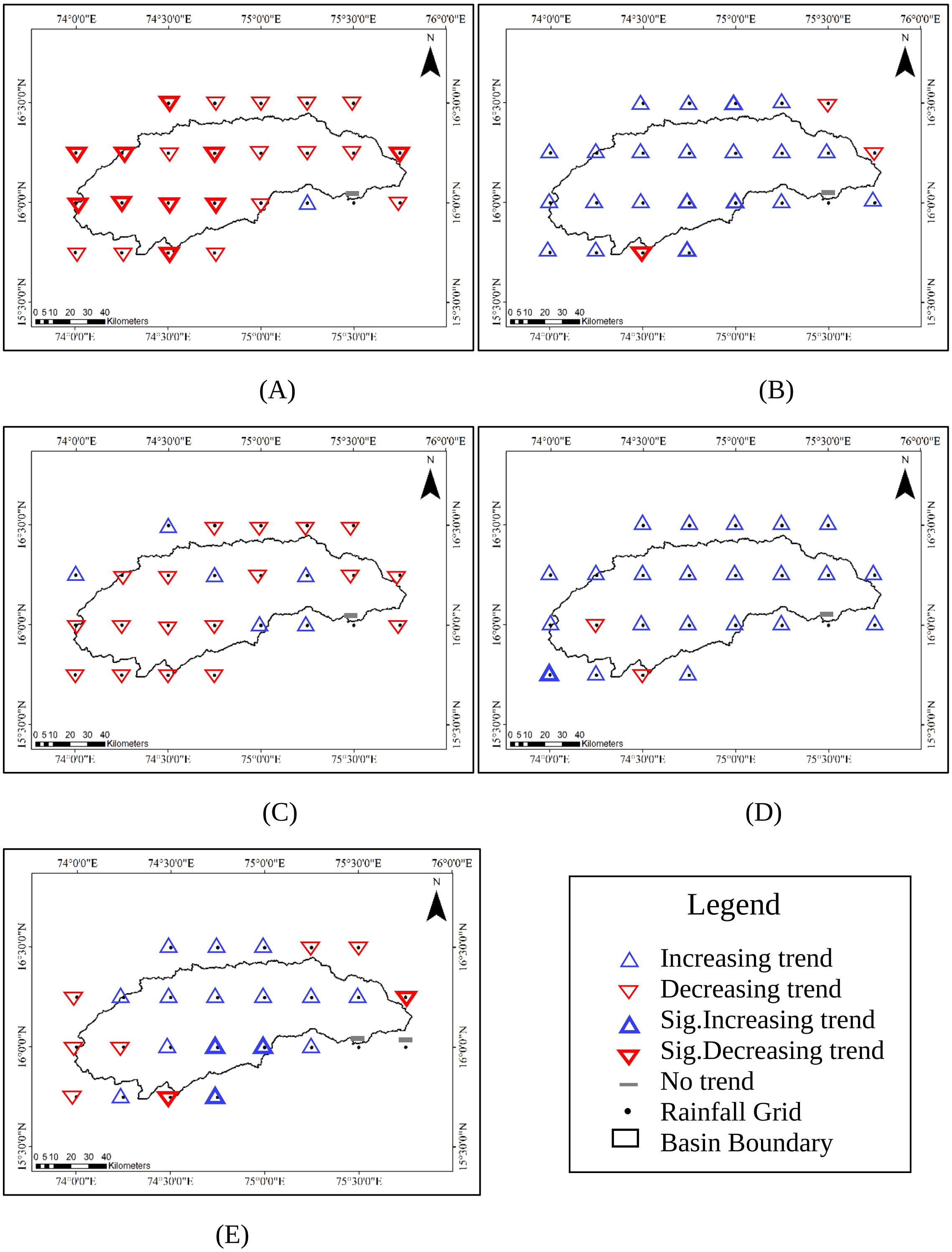


Fig. 4. 5. Rainy day trend for A) Pre-monsoon B) Monsoon (C) Post-monsoon (D) Winter (E) Annual timescale

Table 4.3 Trend analysis of seasonal and annual rainy days

Station ID	Winter		Pre Monsoon		Monsoon		Post Monsoon		Annual	
	p value	**Sen slope**	**p value**	**Sen slope**	**p value**	**Sen slope**	**p value**	**Sen slope**	**p value**	**Sen slope**
A1	0.02	0.00	0.19	-0.08	0.63	0.04	0.79	0.00	0.90	0.00
A2	0.52	0.00	0.19	-0.07	0.22	0.16	0.63	0.00	0.97	0.00
A3	0.43	0.00	**0.00**	**-0.15**	**0.05**	**-0.50**	0.22	-0.04	**0.01**	**-0.64**
A4	0.19	0.00	0.22	-0.04	**0.00**	**0.48**	0.77	0.00	**0.02**	**0.48**
B1	0.20	0.00	**0.01**	**-0.18**	0.95	0.00	0.78	0.00	0.66	-0.11
B2	0.95	0.00	**0.01**	**-0.17**	0.89	0.00	0.46	-0.03	0.24	-0.14
B3	0.20	0.00	**0.01**	**-0.13**	0.12	0.25	0.93	0.00	0.42	0.16
B4	0.45	0.00	**0.02**	**-0.11**	**0.00**	**0.45**	0.91	0.00	**0.03**	**0.35**
B5	0.73	0.00	0.29	-0.05	**0.05**	**0.32**	0.63	0.02	**0.04**	**0.30**
B6	0.22	0.00	0.55	0.00	0.10	0.18	0.35	0.04	0.06	0.25
B7	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
B8	0.26	0.00	0.21	-0.06	0.54	0.06	0.85	0.00	1.00	0.00
C1	0.20	0.00	**0.01**	**-0.10**	0.85	0.00	0.89	0.00	0.92	0.00
C2	0.61	0.00	**0.00**	**-0.14**	0.18	0.19	0.10	-0.08	0.75	0.06
C3	0.42	0.00	0.22	-0.04	0.75	0.06	0.67	0.00	0.87	0.00
C4	0.50	0.00	**0.00**	**-0.11**	0.28	0.11	0.92	0.00	0.59	0.10
C5	0.48	0.00	0.33	-0.03	0.24	0.11	0.99	0.00	0.78	0.01
C6	0.94	0.00	0.45	-0.03	0.43	0.08	0.98	0.00	0.60	0.06
C7	0.23	0.00	0.89	0.00	0.69	0.03	0.81	0.00	0.67	0.05
C8	0.29	0.00	**0.02**	**-0.12**	0.07	-0.18	0.06	-0.10	**0.02**	**-0.46**
D3	0.52	0.00	**0.02**	**-0.08**	0.11	0.18	0.63	0.00	0.26	0.16
D4	0.60	0.00	0.31	-0.03	0.63	0.04	0.82	0.00	0.85	0.00
D5	0.82	0.00	0.13	-0.05	**0.04**	**0.19**	0.73	0.00	0.34	0.13
D6	0.21	0.00	0.78	0.00	0.30	0.10	0.25	-0.06	0.92	0.00
D7	0.54	0.00	0.21	-0.06	0.12	-0.20	0.14	-0.07	0.08	-0.39

Note: Bold values indicate significant trend at 95% confidence level

The Mann-Kendall trend test has been applied to annual and seasonal average temperature and PET for all the stations. Understanding the seasonal and inter-annual variability of evapotranspiration is vital in hydrological and agricultural studies. Variation of evapotranspiration in combination with the rainfall plays a crucial role in influencing terrestrial hydrology, vegetation dynamics. Trends in Evapotranspiration is evaluated through potential evapotranspiration (PET), which represents the maximum evaporative demand on a reference grass crop under climatic conditions where water availability is not a limiting factor. Variation of PET mainly depends on humidity, wind speed, temperature solar radiation. Among the different methods of calculation of PET, Penman-Monteith method has been accepted globally but it requires more climatic datasets like humidity, wind speed and solar radiation which are not available for the study area for longer period of time. To overcome data inadequacy issue, temperature based Penman-Monteith method was employed to calculate PET (Paulo et al. 2012; Pandey and Pandey, 2016).

The results of temperature trend test showed a significant increasing in temperature trend in all the stations during all the seasons. From the values of Sen's slope, it can be noted that temperature trend is increasing with the average magnitude of 0.3^{o}C per decade in monsoon season and 0.2^{o}C in remaining seasons (Table 4.4). Along with the mean temperature, annual and seasonal PET trends were also increasing for all the stations. All the stations of the basin showed a non-significant increasing trend in the post monsoon, monsoon and winter season (Figure 4.5). During pre-monsoon season, two stations (B7 and B8) of semiarid region portrayed significant increment in the PET with the average rise of 3.5mm per decade (Table 4.5). Similarly, significant increasing trend in annual PET was observed in the seven stations (B5, B6, B7, B8, C7, C8 and D7) of semiarid region with the average magnitude of 6 mm per decade. From the results of temperature and PET trend, it was noted that even though, temperature trend is increasing significantly for all the station, PET trends are significant only in semiarid stations. This may be due to that the humidity in the humid region will be higher as compared to semiarid region resulting decreased PET in the region. Moreover, PET is not only depending on temperature but also the function of humidity, wind speed and solar radiation.

Table 4.4 Trend analysis of seasonal and annual Temperature

Station ID	Winter		Pre Monsoon		Monsoon		Post Monsoon		Annual	
	p value	Sen slope	p value	Sen slope	p value	Sen slope	p value	Sen slope	p value	Sen slope
A1	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.01**	**0.02**	**0.00**	**0.02**
A2	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.01**	**0.02**	**0.00**	**0.02**
A3	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.02**	**0.02**	**0.00**	**0.02**
A4	**0.03**	**-0.05**	**0.07**	**-0.04**	**0.03**	**-0.05**	**0.04**	**-0.05**	**0.03**	**-0.04**
B1	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.01**	**0.02**	**0.00**	**0.02**
B2	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.02**	**0.01**	**0.00**	**0.02**
B3	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.03**	**0.02**	**0.00**	**0.02**
B4	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.04**	**0.02**	**0.00**	**0.02**
B5	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.05**	**0.02**	**0.00**	**0.02**
B6	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.05**	**0.02**	**0.00**	**0.02**
B7	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.05**	**0.02**	**0.00**	**0.02**
B8	**0.00**	**0.02**	**0.00**	**0.04**	**0.00**	**0.02**	**0.06**	**0.02**	**0.00**	**0.02**
C1	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.06**	**0.02**	**0.00**	**0.02**
C2	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.05**	**0.02**	**0.00**	**0.02**
C3	**0.00**	**0.02**	**0.00**	**0.04**	**0.00**	**0.02**	**0.04**	**0.02**	**0.00**	**0.02**
C4	**0.00**	**0.02**	**0.00**	**0.04**	**0.00**	**0.02**	**0.06**	**0.02**	**0.00**	**0.02**
C5	**0.00**	**0.02**	**0.00**	**0.04**	**0.00**	**0.02**	**0.06**	**0.02**	**0.00**	**0.02**
C6	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.01**	**0.01**	**0.00**	**0.02**
C7	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.03**	**0.01**	**0.00**	**0.02**
C8	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.05**	**0.02**	**0.00**	**0.02**
D3	**0.00**	**0.02**	**0.00**	**0.03**	**0.00**	**0.02**	**0.04**	**0.02**	**0.00**	**0.02**
D4	**0.00**	**0.02**	**0.00**	**0.04**	**0.00**	**0.02**	**0.04**	**0.02**	**0.00**	**0.02**
D5	**0.00**	**0.02**	**0.00**	**0.04**	**0.00**	**0.02**	**0.04**	**0.02**	**0.00**	**0.02**
D6	**0.00**	**0.02**	**0.00**	**0.04**	**0.00**	**0.02**	**0.06**	**0.02**	**0.00**	**0.02**
D7	**0.00**	**0.02**	**0.00**	**0.04**	**0.00**	**0.02**	**0.06**	**0.02**	**0.00**	**0.02**

Note: Bold values indicate significant trend at 95% confidence level

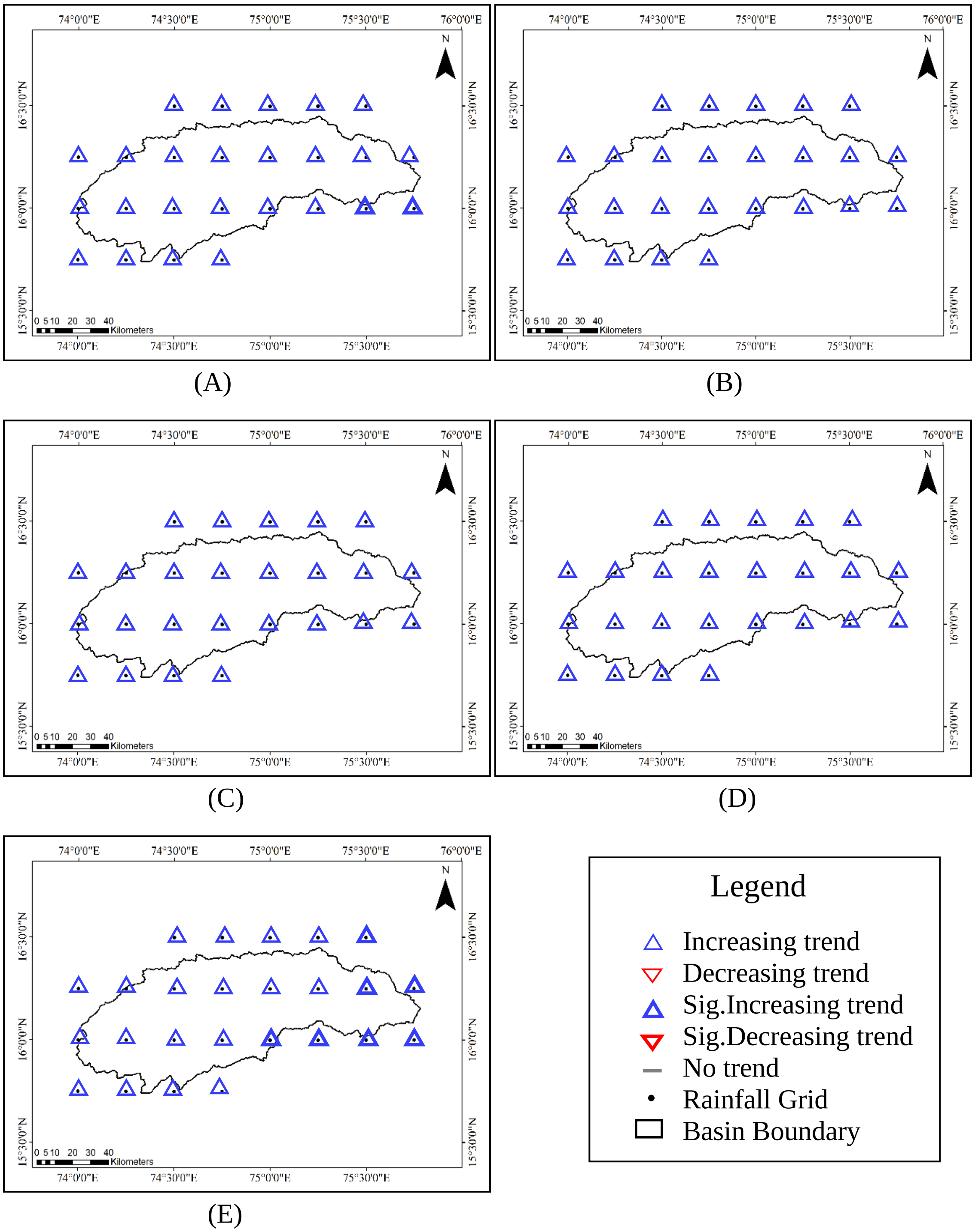


Fig. 4. 5. PET trend for A) Pre-monsoon B) Monsoon (C) Post-monsoon (D) Winter (E) Annual time scale

Table 4.5 Trend analysis of seasonal and annual PET

Station ID	Winter		Pre Monsoon		Monsoon		Post Monsoon		Annual	
	p value	Sen slope	p value	Sen slope	p value	Sen slope	p value	Sen slope	p value	Sen slope
A1	0.14	0.09	0.09	0.19	0.34	0.13	0.22	0.12	0.06	0.48
A2	0.19	0.10	0.10	0.19	0.33	0.15	0.25	0.11	0.06	0.42
A3	0.25	0.09	0.19	0.18	0.61	0.09	0.46	0.06	0.10	0.36
A4	0.29	0.09	0.16	0.20	0.54	0.11	0.54	0.07	0.12	0.39
B1	0.13	0.08	0.13	0.17	0.46	0.13	0.28	0.09	0.06	0.45
B2	0.13	0.09	0.19	0.14	0.55	0.10	0.51	0.06	0.06	0.39
B3	0.26	0.09	0.21	0.15	0.66	0.11	0.61	0.05	0.15	0.37
B4	0.29	0.09	0.21	0.17	0.69	0.09	0.71	0.05	0.16	0.38
B5	0.31	0.10	0.20	0.20	0.72	0.08	0.81	0.04	0.17	0.45
B6	0.30	0.11	0.10	0.23	0.55	0.13	0.78	0.03	0.06	0.51
B7	0.19	0.10	**0.01**	**0.31**	0.39	0.18	0.72	0.04	**0.02**	**0.63**
B8	0.21	0.11	**0.00**	**0.40**	0.19	0.25	0.77	0.04	**0.01**	**0.73**
C1	0.14	0.09	0.35	0.12	0.75	0.06	0.56	0.05	0.18	0.32
C2	0.19	0.09	0.25	0.13	0.72	0.06	0.62	0.05	0.20	0.34
C3	0.24	0.09	0.26	0.15	0.66	0.07	0.68	0.03	0.20	0.37
C4	0.31	0.09	0.24	0.17	0.61	0.08	0.80	0.03	0.21	0.39
C5	0.31	0.10	0.24	0.18	0.51	0.10	0.69	0.04	0.13	0.49
C6	0.19	0.09	0.12	0.24	0.51	0.13	0.69	0.04	0.08	0.61
C7	0.22	0.11	**0.04**	**0.29**	0.49	0.16	0.71	0.06	**0.05**	**0.60**
C8	0.32	0.11	**0.01**	**0.37**	0.27	0.27	0.65	0.06	**0.02**	**0.73**
D3	0.23	0.09	0.26	0.15	0.75	0.09	0.74	0.03	0.21	0.38
D4	0.29	0.10	0.18	0.19	0.62	0.13	0.66	0.05	0.15	0.39
D5	0.32	0.10	0.15	0.22	0.51	0.16	0.66	0.04	0.09	0.54
D6	0.25	0.11	0.10	0.24	0.47	0.14	0.80	0.03	0.07	0.59
D7	0.21	0.11	**0.02**	**0.30**	0.49	0.17	0.65	0.04	**0.03**	**0.59**

Note: Bold values indicate significant trend at 95% confidence level

4.3.3 Trend Analysis of hydrological variables

Assessment of temporal behavior of hydrological variables is one of the crucial aspect in water resources planning and management system. Trend assessments of hydrological variables provide basic information related to long term variation in the water availability of an area. Decision on water management and policies of an area is mainly affected by a detection of a significant trends in hydrological variables. In the study, hydrological variables like groundwater levels, streamflow data and reservoir levels are considered to investigate seasonal and annual trends in the Ghataprabha river basin.

4.3.3.1 Classification of wells based on Cluster Analysis

Hierarchical and non-hierarchical clustering methods identify wells which are having a similar pattern in the water level fluctuation. Initially, grouping of the wells was done with the agglomerative hierarchical clustering with wards minimum variance method. The Euclidian distance was employed as distance metrics. The dendrogram (Figure 4.6) obtained by hierarchical clustering can be used to classify the wells into the different clusters. The number of clusters in hierarchical clustering is depending on the threshold applied to the distance between the groups. In the dendrogram (Figure 4.6) threshold at 85 and 50 will yield 2 and 4 clusters respectively. Similarly, 5 clusters can be obtained at a threshold of 45.

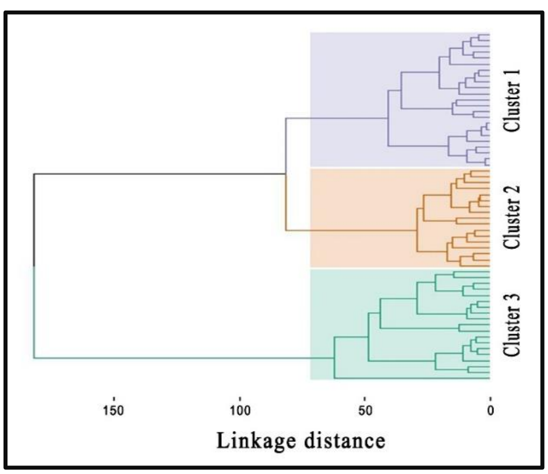
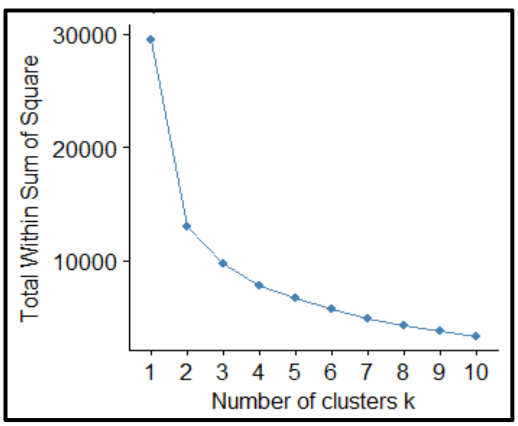
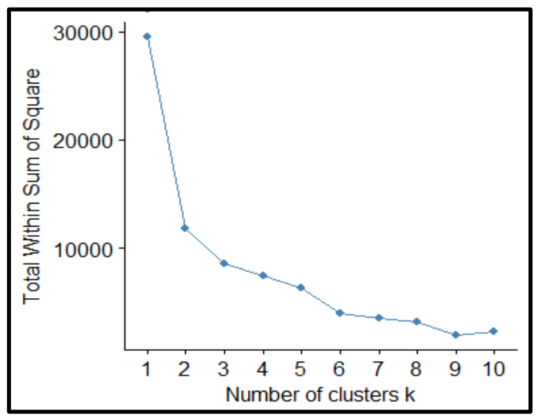


Fig. 4.6 Dendrogram of hierarchical cluster analysis

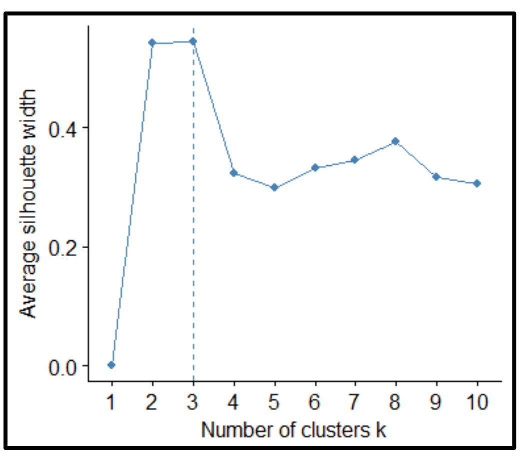
To select an optimum number of clusters, values of Within Sum of Square (WSS) for different numbers of clusters are plotted. A number of clusters corresponding to the bend (Elbow) in the plot represent the optimum number of clusters. In another way, the optimum number of Clusters will occur at the elbow point. Elbow is the point on the WSS curve after that adding another cluster does not reduce the WSS value significantly. The WSS curve (Figure 4.7 A and B) plotted for both the clustering method indicates elbow point at 3 clusters. After that point, there is no significant change in the slope of the WSS curve. Therefore, the optimum number of clusters is 3 for the hierarchical cluster.



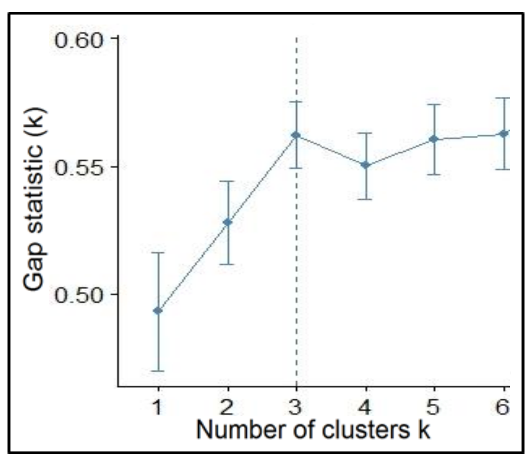
(A)



(B)



(C)



(D)

Figure. 4.7 WSS curve for A) Hierarchical and B) K means clustering C) Average Silhouette Method and (D) Gap statistics for K-mean clustering

Sometimes, choosing the Elbow point becomes ambiguous and leads to confusion for the selection of an optimum number of clusters. To overcome the limitation of the Elbow method, Average Shillout Method and Gap statistics was employed for K-mean clustering.

The Average Shillout Method, suggest the optimum number of clusters is the one, which is having the maximum average Shillout value. Highest value (0.6) of average Shillout can be observed clearly (Figure 4.7 C) for 3 clusters, which reveals the optimum number of clusters for K-means clustering is 3. The outcome of both hierarchical and non-hierarchical clustering methods suggested that 3 clusters are optimum to capture the groundwater level fluctuations of the area.

The Gap statistics was developed by Tibshirani et al. (2001) to identify optimum number of clusters. The Gap statistics compares the variation of the total within sum of squares for different numbers of clusters with their expected values under null reference distribution of data. Variation of Gap statistics is typically plotted for different number of clusters k (Fig. 4.7 D) and the appropriate number of clusters are selected. The optimum number of clusters is obtained based on the corresponding gap statistics in such a way that the rate of increment of the gap statistics from those clusters is insignificant. From Figure 4.7 (D) it can be noticed that, after three clusters, there is no much change in the rate of increment of the Gap statistics, which indicates that the wells can be grouped into three clusters optimally. From the results of hierarchical and non-hierarchical clusters and the methods which are considered to choose optimum clusters, the wells were grouped in to three clusters which are adequate to explain groundwater level fluctuations of the basin effectively.

Spatial distribution of these wells (Figure 4.8.), as clustered by both methods resembles same, and these clusters reflect the groundwater fluctuation dynamics of the wells by suggesting three different clusters with respect to the aquifer systems of the study area. However, small misclassification can be observed. As mentioned previously that the study area is covered by three major aquifer systems, and the results of cluster analysis clearly replicate the aquifer systems of the study area.

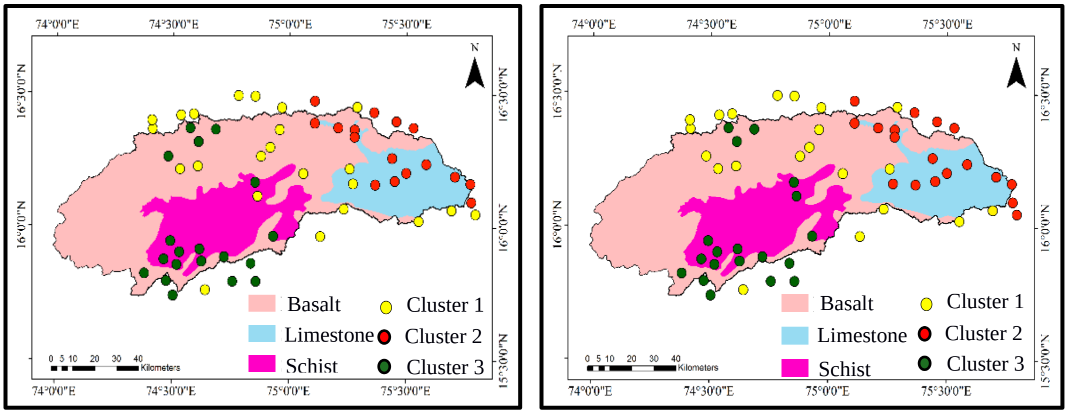


Figure. 4.8. Spatial location of classified wells by A) Hierarchical and B) K means clustering

4.3.3.2 Annual and seasonal groundwater level trends

The non-parametric MK test has been applied at a significance level of α= 0.05, to evaluate Annual and seasonal groundwater level trends for all the wells of the study area. Prior to the MK trend test, serial correlation of the groundwater level for all the wells was calculated and significant lag 1 autocorrelation was observed for annual and seasonal groundwater levels for few wells. To address the autocorrelation effects on trends of groundwater level fluctuation, the Modified Mann Kendall (MMK) test (Hamed and Rao 1998) was employed to identify the seasonal and annual trends in groundwater levels. Because the coefficients of variation of groundwater levels of the most of the wells are low (<0.7) and the value of the Sen's slope is high (>0.01), the results of the MMK do not alter the original decisions of the hypothesis of the MK test (Bayazit and Önöz 2007). Therefore, the MK trend test was applied to the original time series of the groundwater levels of all the wells of each cluster.

The results of annual and seasonal groundwater level trends are presented in Table 4.6 along with respective magnitudes of the trends calculated from the Sen's method. Significant trends were observed in both seasonal and annual groundwater levels.

Table 4.6 Mann-Kendall statistics and Sen's slope values for annual and seasonal groundwater levels

ID	Pre monsoon		Monsoon		Post monsoon		Winter		Annual	
	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope
1	**-3.28**	-0.30	**-2.65**	-0.24	**-2.67**	-0.26	**-2.98**	-0.21	**-2.77**	-0.21
2	**2.48**	0.09	1.05	0.03	0.73	0.02	1.90	0.08	1.63	0.05
3	0.75	0.02	-1.55	-0.05	-0.75	-0.03	0.62	0.02	-0.38	-0.01
4	1.64	0.05	**2.36**	0.09	**2.36**	0.09	0.71	0.03	**2.74**	0.09
5	**-4.01**	-0.16	**-3.65**	-0.15	**-2.22**	-0.06	**-2.60**	-0.06	**-4.46**	-0.12
6	**-1.97**	-0.05	**-3.03**	-0.07	0.01	0.00	-0.59	-0.01	**-2.78**	-0.04
7	**4.35**	0.11	**4.08**	0.11	**2.92**	0.09	**3.45**	0.08	**4.83**	0.10
8	0.54	0.04	-1.18	-0.09	0.77	0.04	1.41	0.10	-0.57	-0.04
9	0.87	0.03	0.22	0.01	1.56	0.05	0.60	0.03	1.16	0.03
10	**-4.55**	-0.27	**-5.10**	-0.27	**-3.50**	-0.21	**-3.73**	-0.17	**-5.17**	-0.24
11	**4.35**	0.29	**2.79**	0.11	**2.40**	0.08	**3.86**	0.15	**4.16**	0.16
12	-0.54	-0.02	0.21	0.00	-1.63	-0.03	-1.07	-0.02	-0.61	-0.01
13	0.26	0.02	-1.10	-0.05	-1.49	-0.09	-1.13	-0.09	-0.82	-0.05
14	**-5.14**	-0.35	**-5.55**	-0.32	**-5.60**	-0.38	**-5.50**	-0.34	**-5.72**	-0.33
15	-1.69	-0.09	**-2.09**	-0.11	-1.83	-0.06	**-2.12**	-0.07	**-3.15**	-0.09
16	**-3.49**	-0.33	**-4.28**	-0.38	**-2.79**	-0.29	**-3.40**	-0.30	**-3.71**	-0.33
17	**3.78**	0.09	**3.63**	0.09	**2.55**	0.06	**3.17**	0.09	**4.15**	0.08
18	**-2.58**	-0.11	**-3.54**	-0.13	**-3.11**	-0.13	**-2.01**	-0.10	**-3.88**	-0.13
19	0.71	0.11	0.39	0.07	-0.21	-0.03	0.73	0.11	0.51	0.06
20	-1.42	-0.07	-1.29	-0.05	-0.59	-0.03	**-2.14**	-0.11	-1.73	-0.08
21	1.78	0.05	**2.08**	0.15	0.15	0.01	-0.13	-0.01	1.28	0.05
22	**-6.40**	-0.41	**-5.80**	-0.39	**-3.86**	-0.21	**-6.16**	-0.28	**-6.48**	-0.35
23	**3.01**	0.08	1.07	0.03	1.54	0.03	**3.18**	0.06	**2.33**	0.04
24	**2.15**	0.07	0.10	0.01	-0.86	-0.03	0.95	0.02	0.65	0.02
25	-0.37	-0.03	1.59	0.08	1.48	0.10	-0.17	-0.02	0.48	0.02
26	-0.64	-0.05	1.50	0.07	1.45	0.10	-0.33	-0.02	0.40	0.01
27	0.60	0.06	0.83	0.05	0.01	0.00	0.68	0.07	0.80	0.04
28	**-2.52**	-0.06	**-2.70**	-0.05	-1.92	-0.03	**-2.37**	-0.04	**-3.10**	-0.04
29	**-3.62**	-0.23	**-3.60**	-0.23	**-2.38**	-0.17	**-3.71**	-0.20	**-4.40**	-0.20
30	**2.37**	0.08	**3.63**	0.12	1.88	0.06	1.69	0.06	**2.71**	0.07
31	**-4.14**	-0.12	**-6.11**	-0.16	**-3.91**	-0.14	**-3.63**	-0.13	**-6.01**	-0.15
32	**-4.45**	-0.14	**-5.92**	-0.22	**-6.06**	-0.39	**-5.78**	-0.26	**-6.28**	-0.22
33	1.26	0.03	-0.93	-0.04	-0.39	-0.01	0.80	0.02	0.01	0.00
34	**-3.18**	-0.07	0.51	0.01	**-4.00**	-0.03	**-2.93**	-0.05	**-3.09**	-0.04

Cont.,

ID	Pre monsoon		Monsoon		Post monsoon		Winter		Annual	
	Z	**Sen's slope**	**Z**	**Sen's slope**	**Z**	**Sen's slope**	**Z**	**Sen's slope**	**Z**	**Sen's slope**
35	**-3.76**	-0.20	**-3.18**	-0.17	**-3.32**	-0.19	**-3.35**	-0.21	**-3.86**	-0.20
36	**-4.82**	-0.10	**-4.88**	-0.08	**-4.24**	-0.07	**-5.48**	-0.09	**-5.93**	-0.08
38	-0.21	0.00	-1.87	-0.03	-1.30	-0.02	-0.80	-0.01	-1.34	-0.03
40	**-3.86**	-0.96	**-2.91**	-0.65	**-3.05**	-0.74	**-3.69**	-0.88	**-3.69**	-0.83
41	1.90	0.17	**3.00**	0.20	1.75	0.14	**2.55**	0.23	**2.87**	0.18
42	-0.81	-0.01	**-1.96**	-0.05	-1.44	-0.02	**-2.25**	-0.04	**-2.82**	-0.04
43	**4.82**	1.03	**4.50**	0.46	**4.32**	0.30	**5.11**	0.32	**4.48**	0.57
44	-0.37	-0.01	-0.31	-0.01	-1.42	-0.02	-0.98	-0.02	-1.22	-0.02
45	**-2.76**	-0.08	**-2.55**	-0.10	**-3.37**	-0.11	**-4.25**	-0.09	**-3.88**	-0.09
46	**-2.17**	-0.07	-1.66	-0.06	-1.28	-0.07	**-2.31**	-0.09	**-2.12**	-0.07
47	0.53	0.02	1.02	0.05	-0.33	-0.02	-0.10	-0.01	0.23	0.01
48	-0.37	-0.01	0.35	0.01	0.54	0.04	1.32	0.08	0.09	0.01
49	**4.52**	0.23	**3.70**	0.20	**3.70**	0.11	**3.66**	0.12	**4.19**	0.15
50	**3.41**	0.21	**3.55**	0.21	**2.59**	0.18	**2.07**	0.16	**2.65**	0.18

Note: Bold values indicate significant trend at 95% confidence level

During the pre-monsoon season (Figure. 4.9 A), 37 wells show a decreasing trend and 22 wells showed an increasing trend. Among these wells, eight wells belonging to cluster 1, 13 wells belonging to cluster 2 and five wells belonging to cluster 3 show significant negative trend with average decrease in groundwater levels by 0.17 m, 0.24 m and 0.36 m per year, respectively. Similarly, 4, 1 and 6 wells belonging to cluster 1, 2 and 3, respectively, show have a significant increasing trend with average increase of groundwater levels by 0.35 m, 0.1 m and 0.14 m per year, respectively.

Decreasing trend in groundwater level was observed in 36 wells and, increasing trend was noted for 23 wells during the monsoon season (Figure. 4.9 B). Among these wells, 23 are depleting significantly with average reduction of 0.23 m per year while in other 10 wells water level is increasing significantly with average rise of 0.18 m per year. Similarly, groundwater level trends are decreasing significantly in 20 and 27 wells in the post monsoon (Figure. 4.9 C) and in winter (Figure. 4.9 D) with the average fall of 0.22 m and 0.19 m, respectively.

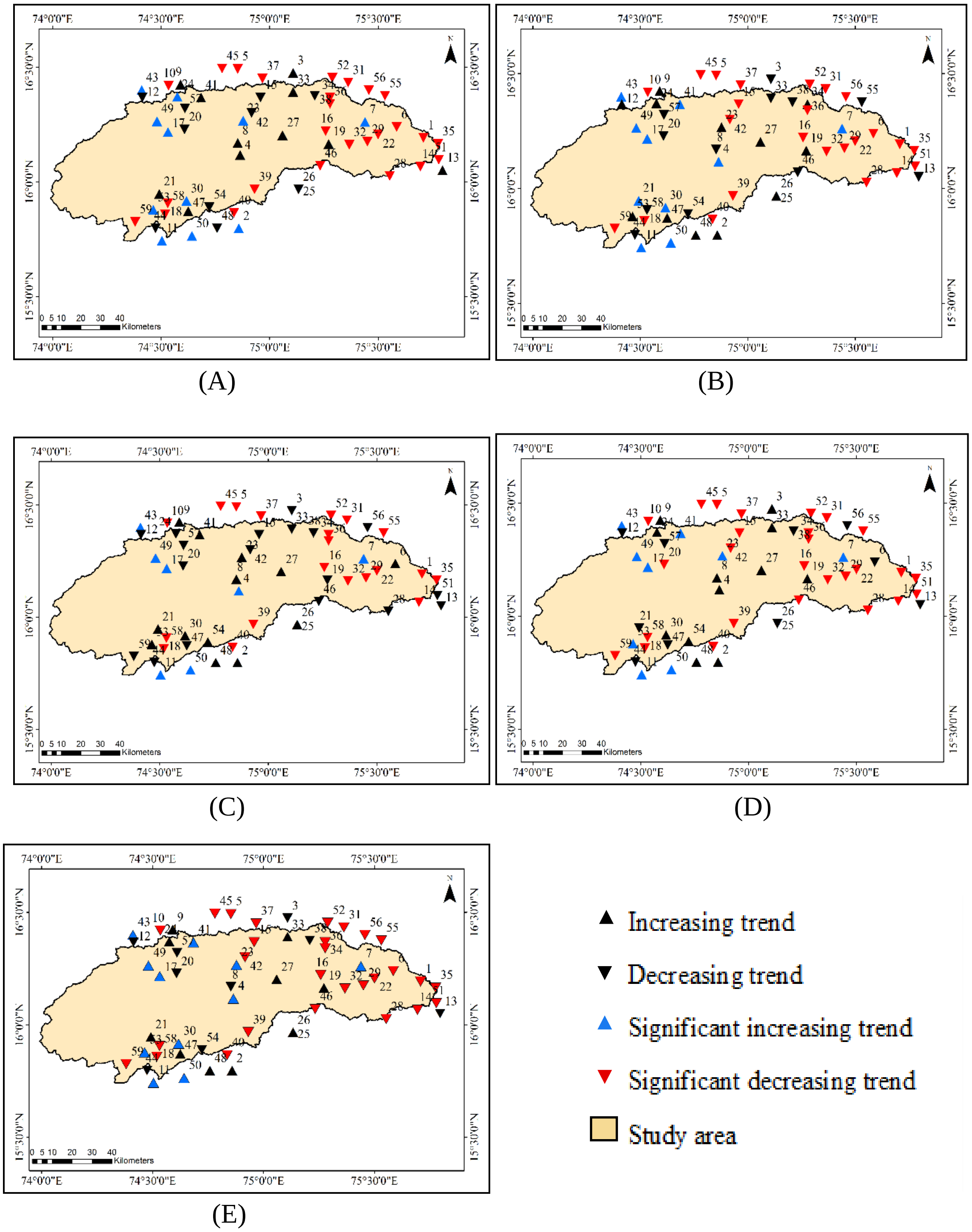


Fig. 4.9. Groundwater level trends for (A) pre-monsoon, (B) monsoon, (C) post-monsoon, (D) winter, and (E) annual

There is a minute difference in the trends of groundwater level observed while comparing post and pre-monsoon trends. On the other hand, most of the wells that show a decreasing trend in the pre-monsoon season continued to be decrease in the post-monsoon season also. This indicates that recharge of groundwater from monsoon rainfall is inadequate to replenish the drawdown that occurred during previous seasons. These observations convey the poor resilience of groundwater system to rainfall variations (Le Brocque et al. 2018) and can also be interpreted as the consequence of diminished monsoon rainfall, which, in turn, leads to extensive groundwater abstraction during the monsoon and subsequent seasons.

Out of 59 wells, 38 show decreasing trends and 21 show increasing trends in the annual groundwater levels (Figure 4.9 E). Cluster 1 comprises of 10 wells with annual groundwater levels decreasing significantly with average drop of 0.14 m annually. Similarly, clusters 2 and 3 comprise 13 and 5 wells that depict significant negative trends in annual groundwater level with average fall of 0.19 m and 0.31 m per annum, respectively. Similarly, significant rise in annual groundwater level was observed in 11 wells of the basin with average increase of 0.15 m per year. The results of the annual and seasonal trend analyses convey that most of the wells belonging to clusters 1 and 2 show decreasing trend as compared to the wells of cluster 3. Among all the wells, the 40th well of cluster 1, showed the highest decrease in groundwater level for all the seasons with an average fall of 0.81 m per season. Likewise, the 43rd well of cluster 1 has the highest increase in groundwater level for all the seasons with average rise of 0.54 m per annum.

The trend analysis of groundwater levels of different clusters (Figure. 4.9), revealed that the water level in the 81% of the wells of cluster 2 and 47% of the total wells of the study area are significantly declining annually and in all the seasons. The results obtained in this study are consistent with the observations made by various researchers at different parts of the country (e.g., Thakur and Thomas 2011; Dhar 2014; Barik et al. 2017). For instance, Patle et al. (2015) reported decreasing groundwater trends during pre and post-monsoon with the rate of 0.3 m/year in the Haryana state, India. Similarly, Panda et al. (2013) observed significant declining groundwater levels in the Gujarat state of western India.

Overall, groundwater levels of more than 61% of the wells in the study area are decreasing with average decline of 0.21 m during all the seasons, which can be attributed to either diminishing rainfall or severe groundwater exploitation or both (GGWB 2011). The water levels in few wells of clusters 1 and 3 are increasing may be due to recharge of aquifers from nearby reservoirs. The Ghataprabha river basin, being an agrarian region of river Krishna, is enriched with cash crops like sugarcane and cotton (FAO 2008; KSAPCC 2011). The water requirement of these crops is high and intensive irrigation practice using groundwater resources for these crops may be one of the key reasons for the significant depletion in groundwater levels in the area. Groundwater, being a dynamic and precious natural resource of Ghataprabha river basin, plays a crucial role in the overall socio-economic development of the area whereas these diminishing groundwater levels will certainly threaten the development of the region.

4.3.3.3 Trend analysis of Streamflow and reservoir levels

Annual and seasonal MK trend analysis along with Sen's slop is worked out for the streamflow gauged at Bagalkot and reservoir levels measured at Hidakl Dam. Daily discharge data is available from 1963 to 2000 at Bagalkot station while daily reservoir levels were available from 1983 to 2013. The results of annual and seasonal streamflow and reservoir levels trends are presented in the table 4.7 and 4.8 respectively.

Table. 4.7. Trend analysis annual and seasonal of streamflow

Statistics	Monsoon	Post-monsoon	Winter	Pre-monsoon	Annual
p value	**0.01**	0.41	0.04	0.08	**0.01**
Sen's Slop	**-720.31**	37.21	26.01	-2.97	**-574.25**

Note: Bold values indicate significant trend at 95% confidence level

Table. 4.8. Trend analysis of annual and seasonal reservoir levels

Statistics	Monsoon	Post-monsoon	Winter	Pre-monsoon	Annual
p value	0.77	0.393	0.694	0.520	0.83
Sen's Slop	-0.028	0.019	-0.037	0.042	0.015

Note: Bold values indicate significant trend at 95% confidence level

Statistics of the trend analysis of streamflow (Table 4.7) conveys that monsoon, pre monsoon and annual streamflow are decreasing however, only monsoon and annual flows (Figure 4.10) are significantly decreasing with the magnitude of 720.31 cumecs/monsoon and 574.25 cumecs/year respectively. The streamflow during post monsoon and winter possessed non-significant increase trend. The results of reservoir levels trends exhibited decreasing trend during monsoon and winter seasons (Table 4.8), while annual (Figure 4.11), post monsoon and pre monsoon season represented increasing trend. However, the reservoir level trends in all the seasons are statistically non-significant.

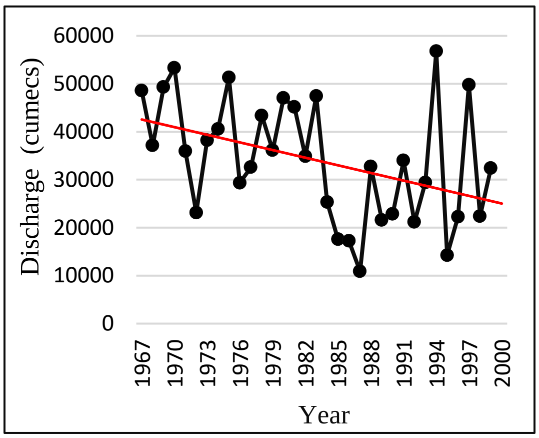


Figure.4.10. Annual streamflow trend

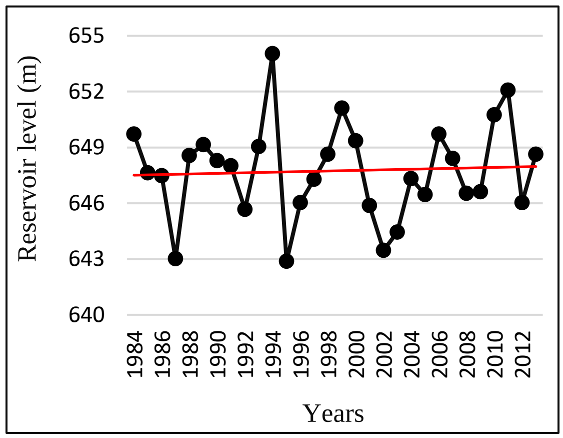


Figure. 4.11 Annual Reservoir level trend

4.4 CLOSURE

Trend analysis of hydro-meteorological variables in the Ghataprabha river basin indicates significant decreasing trends in rainfall and rainy days of semiarid and humid regions. The trends in the annual and seasonal temperature were increasing significantly for all the stations of the basin, whereas, annual PET showed significant increasing trends only in the semiarid region. The results of cluster analysis conveyed three clusters are adequate to explain groundwater-level fluctuations of the basin efficiently. Trend analysis of annual and seasonal groundwater levels of the basin conveyed annual decreasing trends in 64% of the wells with an average fall of 0.21 m per year. Most of the wells of cluster 2 show significant depletion in groundwater levels during all the seasons, which can be attributed to overexploitation coupled with diminishing rainfall and rainy days. A statistically significant decreasing trend was observed in the annual and monsoon streamflow, whereas reservoir trends are non-significant in all the seasons. The maximum number of the stations in the semiarid region exhibited decreasing trends in hydrometeorological variables, indicating that the region will be more vulnerable to frequent droughts in the future.

CHAPTER 5

DROUGHT CHARACTERISTICS OF GHATAPRABHA BASIN

5.1. INTRODUCTION

Identifying and quantifying drought characteristics of a region is crucial to understand the behavior of drought and its profound impacts on society, economy, and environment. Drought indices are useful tools to quantify drought characteristics and they also provide crucial information for bureaucrats, decision-makers, government and to the public stakeholders to take necessary action towards mitigation and preparedness strategies for drought.

Drought indices are normally continuous functions of rainfall and/or temperature, river discharge or other measurable variable. Drought indices evaluate the departure of climate variables in a given time interval (month, season or year) from the "normal" conditions and are used as monitoring tools and operational indicators for water managers. In other words, Drought indices are quantitative measures that characterize drought levels by assimilating data from one or several variables (indicators) such as precipitation and evapotranspiration into a single numerical value. The nature of drought indices reflects different events and conditions; they can reflect the climate dryness anomalies (mainly based on precipitation) or correspond to delayed agricultural and hydrological impacts such as decreasing groundwater levels or lowered reservoir levels.

Many studies have been considered a single drought index to assess drought characteristics of a region and only a few studies were attempted to suggest appropriate drought index for a specific climatic region (Wable et al.2018). Selection of proper drought index for a region is essential because each region has its prevailing climatic variable/s which plays a crucial role in the regional hydrological cycle and each drought index may not be capturing these critical climatic parameters effectively.

Understanding of drought characteristics of region or a basin by application of single drought index for whole region/basin which, possess various climatic regions may yield erroneous results and could lead to wrong interpretation of drought. Further, this may lead to an improper formulation of drought mitigation and preparedness strategies to address the issue. In this study, hydro-meteorological and agricultural drought characteristics for Ghataprabha river basin are analyzed with the help of different drought indices and compared each other. To assess meteorological drought, popularly, used Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI) and Reconnaissance Drought Index (RDI) are considered. The hydrological drought of the basin was studied by Streamflow Drought Index (SDI) and Standardized Reservoir Supply Index (SRSI). Similarly, agricultural drought and groundwater drought characteristics are derived using Vegetation Condition Index (VCI) and Standardized Groundwater level Index (SGI) respectively.

5.2 METHODOLOGY

5.2.1 Standardized Precipitation Index (SPI)

Calculation of SPI involves deriving a suitable distribution function which describes the long term time series of precipitation observations. Then to get SPI value, Inverse normal function with mean zero and stranded deviation one is applied to Cumulative Distribution Function (CDF) of the distribution. Positive SPI values indicate wet event and negative values indicate dry or drought. Since SPI is normally distributed it can also be used to determine periods of wet and dry events. The classification of the drought intensities based on the negative SPI value shown in Table 5.1 (Lloyd-Hughes and Saunders 2002). Pros and cons of SPI are, discussed in detail by Hayes et al. (1999), Mishra and Singh, (2010), Zargar et al. (2011). In this study, monthly rainfall series was fitted to the gamma distribution and its probability distribution function is defined as

$$g(x_k) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x_k^{\alpha-1} e^{-x_k/\beta} \tag{5.1}$$

Where,

α >0 where α is a shape parameter

β >0 β is a scale parameter

x_k >0 x is the precipitation amount over a period and,

$\Gamma(\alpha)$ is gamma function given by,

$$\Gamma(\alpha) = \int_0^\infty y^{\alpha-1} e^{-y} dy \qquad (5.2)$$

Parameters α and β have to be estimate to fit distribution to data. To estimate the parameters method of maximum likelihood (Edwards Mckee, 1997) was adopted and the equations are

$$\alpha = \frac{1}{4A}(1 + \sqrt{1 + \frac{4A}{3}} \qquad (5.3)$$

$$\beta = \frac{\overline{x_k}}{\alpha} \qquad (5.4)$$

Where, $A = \ln(\overline{x_k}) - \frac{1}{n}\sum_{i=1}^{n} \ln((x_k)_i)$ and n = Number of observations.

The cumulative probability $G(x_k)$, can be obtained by integrating the probability density function with respect to x_k which yields to

$$G(x_k) = \int_0^{x_k} g(x_k) dx_k = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^{x_k} x_k^{\alpha-1} e^{-x_k/\beta} dx_k \qquad (5.5)$$

By substituting t = x_k / β, in the this equation (5.5) leads to an incomplete gamma function

$$G(x_k) = \frac{1}{\Gamma(\alpha)} \int_0^{x_k} t^{\alpha-1} e^{-t} dt \qquad (5.6)$$

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

$$H(x_k) = q + (1-q)G(x_k) \qquad (5.7)$$

Where q is the probability of zero rainfall

Then SPI values will be obtained by transforming Cumulative probability distribution $H(x_k)$, into the standard normal distribution with mean zero and variance one. Following the approximate conversion provided by Abramowitz and Stegun (1965) as,

$$SPI = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right) \quad \text{where,} \quad t = \sqrt{\ln\left(\frac{1}{H(x_k)^2} \right)} \qquad (5.8)$$

For 0 <H(x) <0.5 and

$$SPI = \left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right) \quad \text{where,} \quad t = \sqrt{\ln\left(\frac{1}{1 - H(x_k)^2} \right)} \qquad (5.9)$$

For 0.5 <H(x) <1.0

Where C_0 =2:515517; C_1 =0:802853; C_2 =0:010328; d_1 =1:432788; d_2 =0:189269; d_3 =0:001308.

SPI calculation is done with monthly precipitation for 3, 6 and 12-month time scale and classified according to the classification presented in table 5.1. Monthly rainfall data obtained from Indian meteorological department for the duration 1970-2013 was used for calculation of SPI.

Table 5.1. Classification of drought conditions according to the SPI as given by (Lloyd-Hughes and Saunders 2002)

SPI values	Classification
2.0 or more	Extremely wet
1.5 to 1.99	Severe wet
1.0 to 1.49	Moderate wet
0.01 to 0.99	Mild wet
−0.99 to 0	Mild drought
−1.0 to −1.49	Moderate drought
−1.5 to −1.99	Severe drought
−2.0 or less	Extreme drought

5.2.2 Reconnaissance Drought Index (RDI) and Standardized Precipitation Evapotranspiration Index (SPEI)

Reconnaissance Drought Index (RDI) and Standardized Precipitation Evapotranspiration Index (SPEI) were developed to overcome the limitations of SPI by accounting climatic water demand. RDI and SPEI consider the effect of temperature in the form of evapotranspiration. RDI is extended version of Aridity Index and formulated by Tsakiris and Vangelis (2005) as a quotient of atmospheric water deficit. The ratio of monthly Precipitation (P) to Potential evapotranspiration (PET) is considered as input for RDI. During initial formulation of RDI, lognormal distribution was implemented but latter Gamma distribution was suggested (Tsakiris et al. 2007). SPEI was developed by (Vicente-Serrano et al. 2010), which reflects monthly climatic water balance. This index provides the measure of water surplus or deficit for a given time period. SPEI considers fitting of 3 parameter log logistic distribution to the difference between P and PET. Calculation procedure of RDI and SPEI are as same as SPI, the only difference is the input variables. Therefore, drought intensity expressed through these indices can be classified using a unified class definition (Table 5.1).

The detailed description of SPEI and RDI was provided by (Vicente-Serrano et al. 2010, Beguería et al. 2014; Tsakiris et al. 2007; Zarei et al. 2016). The present study calculates SPI, RDI and SPEI at 3, 6 and 12month time scales for all the stations and implemented 2 parameter Gamma distribution for SPI and RDI whereas 3 parameter Log-Logistic distribution was considered to calculate SPEI with R package ''SPEI'' developed by Beguería and Vicente-Serrano (2013).

Drought characteristics like severity, duration and intensity can be defined by considering a threshold value (in this study -1) for all the indices. Drought event (episode) is the period when the magnitude of SPI, RDI and SPEI falls below threshold level, and drought duration is the period in which the magnitude of drought index is below the threshold value. The severity is the sum of negative values during the drought duration, and intensity is defined as the ratio of the drought severity to drought duration. In the study, Monthly rainfall, temperature and monthly PET calculated from temperature based Penman-Monteith method for the duration 1970-2013 were considered as input for SPEI and RDI.

5.2.3 Streamflow Drought Index (SDI) and Standardized Reservoir Supply Index (SRSI)

SDI is an indicator of hydrological droughts, which was developed by Shukla and Wood (2008) on the bases of SPI concept. SDI requires monthly streamflow data as in put and follows same procedure as SPI. Gusyev et al., (2015) developed SRSI for an efficient way to analyses reservoir data in drought conditions. SRSI also follows SPI procedure and it require monthly reservoir level data as input. Monthly streamflow data from 1970-2000 measured at Bagalkot was used for calculation of SDI and monthly averaged reservoir levels of Hidkal reservoir from 1983-2013 was considered for SRSI. The SDI and SRSI are classified similar to SPI classification (table 5.1).

5.2.4 Vegetation Condition Index (VCI)

Kogan (1995) developed a vegetation based drought index called the Vegetation Condition Index (VCI) to monitor global vegetation health using remotely sensed NDVI data. The VCI is defined as follows:

$$\mathrm{VCI} = \frac{(\mathrm{NDVI} - \mathrm{NDVI}_{\min}) \times 100}{\mathrm{NDVI}_{\max} - \mathrm{NDVI}_{\min}} \tag{5.10}$$

Where NDVI is the monthly / weekly vegetation Index of each pixel of the image and $NDVI_{max}$, and $NDVI_{min}$ are the long term maximum and minimum values of NDVI of each pixel of that month/ week respectively. The value of VCI ranges from 0 to 100. The value 0 indicates extremely unfavorable condition and 100 indicates optimum. During extreme dry period the vegetation condition will be poor and VCI will be nearer to 0. According to Kogan (1995), the value of VCI ranging from 50 to 100 is classified as normal condition whereas the values ranges from 35 to 50 is categorized as moderate drought. Similarly, the VCI falls below 35 is classified as severe drought. In the study, multi temporal Normalized Difference Vegetation Index (NDVI) of 16-day composite with resolution 250 m from 2000-2013 was collected from Terra MODIS Vegetation Indices Product (MOD13Q1). The obtained NDVI images were further processed to derive VCI.

5.2.5 Groundwater drought by Standardize Groundwater level Index (SGI)

In the study, groundwater drought has been assessed with the help of Standardize Groundwater level Index (SGI). Bloomfield et al. (2013) proposed SGI to analyses groundwater drought using groundwater levels. SGI is a non-parametric method in which normal scores of monthly groundwater data has been transformed with inverse normal cumulative distribution function and values are arranged according to months continuously to get SGI time series. Since SGI considering invers normal function, classification of SGI is done similar to Standardize Precipitation Index as presented in Table 5.1.

Groundwater drought characteristics like severity, duration and intensity can be defined by considering a threshold value (in this study -1) for SGI. Drought event (episode) is the period when the magnitude of SGI falls below truncation level, and drought duration is the period in which the magnitude of drought index is below the threshold value. The severity is the sum of negative values during the drought duration, and intensity is defined as the ratio of the drought severity to drought duration. Monthly groundwater-level data from 59 wells situated in and around the study area spanning not less than 25 years, were considered to derive SGI characteristics.

5.2.6. Comparison of SPI, SPEI with SGI and analysis of Autocorrelation characteristics of SGI time series

Groundwater drought derived through SGI was compared with the meteorological drought obtained by SPI and SPEI at different accumulation periods (1 month to 24 Month). The Meteorological drought of particular accumulation period which follows a similar pattern of SGI time series was considered as maximum accumulation period (Qmax) of that index. The cross-correlation between SGI and SPI (SPEI) of Qmax was analyzed in the study to measure the degree of association between meteorological and groundwater drought. The cross-correlation is a standard method of estimating the extent of correlation between two variables at various time lags.

The autocorrelation structure for the SGI time series was derived to analyze the relationship between significant autocorrelations of SGI (Amax) with the meteorological drought. The SGI autocorrelation conveys the propagation of meteorological drought to the groundwater drought by a linear relationship between Qmax and Amax (Motlagh et al. 2016). The autocorrelation of SGI is said to be significant at 95% confidence level ($p=0.05$) when it is $> 2/\sqrt{n}$ where n is the length of groundwater data in months. The formulations and detailed explanation of SGI autocorrelation can be found in Bloomfield and Marchant (2013) and Bloomfield et al. (2015). In addition to this, the effect of local hydrogeological property on the drought propagation was analyzed through the hydraulic diffusivity (Hd) which is defined as the ratio of aquifer transmissivity (T) to storage coefficient (S).

5.3. APPLICATION OF HYDROLOGICAL MODEL TO GHATAPRABHA RIVER BASIN

The long-term streamflow data available at Bagalkot station of the basin is up to the year 2000. Therefore, to simulate streamflow data till the year 2013 popularly used hydrological model, Soil and Water Assessment Tool (SWAT) was employed to predict streamflow data from the year 2001 to 2013. The SWAT is a semi-empirical and semi-physically based, distributed, agro hydrological model that operates on a daily time step at the watershed scale. SWAT is designed to predict the impact of change in management on water, sediment, and agricultural chemical yields in ungauged catchments (Arnold et al. 1998).

The SWAT can analyze small or large catchments by discretizing them into sub-basins, which are then further subdivided into hydrologic response units (HRUs) with homogeneous land use, soil type, and slope. The SWAT model underlies the ArcSWAT interface where ArcGIS is used to provide geographic analyses, which feed into the SWAT model and provide hydrological outputs. A detailed description and comprehensive review of the SWAT model can be found in Neitsch et al. (2005) and Gassman et al. (2007) respectively.

To improve the reliability of the model with respect to dam operations, 17 years (1983–2000) of monthly measured release and storage volume data from Hidkal reservoir was obtained from the Karnataka Water Resources department. The river discharge at downstream of the Ghataprabha basin are affected by the discharge operations of the Hidkal dam; therefore, dam operations must be incorporated into the modeling framework to enable successful modeling. In the SWAT model, reservoir module can be included based on measured daily reservoir out flow, measured average monthly reservoir out flow or average annual reservoir out flow with basic reservoir information.

The SWAT model setup with reservoir is carried out with Arc GIS interface. The Digital Elevation Model (DEM) at 90 m resolution from the Shuttle Radar Topography Mission (SRTM), Daily rainfall and temperature, FAO soil map, 100-meter spatial resolution land use and land cover map of year 1995 and average monthly reservoir out flows are considered for SWAT input. The model was calibrated and validated using observed streamflow data from 1983- 2000 of which 1983-1985 was considered as warmup period for the model and data of 1986- 1994 and 1995-2000 are considered for model calibration and validation respectively. Sensitivity analysis was performed with the SUFI-2 algorithm to identify the most important model parameters influencing the runoff output. The model performance as assessed by Nash–Sutcliffe Efficiency (NSE) and coefficient of determination (R^2).

The time series of streamflow during calibration and validation are presented in figure 5.1. The scatter plot of observed with those of simulated monthly averaged streamflow during calibration and validation period with R^2 are presented in figure 5.2. The value of NSE during calibration and validation period was 0.82 and 0.83 respectively. The high positive values of NSE and R^2 indicates good performance of the SWAT model during both calibration and validation phase. With the validated SWAT model, streamflow for the period 2001-2013 was generated and considered for further analysis.

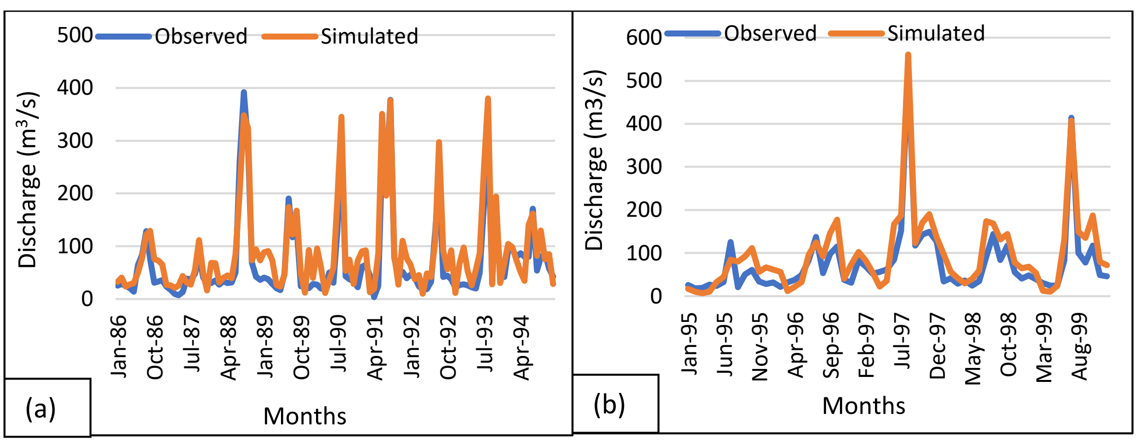


Figure 5.1 Monthly averaged time series of simulated vs. observed flows during model a) calibration and b) validation

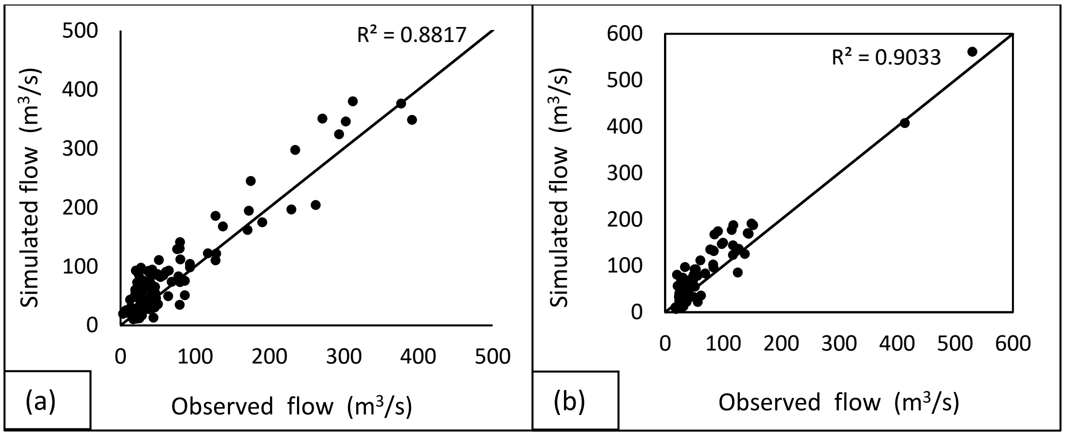


Figure 5.2 Comparison of simulated vs. observed monthly averaged flows during model a) calibration and b) validation

5.4 RESULTS AND DISCUSSION

5.4.1 Spatio-temporal variation of meteorological drought

Meteorological drought in the study area was assessed by considering three drought indices namely SPI, RDI and SPEI. These indices follow similar calculation procedure by considering rainfall for SPI and both rainfall and PET for calculation of RDI and SPEI. Analysis of drought indices with various times scales will picturize the influence of drought on different sectors of water resources. Drought at smaller time scales (3, 6 months) will have the impact on seasonal crop failure and soil moisture; while higher time scale (12, 24 and 48 months) will affect the reservoir levels, streamflow and groundwater levels. In this study SPI, RDI and SPEI were calculated for the stations B2, B4 and C7 for various time scales (3, 6 and 12 month).

Significant number of droughts were observed from all the indices for various time scales. Temporal variation of SPI, RDI and SPEI for 3-month time scale is depicted in Figure 5.3 and major drought episodes were observed in the years of 1971-72, 1982-83, 2002-2003 and in 2012. SPI of 3-month time scale, identified 2, 6, 11 number of extreme droughts in the humid, sub humid and in the semiarid stations respectively. It was also noted that the stations B2, B4 and C7 are under extreme drought during the years 1994 (Jun), 2003 (Jun-Sep) and in 2012 (May-Jun). Results of the 3-month SPEI identified the highest number of extreme droughts in the semiarid station (9 times) as compared to sub humid (2 times) and humid station (8 times). According to the 3-month SPEI, the basin was under severe drought during the year 1991 (Mar-May) and in 1991 (Aug-Sep).

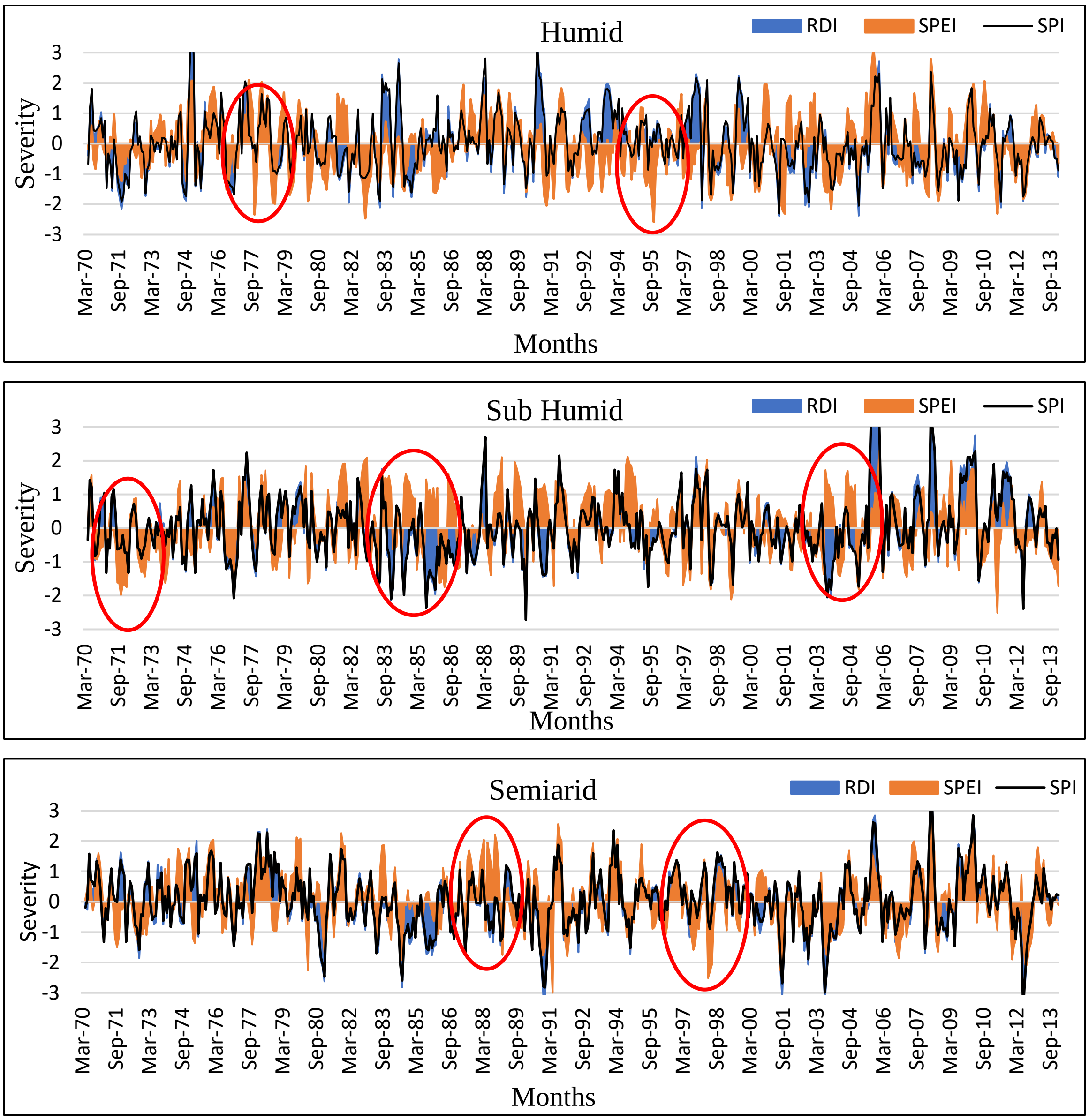


Fig. 5.3. Temporal variation of drought severity for selected stations of humid, sub-humid and semiarid regions of the basin

In the humid station, severe drought condition was observed through RDI with duration of seven months (July 1971 to January 1972) and severity of 10.87 with the average intensity of -1.55. In the sub humid station, SPEI captured critical drought with the severity of 10.30 and duration of 6 month (July-71 to December-71) with the average intensity of -1.71. Similarly, RDI identified severe drought in the semiarid station with duration of five months (August 90 to December 90) and severity of 10.48 with the average intensity of -2.328.

Drought characteristics for 3-month SPI (Table 5.2) showed that the humid station experiences 70 drought months among them, 32 months with 7 drought episodes were having duration ≥ 3 months. Similarly, in the sub humid and in the semiarid station 17 and 29 months out of 57 and 65 months of drought duration lasts equal or more than 3 months respectively. Details of drought characteristics of 3month SPI, RDI and SPEI at each climatic station is presented in Table 5.2.

Table. 5.2. Drought characteristics of 3month SPI, RDI and SPEI

Station	Index	Total Duration (months)	Drought with duration ≥3 months		
			Duration (months)	No. of Drought Events	Severity
B2	SPI	70	32	7	43.78
	RDI	80	30	7	45.47
	SPEI	107	67	17	102.98
B4	SPI	57	17	4	26.47
	RDI	66	19	4	28.90
	SPEI	79	35	9	51.06
C7	SPI	65	29	7	55.94
	RDI	83	43	10	75.35
	SPEI	80	44	12	66.51

Characteristics of SPI, RDI, and SPEI are susceptible to vary with the timescales. Smaller time scale (3month) possess shorter drought duration and higher number of drought episodes, with the instant shift of severity from dry condition to wet condition and the other way around, however, droughts of higher (12 month) time scale indicates less drought episodes with higher duration. Effect of variation of time scale on SPEI characteristics is portrayed in Table 5.3, and it was noted that there is no much difference between drought durations of SPEI for the humid station with the change in timescale. While in sub humid and semiarid station, drought duration increases significantly with the time scale, and the corresponding decrease in drought episodes can be observed. Similar variations are noted for SPI and RDI also.

Table .5.3. SPEI drought characteristics with different time scale

Station	Time scale	Duration (months)	Episodes	Average severity
	3	107	48	3.3
B2	6	108	34	4.6
	12	109	18	9.01
	3	79	41	2.6
B4	6	86	33	3.12
	12	93	14	12.35
	3	80	41	2.8
C7	6	87	30	4.12
	12	101	16	8.79

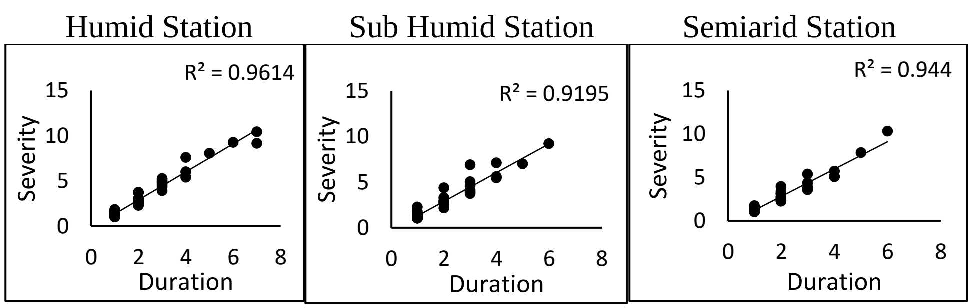


Fig. 5.4. Relationship between drought duration and severity of SPEI-3 for representative stations of each climatic region

Drought characteristics revealed through SPEI indicates that, the drought duration and severity are well correlated and as the duration of drought increases severity will also increase (Figure 5.4). SPI and RDI also possessed similar relation between duration and severity. An empirical relationship between drought duration and severity was developed for all the three indices of each station and presented in Table 5.4. The negligible numeric difference was observed between the coefficients of the equations of SPEI and RDI in the humid station, where as in the semiarid station, SPEI and SPI produced similar equation for the relationship between severity and duration.

Table. 5.4 Empirical relationship between drought severity and duration

Climatic Station	Index	Equation
Humid	SPI	Y=1.40X-0.29
	RDI	Y=1.54X-0.37
	SPEI	Y=1.56X-0.34
Sub Humid	SPI	Y=1.60X-0.34
	RDI	Y=1.62X-0.51
	SPEI	Y=1.56X-0.34
Semiarid	SPI	Y=1.58X-0.73
	RDI	Y=1.91X-0.93
	SPEI	Y=1.55X-0.45

The numerical difference between coefficients of the equations, which explains drought severity and duration of SPEI index for all stations is low. From this, a single equation which describes relation between drought duration and severity of SPEI for whole basin was deduced and presented in the following equation.

$$Y=1.56X-0.38 \quad (5.11)$$

Where Y is drought severity and X is duration of drought. These equations will help to estimate drought severity directly based on drought duration for different time scales and it will also helpful to prepare drought mitigation and preparedness strategies for the area.

5.4.1.1 Comparison of SPI, RDI and SPEI at different climatic regions

Similar behavior of RDI and SPI was observed in all the stations and SPEI follows the similar pattern of SPI (RDI) in the semiarid station (C7), but significant difference in the intensity can be observed (Figure 5.3). In the humid and sub humid station (B2 and B4), the behavior of SPEI differed from SPI (RDI). In the humid station (Figure 5.3), RDI and SPI represents mild wet conditions in the months of July, August and September of 1995 while, SPEI remarked severe drought in the period. Similarly, several discrepancies (highlighted with circle) between SPEI and RDI (SPI) can be noted for other two stations also. Comparison of drought characteristics of the drought indices exposed that SPI and RDI were showing similar drought duration (≥3months) and severity in humid and sub humid stations (Table 5.2). Highest number of droughts were identified by SPEI for all the stations.

Spatial variation of 3-month SPI, RDI and SPEI denote the propagation of drought severity and its withdrawal for the months of October, November, December of the year 1980 and January 1981 (Figure 5.5). Severe drought was observed by SPI and RDI in the semiarid region during the month of October. Whereas SPEI demarcated mild drought in the semiarid and trace of severe drought in the humid region.

In the month of November, SPEI picturized moderate drought in the semiarid region and in the portions of the humid region. Severe drought along with the trace of extreme drought was observed through SPI and RDI in the semiarid region. Severe and extreme droughts identified by SPI and RDI were further creeps into the basins covering most of the semiarid region in the month of December. Whereas SPEI possesses moderate and severe drought in humid and semiarid regions respectively.

SPI captures the initiation of drought recovery in the humid region in the month of December. During January, SPI and RDI showed most of the basin recovered from drought except, mild drought in the small portion of the semiarid region while, SPEI possess mild drought in the semiarid and humid region. Spatial analysis of SPI, RDI, and SPEI at various climatic regions reveals that semiarid region suffers severe and extreme drought events regularly whereas sub humid region exposed the least number of severe drought events. SPEI was significantly differed from SPI and RDI in both severity and area coverage. This is because the variation of P, P/PET and P-PET behaves differently in the different regions and calculation of PET will also play the crucial role in the variation of SPEI and RDI ((Beguería et al. 2014; Mohammed and Scholz 2017). These results convey that, even though SPEI and RDI considers same inputs and follows same procedure of calculation, a remarkable difference among these indices can be observed both in spatial and temporal scale.

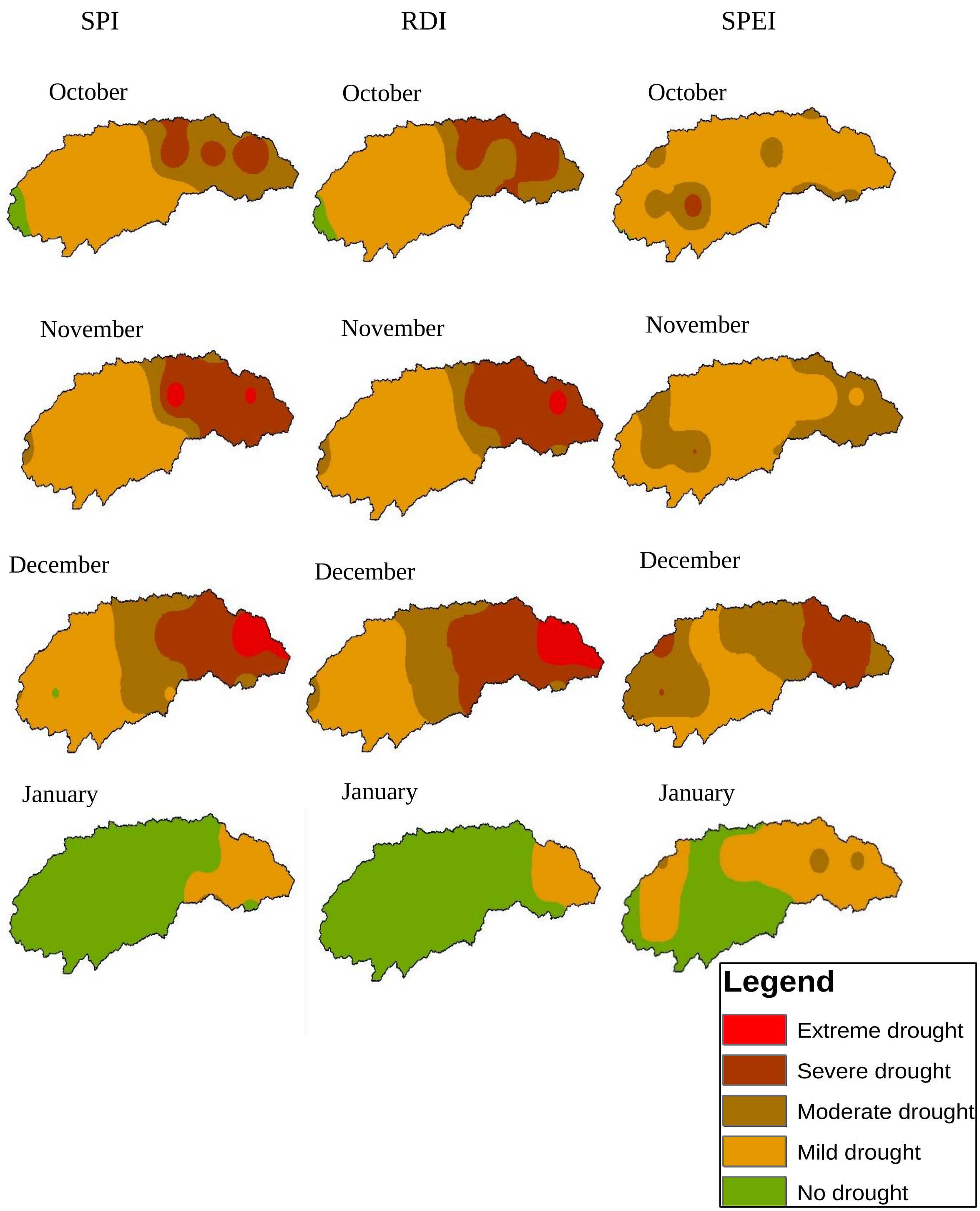
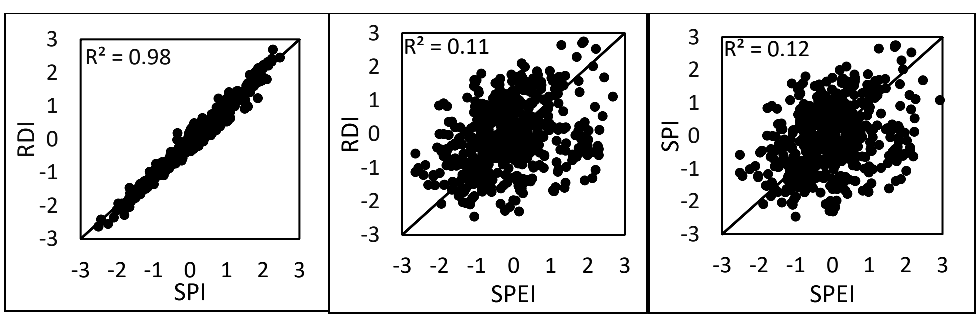


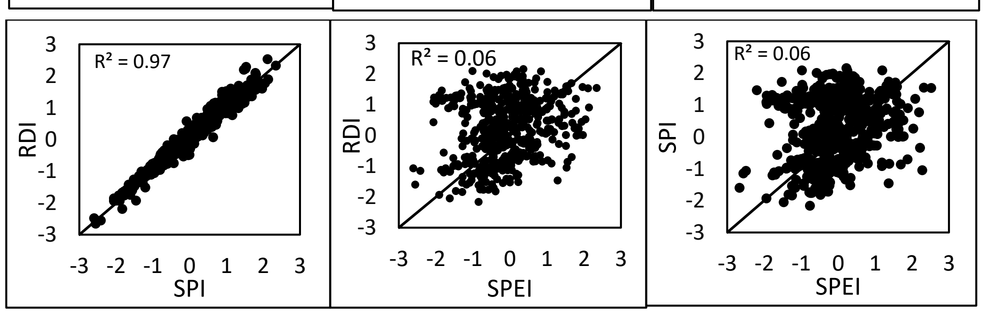
Fig. 5.5. Spatial variation of drought severity over the basin for the selected months of year 1980-1981

Comparison between SPI, RDI and SPEI was further analyzed with Pearson correlation coefficient and graphical approach. The Correlation Coefficient (CC) between SPI and RDI is very high for all the time scales and for all the stations (Table 5). In the semiarid station CC between SPI and RDI with SPEI varies from 0.51 to 0.6 while in the humid and sub humid station poor CC was observed. High correlation between SPI and RDI and poor correlation of SPI (RDI) with SPEI may be due to the fitting of predefined two parameter Gamma distribution to the inputs of SPI and RDI whereas three parameter Log-Logistic distribution to the input of SPEI.

To compare different meteorological indices scatter plots of SPI vs RDI, SPI vs SPEI and RDI vs SPEI are plotted (Figure 5.6) for different time scales for all the stations. A strong linear relationship between SPI and RDI was observed for all the stations and R^2 value between the indices increases with increases in the time scale. Similar results were also reported by Xu et al. (2015) in China. There was no exact relationship observed among SPI (RDI) and SPEI in the humid and sub humid station, however, scatter between SPI (RDI) and SPEI is less in the semiarid region as compared to humid and sub humid region. This may be due to the reason that the RDI respond more to rainfall while SPEI gives equal weightage to both precipitation and PET (Vicente-Serrano et al. 2015).



(a)



(b)

Cont.,

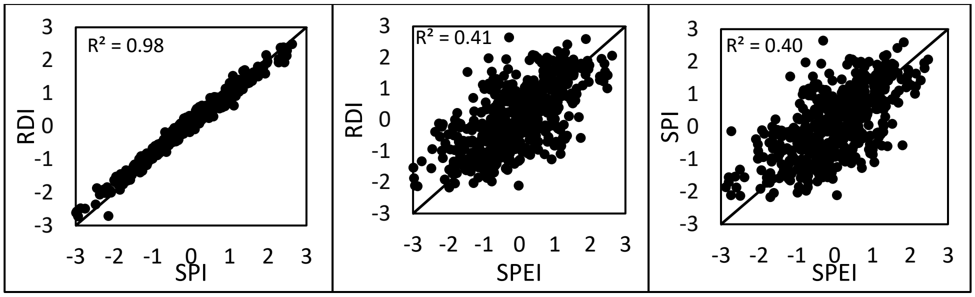
(c) 

Fig. 5.6. Scatter plots between drought indices for representative stations of a) Humid b) Sub-humid and (c) Semiarid climatic region

Frequencies of different dry and wet classes for each time scale are presented in Figure 5.7 in terms of percentage of months. RDI exhibited the highest number of extreme droughts in the semiarid and sub humid region whereas SPEI and RDI presented highest no of severe droughts in semiarid and humid (sub humid) station respectively. It was noted that as time scale increases, the number of extreme droughts identified by RDI and SPEI is also increasing in the semiarid and humid station. Whereas it is the fact that as time scale of analysis increases, the frequency of extreme drought decreases (Thomas et al. 2016a). As per above observation SPEI and RDI were giving contradictory results in humid and semiarid stations respectively.

The humid region is characterized by more rainfall whereas PET will be dominating in the semiarid region. RDI was inclined more towards rainfall and Coefficient of Variation (CV) of rainfall (0.47) of the humid station is higher than that of the semiarid station (0.33). The semiarid region was characterized by high PET as compared to that of the humid region and SPEI was equally governed by PET, therefore, it is advocated to use SPEI in semiarid region whereas RDI or SPI in humid and sub humid region to get reliable results. Since SPI and RDI are yielding similar results, RDI has not been considered in further analysis.

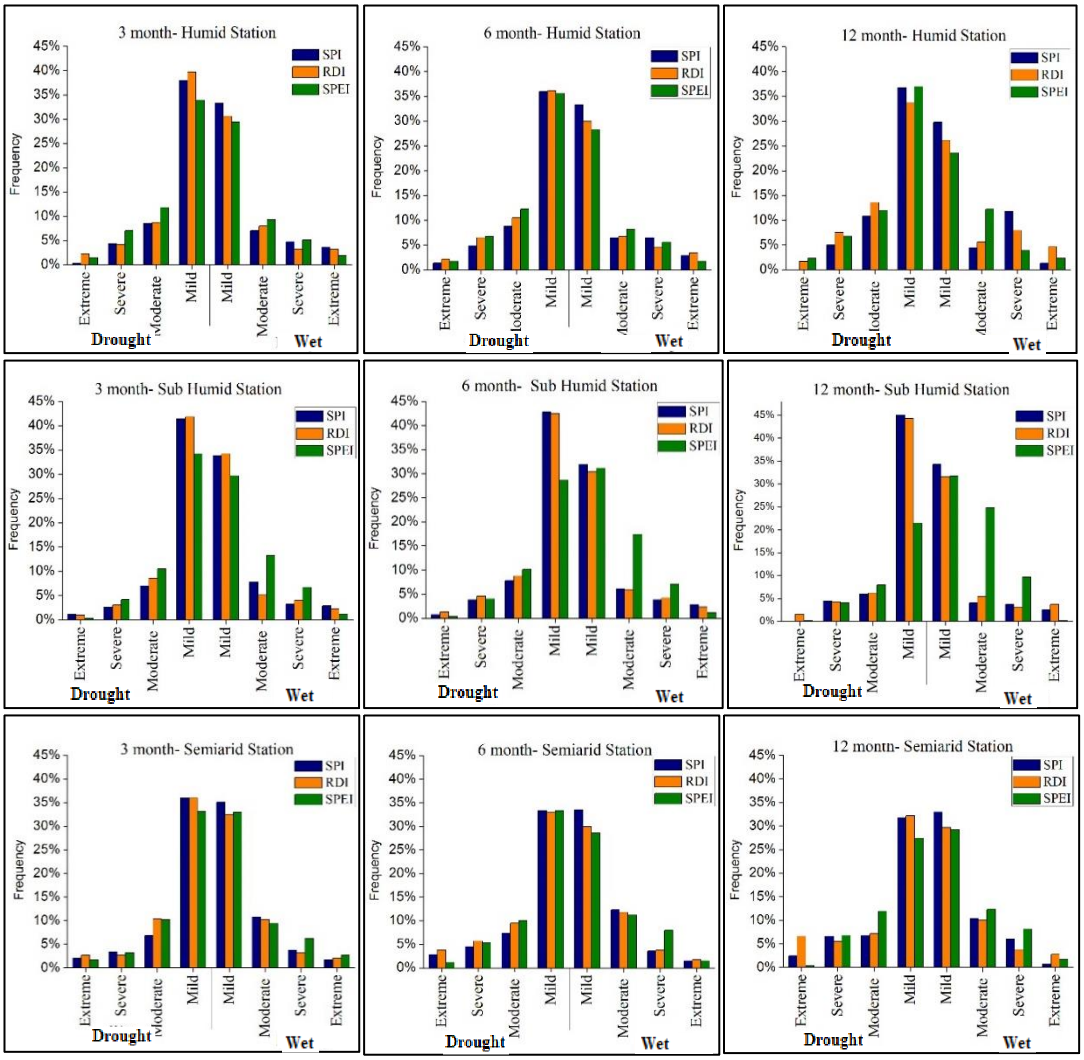


Fig.5.7. Frequencies of SPI, RDI and SPEI in each category of wet and drought in terms of percentage of months

5.4.1.2 Meteorological drought at basin scale

Since, SPI and RDI are behaving similarly in all the stations, RDI has been omitted from assessing meteorological drought characteristics at basin scale. SPI and SPEI was calculated at 3, 6 and 12-month time scale considering basin as whole. Average SPI and SPEI gives an overall picture of drought at different time scale (Ionita et al. 2016). Five severe drought events were observed in the years of 1983, 1984, 1989, 2001 and in 2012 by 3 month SPI (Figure 5.6 a). Similarly, 7 severe droughts were observed through SPEI 3 during 1980, 1991, 1998, 2001, 2006, 2011, and in 2012. The SPI-6 and SPEI-6 disclosed (Figure 5.8 b) four severe drought episodes each during the years 1984, 1990, 2001, 2012 and 1985, 1986, 2001 and in 2012 respectively. SPEI of 12 month showed only two severe droughts during 1986 and in 2004 where as SPI-12 showed no severe droughts (Figure 5.6 c). However, both the Indies portrayed two major mild drought episodes during 1985-1986 and 2003-2004 with average duration greater than 8 months.

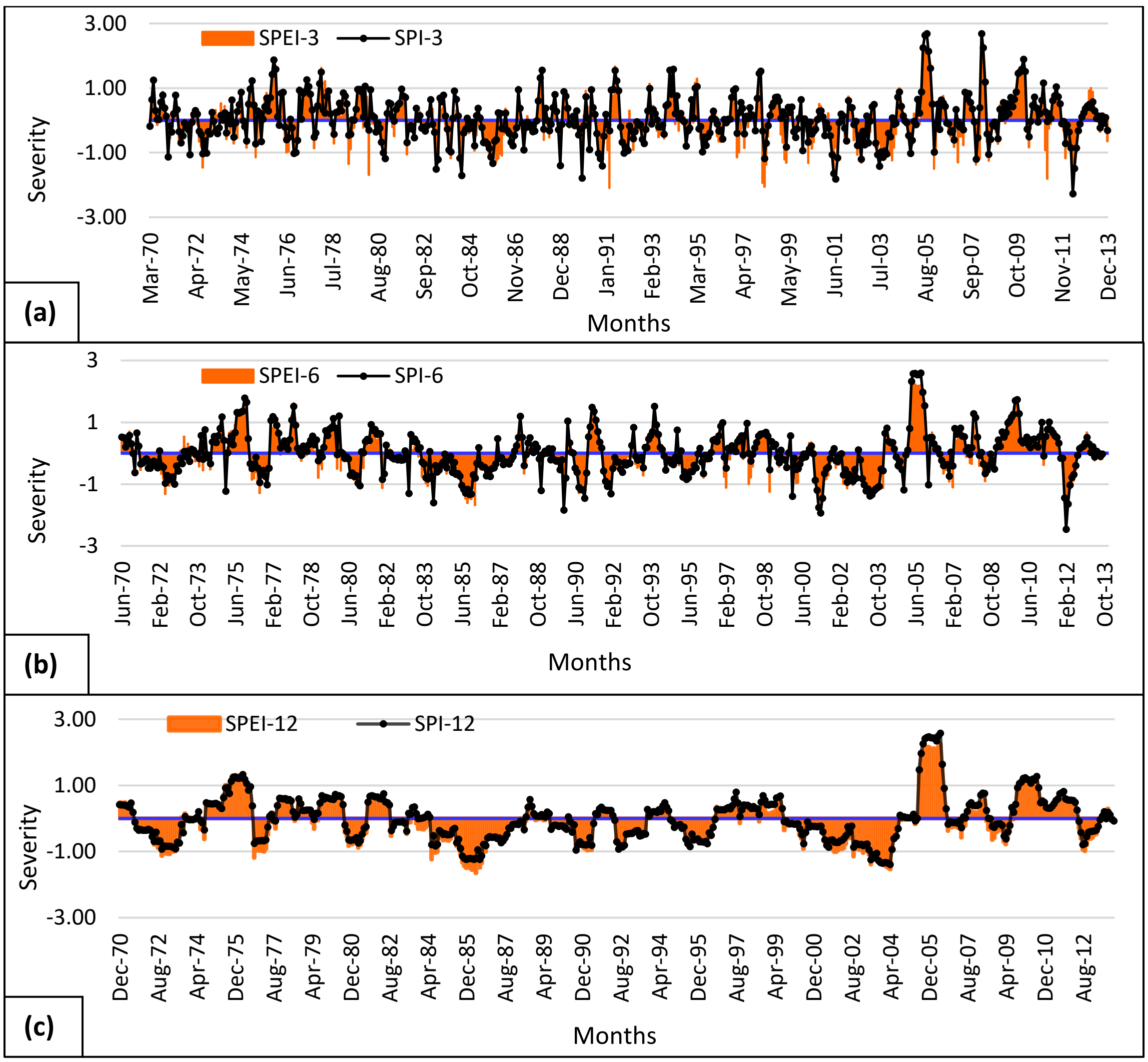
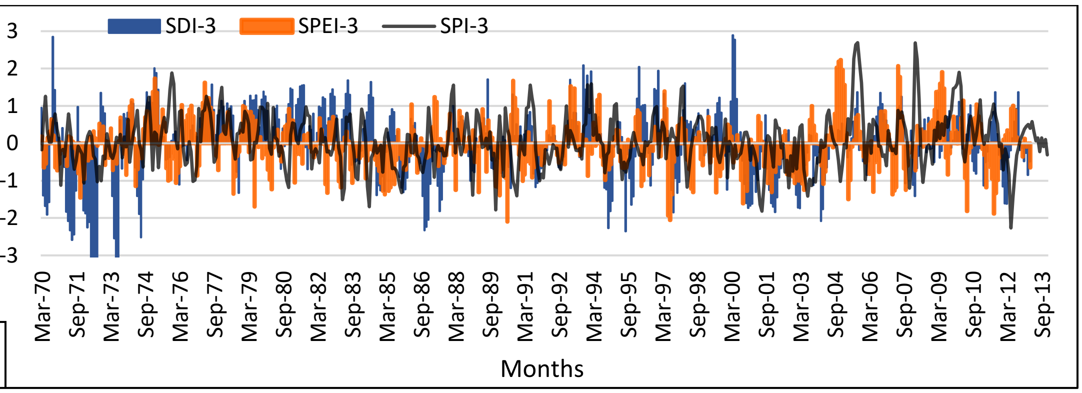


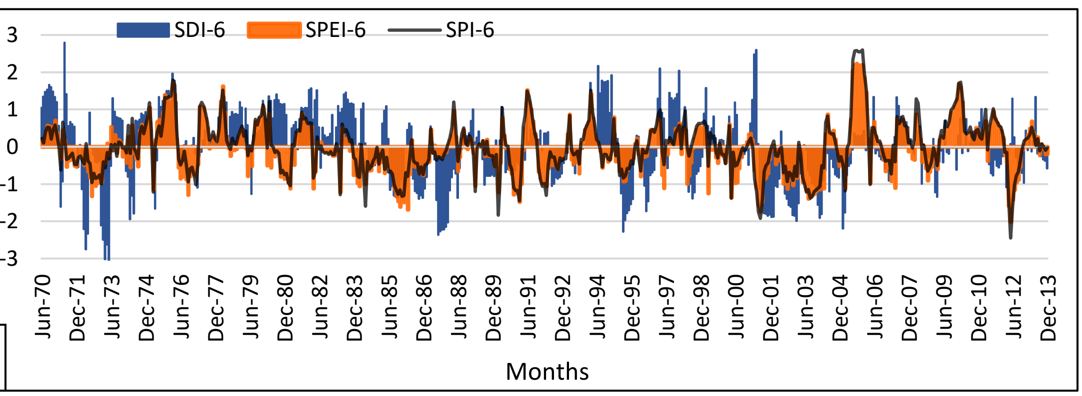
Fig 5.8. Temporal variation of a) 3-month b) 6-month c) 12-month SPI and SPEI at basin scale

5.4.2 Assessment of hydrological drought and its comparison with meteorological drought

Hydrological drought in the study area was assessed by SDI and SRSI for different time scale (3, 6 and12 month). Monthly streamflow data from 1970-2013 (2001-2013 are simulated from SWAT) at Bagalkot was considered for calculation of SDI. Average monthly reservoir level measured from 1984 to 2013 was considered as input for calculation of SRSI. Since calculation of SDI and SRSI is similar to SPI, drought classification for SDI and SRSI can also be done as similar to SPI classification (Table 5.1). The results of three-month SDI indicated (Figure 5.9a) 87 drought months among them 46 are severe and it also showed 16 drought episodes which are having duration ≥ 3months. Similarly, SDI-6 and SDI-12 conveyed (Figure 5.9 a and b). 42 severe drought months each with the 12 and three drought episodes having duration ≥ 3months respectively. The results of SDI suggested that the basin was under acute water stress during 1984-1987 and during 2001-2004.



(a)



(b)

Cont.,

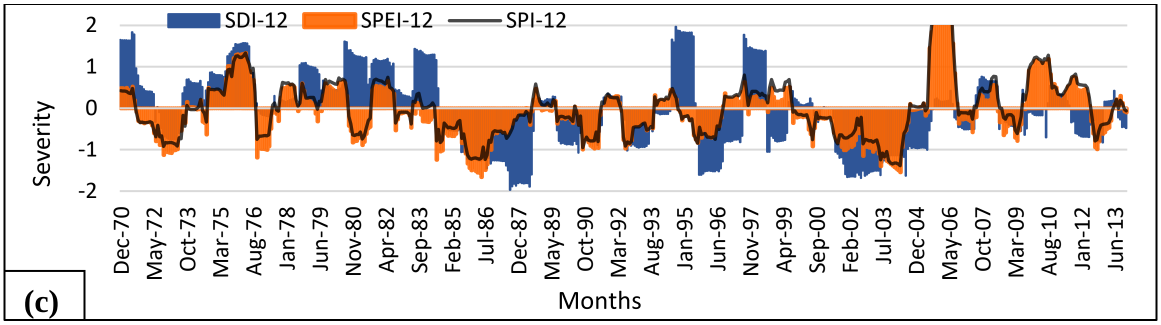


Fig 5.9. Temporal variation of a) 3-month b) 6-month c) 12-month SDI and comparison with meteorological drought

Comparison of SDI of different timescale was done with basin averaged SPI and SPEI. From the comparison it was noted that SDI did not follow the exact trend of SPI or SPEI. In 3 and 6-month time scale of SDI, the years 1972-1973 and 1986-1987 are in extreme drought whereas the same is not reflected in severities of SPI and SPEI time series. Similarly, SDI-12 disclosed moderate wet condition during 1980-1981where as SPI and SPEI-12 showed mild drought (Figure 5.9 c). Out of 44 years of data, 3-month SDI disclosed 87 drought months among them 16 drought episodes having duration ≥3 months. Whereas, SPI and SPEI exhibited 33 and 53 drought months having 5 and 8 drought episodes with duration ≥3 months. Similarly, an enormous discrepancy was noted in the drought duration and severities of SDI and SPI (SPEI) for other time scale also. The detailed drought characteristics of SDI and SPI (SPEI) of different time scale are given in table 5.5.

Table. 5.5 Comparison of SDI, SPI and SPEI drought characteristics

Time scale	Index	Total Duration (months)	Drought with duration ≥3 months		
			Duration (months)	No. of Drought Events	Severity
3-Month	SDI	87	69	16	127.10
	SPI	33	17	5	21.73
	SPEI	53	25	8	31.04
6-Month	SDI	83	69	12	116.64
	SPI	39	30	6	39.02
	SPEI	49	36	7	54.83
12-Month	SDI	92	87	3	124.35
	SPI	21	19	3	26.62
	SPEI	41	31	5	52.66

Further, Pearson correlation coefficient was calculated between SDI, SPI and SPEI of different time scales with few lags and results indicated poor correlation for 3 and 6-month time scale. The highest correlation observed was 0.49 between SDI-12 and SPEI-12 with the lag of 2 months. The poor correlation between SDI and meteorological drought indies convey that for Ghataprabha river basin, prediction of SDI or hydrological drought is not possible with SPI and SPEI if the streamflow data is missing and with the known meteorological condition. Similar observations are also pointed out by Surendran et al., (2017). The possible reason for the difference in SDI with that of meteorological indices is that it is being calculated based on the streamflow. The streamflow in a particular watershed will largely depend on the rainfall period, and its intensity, land use, topography, upstream reservoir regulations etc., and hence the hydrological drought sometimes will not be reflected accurately in meteorological drought indices.

Similar to SDI, SRSI has been assessed at different time scales. The 3 month SRSI indicated 52 drought months among them, 35 are severe and it also consists seven extreme drought episodes (1987, 1982, 1995,1997,2002,2004 and in 2005) during the period of 1984 to 2013 (Figure 5.10). The results of SRSI-6 and 12 disclosed 55 and 50 drought months respectively within that nine and four drought episodes are having duration ≥ 3months with average severity of -1.665 and -1.586 respectively. The overall result of SRSI highlighted 3 major drought events during the year 1987-1988, 1995-1996 and in 2002-2004 which conveyed negative rainfall anomaly in the catchment of the Hidkal reservoir. To study the propagation of hydrological drought from SRSI to SDI has been studded by comparing SRSI with the different time scale of SDI from 1984 to 2013. It will also convey the effect of SRSI on the downstream region of the study area. The results indicated that SDI follows general pattern of SRSI in all the time scales and better correlation was observed (ranging from 3.8 to 5.9) compared to the correlation between SDI and meteorological drought. However, few discrepancies can also be observed (Figure 5.10) this may be due to the reason that the other higher order streams will join the mainstream of the river Ghataprabha beyond the reservoir and total water stored in the reservoir will not only releasing to the river but also suppling to irrigation through canal networks.

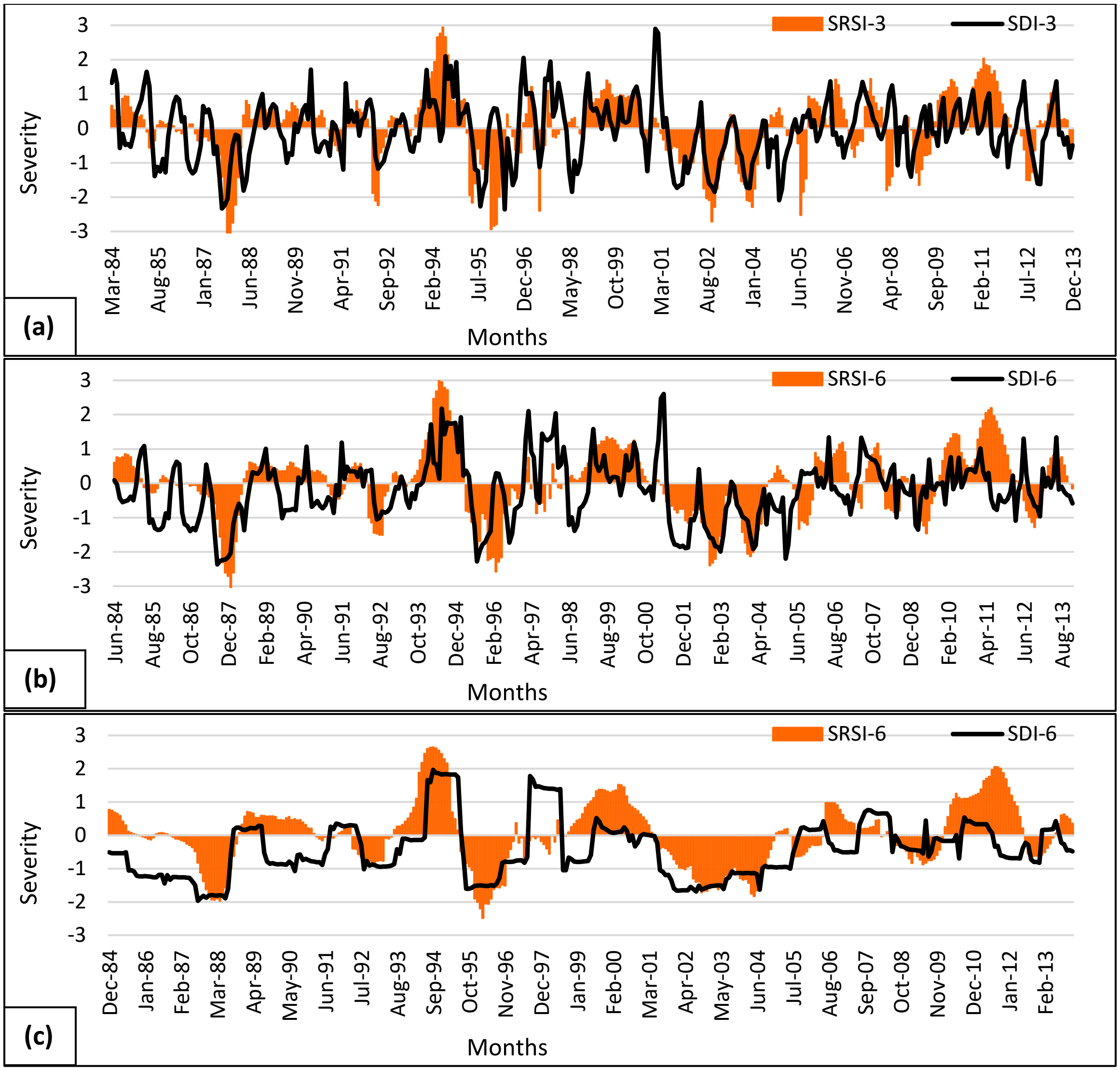


Fig 5.10. Temporal variation of a) 3-month b) 6-month c) 12-month SRSI and comparison with SDI

5.4.3 Assessment of Agricultural drought and its comparison with meteorological drought

Long term MODIS Normalized Difference Vegetation Index (NDVI) from 2000-2013 with temporal resolution of 16-days was considered to derive VCI. Later, the VCI of 16days were averaged over the respective months to obtain monthly VCI. During the study period (2000-2013) the basin suffered by 26 drought episodes over the 53 months consisting of 38 severe droughts in it. Temporal variation of average VCI of the basin (Figure 5.11) showed the severe agricultural droughts in the beginning of the decade 2000-2010. Among them, average VCI in the most of the months of the year 2003-2004 are less than 35 which indicate that the basin is under high severe drought during that period and it can be attribute to the deficit rainfall during the year 2002-2003. However, the high value VCI observed during 2005 and 2009-2010 indicate healthy vegetation conditions in the basin. The regression trend line (Figure 5.11) of VCI showed increasing trend in contrast to the decreasing trends in rainfall and rainy days which emphasizes the usage of alternate source of water (mainly groundwater) for the crops in the basin. VCI of drought year (2002-2003) and normal year (2005-2006) is considered for further assessment.

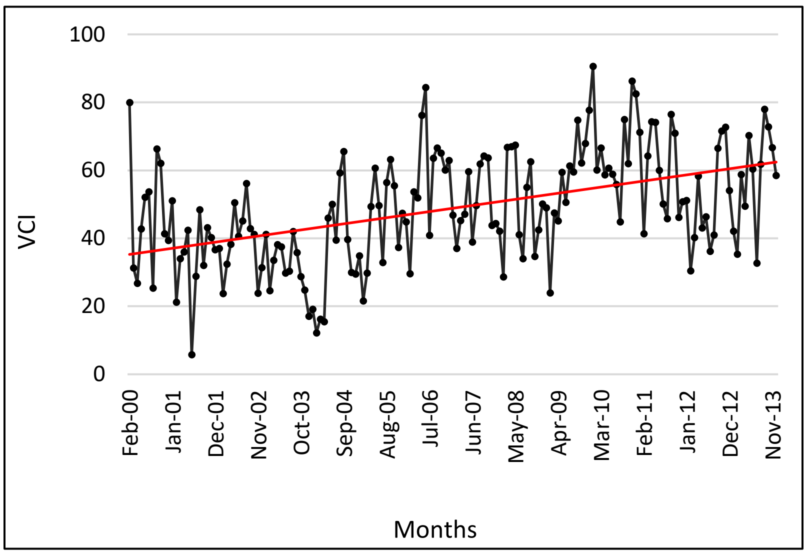


Figure 5.11. Temporal variation of average VCI of the basin

To understand the temporal variation of VCI, the values of the VCI during drought (2003-2004) year is compared with the normal year (2005-2006) (Figure 5.12). A clear discrepancy can be observed in the values VCI during drought and normal year. During the drought year the average VCI of the basin fall below 50 with the average of 33.5 indicating the severe drought condition. The maximum difference in the VCI was observed in the pre and post monsoon seasons of the drought and normal year which reveals the effect of varied rainfall and rainy days over the vegetation condition of the study area.

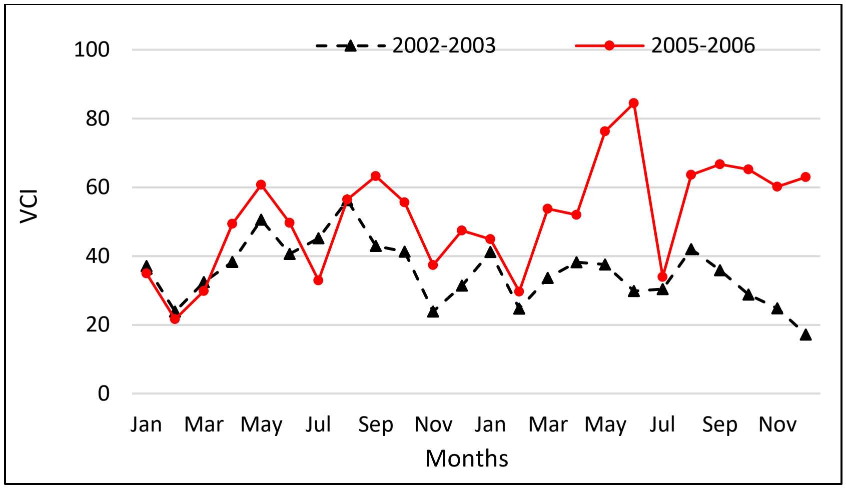


Figure 5.12. Comparison of VCI during drought (2002-2003) and normal year (2005-2006)

Spatial variation of VCI during the monsoon season of drought and normal year is depicted in the figure 5.13. It was observed that the large area of the basin was under severe drought in the monsoon of the year 2003. The intense vegetation stress was observed in the month of June 2003 and the same condition was prevailed in the successive months. However, after the month of June the vegetation health was improved in the western part of the basin. This part of the basin is comprised by the Western Ghats of India characterized by high rainfall as compared to other portion of the basin which helps to maintain good vegetation cover even during the drought year. Apart from the west portion, the basin experienced severer drought in the successive years of 2002-2003-2004. The similar drought conditions are also observed by Biradar and Sridhar (2009) during these years and reported significant reduction in the area under different crops. During normal year it can be noted that the area covered by vegetation is higher than that of the drought year.

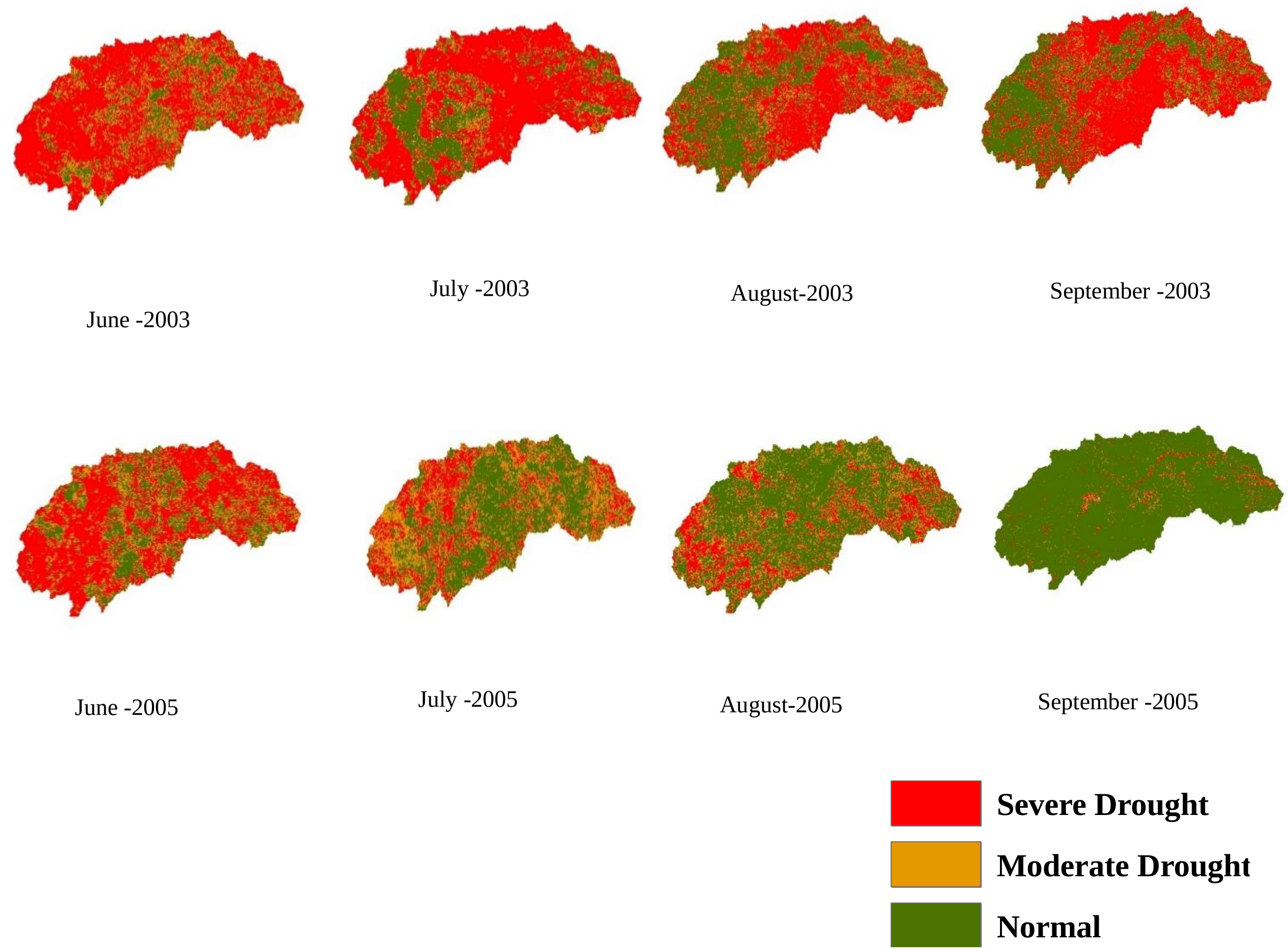


Figure 5.13. Vegetation Condition Index (VCI) for drought year (2003) and normal year (2005)

To study the effect of meteorological drought on agricultural drought, basin averaged SPI and SPEI values of different time scales were compared with VCI of 2000-2013. Before comparing the VCI with meteorological, the values of VCI were rescaled to the SPI classes so that the comparison can be done easily. The VCI were rescaled between -3 to +3 and denoted as SVCI in such a way that the lowest value of VCI (i.e zero) should get -3 and highest value of VCI (i.e 100) represents +3. The similar behavior was observed between 3 and 6 month SPI during 2000-2013 and both are following the SVCI pattern (Figure 5.14). Even though both the time scales of SPI and SPEI follows SVCI, significant discrepancies can be observed however 6 month SPI/SPEI is more likely to follow the SVCI. During the study period, the SVCI disclosed 33 drought months among them 15 months are severe drought with average magnitude of -1.57. Similarly, SPI-3 and SPI-6 revealed 14 and 20 drought months with average magnitude of -1.32 and -1.35 respectively. Whereas, SPEI-3 and SPEI-6 disclosed 23 and 22 drought months with average severity of -1.3 each.

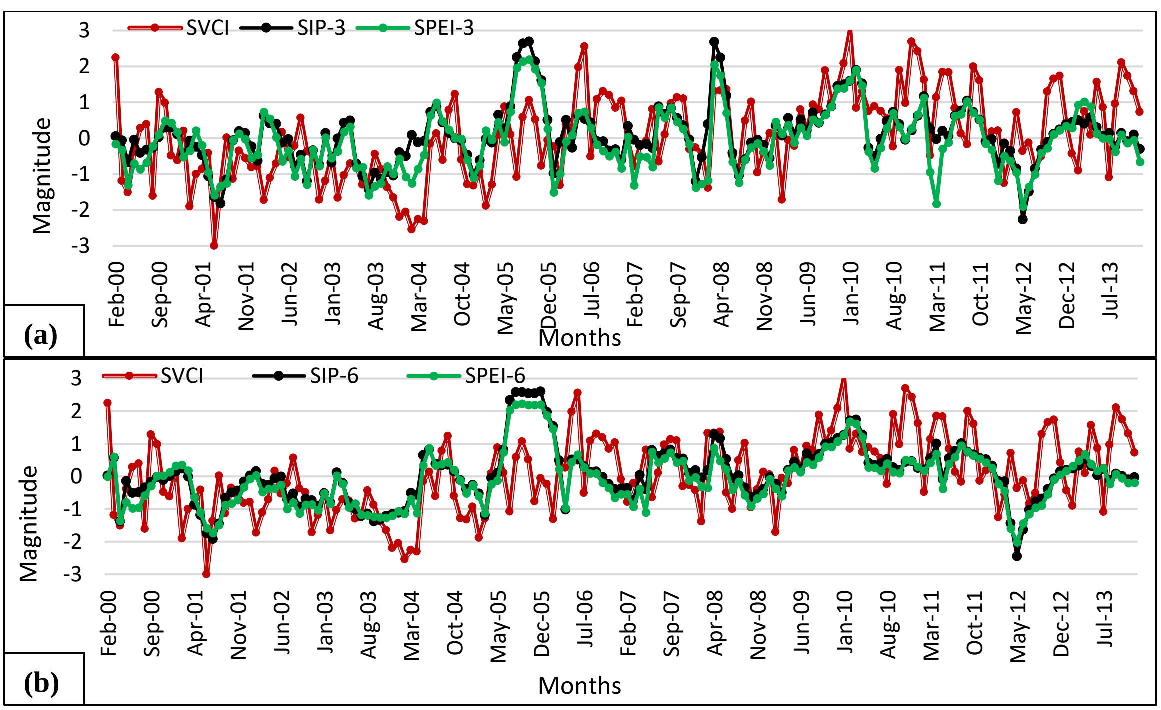


Figure 5.14. Comparison of SVCI with a) 3 and b) 6-month SPI and SPEI

5.4.4 Groundwater drought characteristics and its propagation from meteorological drought

Groundwater drought in the Ghataprabha river basin was assessed through SGI for all 59 wells. It was difficult and unfeasible to present groundwater drought for all the wells of the basin. Since all the wells are grouped into three clusters based on similar water-level fluctuation, a typical well from each cluster was selected as a representative well of a respective cluster. Therefore, a typical well from each cluster was selected as representative well from that cluster and results of analysis of these wells are presented and discussed further. The representative well from each clusters was chosen in such a way that, the selected wells represent different aquifer systems and different climatic zones of the study area. The selected wells from each cluster are demarcated with black circles (Figure 5.15) in the K means clustering background and named as C1, C2 and C3 for the wells of Cluster1, 2 and 3 respectively.

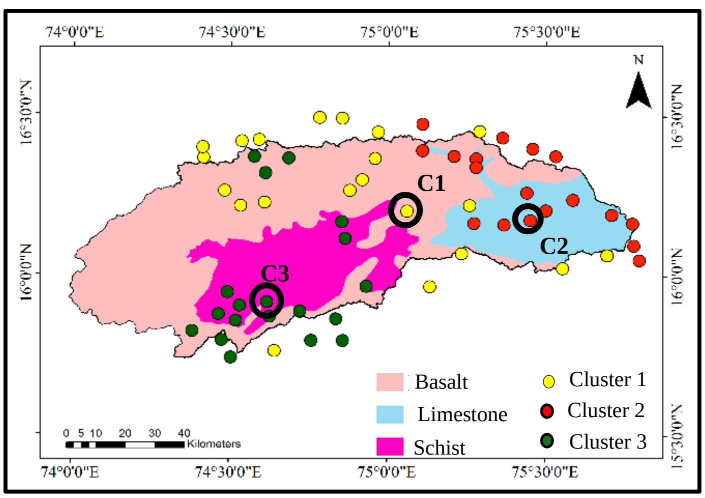


Figure 5.15. Representative wells of Cluster 1,2 and 3

SGI was calculated for representative wells of each cluster and compared with the widely used meteorological indices (SPI and SPEI), at different time scales (3, 6,9,12 and 24 month). Since SPI and SPEI derived at 0.25º×0.25º grid, the SGI of C1, C2, and C3 was compared with the corresponding grid of SPI (SPEI), where the well lay within the grid.

The time series of SGI for the wells are presented in figure 5.16 along with the SPI and SPEI. For C1, extreme groundwater drought episodes were observed during the year 1999-2000 with the average magnitude of -1.81. Similarly, for C2 and C3 the critical drought was observed during the year 2002-2003 and in 1995-1998 with the average magnitude of -1.65 and -1.57 respectively.

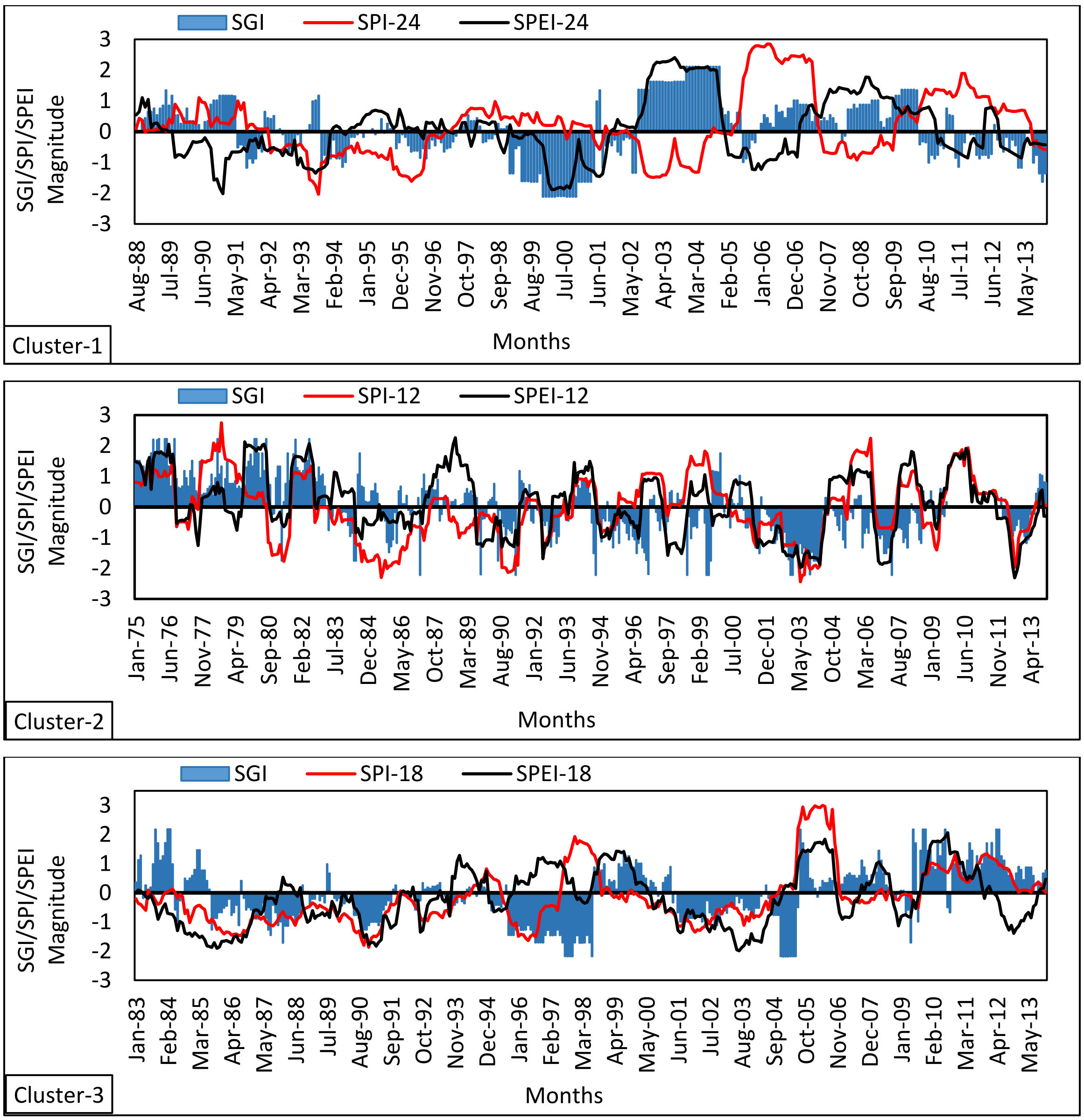


Figure. 5.16. Temporal variation of groundwater drought along with Meteorological drought

SGI drought characteristics (Table 5.6) revealed that the representative well of cluster 2 (C2) experiences highest number of drought events (SGI <0) as compared to C1 and C3. Among them, 72 events were possessing SGI value < -1 with the average severity and duration of -3.48 and 2.32 months respectively, however, maximum average severity was observed in the well of C3 with the average duration of 5.25 months. It can be observed that the well C2 experienced the highest number of droughts with less severity and duration as compared to the wells C1 and C3, which indicates that the number of groundwater droughts are more frequent in C2 with less severity. Number of severe droughts were more in recent decades for C2, which is a clear forewarning for upcoming dreadful drought events in the area of cluster 2.

Table 5.6. SGI drought characteristics

Well Of Cluster	Total Drought Months	Drought Months SGI< -1	Drought Episodes	Average Duration (Months)	Maximum Duration (Months)	Average Severity	Maximum Severity
1	144	43	14	3.10	30	4.74	45.90
2	224	72	31	2.32	18	3.48	29.70
3	196	63	12	5.25	35	7.98	55.11

Variation of SGI with meteorological drought was analyzed with different accumulation period (Q) of SPI and SPEI. It was observed (Figure 5.14) that SGI of C1 and C2 having a similar pattern of SPEI with the optimal accumulation period (Qmax) of 24 and 12, whereas, SGI of the C3 well follows SPI 18. This is because that the C1 and C2 are in the semiarid region where the effect of temperature in the form of PET plays a critical role in the drought formation and SPEI captures this significantly. Likewise, C3 well lays in humid zone, where precipitation dominates over PET and SPI would perform better for capturing the SGI of C3.

The cross-correlation technique was implemented to assess the degree of association between SGI and meteorological drought derived from SPEI and SPI of optimum accumulation period (Qmax) with the lag of 30 months. For C1 well, Maximum positive correlation (0.48) between SGI and SPEI-24 was observed (Figure 5.17 a) at the lag of 6 months. Whereas SGI of well C2 and C3 had highest correlation (Figure 5.17 b and Figure 5.17 c) with SPEI-12 and SPI-18 at the lag of zero and 12 months respectively. It was noted that low to moderate correlations was observed between SGI and meteorological drought indices. This may be because that, the study area is highly potential for agriculture and severe groundwater exploration is taking place for the agricultural purpose, which might be affecting the groundwater levels drastically. Similarly, low (moderate) correlations between SGI and meteorological drought indices were also reported by Motlagh et al. (2016), Loon et al. (2017) and Kumar et al. (2016). Along with meteorological drought, anthropogenic activity, land use/cover, soil characteristics, and underlying hydrogeological properties will also affect the SGI (Bloomfield et al. 2015, Kumar et al. 2016).

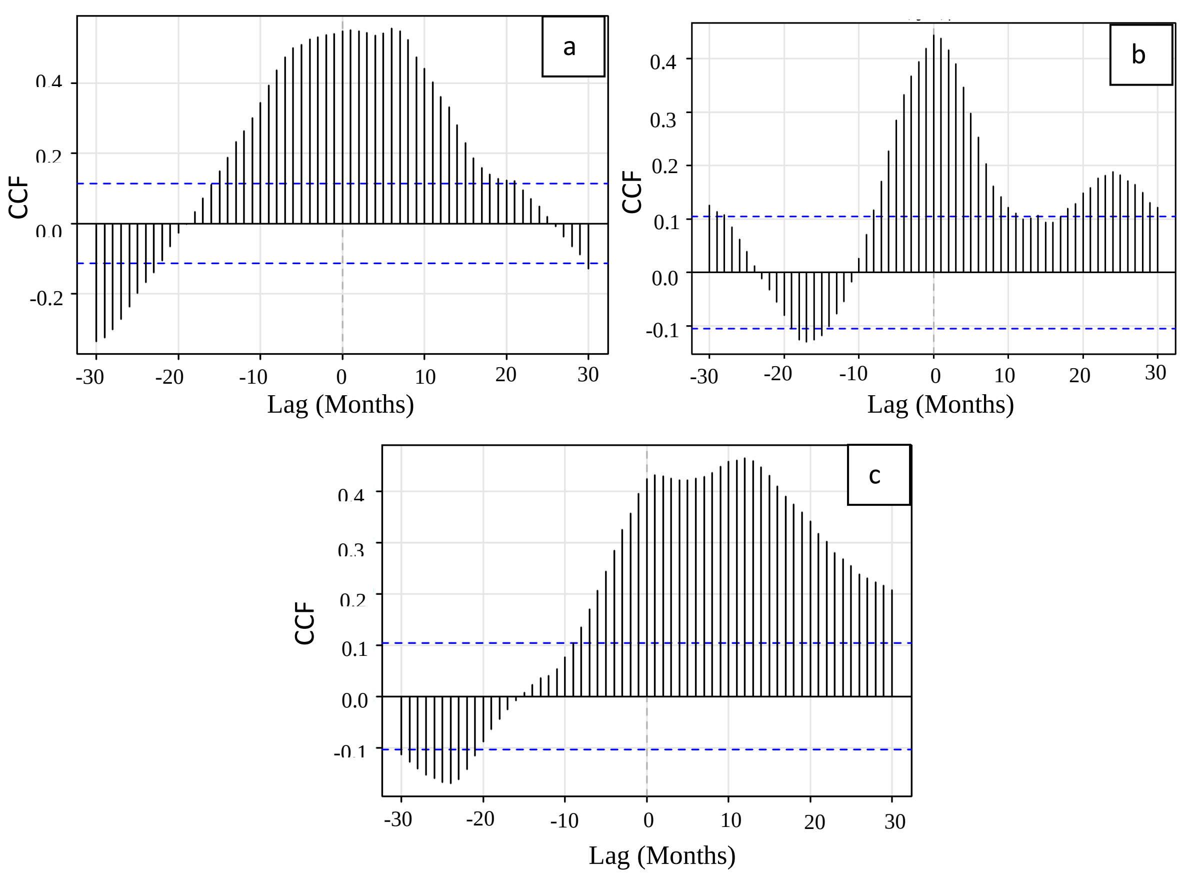


Figure 5.17. Cross correlation between SGI of a) C1 with SPEI-24, b) C2 with SPEI-12, and a) C3 with SPI-18

Further autocorrelation structure of SGI and hydraulic diffusivity values were derived to assess the drought propagation from meteorology to groundwater and to study the role of underlying hydrogeological characteristics on groundwater drought respectively. Significant autocorrelation (Amax) was observed (Figure 5.18) up to the lag of 37, 22 and 26 months for C1, C2, C3 respectively. The threshold of significance for the autocorrelation (0.11) was presented with the blue lines.

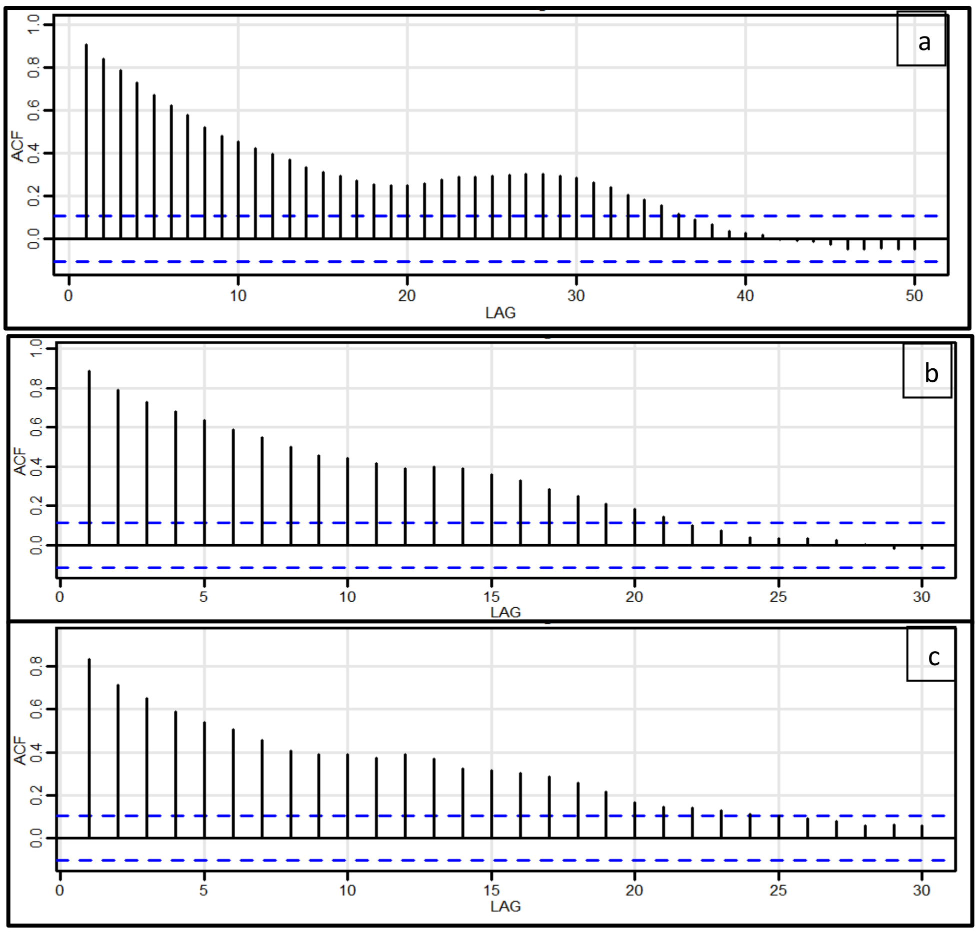


Figure 5.18. Autocorrelation for the wells of a) C1 b) C2 and c) C3

The strong correlation between Amax and Qmax (Figure 5.19) will convey the assured propagation of meteorological drought in the form of Q max into the memory of groundwater drought along with this, good -ve (0.69) correlation between log hydraulic diffusivity (Hd) and Amax was observed. As hydraulic diffusivity (hydraulic stress) propagate faster, the memory (autocorrelation) associated with the SGI decreases, indicating the hydraulic diffusivity being a regional hydrogeological property has its crucial role in the drought propagation from meteorological to groundwater. These results were also ensured by Motlagh et al. (2016), Bloomfield et al (2013, 2015). However, characteristics like LULC, soil properties of the area and interaction of anthropogenic activities need to be evaluate further, for their significance in the drought propagation.

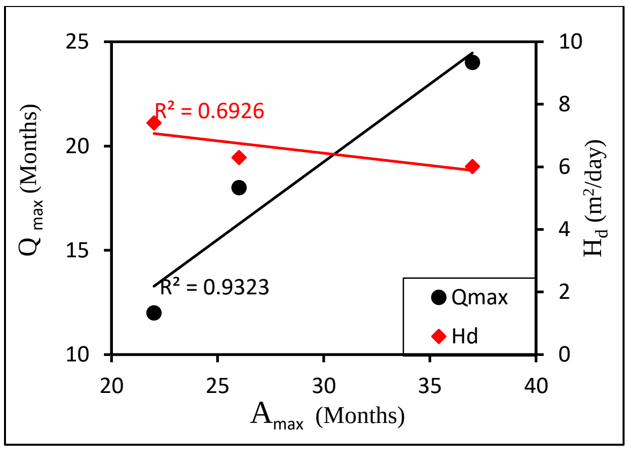


Figure 5.19. Correlation between Amax and Hd with Qmax

In the overall, the results of SGI for clusters 1 and 2 revealed that severe droughts were more frequent in the last two decades and, on the other hand, lower frequency of severe droughts affected the wells of cluster 3. Similar groundwater drought conditions were reported by Ganapuram et al. (2016) and Thomas et al. (2016) in the tributaries of river Krishna and in the Bundelkhand Region of Central India, respectively. The groundwater droughts observed in the representative wells per cluster explain the future risks involved in the agricultural and groundwater sectors of the basin. Recurrent droughts that affected the wells of clusters 1 and 2 during the last two decades strongly convey the message that the underlying aquifer is getting deteriorated from year to year. In addition to frequent droughts, significant decreasing groundwater levels will magnify the drought intensity in the study area.

5.5 CLOSURE

In this chapter drought characteristics of Ghataprabha river basin was characterized by various hydro-meteorological indices at different time scales. During the study period the basin suffered large number of drought episodes leading to adverse effects on streamflow, groundwater levels and agriculture of the basin. The major drought episode as represented by most indices are during 1985-1987, 1995-1996 and in 2001-2004. Remarkable dissimilarities were observed among meteorological drought indices at different climatic regions of the study area and by comparing those it was advocated that SPI or RDI could be considered in the humid region where it experiences high rainfall. However, SPEI can be utilized to capture drought characteristics effectively in the semiarid region, where it was characterized by high PET. Comparison of hydrological drought implicitly highlighted the effect of reservoir regulation on streamflow drought. The VCI showed increasing trend in emphasizing the usage of alternate source of water (mainly groundwater) for the crops in the basin. Hydraulic diffusivity being a local aquifer property showed good agreement with SGI autocorrelation underlines the role of hydraulic diffusivity in the propagation of meteorological drought to groundwater drought. Since semiarid region of the basin is susceptible to recurrent severe meteorological, agricultural and groundwater droughts, a serious attention is required in the planning and management of the water resources of that area and while preparing drought mitigation and preparedness strategies.

CHAPTER 6

COPULA BASED BIVRIATE DROUGHT FREQUENCY ANALYSIS

6.1. INTRODUCTION

Droughts being a multivariate phenomenon, characterized by mutually correlated variables (severity, duration, and intensity) the univariate drought frequency analysis may not provide a comprehensive view of drought events and it may lead to an inadequate and inaccurate drought risk valuation. The traditional multivariate analysis has imitation that the drought variables considered in the multivariate analysis must be derived by the same family of univariate distributions (Tosunoglu and Kisi 2016). Since, each drought event is associated with different severity and prolonged duration following different distributions by nature. Therefore, traditional multivariate methods may not be representing true joint behavior of drought characteristics. In this context, copulas provide a flexible way for constructing the joint distribution to model the dependence structure of multivariate random variables, which is independent of marginal distributions. Application of copulas give great flexibility to select suitable marginal distributions for drought characteristics.

The term Copula is Latin word which means “a link, tie, bond” referring to joining together. Copula is defined as a function that joins multivariate distribution functions to their one-dimensional marginal distribution functions (Shiau, 2006). Copulas are mathematical functions which can model the joint dependency of candidate variables irrespective of the type of their probability distributions. In 1956 Sklar proposed Copula functions and the theorem states that for a joint distribution function H with margins F and G, there exists a copula C for all (x, y) such that

$$H(x,y) = C\,[F(x), G(y)] \qquad 6.1$$

The copula has been extensively used in economics studies however, it gained popularity in water resources or hydrological domain just in the beginning of 20th century. Different copula functions had been applied by the various researchers for the modeling of dependency structure between various hydro climatic variables (Maity and Kumar 2008; Ghosh 2010; Yang and Zhang 2013; Das and Maity 2015; Fan et al., 2017).

Among the different copulas, Archimedean copulas are widely used for bivariate and multivariate frequency analysis of meteorological and hydrological drought (Shiau 2006; Madadgar and Moradkhani 2011; Mirabbasi et al., 2012, Sadri and Burn 2012; Chen et al., 2013; Ganguli and Reddy 2014; Rajshekar et al., 2015; Tosunoglu and Can 2016; Rad et al., 2017; Hangshing and Dabral 2018). However, in Indian sub-continent only countable researchers are deviated their efforts to characterize bivariate nature of different droughts. Therefore, this chapter deals with joint modelling of different drought characteristics and regional bivariate frequency analysis for development of severity duration frequency curves by employing copula theory. In the study, three copulas from Archimedean family (Clayton, Gumbel-Hougaard and Frank) were employed for bivariate modelling of meteorological and hydrological and groundwater droughts.

6.2 METHODOLOGY

Drought characteristics were defined with the help of "Run Theory" (Yevjevich 1967) and to avoid the influence of smaller drought events, the threshold value of -1 was fixed (Rajsekhar et al., 2015, Mirabbasi et al., 2012). The present study considers Drought duration (D) is the period in which the drought index value is less than or equal to -1. Whereas Severity (S) is the cumulative value of magnitude of the index in the drought duration. Inter-arrival time defined in the study is the time interval between the beginning of one drought event to start of another (Madadgar and Moradkhani, 2013). These Drought characteristics (S and D) must have strong dependence structure between them to justify the application of copula for joint modelling.

Before using a copula to obtain the bivariate distribution of drought variables, appropriate marginal distributions must be identified for each drought characteristics. The candidate distributions recommended for drought durations are the exponential distribution (Shiau 2006), lognormal, and Weibull distributions (Wong et al. 2010); whereas for drought severity, the gamma distribution was suggested (Shiau 2006). In the study all four suggested distributions are examined to fit drought severity, and duration. The maximum likelihood method was used for the parameter estimation of these distributions. The best fitted distribution for each drought variable was determined by five Goodness Of Fit (GOF) tests namely Kolmogorov-Smirnov (KS) statistic, Cramer-von Mises statistic (CVM), Anderson-Darling statistic (AD), Akaike's Information Criterion (AIC) and Bayesian Information Criterion (BIC). After selecting suitable marginal distributions for drought characteristics different types of copula can be applied to assess bivariate characteristics of drought.

6.2.1 Application of Copula for drought characteristics

Among the different families of the copula, Archimedean copula had been widely applied in the field of water resources and are also more convenient and easier to construct. Therefore, the present study considers Clayton, Gumbel and Frank copulas osf Archimedean family to develop joint probabilities of meteorological, hydrological and groundwater drought. The summary of the Archimedean copula family is tabulated in table 6.1. Selection of copula depends on the degree of dependency between the variables. Clayton and Gumbel–Hougaard copulas are suitable only for positive dependence, while Frank copula is quite acceptable for both negative and positive dependence structure (Tosunoglu and Can 2016).

Steps involved in fitting Archimedean copula are

1) Calculation of Kendall's τ (Tao) (Mirabbasi et al., 2012).

2) Calculation of copula parameter (θ) using Kendall's τ (Tao).

3) Calculate copula using the relationship between u, v and θ. where u and v are the univariate cumulative distribution functions of random variable x and y respectively.

The performance of these copulas in establishing joint behavior of drought characteristics are tested with the KS (T_n) and CVM (S_n) tests (Maity et.al.2013).

Table 6.1. Description of the bivariate Archimedean copulas considered in the study

Connection function	Expression	Relationships between τ and θ
Gumbel	$C(u,v)=\exp\left(-\left((-In\,\mathrm{u})^{\theta}+(-In\,\mathrm{v})^{\theta}\right)^{\frac{1}{\theta}},\ \theta\in[1,\infty\right)$	$\tau=1-\frac{1}{\theta}$
Clayton	$C(u,v)=\left(u^{(-\theta)}+\mathrm{v}^{(-\theta)}-1\right)^{-\frac{1}{\theta}},\quad \theta\in(0,\infty)$	$\tau=\frac{\theta}{2+\theta}$
Frank	$C(u,v)=\frac{1}{\theta}In\left(1+\frac{\left(e^{-\theta u-1}\right)\left(e^{-\theta v-1}\right)}{e^{-\theta}-1}\right),\quad \theta\in R$	$\tau=1+\frac{4}{\theta}\left(\frac{1}{\theta}\int_0^{\infty}\frac{t}{e^t-1}dt-1\right)$

6.2.2 Joint and conditional probability of droughts

The joint probabilities derived for drought condition provides a crucial information on combined deficit status and will help to derive probabilistic quantities such as return period and associated risk of a drought. In the study joint probability for duration and severity exceeding a certain value is derived for the marginal distributions of drought duration and drought severity by equation (Shiau 2006)

$$P(D\geq d,S\geq s)=1-F_D(d)F_s(s)+C\left(F_D(d),F_S(s)\right) \qquad 6.2$$

where, $F_D(d)$ and $F_S(s)$ are the univariate cumulative distribution functions of duration and severity respectively and $C\left(F_D(d),F_S(s)\right)$ is copula function for $F_D(d)$ and $F_S(s)$. Along with the joint probability, conditional probabilities will add valuable information for assessment of regional drought risk. The conditional probability can be derived for two cases 1) Drought severity distribution given that drought duration exceeding a certain threshold d′ (Equation 6.3) and 2) The drought duration given that drought severity exceeding a certain threshold s′ (Equation 6.4). The respective equations for conditional probabilities (Shiau, 2006) of the case 1 and 2 are given by

$$P(S\geq s|\mathrm{D}\geq d')=\frac{F_S(s)-C\left(F_D(d'),F_S(s)\right)}{1-F_D(d')} \qquad 6.3$$

$$P\left(D \geq d \middle| S \geq s'\right) = \frac{F_D(d) - C\left(F_D(d), F_S(s')\right)}{1 - F_S(s')} \qquad 6.4$$

6.2.3 Joint and conditional return periods of droughts

Joint and conditioned returned period for drought characteristics can be derived for two cases each. Joint return period can be estimate for case a) Duration (D) or Severity (S) exceeding a certain duration (d) or severity(s) respectively (D≥d or S≥s). b) Both Duration (D) and Severity (S) exceeding a certain duration (d) and severity (s) respectively (D≥d and S≥s) and these cases are denoted by Ta and Tb respectively. Similarly, conditional return period can also be expressed for case A) Conditional return period of drought duration at given severity S ≥ s. B) Conditional return period of drought severity at given duration D ≥ d and these conditions are represented as $T_{D|S}$ and $T_{S|D}$ respectively. The equations of joint return periods and conditional return periods are also obtained form (Shiau, 2006). The joint return periods for case Ta and Tb can be calculated by the equation 6.5 and 6.6 respectively.

$$T'_{DS} = \frac{E(L)}{P\left(D \geq d \ or \ S \geq s\right)} = \frac{E(L)}{1 - C\left(F_D(d), F_S(s)\right)} \qquad 6.5$$

$$T_{DS} = \frac{E(L)}{P\left(D \geq d, S \geq s\right)} = \frac{E(L)}{1 - F_D(d) - F_S(s) + C\left(F_D(d), F_S(s)\right)} \qquad 6.6$$

where, E(L) is expected inter arrival time defend as a time period between the beginning of a drought and the beginning of the next drought.

The equations for the conditional return periods for $T_{D|S}$ and $T_{S|D}$ are presented in the equation 6.7 and 6.8 respectively.

$$T_{D|S \geq s} = \frac{E(L)}{\left[1 - F_S(s)\right]\left[1 - F_D(d) - F_S(s) + C\left(F_D(d), F_S(s)\right)\right]} \qquad 6.7$$

$$T_{S|D \geq d} = \frac{E(L)}{\left[1 - F_D(d)\right]\left[1 - F_D(d) - F_S(s) + C\left(F_D(d), F_S(s)\right)\right]} \qquad 6.8$$

6.3 RESULTS AND DISCUSSION

6.3.1 Bivariate characteristics of meteorological drought

Bivariate frequency analysis of meteorological drought has been carried out for different climatic regions of the basin by considering drought characteristics (severity and duration) obtained from 3-month SPI (Humid and sub-humid region) and SPEI (Semiarid region). Different distributions are fitted to drought severity (Figure 6.1) and durations (Figure 6.2) of each region. The results of GOF statistics suggests, lognormal distribution fits best for duration of both semiarid and sub humid regions while, Gamma and Weibull distributions are fitting good for the severities of semiarid and sub humid regions, respectively. However, severity and duration of humid region follows exponential distribution. The parameters of best fit distributions of severity and durations are given in the table 6.2.

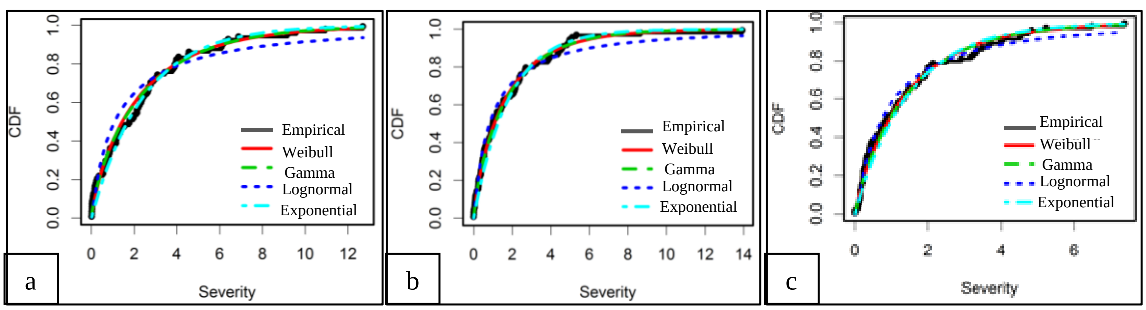


Fig. 6.1 Marginal distributions for severity of a) Semiarid b) Sub-humid and c) Humid region

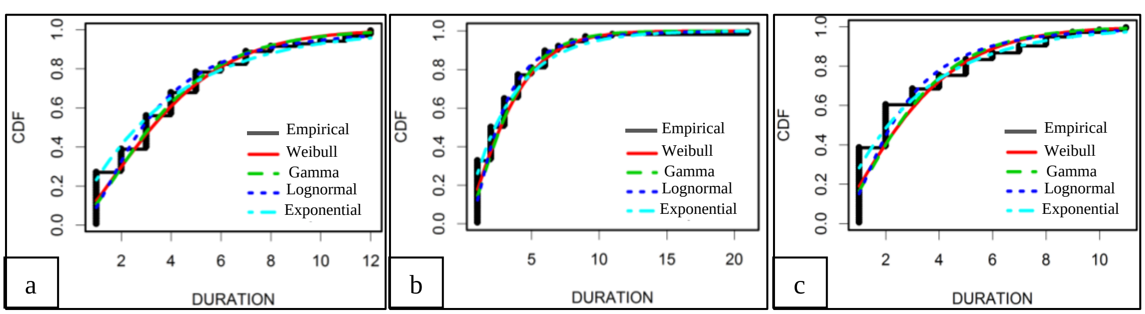


Fig. 6.2 Marginal distributions for duration of a) Semiarid b) Sub-humid and c) Humid region

Table 6.2. Parameters for the best fitted distribution of meteorological droughts

Climatic Regions	Index	Drought Characteristics	Best fit Distribution	Parameters
Semiarid	SPEI	Severity	Gamma	shape = 0.73, rate = 0.30
		Duration	Lognormal	meanlog = 1.04, sdlog = 0.78
Sub-Humid	SPI	Severity	Weibull	shape = 0.83, scale = 1.65
		Duration	Lognormal	meanlog = 0.89, sdlog = 0.76
Humid	SPI	Severity	Exponential	rate = 0.67
		Duration	Exponential	rate = 0.53

6.3.1.1 Application of bivariate copula for meteorological droughts

Preceding to application of the bivariate copulas, it is important to examine dependence structure between the drought characteristics. In this study, Pearson's (r) and Kendall's (τ) correlation coefficients were applied for to check the dependency between severity and duration. The test results indicated that there is a statistically significant positive dependence between the drought characteristics for all the climatic regions of the study area (Table 6.3). However, the Pearson coefficient represent only a linear dependence and therefore it may not be useful for heavy-tailed variables. It can be strongly affected by outliers. On the other hand, the Kendall (τ) can describe a wider class of dependencies and shows resistance to outliers (Klein et al., 2011). Hence, the Kendal's correlation might be more appropriate to describe dependence structure between drought characteristics.

Table 6.3 Dependence structure between meteorological drought characteristics

Index (Region)	Pearson's (r)	Kendall's (τ)
SPEI-3 (Semiarid region)	0.88	0.76
SPI-3 (Sub Humid region)	0.93	0.77
SPI-3 (Humid region)	0.85	0.70

Since there is significant positive association between the drought characteristics of all region and they are well fitted by different distributions, the copula functions are employed to model the joint distribution. In this study, families of Archimedean copula namely, Clayton copula, Gumbel copula and Frank copula were considered. KS test statistics (T_n) and CVM test statistics (S_n) are facilitated to identify the performance of the copulas. The best fit copula was selected in such a way that the calculated P value for KS test and CVM test should have higher than the significance level (0.05). Thus the best fit copula in the one which possess high P value and low test statistics (Maity et al., 2013, Ramadas and Govindaraju, 2015). The results of GOF tests showed (Table 6.4), Gumbel copula fits best for both semiarid and humid regions because it has lowest statistics value and highest p value. Similarly, Clayton copula is good for sub humid region

Table 6.4. Results of Goodness of fit for copula of meteorological droughts

Index (Region)	Test statistics and P value	Clayton	Gumbel	Frank
SPEI-3 (Semiarid region)	CVM test	0.037	0.02	0.031
	KS test	0.63	0.50	0.473
	CVM (p. value)	0.41	**0.78**	0.57
	KS (p. value)	0.31	**0.66**	0.77
SPI-3 (Sub Humid region)	CVM test	0.03	0.04	0.03
	KS test	0.48	0.63	0.50
	CVM (p. value)	**0.59**	0.23	0.42
	KS (p. value)	**0.72**	0.19	0.59
SPI-3 (Humid region)	CVM test	0.05	0.01	0.03
	KS test	0.603	0.38	0.56
	CVM (p. value)	0.32	**0.97**	0.66
	KS (p. value)	0.50	**0.97**	0.37

6.3.1.2 Joint and conditional probabilities of meteorological droughts

Joint probability contour plots for drought characteristics were plotted for each region and are portrayed in Figure 6.3. These graphs will convey the chances of occurrence of both severity and duration together exceeding a certain value. In the other way higher the exceedance probability less the chances of occurrence of drought.

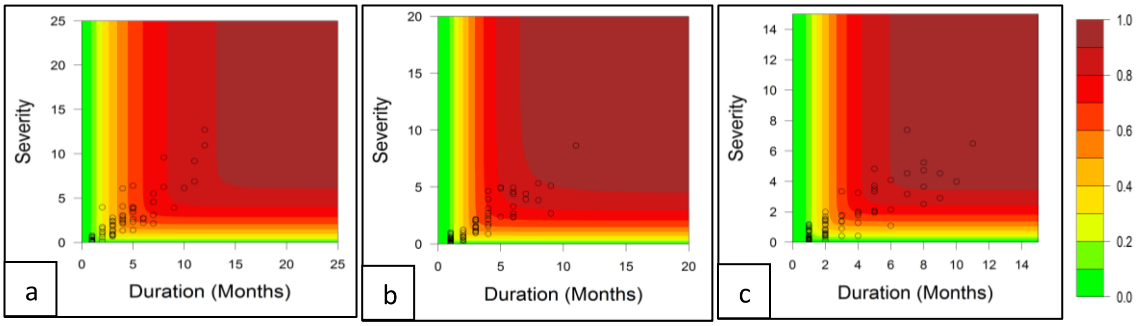


Fig. 6.3 Joint probability of meteorological drought for a) semiarid b) sub humid and c) humid region. The color scale given at right side of figure indicates joint probability ranges.

For example, probabilities of drought duration exceeding five months with the severity more than five is 0.35, 0.1,0.08 for semiarid, sub humid and humid region respectively. Which reveals that, semiarid region of the basin is having high probability (0.35) of occurrence of drought with duration and severity exceeding a certain value. Similarly, conditional joint probabilities are also derived to understand the chances of occurrence of drought severity given that the drought duration exceeds a certain threshold d' and the drought duration distribution given that drought severity exceeds a certain threshold s' were reported for each region in figure 6.4 and 6.5 respectively. In a water resources management, along with joint probability, it is equally important to evaluate conditional probabilities of drought duration (or severity) given drought severity (or duration) of a certain threshold value (d' or s'). These conditional probability plots are useful in water-supply management systems, where one determines if the drought duration given severity exceed certain thresholds, to activate a drought contingency plan. For instance, exceedance probability for drought duration less than 5 months given a specific severity exceeding 5 for semiarid, sub-humid and humid region are equal to 0.08, 0.30 and 0.42 respectively. Similarly, exceedance probability for drought severity less than 5 given a specific duration exceeding 5 months for semiarid, sub-humid and humid region are equal 0.4, 0.62 and 0.75 respectively.

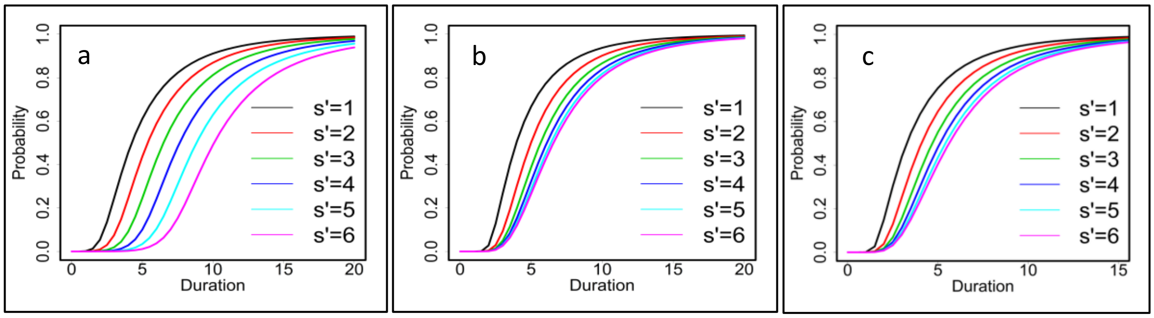


Fig. 6.4. Conditional distribution of Drought duration given severity exceeding a certain value, s' for a) semiarid b) sub humid and c) humid region.

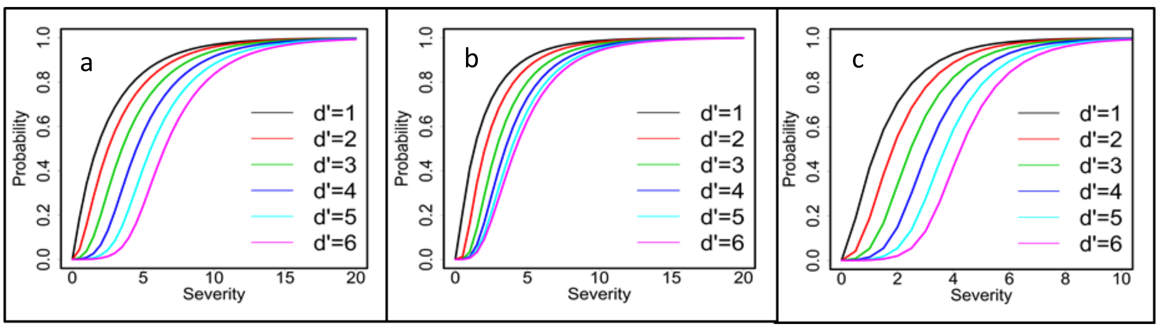


Fig. 6.5. Conditional distribution of Drought severity given drought duration exceeding a certain value, d' for a) semiarid b) sub humid and c) humid region

6.3.1.3 Joint and conditional return periods of meteorological droughts

The joint return period contours of 5, 10, 25, 50, and 100 years for the case Ta and Tb are derived with help of marginal distribution and best fitted copula. The results give a good level of differences in all the climatic regions. The inter arrival time which was calculated to derive joint return periods are 1.76, 1.90 and 2.02 years for semiarid, sub-humid and humid regions respectively. Since different combinations of the correlated drought severity and duration can occur in the same period, the return periods are shown using the contour lines. The contour plots for joint return periods of each region for the Ta and Tb cases are portrayed in figure 6.6 and 6.7 respectively. From the contour plots of case Ta (Figure 6.6) it was observed that the semiarid region experience frequent drought of high severity and high duration as compared to humid and semiarid regions.

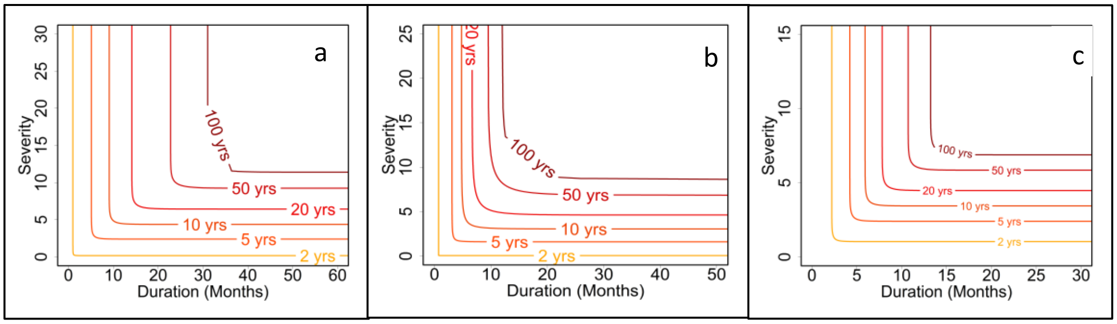


Fig 6.6. Joint return period of duration and severity for case Ta of a) semiarid b) sub humid and c) humid region.

For example, drought severity ≥ 5 or drought duration ≥ 10 months has return period approximately 10 years in semiarid region. However, the same condition was experienced by sub-humid and humid region with the return period of 20 and 25 years respectively. The similar observation was noted for the case Tb also (Figure 6.7). From the contours of case Tb, it was observed that drought of severity ≥ 5 and duration ≥ 5 months will appear once in 16 years in semiarid region whereas in sub humid and humid it will take nearly 35 and 95 years to reappear respectively. From the results of Ta and Tb it was noted that return periods of drought for the case Tb are high as compared to the case Ta. This is obvious that the chances of occurrence of drought severity and duration exceeding a certain value will be always less compared to occurrence of drought severity or duration exceeding a value.

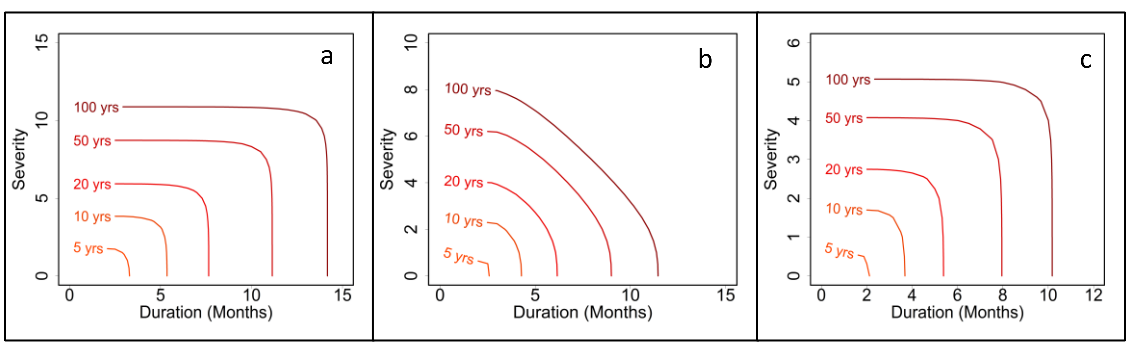


Fig 6.7. Joint return period of duration and severity for case Tb of a) semiarid b) sub-humid and c) humid region

Similar to conditional joint probabilities, conditional joint return periods are also derived for all the three regions for $T_{D|S}$ and $T_{S|D}$ cases. Contours obtained from conditional joint return periods for $T_{D|S}$ and $T_{S|D}$ cases for all the regions were depicted in figure 6.8 and 6.9

respectively. These graphs shows that the conditional return period increases when the values of drought variables increase. From the results of conditional joint return periods it was noted that return periods of drought duration (severity) given severity (duration) are less in semiarid region compared to humid and sub-humid regions. In the overall, bivariate frequency analysis for meteorological droughts for each region conveyed that droughts of high severity with prolonged duration are frequent in semiarid region as compared to other two regions. These results emphasize the risk of upcoming droughts in semiarid region.

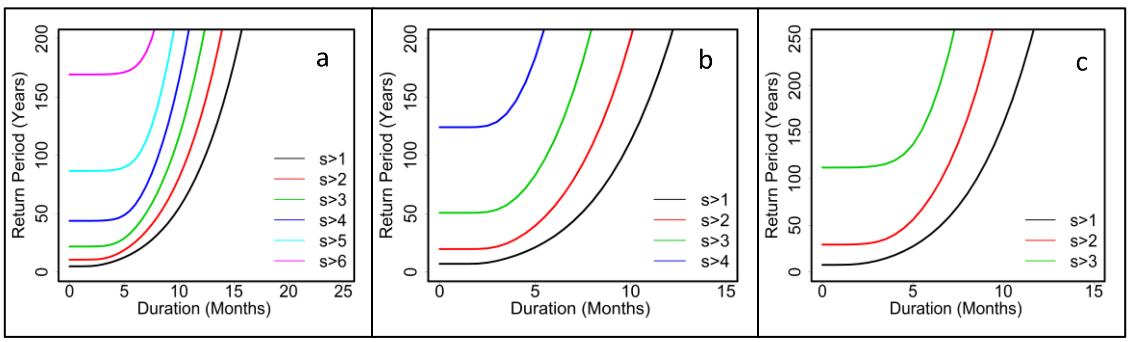


Fig. 6.8. Conditional joint return periods of case $T_{D|S}$ for a) semiarid b) sub humid and c) humid region

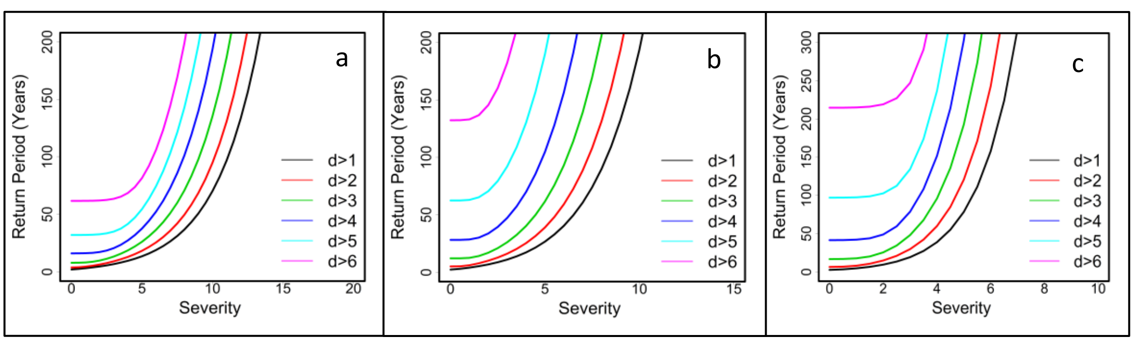


Figure 6.9. Conditional joint return periods of case $T_{S|D}$ for of a) semiarid b) sub humid and c) humid region.

6.3.2 Bivariate characteristics of hydrological drought

To examine the bivariate nature of hydrological drought for Ghataprabha river basin, the hydrological drought characteristic of SDI-3 was considered. Gamma, Weibull, Lognormal and exponential distributions were checked (Figure 6.10) for their suitability in representing severity and duration of hydrological drought. The results of GOF suggested that the gamma distribution captures both severity (shape=0.66, rate =0.15) and duration (shape=1.97, rate =0.46) of SDI-3 better than other distributions.

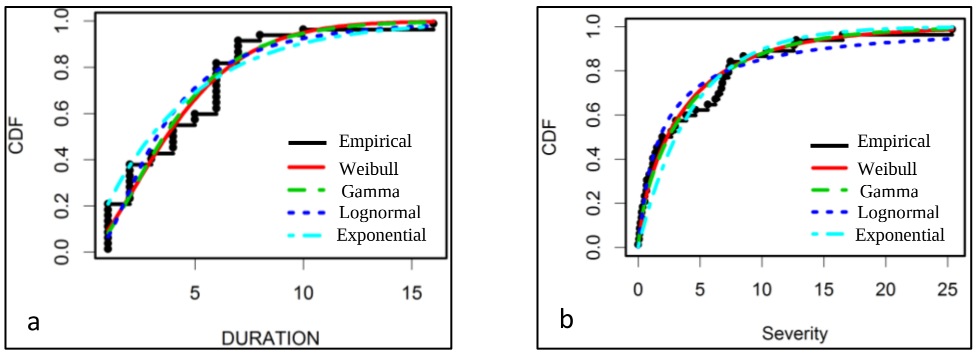


Fig. 6.10 Marginal distribution for a) Severity and b) Duration of SDI-3

After fitting marginal distributions for hydrological drought characteristics, dependence structure between hydrological drought characteristics were examined by Pearson's (r) and Kendall's (τ) correlation coefficients and significant positive correlations (r =0.82 and τ = 0.76) were observed. This indicates hydrological drought characteristics are well correlated and copula can be applied for joint modelling of severity and duration of hydrological drought. Performance statistics (S_n and T_n) of Archimedean copulas applied to study the bivariate nature of hydrological drought indicated Frank copula is better (Table 6.5) for modelling severity and duration of hydrological drought of the basin.

Table 6.5. Results of Goodness of fit for copula of hydrological drought

Index	Copula Family	S_n		T_n	
		p Value	Test Statistics	p Value	Test Statistics
SDI-3	Clayton	0.81	0.022	0.57	0.522
	Gumbel	0.75	0.026	0.22	0.598
	Frank	**0.650**	**0.022**	**0.770**	**0.417**

6.3.2.1 Joint and conditional probabilities of hydrological drought

To understand the combined occurrence of severity and duration of hydrological drought, joint and conditional probabilities are derived and resulting contours are presented in figure 6.11. These are useful in evaluating the water-supply capability and needed auxiliary water resources during severe droughts for a specific water– supply system. For example exceedance probability of severity 5 and duration of 5 month is 0.65 (Figure 6.10). In other words joint probabilities of severity ≥ 5 and duration ≥ 5 months is 0.35. Similarly, exceedance probability of drought duration 5 given severity 5 is 0.1 and exceedance probability for its convers case is 0.19.

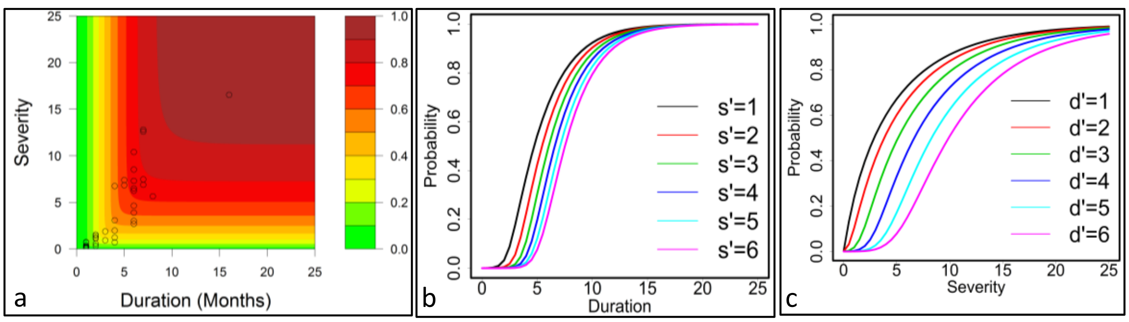


Fig. 6.11. Probabilities of hydrological drought a) Joint probability b) Conditional probability of drought duration given severity exceeding a certain value, s' and c) Conditional probability of drought severity given drought duration exceeding a certain value, s'

6.3.2.2 Joint and conditional return periods of hydrological drought

Similar to meteorological drought return periods, hydrological drought return periods can also be derived in two ways. One is the joint return periods for drought characteristics and the other one is the conditional return periods for drought characteristics. The contour lines of joint return periods of hydrological drought for the cases Ta and Tb are presented in figure 6.12. From the case Ta it was observed that smaller drought duration (less than 5 months) or severity (less than 5) are more prominent in the basin which is also evident from conditional return periods (Figure 6.13)

For instance, in the joint return period of case Ta, drought duration and severity less than 5 has return period less than two years. Similarly in conditional return period of case $T_{S|D}$ it was noticed that severity for given duration > up to four months has return period less than 5 years. The results of hydrological droughts conveyed that the basin experience frequent droughts of smaller severity with lesser duration.

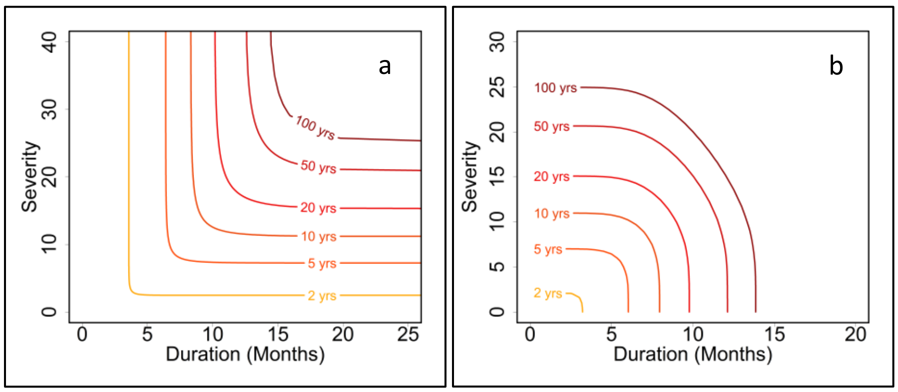


Fig. 6.12. Joint return periods of hydrological drought for case a) Ta b) Tb

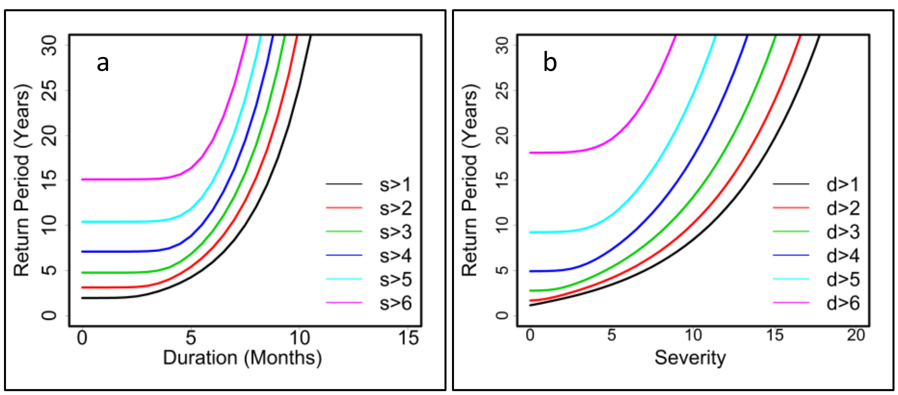


Fig. 6.13. Conditional joint return periods for hydrological drought of case a) $T_{D|S}$ b) $T_{S|D}$

6.3.3 Bivariate characteristics of groundwater drought

The groundwater drought characteristics obtained from the SGI of the wells C1, C2, and C3 are used in the bivariate assessment of groundwater drought. Severity and duration of SGI of each well possessed strong inter dependency among them (Table 6.6) which justifies the application of copula for joint modelling of drought characteristics of SGI.

Table 6.6 Dependence structure between groundwater drought characteristics

Well	Pearson's (r)	Kendall's (τ)
C1	0.97	0.95
C2	0.98	0.96
C3	0.98	0.96

Four distributions namily Weibull, Gamma, Lognormal and Exponential were selected to fit drought duration (Figure 6.14) and severity (Figure 6.15) obtaintained from SGI for the representative wells of each clusters. Based on the results of GOF it was noted that the severity and duration of SGI for the well C1 and C2 follows lognormal distributions. Whereas the severity of the well C3 ensures Weibull distribution while lognormal distribution befits with the duration. Parameters of best fitted distributions were presented in table 6.7.

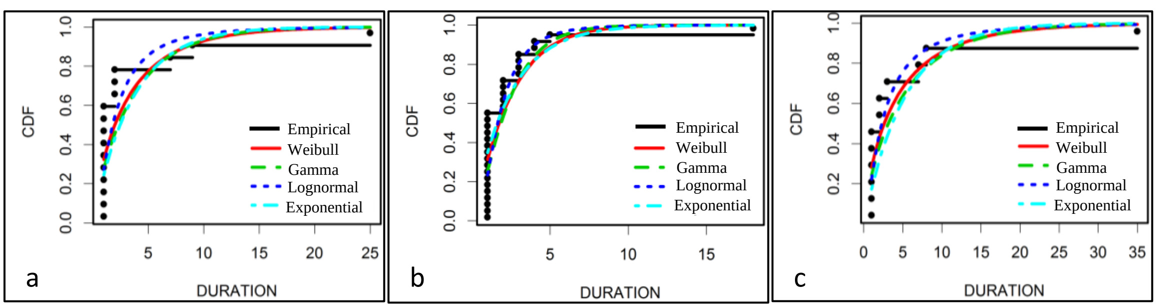


Figure 6.14. Marginal distribution of duration of SGI for a) C1 b) C2 and c) C3.

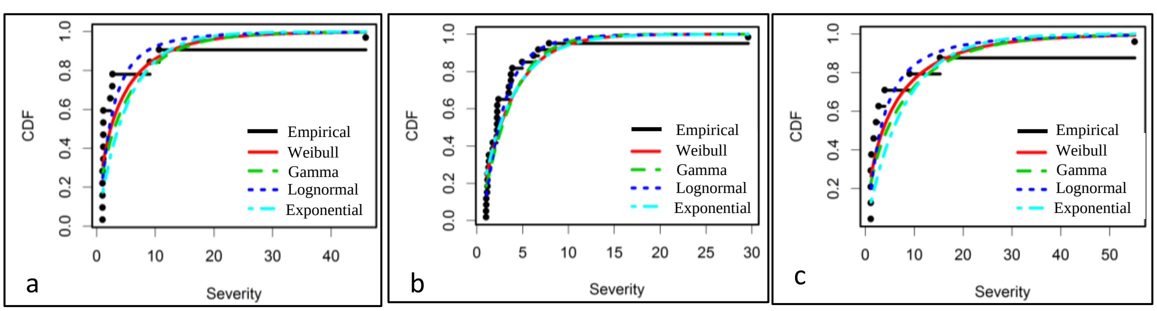


Figure 6.15. Marginal distribution of severity of SGI for a) C1 b) C2 and c) C3.

Table 6.7. Parameters for the best fitted distribution of SGI

Well of	Drought Characteristics	Best fit Distribution	Parameters
C1	Severity	Lognormal	meanlog = 0.75, sdlog=1.085
	Duration	Lognormal	meanlog =0.59, sdlog=0.96
C2	Severity	Lognormal	meanlog = 0.86, sdlog= 0.76
	Duration	Lognormal	meanlog = 0.50, sdlog= 0.690
C3	Severity	Weibull	shape=0.707, scale=5.89
	Duration	Lognormal	meanlog = 0.83, sdlog= 1.09

In the study families of Archimedean copula namely, Clayton copula, Gumbel-Hoggard copula and Frank copula were considered for joint modelling of SGI characteristics. The values of S_n and T_n revels (Table 6.8) Clayton copula has good potential to model the bivariate drought characteristics of the well C1 and C3. Whereas for the well C2, S_n and T_n values are low for Gumbel copula which indicates that the Gumbel copula performs better for the well C2.

Table 6.8. Goodness of fit test statistics for copula of SGI

Well	Copula Family	S_n		T_n	
		p Value	Test Statistics	p Value	Test Statistics
C1	Clayton	**0.850**	**0.019**	**0.930**	**0.381**
	Gumbel	0.530	0.024	0.570	0.469
	Frank	0.650	0.022	0.770	0.417
C2	Clayton	0.630	0.027	0.700	0.482
	Gumbel	**0.600**	**0.026**	**0.940**	**0.404**
	Frank	0.590	0.026	0.850	0.426
C3	Clayton	**0.710**	**0.016**	**0.600**	**0.431**
	Gumbel	0.150	0.027	0.360	0.472
	Frank	0.520	0.020	0.740	0.380

6.3.3.1 Joint and conditional probability of groundwater drought

Joint exceedance probabilities of severity and duration of SGI for the wells (C1, C2 and C3) of each cluster are portrayed in figure 6.16. These graphs will convey the chances of occurrence of both severity and duration together exceeding a certain value. In the other way higher the exceedance probability lesser the drought frequency. For example, probabilities of drought duration exceeding six months with the severity more than six is 0.75, 0.82,0.60 for the wells C1, C2 and C3 respectively which reveals that high severity and high duration droughts are more frequent in the C1 and C3 wells whereas, it is comparatively less for the well C2. Similarly, conditional probabilities are also derived to understand the chances of occurrence of drought duration given that the drought severity exceeds a certain threshold s' and the drought severity given that drought duration exceeds a certain threshold d' were reported for each well in figure 6.17 and 6.18 respectively. The conditional probability of severity and duration of SGI is necessary for better management of groundwater resources because it provides information on the encounter probability of two conditions. For instance, exceedance probability for drought duration less than 5 months given a specific severity exceeding 5 for C1, C2 and C3 wells are equal to 0.42, 0.65 and 0.42 respectively. Similarly, exceedance probability for drought severity less than 10 given a specific duration exceeding 5 months for C1, C2 and C3 wells are equal to 0.62, 0.50 and 0.0.2 respectively.

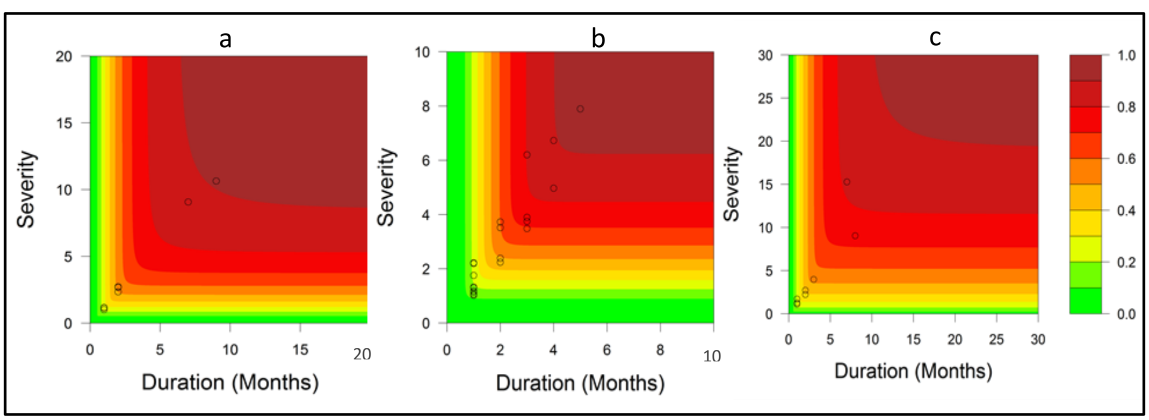


Figure 6.16. Joint probabilities of severity and duration for SGI of a) C1 b) C2 and c) C3. The colour scale at the right side of the figure indicates the probabilities.

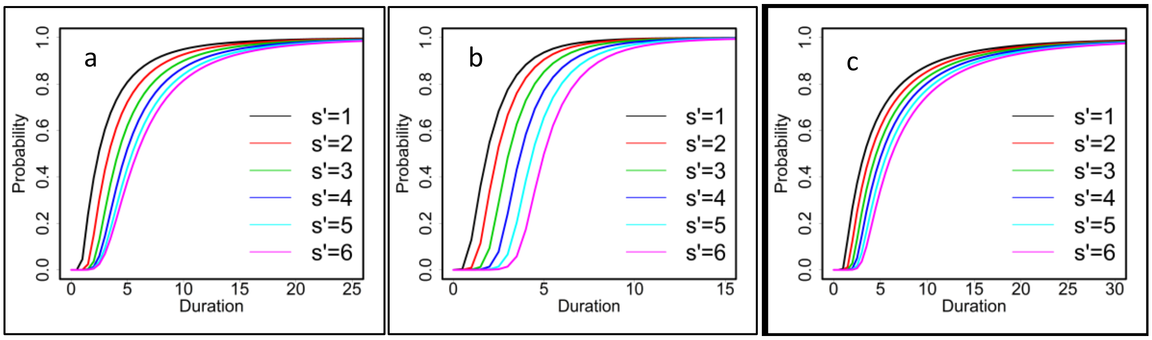


Fig. 6.17. Conditional probability of SGI Drought duration given drought severity exceeding a certain value, s' for a) C1 b) C2 and c) C3 well.

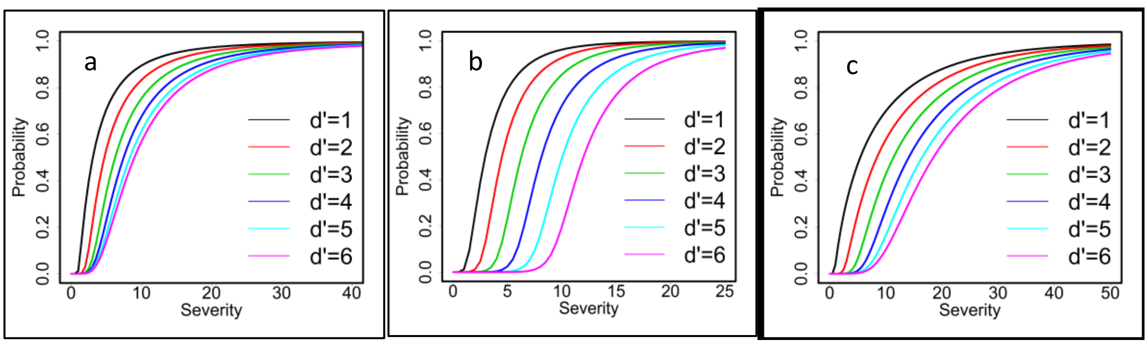


Fig. 6.18. Conditional probability of SGI Drought severity given drought duration exceeding a certain value, d' for a) C1 b) C2 and c) C3 well.

6.3.3.2 Joint and conditional return periods of SGI

In this study joint return period of SGI was calculated for the wells of each cluster with the respective best fit copula for various return periods(2, 5, 10, 20, 50, 100 and 200 years). From the contour plots of case Ta (Figure 6.19) it was observed that SGI with high severity or high duration are more frequent for the wells of C1 and C3 whereas, less severe or smaller duration droughts are more often in the C2 well. For instance, joint return period for drought duration of 10 months or severity 10 may appear once in 6 and 2 years for C1 and C3 wells respectively while, that will happen ones in 25 years for the well C2. Similarly, the plots for case Tb (Figure 6.20) will also convey that, the well C1 and C3 possess smaller return periods for high drought duration and high severity as compared to the well C2. From joint return period plots, one can see that the return period for case Tb is higher than that of the case Ta. It is obvious that the probability of occurrence of both duration and severity exceeding a certain threshold is less compared to the probability of occurrence of either drought duration or severity exceeding a certain threshold.

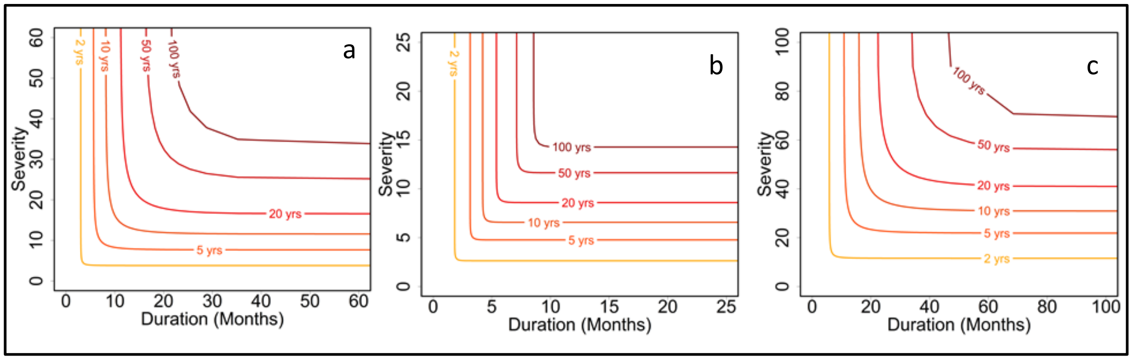


Fig 6.19. Joint Return periods of SGI for case Ta for the wells of a) C1 b) C2 and c) C3

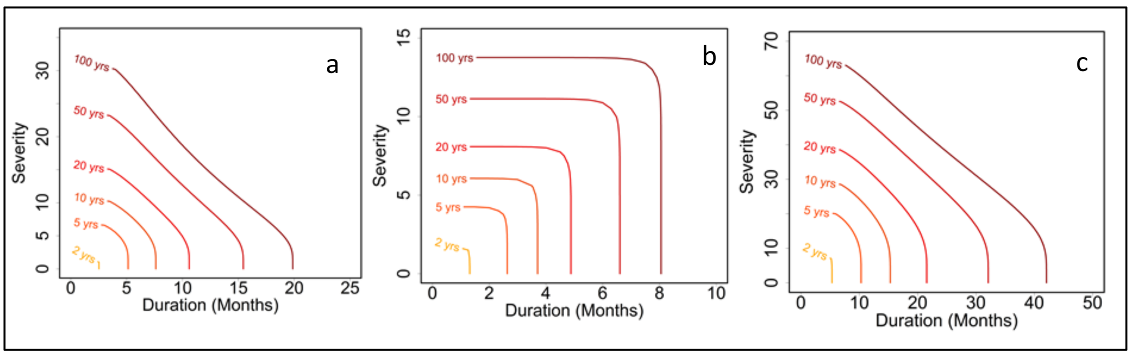


Figure 6.20. Joint Return periods of SGI for case Tb for the wells of a) C1 b) C2 and c) C3

Similar to the joint return period, the conditional return period can be facilitated with the copula, and these analyses are of interest in the drought risk assessment. The conditional return period plots for $T_{D|S}$ and $T_{S|D}$ are presented in figure 6.21 and 6.22 respectively. From these graphs, it can be observed that the return period for drought duration for given severity ($T_{D|S}$) is high for the well C2 in comparison with the wells C1 and C3. Similarly, the conditional return period of drought severity given drought duration ($T_{S|D}$) revealed that severe droughts are less often for the well C2 as compared to the wells C1 and C3. For example, the conditional return period of drought severity $S \geq 5$ conditioned on drought duration $D \geq 5$ months are nearly equal to 30 and 8 years for the wells C1 and C3 respectively, while it is more 150 years for well C2.

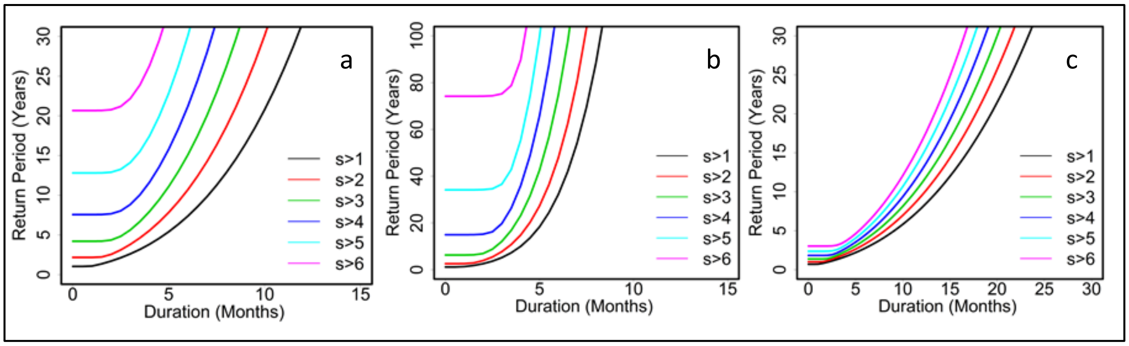


Fig. 6.21. Conditional return period of SGI for case $T_{D|S}$ for the wells of a) C1 b) C2 and c) C3

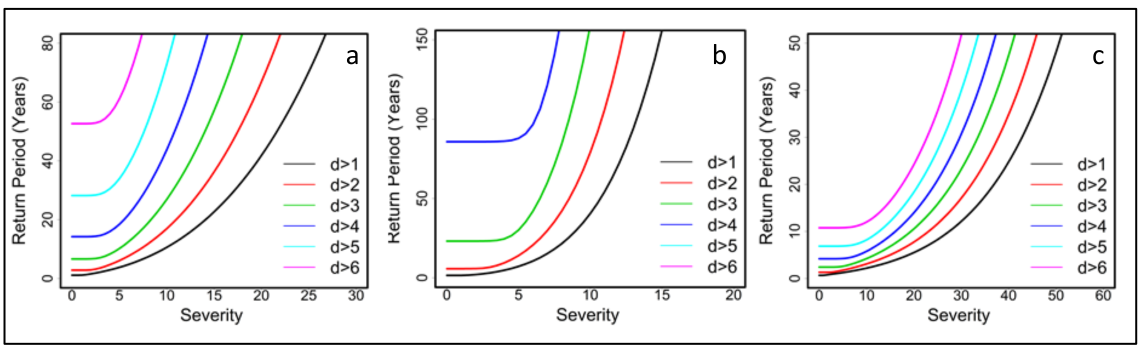


Fig.6.22. Conditional return period of SGI for case $T_{S|D}$ for the wells of a) C1 b) C2 and c) C3

From the results of return period analysis of groundwater, it was noticed that, even though the well C3 lies in the humid region characterized by high rainfall, portrayed frequent severe groundwater droughts compared to the wells of other two clusters which are in the semiarid region. The possible reason for this preposterous behavior of SGI is may be due to the human interface like excess water withdrawal and other hydrogeological characteristics. Whereas the well C2, possess less severe and small duration drought episodes this may be because of, the well C2 is near to the major stream of the river Ghataprabha, and river-aquifer interaction may play a critical role in the frequent groundwater fluctuation and thus affecting the SGI.

6.3.4 Development of Standardized Hydro Meteorological Index (SHMI)

The characterization of drought from a multivariate perspective is required to alleviate the inadequacy of drought characterization from a single aspect, which encompasses a multitude of cases. It can be the development of drought indices by combining or consolidating multiple hydrological variables and drought indices. Combing multiple indicators (drought related variables such as precipitation, soil moisture and streamflow, or drought indices such as PDSI) is important to capture different aspects of drought conditions for efficient drought monitoring and early warning systems. The joint probability (or percentile) characterizes the joint behaviour of two variables X and Y and can be regarded as a measure of the drought condition. The SHMI has been proposed by considering joint probabilities of precipitation and streamflow. The SHMI characterizes the joint deficit of precipitation and streamflow. To assess the integrated behaviour of meteorological and hydrological droughts, first the correlation between precipitation and streamflow time series must be taken into consideration.

The steps involved in the calculation of SHMI are

1) Fitting suitable distribution for precipitation and streamflow.
2) Calculation of joint cumulative probabilities for precipitation and streamflow using appropriate copula.
3) Application of inverse normal function with mean 0 and standard deviation 1 to join cumulative probabilities to obtain SHMI.

The Pearson and Kendall correlation coefficients calculated for precipitation and streamflow showed good association with the correlation of 0.70 and 0.47 respectively. Four distributions (Weibull, Gamma, Lognormal and Exponential) were tested to fit precipitation and streamflow and five Goodness Of Fit (GOF) test, namely Kolmogorov-Smirnov (KS) statistic, Cramer-von Mises statistic (CVM), Anderson-Darling statistic (AD), Akaike's Information Criterion (AIC) and Bayesian Information Criterion (BIC) were calculated to select suitable distributions. The results of GOF conveyed that both rainfall and streamflow followed Gamma distribution.

To derive joint probabilities of precipitation and streamflow, three copulas of Archimedean family were tested and based on K-S and CVM test suitable copula was selected. The P values and test statistics of GOF test showed (Table 6.9), Frank copula is best to derive joint probabilities of precipitation and streamflow.

Table 6.9 Goodness of fit for SHMI

Copula Family	K-S test		CVM-test	
	p Value	Test Statistics	p Value	Test Statistics
Clayton	0.51	0.647	0.74	0.044
Gumbel	0.10	0.860	0.05	0.134
Frank	**0.91**	**0.500**	**0.72**	**0.040**

With the Frank copula, Joint distribution of precipitation and streamflow were derived, and invers normal function with mean 0 and standard deviation 1 is applied to obtain SHMI. Temporal variation of SHMI from 1970 to 2013 is portrayed in the Figure 6.23.

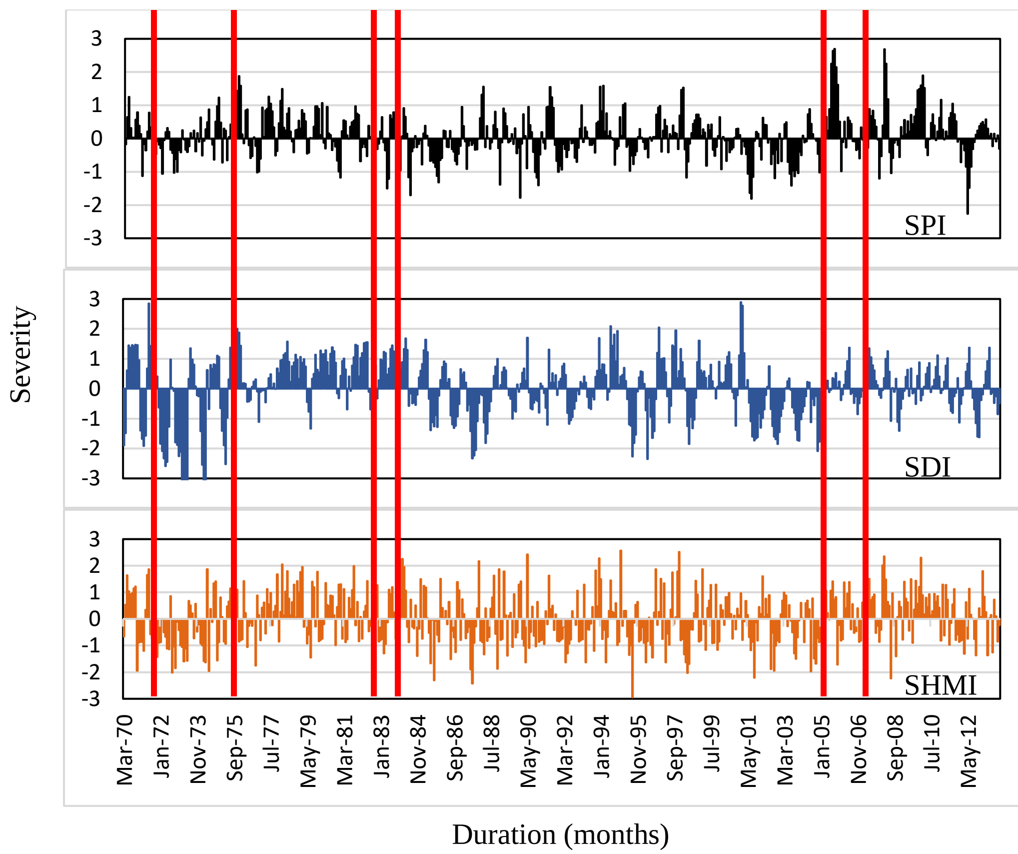


Fig 6.23 Comparison of SHMI with SDI and SPI

The results indicates severe drought during 1971-1973, 1985, 1987, 1995, 2001-2002 and in 2008. By comparing the results of SHMI with SPI and SDI it was observed that, SHMI captured both severe droughts of streamflow and precipitation occurred during the period of 1971-1973 and in 1983 respectively. Thus, SHMI attributes combined effects of precipitation and streamflow to picturize a unique drought scenario of the basin. However, multivariate drought indices are only comparable with the other multivariable indices (Kao and Govindaraju, 2010) and evaluation of socio economic status in the drought period is also required to assess the compatibility of the drought index. The SHMI portrays a logical and near realistic drought situation of the basin, which will be helpful to build an effective drought resilience environment in the basin.

CLOSURE

In this chapter bivariate characteristics of meteorological, hydrological and groundwater droughts has been analyzed by applying different copulas of Archimedean family. An attempt has been made to characterize drought in multivariate perspective by developing SHMI. From the results of bivariate frequency analysis of meteorological drought, it was observed that, droughts of high severity with prolonged duration are frequent in semiarid region as compared to humid and sub-humid regions. These results emphasize the risk of upcoming droughts in semiarid region. The contour lines of joint return periods of hydrological drought conveyed smaller drought duration or severity are more prominent in the basin. The Severity- duration – frequency curves plotted for joint and conditional return period of SGI conveyed that, high severity and high duration droughts are more frequent in the C1 and C3 wells whereas, it is comparatively less for the well C2. The developed SHMI considers combined effects of precipitation and streamflow to picturize a near realistic drought scenario of the basin. Which will helpful to build an effective drought resilience environment in the basin.

CHAPTER 7

ANALYSIS OF DROUGHT CHARACTERISTICS FOR THE FUTURE CLIMATE

7.1. INTRODUCTION

Climate change is one of the most influential topics in the present world causing adverse effect on agriculture, energy, water resources, biodiversity, Socio-economic and ecological condition of a region. Climate change and its potential hydrological impacts are predominantly contributing to the uncertainties in the hydrological cycle. Climatic changes are expected to cause increase in temperatures and changes in precipitation patterns and other climatic variables across the globe (Houghton et al. 1990). Increasing global average temperature will lead to more disturbance in hydrological cycle with changes in precipitation and evapotranspiration patterns. These changes will in turn affect the water availability of an area causing frequent floods and droughts.

Understanding the recurrent behaviour of drought characteristics is complex because of its inherent creeping phenomena and multifaceted nature. Addition to this complexity, changing climate will add further hurdles in it. Therefore, assessment of drought characteristics in future have not only become scientifically necessary, but also economically and socially is valuable (Medina 2010; Zhang et al. 2012). General circulation models (GCMs) are the important tools which provides future climatic projections of a region but are in coarser resolution. Therefore, many Regional Climatic Models (RCM) are evolved to downscale the GCMs to local scale to provide climatic projections at finer resolutions. However, these RCMs comes with the inherent bias (error) within them. Therefor bias correction is essential to these RCMs to represent accurate future climatic information of a region. With the changing climate, providing a comprehensive overview of future drought projections is a vital step in ensuring future water and food security of the region. Therefore, this chapter is devoted to understand the dynamics of drought characteristics with the future climate projections in the Ghataprabha river basin.

7.2 METHODOLOGY

Rainfall and temperature data from four climate models CNRM-CM5, HadCM3, SHMI-RCA4 and REMO were downloaded for the historic (1970–2005) and future projections (2006–2100) from Earth System Grid Federation (ESGF) (https://esg dn1.nsc.liu.se) for RCP4.5 scenario and bias corrected. The bias correction was done for historical and future scenarios using different bias correction methods with the daily gridded rainfall and temperature datasets of 1970-2006. The bias correction methods adopted and compared in this study are the Linear Scaling (LS), Delta Change (DC), Local Intensity scaling (LI), Power Transform (PT), Variance Scaling (VS), and the Distribution Mapping (DM) method. Validation of these bias correction methods was done by comparing the bias corrected future monthly projections with the monthly gridded rainfall and temperature data of 2006-2013. The performance of the bias correction methods is checked by Taylor diagram NSE and Pbias. The bias corrected future rainfall and temperature data from 2014 to 2050 are fed in to the validated SWAT model to derive future streamflows of the study area.

Before assessing future drought characteristics, annual and seasonal trends in future hydro-meteorological variables (rainfall, temperature and streamflow) were analysed to understand the changing pattern of these variables with respect to the past. The non-parametric Mann-Kendell (MK) and Sen's slop tests are employed assess trends in future hydro-meteorological projections. The details of trend tests are already presented in chapter 4. The future (2014-2050) hydro-meteorological drought characteristics of the basin was assessed in different climatic regions of the basin using different drought indices. SPI and SPEI are considered to derive drought characteristics for semiarid and humid/sub humid regions respectively. The future hydrological drought characteristics of the basin were derived for various time scales using SDI. Further, joint behaviour of hydro-meteorological drought characteristics and their return periods were analysed for future periods using copula theory. The detailed methodologies for deriving hydrometeorological drought indices and joint behaviour of droughts were presented in the chapter 5 and 6 respectively.

7.3 RESULTS AND DISCUSSION

7.3.1 Performance of bias correction methods

Even though RCMs were obtained for finer resolution closer to catchment scale contains inherent biases within them. Therefore, the future projections of rainfall and temperature obtained from the four climatic models were bias corrected using different bias correction methods. The results of performances of bias correction method for correcting monthly rainfall of future projections of all the models are portrayed in figure (7.1 and 7.2). The figure 7.1 and 7.2 consists variation of NSC and Pbias value obtained for different bias correction methods for all the stations with the different climatic models respectively.

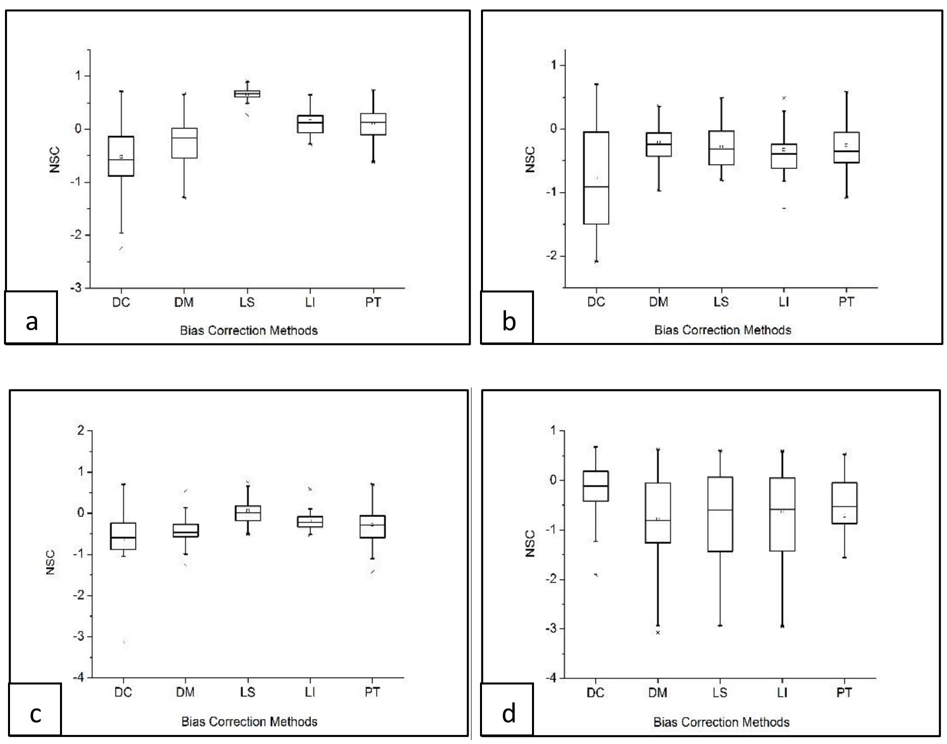


Fig. 7.1 Variation of NSE of all the stations for a) CNRM-CM5 b) HadCM3 c) SHMI-RCA4 and d) REMO

From the figure 7.1 it was observed that, LS method is performing good for CNRM-CM5 and SHMI-RCA4 whereas, DM and DC methods performing good for HadCM3 and REMO respectively. However, LS method for CNRM-CM5 performed better with the highest average NSE value (0.70) comparing to other bias correction method and climatic models. Similarly, from variation Pbias (Figure 7.2). For the REMO model all the methods showed strong positive bias. However, average Pbias of LS method applied for CNRM-CM5 has near to zero proves better performance compared to other bias correction methods and climatic models while correcting the monthly rainfall of all the stations.

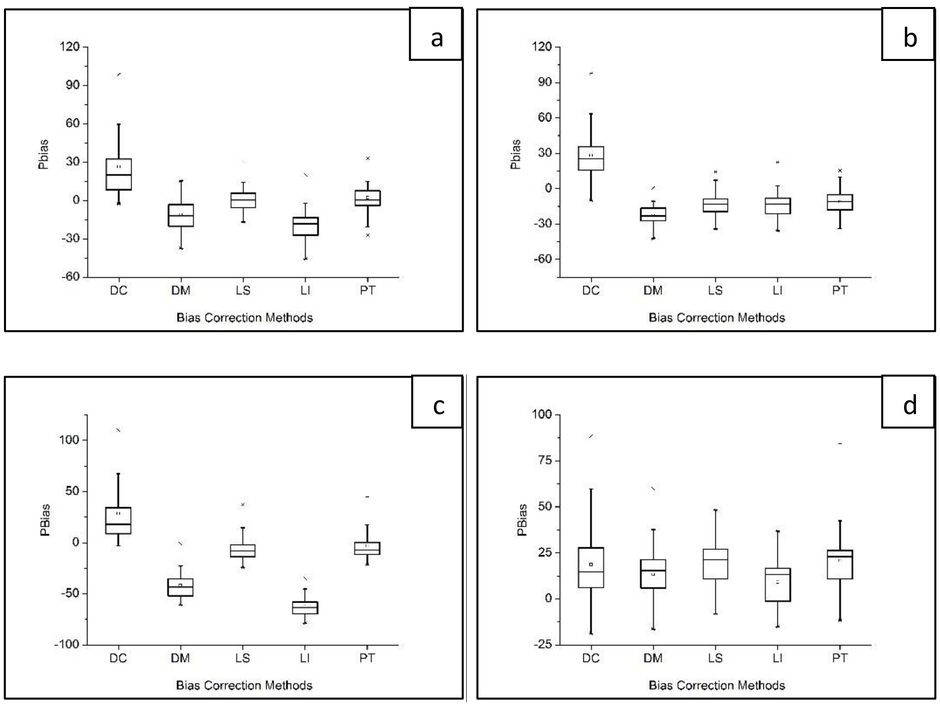


Fig. 7.2 Variation of Pbias of all the stations for a) CNRM-CM5 b) HadCM3 c) SHMI-RCA4 and d) REMO

In addition to NSE and Pbias, compatibility of different climatic models in correcting monthly rainfall are further checked by Taylor diagrams. These diagrams are used to evaluate the degree of association between the modelled and observed data by Pearson correlation coefficient, the root-mean-square error (RMSE) and the standard deviation. The Taylor diagram for bias corrected rainfall of climatic models of semiarid station (C7) with the observed are presented in figure 7.3.

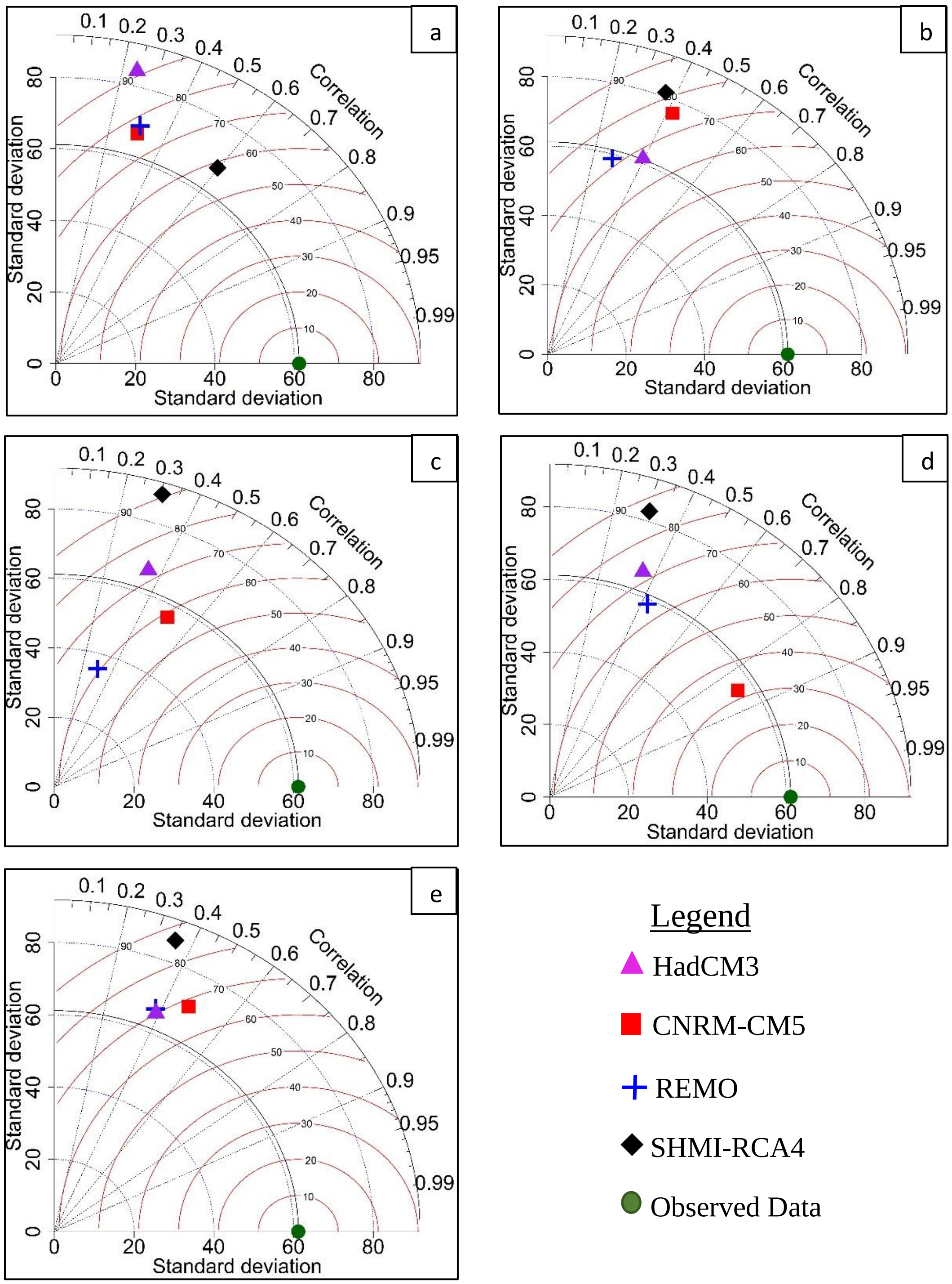


Fig 7.3 Taylor Diagrams for performance evaluation of climatic models with a) DC b) DM c) LS bias correction methods.

The red lines in the Taylor diagram indicate scale of RMSE and blue line joining x and y axies represents range of standard deviation. The line radiating from zero specifies correlation coefficient between observed and corrected rainfall. From the Taylor diagram it was observed that HadCM3 with DM method performs well in correcting standard deviation of the rainfall projections however it has poor correlation with the observed data. However, LS method applied to the rainfall data from CNRM-CM5 has better correlation and low RMSE compared to other models and bias correction methods. The results of NSE, Pbias and Taylor diagram indicates that, LS method applied for CNRM-CM5 model performs better while correcting monthly rainfall data of future scenario.

Since, rainfall projections of CNRM-CM5 with LS method proved to be better for future rainfall, the temperature projections from the same model was considered for the study. The four bias correction methods are applied to correct the future temperature data. The results of performance statistics expressed high average NSE (Figure 7.4 a) for all the bias correction methods indicating all the method have good potential to correct future monthly average temperature data. However, average Pbias (Figure 7.5 a) confirms better performance of VS method compared to other methods.

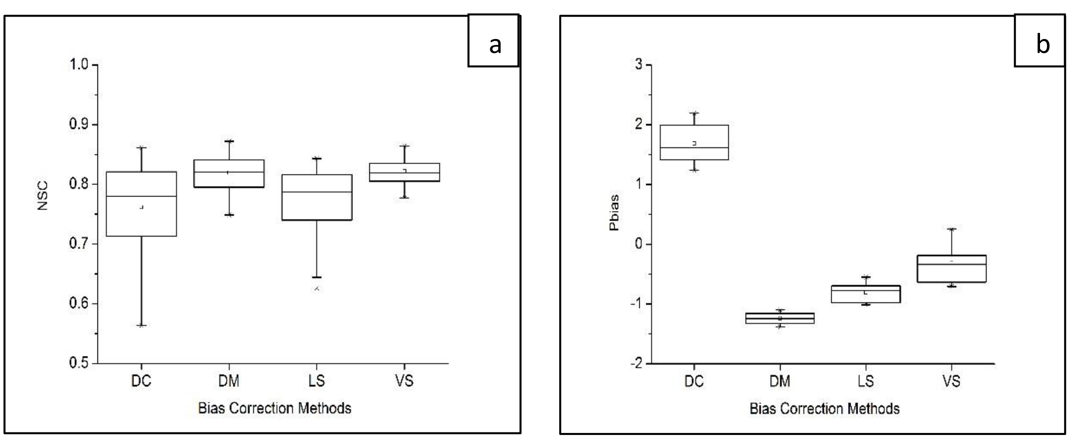


Fig 7.4. Variation of a) NSE and b) Pbias of all the stations for CNRM-CN5 model

7.3.2 Future trends in hydro-climatic variables

Before trend analysis, the bias corrected rainfall and temperature of CNRM-CN5 model from the year 2014 to 2050 were fed in to the validated SWAT model to simulate future streamflows for Ghataprabha basin. The non-parametric MK test along with the Sen's slope test was employed to investigate annual and seasonal trends in bias corrected future rainfall and temperature along with simulated future streamflow.

The result of future rainfall trends (Figure 7.5) showed decreasing trends in monsoon, post-monsoon and annual rainfall. Among them, eight and six stations of the basin are decreasing significantly in annual and post monsoon seasons with the average rate of 9.62 and 2.8-mm per year respectively (Table 7.1). The future rainfall of winter and pre-monsoon season is increasing but are statistically non-significant. Most of the stations in semiarid region experienced significant decreasing trends in annual and post monsoon seasons with the average decrease of 8 mm and 2.8 mm per year respectively. However, it was noted that, no stations in the basin were significant in annual and post-monsoon rainfall for the historical period (1970-2013).

The annual and seasonal average temperature of the basin continued show its significant increasing trends in future period with the average rise of 0.15^0 C per decade. However only winter temperature is non-significant for future period. Along with the rainfall, annual and seasonal streamflows of the basin are also decreasing with the average decrease of 682cusecs/year but are statistically insignificant. In the over all, future trends of rainfall are decreasing with the significant escalation in temperature trends. Most of the station of semiarid region experienced significant decrease in future rainfall which emphasizes that the region will experience more frequent droughts compared to historical period.

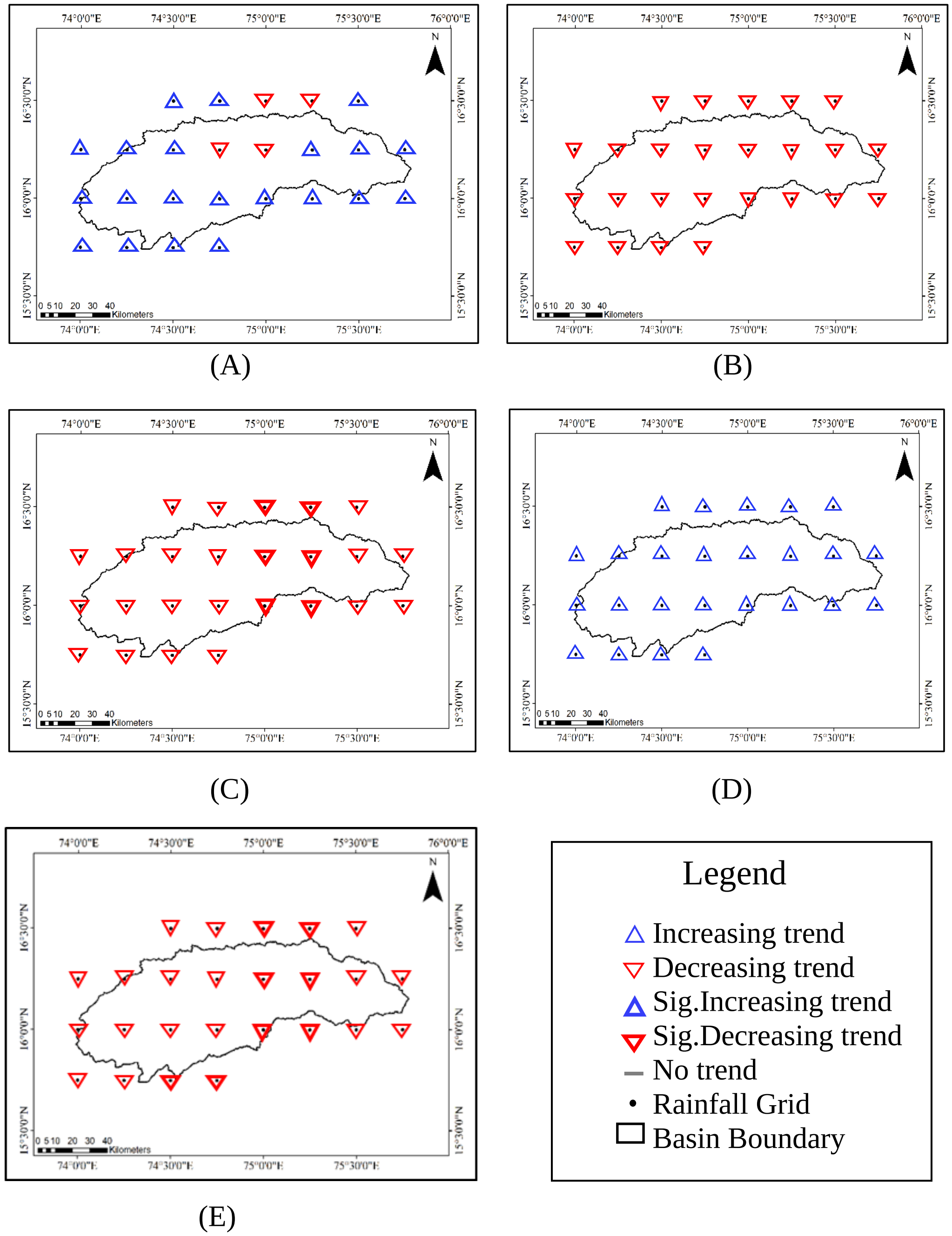


Fig. 7. 5. Future Rainfall trend for A) Pre-monsoon B) Monsoon (C) Post-monsoon (D) Winter (E) Annual timescale

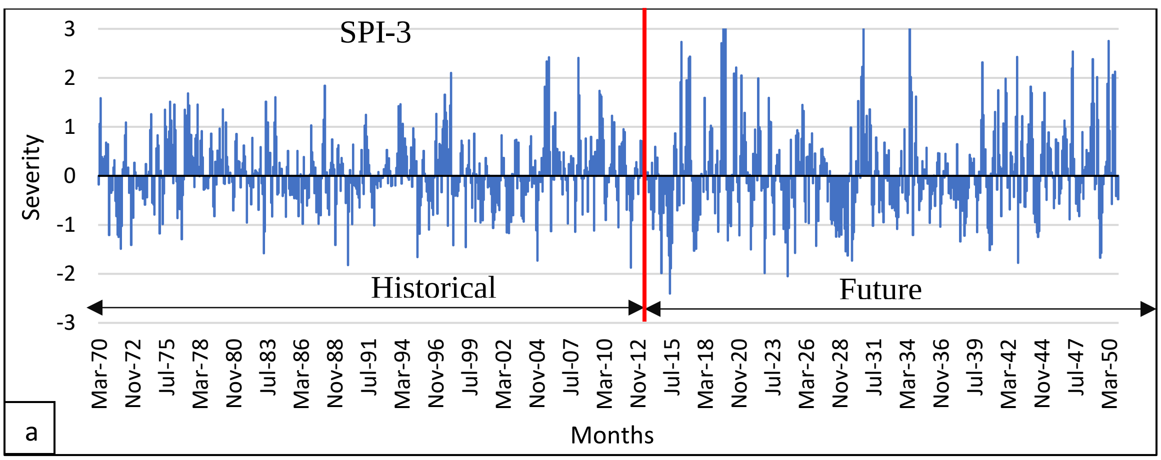
Table 7.1. Future trends in seasonal and annual rainfall

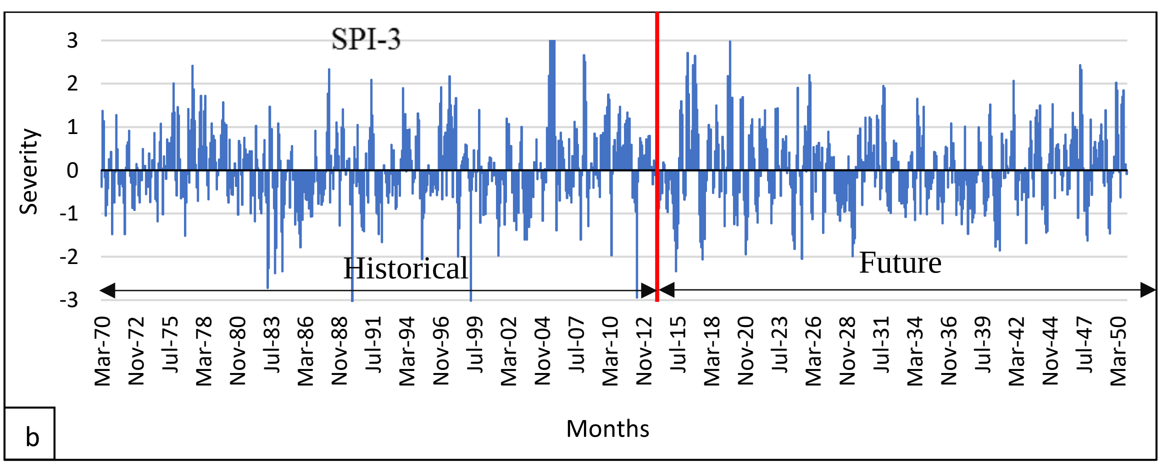
Station ID	Winter		Pre Monsoon		Monsoon		Post Monsoon		Annual	
	p value	Sen slope	p value	Sen slope	p value	Sen slope	p value	Sen slope	p value	Sen slope
A1	0.25	0.02	0.97	0.01	0.7	-15.8	0.5	-1.5	0.40	-32.1
A2	0.10	0.01	0.90	0.25	0.6	-16.0	0.5	-1.4	0.43	-25.6
A3	0.40	0.01	0.83	0.71	0.1	-11.6	0.2	-3.2	**0.03**	**-19.3**
A4	0.47	0.00	0.80	0.62	0.1	-5.3	0.2	-2.9	**0.04**	**-9.79**
B1	0.22	0.02	0.90	0.22	0.7	-4.6	0.5	-1.2	0.32	-15.3
B2	0.11	0.02	0.90	0.22	0.7	-6.1	0.5	-1.4	0.32	-17.3
B3	0.47	0.01	0.83	0.66	0.1	-9.4	0.2	-3.1	0.05	-16.5
B4	0.47	0.00	0.83	0.65	0.1	-4.7	0.2	-2.8	0.07	-8.84
B5	0.31	0.01	0.93	0.07	0.1	-5.6	**0.0**	**-3.8**	**0.02**	**-9.16**
B6	0.24	0.01	0.87	0.10	0.1	-4.9	**0.0**	**-3.7**	**0.02**	**-8.69**
B7	0.93	0.00	0.90	0.05	0.5	-2.1	0.9	0.2	0.24	-5.36
B8	0.90	0.00	0.90	0.04	0.5	-2.2	0.9	0.2	0.21	-5.27
C1	0.18	0.01	0.53	0.59	0.5	-6.5	0.7	-0.8	0.36	-11.9
C2	0.32	0.02	0.53	0.82	0.5	-3.1	0.7	-0.9	0.38	-5.85
C3	0.50	0.01	0.65	0.83	0.2	-3.4	0.2	-2.5	0.08	-7.03
C4	0.56	0.00	0.59	0.70	0.3	-3.1	0.2	-2.3	0.09	-5.64
C5	0.21	0.01	0.90	-0.22	0.2	-3.5	**0.0**	**-3.7**	**0.04**	**-6.69**
C6	0.29	0.01	0.90	-0.26	0.2	-3.8	**0.0**	**-3.7**	**0.04**	**-7.95**
C7	0.50	0.01	0.62	0.25	0.4	-1.8	0.6	-0.6	0.50	-3.14
C8	0.45	0.00	0.68	0.23	0.4	-1.8	0.6	-0.6	0.45	-2.64
D3	0.53	0.01	0.65	0.56	0.2	-3.1	0.2	-2.3	0.10	-7.15
D4	0.52	0.01	0.62	0.55	0.3	-3.5	0.2	-2.0	0.09	-5.78
D5	0.20	0.02	0.87	-0.26	0.2	-3.7	**0.0**	**-4.0**	**0.04**	**-6.67**
D6	0.29	0.01	0.90	-0.23	0.1	-3.9	**0.0**	**-3.9**	**0.03**	**-8.68**
D7	0.45	0.01	0.74	0.17	0.4	-2.0	0.6	-0.8	0.45	-3.12

Note: Bold values indicate significant trend at 95% confidence level

7.3.3 Future characteristics of meteorological and hydrological droughts

Meteorological drought of future period (2014-2050) was assessed in semiarid, sub-humid and humid regions at various time scales. The SPEI and SPI are considered to derive meteorological droughts in semiarid and humid (sub-humid) region respectively. The monthly PET for the future years was deduced using bias corrected rainfall and temperature of the future years. The temperature based Penman-Monteith method (Allen et al. 1998; Paulo et al. 2012; Pandey and Pandey, 2016) was employed for calculation of monthly PET for future. Significant number of droughts were observed from future SPI and SPEI various time scales. Temporal variation of meteorological drought of 3-month time scale for historical and future period is depicted in Figure 7.6.





Cont.,

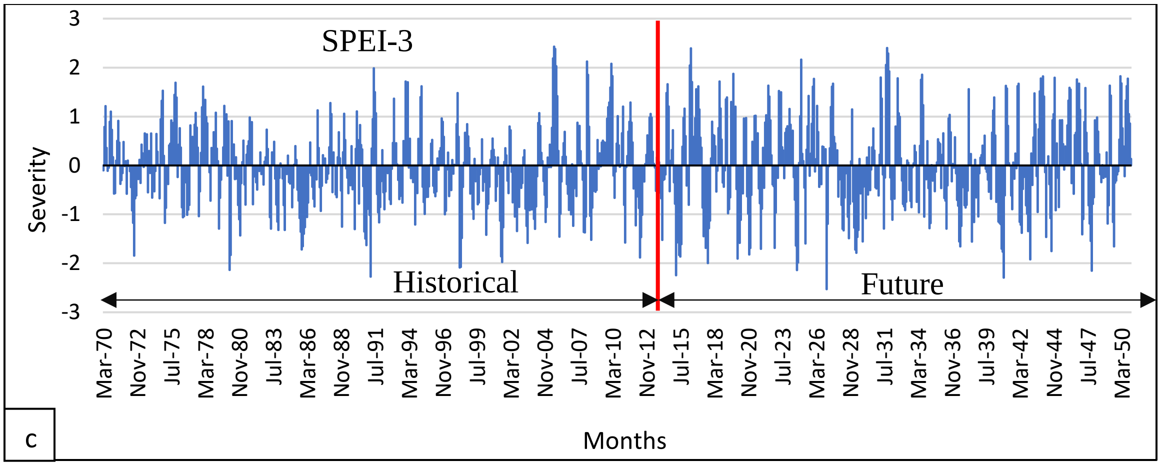


Fig. 7.6. Temporal variation of future drought severity for a) humid, b) sub-humid and c) semiarid regions of the basin

The temporal variation of future meteorological drought (SPI-3) in the humid region showed four extreme drought months, whereas no extremes were recorded in history. Similarly, the sub-humid region portrayed five extreme meteorological drought (SPI-3) months in the future period, whereas the region experienced eight extreme drought months in the historical period. The semiarid region witnessed three and six extreme drought months during historical and future period with SPEI-3. The humid region will experience major drought event during the 2028 -2029 consisting 14 drought months with the average intensity of -1.24.

The sub-humid region will experience three major drought events in the year 2020, 2028-2029 and 2037-2038, which consists average drought duration of four months with the average intensity of -1.1. Likewise, the semiarid region is susceptible to 5 major drought events occurring in the year 2015, 2017, 2028-2029, 2040 an in 2042 however, the drought of 2028-2029 will be the massive event with consisting 16 drought months with the average intensity of -1.2. From figure 7.6 it is interesting to note that, all the regions possessed extreme drought during year 2028-2029 which highlights, that the entire basin will be under extreme drought during that period. By comparing the temporal variation of droughts in humid and semiarid region indicated extreme droughts are more in future period compared to the historical which can be attributed to decreasing rainfall trends and significant increasing temperature trend during the future period. Likewise, meteorological drought in the semiarid region possessed less extreme droughts in future compare to its past however, it was noted that the region experienced more severe droughts in future (61 no.) compared to historical period (56 no.). The meteorological drought characteristics of the future period with different time scales for each climatic region is presented in table (7.2) and it was noted that as the time scale increases, the drought months having duration ≥ 3months are also increasing. The highest number of drought events were observed in SPEI-3 and SPI-6 of semiarid and sub-humid region, whereas, highest severity (sum of SPEI ≤ -1) was observed in all the time scales. These results warn that the semiarid region is even more vulnerable to frequent severe droughts associated with high risk involved in it.

Table. 7.2 Drought characteristics for future period

Climatic region	Time scale	Drought with duration ≥3 months			
		Duration (months)	Events	Severity (-ve sum)	Average severity (-ve)
Humid	3	34	8	44.11	1.33
	6	41	6	57.97	1.41
	12	55	6	76.45	1.39
Sub-humid	3	31	7	47.80	1.54
	6	46	10	69.87	1.51
	12	61	7	89.92	1.47
Semiarid	3	43	10	66.60	1.55
	6	46	9	72.30	1.57
	12	73	7	107.52	1.47

Similar to meteorological drought, hydrological drought characteristics of the basin for the future was studied. The streamflow data (2014-2050) simulated from validated SWAT model was used as input for calculation of SDI of different time scale. The temporal variation of SDI-3 showed 13 extreme drought months in future, whereas, 11 extreme drought months were present in the past. Similarly, SDI-6 and SDI-12 exhibited 9 and 2 extreme droughts in future and 16 and none in the historical period respectively. The major hydrological drought of the basin will occur during year 2038-2041 consist of 36 drought months with the average intensity of -1.35. The result of future SDI-3 highlighted 8 and 11 drought events with the duration ≥ 3 months in future and historical period respectively. Similar observations were made from the SDI-6 and SDI-12. The results of various scales of SDI indicated that the basin will experience slightly more number of droughts in future compared to the past.

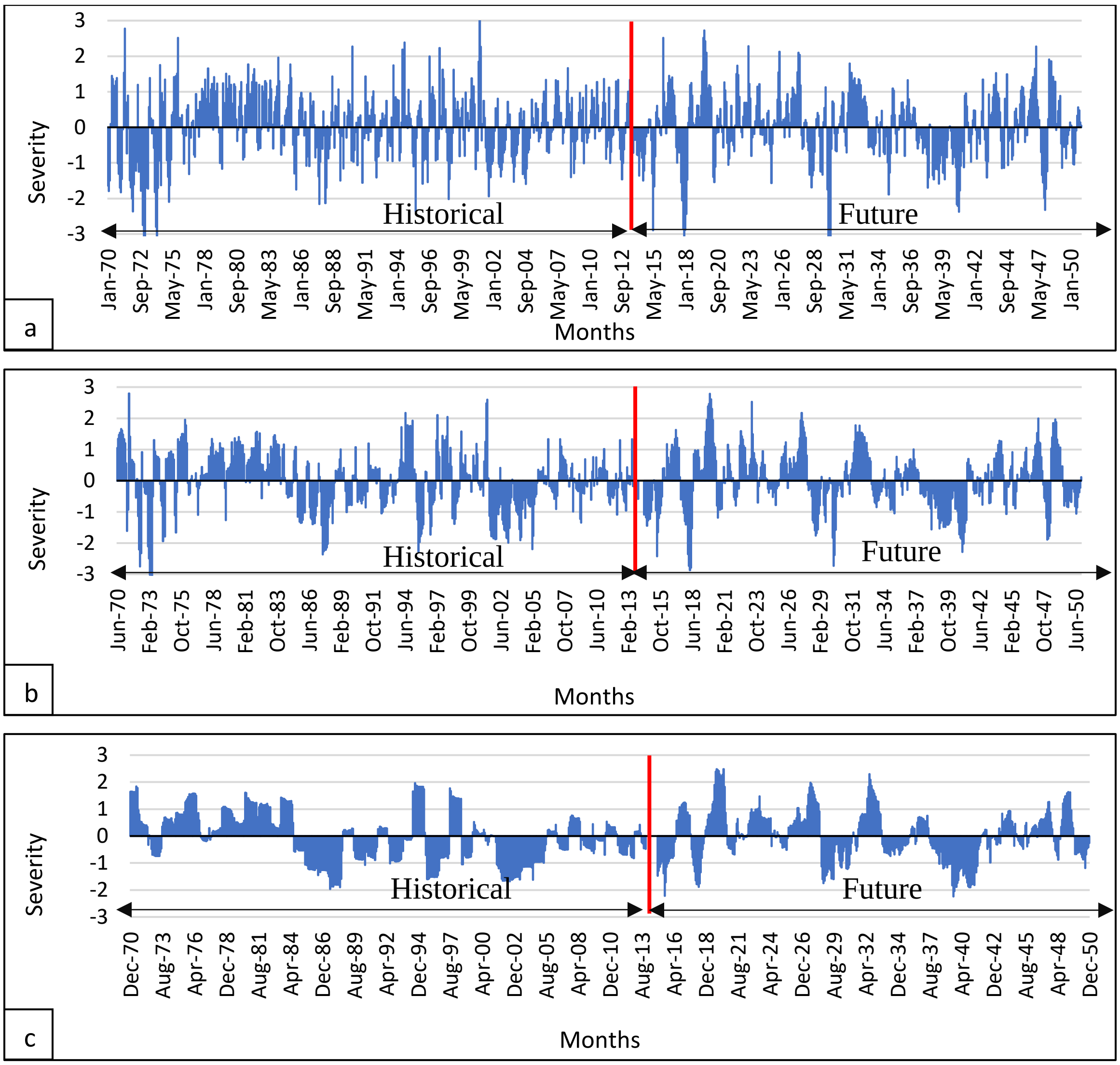


Fig 7.7 Temporal variation of historical and future SDI of a) 3-month b) 6-month and c) 12-month time scale

7.3.4 Bivariate characteristics of future droughts

To understand the future bivariate nature of meteorological drought in different regions of the basin, drought characteristics of 3-month SPEI (for semiarid region) and 3-month SPI (for humid and sub-humid region) were considered. Similarly, drought characteristics of SDI-3 was used to derive joint behaviour hydrological drought of the basin. Before applying copula to drought variables, appropriate marginal distributions must be identified. The results of Pearson's (r) and Kendall's (τ) obtained for severity and duration of all the indices showed significant correlation (>0.7). The Gamma, Weibull, lognormal and exponential distribution are selected to derive marginal of hydro-meteorological drought characteristics. The results of GOF indicated that exponential and gamma distribution fits better for severities of future SPEI-3 and SPI-3 of semiarid and sub-humid region respectively. Whereas, Weibull distribution suits better for representing the future severities of SPI-3 of humid region and SDI-3 of the basin respectively. The future duration of all meteorological and hydrological droughts followed the lognormal distribution. The parameters of the best fit distributions of severity and durations of future hydro-meteorological droughts are given in the table 7.3.

Table 7.3 Parameters of the best fitted distribution of future hydro-meteorological drought characteristics.

Climatic Regions	Index	Drought Characteristics	Best fit Distribution	Parameters
Semiarid	SPEI	Severity	Exponential	rate = 0.34
		Duration	Lognormal	meanlog = 1.04, sdlog = 0.72
Sub-Humid	SPI	Severity	Gamma	shape = 0.74, rate = 0.24
		Duration	Lognormal	meanlog = 1.02, sdlog = 0.86
Humid	SPI	Severity	Weibull	shape = 0.80, rate = 1.97
		Duration	Lognormal	meanlog = 0.85, sdlog = 0.79
-	SDI	Severity	Weibull	shape = 0.73, scale = 3.10
		Duration	Lognormal	meanlog = 0.33, sdlog = 1.78

7.3.5 Application of copula to future droughts

In this study, aforementioned copulas namely, Clayton copula, Gumbel copula and Frank copula are considered to model joint behaviour of future droughts. The performances of these copulas are examined by KS (Tn) and CVM test statistics (Sn). The best fit copula was selected in such a way that the calculated P value for KS test and CVM test should have higher than the significance level (0.05). Thus the best fit copula in the one which possess high P value and low test statistics (Maity et al., 2013, Ramadas and Govindaraju, 2015). The results performance tests of different copulas (Table 7.4) suggested that frank copula suits better for future meteorological drought characteristics of humid region, whereas, the Clayton copula showed its potential to model both the future hydrological drought characteristics of the basin and meteorological drought characteristics of semiarid and sub-humid regions.

Table 7.4 Goodness of fit statistics for copula of future droughts

Index (Region)	Test statistics and P value	Clayton	Gumbel	Frank
SPEI-3 (Semiarid region)	Sn	0.024	0.029	0.032
	Tn	0.445	0.620	0.540
	Sn (p. value)	**0.73**	0.58	0.52
	Tn (p. value)	**0.84**	0.18	0.42
SPI-3 (Sub Humid region)	Sn	0.024	0.025	0.034
	Tn	0.473	0.478	0.549
	Sn (p. value)	**0.72**	0.70	0.39
	Tn (p. value)	**0.73**	0.72	0.26
SPI-3 (Humid region)	Sn	0.027	0.027	0.023
	Tn	0.406	0.480	0.384
	Sn (p. value)	0.60	0.65	**0.76**
	Tn (p. value)	0.81	0.63	**0.89**
SDI-3 (For basin)	Sn	0.022	0.026	0.028
	Tn	0.522	0.598	0.424
	Sn (p. value)	**0.81**	0.75	0.62
	Tn (p. value)	**0.57**	0.22	0.82

To understand the combined occurrence of future severity and duration of meteorological and hydrological drought, the joint probabilities are derived from the respective best fit copula and resulting contours are presented in figure 7.8. The joint probability plots for future drought are crucial to obtain the chances of incidence of both severity and duration together exceeding a certain value. The results of joint probabilities of meteorological and hydrological droughts indicated high joint probabilities compared to historical droughts. For instance, drought duration ≥ five months with the severity more than five is 0.35, 0.35, and 0.18 for semiarid, sub humid and humid region respectively (Figure 7.8). Whereas, the joint probabilities of historical period for same conditions are 0.35, 0.1, 0.08 for semiarid, sub humid and humid region respectively (Figure 6.3). Similar observation was made with the past and future hydrological droughts also.

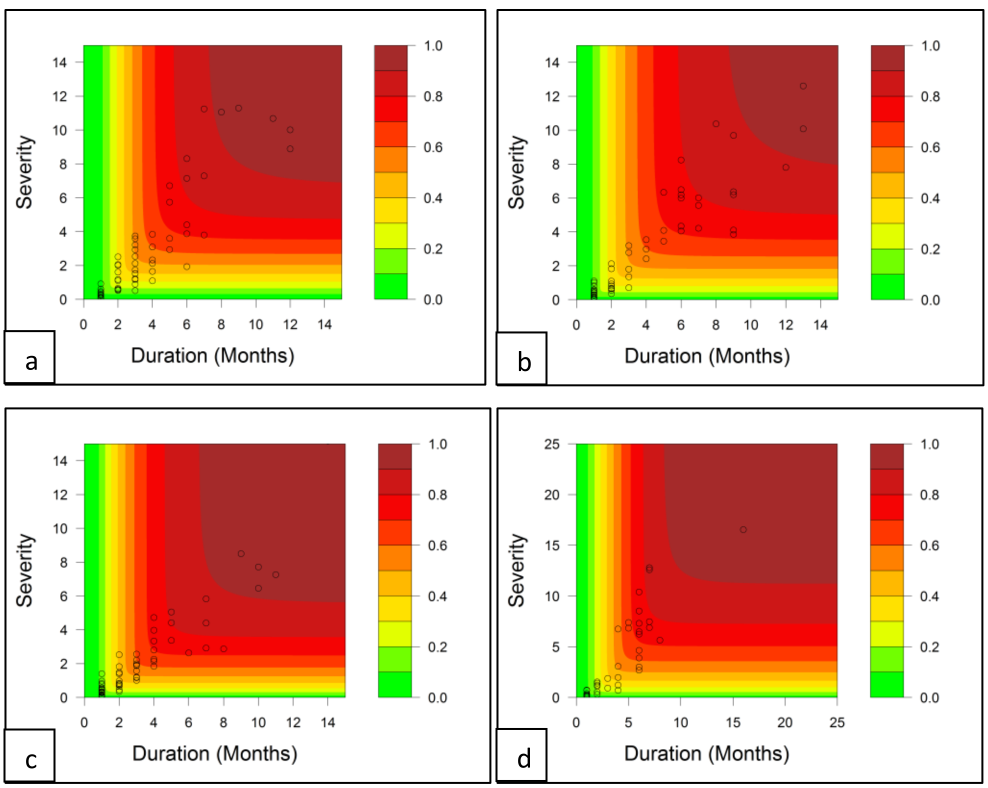


Fig. 7.8. Joint probability of future droughts for a) semiarid b) sub humid c) humid region and d) hydrological drought of the basin. The colour scale given at right side of figure indicates exceedance probabilities

7.3.4 Joint and conditional return periods of future droughts

The joint return period contours of 5, 10, 25, 50, and 100 years for the case Ta and Tb are derived with help of marginal distribution and best fitted copula of future droughts. The contour plots for joint return periods of future droughts with Ta and Tb cases are portrayed in figure 7.9 and 7.10 respectively. From the contour plots of case Ta (Figure 7.9) it was observed that in the future, the semiarid region experiences frequent drought of high severity and high duration as compared to humid and semiarid regions. For example, drought severity ≥ 5 or drought duration ≥ 10 in future has return period approximately 2.5, 5 and 10 years in semiarid, sub-humid and humid region respectively and, these future return periods are less as compared to historical return periods of meteorological droughts. Whereas, the return periods of hydrological droughts are almost same for smaller duration and severity, while the return periods of high severity and duration are less in future compared to historical return periods. For instance, hydrological drought severity ≥ 20 or drought duration ≥ 10 in future has return period approximately 7 years whereas, the same has return period approximately 15 years in the past.

From the contours of case Tb, also highlighted that both meteorological and hydrological droughts are more frequent in future period compared to that of historical. The return period of future meteorological drought having severity ≥ 5 and duration ≥ 5 month are 12, 12, and 20 while it was 16, 35, and 95 in the past. Similarly, hydrological drought of future period having severity ≥ 10 and duration ≥ 10 has return period near to 15 years while it has approximately 20 years in the past. In the overall the results indicate that return periods of future droughts are less compared to historical period which indicated that the basin will suffer more frequent droughts in future compared to the past.

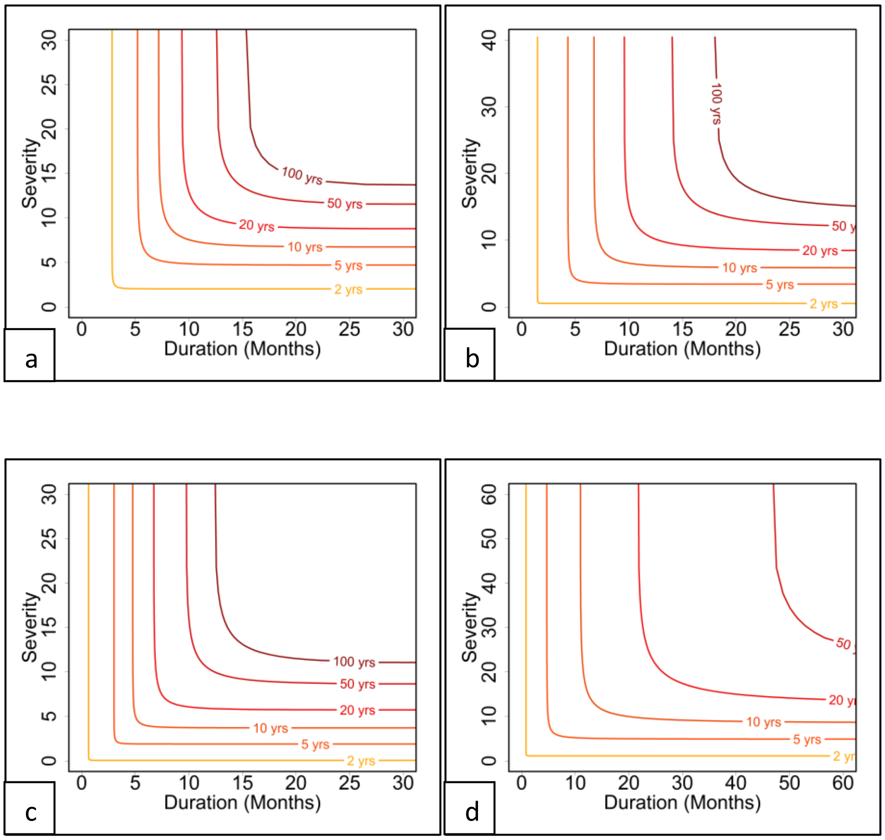
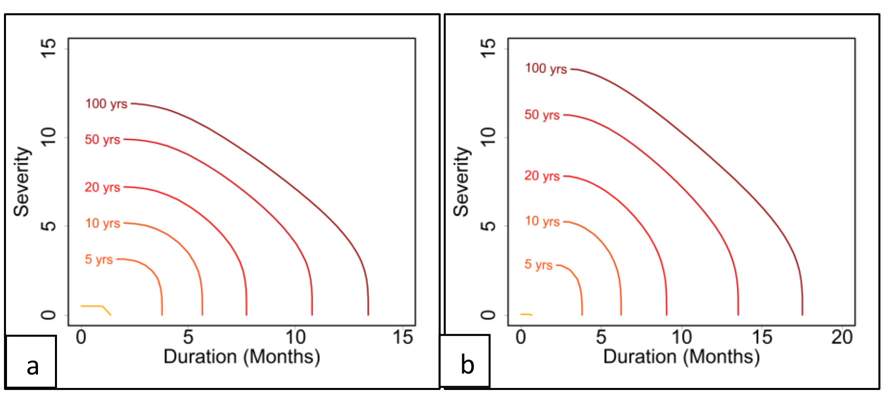


Fig. 7.9 Joint return periods of future droughts of case Ta for a) semiarid b) sub humid c) humid region and d) hydrological drought of the basin.



Cont.,

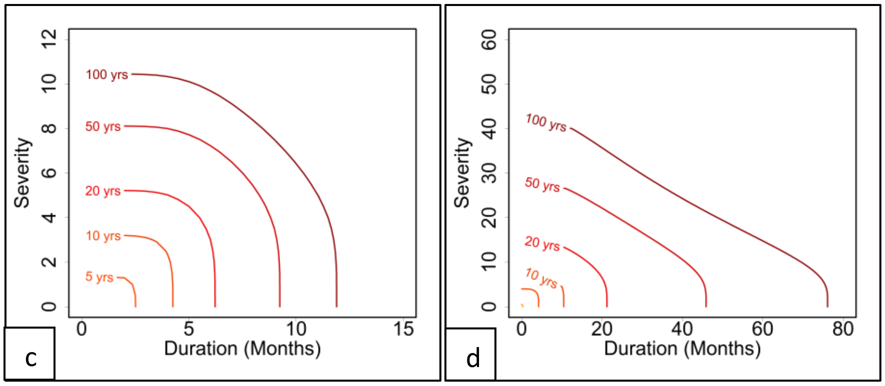


Fig. 7.10 Joint return periods of future droughts of case Tb for a) semiarid b) sub-humid c) humid region and d) hydrological drought of the basin.

CLOSURE

This chapter aimed to assess hydro-meteorological drought characteristics and joint behaviour in the future climatic condition using different RCMs. The different bias correction methods were applied to rainfall and temperature to raw RCMs and observed that CNRM-CM5 with LS bias correction method performed better for correcting the rainfall and VS is proved to be superior for correcting the temperature projections. The trends in future rainfall is decreasing significantly during post monsoon and in annual scale whereas, temperature is increasing significantly. The future hydro-meteorological drought characteristics reviled that the basin will experience more number of extreme droughts compared to the past and can be attributed to decreasing rainfall trend and significant rise in temperature of the basin. The joint probabilities and return periods conveyed high frequency of hydro-meteorological droughts in future compared to the historical frequencies and chances of occurrence of high severe droughts are more in semiarid region compared to humid and sub-humid regions in future. On the whole, the basin will further experience frequent hydro-meteorological droughts with high severity and duration.

CHAPTER 8

CONCLUSIONS

The present studies were taken up to characterize historical and future hydrometeorological droughts and to explore the applicability of copula theory in joint modelling of drought characteristics. In this chapter point-wise conclusions drawn from results obtained are presented. For convenience, chapter-wise conclusions are given. The limitations of the study and scope for future endeavors of the study are also itemized.

8.1 TREND ANALYSIS OF HYDROMETEOROLOGICAL VARIABLES

The present study examined the annual and seasonal trends in the rainfall, rainy days, monthly average temperature, PET, streamflow, reservoir levels and groundwater levels of the study area. Before, trend analysis the Ghataprabha river basin was classified in to different climatic regions using aridity index. Similarly, groundwater well of the study area are grouped in to different clusters using hierarchical and non-hierarchical clustering methods.

- The results of aridity index yields three climatic zones in the study area. Humid climate was observed in the western side of the basin while semiarid condition in the eastern part. A layer of transition zone in between was termed as sub-humid.

- Trend analysis of hydro-meteorological variables in the Ghataprabha river basin indicates decreasing trends in rainfall and rainy days among them few stations of semiarid and humid regions are statistically significant. The annual and seasonal temperature trends of the basin are increasing significantly with the average rise of 0.2^0C / decade. The annual and seasonal PET trends of the basin are increasing in all the stations but are significant only in semiarid region with the average rise of 3.5mm/ decade. The trends in annual and streamflow of the basin are decreasing with magnitude of 574.25 cumecs/year, whereas, no significant trends were observed in the reservoir levels

- The cluster analysis applied to groundwater wells suggested that three clusters are adequate to explain groundwater-level fluctuations of the basin efficiently. Trend analysis of annual and seasonal groundwater levels of the basin conveyed annual decreasing trends in 64% of the wells, of which 28 wells show significantly decreasing trend with average fall of 0.21 m per year.

- Maximum number of the stations in the semiarid region exhibited decreasing trends in hydro-meteorological variables, indicating that the region will be more vulnerable to frequent droughts in the future.

8.2 DROUGHT CHARACTERISTICS OF GHATAPRABHA BASIN

The hydrometeorological and agricultural drought assessment with different indices was done and compared with the meteorological drought SPI, RDI and SPEI was employed. The hydrological drought of the basin was studied by SDI and SRSI. Similarly, agricultural drought and groundwater drought characteristics are derived using Vegetation Condition VCI and SGI respectively.

- Significant number of droughts were observed from all the indices for various time scales. Even though SPEI and RDI consider same inputs and follows the same procedure of calculation, a remarkable difference among these indices can be observed both in spatial and temporal scale. The high correlation between SPI and RDI for all the stations and for all the time scales emphasizes the tendency of RDI towards rainfall.

- The hydrological drought assessed with SDI followed similar pattern with SRSI whereas it showed significant divergence with meteorological droughts. Similarly, Agricultural drought derived through VCI followed similar pattern of SPI-6 in comparison with SPI-3.

- Meteorological drought derived from SPEI is more likely to follow the SGI signals in the wells of cluster 1 and 2 laying in the semiarid region and, SGI of cluster 3 was captured by SPI in the humid region. Hydraulic diffusivity being a local aquifer property showed good agreement with SGI autocorrelation underlines the role of hydraulic diffusivity in the propagation of meteorological drought to groundwater drought. High correlation (0.93) between SGI autocorrelation with the different association period of meteorological drought emphasises the teleconnection between meteorological and groundwater drought with the crucial role of underlying hydrogeological characteristics.

8.3 COPULA BASED BIVRIATE DROUGHT FREQUENCY ANALYSIS

In this chapter the copula theory has been implemented derive the joint probabilities and joint return period of hydrometeorological droughts in different climatic region. An attempt has also been made to characterize drought in multivariate perspective by developing Standardized Hydro Meteorological drought Index.

- A good dependency structure ($R^2 > 0.70$) was observed between drought characteristics of all the indices justifies the application of copula for joint modelling of droughts.

- Bivariate frequency analysis of meteorological drought, portrayed drought of high severity with prolonged duration are frequent in semiarid region compared to humid and sub-humid regions.

- The joint probability of hydrological drought conveyed drought of smaller duration or severity are more prominent in the basin whereas joint return periods of groundwater drought is high in the well of cluster 2. The developed SHMI considers combined effects of precipitation and streamflow to picturize a near realistic drought scenario of the basin.

8.4 ANALYSIS OF FUTURE DROUGHT CHARACTERISTICS

To understand the drought characteristics in future climatic condition, the rainfall and temperature projections of different RCMs were considered. The projections of raw RCM data were corrected using different bias correction methods and future drought characteristics are derived.

- Bias correction methods for different models conveyed that the CNRM-CM5 performed well with the LS bias correction method for rainfall. Whereas for temperature all the models performed well however, VS performed better.

- Most of the stations in semiarid region experienced significant decreasing trends in annual and post monsoon seasons with the average decrease of 8 mm and 2.8 mm per year respectively. The annual and seasonal average temperature of the basin continued show its significant increasing trends in future period with the average rise of 0.15^0 C per decade and streamflow trends are non-significant.

- Most of the station of semiarid region experienced significant decrease in future rainfall which emphasizes that the region will experience more frequent droughts compared to historical period.

- The future hydro-meteorological drought characteristics reviled that the basin will experience more number of droughts compared to the past and it can be attributed to decreasing rainfall trend and significant rise in temperature of the basin.

- The return periods of future hydrometeorological droughts are less compared to historical period which indicates that the basin will suffer more frequent droughts in future compared to the past.

8.5 LIMITATIONS AND SCOPE FOR FUTURE ENDEAVORS

- In the study agricultural drought is studied only based on NDVI and a near realistic study can be taken up by considering crop yield, soil moisture.

- In the study only bivariate drought characteristics are assessed whereas, multivariate nature of drought can be studied by applying higher order copulas.

- The study did not attempted to evaluate reliability of existing mitigation and preparedness strategies for future drought events.

- Anthropogenic activities associated with the groundwater levels are not considered in the work. The study can be taken up in this regard.

REFERENCES

- Abramowitz M, Stegun I A (1965). “Handbook of mathematical functions: With formulars, graphs, and mathematical tables”. *DoverPublications. Com,* (55).
- Ahmadalipour, A., Rana, A., Moradkhani, H., Sharma, A., (2014). “Multi-criteria evaluation of CMIP5 GCMs for climate change impact analysis”. *Theor. Appl. Climatol.* http://dx.doi.org/10.1007/s00704-015-1695-4
- Ahn, K., Palmer, R.N., (2015). “Trend and Variability in Observed Hydrological Extremes in the United States”. *J. Hydrol. Eng*. 21, 4015061. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001286
- Allen, R. G., Pereira, L. S., Raes, D., and Smith, M., (1998). Crop Evapotranspiration, Guidelines for Computing Crop Water Requirements, Irrigation and Drainage Paper 56, FAO, Rome, 300 pp.,
- American Meteorological Society (AMS) (2004) “Statement on meteorological drought”. *Bull Am Meteorol* Soc 85:771–773
- American Meteorological Society. (1997). “Meteorological drought-policy statement”. *Bulletin of the American Meteorological Society,* 78, 847-849.
- Amorim, R. C., and Hennig, C.,(2015). “Recovering the number of clusters in data sets with noise features using feature rescaling factors”. *Inform. Sci*. 324, 126–145. doi: 10.1016/j.ins.2015.06.039
- Anderson, M. C., Norman, J. M., Mecikalski, J. R., Otkin, J. A., & Kustas, W. P. (2007). “A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 1. Model formulation”. *Journal of Geophysical Research: Atmospheres,* 112(D10).
- Angelidis, P., Maris, F., Kotsovinos, N., & Hrissanthou, V. (2012). “Computation of drought index SPI with alternative distribution functions”. *Water resources management*, 26(9), 2453-2473.

- Anne F. Van Loon, Rohini Kumar, V.M., (2017). "Testing the use of standardised indices and GRACE satellite data to estimate the European 2015 groundwater drought in near-real time." *Hydrol. Earth Syst. Sci*., 21, 1947–1971 Available at http://www.fao.org/3/a-bc049e.pdf
- Anon, (2010). "Annual Report. 2009–10. Department of Agriculture & Co-cooperation", *Ministry of Agriculture, Government of India*, 1–3, (www.agricoop.nic.in).
- Anyamba, A., & Tucker, C. J. (2006). "Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981–2003". *Journal of arid environments*, 63(3), 596-614.
- Barik B., Ghosh, S., Sahana, A. S., Pathak A., Sekhar M., (2017). "Water–food–energy nexus with changing agricultural scenarios in India during recent decades". *Hydrol. Earth Syst. Sci*. 21.
- Bayarjargal, Y., Karnieli, A., Bayasgalan, M., Khudulmur, S., Gandush, C., & Tucker, C. J. (2006). "A comparative study of NOAA–AVHRR derived drought indices using change vector analysis". *Remote Sensing of Environment,* 105(1), 9-22.
- Bayazit, M. & Önöz, B. (2008) "To prewhiten or not to prewhiten in trend analysis?" *Hydrol. Sci. J.* 52(4), 611–624.
- Begueria, S., Vicente-Serrano, S. M., (2015). "SPEI: Calculation of the Standardised Precipitation-Evapotranspiration Index" *R Package Version 1.6.* https://cran.r project.org/web/packages/SPEI/SPEI.pdf
- Beguería, S., Vicente-Serrano, S.M. & Angulo-Martínez, M. (2014). "A multiscalar global drought dataset: The SPEI base: A new gridded product for the analysis of drought variability and impacts". *Bulletin of the American Meteorological Society*, 91(10), 1351–1356.
- Beguería, S., Vicente-Serrano, S.M., (2013). "SPEI: calculation of the standardised precipitation-evapotranspiration index". URL: http:// CRAN.R-project.org/package=SPEI
- Beguería, S., Vicente-Serrano, S.M., Reig, F., Latorre, B., (2014). "Standardized precipitation evapotranspiration index (SPEI) revisited:

Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring". *Int. J. Climatol*. 34, 3001–3023. https://doi.org/10.1002/joc.3887

- Bergman, K. H., Sabol, P., & Miskus, D. (1988). "Experimental indices for monitoring global drought conditions". *In Proc. 13th Annual Climate Diagnostics Workshop, Cambridge, MA, US Dept. of Commerce*, 190-197.
- Bhanja, S.N., Mukherjee, A., Saha, D., Velicogna, I., Famiglietti, J.S., (2016). "Validation of GRACE based groundwater storage anomaly using in-situ groundwater level measurements in India". *J. Hydrol* 543, 729–738. doi:10.1016/j.jhydrol.2016.10.042
- Bhuiyan C, Singh RP, Kogan FN. (2006). "Monitoring drought dynamics in the Aravalli region (India) using different indices based on ground and remote sensing data". *Int J Appl Earth Obs Geoinf*. 8:289–302
- Bhuiyan C., (2004). "Various drought indices for monitoring drought condition in Aravalli terrain of India. In: Proceedings of the XXth ISPRS Conference; Istanbul": *Int. Soc. Photogramm. Remote Sens.* Available from: http://www.isprs.org/istanbul2004/comm7/papers/243.pdf.
- Bloomfield J P, Marchant, B P (2013) "Analysis of groundwater drought building on the standardised precipitation index approach." *Hydrology and Earth System Sciences* 17: 4769–4787. doi:10.5194/hess-17-4769-2013
- Bloomfield, J.P., Marchant, B.P., Bricker, S.H., Morgan, R.B., (2015). "Regional analysis of groundwater droughts using hydrograph classification". *Hydrology and Earth System Sciences* 19, 4327–4344
- Bonaccorso, B., Peres, D. J., Castano, A., & Cancelliere, A. (2015). "SPI-based probabilistic analysis of drought areal extent in Sicily". *Water resources management*, 29(2), 459-470.
- Brocque Le, A.F., Kath, J., Reardon-Smith, K., (2018). "Chronic groundwater decline: A multi-decadal analysis of groundwater trends under extreme climate cycles." *Journal of Hydrology*, 561: 976-986
- Brown, J. F., Wardlow, B. D., Tadesse, T., Hayes, M. J., & Reed, B. C. (2008). "The Vegetation Drought Response Index (VegDRI): A new integrated

approach for monitoring drought stress in vegetation". *GIScience & Remote Sensing*, 45(1), 16-46.

- Buttafuoco G, Caloiero T, Coscarelli R. (2015). "Analyses of drought events in Calabria (southern Italy) using Standardized Precipitation Index." *Water Resources Management*, 29(2): 557–573.
- Byun, H. R., & Kim, D. W. (2010). "Comparing the effective drought index and the standardized precipitation index. Economics of drought and drought preparedness in a climate change context". López-Francos A.(comp.), LópezFrancos A.(collab.). Options Méditerranéennes. Sér. *A. Séminaires Méditerranéens*, (95), 85-89.
- Cai, W., Zhang, Y., Yao, Y., Chen, Q., (2015). "Probabilistic analysis of drought spatiotemporal characteristics in the Beijing-Tianjin-Hebei metropolitan area in China." *Atmosphere (Basel).* 6, 431–450. https://doi.org/10.3390/atmos6040431
- Castle, S.L., Thomas, B.F., Reager, J.T., Rodell, M., Swenson, S.C., Famiglietti, J.S., (2014). "Groundwater depletion during drought threatens futurewater security of the Colora- do River Basin". *Geophys. Res. Lett.* 41 (16):5904–5911
- CGWB. (2011). "CGWB Report. Groundwater year book – India 2010- 11. Ministry of Water Resources", *Govt. of India*, http://www.cgwb.gov.in/documents
- CGWB., (2012). "Aquifer system of India. CGWB report. Ministry of Water Resources," *Govt. of India.* Retrieved on Nov 15, 2017, from http://cgwb.gov.in/AQM/.
- Chang, T. J., & Kleopa, X. A. (1990). "A proposed method for drought monitoring 1". *Jawra Journal of the American Water Resources Association*, 27(2), 275-281.
- Chen, L., Singh, V. P., Guo, S., Mishra, A. K., & Guo, J. (2013). "Drought analysis using copulas". *Journal of Hydrologic Engineering*, 18(7), 797-808.
- Conrad, G.E. (1944). "Drought, its effect and measure of control in Nebraska, Nebraska University". *Conservation and Survey Division*, Conservation Bulletin 25.

- Dahal P, Shrestha N S et al (2015) “Drought risk assessment in central Nepal: temporal and spatial analysis”. *Nat. Hazards.* 80: 1913–1932. doi:10.1007/s11069-015-2055-5
- Dalezios, N. R., Blanta, A., & Spyropoulos, N. V. (2012). “Assessment of remotely sensed drought features in vulnerable agriculture”. *Natural Hazards and Earth System Sciences*, 12(10), 3139-3150.
- Das, P.K., Dutta, D., Sharma, J.R., Dadhwal, V.K., (2016). “Trends and behaviour of meteorological drought (1901-2008) over Indian region using standardized precipitation-evapotranspiration index.” *Int. J. Climatol*. 36, 909–916. https://doi.org/10.1002/joc.4392
- Dash S K, Jenamani R K, Shekhar M S (2004) “On the decreasing frequency of monsoon depressions over the Indian region”. *Current Sci*., 86:1404–1411
- Dhanya CT, Nagesh Kumar D (2009) “Data mining for evolution of association rules for droughts and floods in India using climate inputs”. *J Geophys Res Atmos*. doi:10.1029/2008JD010485
- Dhar A., Sahoo S., Dey S., Sahoo M., (2014). “Evaluation of Recharge and Groundwater Dynamics of a Shallow Alluvial Aquifer in Central Ganga Basin, Kanpur (India).” *Natural Resources Research*. 23(4)
- Dogan, S., Berktay, A., & Singh, V. P. (2012). “Comparison of multi-monthly rainfall-based drought severity indices, with application to semi-arid Konya closed basin, Turkey”. *Journal of Hydrology,* 470, 255-268.
- Dracup, J. A., Lee, K. S., & Paulson Jr, E. G. (1980). “On the definition of droughts”. *Water resources research*, 16(2), 297-302.
- Dragota, C., Vasenciuc, F., Claudia, N., (2009). “Combining the standardized precipitation index and climatic water deficit in characterizing droughts : a case study in Romania” 219–233. *Theoretical and Applied Climatology* https://doi.org/10.1007/s00704-008-0061-1
- Dutta, D., Kundu, A., Patel, N. R., Saha, S. K., & Siddiqui, A. R. (2015). “Assessment of agricultural drought in Rajasthan (India) using remote sensing derived Vegetation Condition Index (VCI) and Standardized Precipitation

Index” *The Egyptian Journal of Remote Sensing and Space Science.* 18(1), 53-63.

- Easterling, W. E. (1988). “Coping with drought hazard: recent progress and research priorities”. In Proc., *Selected Papers from Workshop on Natural Disasters in European Mediterranean Countries, Perugia, Italy: Italian National Research Council,* 231-270.
- Edossa, D. C., Babel, M. S., & Gupta, A. D. (2010). “Drought analysis in the Awash river basin, Ethiopia”. *Water resources management,* 24(7), 1441-1460.
- Edwards D C, and McKee T B (1997) “Characteristics of 20th century drought in The United States at multiple time scales.” *Climatology Rep.* 97-2, ⟨http://ccc.atmos.colostate.edu/edwards.pdf⟩ (Apr. 20, 2015).
- Eidenshink, J. C., & Haas, R. H. (1992). “Analyzing vegetation dynamics of land systems with satellite data”. *Geocarto International,* 7(1), 53-61.
- England K, Hisdal H, Frigessi A (2004) “Practical extreme value modeling hydrological flood and drought: a case study.” *J Extremes* 7:5–30.
- FAO., (2008). “A MASSCOTE Case Study in KARNATAKA – INDIA.” Modernization Strategy for Irrigation Management (Working Document-14/03/08).
- Fishman, R.M., Siegfried, T., Raj P., Modi, V, Lall, U., (2011). “Over-extraction from shallow bedrock versus deep alluvial aquifers: reliability versus sustainability considerations for India’s groundwater irrigation*” Water Resour Res.* 47:1–15
- Ganapuram, S., Nagarajan, R., Sekhar, G.C., (2015). “Identification of groundwater drought prone zones in Pedda vagu and Ookachetti vagu watersheds, tributaries of the Krishna River, India”. *Geocarto International,* 31(4), 385–407.
- Ganguli P, Reddy MJ (2013) “Evaluation of trends and multivari- ate frequency analysis of droughts in three meteorological subdivisions of western India”. *Int. J. Climatol.* 34(3): 911–928, DOI: 10.1002/joc.3742
- Ganguli, P..and Reddy, M. J., (2014). “Application of copulas for derivation of drought severity–duration–frequency curves”. *Hydrological Processes,* 26(11), 1672-1685.

- Gao, L., & Zhang, Y. (2016). "Spatio-temporal variation of hydrological drought under climate change during the period 1960–2013 in the Hexi Corridor, China". *Journal of Arid Land*, 8(2), 157-171.
- Garen, D. C., (1993): "Revised Surface-Water Supply Index for western United States". *J. Water Resour. Plan. Manage.*, 119, 437–454
- Ghosh, S., & Srinivasan, K., (2016). "Analysis of spatiotemporal characteristics and regional frequency of droughts in the southern peninsula of India". *Water Resources Management*, 30, 3879–3898
- Gibbs, W. J. (1975). "Drought: its definition, delineation and effects". WMO Drought p 11-39(SEE N 76-12595 03-47).
- Gibbs, W. J., & Maher, J. V. (1967). "Rainfall deciles as drought indicators", *bureau of meteorology bulletin no. 48.* Commonwealth of Australia, Melbourne, 29.
- Gillette, H. P. (1950). "A creeping drought under way". *Water and sewage works,* 104(5).
- Gleeson, T.,Wada, Y., Bierkens, M. F., van Beek, L.P., (2012)."Water balance of global aquifers revealed by groundwater footprint." *Nature* 488 (7410):197–200.
- Goodarzi, M., Abedi-koupai, J., Heidarpour, M., Safavi, H.R., (2016). Development of a New Drought Index for Groundwater and Its Application in Sustainable Groundwater Extraction 142, 1–12
- Guttman, N. B. (1999). "Accepting the standardized precipitation index: a calculation algorithm 1". *JAWRA Journal of the American Water Resources Association*, 35(2), 311-322.
- Hamed, K. H., and Ramachandra Rao, A. (1998). "A modified Mann- Kendall trend test for autocorrelated data." *J. Hydrol*., 204(1–4), 182–196
- Hangshing, L., Dabral, P.P., (2018). "Multivariate Frequency Analysis of Meteorological Drought Using Copula." *Water Resources Management*. 32(5), 1741-1758

- Hao, Z., & AghaKouchak, A. (2015). "Multivariate standardized drought index: a parametric multi-index model". *Advances in Water Resources,* 57, 12-18.
- Hao, Z., Hao, F., & Singh, V. P. (2015). "A general framework for multivariate multi-index drought prediction based on Multivariate Ensemble Streamflow Prediction (MESP)". *Journal of Hydrology*, 539, 1-10.
- Hartigan, J., and Wong, M.,(1979). "Algorithm AS 136: A K-Means Clustering Algorithm". *Applied Statistics*, 28, 100-108.
- Hayes, M, Svoboda, M, Wilhite D. and Vanyarkho O (1999). "Monitoring the 1996 drought using the SPI." Bull Amer Meteor Soc 80: 429-438.
- Hayes, M., M. Svoboda, N. Wall, and M. Widhalm, (2012): "The Lincoln declaration on drought indices: universal meteorological drought index recommended." *Bull. Amer. Meteor. Soc*, 92, 485-488.
- Hewitt, K. (1997). "Regions at risk: a geographical introduction to hazards".
- Hisdal, H., Tallaksen, L.M., (2000). "Drought event definition. Technical Report No. 6. Assessment of Regional Impact of Droughts in Europe"
- Hughes, J.D., Petrone, K.C., Silberstein, R.P., (2012). "Drought, groundwater storage and stream flow decline in southwestern Australia". *Geophys. Res. Lett.* 39 (3)
- Hutchinson, C. F. (1991). "Uses of satellite data for famine early warning in sub-Saharan Africa". *International Journal of Remote Sensing*, 12(6), 14051421.
- IMD. (2005). :Climatological Features of Drought Incidences in India. Meteorological Monograph Climatology" No. 21/2005, India Meteorological Department.
- Ionita M, Scholz P, Chelcea S (2016). "Assessment of droughts in Romania using the Standardized Precipitation Index." *Natural Hazards,* 81(3):1483–1498. https://doi.org/10.1007/s11069-015-2141-8
- Jakson, R. D., Kustas, W. P., & Choudhury, B. J. (1988). "A reexamination of the crop water stress index". *Irrigation science*, 9(4), 309-317.
- Jain S K, & Kumar V (2012). "Trend analysis of rainfall and temperature data for India." *Current Science,* 102(1):37–49.

- Jain, K. V., Pandey, R. P., Jain, M. K., & Byun, H. R. (2014). “Comparison of drought indices for appraisal of drought characteristics in the Ken River Basin”. *Weather and Climate Extremes*, 8, 1-11.
- Justice, C. O., (1986), “Monitoring the grasslands of semi-arid Africa using NOAA-AVHRR data”. *Advances in Space Research*, 13, 219–222
- Kao, S. C., & Govindaraju, R. S. (2010). “A copula-based joint deficit index for droughts”. *Journal of Hydrology*, 380(1-2), 121-134.
- Karimi, M., & Shahedi, K. (2013).” Hydrological drought analysis of Karkheh River basin in Iran using variable threshold level method”. *Current World Environment*, 8(3), 419.
- Karnieli A, Bayasgalan, M. Bayarjargal Y., Agam N., Khudulmur S. & Tucker C. J. (2006) “Comments on the use of the Vegetation Health Index over Mongolia.” *International Journal of Remote Sensing*, 27:10, 2017-2024, DOI: 10.1080/01431160500121727
- Karnieli, A., Agam, N., Pinker, R. T., Anderson, M., Imhoff, M. L., Gutman, G. G., ... & Goldberg, A. (2010). “Use of NDVI and land surface temperature for drought assessment”: *Merits and limitations. Journal of climate*, 23(3), 618633.
- Kaufman, L., and Rousseeuw, P.J.,(1990). “Finding Groups in Data: An Introduction to Cluster Analysis”, New York: Wiley
- Kendall M G (1975). “Rank correlation methods.” Charles Griffin, London.
- Kendall, D. R., & Dracup, J. A. (1992). “On the generation of drought events using an alternating renewal-reward model”. *Stochastic Hydrology and Hydraulics*, 6(1), 55-68.
- Kenji et al., (1995). “Risk Assessment of a Water Supply System during Drought.” *Int. J. Water Resour. Dev.* 11, 185–204. https://doi.org/10.1080/07900629550042399
- Keshavarz, M. R., Vazifedoust, M., & Alizadeh, A. (2014). “Drought monitoring using a Soil Wetness Deficit Index (SWDI) derived from MODIS satellite data”. *Agricultural Water Management*, 132, 37-45.

- Kogan, F. N. (1990). “Remote sensing of weather impacts on vegetation in nonhomogeneous areas”. *International Journal of Remote Sensing*, 11(8), 14051419.
- Kogan, F. N. (1991). “Observations of the 1990 U.S. drought from the NOAA-11 polar-orbiting satellite”. *Drought Network News*, 3, 7–11.
- Kogan, F. N. (1995). “Droughts of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data”. *Bulletin of the American Meteorological Society*, 76(5), 655-668.
- Kogan, F. N. (1995a). “Application of vegetation index and brightness temperature for drought detection”. *Advances in space research*, 15(11), 91100.
- Kogan, F. N. (1997). “Global drought watch from space”. *Bulletin of the American Meteorological Society*, 78(4), 621-636.
- Krishnan, A. (1979). “Key paper on definition of droughts and factors relevant to specification of agricultural and hydrologic droughts”. *In Hydrological aspects of droughts: international symposium, 3-7 December 1979, New Delhi: proceedings. New Delhi: Indian National Committee for IHP, CSIR: Indian Institute of Technology*, 67-102.
- KSAPCC. (2011). “Karnataka climate change action plan. Bangalore climate change initiative—Karnataka (BCCI-K).” Retrieved Nov 18, 2017, from http://www.lse.ac.uk/asiaResearchCentre/_files/KarnatakaCCactionPlanFinal.pdf.
- KSNDMC (2017) “Drought Vulnerability Assessment in Karnataka (A Composite Index: using Climate, Soil, Crop Cover and Livelihood components).” KSNDMC. Bengaluru, 114p
- Kumar R, Musuuza J L, Loon A F Van, Teuling A J, Barthel R Broek J, Ten Mai J, Samaniego L, Attinger S, (2016). “Multiscale evaluation of the Standardized Precipitation Index as a groundwater drought indicator” 1117–1131. *Hydrology and Earth System Sciences* doi:10.5194/hess-20-1117-2016
- Kumar Raju, B.C., Nandagiri, L., (2017). “Analysis of historical trends in hydrometeorological variables in the upper Cauvery Basin, Karnataka, India.” *Curr. Sci.* 112, 577–587. https://doi.org/10.18520/cs/v112/i03/577-587

- Kumar V, Jain S K, Singh Y (2008). “Analysis of long-term rain- fall trends in India”. *Hydrol. Sci. J.*,55(4):484–496.
- Kwak.J.et.al(2014),“Drought severity-Duration-frequency Analysis of hydrological Drought Based on copula Theory” hydrology day 2012.
- Lal M (2001) “Climatic change – implications for India’s water resources”. *J. Ind. Water Resour. Soc*. 21:101–119.
- Leelaruban N, Padmanabhan G, Oduor P (2017) “Examining the Relationship between Drought Indices and Groundwater Levels.” *Water* 9:82. doi:10.3390/w9020082
- Li J, Zhou S, Hu R (2014) “Hydrological Drought Class Transition Using SPI and SRI Time Series by Loglinear Regression.” *Water Resources Management* 30:669–684. doi:10.1007/s11269-015-1184-7
- Linsley Jr, R. K., Kohler, M. A., & Paulhus, J. L. (1975). *Hydrology for engineers*.
- Liu, W. T., & Kogan, F. N. (1996). “Monitoring regional drought using the vegetation condition index”. *International Journal of Remote Sensing*, 17(14), 2761-2782.
- Liu, X., Wang, S., Zhou, Y., Wang, F., Li, W., Liu, W., (2015). “Regionalization and Spatiotemporal Variation of Drought in China Based on Standardized Precipitation Evapotranspiration Index” *Adv. Meteorol*. (1961-2013). https://doi.org/10.1155/2015/950262
- Lloyd-Huhes B, Saunders M A (2002). “A drought climatology for Europe.” *Int J Climatol* 22:1571–1592
- Loon, A.F. Van, Rohini, K., Mishra, V., (2017). “Testing the use of standardised indices and GRACE satellite data to estimate the European 2015 groundwater drought in near-real time.” *Hydrology and Earth System Sciences.* 21, 1947–1971. doi:10.5194/hess-21-1947-2017
- Loukas A, Vasiliades L (2004) “Probabilistic analysis of drought spatiotemporal characteristics in Thessaly region, Greece.” *Nat Hazards Earth Syst Sci* 4:719–731

- Madadgar, S., & Moradkhani, H. (2011). "Drought analysis under climate change using copula". *Journal of hydrologic engineering*, 18(7), 746-759.
- Madadgar, S., Moradkhani, H., (2013). "A Bayesian framework for probabilistic seasonal drought forecasting". *J. Hydrometeorol*. 14, 1685–1705.
- Mahajan, D. R., & Dodamani, B. M. (2015). "Trend analysis of drought events over upper Krishna basin in Maharashtra". *Aquatic Procedia*, 4, 1250-1257.
- Maity, R., Sharma, A., Nagesh Kumar, D., & Chanda, K. (2013). "Characterizing drought using the reliability-resilience-vulnerability concept". *Journal of Hydrologic Engineering*, 18(7), 859-869.
- Mann H B (1945) "Nonparametric tests against trend." *Econometrica* 13:245–259.
- Martínez-Fernández, J., González-Zamora, A., Sánchez, N., & Gumuzzio, A. (2015). "A soil water based index as a suitable agricultural drought indicator". *Journal of Hydrology*, 522, 265-273.
- Martínez-Fernández, J., González-Zamora, A., Sánchez, N., Gumuzzio, A., & Herrero-Jiménez, C. M. (2016). "Satellite soil moisture for agricultural drought monitoring: Assessment of the SMOS derived Soil Water Deficit Index".*Remote Sensing of Environment*, 177, 277-286.
- McGUIRE, J. K., & Palmer, W. C. (1957). "The 1957 drought in the eastern United States". *Mon. Weather Rev*, 85(9), 305-314.
- McKee T B, Doesken N J, Kleist J (1993) "The relationship of drought frequency and duration to time scales. In: Paper Presented at Eighth Conference on Applied Climatology", *Am. Meteorol.* Soc. Anaheim, CA.
- McVicar, T. R., & Jupp, D. L. (1998). "The current and potential operational uses of remote sensing to aid decisions on drought exceptional circumstances in Australia: a review". *Agricultural systems*, 57(3), 399-468.
- Mendicino, G., Senatore, A., & Versace, P. (2008). "A Groundwater Resource Index (GRI) for drought monitoring and forecasting in a Mediterranean climate". *Journal* of *Hydrology*, 357(3-4), 282-302.
- Meyer, S. J., Hubbard, K. G., & Wilhite, D. A. (1993). "A crop-specific drought index for corn: I. Model development and validation". *Agronomy Journal*, 85(2), 388-395.

- Mirabbasi, R., Fakheri-Fard, A., & Dinpashoh, Y. (2012). “Bivariate drought frequency analysis using the copula method”. *Theoretical and Applied Climatology*, 108(1-2), 191-206.
- Mirzavand, M., Ghazavi, R., (2015) “A stochastic modeling technique for groundwater level forecasting in an arid environment using time series methods.” *Water Resour Manag*. doi:10.1007/s11269-014-0875-9
- Mishra A K, Desai V R (2005) “Spatial and temporal drought analysis in the Kansabati river basin, India.” *International Journal of River Basin Management* 3:31–41. doi10.1080/15715124.2005.9635243
- Mishra A K, Singh, V.P., (2010). “A review of drought concepts.” *Journal of Hydrology* 391: 202–216. doi:10.1016/j.jhydrol.2010.07.012.
- Mishra S. & R. Nagarajan (2010) “Spatio-temporal drought assessment in Tel river basin using Standardized Precipitation Index (SPI) and GIS” *Geomatics Natural Hazards and Risk*, 2:1, 79-93, DOI: 10.1080/19475705.2010.533703
- Mishra, A. K., & Singh, V. P. (2010). “Drought modeling–A review”. *Journal of Hydrology*, 403(1-2), 157-175.
- Mishra, A. K., Desai, V. R., & Singh, V. P. (2007). “Drought forecasting using a hybrid stochastic and neural network model”. *Journal of Hydrologic Engineering*, 12(6), 626-638.
- Mishra, A. K., Singh, V.P. (2010) “A review of drought concepts”. *J Hydrol* 391(1–2):202–216
- Mohammed, R., Scholz, M., (2017). “Impact of Evapotranspiration Formulations at Various Elevations on the Reconnaissance Drought Index”. *Water Resour. Manag.* 31, 531–548. https://doi.org/10.1007/s11269-016-1546-9
- Mosadi, A., Abyaneh, H. Z., Sough, M. G., & Samadi, S. Z. (2015). “Quantifying changes in reconnaissance drought index using equiprobability transformation function”. *Water Resources Management*, 29(8), 2451-2469.
- Motlagh, M.S., Ghasemieh, H., (2016). “Identification and Analysis of Drought Propagation of Groundwater During Past and Future Periods.” *Water Resources Management.* 19,23-40

- Murthy, C. S., Singh, J., Kumar, P., & Sai, M. S. (2016). “Meteorological drought analysis over India using analytical framework on CPC rainfall time series”. *Natural Hazards,* 81(1), 573-587.
- Mussá, F.E.F., Zhou, Y., Maskey, S., Masih, I., Uhlenbrook, S., (2015). “Groundwater as an emergency source for drought mitigation in the Crocodile River catchment, South Africa.” *Hydrol. Earth Syst. Sci.* 19, 1093–1106
- Nalbantis, I., & Tsakiris, G. (2008). “Assessment of hydrological drought revisited”. *Water Resources Management*, 23(5), 881-897.
- Narasimhan, B., & Srinivasan, R. (2005). “Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring”. *Agricultural and Forest Meteorology*, 133(1-4), 69-88.
- Naresh Kumar M, et al (2009) “On the use of Standardized Precipitation Index (SPI) for drought intensity assessment.” *Meteorological Applications*, 16(3):381–389.
- Nikbakht J, Tabari H, Hosseinzadeh Talaee P (2012) “Streamflow drought severity analysis by percent of normal index (PNI) in northwest Iran”. *Theor Appl Climatol* 112:565–573
- Otkin, J. A., Anderson, M. C., Hain, C.,Mladenova, I. E., Basara, J. B., & Svoboda,M. (2013). “Examining rapid onset drought development using the thermal infrared-based evaporative stress index.” *J. Hydrometeor*., 14,1057–1074.
- Padhee SK, Nikam BR, Aggarwal SP, Garg V. (2014) “Integrating effective drought index (EDI) and remote sensing derived parameters for agricultural drought assessment and prediction in Bundelkhand Region of India”. *Int Arch Photogramm Remote Sens Spat Inf Sci - ISPRS Arch*. 40(8):89-100. doi:10.5194/isprsarchives-XL-8-89-2014.
- Pai D S, Latha S, Guhathakurta P, Hatwar, H R (2011) “District-wide drought climatology of the southwest monsoon season over India based on standardized precipitation index (SPI).” *Nat Hazards*, DOI 10.1007/s11069-011-9867-8.
- Palmer W.C. (1957), ‘Meteorologic Drought’, US Weather Bureau, Research Paper No. 45.

- Panda, D.K., Mishra, A. and Kumar, A. (2012) "Quantification of trends in groundwater levels of Gujarat in Western India". *Hydrolog. Sci. Jour.,* .57,1323–1336
- Pandey RP, Mishra SK, Singh R, Ramasastri KS (2007) "Streamflow drought severity analysis of Betwa River System (India)." *Water Resour Manage* 22:1127–1141.
- Pandey, P.K., Pandey, V. (2016). "Evaluation of temperature-based Penman–Monteith (TPM) model under the humid environment." *Model. Earth Syst. Environ*. 2, 152 .https://doi.org/10.1007/s40808-016-0204-9
- Parasuraman, S. and P. V. Unnikrishnan, Eds. (2000). India Disasters Report, Oxford Press.
- Patel N R, Chopra P , Dadhwal V K (2007) "Analyzing spatial patterns of meteorological drought using standardized precipitation index." *Meteorol. Appl.* 14:329–336.
- Patle G. T., Singh D. K., Sarangi A., Rai, A., Khanna M., Sahoo R. N., (2015). "Time Series Analysis of Groundwater Levels and Projection of Future Trend". *Journal geological society of India*. 85:12-25
- Paulo, A. A., Pereira, L.S., (2006) "Drought Concepts and Characterization." *Water Int.* 31, 37–49. https://doi.org/10.1080/02508060608691913
- Paulo, A.A., Rosa, R.D., Pereira, L.S., (2012). "Climate trends and behaviour of drought indices based on precipitation and evapotranspiration in Portugal." *Nat. Hazards Earth Syst. Sci.* 12, 1481–1491. https://doi.org/10.5194/nhess-12-1481-2012
- Peters, E., Bier, G., van Lanen, H.A.J., Torfs, P.J.J.F., (2006). "Propagation and spatial distribution of drought in a groundwater catchment". *Journal of Hydrology* 321, 257–275. doi:10.1016/j.jhydrol.2005.08.004
- Peters, E., van Lanen, H.A.J., (2005). "Separation of base flow from streamflow using groundwater levels – Illustrated for the Pang catchment (UK)." *Hydrological Processes* 19, 921–936. doi:10.1002/hyp.5548.
- Peters, E., van Lanen, H.A.J., Bradford, R.B., Cruces de Abia, J., Martinez Cortina, L., (2001). "Droughts derived from groundwater heads and

groundwater discharge. In: Assessment of the Regional Impact of Droughts in Europe. Final Report to the European Union. Institute of Hydrology", University of Freiburg, (35–39)

- Peters, E., van Lanen, H.A.J., Torfs, P.J.J.F., Bier, G., (2005). "Drought in groundwater-drought distribution and performance indicators." *J. Hydrol.* 306, 302–317
- Rajshekar.D,singh.V.P, Mishra A.K(2015).,"Hydrological Drought Atlas for Texas".*j.hydrol.Eng*.2015.20
- Raju K B C, Nandagiri, L., 2017. "Analysis of historical trends in hydrometeorological variables in the upper Cauvery Basin, Karnataka, India." *Current science*. 112(3), 577-587.
- Rama Prasad (1990), 'Drought Analysis and Management', Proceedings of the National Workshop on Water Resources Project Management, IIT, Chennai, pp.
- Ramadas, M., Govindaraju, R.S., (2015). "Probabilistic assessment of agricultural droughts using graphical models." *Journal of Hydrology* 526, 151–163. doi:10.1016/j.jhydrol.2014.09.026
- Rhee, J. Y., Im, J. H., & Carbone, G. J. (2010). "Monitoring agricultural drought for arid and humid regions using multi-sensor remote sensing data." *Remote Sensing of Environment*, 114, 2875–2887.
- Rojas, O., Vrieling, A., & Rembold, F. (2011). "Assessing drought probability for agricultural areas in Africa with coarse resolution remote sensing imagery." *Remote Sensing of Environment*, 115, 343–352.
- Rossi, G., Benedini, M., Tsakiris, G., and Giakoumakis, S.(1992). "On regional drought estimation and analysis." *Water Resour. Manage.* 6, 249–227
- Rousseeuw, P., (1987). "Silhouettes: A graphical aid to the interpretation and validation of cluster analysis." *J. Comput. Appl. Math.*, 20:53–65
- Sadri, S., and D. H. Burn, (2012). "Nonparametric methods for drought severity estimation at ungauged sites." *Water Resour. Res.*, 48,W12505, doi:10.1029/2011WR011323

- Saeid M, Smakhtin V, and Moghaddasi, M, (2006). "Comparison of seven meteorological indices for drought monitoring in Iran," *International Journal of Climatology*, 26, pp. 971–985.
- Sánchez, N., Martínez-Fernández, J., González-Zamora, A., (2016.) "A Combined Approach with SMOS and MODIES To Monitor Agricultural Drought." *ISPRS - International Archives of the Photogrammetry*, Remote Sensing and Spatial Information Sciences XLI-B8, 393–398. doi:10.5194/isprsarchives-XLI-B8393-2016.
- Sandholt I, Rasmussen K, Andersen J, (2002) "A simple interpretation of the surface temperature/vegetation index space for assessment of surface moisture status." *Remote Sensing of Environment*, 79(2): 213–224.
- Sarker R P, Thapliyal V (1988) "Climate change and variability." *Mausam* 39:127-138.
- Sen P K (1968). "Estimate of the regression coefficient based on Kendall's tau." *J Am Stat Assoc.*, 63:1379–1389
- Shafer BA, Dezman LE (1982) "Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snowpack runoff areas." In Proceedings of the (50th) 1982 *Annual Western Snow Conference* , pp 164–75 Fort Collins, CO: Colorado State University.
- Shahid, S., Hazarika, M.K., (2009). "Groundwater drought in the northwestern districts of Bangladesh". *Water Resources Management* 24, 1989–2006. doi:10.1007/s11269-009-9534-y.
- Shantz K.J. (1970), "Consumptive Use of Water for Irrigation Requirements", Technical Note, Virginea State University, USA.
- Shiau JT (2006) "Fitting drought duration and severity with two- dimensional copulas." *Water Resour Manag* 20:795–815.
- Shukla, S., Wood, A.W., (2007). "The value of a standardized runoff index for characterizing hydrologic aspects of drought." Agu.
- Singh, R.P., S. Roy, and F. Kogan. (2003). "Vegetation and temperature condition indices form NOAA AVHRR data for drought monitoring over India."

- Sivakumar, M. V. K., Motha, R. P., Wilhite, D. A., and Wood, D. A. (2011). “Agricultural Drought Indices” — *Proceedings of an Expert meeting*. 219 pp.
- Skakun S, Kussul N, Shelestov A, Kussul O. (2015) “The use of satellite data for agriculture drought risk quantification in Ukraine.” *Geomatics, Nat Hazards Risk*; 5705(March):1-18. doi:10.1080/19475705.2015.1016555.
- Sklar, K., (1959). “Fonctions de repartition ‘an n dimensions et leura marges.Publications de l’Institut de Statistique de l’Universit´e:” Paris 8, 229–231.
- Smakhtin, V. U. and D.A. Hughes. (2005). “Automated estimation and analyses of drought indices in South Asia. A review.” *International Water Management Institute,* Colombo, Sri Lanka.
- Sridhar, V., Hubbard, K.G., You, J., Hunt, E.D., (2009). “Development of the soil moisture index to quantify agricultural drought and its user friendliness in severity-area- duration assessment.” *J. Hydrometeorol*. 9, 660–676.
- Steinemann, A., M. Hayes, and L. Cavalcanti. (2005). “Drought indicators and triggers. In Drought and Water Crises:” *Science, Technology, and Management* Issues, ed. D. Wilhite. Boca Raton, FL: CRC Press.
- Su, H., M.McCabe, E.Wood, Z. Su, and J. Prueger (2005), “Modeling evapotranspiration during SMACEX: Comparing two approaches for local-and regional-scale prediction,” *J. Hydrometeorol*., 6(6), 910–922
- Su, X., Singh, V.P., Niu, J., Hao, L., (2015). “Spatiotemporal trends of aridity index in Shiyang River basin of northwest China.” *Stoch. Environ. Res. Risk. Assess*. 29, 1571–1582
- Sung, J.H.,Chung, E.S., (2013). “Development of streamflow drought severity and frequency curves using the threshold level method.” *Hydrology and Earth System Sciences* 18, 3341–3351. doi:10.5194/hess-18-3341-2014.
- Surendran, U., Kumar, V., Ramasubramoniam, S., Raja, P., (2017). “Development of Drought Indices for Semi-Arid Region Using Drought Indices Calculator (DrinC) – A Case Study from Madurai District, a Semi-Arid Region in India.” *Water Resour. Manag.* 31, 3593–3605. https://doi.org/10.1007/s11269-017-1687-5

- Tabari H, Abghari H, Hosseinzadeh Talaee P (2012) “Temporal trends and spatial characteristics of drought and rainfall in arid and semi-arid regions of Iran.” *Hydrol Process* 26(22):3351–3361
- Tallaksen, L.M., Hisdal, H., (1997). “Regional analysis of extreme streamflow drought duration and deficit volume,” FRIEND ‘97 – regional hydrology: concepts and models for sustainable water resource management. In: Proc. International Conference, Postojna, vol. 246, pp. 141–150.
- Thakur, G. S., Thomas, T., (2011). “Analysis of Groundwater Levels for Detection of Trend in Sagar District, Madhya Pradesh.” *Journal geological society of India* 77:12-25
- Thilakarathne, M., Sridhar, V., (2017). “Characterization of future drought conditions in the Lower Mekong River Basin.” *Weather Clim. Extrem*. 17, 47–58. https://doi.org/10.1016/j.wace.2017.07.004
- Thomas J, Prasannakumar V (2016). “Temporal analysis of rainfall (1871–2012) and drought characteristics over a tropical monsoon-dominated State (Kerala) of India.” *J. Hydrol.* 534:266–280.
- Thomas T, Jaiswal R K, Galkate R, Nayak P C, Ghosh N C (2016) “Drought indicators-based integrated assessment of drought vulnerability: a case study of Bundelkhand droughts in central India.” *Natural Hazards*, 81(3):1627–1652. https://doi.org/10.1007/s11069-016-2149-8.
- Thomas T, Nayak P C, Narayan C (2015) “Spatiotemporal Analysis of Drought Characteristics in the Bundelkhand Region of Central India using the Standardized Precipitation Index.” *J. Hydrol. Eng.*, 1(11):1–6. https://doi.org/: 10.1061/(ASCE)HE.1943-5584.0001189.
- Thomas, B.F., Famiglietti, J.S., Landerer, F.W., Wiese, D.N., Molotch, N.P., Argus, D.F., (2017). “GRACE Groundwater Drought Index: Evaluation of California Central Valley groundwater drought.” *Remote Sensing of Environment* 198, 384–392.
- Thomas, T., Jaiswal, R.K., Galkate, R., Nayak, P.C., Ghosh, N.C., (2016a.) “Drought indicators-based integrated assessment of drought vulnerability: a

case study of Bundelkhand droughts in central India." *Nat. Hazards* 81, 1627–1652. https://doi.org/10.1007/s11069-016-2149-8

- Thrasher, B., Xiong, J., Wang, W., Melton, F., Michaelis, A., Nemani, R., (2013). "Downscaled climate projections suitable for resource management." *Am. Geophys. Union* 94, 321–323. http://dx.doi.org/10.1002/2013EO370002.
- Tibshirani, R., G. Walther, and T. Hastie (2001). "Estimating the number of clusters in a data set via the gap statistic." *J. R. Statist. Soc*. B 63 (2), 411–423
- Timo S, Anu M, Pia A, Tuija R A, Toni A (2002) "Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates—the Excel template application MAKESENS." Finnish Meteorological Institute Publications on Air Quality, Helsinki, p 31
- Tosunoglu, F., Can, I., (2016.) "Application of copulas for regional bivariate frequency analysis of meteorological droughts in Turkey." *Natural Hazards* 82, 1–21. doi:10.1007/s11069-016-2253-9
- Tosunoglu, F., Kisi, O., (2016). "Joint modelling of annual maximum drought severity and corresponding duration." *Journal of Hydrology.* doi:10.1016/j.jhydrol.2016.10.018
- Tsakiris G, Vangelis H (2005) "Establishing a drought index incorporating evapotranspiration." *EurWater Manag* 9(10):3–1.
- Tsakiris, G., Pangalou, D., Vangelis, H., (2007). "Regional drought assessment based on the Reconnaissance Drought Index (RDI)." *Water Resour. Manage*. 21 (5), 821–833.
- Tsakiris, G., Pangalou, D., Vangelis, H., (2008). "Regional drought assessment based on the Reconnaissance Drought Index (RDI)." *Water Resour. Manag*. 21, 821–833. https://doi.org/10.1007/s11269-006-9105-4.
- Tucker, C. J. (1979). "Red and photographic infrared linear combinations for monitoring vegetation". *Remote Sens. Environ*. 8(2): 127– 150.
- Tucker, C.J., C.O. Justice, and S.D. Prince. (1991). "Monitoring the grasslands of the Sahel 1984–1985". *International Journal of Remote Sensing* 7:1571–1581.
- Tucker, C.J., Choudhury, B.J., (1987). "Satellite remote sensing of drought conditions". *Remote Sens. Environ*., 23, pp. 243?251.

- United Nations Environment Programme (UNEP), (1992), "World Atlas of Desertification".
- Van Lanen, H. A. J. and Peters, E., (2000). "Definition, effects and assessment of groundwater droughts, in: Drought and Drought Mitigation in Europe" edited by: Vogt, J. V. and Somma, F., Kulwer, Dordrecht, 49–61.
- Van Lanen, H. A. J., (2004). "On the definition of groundwater drought," *Geophys. Res. Abstr.*, 7, 10867.
- Van Loon, A.F., Laaha, G., (2015). "Hydrological drought severity explained by climate and catchment characteristics." *Journal of Hydrology* 526, 3–14. doi:10.1016/j.jhydrol.2014.10.059
- Vangelis H, Spiliotis M, Tsakiris G (2011) "Drought severity assessment based on bivariate probability analysis." *Water Resour Manag* 25:357–371
- Vangelis, H., Tigkas, D., Tsakiris, G., (2013). "The effect of PET method on Reconnaissance Drought Index (RDI) calculation." *J. Arid Environ*. 88, 130–140.
- Vicente-Serrano, S.M. , Beguería, S. , López-Moreno, J.I. , (2010). "A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index." *J. Clim*. 23 (7), 1696–1718.
- Vicente-Serrano, S.M., Van der Schrier, G., Beguería, S., Azorin-Molina, C., Lopez-Moreno, J.I., (2015). "Contribution of precipitation and reference evapotranspiration to drought indices under different climates." *J. Hydrol.* 526, 42–54. https://doi.org/10.1016/j.jhydrol.2014.11.025
- Vincente-Serrano, S. M., Beguerıa, S., Lorenzo-Lacruz, J., Camarero, J. J., Lopez-Moreno, J. I., Azorin-Molina, C., Sanchez-Lorenzo, A. (2012). "Performance of drought indices for ecological, agricultural and hydrological applications." *Earth Interactions,* 16, 010. https://doi. org/10.1175/2012EI000434.1
- Vittal K P R, Rao K V, Sharma K L, Victor U S, Chary G R, Sarkar G M (2005) "Guidelines for Rainfed Production System and Management. In: Drought Management:" Allied Publisher Private Limited, pp. 76–106

- Vyas, S. S., Bhattacharya, B. K., Nigam, R., Guhathakurta, P., Ghosh, K., Chattopadhyay, N., & Gairola, R. M. (2015). "A combined deficit index for regional agricultural drought assessment over semi-arid tract of India using geostationary meteorological satellite data". *International journal of applied earth observation and geoinformation*, 39, 28-39.
- Wable, P. S., Jha, M. K., Shekhar, A., (2018) "Comparison of Drought Indices in a Semi-Arid River Basin of India" *Water Resour Manag* doi.org/10.1007/s11269-018-2089-z
- Wambua R. M., Benedict M. Mutua, and James M. Raude, (2015) "Spatio-temporal Drought Characterization for the Upper Tana River Basin, Kenya Using Standardized Precipitation Index (SPI)." *World Journal of Environmental* Engineering, vol. 3, no. 4 :111-120. doi: 10.12691/wjee-3-4-2
- Wang, L., Chen, W., & Zhou, W. (2014). "Assessment of future drought in Southwest China based on CMIP5 multimodel projections". *Advances in Atmospheric Sciences*, 31(5), 1035-1050.
- Wang, P. X., Li, X. W., Gong, J. Y., & Song, C. (2001). "Vegetation temperature condition index and its application for drought monitoring. In IGARSS 2001. Scanning the Present and Resolving the Future". *Proceedings. IEEE 2001 International Geoscience and Remote Sensing Symposium* (Cat. No. 01CH37217), IEEE, 1, 141-143.
- Wang, X. (2000). "Characteristics analysis of rainfall in the upper reaches of the Shaying River Basin". *Hydrology*, 20(1), 53-55.
- Ward, J.H., (1963). "Hierarchical grouping to optimize an objective function," *Journal of the American Statistical Association*, 58:236–244
- Warrick R.A. (1965), "Drought Hazard in the United States - A Research Assessment", National Technical Information Service, Springfield, Virginea, USA.
- Wilhite D A (2000) Drought as a natural hazard: concepts and definitions. In: Wilhite, D.A. (Ed.), Drought: A Global Assessment. Routledge Publishers, London, pp. 3–18.
- Wilhite, D. A. (2005). "Drought and water crises: science, technology, and management issues". *Crc Press.*

- Wilhite, D.A., (2000). “Drought: A Global Assessment, Vols. 1 and 2. Routledge, New York, 89-104, 1 and 2, Routledge, New York”, 129–448.
- Wilhite, D.A., (2000a). “Preparing for drought: a methodology. In: Wilhite, D.A. (Ed.), Drought: A Global Assessment, Routledge Hazards Disaster Ser”., *Routledge, Boca Raton,* Fla, 2, 89–104.
- Wilhite, D.A., and M.H. Glantz. (1987). “Understanding the drought phenomenon.” In: D.A. Wilhite, W.E. Easterling, and D.A. Wood (eds.), Planning for Drought: Toward a Reduction of Societal Vulnerability. Westview Press, Boul- der, CO, pp. 11–27.
- William M., Alley (1984)."The Palmer Drought Severity Index: Limitations and Assumptions.*" Journal of Climate and Applied Meteorology*.Vol. 23, pp 1100-1109
- Wong, G., Lambert, M. F., & Metcalfe, A. V. (2010). “Trivariate copulas for characterisation of droughts”. *Anziam Journal,* 49, 306-323.
- Wu H, Soh Leen-Kiat, Samal A, Chen X H (2008) “Trend analysis of streamflow drought events in Nebraska.” *Water Resources Management*. DOI 10.1007/ s11269-006-9148-6
- Wu, H., Soh, L. K., Samal, A., & Chen, X. H. (2007). “Trend analysis of streamflow drought events in Nebraska”. *Water Resources Management*, 22(2), 145-164.
- Xu, K., Yang, D., Yang, H., Li, Z., Qin, Y., & Shen, Y. (2015). “Spatiotemporal variation of drought in China during 1961–2012: A climatic perspective”. *Journal of Hydrology,* 526, 253-264.
- Yevjevich, V. M. (1969). “Objective approach to definitions and investigations of continental hydrologic droughts”, *An. Hydrology papers* (Colorado State University); no. 23.
- Yevjevich, V., (1967). “An objective approach to definitions and investigations of continental hydrologic droughts.” Report, Colorado State University.
- Yevjevich, V., Da Cunha, L., Vlachos, E., (1983). “Coping with droughts”, *Water Resources Publications*, Littleton, Colorado.

- Yildiz, O., (2014). “Spatiotemporal Analysis of Historical Droughts in the Central Anatolia, Turkey” 27, 1177–1184.
- Yu, P.-S., Yang, T.-C., Kuo, C.-M., Tseng, H.-W., Chen, S.-T., (2014). “Climate Change Impacts on Streamflow Drought: A Case Study in Tseng-Wen Reservoir Catchment in Southern Taiwan.” *Climate* 3, 42–62. https://doi.org/10.3390/cli3010042
- Yu, X., He, X., Zheng, H., Guo, R., Ren, Z., Zhang, D., & Lin, J. (2014). “Spatial and temporal analysis of drought risk during the crop-growing season over northeast China”. *Natural Hazards*, 71(1), 275-289.
- Yue S, Pilon P, Phinney B (2003) “Canadian streamflow trend detection: Impacts of serial and cross-correlation”. *Hydrological Sciences Journal*, 48(1): 51-64.
- Zang, R., Chen, X., Zhang, Z., & Shi, P. (2014). “Evolution of hydrological drought under the regulation of two reservoirs in the headwater basin of the Huaihe River, China”. *Stochastic environmental research and risk assessment*, 29(2), 487-499.
- Zarch, M. A. A., Malekinezhad, H., Mobin, M. H., Dastorani, M. T., & Kousari, M. R. (2011). “Drought monitoring by reconnaissance drought index (RDI) in Iran”. *Water resources management*, 25(13), 3485.
- Zarei, A.R., Moghimi, M.M., Mahmoudi, M.R., (2016). “Analysis of Changes in Spatial Pattern of Drought Using RDI Index in south of Iran”. *Water Resour. Manag.* 30, 3723–3743. https://doi.org/10.1007/s11269-016-1380-0
- Zargar A, Sadiq R, Naser B, Khan F I (2011) “A review of drought indices.” *Environmental Reviews*, 19:333–349. https://doi.org/10.1139/a11-013
- Zhang A, Jia G (2013) “Monitoring meteorological drought in semiarid regions using multi-sensor microwave remote sensing data.” *Remote Sens Environ* 134:12–23
- Zhang, H., Li, N., Zhang, W., & Pei, X. (2012). “Experiments to automatically monitor drought variation using simulated annealing algorithm”. *Natural Hazards*, 84(1), 175-184.
- Zhao L, Lyu A, Wu J, Hayes M, Tang Z, He B, Liu J, Liu M (2014). “Impact of meteorological drought on streamflow drought in Jinghe River Basin of

China." *Chinese Geographical Science* 24:694–705. doi:10.1007/s11769-014-0726-x

PUBLICATIONS

International Journals

- **Pathak, A.A**., Dodamani, B.M., (2019). “Application of remotely sensed NDVI and soil moisture to monitor long-term agricultural drought”. Earth Resources and Environmental Remote Sensing/GIS Applications. 111 56. doi.org/10.1117/12.2532852.

- **Pathak, A.A**., Dodamani, B.M., (2019). “Comparison of Meteorological Drought Indices for Different Climatic Regions of an Indian River Basin”. Asia-Pacific Journal of the Atmospheric Sciences. DOI: 10.1007/s13143-019-00162-5.

- **Pathak, A.A**., Dodamani, B.M., (2018). “Trend Analysis of Groundwater Levels and Assessment of Regional Groundwater Drought: Ghataprabha River Basin, India”. Natural Resources Research. 28-3 (631–643) doi.org/10.1007/s11053-018-9417-0.

- **Pathak, A.A.,** Dodamani, B.M., (2018). “Assessment of Agricultural Drought by Remote Sensing Technique”. Remote Sensing for Agriculture, Ecosystems, and Hydrology. 10783, (1-13). doi.org/10.1117/12.2325494.

- **Pathak, A.A.,** Nizar, S., Dodamani, B.M., (2018) “Trends in Agro-Meteorological Parameters as Groundwater Exploitation Indicators”. Earth and Environmental Science., 167(1-9). doi :10.1088/1755-1315/167/1/012004.

- **Pathak, A.A.,** Channaveerappa, Dodamani, B.M., (2016). “Comparison of Two Hydrological Drought Indices”. Perspectives in Science 8 (1–4). doi:10.1016/j.pisc.2016.06.039.

- **Pathak A.A,** Dodamani B.M. (2019) "Trend Analysis of Meteorological Drought- A Case Study for Ghataprabha River Basin, India". Journal of Hydraulic Engineering. (Under review)

- **Pathak A.A**, Dodamani B.M. (2019) "Assessment of regional groundwater drought and bivariate frequency analysis using the copula" Journal of Hydrology (Under review).

International Conferences

- **Pathak, A.A**, Dodamani, B.M. (2019) ‘‘Enhancement in the Characterization of Historical and Future Droughts with a Copula Based Integrated Drought Index" AGU General Assembly 2019, to be held at San-Francisco, CA, USA from 9-13 December 2019.

- Datta R., **Pathak A.A**, Dodamani B.M. (2019) ‘’Assessment of Meteorological Drought Return Periods Over A Temporal Rainfall Change’’ International conference on "Civil Engineering Trends and Challenges for Sustainability" (CTCS-2019). Held from 23-24 May 2019 at NMAM Institute of Technology, Nitte, Karkala, India.

- **Pathak, A.A**, Dodamani, B.M. (2019) "Analysis of Agricultural Drought and Investigation of Bivariate Return Periods using Copula" EGU General Assembly 2019, 7–12 April 2019, Vienna, Austria.

- **Pathak A.A**., Dodamani B.M. (2018) "Assessment of Agricultural Drought by Remote Sensing Technique" SPIE Remote Sensing 2018. 10-13 September 2018, Berlin, Germany.

- **Pathak A.A**., Dodamani B.M. (2017) "Drought assessment for Ghataprabha River basin - a multi probability approach" 3rd World's Large River Conference on the

"Status and Future of the World's Large Rivers". April 18 - 21, 2017. New Delhi, India

- **Pathak A.A.**, Dodamani B.M. (2016) "A Review on Agricultural Drought Indices", HYDRO 2016 - 21st International Conference on Hydraulics, Water Resources and Coastal Engineering, 8-10 December 2016. ISH-Pune, India.

RESUME

Name : ABHISHEK A PATHAK.

Date of Birth : 13-08-1991

Address : S/o A.S. Pathak,
#3555/C,
Near Dwarakanatha temple,
Hulyalkar Galli, Jamkhandi
District: Bagalkot
Karnataka, India-587301

Mobile : (+91) 7411758251

Email(s) : abhipathak2013@gmail.com

Qualification : B.E. (Civil), M.Tech. (WRE)

Journal Publications : 6

No. of Conference Publications : 6

Awards / Fellowships

- American Geophysical Union (AGU) Travel grant.
- DST International Travel Support (ITS) For Young Scientists, from Science & Engineering Research Board (SERB), India.
- India-UK water center sponsorship for the workshop held at Lancaster University UK.