DROUGHT DETECTING AND MONITORING OVER TERAI AND MOUNTAIN REGION OF NEPAL

A THESIS SUBMITTED TO THE

CENTRAL DEPARTMENT OF HYDROLOGY AND METEOROLOGY

INSTITUTE OF SCIENCE AND TECHNOLOGY

TRIBHUVAN UNIVERSITY

NEPAL

FOR THE AWARD OF

DOCTOR OF PHILOSOPHY

IN HYDROLOGY AND METEOROLOGY

BY

DAMODAR BAGALE

JULY 2023

DROUGHT DETECTING AND MONITORING OVER TERAI AND MOUNTAIN REGION OF NEPAL

A THESIS SUBMITTED TO THE

CENTRAL DEPARTMENT OF HYDROLOGY AND METEOROLOGY
INSTITUTE OF SCIENCE AND TECHNOLOGY
TRIBHUVAN UNIVERSITY
NEPAL

FOR THE AWARD OF
DOCTOR OF PHILOSOPHY
IN HYDROLOGY AND METEOROLOGY

BY

DAMODAR BAGALE

JULY 2023

TRIBHUVAN UNIVERSITY
Institute of Science and Technology
DEAN'S OFFICE
Kirtipur, Kathmandu, Nepal

Reference No.:

Institute of Science & Technology
Dean's Office
Kirtipur 2045

EXTERNAL EXAMINERS

The Title of Ph.D. Thesis: " Drought Detecting and Monitoring over Terai and Mountain Region of Nepal "

Name of Candidate: Damodar Bagale

External Examiners:

(1) Dr. Dhiraj Pradhananga
Tri-Chandra Multiple Campus
Tribhuvan University, NEPAL

(2) Dr. Fatima Akter
University of Dhaka
Dhaka, BANGLADESH

(3) Prof. Dr. Toru Terao
Kagawa University
Takamatsu, JAPAN

March 13, 2024

(Dr. Surendra Kumar Gautam)
Asst. Dean

DECLARATION

Thesis entitled "**Drought Detecting and Monitoring over Terai and Mountain Region of Nepal**" which is being submitted to the Central Department of Hydrology and Meteorology, Institute of Science and Technology (IOST), Tribhuvan University, Nepal for the award of the degree of Doctor of Philosophy (Ph.D.), is a research work carried out by me under the supervision of Prof. Dr. Deepak Aryal of Central Department of Hydrology and Meteorology, Tribhuvan University.

This thesis is original and has not been submitted earlier in part or fulfill in this or any other form to any university or institute, here or elsewhere, for the award of any degree.

Damodar Bagale

RECOMMENDATION

This is to recommend that **Mr. Damodar Bagale** has carried out research entitled "**Drought Detecting and Monitoring over Terai and Mountain Region of Nepal**" for the award of Doctor of Philosophy (Ph.D.) in **Hydrology and Meteorology** under my supervision. To my knowledge, this research work has not been submitted for any other degree.

He has fulfilled all the requirements laid down by the Institute of Science and Technology (IOST), Tribhuvan University, Kirtipur for the submission of the thesis for the award of Ph.D. degree.

Prof. Dr. Deepak Aryal
Supervisor
Central Department of Hydrology and Meteorology
Tribhuvan University
Kirtipur, Kathmandu, Nepal.

Accredited by University Grants Commission (UGC), Nepal, (2021)
TRIBHUVAN UNIVERSITY
CENTRAL DEPARTMENT OF HYDROLOGY & METEOROLOGY
Kirtipur, Kathmandu, Nepal

LETTER OF APPROVAL

Date: March 13, 2024

On the recommendation of **Prof. Dr. Deepak Aryal**, this Ph.D. thesis submitted by **Mr. Damodar Bagale,** entitled "**Drought Detecting and Monitoring over Terai and Mountain Region of Nepal**" is forwarded by Central Department Research Committee (CDRC) to the Dean, IOST, T. U..

Prof. Dr. Deepak Aryal
Head
Central Department of Hydrology and Meteorology
Tribhuvan University
Kirtipur, Kathmandu
Nepal

Phone No.: 4-331418, 4-333887, Fax No.: 977-1-4331964

ACKNOWLEDGEMENTS

First, I would like to express my sincere gratitude to my supervisor Prof. Dr. Deepak Aryal for the continuous support of my Ph.D. study and research work, for his invaluable advice, encouragements, patience, motivation, knowledge and constantly guiding me throughout the Ph.D. research journey. I also would like to thank Associate Prof. Dr. Madan Sigdel, for his insightful comments and valuable advice on journal review processes and the writing of this thesis. I gratefully acknowledge the University Grants Commission (UGC), Nepal for the Ph.D. fellowship.

I am grateful to Prof. Dr. Tek bahadur Chettri, Associate Prof. Dr. Binod Dawadi, Dr. Suraj Shrestha, Dr. Dibash Shrestha, Dr. Sunil Acharya and all the faculties and members of the Central Department of Hydrology and Meteorology (CDHM) TU. Similarly, I would like to thanks all the administrative staff of CDHM for their support.

I would like thank my beloved wife Sahiva Atreya and my lovely children Anuska Bagale and Bashudev Bagale for their patience and support during this challenging time. Last but not least, I feel highly indebted to my parents, brothers and sisters including the other family members, who have always been a constant source of support and love to me.

Damodar Bagale
July 2023

ABSTRACT

This study was conducted using 42 years rainfall data since 1977 to 2018 of 107 meteorological stations to examine monthly to decadal rainfall variability of 107 stations over the country were used. The western region has observed low rainfall in pre-monsoons, monsoon, and post-monsoon seasons but observed heavy rainfall in winter season in comparison with the central and eastern regions. The contribution of winter rainfall to annually varied from 0.68% in the year 2006 to 7.04 % in the year 1989. Similarly, the contribution of monsoon rainfall annually varied from 76 % in the year 1992 to 86 % in 1984.The decadal wise rainfall was decreased both in monsoon and winter seasons in the recent couple of decades. There was a strong correlation between the rainfall and Southern Oscillation Index (SOI) in the monsoon season and weak in winter. Generally, large negative/positive magnitudes of SOI on the Indian and Pacific Ocean influence weakening/strengthening monsoon rainfall in Nepal. During El Niño year's average deficit rainfall was approximately 9 % below the average monsoon rainfall. However, the negative trends of annual rainfall dominated over the country.

This study identified winter, summer and annual drought events using the Standard Precipitation Index (SPI). Monthly rainfall was used as an input variable to generate the SPI of 107 stations from 1977 to 2018. The SPI threshold was used to identify, categorize and monitor droughts over Nepal. For this, we investigated the frequency, duration, and severity of drought events. The SPI3, SPI4 and SPI12 month time scales were interpolated to illustrate the spatial patterns of major drought episodes and their severity. In winter large percentage of stations over the country showed a significant decreasing trend for SPI3 in comparison with the monsoon (SPI4) and annual (SPI12).The drought events in El Niño years and non-El Niño years were more strongly related between SPI and SOI than the average years. The relationship between SPI and the climate indices such as the SOI and ONI anomaly over the Niño 3.4 has suggested that one of the causes for summer droughts is El Niño. This study indicated that summer droughts occurred in both El Niño and non-El Niño years. Out of eight drought years, only four drought years were associated with El Niño episodes (1982,1992, 2009, and 2015), and the remaining four drought years (1977,1979, 2005, and 2006) were recorded in non-El Niño years. Similarly, winter and annual droughts evolved in El Niño and non-El Niño years.

There is a strong correlation (0.53) between SPI4 and SOI in the monsoon season and a weak in SPI3 and SOI is - 0.31 in the winter at 95 percent confidence level. The regional analysis identified that there is strong correlation between rainfall and SOI for the western region than the central and eastern regions in the monsoon season. Similarly, the correlation coefficient between rainfall and SOI in winter is strong in the western region than in the central eastern regions. Generally, during drought years; SPI and SOI have a strong phase relation compared to average years. Droughts have been recorded more frequently in Nepal since 2000.The areas of Nepal affected by extreme, severe and moderate drought in winter were 4, 21 and 37 percent. Likewise, the areas of Nepal affected by average extreme, severe and moderate drought both in summer and annual events are 7, 9, and 18 percentages and 7, 11, and 17 percentages respectively. The drought-hazardous zones are highest in the western and northwest parts in comparison with the central and eastern regions on both SPI4 and SPI12 time scales. About 47 and 30 percent of areas of Nepal were found to be under high and very high drought hazardous zones of the total area based on SPI4 and SPI12 time scales.

Keywords: Monsoon rainfall, Drought, El Nino, SOI, SPI, Nepal

शोधसार

यो शोधकार्य नेपालका एक सय सात वटा मौसमी केन्द्रहरूको मासिक तथा वार्षीक वर्षाको परिवर्तनशीलता तथा परिणात्मक अनुसन्धान अन्वेषण गर्नका लागि गत ४२ वर्ष (सन् १९७७–२०१८) को तथ्यङ्क प्रयोग गरी गरीएको हो । पश्चिम क्षेत्रमा प्रि–मनसुन, मनसुन र मनसुन पश्चातको मौसममा कमवर्षा हुने गरेको छ । तर मध्य र पूर्वी क्षेत्रको तुलनामा त्याँहा हिउँदमा भारी वर्षा हुने गरेको पाइयो । हिउँदे वर्षा सन् २००६ मा ०.६८ प्रतिशत र सन् १९८९ मा ७.०४ प्रतिशतसम्म परेको देखियो । त्यसैगरी मनसुन वर्षाको योगदान १९९२ मा ७६ प्रतिशत र सन् १९८४ मा ८६ प्रतिशत सम्म वार्षिक भिन्नता पाइयो । पछिल्ला चार दशकहरुमा वर्षे मनसुन र जाडो मौसममा हिउदे वर्षा घटेको अनुसन्धान बाट देखिएको छ । मनसुनी वर्षा र साउदन ओसिलेसन इन्डेक्स (SOI) विचको सम्बन्ध वर्षा याममा बलियो र जाडोमा कमजोर पाइयो । सामान्यतया हिन्द र प्रशान्त महासागरमा SOI को नकारात्मक र सकारात्मक परिणामले नेपालमा मनसुन वर्षालाई कमजोर र सशक्त बनाउन प्रभाव पार्दछ ।

एलनिनो वर्षको समयावधीमा (कम बर्षाको अवधिमा) औसत मनसुन वर्षा भन्दा लगभग ९ प्रतिशत कम वर्षा परेको अनुसन्धानले देखायो । यद्यपि वर्षाको घढ्दो क्रम देशमा बढिरहेको छ । यस अध्ययनले जाडो, गर्मी तथा वार्षिक खडेरी घटनाहरू मानक वर्षा सूचकांक (SPI) प्रयोग गरी पहिचान गरेको छ । सन् १९७७ देखि २०१८ सम्म एक सय सात वटा मौसमी केन्द्रहरुको SPI निकाल्नको लागि मासिक वर्षालाई उपायोग गरिएको थियो । SPI थ्रेसहोल्डलाई नेपालमा खडेरी पहिचान गर्न, वर्गीकरण गर्न र निरन्तर निगरानी गर्न प्रयोग गरिएको थियो । यसका लागि खडेरीका घटनाहरुको आवृति, अवधि र गम्भीरताको अनुसन्धान गरियो । हिउँदमा (SPI3), वर्षामा (SPI4) र वार्षिक रूपमा परिमाण (SPI12), विभिन्न अवधिहरुमा, प्रमुख खडेरी एपिसोडहरु र तिनीहरुको वार्षीक मनसुनी प्रभाव को तुलनामा हिउदमा उल्लेखनीयरुपमा घट्ने प्रवृत्ति देखायो । एलनिनो वर्ष र गैर एलनिनो वर्षहरुमा खडेरीका घटनाहरु SPI र वर्षा बिचमा बढी जोडदार रूपमा सम्बन्धित बडेको पाइयो । औसत वर्ष भन्दा SPI, निनो (३.४) क्षेत्रमा SOI र ONI जस्ता जलवायु सुचकाङ्कहरु बिचको सम्बन्धले ग्रीष्म कालीन खडेरीको समयको कारण

एलनिनो हो भनी कीटान गरिएको छ । यस अध्ययनले ग्रीष्मकालीन खडेरी एलनिनो (१९८२, १९९२, २००९ र २०१५) वर्षहरुमा र आठ खडेरी वर्षहरु मध्ये केवल चार खडेरी वर्षहरु एलनिनो एपिसोडहरुसंग सम्बन्धित थिए र बाकि खडेरी वर्षहरु (१९७७, १९७९, २००५ र २००६) समेत पाइएको थियो । त्यस्तै खडेरीका घटनाहरु हिउद, ग्रीष्म कालीन र वार्षिक खडेरी एलनिनो र गैर–एलनिनो वर्षहरुमा विकसित भयको पाइयो । मनसुन याममा SPI र SOI बिच बलियो सम्बन्ध र हिउँदमा केही कमजोर सम्बन्ध रहेको (९५ प्रतिशत) सार्थक स्तरमा देखियो । क्षेत्रीय विश्लेषणगर्दा मनसुन समयमा मध्य र पूर्वी क्षेत्रको तुलनामा पश्चिमी क्षेत्रको वर्षा र SOI बिच कमजोर सम्बन्ध रहेको पाइयो । त्यसैगरी, हिउँदे वर्षा र SOI बिचको सम्बन्ध गणांक मध्य पूर्वी क्षेत्रहरु भन्दा पश्चिमी क्षेत्रमा बलियो देखियो । सामान्यतया खडेरी वर्षहरुमाः SPI र SOI बिच औसत वर्षको तुलनामा बलियो चरण सम्बन्ध अध्यनले पुष्टी गरेको छ । नेपालमा सन् २००० यता खडेरी धेरै पटक रेकर्ड गरिएको छ । नेपालको हिउँदमा चरम, गम्भीर र मध्यम खडेरीबाट प्रभावित क्षेत्रहरु क्रमश ४, २१ र ३७ प्रतिशत पाइयो । त्यसैगरी ग्रीष्म र वार्षीक समयावधीमा औसत चरम, गम्भीर र मध्यम खडेरीबाट प्रभाभित क्षेत्रहरु क्रमश ७, ९ र १८ प्रतिशत र ७, ११ र १७ प्रतिशत छन् । त्यसैगरि मध्य र पूर्वी क्षेत्रहरुको तुलनामा पश्चिम र उत्तर–पश्चिमी भागहरुमा खडेरीको आँकडा उच्च र अति उच्च भएको पाइयो । दुवै क्षेत्रहरुमा वर्षाका परीमाणहरु भने सबैभन्दा बढी भएको अध्यनले देखायो । नेपालका करिब ४७ र ३० प्रतिशत क्षेत्रहरु SPI4 र SPI12 टाइम स्केलमा उच्च र अति उच्च खडेरीको जोखिमयुक्त क्षेत्रहरु अन्तर्गत रहेको पाइयो ।

प्रमुख वाक्यहरु: मनसुन वर्षा, खडेरी, एलनिनो, SOI, SPI र नेपाल

LIST OF ACRONYMS AND ABBREVIATIONS

CBS	: Central Bureau of Statistics
DHM	: Department of Hydrology and Meteorology
DHI	: Drought Hazard Index
GIS	: Geographic Information System
ENSO	: El Nino Southern Oscillation
IPCC	: Intergovernmental Panel on Climate Change
IDW	: Inverse Distance Weighted
ITCZ	: Inter-tropical Convergence Zone
JIST	: Journal of Institute of Science and Technology
MK	: Mann-Kendall Test
NDVI	: Normalized Difference Vegetation Index
NOAA	: National Oceanic and Atmospheric Administration
NMHS	: National Meteorological and Hydrological Service
NSMR	: Nepal Summer Monsoon Rainfall
PDNSMR	: Percent Departure Nepal Summer Monsoon Rainfall
RDI	: Reconnaissance Drought Index
SDI	: Stream flow Drought Index
SPEI	: Standard Precipitation and Evaporation Index
SPI	: Standard Precipitation Index
SOI	: Southern Oscillation Index
SST	: Sea Surface Temperature

ONI	: Ocean Nino Index
PDSI	: Palmer Drought Severity Index
PN	: Percent of Normal
WCE	: Western, Central and Eastern
WMO	: World Meteorological Organization

LIST OF SYMBOLS

%	: Percent
>	: Greater Than
<	: Smaller Than
°C	: Degree Celcius
F_s	: Drought Frequency in Percent
n_s	: Number of Drought Events
N_s	: Total Number of Years for the Study Period
s	: Station
P_j	: Drought Station Proportion at a Given Time Scale in Percentage
J	: Time Scales
n_j	: Number of Droughts in the Given Time
N_j	: The Total Number of Stations
$\mathrm{R_i}$	: Monsoon Rainfall
$\overline{\mathrm{R}}$	: Mean Monsoon Rainfall

LIST OF TABLES

LIST OF FIGURES

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Background

Drought is a typical, natural, locally or regionally recurring characteristic of the climate. It occurs in virtually all climatic regimes in areas with high and low rainfall. Drought is one of the most complexes and recurring phenomena in different regions of the globe (Van Loon *et al.*, 2016; Wilhite *et al.*, 2007). Drought is considered to be the most complex but least understood of all-natural hazards, affecting more people and the environment, and causing more substantial economic losses than any other hazard (Wilhite *et al.*, 2007; Hagman, 1984). It is insidious, slow- onset that produces a complex web of impacts that ripple through many sectors of the economy (Wilhite *et al.*, 2007; Hagman, 1984). The effects of drought often accumulate slowly over a considerable period of time and many linger for years after the termination of the event, the onset and end of drought are difficult to determine (Wilhite, 2000). The characteristics and quantity of drought are really useful for enabling both severities versus impacts analysis and risk assessment (Zargar *et al.*, 2011). Drought is a critical water shortage resulting from prolonged deficiency of precipitation that affects groundwater, river flows, and water storages, affects vegetation growth, agriculture, and hydropower generation, in various territories and ultimately communities (Portner *et al.*, 2022; Sternberg, 2011; Mishra and Singh, 2010; IPCC, 2007; Wilhite and Glantz, 1985). The effect of global warming and climate change (rising temperature and changing rainfall pattern) affect the occurrence severity of drought which has increased in many parts of the world (Portner *et al.*, 2022; Trenberth *et al.*, 2014; IPCC, 2007). A combination or sequence of droughts has severe impacts on human and environmental welfare (Sheffield and Wood, 2008). Drought can be grouped into five kinds, namely, Meteorological drought; Hydrological drought; Agricultural drought, Socio-economic drought, and Groundwater drought (Mishra and Singh, 2010). Meteorological drought is the consequence of a natural reduction in the amount of precipitation received over an extended period, usually a season or more in length (Wilhite, 2000). The World Meteorological Organization (WMO) has recommended using the standard precipitation index (SPI) for extensive use by all national Meteorological and Hydrological Services to ascertain Meteorological drought and complement local drought indices currently being used (WMO, 2012). The Southern Oscillation Index (SOI) measures a large-scale fluctuation in sea-level pressure between La Niña and El Niño. The years of abnormally high sea surface temperature (SST) from the west coast of South America towards the equatorial mid-pacific are known as El Niño years, and the years of abnormally colder waters in the same region are known as La Nina years (Sikka, 1980). Most drought years are associated with El Niño episodes, followed by non-El Niño events in India (Varikoden *et al.*, 2015; Krishnamurthy and Goswami, 2000; Kripalani and Kulkarni, 1996). During the El Niño years, a strong tendency for below-normal Indian monsoon rainfall spread over most parts of the country (Varikoden et al., 2015; Bhalme and Jadhav, 1984; Sikka, 1980). There is good agreement between the significant negative/positive value of SOI and droughts/floods; however, some exceptions are unexplained by the SOI (Bhalme and Jadhav, 1984). The decrease in Indian monsoon rainfall was associated with the warm phase of El Nino Southern Oscillation (ENSO) due to anomalous regional Hadley circulation with decreasing motion over the Indian subcontinent (Varikoden *et al.*, 2015).

Nepal observes excess rainfall in the monsoon months of the year, while there is a deficit in some other months. Almost 80% of the annual rainfall occurs during the monsoon months from June to September, and the remaining months face a deficit of water (Ichiyanagi *et al.*, 2007; Shrestha, 2000). Summertime is dominated by a monsoonal climate, while wintertime is by western disturbances. However, winter precipitation (December to February) is significant as it accounts for approximately about 3% of Nepal's annual precipitation total (Bagale *et al.*, 2023). Precipitation plays a major role in the mass balance of glaciers in the western region while playing a secondary role in the glaciers of eastern and central Nepal (Katsumoto *et al.*, 1998).

There are four seasons in Nepal, namely, pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November), and winter (December-February). Pre-monsoon is characterized by hot, dry, and westerly windy weather with mostly localized precipitation in a narrow band, whereas the monsoon is characterized by moist southeasterly monsoonal winds coming from the Bay of Bengal and occasionally from the Arabian Sea with widespread precipitation. Post-monsoon refers to a dry season with sunny days featuring the driest month, November. Winter is a cold season with precipitation mostly in the form of snow in high-altitude mountainous regions (Ichiyanagi *et al.*, 2007).

Many studies have been undertaken to detect rainfall variability in Nepal; however, very few studies have been conducted on drought monitoring. Although few historical droughts monitoring research has been conducted, real-time drought monitoring by the national meteorological and hydrological service (NMHS) has not been carried out in Nepal. Instead, with the rainfall data, NMHS issues the seasonal precipitation analysis (above normal/normal/below normal) based on the meteorological observatories. A number of previous drought studies have been carried out in Nepal (Aryal *et al.*, 2022; Bagale *et al.*, 2021; Sharma *et al.*, 2020; Baniya *et al.*, 2019; Sigdel and Ikeda, 2010). Drought events have occurred frequently in Nepal after 2000 (Bagale *et al.*, 2021). Therefore, the impacts of drought assessment are essential for reducing the drought impact. Drought events have been observed frequently associated with El Nino and normal years. There was a strong correlation between standardized monsoon rainfall and southern oscillation index (Sigdel and Ikeda, 2010). Generally, the drought year has been dominated by ENSO (Sharma *et al.*, 2020). Aryal *et al.* (2022) identified the drought years using both SPI and anomaly methods; indicating that the drought events have been marked frequently after 1990. Baniya *et al.* (2019) observed the drought variability using normalized difference vegetation index (NDVI) from 1982 to 2015. The findings noticed that the drought was marked frequently in Nepal. The major factor for drought evolution in Nepal is the lack of precipitation (Sigdel and Ikeda, 2010). During drought events climatic hazards were observed in South Asia (Abeysingha and Rajapaksha, 2020; Uddin *et al.*, 2020; Mondol *et al.*, 2017; Xie *et al.*, 2013).

Drought hazard monitoring is important for agriculture, water resources management and planning, hydropower generation, biodiversity, and socio-economic sector. Shahid and Behrawan (2008) monitor the drought-hazardous zones in Bangladesh. It has been identified as one of the drought-affected countries (Rahman and Lateh, 2016; Shahid and Behrawan, 2008; Chowdhury, 2003). Similarly, different earlier researchers have worked on drought hazard of an extreme event and its risk analysis in different regions of the globe (Dabanli, 2018; Rajsekhar *et al.*, 2015; Shahid and Behrawan, 2008). However, drought hazard monitoring over Nepal is still new. This study also monitors the drought hazardous zone, based on SPI time scales. For this purpose, using SPI technique drought hazard monitoring has not been done yet in Nepal. This study has calculated drought hazard Index (DHI) using SPI rating and weight values. The major aim of the study is to monitor the historical (seasonal and annual) drought over Nepal and its relationship with El Niño and Southern Oscillation. Similarly, this study has focused on the temporal and spatial progression of major drought.

1.2 Rational of the study

Drought study in Nepal is crucial for the agricultural and water resources aspects. Nepal is agricultural country most of people depend on the agriculture (CBS, 2013). Different previous researchers (Sigdel and Ikeda, 2010; Kafle, 2015, Wang *et al.*, 2013; Dahal *et al.*, 2016; Khatiwada and Pandey, 2019; Bania *et al.*, 2019; Sharma *et al.*, 2021; Dahal *et al.*, 2021; Aryal *et al.*, 2021) has been studied the drought study in Nepal. Above mention researchers conducted the basin wise, regional and country wise drought studies. Most of the above mention researchers have been focused on temporal variability of drought events. Different researchers have different objectives and set different questions to fulfill the objectives of the study. Reviewing the national and international journal papers of droughts, extreme events, and relevant papers, reports, and documents (Hagman, 1984; McKee *et al.*, 1993, Mishra and Singh, 2010; Kumar et al., 2013, Hayes *et al.*, 1999; Varikoiden *et al.*, 2015; Van Loon *et al.*, 2016; Portner *et al.*, 2022;). This study identified the research gaps in this field which are relevant to Nepal. Based on research objectives we have documented the seasonal, annual and decadal rainfall patterns. Identified the historical major extreme drought events, and the drought hazard zones of Nepal. This research work identified and focused the winter, summer and annual major drought events during the last four decades from 1977 to 2018. In each episode of extreme events, spatial variability of SPI dynamics and its connection with large atmospheric circulations has been illustrated. The influence of SOI and SST anomalies and rainfall variability in Nepal has been documented. The drought/flood events in Nepal are associated with the strong El Nino and La Nina events. From this study we have identified and quantify the rainfall amounts in different episodes by using the SPI methods and rainfall analysis for different perspectives. We have analyzed the drought intensity, duration, severities of the extreme drought events. We have identified the frequency of different droughts events in different locations of the country. From this study we have identified the variability of drought events in El Nino and normal year's drought intensity duration and severities in different locations as well as regional and National wise. In this study we have documented the spatial variability of each major drought event in winter, summer and annual time periods which clearly showed the variability of SPI dynamics in the western, central and eastern regions of Nepal. At last, we have creating the drought hazard map first time in Nepal for the monsoon and annual time periods.

1.3 Motivation for the study

Drought and its impacts are increasing in the recent couple of decades in Nepal. Drought identification, monitoring, assessment, management and forecasting are major challenging components for agriculture, livelihood and water resources management. In this regard, drought research is essential in Nepal.

This study was motivated by the fact that drought monitoring, is not well initiating in Nepal till now. Therefore, the lack of monitoring of major drought episodes and their dynamics in major drought events is necessary for knowing the extreme drought episodes in recent years which was the main motivation of this research project. The key aim is to understand the influence of large-scale circulations pattern under monsoon and winter systems in Nepal.

1.4 Hypothesis

The research hypothesis behind this study is that drought frequency and intensity is continuously increasing over Nepal in recent decades, and this could be accelerated due to large-scale atmospheric circulations, such as El Nino and Southern Oscillation.

1.5 Research Questions

The research questions raised in this study are as follows:

- How are the precipitation and drought trends in Nepal?
- How does drought occur?
- What are the severities of drought in different regions of Nepal?
- What are the frequencies of drought in different regions of Nepal?
- Which regions are the more droughts hazardous in Nepal?

1.6 Research objectives

This thesis sketches the general to specific outcomes in different ways. However, the main objective of the study was to monitor the historical (seasonal and annual) drought over Nepal and its relationship with El Niño and Southern Oscillation.

Similarly, this study has focused on the temporal and spatial progression of major drought events.

The specific objectives are to: (i) identify the seasonal, annual and decadal rainfall pattern during the study period (ii) identify the extreme drought episodes during the last four decades; (iii) study the temporal and spatial progression of major drought events during El Niño and non-El Niño years; (iv) to identify the frequency of moderate, severe and extreme drought, and (v) to monitor drought hazardous zones in Nepal.

1.7 Limitations

Insufficient number of rainfall stations in the northern part of the country therefore the lack of sufficient data is the key limitation of this study.

1.8 Research Significance, Outcomes, and Innovations

In this section, the significance of the research and the important outcomes are discussed. These contributions are outlined below.

- Trend analysis showed both the increasing and decreasing trends of precipitation as well as drought over the regions. For this, we investigated a trend of precipitation and drought in different regions of Nepal.
- Quantification of seasonal, annual and decadal seasonal rainfall patterns in the last four decades.
- Identification of large circulation patterns effect in summer and winter seasons.
- Identification of the major drought intensities in particular years.
- Correlation between seasonal (summer and winter) SPI and SOI indices.
- Monitoring the spatial variability of SPI intensity in extreme drought years in different parts of the country.
- Monitoring the severities, frequencies and duration of SPI time scales.
- Identification and monitoring of the drought hazardous zone in Nepal.

This thesis reflects the summer and annual drought episodes temporal and spatial wise and their correlation with SOI during the El Nino and normal years. This study has tried to show the linkage and relation of drought episodes with ENSO. The study has identified the eight summers, and 10 annual drought episodes based on SPI time scales which were published in (Bagale *et al.*, 2021). Depending on the under-review manuscript third, I have investigated the eight major winter drought episodes. The one of the objective of this paper is to quantify the intensity of winter drought that Nepal has received during the recent last four decades. The specific objectives are to (a) identify the major dry episodes during the study period, and (b) study the temporal and spatial progression of major dry episodes. These results have shown the drought phenomena in Nepal and how it proceeds from mild to extreme drought events. Furthermore, the overviews of the SPI variability, spatial extents and trends in SPI time scales have been studied in these studies. In Bagale *et al.* (2023), I have quantified the monsoon rainfall in deficit episodes. Moreover, this study briefly sketches the trends of monsoon rainfall and its relations with SOI in ENSO phenomena. The main objective of this research is to investigate the large monsoon deficient years associated with El Niño and normal years during the last 42 years (1977-2018). Similarly, this research focused on rainfall variability in the eastern, central, and western regions during the monsoon period. Furthermore, the drought hazardous zone has been monitored in the result section of this work which is a novel kind of research in Nepal. I have found the research gap in drought study by reviewing many journal papers and scientific reports. Then I have mentioned the novel results in this research which are drawn from individual components of the research topic.

I have quantified the summer and winter rainfall in each large deficient episodes. On El Niño episode's average deficit, the rainfall was observed approximately 9 % below the average monsoon rainfall value (1977 to 2018). Previously there was very little research on drought trends, monitoring and assessment of drought studies conducted in Nepal. Monitoring droughts in countrywide physiographic regions of Nepal are recent studies. This study also classifies the frequency of drought in recent four decades, which have different regional drought episodes and dynamics in Nepal. The spatial variability of the SPI time scales over Nepal in each episode of the major drought shows the novel kinds of drought research found in Nepal. Depending on the observed rainfall values and SPI intensity I have estimated the future drought return periods. The novelty of the result is that drought hazard monitoring is the first time in Nepal.

1.9 Outline of the thesis

The major body of the thesis is divided into six chapters including references and appendices. The thesis is summarized as follows.

Chapter 1

Chapter 1 describes the background, significance and objectives of the research. Research questions are formulated to address the objectives of the thesis. It includes the overall picture of the research tasks undertaken in the thesis.

Chapter 2

Chapter 2 presents a review of the journal papers, reports and books relevant to the objectives of the study. Including a drought history in Nepal, this chapter identifies the gaps in drought research in Nepal.

Chapter 3

This chapter mainly presents the used data and applied methodology framework. It describes the study area, missing data fill (the daily rainfall data gaps of each station are filled by the Normal Ratio Method), and quality of the data that has been used for this study and geographic information on the used rainfall stations.

Further, this chapter also presents the SPI methodologies. Monthly data were used for SPI generation for SPI time scales used for the winter, summer and annual drought identification. The major aim is monitoring and computation the hazard index and drought hazardous zone in this study.

Chapter 4

Chapter 4 presents results and discussions relevant to the objectives of the study. The findings of the SPI4 and SPI12 time-scale drought study were published in the review journal. Similarly, the findings of SPI3 time scales for winter drought monitoring over Nepal have also been reviewed. Rainfall anomalies were used to detect the large deficit and excess years accepted in the Journal of Institute of Science and Technology (JIST) and decadal rainfall, results remaining relevant topics and drought hazard monitoring has presented in this chapter.

Chapter 5

Finally, Chapter 5 presents the conclusion of the research study which is drawn from individual components of the research topics. It also finds recommendations for future possible research works that are important for the reduction of drought risk.

Chapter 6

Chapter 6 presents the brief summary of specific and major objectives of thesis work. All the headings of each chapter are listed in table 1

Table 1: List of chapters

Chapter 1	Introduction
Chapter 2	Literature Review
Chapter 3	Materials and Methods
Chapter 4	Results and Discussion
Chapter 5	Conclusion and Recommendations
Chapter 6	Summary

CHAPTER 2

LITERATURE REVIEW

2.1 Background

This chapter discusses the comprehensive review of the drought, the definitions of drought, intensity, duration and severities of droughts, trends of SPI, the relationship between SPI and SOI, ENSO including its effect and research gaps on the available relevant literatures. The relevant events have been widely discussed in the literature and remain major topics. Beginning from observed rainfall in different seasons associated with westerly and southeast monsoon circulations process, rainfall patterns, characteristics and trends of the rainfall in Nepal, drought hazard monitoring. Some results from other research that have been published are also studied and discussed.

Meteorological drought can be said to be the shortage of rainfall in near or above-normal conditions. It occurs generally as a result of climatic change variable factors such as precipitation deficiency, high temperature, high wind, low relative humidity, greater sunshine, reduced infiltration, runoff, deep percolation and groundwater recharge, less cloud cover, increase evaporation and transpiration rates which are made worse by human activities such as deforestation, bush burning, overgrazing and poor cropping methods that reduce water retention of the soil (Adegboyega *et al.*, 2016; Abubakar and Yamusa, 2013). These climatic parameters vary temporally and spatially. Meteorological drought is defined as the deficit of precipitation over period of time for a region. Meteorological drought is the consequence of a natural reduction in the amount of precipitation received over an extended period, usually a season or more in length (Wilhite, 2000). A meteorological drought's long-term effects eventually give rise to other types of drought, such as agricultural, hydrological, or socio-economic droughts (Khalili *et al.*, 2011; Dracup *et al.*, 1980). Many studies in South Asia using precipitation have been carried out for meteorological drought studies (Abeysingha and Rajapaksha, 2020; Uddin *et al.*, 2020; Mondol *et al.*, 2017; Kumar *et al.*, 2013; Xie *et al.*, 2013; Patel *et al.*, 2007; Chowdhury, 2003). The climate of Nepal has been affected from southwest Indian monsoon in monsoon season and remaining months was affected by westerly. Almost 80% rainfall is observed in monsoon and remaining 20 % observed in remaining eight months.

2.2 Western Disturbances Influence on Winter Season

The Asian monsoon circulation system of an annual cycle has been divided into two distinct wet and dry phases; which undergoes a periodic and high amplitude variation on intra-seasonal, annual and inter-annual timescales (Webster et al., 1998). The wet phase is the rainy season during which warm, moist and widely distributed winds inland from the warm tropical oceans and the dry phase refers to the other half of the year when wind transports cool and dry air from the continents (Webster et al., 1998). The Western Disturbances originated in the Mediterranean region (Dimri and Mohanty, 2009), and cause winter rainfall especially over the Karakoram, Hindu Kush regions of Pakistan, north India and Nepal (Dimri *et al.*, 2015; Dimri, 2006; Lang and Barros, 2004). The Northwestern mountainous region of India and Pakistan played a vital role in the formation of snow/glaciers in this region (Dimri *et al.*, 2015). The winter monsoon appears as strong when northeasterly winds under the influences of the Siberian High and is marked by occasional, short rainfall in the lowlands and plains and snowfalls on the high-altitude areas (Kalsi, 1980).

In the winter season, the westerly jet stream develops over the southern Himalayans and directs the passage of extra-tropical storms (known as western disturbances) toward Nepal (Wang *et al.*, 2013). Pronounced inter-annual variability of winter storm occurrences is correlated with the polar/Eurasian teleconnection pattern (Li *et al.*, 2008; Lang and Barros, 2004), which links other larger-scale natural climate variability, such as the Arctic Oscillation and the North Atlantic Oscillation to the winter climate of Nepal (Wang *et al.*, 2013). While winter precipitation contributes less to the annual total in Nepal, it plays a crucial role in groundwater recharges, drinking water management, irrigation and agricultural practices. The complexity and unique pattern of the mountainous regions of central and eastern Nepal remain largely unexplored and interesting in intrinsic high rainfall patterns. The fluctuation of the winter precipitation pattern induced dry conditions in mountainous and Terai regions. Dry condition has affected the drinking water, agricultural productivity and livelihoods in mountainous rural areas and Terai. However, it is not systematically documented from regional as well as national perspectives till now.

There were very limited winter rainfall studies as concerned over Nepal (Hamal *et al.*, 2020; Karki *et al.*, 2016; Sigdel and Ikeda, 2012; Shrestha et al., 2000). Hamal *et al.* (2020) investigated the inter-annual variability of winter precipitation over Nepal, coupled with the ocean-atmosphere circulations. This study identified the deficit and excess episodes from 1987 to 2015. Karki *et al.* (2016) focused on seasonal rainfall trends in their studies of Nepal notice the significant increasing\decreasing locations. Sigdel and Ikeda (2012) observed seasonal contrasting of ocean-atmospheric circulations and their impacts on rainfall variability in Nepal. This study noticed the root of moisture flux towards Nepal. Shrestha et al. (2000) identified the relationship between rainfall and large-scale circulations for different seasons. Winter rainfall and SOI are in weak correlation in Nepal (Shrestha *et al.*, 2000). Moreover, there are few regional and basin-specific studies focused on winter dry years. However, in recent years the winter rainfall study including many stations and long-term observed data sets over Nepal is still lacking. There is no documentation of the spatial distribution of winter rainfall variability in individual major dry years in Nepal. There is a clear research gap in major dry episodes of spatial variability of winter rainfall across the country. One of the aims of this study is to quantify the amount of winter rainfall that Nepal has received during the recent last four decades.

2.3 El Niño Southern Oscillation (ENSO) Effects on Monsoon

The active and break period of the Asian monsoon is characterized by precipitation maxima and minima over South Asia (Ramanadham *et al.*, 1973). The atmosphere is highly complex, and it cannot be expected that the Southern Oscillation could account for most of the monsoon variability (Bhalme and Jadhav, 1984). Although large positive/negative value of SOI signifying strengthening/weakening of the Walker circulation coincides with a large excess/deficient monsoon rainfall in India (Bhalme and Jadhav, 1984; Rasmusson and Carpenter, 1983). Generally, there is a good correlation between a large negative/positive value of SOI and droughts/floods in India, however, there are some exceptions unexplained by the SOI (Bhalme and Jadhav, 1984; Mooley and Parthasarathy, 1983). The Southern Oscillation shows an irregular period, ranging from 2 to 6 years, usually averaging between 2 and 3 years (Fredriksen *et al.*, 2020; Trenberth, 1976; Wright, 1975). During the El Niño year in India there is a strong tendency for below-normal Indian monsoon rainfall over most parts of India (Varikoden *et al.*, 2015; Bhalme and Jadhav, 1984; Sikka, 1980). Similarly, during the El Niño/La Nina phenomena there is a good correlation between a large negative/positive value of SOI and droughts/floods in Nepal (Bagale *et al.*, 2023; Shrestha *et al.*, 2000). El Niño Southern Oscillation (ENSO) develops weaker monsoon rainfall in South Asian countries Nepal, India, Bangladesh and Sri Lanka described in details by the researchers (De Silva M and Hornberger, 2019; Varikoden *et al.*, 2015; Chowdhury, 2003; Shrestha *et al.*, 2000). The effect of ENSO and Indian Ocean Dipole (IOD) events on rainfall variability is still undefined and unclear (Muangsong *et al.*, 2014; Cherchi and Navarra, 2013). The influence of SOI on monsoon rainfall over Myanmar was more significant than the linkage with IOD (Sein *et al.*, 2015). Similarly, the influence of SOI on monsoon rainfall in Nepal was more significant than the effect of IOD (Sigdel and Ikeda, 2012). Shrestha (2000) identified that there is a strong correlation between SOI and summer rainfall in Nepal. Strong El Niño episodes develop into weaker monsoons and droughts in the South Asian region (Fan *et al.*, 2017). El Niño characterized by warming of surface temperatures in the Pacific Ocean, is associated with lower-than-normal monsoon rainfall in the South Asian region (Wang *et al.*, 2020; Varikoden and Babu, 2015). ENSO phenomena that can enhance pronounced impacts on the Indian Ocean (Du *et al.*, 2009; Wu *et al.*, 2009; Xie *et al.*, 2009). It induces diverse atmospheric and oceanic responses in both the Indian and Pacific Oceans (Wang *et al.*, 2020; Wu *et al.*, 2009). In South Asia, the ENSO is a major driver of ocean-atmosphere circulations. The Indian subcontinent receives most of its rainfall during the monsoon season when the inter-tropical convergence zone (ITCZ), synonymously termed the monsoon trough, carries large amounts of moisture from the ocean inland (Gadgil *et al.*, 2005; Gadgil and Joseph, 2003; Benn and Owen, 1998; Krishnamurti, 1985).The record of the annual cycle of the monsoon system shows that most of the rainfall occurs from June to September as the southeast monsoon enters Nepal. Southeasterly circulation brings abundant rainfall (moisture) from the Bay of Bengal and occasionally from the Arabian Sea (Bohlinger *et al.*, 2017). The winter season is dominated by westerly circulation originating from the Mediterranean Sea and Siberia (Kansakar *et al.*, 2004). The influence of these two circulation systems is heterogeneously distributed over Nepal; summer rainfall is greater in the central and eastern regions causing from southeasterly and westerly derived winter rainfall most significant in the western region of Nepal (Kansakar *et al.*, 2004). Moreover, Wang *et al.* (2013) studied the drought in the western region of Nepal and found the winter deficit rainfall. Rainfall is the only primary source for both surface and groundwater in Nepal. It is essential to understand large-scale atmospheric circulation system connections to monsoonal variability over Nepal from a socioeconomic aspect, such as drought risk, flood damage, effect on hydropower generation, and crop production practices.

Many studies had concentrated on rainfall variability in Nepal, (Pokharel *et al.*, 2020; Shrestha *et al.*, 2019; Karki *et al.*, 2017; Karki *et al.*, 2016; Panthi *et al.*, 2015; Sigdel and Ma, 2017; Salerno *et al.*, 2015; Ichiyanagi *et al.*, 2007; Kansakar *et al.*, 2004). However, few Authors have researched monsoon rainfall connecting with large-scale atmospheric circulation (Bagale *et al.*, 2023; Sharma *et al.*, 2020; Sigdel and Ikeda, 2012; Ichiyanagi *et al.*, 2007; Shrestha *et al.*, 2000). Shrestha *et al.* (2000) identified that strong El Niño episodes develop into weaker monsoons and deficit rainfall in Nepal. Sigdel and Ikeda (2012) examined the moisture fluxes in Nepal and focused on how ENSO affected the summer monsoon rainfall. Strong El Nino occurrences lead to lesser monsoons and deficit rainfall in Nepal (Shrestha *et al.*, 2000).). Similarly to this, earlier researchers found a high correlation between monsoon rainfall and SOI (Ichiyanagi *et al.,* 2007; Shrestha, 2000). Bagale *et al.* (2023) concluded main large-scale pattern influential on the monsoon rainfall variability was explained by ENSO as a significant correlation with SOI. Sharma et al. (2020) identified the year-to-year dominant variability of summer rainfall in Nepal which corresponds with ENSO. However, there is still a gap in identifying the large deficient monsoon years and their spatial variability relating to SOI across the country. Similarly, the quantitative decadal rainfall and its tracking with synoptic scale atmospheric circulations, such as El Niño and Southern Oscillation are urgent to identify the changing decadal rainfall patterns.

One of the main aims of this study is to quantify the seasonal decadal rainfall in Nepal within the recent last four decades. Similarly, this study focused on spatial rainfall variability in the different decadal periods in different windows.

2.4 Drought Perspective

Drought is considered by many to be the most complex of all natural hazards (Wilhite *et al*., 2007); it is insidious, slow-onset that produces a complex web of impacts that ripple through many sectors of the economy (Wilhite *et al.*, 2007; Hagman, 1984). The characteristics and quantification of drought are really useful for enabling both severities versus impacts analysis and risk assessment (Zargar *et al.*, 2011). Drought and flood years of summer season are generally linked between atmospheric large circulations with correspond to El Niño and La Niña episodes in South Asia (Varikoden *et al.*, 2015; Chowdhury, 2003; Krishnamurthy and Goswami, 2000). There was strong correlation between negative/positive values of SOI and summer drought/flood years than the normal years in Nepal lies on the central Himalayans (Bagale *et al.*, 2021).

The winter rainfall is observed high in the western regions, decreasing western-central to eastern regions in Nepal. Precipitation plays a major role in the mass balance of glaciers in the western region while playing a secondary role in the glaciers of eastern and central Nepal (Katsumoto *et al.*, 1998). The major factor for drought evolution in Nepal is the lack of precipitation. Adequate understanding of drought dynamics and subsequent impacts is required in Nepal.

There were very limited drought studies concerning Nepal. Sigdel and Ikeda (2010) analyzed the spatial and temporal variation to investigate drought patterns using the 26 stations over Nepal during 1971–2003, and point out extreme drought events. There are few regional and basin-wise studies concerned with drought events. Wang *et al.* (2013) studied only the western region of Nepal using different rainfall sources. The study of Wang *et al.* (2013) indicates the worst winter deficit episodes were in the years 2006 and 2009 in western Nepal. Similarly, a winter drought study by Khatiwada and Pandey (2019) has conducted over the Karnali region of western Nepal; using different indices and noticed that SPI is the best tool for drought identification in this region. Dahal *et al.* (2016) concentrated on a drought study in central Nepal and pointed out that droughts have a crucial effect on the livelihood of villager’s people. Dahal *et al.* (2021) examined the spatio-temporal variability of drought episodes in Koshi river basin located in eastern Nepal; noticed that droughts were frequently observed in recent decades. Likewise, Kafle (2014) concentrated on research on drought in Nepal's far-western and mid-western regions, where she observed an increase in recent years in the number of extreme dry spells. Though, there is not any document of spatial coverage of extreme drought effects in recent episodes over Nepal. There is a clear research gap in spatial drought variability across the country. This study reviews winter, summer and annual spatial drought variability on drought across the country. So this study has tried to study the overall drought statistics in seasonal and annual deficit events in recent 42 years (1977-2018). The study of seasonal and annual drought variability over Nepal is essential for the climatologically as well as socioeconomic prospective.

One of the aims of the study is to quantify the drought events and to monitor the historical drought over Nepal and its relationship with El Niño and Southern Oscillation.

2.5 Drought Frequency, Intensity and Duration

Drought events are specified by variables: frequency, duration and severity of intensity (McKee *et al.*, 1993). The spatial extent of the severity of drought episodes is a feature of droughts. Frequency is usually expressed by its return periods or recurrence interval which may be defined as the average interval of time within which the magnitude of the event is reached or exceeded once. For the estimation of extreme events, such as droughts and floods; knowledge of the return periods for events of particular depth and duration is required, it is necessary to assume a particular mathematical form of the frequency distribution.

Planning and management of water resources systems under drought conditions often require the estimation of return periods of drought events characterized by high severities (Bonaccorso *et al.*, 2003). From the estimation of probable drought events, we can reduce the drought risk from prepared assessment processes. Drought probabilistic characterization is extremely important, primarily in those regions where accurate water resource planning and management requires detailed knowledge of water shortages due to hydrological droughts (Rossi *et al.*, 1992; Frick, 1990). Moreover, the estimation of return periods associated to improve droughts can provide useful information in order to improve agricultural practices and water resources management under drought conditions.

2.6 Spatial and Temporal Variation of Drought

Droughts are regional and localized conditions that are frequently characterized by deviations from normal precipitation and cause severe water shortages (Ganguli and Reddy, 2014; Wilhite *et al.*, 2007). Temperature, wind, and relative humidity are climatic factors that influence drought. Significant trends were observed in precipitation and drought in many regions from 1900 to 2005 (IPCC, 2007). Similar decreasing trends of precipitation have been observed in Nepal during recent decades (Karki *et al.*, 2016). Bagale *et al.* (2021) have reported that there is large spatial and temporal variability of SPI dynamics in the western, central and eastern regions of the country. Sigdel and Ikeda (2010) applied the SPI to analyze dry/wet conditions and for monitoring the drought conditions in the country. Similarly, Dahal *et al.* (2016) and Shrestha *et al.* (2017) have studied the drought and monitored the dry conditions in the central and eastern regions of Nepal. While, Kafle (2016) analyzed drought by using Reconnaissance Drought Index (RDI) in Western, Central and Eastern development regions of Nepal this paper concludes that maximum number of droughts events were recorded in the years 1991, 1992, 1994, 2002, 2006 and 2009 in all three development regions however in 1992 and 2009 were the only time period when drought occurred in studied area. Likewise, Du *et al.* (2013) investigated extreme conditions in Hunan province, China. Ganguli and Reddy (2014) have invested in drought trends, spatial and temporal progression in western India in order to investigate the climatic variability. Monitoring of SPI identified the actual conditions of the dry/wet areas in the country as well as the different locations. SPI is important to identify the varying characteristics of dryness brought by extreme events such as drought. The SPI covering a 100-year period (1906-2005) was used by Subash and Ram Mohan (2011) to examine potential trends in monsoon rainfall and the frequency of droughts in order to evaluate rice-wheat productivity in India. In a similar manner, Raziei *et al.* (2008) used principal component analysis (PCA) and cluster analysis (CA) approaches to regionalize data based on precipitation in western Iran. The Standardized Precipitation Index (SPI) and PCA were both used by Raziei *et al.* (2009) to analyze the temporal and spatial variability of the hydrological drought. Water scarcity and significant geographical and temporal climatic variability make rational water management decision-making challenging (Nikbakht *et al.*, 2013; Raziei *et al.*, 2008). To help with the planning and management of water resources, it is crucial to identify homogenous areas that show a consistent drought pattern.

2.7 Relationship Between Drought Index such as SPI and SOI

The SOI shows the progression and strength of El Nino and La Nina events in the Pacific Ocean. To calculate SOI, the pressure differences between Tahiti and Darwin are employed. For this investigation, the SOI measures the broad variations in sea level pressure over region 3.4. The link between SPI and SOI has been the subject of numerous studies in various South Asian nations (Varikoden *et al.*, 2015; Kumar *et al.*, 2013; Sigdel and Ikeda, 2010; Chowdhury, 2003). Previous research on SPI and SOI seasonal time scales in Nepal was done by (Bagale *et al.*, 2021; Sigdel and Ikeda, 2010). The findings indicate a high link between SPI and SOI during the monsoon and a weak relationship throughout the winter. Varikoden *et al*. (2015) and Kumar *et al.* (2013) both revealed comparable findings in India. In addition, Chowdhury (2003) found that in Bangladesh, there is a substantial association between SPI and SOI during the monsoon season and a minor correlation during the winter. The low and high phases of SOI are also strongly correlated with drought and flood occurrences in South Asia (Varikoden *et al.*, 2015; Kumar *et al.*, 1999; Kripalani and Kulkarni, 1996; Mooley and Parthasarathy, 1983; Sikka, 1980). Additionally, variations in the tropical Pacific's sea surface temperature (SST) are linked to the low and high phases of SOI.

2.8 Drought in Nepal

Drought is a slowly induced natural disaster and is complex in Nature. Drought monitoring gives a clear picture of the severities, intensity and duration of drought. Droughts were recorded over different regions of Nepal ranges altitude from 60 m to 8848 m; in both semi-dry and wet regions and it affect human livelihood and food security. Several major droughts events with different severities have been recorded in the past decades in different regions of Nepal. The drought study gives attention since 2010. It is comparatively new in Nepal. Drought indices were used to monitor the onset and end of droughts.

A number of previous drought studies have been carried out in Nepal (Aryal *et al.*, 2022; Bagale *et al.*, 2021; Sharma *et al.*, 2020; Baniya *et al.*, 2019; Sigdel and Ikeda, 2010). Drought events have occurred frequently in Nepal after 2000 (Sharma *et al.*, 2020). Therefore, the impacts of drought assessment are essential for reducing the drought impact. Drought events have been observed frequently associated with El Nino and normal years.

The years with the worst drought conditions were 2015, 1992 for the summer and year, and 2006 and 2009 for the winter. According to a previous analysis by Sigdel and Ikeda (2010), the winter drought years were 1974, 1977, 1985, 1993, 1999, and 2001. The summers of 1977, 1982, 1991, and 1992 were all dry. The following years experienced an annual drought: 1977, 1982, 1983, 1992, 1993, and 1995.

There was a strong correlation between standardized monsoon rainfall and southern oscillation index (Sigdel and Ikeda, 2010). Generally, the drought year has been dominated by ENSO (Sharma *et al.*, 2020). Aryal *et al.* (2022) identified the drought years using both SPI and anomaly methods; indicating that the drought events have been marked frequently after 1990. Baniya *et al.* (2019) observed the drought variability using normalized difference vegetation index (NDVI) from 1982 to 2015. The findings noticed that the drought was marked frequently in Nepal.

Each drought has different SPI dynamics. Overall drought events are frequently recorded in recent decades in Nepal. There are consecutive drought episodes in the years 2005 and 2006. Such consecutive drought events are more destructive for livelihood and economic perspectives.

The previous researcher pointed out that the droughts are increasing in Nepal which indicates that the SPI values are decreasing (Bagale *et al.*, 2021; Dahal *et al.*, 2016; Sigdel and Ikeda, 2010). In recent years (from 1977 to 2018), more than 35% of the territory of the country suffered from precipitation deficit-driven drought over an average in drought years (Bagale *et et al.*, 2021). The major drought episodes for summer and annual events were in the year 1992 and 2015 and for winter 2006 and 2009. However, drought events were recorded frequently since 2000 in Nepal. Most dry and flood years are associated with El Niño and La Niña episodes, followed by normal year episodes in Nepal (Bagale *et al.*, 2021). There is a good agreement between a significant negative/positive value of SOI and droughts/floods in Nepal; however, with some exceptions (Bagale *et al.*, 2023; Shrestha et al., 2000).

Many studies have been undertaken to detect rainfall variability in Nepal; however, very few studies have been conducted on drought monitoring. NMHS issues the seasonal precipitation analysis (above normal/normal/below normal) based on the meteorological observatories. In Nepal, there is no special mechanism to take responsibility for drought analyzing, monitoring and forecasting. Though, Department of Hydrology and Meteorology (DHM) is the official agency for climate.

Droughts studies have been conducted in Nepal based on the different drought indices. Out of them most of the research is based on SPI indices conducted on regional scale and river basin wise. National, Regional and river basin drought studies have focused the results on respective ways. The researchers conducted their study in Nepal mostly on a temporal basis and identified the major drought episodes but there is a clear research gap on major drought events spatial extent for different SPI time scales.

The National level drought study was conducted in Nepal by previous researchers (Sharma *et al.*, 2021; Sigdel and Ikeda, 2010). Till now there is also a lack of comparative regional drought studies for winter, summer and annual based on different SPI time scales. However, there is a clear research gap in understanding SPI dynamics and SOI variability. Furthermore, the monitoring of drought-hazardous areas is still new in Nepal.

The drought in Nepal has been affected by local, regional and large-scale circulations. The topography of Nepal, the windward and leeward sides of Nepal are in different rainfall patterns. A national report by CBS (2013) indicates that the western regions of

Nepal are affected by winter drought in 2006. But there is a gap in winter drought studies in central and eastern regions. This research tries to fulfill comparative regional drought research in the eastern, central and western regions of Nepal. In the year 2006, Nepal faced extreme winter drought events. The event was extreme during the last four decades. The average rainfall observed this year is around 10 mm/winter. The regional study showed that the eastern region of Nepal observed the minimum rainfall than the western and central regions of Nepal.

Similarly, the summer of 2015 observed extreme drought events in Nepal after 1992. Drought has a more detrimental effect on the poor than on other demographics. Droughts make life more demanding and tough for Nepal's residents because agriculture is their sole source of income. Systems for early warning are essential for reducing the effects of droughts. The drought hazard is more expensive and enduring than other threats, yet it develops gradually. The effects of drought and flood should be lessened by drought and flood assessment work in order to discourage communities from migrating to Terai regions due to a lack of drinking water.

Drought has been recorded in several areas of Nepal and experienced the worst drought episodes in years and successive years over the recent last two decades (Bagale *et al.*, 2021; Wang *et al.*, 2013).

Numerous studies have been conducted on various drought-related topics, including identifying and tracking the length and severity of droughts. The application of appropriate approaches to the commencement and termination points of droughts, notably in Nepal, remains a significant scientific problem. Though, drought hazard monitoring over Nepal is still new.

One of the major objectives of the present study is to monitor drought hazards in Nepal. The specific objectives are; (i) to identify the frequency of moderate, severe and extreme drought and (ii) to create drought hazard maps for Nepal.

2.9 Drought Hazard Perspective

Drought is a critical water shortage resulting from prolonged deficiency of precipitation that affects groundwater, river flows, and water storages, affects vegetation growth, agriculture, and hydropower generation, in various territories and ultimately communities (Portner *et al.*, 2022; Mishra and Singh, 2010; IPCC, 2007; Wilhite and Glantz, 1985). The effect of global warming and climate change (rising temperature and changing rainfall pattern) affects the occurrence severity of the drought has increased in many parts of the world (Portner *et al.*, 2022; IPCC, 2007). Drought is one of the most complex and recurring phenomena in different regions of the globe (Wilhite *et al.*, 2007). This phenomenon has an impact on different aspects of society, such as agricultural, socioeconomic, biological, and political. Furthermore, drought is one of the most poorly understood natural phenomena and is perceived as one of the most expensive one of severe hazard that impacts every location and climate regime around the world (Wilhite *et al.*, 2007). In Asia, many countries (Philippines, Australia, Vietnam, Iran, Thailand, Pakistan, Bangladesh, India, Nepal, China, and Myanmar) have been affected by drought during strong El Nino years. In South Asia, large population of India has been affected by drought events during strong El Nino years than normal years (Varikoden *et al.*, 2015; Kripalani and Kulkarni, 1996; Mooley and Parthasarathy, 1983; Sikka, 1980). Similarly, Bangladesh and Nepal have received low rainfall in strong El Nino episodes (Bagale *et al.*, 2021; Chowdhury, 2003). The correlation between monsoon rainfall and southern oscillation index is strong during the drought and flood years than in normal years in India (Bhalme and Jadhav, 1984). The relationship between summer drought and Nino index over 3.4 regions was investigated by previous researchers (Varikoden and Babu, 2015) who noticed that rainfall in India decreased in strong El Nino episodes.

In South East Asia, Vietnam has been identified as one of the drought-prone areas, being severely affected by El Nino-induced drought hazards (Le *et al.*, 2021). Similarly, in South Asia Bangladesh has been identified as one of drought-affected countries (Rahman and Lateh, 2016; Shahid and Behrawan, 2008; Chowdhury, 2003). During El Niño years Myanmar observed an estimated 10 % below average rainfall (Sen Roy and Kaur, 2000). During drought events climatic hazards were observed in South Asia (Abeysingha and Rajapaksha, 2020; Uddin *et al.*, 2020; Mondol *et al.*, 2017; Xie *et al.*, 2013).

A number of previous drought studies have been carried out in Nepal (Aryal *et al.*, 2022; Bagale *et al.*, 2021; Sharma et al., 2020; Baniya *et al.*, 2019; Sigdel and Ikeda, 2010). The impacts of drought assessment are essential for reducing the drought impact. Drought events have been observed frequently associated with El Nino and normal years. Generally, the drought year has been dominated by ENSO (Sharma *et al.*, 2020). Aryal *et al.* (2022) identified the drought years using both SPI and anomaly methods; indicating that the drought events have been marked frequently after 1990. Baniya *et al.* (2019) observed the drought variability using normalized difference vegetation index (NDVI) from 1982 to 2015. The findings noticed that the drought was marked frequently in Nepal. Though, drought hazard monitoring over Nepal is still new. This study identified and monitored the drought hazard, based on SPI time scales. For this using SPI, this study has calculated drought hazard Index (DHI) as the novel in Nepal.

One of the aims of the present study is to monitor drought hazards in Nepal. The specific objectives are; (i) to identify the frequency of moderate, severe and extreme drought and (ii) to create drought hazard maps for Nepal.

2.10 Drought Hazard Monitoring

Drought Hazard Index (DHI) is defined as the frequency and intensity of drought events. Frequent droughts with high levels of intensity could result in severe hazardous effects. The SPI was used as a proxy to quantify drought events. We used SPI to identify drought events and their intensities during the periods of 1977–2018. Drought Hazards of an extreme event can be carried out using SPI (Dabanli, 2018; Rajsekhar *et al.*, 2015; Shahid and Behrawan, 2008) in different regions of the globe. The detailed methodology for the calculation of the DHS and correspondence DHI is described by previous researchers (Dabanli, 2018; Rajsekhar *et al.*, 2015; Shahid and Behrawan, 2008). This study uses Shahid and Behrawan (2008) for DHI calculation and monitoring of drought-hazardous zone of a country which was documented through the spatial interpolation technique performed by the IDW algorithms followed by (Shahid and Behrawan, 2008). The interpolated hazardous maps of SPI4 and SPI12 have been presented in [Fig 6(a, b)]. Furthermore, considering that drought impact evolves at a shorter temporal scale we selected SPI4 and longer for SPI12 to quantify drought hazard for different regions of the country. The DHI-based drought hazardous classification is presented in Table 5.

Different drought indices have been used for drought assessment and drought hazard assessment, monitoring, drought-induced vulnerability and risk analysis in different regions of the world (Asadi Zarch *et al.*, 2011; Barua *et al.*, 2011; Tigkas, 2008; Patel *et al.*, 2007; Hayes *et al.*, 1999). Researchers in South Asia and other parts of the world are now paying close attention to it.

2.11 Review of Drought Indices

The success of drought awareness and mitigation depends on knowledge about the beginning and end of drought episodes, the monitoring of spatially extensive drought severities, the lengths of drought periods, and the frequency of droughts. Using drought indices, the information described above was discovered. Drought indices are often used to calculate rainfall deficits and water availability (Bagale *et al.*, 2021; Mishra and Singh, 2010; Morid *et al.*, 2006). To date, numerous drought indexes have been created. Among them, the Palmer Drought Severity Index (PDSI) (Palmer, 1965), the Standardized Precipitation Index (SPI) (McKee *et al.*, 1993), and the Reconnaissance Drought Index (RDI) (Tsakiris and Vangelis, 2005) have been in widespread use. The following section discusses commonly-used drought indices, their usefulness and limitations.

2.11.1 Palmer Drought Severity Index (PDSI)

The Palmer Drought Severity Index (PDSI) was initially made available in the United States by (Palmer, 1965). The United States Department of Agriculture frequently uses the Palmer Drought Severity Index (PDSI) to assess when to provide emergency drought assistance, but the PDSI performs better when employed in large areas of uniform topography. For areas with significant topographic variation, this method might not be very useful. Furthermore, the method used to calculate PDSI does not do well in regions where there is extreme variability of rainfall or runoff (Hayes et al., 2000). The PDSI is calculated based on precipitation and temperature data, as well as the locally available water content of the soil. From the above input parameters, all the basic terms of the water balance equation can be determined, including evapotranspiration, soil recharge, runoff and moisture loss from the surface layer (Hayes et al., 2000). Despite its widespread use, PDSI has many limitations (Hayes *et al.*, 2000; Alley, 1984).

2.11.2 Standard Precipitation Index (SPI)

The SPI was used to quantify drought due to its simple procedures and standardization (Guttman, 1999; McKee *et al.*, 1993). SPI ensures that drought quantification at any location and on any time scale is consistent.

The computational procedure for deriving SPI involves the following steps: (a) First an appropriate probability density function (PDF) is fitted to the precipitation aggregated over the time scale of interest, and (b) each PDF is then transformed into a standardized normal probability distribution.

The detailed mathematical procedure for the calculation of SPI can be found in (Sein *et al.*, 2015; Mishra and Singh, 2010; Guttman, 1999; McKee *et al.*, 1993).

Considering that drought and its socio-economic impact evolve at a longer temporal scale (window), we selected SPI12 to quantify drought hazard, vulnerability and risk.

SPI was developed to detect, calibrate, quantify and monitor drought using long-term precipitation data sets (McKee *et al.*, 1993). SPI is normalized so that wetter and drier climates of different time scales can be represented simultaneously (Hayes et al., 1999). The index computation is simple and is based on precipitation only as an input, and the outputs have multiple time scales of SPI. However, the SPI is produced by standardizing the probability of observed precipitation for multiple timescales, simply recognized by the WMO and utilized worldwide (WMO, 2012). The duration of weeks or months and seasons can be used to apply this index to agricultural interests, and a longer duration of years can be used to apply this index to water supply and water management interests (Di Lena *et al.*, 2014; Patel *et al.*, 2007). It has also been demonstrated in several studies in different regions of the world.

The threshold for indicating the severity of meteorological drought based on SPI was adopted (McKee *et al.*, 1993). First, SPI3, SPI4 and SPI12 data sets were interpolated using the inverse distance weighted (IDW) function (Patel *et al.*, 2007). Then, the interpolated maps were reclassified into different severity classes using the SPI threshold (Table 3). For example, the interpolated SPI4 of September months was reclassified because the SPI4 of September comprises the accumulated precipitation total of the rainfall received in June, July, August, and September, which is crucial to the significant cropping season in Nepal. Similarly, the interpolated SPI12 of the December months was reclassified because the SPI12 of December comprises the accumulated precipitation total of the rainfall from January to December, which is crucial for water resource planning.

Time series of SPI for individual stations were obtained to determine the variation in SPI time length. Time series were also utilized to observe the variation in detecting drought length of data sets. A typical drought year was detected from the average SPI time series analysis.

The threshold for indicating the severity of meteorological drought based on SPI was adopted (McKee *et al.*, 1993).

2.11.3 Other Drought Indices

Many drought indices have been developed to date. Other indices that have been used widely include the Palmer Drought Severity Index (PDSI) (Palmer, 1965), Percent of

Normal (PN), Deciles (Gibbs and J.V., 1967), Standardized Precipitation Index (SPI) (McKee *et al.*, 1993), Reconnaissance Drought Index (RDI) (Tsakiris and Vangelis, 2005), Streamflow Drought Index (SDI) (Nalbantis and Tsakiris, 2009).

2.11.4 Advantages and Limitations of SPI

Table 2: Advantages and limitations of SPI

SPI is widely accepted index for the quantification of drought.	Sensitive to access a long term and reliable temporal time series of the data.
Simple, based on precipitation only. It can quantify the drought severities.	Access to a long, reliable temporal time series.
Versatile; Can be computed for any time scale	Regions with low precipitations can give misleading SPI values for short time periods (1, 2 months).
Can provide early warning of drought and help access drought severity.	Does not consider the intensity of rainfall and its potential impacts on runoff, and water availability within the system of interest.

2.12 Interpolation of Time Series Data

Numerous spatial interpolation methods are applied in climatic studies around the globe. There are several different simple spatial interpolation techniques, including Thiessen polygons, splines, various forms of Kriging, and inverse distance weighting (IDW). Because they are generally simple to use, need little input data, and are rather basic, these interpolation techniques are widely used in small and medium-sized catchments or basins. Higher-resolution rainfall data can be estimated in the center of Taiwan using IDW spatial interpolation techniques, which are widely used to build continuous rainfall surfaces bridging the geographical gaps in the time series data (Chen and Liu, 2012). A previous study Dirks *et al.* (1998) compared spatial interpolation methods (IDW, Kriging and Thiessen polygons) using rainfall data from a network of 13 rain gauges on Norfolk Island, and the results found IDW method is slightly better than those other spatial interpolation methods.

According to the findings, IDW created more logical representations than Ordinary Kriging (OK). For the spatial interpolation and visualization of SPI intensity in drought studies, earlier researchers in Asia used the IDW interpolation technique (Chen and Liu, 2012; Patel *et al.*, 2007). Similar to this, the inverse distance weighted

(IDW) technique was used in Nepal to interpolate and depict seasonal and yearly rainfall as well as drought (Bagale *et al.*, 2021). The Inverse Distance Weighting (IDW) method is somewhat superior to the alternatives, according to the results of the aforementioned studies, and it is also straightforward to implement into a geographic information system (GIS). According to earlier research on spatial interpolation methods for rainfall and drought, each strategy has pros and cons depending on its goals.

2.13 The Nonparametric Rank-based Mann-Kendall Test (M.K.)

M.K. test was applied to assess the time series data (Kendall, 1975; Mann, 1945). Many researchers have used this method (Nouri and Homaee, 2020; Di Lena *et al.*, 2014; Santos *et al.*, 2011) to detect trends in climatic time series data in different regions of the globe. In recent decades MK test is used by earlier researchers (Bagale *et al.*, 2021; Shrestha *et al.*, 2019; Karki *et al.*, 2016; Di Lena *et al.*, 2014; Santos *et al.*, 2011) in different regions of the globe to identify the trends of the climatic parameters. In South Asia, it is widely used to test the decreasing and increasing trends of climatic time series datasets (Karki *et al.*, 2016; Taxak *et al.*, 2014). In central India Taxak *et al.* (2014) examined the monsoon rainfall trends using MK test and indicates the monsoon rainfall is decreasing in central India.

2.14 Summary of the Literature Review

To examine the deficit of rainfall in different regions of the globe different indices were used (PDSI, RDI, SPEI, SPI,). Different indices have advantages and disadvantages. WMO (2012) recommended that SPI is the best drought monitoring tool in different regions of the world. SPI is used to identify deficit of rainfall and climatic risk analysis in different regions of the world. In South Asia, SPI is widely used by previous researchers (Abeysingha and Rajapaksha, 2020; Uddin *et al.*, 2020; Mondol *et al.*, 2017; Xie *et al.*, 2013; Patel *et al.*, 2007) to identify the temporal and spatial variability of dry conditions. In Nepal, SPI is quite a new tool for the investigation of dry conditions in different regions of the country. It is used to identify the temporal scales by different researchers but the spatial variability of dry conditions in major events is still lacking. Though Khatiwada and Pandey (2019) identified that the SPI is focused foremost on capturing the duration and intensity of drought in the Karnali river basin, Nepal. So, this study chooses to use SPI indices to monitor the dry conditions in the past four decades. The dry conditions of Nepal are associated with the warm phase of the El Niño events. This study introduced the drought hazard monitoring in Nepal based on SPI indices that provides insightful information fora scientific society as well as to the educational field in the nation.

CHAPTER 3

MATERIALS AND METHODS

3.1 Background

This chapter describes materials and methods used for the study of rainfall departure, seasonal to decadal rainfall, dry and wet episodes, rainfall trends, relationship between SOI and precipitation, drought and drought hazard monitoring. Secondary data on precipitation have been used for this study. The quality of the data was checked with robust statistical tools. SPI indices at different time scales were generated, to the identification of severity of droughts, duration, monitoring the major dry episodes, SPI trends and DHI monitoring. The following sub-sections describe the methods in detail.

3.2 Study Area

Nepal is a landlocked mountainous country situated in the central Himalayas of South Asian territory. The northern side is situated in Highland Tibet of China, and the remaining sides surround India. It extends from 80° 04' to 88° 12' E in longitude and 26° 22'to 30° 27' N in latitude (Sigdel and Ikeda, 2010). The country extends 885 km from east to west, varies from 130 km to 260 km from North to south (Karki *et al.*, 2017), and covers 147516 sq. km (Shrestha *et al.*, 2021). The complex topography of Nepal ranges from the low land of Terai 60 meters in the south to Mount Everest 8848.86 m above sea level in the Himalayan region towards the North. The climate of Nepal is sub-tropical, with most of the rainfall concentrated in the monsoon season (Karki *et al.*, 2016). We have further classified the country into the western, central and eastern regions to identify the differences of the spatial and temporal variations of seasonal rainfall. The distribution of the meteorological stations in study area is shown in Figure 1. The climate of the country is divided into four seasons pre-monsoon (March to May), monsoon (June to September), post-monsoon (October to November) and winter (December, January, February) (Bagale *et al.*, 2021; Kansakar *et al.*, 2004).

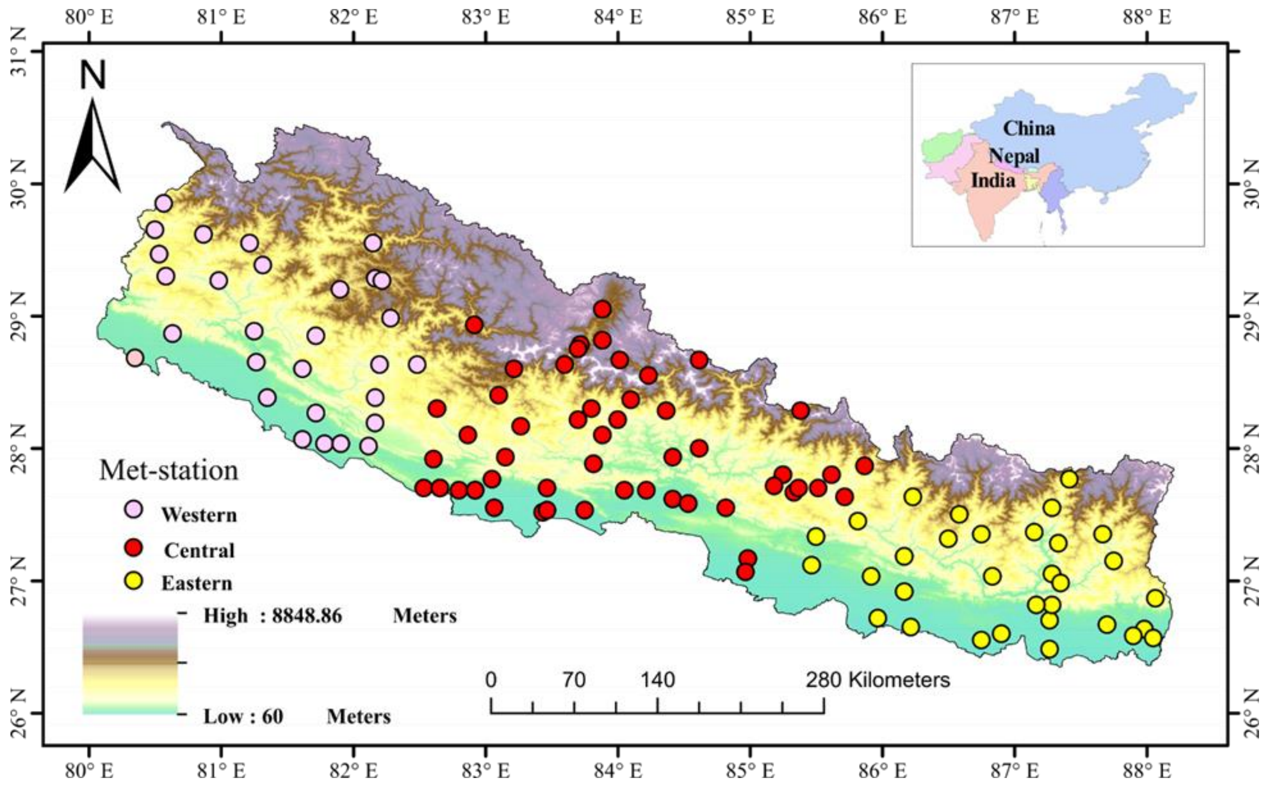

Figure 1: Spatial distributions of the met-stations (1977-2018) over the study area; the yellow, red and pink color represents respectively the stations for eastern, central and western parts of Nepal.

Table 3: Meteorological stations and 42 years mean rainfall values.

S.N	Station Name	Index No	Latitude (^{0}N)	Longitude (^{0}E)	Elevation (masl)	Missing rainfall %	No of years	Annual rainfall
1	Belaurisantipur	106	28.68	80.35	159	0.0	42	1658.30
2	Naubasta	412	28.27	81.72	135	2.2	42	1428.53
3	Nepaljunj(Reg. off)	416	28.07	81.62	144	0.0	42	1387.93
4	Ranijaruwa Nursery	417	28.38	81.35	200	0.4	42	1287.65
5	Bhairawa airport	705	27.52	83.43	109	1.4	42	1681.83
6	Bhairahawa (Agric)	707	27.53	83.47	120	1.3	42	1795.92
7	Taulihawa	716	27.55	83.07	94	2.2	42	1456.66
8	Bhagwanpur	723	27.68	82.80	80	2.6	42	1748.35
9	Simari	728	27.53	83.75	154	1.0	38	1887.08
10	Simara airport	909	27.17	84.98	130	0.0	42	1815.39
11	Parwanipur	911	27.07	84.97	115	0.4	42	1558.13
12	Janakpur airport	1111	26.72	85.97	90	0.0	42	1451.77
13	Karmaiya	1121	27.12	85.47	131	2.9	42	1809.45
14	Siraha	1216	26.65	86.22	102	2.6	42	1400.08
15	Rajbiraj	1223	26.55	86.75	91	0.8	42	1472.58
16	Barmajhiya	1226	26.60	86.90	85	0.8	42	1659.23

17	Biratnagar airport	1319	26.48	87.27	72	0.0	42	1789.51
18	Tarahara	1320	26.70	87.27	200	0.8	42	1916.59
19	Damak	1408	26.67	87.70	163	0.6	42	2334.92
20	Anarmanibirta	1409	26.63	87.98	122	1.5	42	2477.75
21	Chandragadhi	1412	26.57	88.05	120	1.2	42	2284.89
22	Gaida (Kankai)	1421	26.58	87.90	143	0.4	35	2650.99
23	Godawari (west)	215	28.87	80.63	288	2.8	42	2275.83
24	Chisapani (Karnali)	405	28.65	81.27	225	4.0	41	2300.36
25	Kusum	407	28.02	82.12	235	4.1	36	1292.17
26	Sikta	419	28.03	81.78	195	1.4	41	1493.77
27	Nayabasti (Dang)	507	28.22	82.12	698	0.8	42	1738.20
28	Koilabas	510	27.70	82.53	320	0.6	42	1625.36
29	Butwal	703	27.70	83.47	205	1.5	42	2330.04
30	Beluwa (Girwari)	704	27.68	84.05	150	0.2	42	2643.95
31	Dumkauli	706	27.68	84.22	154	0.2	41	2324.56
32	Pattharkot (West)	721	27.77	83.05	200	4.5	42	1605.86
33	Rampur	902	27.62	84.42	256	3.8	42	1992.51
34	Jhawani	903	27.58	84.53	270	2.9	42	1965.79
35	Beluwa (Manahari)	920	27.55	84.82	274	2.9	42	1890.22
36	Tulsi	1110	27.03	85.92	457	0.1	40	1680.37
37	Chisapanibazar	1112	26.92	86.17	165	0.2	42	1553.31
38	Harharpur gadhi valley	1117	27.33	85.50	250	0.0	41	2423.78
39	Dharan bazar	1311	26.82	87.28	444	0.2	42	2172.34
40	Chatara	1316	26.82	87.17	183	0.5	42	2093.98
41	Kakerpakha	101	29.65	80.50	842	0.6	42	1694.89
42	Patan (west)	103	29.47	80.53	1266	0.2	42	1307.81
43	Dadeldhura	104	29.30	80.58	1848	0.1	42	1381.69
44	Pipalkot	201	29.62	80.87	1456	0.4	42	2262.11
45	Silgadi doti	203	29.27	80.98	1360	2.8	42	1354.60
46	Pusma camp	401	28.88	81.25	950	3	42	1560.29
47	Dailekh	402	28.85	81.72	1402	1.4	42	1750.88
48	Surkhet (Birendranagar)	406	28.60	81.62	720	0.0	42	1595.05
49	Libang Gaun	504	28.30	82.63	1270	0.6	42	1632.03
50	Bijuwartar	505	28.10	82.87	823	1.6	42	1256.70
51	Salyan bazar	511	28.38	82.17	1457	0	42	1216.69
52	Chaur jharitar	513	28.63	82.20	910	0.4	42	1217.39
53	Kushma	614	28.22	83.70	891	3.2	42	2461.33
54	Kanchikot	715	27.93	83.15	1760	1.4	42	1782.31

55	Musikot	722	28.17	83.27	1280	0.9	42	2295.27
56	Khudi bazar	802	28.28	84.37	823	3.3	42	3268.41
57	Pokhara airport	804	28.22	84.00	827	0.0	42	3825.05
58	Syangja	805	28.10	83.88	868	1.1	42	2835.34
59	Bandipur	808	27.93	84.42	965	3.2	42	1752.49
60	Gorkha	809	28.00	84.62	1097	3.4	42	1687.24
61	Chapkot	810	27.88	83.82	460	0.2	42	1849.63
62	Kakani	1007	27.80	85.25	2064	0.5	42	2787.71
63	Nawalpur	1008	27.80	85.62	1592	2.0	42	2463.26
64	Dolalghat	1023	27.63	85.72	710	0.0	42	1132.62
65	Khumaltar	1029	27.67	85.33	1350	0.1	42	1186.53
66	Kathmandu airport	1030	27.70	85.37	1337	0.0	42	1469.85
67	Dhunibesi	1038	27.72	85.18	1085	0.1	42	1550.43
68	Nagarkot	1043	27.70	85.52	2163	0.9	42	1813.14
69	Jiri	1103	27.63	86.23	2003	0.4	42	1451.77
70	Bahun tilpung	1108	27.18	86.17	1417	0.7	42	1855.78
71	Nepalthok	1115	27.45	85.82	1098	0.6	42	848.15
72	Aisealukhark	1204	27.35	86.75	2143	0.2	42	2160.32
73	Okhaldhunga	1206	27.32	86.50	1720	0.2	42	1746.63
74	Khotang bazar	1211	27.03	86.83	1295	3.2	42	1169.92
75	Chainpur (east)	1303	27.28	87.33	1329	0	42	1430.02
76	Pakhribas	1304	27.05	87.28	1680	2.4	42	1533.01
77	Dhankuta	1307	26.98	87.35	1210	0.4	42	956.09
78	Dingla	1325	27.37	87.15	1190	0.8	42	1934.60
79	Taplejung	1405	27.35	87.67	1732	0.2	41	1971.13
80	Kanyam tea estate	1416	26.87	88.07	1678	3.9	42	2950.86
81	Phidim (Panchther)	1419	27.15	87.75	1205	1.7	41	1284.51
82	Darchula	107	29.85	80.57	1097	0.0	42	2449.21
83	Chainpur (west)	202	29.55	81.22	1304	2.2	37	1576.96
84	Bajura	204	29.38	81.32	1400	5	42	2001.48
85	Jumla	303	29.28	82.17	2300	0.2	42	824.43
86	Gamshree nagar	306	29.55	82.15	2133	7.5	42	821.60
87	Nagma	308	29.20	81.90	1905	0.4	42	784.40
88	Dipalgaun	310	29.27	82.22	2310	6.8	42	884.61
89	Dunai	312	28.93	82.92	2058	7.5	42	394.40
90	Mainagaun (D.Bas)	418	28.98	82.28	2000	4.0	42	1829.04
91	Musikot (Rukumkot)	514	28.63	82.48	2100	1.0	42	2137.60
92	Bobang	615	28.40	83.10	2273	5.2	41	2419.52
93	Gurja Khani	616	28.60	83.22	2530	4.5	39	1886.44
94	Lumle	814	28.30	83.80	1740	0.2	42	5371.14

95	Siklesh	824	28.37	84.10	1820	1.0	42	3760.34
96	Timure	1001	28.28	85.38	1900	3.0	41	949.64
97	Gumthang	1006	27.87	85.87	2000	1.6	42	3785.89
98	Salleri	1219	27.50	86.58	2378	2.6	42	1651.27
99	Num	1301	27.55	87.28	1497	7.8	42	4410.64
100	Chepuwa	1317	27.77	87.42	2590	2.2	42	2638.42
101	Jomsom	601	28.78	83.72	2744	4.5	42	270.78
102	Thakmarpha	604	28.75	83.70	2566	3.1	42	410.56
103	Lete	607	28.63	83.60	2384	1.4	42	1367.11
104	Panipauwa (M.Nath)	608	28.82	83.88	3609	11.0	34	291.71
105	Ghami (Musthang)	610	29.05	83.88	3465	10.7	32	163.35
106	Larke samdo	806	28.67	84.62	3650	7.0	41	993.30
107	Manang bhot	820	28.67	84.02	3420	5.7	42	409.94

3.3 Data and Methods

3.3.1 Data Collection

The daily rainfall data of 107 weather stations were obtained from the Department of Hydrology and Meteorology, Government of Nepal. Monthly total rainfall values were obtained by summing up daily rainfall data. Similarly, the annual total rainfall data were calculated by adding monthly total rainfall data from January to December, and for summer monsoon (June–September), the total annual rainfall at each station was computed after obtaining the missing data. The distributions of the meteorological stations are shown in (Figure 1). Observed rainfall data from (1977 to 2018) was used in this study. Time range was determined by evaluating the data records of the stations as possible as more stations. Annual, seasonal and monthly means were calculated for all stations using the arithmetic mean method. The annual mean is averaged over January-December. After data collection and study of climate datasets, stations were selected based on less than 10 % missing records, and most of the stations (95 %) were lower than 3 % of the total number of annual values. Some high-altitude stations are used for spatial coverage having 30 years' time series with 5-10 % missing values. We have adopted the Normal ratio method to estimate missing rainfall values of climate datasets from nearby three weather stations (Bagale *et al.*, 2021; Myronidis and Nikolaos, 2021).

Normal ratio method is used if any surrounding gauges have a mean annual precipitation exceeding 10% of the gauge under consideration (Equation 1). This weighs the effect of each surrounding station. The missing data are estimated by:

$$P_x = \frac{1}{n}\sum_{i=1}^{n}\left[\frac{N_x}{N_i}\right]P_i \qquad (1)$$

where,

Px =estimate of the missing value

Pi =rainfall values of rain gauges used for estimation

Nx =mean annual precipitation of X station

Ni =mean annual precipitation of surrounding station

n =number of surrounding stations

The SOI is one measure of the large-scale fluctuations in air pressure observed between the western and eastern tropical Pacific during El Niño and La Niña episodes (Yan *et al*., 2011). The negative phase of the SOI represents below-normal air pressure at Tahiti and above-normal air pressure at Darwin. The monthly Southern Oscillation Index (SOI) data and Ocean Nino Index (ONI) monthly sea surface temperature (SST) anomaly over the Nino3.4region were acquired from the National Weather Service Climate Prediction Centre of National Oceanic and Atmospheric Administration (NOAA) for the time 1977 to 2018 available in https://origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml. The ONI is defined by three months running mean SST anomalies in the Nino-3.4 regions, which is also known as the Nino-3.4 index.

3.4 Data Quality

3.4.1 Introduction

As a preliminary quality control, the 107 stations monthly rainfall data series were manually inspected. In order to assure the quality of data, and to examine the strength of relationship, many statistical methods were used. The identification of unusual data and its consistency with respect to time is the primary assessment for quality control. The homogeneity test is primarily used to determine the data quality, and homogeneity of the data series. In order to ascertain whether the data series are homogeneous or not the homogeneity tests were performed with respect to time. Pettit's, Standard Normal Homogeneity tests, Buishand's Range and Von Neumann's ratio tests were performed to analyze the data. The statistical software package R trends were used to obtain the result. As the computed p-value is higher than the significance level alpha (0.01 and 0.05), the null hypothesis (Ho) (data are homogeneous) cannot be rejected. Those 107stationswith significance values in excess of 0.01 have been used in this analysis. Out of 122 stations 15 failed the in the homogeneity tests ($p< 0.001$) and were not used.

The correlation coefficient(r) and proportion of variation (r^2) are used in this work in order to understand the strength of relationship.

3.4.2 Homogeneity Test

This study applied many robust methods; in order to ascertain whether the monthly data series are homogeneous or not by using Buishand's Range (Buishand, 1982), Von Neumann's ratio (Von Neumann, 1941), Pettit test (Pettitt, 1979) and Standard Normal Homogeneity tests (SNHT) for a single break (Alexandersson, 1986) with respect to time was performed using trend packages in R-Studio to recognize weather the datasets are homogeneous or not, with p values of the relevant results of climate dataset (Costa and Soares, 2009; Wijngaard *et al.*, 2003; Pettitt, 1979).

3.4.3 Mann-Kendall Test

Mann-Kendall test is the rank-based nonparametric test and has recently been used by several researchers to detect trends in rainfall data (Dahal *et al.*, 2016; Tabari *et a*l., 2011).

$$\boldsymbol{S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} Sgn(x_j - x_k)} \qquad (2)$$

Test statistic S defined as:

$$\boldsymbol{S = Sgn(x_j - x_k)} \qquad (3)$$

where n is the length of the data set. X_j and X_k are the annual values in years j and k, $j > k$ respectively.

$$\mathbf{Sgn}(\mathrm{x_j} - x_k) = \begin{cases} \mathbf{1} & \boldsymbol{if}\ \mathrm{x_j} - x_k > 0 \\ \mathbf{0} & \boldsymbol{if}\ \mathrm{x_j} - x_k = \mathbf{0} \\ \mathbf{1} & \boldsymbol{if} \mathrm{x_j} - x_k < 0 \end{cases}$$

It has been documented that when $N \geq 10$, the statistic S is approximately normally distributed the variance as

$$\mathbf{VAR}(\boldsymbol{S}) = \frac{\mathbf{1}}{\mathbf{18}}[\mathbf{n}(\mathbf{n}-\mathbf{1})(\mathbf{2n}+\mathbf{1}) - \textstyle\sum_{\mathbf{p=1}}^{\mathbf{q}} \mathbf{t_p}(\mathbf{t_p}-\mathbf{1})(\mathbf{2t_p}+\mathbf{5})] \qquad (4)$$

Here, q is the number of tied groups and t_p is the number of data values in the p^{th} group. The standard test statistic Z is computed by

$$Z = \begin{cases} \frac{\boldsymbol{S-1}}{\boldsymbol{VAR(S)}} \boldsymbol{ifS} > 0 \\ \boldsymbol{0} \qquad \boldsymbol{ifS = 0} \\ \frac{\boldsymbol{S+1}}{\sqrt{\boldsymbol{VAR(S)}}} \boldsymbol{ifS} < 0 \end{cases}$$

Mann-Kendall test was performed for checking the consistency and non-consistency of the dataset [Karki *et al*., 2017; Dahal *et al.*, 2016; Taxak *et al.*, 2014; Costa and Soares, 2009]. Such criteria have been tested for continuous, homogeneous and consistency to get quality rainfall data of selected stations for further analysis.

3.5 Methodology

3.5.1 Identification Departure of Deficit and Excess Years

Bhalme and Jadhav (1984) and Varikoden *et al.* (2015) used the ±10 % departure from long-term mean to excess /deficit Indian Summer Monsoon Rainfall climatology was identified as severe flood/drought years in India. Flood/Drought document in Nepal using anomalies is limited; it is new; this study used ± 10 % departure from long-term mean monsoon rainfall to identify the severe extreme events. Percent Departure Nepal Summer Monsoon Rainfall (PDNSMRi) was easily calculated. Using;

$$\boldsymbol{PDNSMR_i} = \frac{\boldsymbol{R_i - \bar{R}}}{\boldsymbol{\bar{R}}} * \boldsymbol{100}\ \% \qquad (5)$$

where R_i and $\bar{R}$ denote all Nepal summer monsoon rainfall and means all Nepal monsoon rainfall for 42 years datasets, the Percent Departure Summer Monsoon Rainfall of each 107 stations was calculated the same.

The student's t-test is used to check the statistically significant of the monsoon rainfall anomalies.

The El Niño years were identified based on the three-month running average SST anomalies over the Nino 3.4 regions. We considered a year as El Niño when the value of Nino 3.4 SST anomaly is greater than 0.5 ºC and a year as La Niña when the value of Nino 3.4 SST anomaly is lower than 0.5 ºC in any five consecutive months (NOAA). The detailed information on El Niño episodes was obtained from NOAA URL, https:/origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml.

3.5.2 Identification of Drought Severities using SPI Thresholds

SPI was developed to detect, calibrate, quantify and monitor drought using long-term precipitation data sets (McKee *et al*., 1993). SPI is normalized so that wetter and drier climates of different time scales can be represented simultaneously (Hayes *et al*., 1999). The duration of weeks or months and seasons can be used to apply this index to agricultural interests, and a longer duration of years can be used to apply this index to water supply and water management interests (Di Lena *et al.*, 2014; Patel *et al.*, 2007). It has also been demonstrated in several studies in different regions of the world.

The SPI calculation method is as follows; the monthly precipitation is fitted to gamma distribution. The probability density function of Gamma distribution is defined as

$$\mathbf{g}\,(\mathbf{x}) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \tag{6}$$

for x >0

where,

$\alpha > 0\alpha$ is a shape parameter

$\beta > 0\beta$ is scale parameter

x >0 x is the precipitation amount

$$\Gamma(a) = \int_0^{\infty} y^{\alpha-1} e^{-y} dy \tag{7}$$

$\Gamma(a)$ is the gamma function

Fitting the distribution to the data requires alpha and beta to be estimated. The maximum likelihood function is given as follows:

$$\hat{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \tag{8}$$

$$\hat{\beta} = \frac{\overline{x}}{\hat{\alpha}}$$

where$A = ln(\overline{x}) - \frac{\sum ln(x)}{n}$ (9)

n =number of precipitation observations

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

$$\boldsymbol{G}(\boldsymbol{x}) = \int_{0}^{x} \boldsymbol{g}(\boldsymbol{x})\boldsymbol{dx} = \frac{\mathbf{1}}{\hat{\beta}\alpha\Gamma(\hat{\alpha})}\int_{0}^{x} \boldsymbol{x}^{\hat{\alpha}-\mathbf{1}}\boldsymbol{e}^{-x/\hat{\beta}}\,\boldsymbol{dx} \qquad (10)$$

letting $t = x/\hat{\beta}$ equation becomes

$$\boldsymbol{G}(\boldsymbol{x}) = \frac{\mathbf{1}}{\Gamma(\hat{\alpha})}\int_{0}^{x} \boldsymbol{t}^{\hat{\alpha}-\mathbf{1}}\boldsymbol{e}^{-t}\boldsymbol{dt} \quad (11)$$

since gamma function is undefined for x=0 and precipitation distribution may contain zero, cumulative probability becomes:

$$\boldsymbol{H}(\boldsymbol{x}) = \boldsymbol{q} + (\mathbf{1} - \boldsymbol{q})\boldsymbol{G}(\boldsymbol{x}) \qquad (12)$$

where q is the probability for zero. H(x) is then transformed into a normal distribution with a zero mean and unit variance. The solution of the above approach is as follows,

$$Z = SPI = -\left(t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \qquad (13)$$

for 0<H(x) <0.5

$$Z = SPI = +\left(t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \qquad (14)$$

for 0.5<H(x)<1.0

$$\text{where, } t = \sqrt{ln\left(\frac{1}{(H(x))^2}\right)} \qquad (15)$$

for 0<H(x) <0.5

$$t = \sqrt{ln\left(\frac{1}{(1.0 - H(x))^2}\right)} \qquad (16)$$

for 0.5<H(x)<1.0

c_0 = 2.515517; c_1= 0.802853; c_2 = 0.010328

d_1=1.432788; d_2 = 0.189269; d_3 = 0.001308

In this study, the SPI was computed at 3-, 4- and 12-month timescales using the "SPEI" package in R-statistical software. The index computation is simple based on precipitation only as an input, and the outputs have multiple time scales of SPI. We defined 3 months' time-scale of SPI as SPI3, 4 months' time-scale of SPI as SPI4similarly, 12 months' time-scale SPI as SPI12 for winter, summer and annual drought identification respectively.

The threshold for indicating the severity of meteorological drought based on SPI was adopted (McKee *et al*., 1993). First, SPI3, SPI4 and SPI12 data sets were interpolated using the inverse distance weighted function (IDW) (Patel *et al*., 2007). Then, the interpolated maps were reclassified as different severity classes using the SPI threshold (Table 4). For example, the interpolated SPI4 of September months was reclassified because the SPI4 of September comprises the accumulated total precipitation of the rainfall received in June, July, August, and September, which is crucial to the significant cropping season in Nepal. Similarly, the interpolated SPI12 of December month was reclassified because the SPI12 of December comprises the accumulated total precipitation from January to December, which is crucial for water resource planning.

Table 4: SPI classification thresholds based on McKee *et al.* (1993)

SPI values	Drought category
0 to –0.99	Mild drought
–1.00 to –1.49	Moderate drought
–1.50 to –1.99	Severe drought
–2.00 or less	Extreme drought

Time series of SPI for individual stations were obtained to determine the variation in SPI time length. Time series were also utilized to observe the variation in detecting drought length of data sets. A typical drought year was detected from the average SPI time series analysis.

3.5.3 Identification of Drought Trends

The nonparametric rank-based Mann-Kendall test (M.K.) was applied to assess the time series data (Kendall, 1975; Mann, 1945). Many researchers have used this method (Nouri and Homaee, 2020; dos Santos *et al.*, 2017; Di Lena *et al.*, 2014) to detect trends in climatic time series data in different regions of the globe.

3.5.4 Drought Hazard Index Methodology

Drought hazard index (DHI) is defined as the frequency and intensity of drought events. Frequent droughts with high levels of intensity could result in severe hazardous effects. The SPI was used as a proxy to quantify drought events. We used SPI to identify drought events and their intensities during the periods of 1977–2018. Drought Hazards of an extreme event can be carried out using SPI by previous researchers (Dabanli, 2018; Rajsekhar *et al.*, 2015; Shahid and Behrawan, 2008) in different regions of the globe. The detailed methodology for the calculation of the DHI is described and mentioned by previous researchers (Dabanli, 2018; Rajsekhar *et al.*, 2015; Shahid and Behrawan, 2008).

Each drought severity theme is given a particular weight and each feature of the theme is given a rating to compute drought severity of the integrated layer (of station).The weights and ratings used for integration layer of stations are given in Table 5.

Table 5: Weights and ratings assigned to drought severity themes and features of the themes, respectively based on Shahid and Behrawan (2008)

Drought severity	Weight	Percentages of occurrences	Rating
Moderate	1	≤ 9.0	1
		9.1- 10.0	2
		10.1-11.0	3
		≥ 11.1	4
Serve	2	≤3.5	1
		3.6-4.5	2
		4.6- 5.5	3
		≥5.6	4
Very serve	3	≤ 1.5	1
		1.6 – 2.0	2
		2.1-2.5	3
		≥2.6	4

Drought hazard index (DHI) of integrated layer of station is calculated as:

$$\mathbf{DHI = (MDr * MDw) + (SDr * SDw) + (VSDr * VSDw)} \qquad (17)$$

Where,

DHI is the drought hazard index;

MDr is the moderate drought rating;

MDw is the moderate drought weight;

SDr is the severe drought rating;

SDw is the severe drought weight;

VSDr is the very severe drought rating; and

VSDw is the very severe drought rating.

Weight scores are determined by considering the SPI intervals, such that weight =1 for moderate drought (MD), weight = 2 for severe drought (SD), and weight = 3 for very serve drought (VSD). The weight and rating scores are assigned based on the intervals which are illustrated in Table 5. Drought Hazard Index (DHI) is calculated for each SPI value between 1977 and 2018. The aggregated DHI is obtained by using Equation 17, from 107 rain gauges data. GIS is used to overlay drought hazards index dataset to the individual station of the country. The interpolated DHI maps in GIS by natural break methods and categorizing the different hazardous categories such as low to high.

3.6 Definition of Some Terminology used in This Study

3.6.1 Definition of drought

A drought event is defined as a period in which the drought index value is continuously negative and reaches the value of –1.00 or less. Drought starts when the value falls below zero and ends when it reaches a positive value following the value of –1.00 or less (McKee *et al.*, 1993).

3.6.2 Drought frequency

It is defined as the number of drought events in the total years of the study period. It is calculated as follows:

$$\mathbf{F_s = \frac{n_s}{N_s} * 100\%} \qquad (18)$$

where,

F_s is the drought frequency (%);

n_s is the number of drought events;

N_s is the total years for the study period; and

s is the station.

3.6.3 Drought intensity (DI*e*)

It is obtained by dividing severity by duration. The larger the intensity, the greater the drought severity.

$$\boldsymbol{DI_e = \frac{S_e}{m} * 100\%} \qquad (19)$$

where,

DI_e is the drought intensity;

S_e is the drought severity; and

m is the months of drought.

3.6.4 The drought station proportion

It is the number of drought stations on a time scale relative to the total number of stations studied. It provides the spatial extent of drought events during a period over the stations (Gumus and Algin, 2017). It is calculated as follows:

$$\boldsymbol{P_j = \frac{n_j}{N_j} * 100\%} \qquad (20)$$

where,

P_j is the drought station proportion at a given time scale (%);

J is the time scale;

n_j is the number of droughts in the given time scale; and

N_j is the total number of stations.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Background

This chapter is based on the results of three manuscripts submitted to the journal. Till now one manuscript published paper on journal of water and another accepted paper in the journal of the institute of science and technology and one under review manuscript and some more relevant topics results.

The result section includes information on the seasonal and yearly rainfall patterns. The results are presented in different sections. Starting with a study of the precipitation, this part offers the rainfall pattern on monthly to decadal scales. In order to generate the seasonal and yearly SPI values, this study used SPI packages. Seasonal and annual SPI time scales were analyzed regional and national-wise and monitoring over Nepal. MAKESENS Excel Template was used to examine the trends of the time series data. At last drought hazard monitoring is presented.

4.2 Rainfall Statistics

The monthly rainfall metrics from 1977 to 2018 revealed that the rainfall strongly increased from May (7%), with highest in July (27 %) due to influence of summer monsoon, while the lowest was recorded in November (approximately 1 %). In winter months, December (0.8%), January (1.2 %) and February (1.6 %) rainfall was recorded respectively. However, winter rainfall (i.e., December through February) is significant as it accounts for approximately about 3 % of Nepal's total annual rainfall is shown in Figure 2. Furthermore, approximately 50 % of the annual rainfall was recorded during July and August in two months, and 80 % of the annual rainfall contributes to the monsoon season across the country followed by pre-monsoon 13 %, and post-monsoon 4 %. Moreover, the regional rainfall metrics are tabulated in Table 6.

Rainfall in Nepal is primarily dominated by the monsoon, characterized by high rainfall from June to September, the remaining period (8 months) of the year received about 20 % of the annual rainfall facing water scarcity. Table 6 illustrates that the western region received a high amount of westerly derived rainfall in winter than other regions but in contrast the low annual rainfall total. The monsoon rainfall dominates the annual rainfall, observed high in the central mountainous region than in other regions. The annual rainfall decreases from the eastern to western region however some mountainous regions of the central region recorded high rainfall values. The pre-monsoon and post-monsoon rainfall amount increases from western to eastern Nepal.

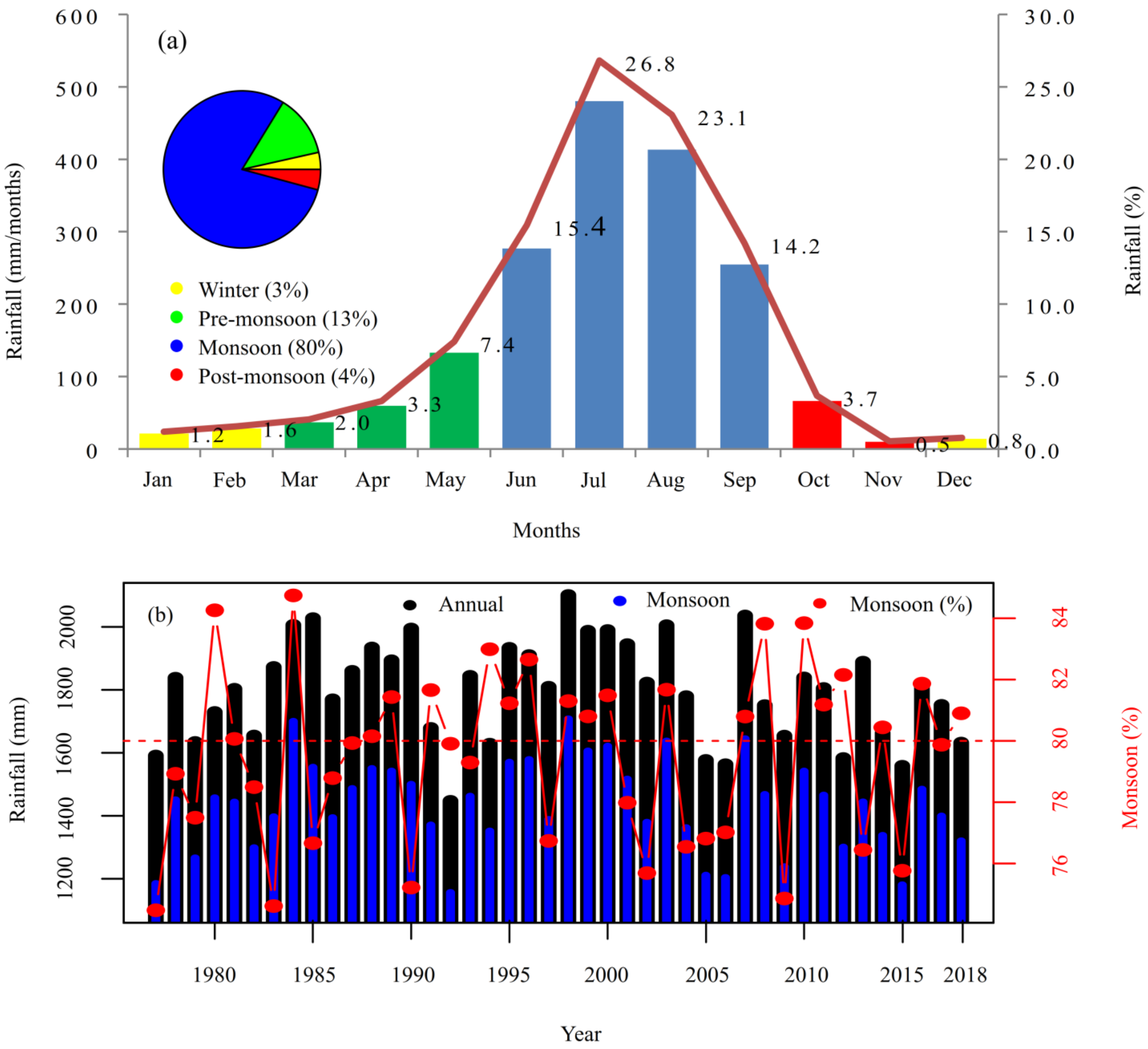

Figure 2: Variability of (a) Monthly rainfall statistics averaged from 1977 to 2018 and Pie chart shows the seasonal amount of rainfall (%). (b) Annual, monsoon rainfall Variability and percent monsoon rainfall for the period 1977-2018.

Summer rainfall was observed greater in the central region with comparisons to the eastern and western regions of Nepal. However, the western region observed low annual rainfall but high amount of Westerly-derived winter rainfall in winter season than other regions of Nepal (Table 6). Pre- and post-monsoon rainfall increases from western to eastern Nepal. Though, the annual total rainfall decreases from eastern to western Nepal.

Table 6: Regional rainfall (mm) statistics

Region	Western	Central	Eastern
Winter	91.40	61.46	40.28
Pre-monsoon	171.41	229.42	281.94
Monsoon	1239.36	1515.31	1491.19
Post-monsoon	51.50	74.92	98.12
Annual	1553.68	1881.11	1911.53

4.2.1 Contribution of Monsoon and Winter Rainfall to the Annual values

The contributions of winter rainfall to the annual total were distinct in individual years. Figure 3 (a, b) shows the year-to-year annual and winter rainfall. Annually in percentage of winter rainfall varies with 0.68 % in the year 2006 and 7.04 % in the year 1989.

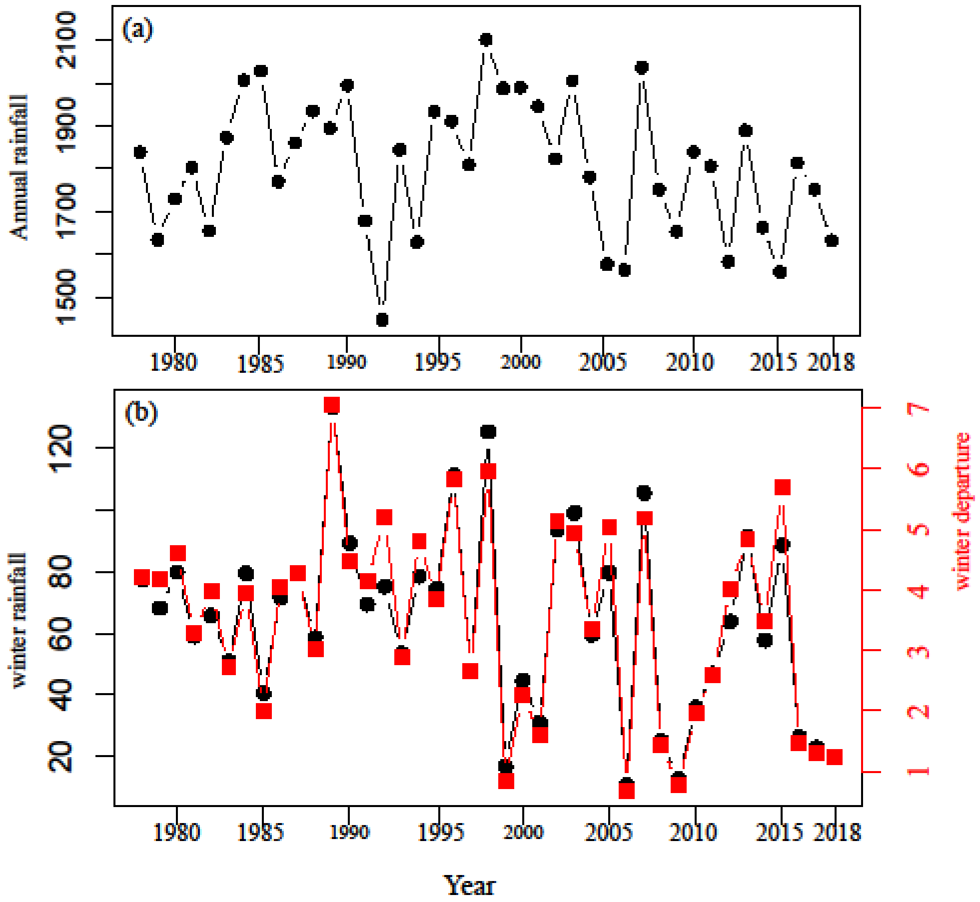

Figure 3: Temporal variability observed for (a) annual rainfall, (b) winter rainfall variability and percentage winter rainfall in period 1977-2018.

About 15 winter seasons contributed more than 3 % and 26 seasons contribute less than 3 % for annual rainfall (Figure 3b). The excess winter episodes observed in eight seasons found having more than 5 % of rainfall to the annual.

Monsoon rainfall variability with respect year to year varied from 74 % to 86 % in 1992 and 1984 (Figure 2b). Other18 monsoon seasons contributed more than 80 % and 19 seasons contribute less than 80 % of annual rainfall. Six monsoon episodes were observed having about 80 % rainfall to the annual.

4.2.2 Spatial Distributions of Mean Seasonal Precipitation in Nepal

There was large intra-seasonal variability of rainfall in Nepal. The seasonal rainfall characteristics are depicted in [Figures 4 (a, b, c, and d)]. In this study, in the winter season the maximum intrinsic rainfall amounts received in high mountainous mid-lands of the central and eastern regions [Figure 4(a)], which shows the spatial variations of the winter rainfall over the country. In winter season the highest rainfall has been received over western region of Nepal as comparing to the central and eastern regions. Generally, the winter rainfall increases with elevation over the western, central and eastern (WCE) regions. Furthermore, the low and mid land of western part received more rainfall in winter and decreases towards eastern parts.

The far western region, higher mountainous of the central region and Northeast of Nepal are rainfall pocket regions as observed greater than 100 mm in winter. The west-east mountainous range observed intrinsic heavy rainfall patterns, at the same time dry areas of the central and eastern regions located at lower land comparatively observed low rainfall. Generally, the far western region observed heavy rainfall than other regions of Nepal. The 16 (14.96 %) stations record more than 100 mm different regions in winter. The study has identified the dry areas as well as wet areas in different regions over the country. Generally, the mean rainfall of winter season decreases from the western to the eastern region. However, the central and eastern mountainous stations record heavy winter rainfall. The far -western part of Nepal recorded higher rainfall than the central and eastern Nepal. The large spatial variability of winter rainfall observed ranging from 12 mm/month and more than 150 mm/month in the western and central high-mountainous areas.

In the winter rainfall over the mountain terrain notably indicates very intricate heavy rainfall patterns but low land of eastern Nepal shows very low rainfall patterns. Generally, the winter rainfall increases with elevation in Nepal (Figure 4a).

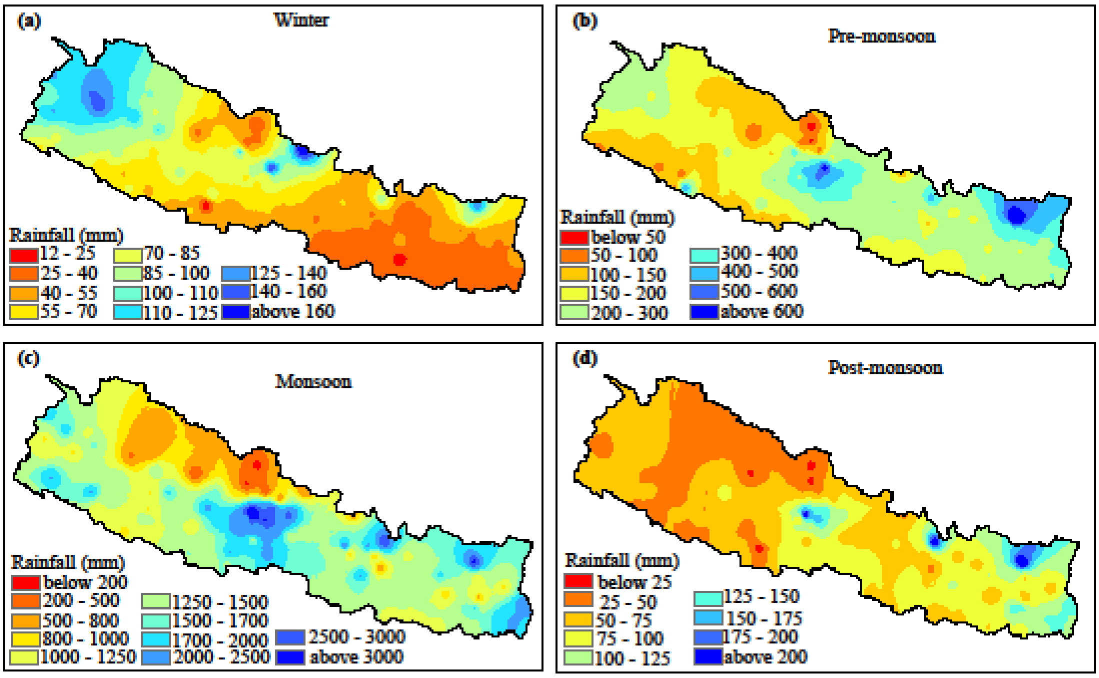

Figure 4: Spatial distribution of mean seasonal precipitation (mm) for a) winter season; b) pre-monsoon; c) monsoon; d) and post-monsoon season over period of 1977 to 2018. Note legend scales of all four seasonal maps are different.

During the pre-monsoon season on March to May, the country receives the second-highest rainfall during the study period. The highest rainfall observed in eastern Nepal, which decreases towards western Nepal. The spatial variability of pre-monsoon rainfall in the country is shown in the isohyetal map (Figure 4b). The central and eastern high mountainous regions observed intrinsic heavy rainfall amounts in the study period.

In contrast to the winter, during Monsoon, June to September, the country receives intense rainfall. Monsoon is the wettest season and main source of rainfall in Nepal. The monsoon rainfall dominates the annual rainfall as receives about 80 % of the annual total rainfall (Figure 2b). There is a marked variation in the amount of monsoon rainfall from the east to the west and from the south to the north within a short distance. The contribution of the monsoon rainfall is substantially high in the eastern part of the country as compared to western part. Monsoon rainfall widely varies over different parts of the country with lowest over Northwest part (< 200 mm) and highest over central mid-mountainous part (> 3000 mm) of the country followed by Northeast part (Figure 4c). Analyzing from south to north, High-land has low rainfall in comparison to mid-lands and low-lands. The spatial variation of monsoon rainfall shows dry areas as well as wet areas in different regions over the country in the isohyetal map (Figure 4c). Generally, the amount of mean monsoon rainfall observed decreasing from the east to west region. However, in the central region of Nepal, certain pockets are observed with heavy monsoon rainfall totals.

Post-monsoon, season occurs in the months of October to November, just after the retreat of southeasterly monsoon. There is a predominance of westerly wind and this season gets very little rainfall in the country. This season is characterized by the presence of fine weather with sunny days. November receives the lowest rainfall of the year. The spatial distribution of rainfall is similar to the pre-monsoon seasons. In this season the eastern part of Nepal receives more rainfall than the central and western parts of Nepal (Figure 4d). The spatial variation of post-monsoon rainfall of the country is shown in the isohyetal map (Figure 4d).

4.2.3 Spatial Distributions of Annual Rainfall and its Trends

Due to the large topographic variations, annual rainfall ranges from more than 4,000 mm along the southern slopes of the Annapurna range in the central region of the country to less than 150 mm in the north of the Annapurna range. The rainfall pattern in the region is highly affected by the terrain. Topography which plays an important role in the distribution of rainfall. The region on the windward side receives very high rainfall and that on the leeward side receives very little. The country's maximum precipitation was observed at an altitude up to mid-lands, and then it gradually decreased due to the dominance of orographic influences. Spatial variation of annual rainfall observed in Nepal from 107 stations over different physiographic regions since 1977 to 2018 as shown in Figure 5.

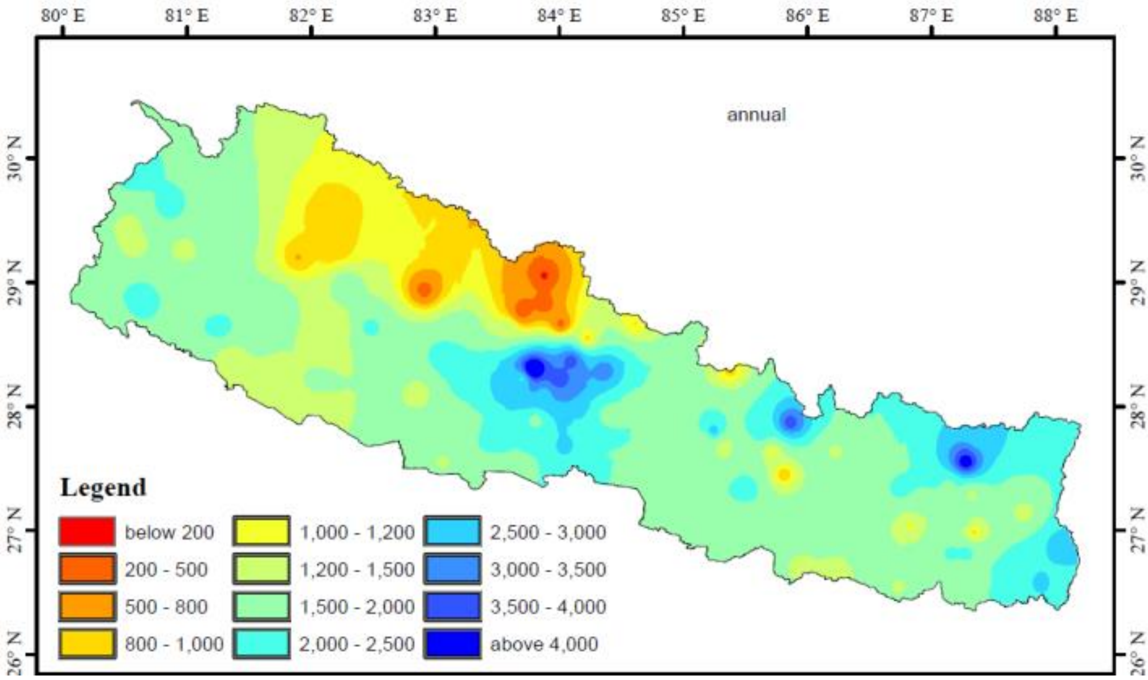

Figure 5: Spatial distributions of annul precipitation (mm) and its station wise annual trends over period of 1977 to 2018.

Furthermore, Non-parametric Mann-Kendall trend identified the increasing or decreasing annual rainfall trends of individual stations over different physiographic regions of Nepal. For this, we have used annual precipitation for the time period (1977 to 2018). Annual rainfall trends over Nepal noticed most of the country's regions showed a decreasing trend (Figure 6).

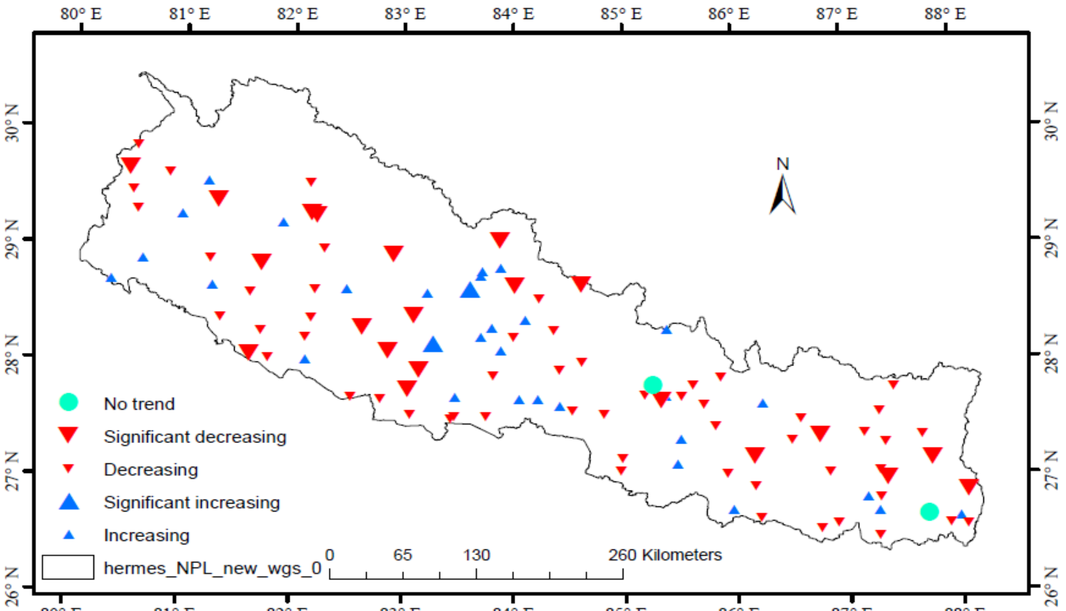

Figure 6: Spatial distribution of station-wise annual rainfall trends over period of 1977 to 2018.

The rainfall stations of lowland and midlands of central region show an increasing trend than the other parts of Nepal. Moreover, out of 107 stations, 28 stations show increasing trends, 52 stations show decreasing trends, 3 stations show significant increases, 22 stations show significant decreases and 2 stations show no trends in different regions over Nepal. This study identified annual rainfall decreased by 0.9 mm/year over Nepal during the period 1977 to 2018. This is brought on by the frequently occurrence of El Nino and the decline summer and winter rainfall.

4.2.4 Temporal Variability of Annual Rainfall

This study has used 107 stations for average rainfall to produce the temporal variability of annual rainfall. The average annual rainfall of Nepal is 1791.52 mm/annual from long-term climatology for the period 1977–2018. There is a large inter-annual variation during the study periods. From the statistical analysis, the annual rainfall recorded below the mean is 19 seasons and above is 23 seasons (Figure 7). During annual episodes, the temporal variability varies between minimum rainfall in the year 1992 and maximum in year 1986.

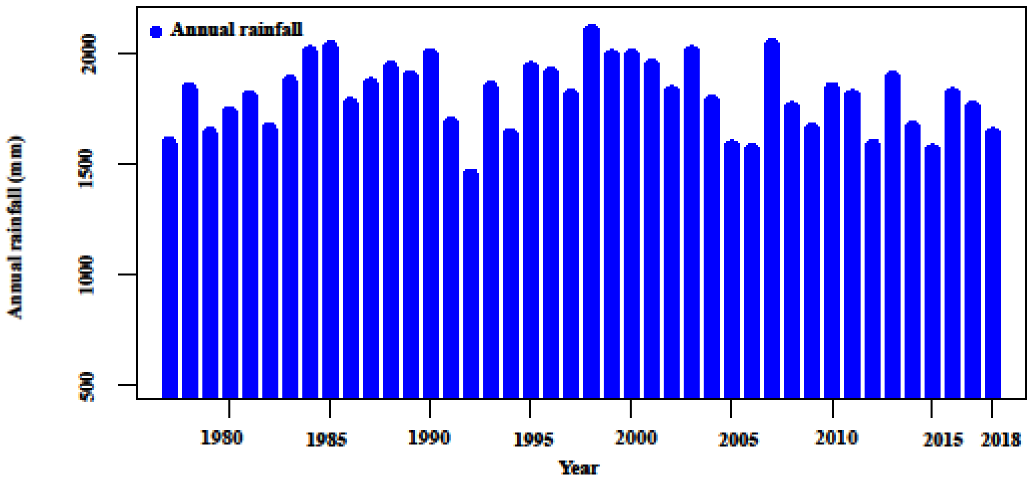

Figure 7: Temporal variability observed of annual rainfall for the period 1977-2018 in Nepal.

4.2.5 Decadal Rainfall Patterns of Summer and Winter Seasons in Nepal

In this study, we also analyzed the spatial and temporal variability of decadal rainfall. The variability of multi-decadal monsoon and winter rainfall clearly depicted that during monsoon season, the northwest region showed less than 399 mm and central Nepal as more than 3500 mm within the multi-decadal windows(1981-1990), (1991-2000), (2001-2010), and (2011-2018). Generally, the western region observed less monsoon rainfall in comparison with the central and eastern regions of Nepal.

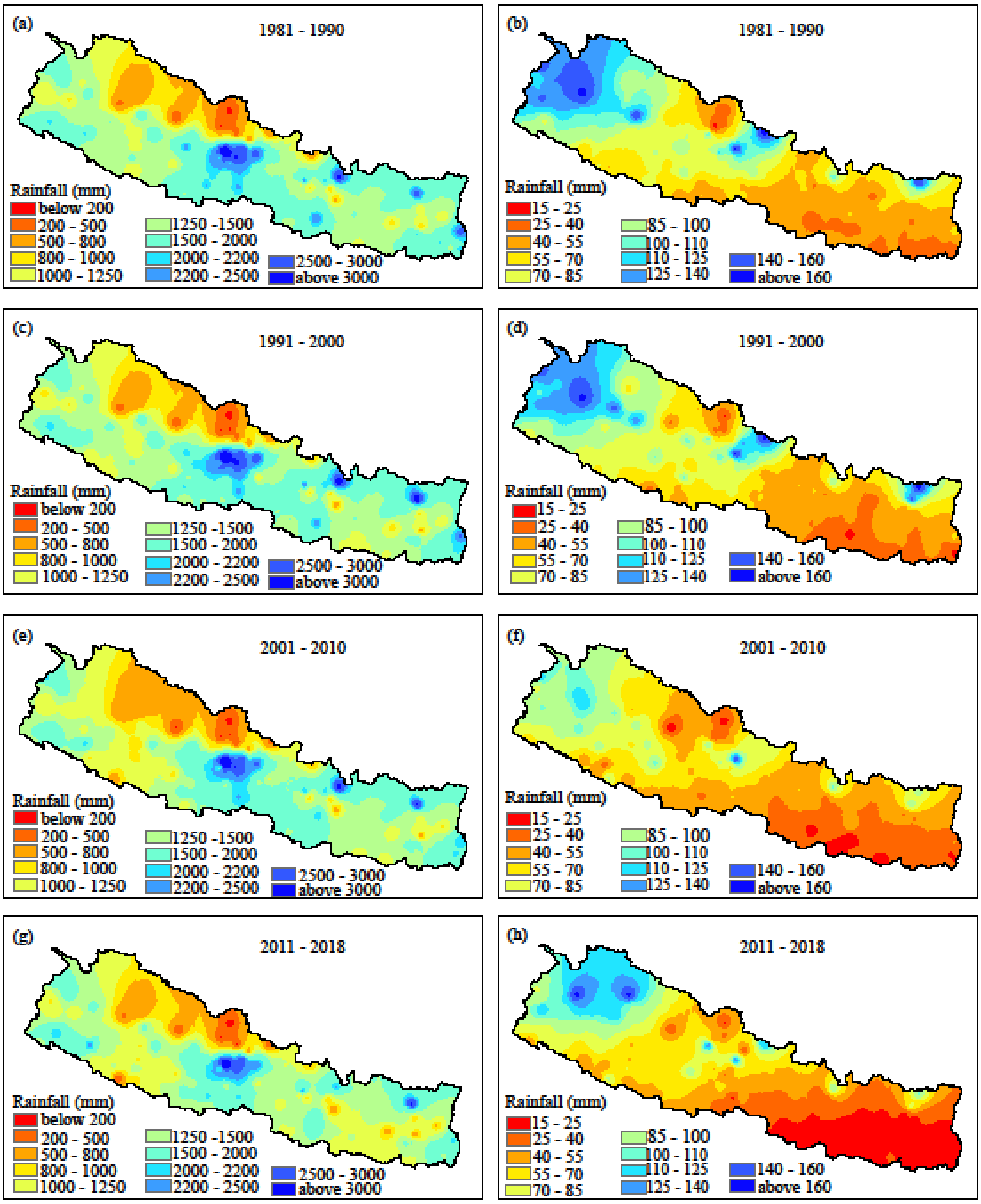

Figure 8: Spatial distribution of decadal precipitation (mm) for monsoon and winter seasons; over period of 1977 to 2018. Note legend scales of summer and winter seasonal maps are different.

Similarly, the winter decadal rainfall windows showed the lower rainfall region of eastern Nepal that observes the minimum rainfall as compared to the western, central and eastern regions of Nepal in winter season. The mountainous region of mid-lands of central and eastern regions observed the intrinsic heavy rainfall values [Figures 8 (e, f, g, and h)]. In contrast, winter precipitation in lowlands of eastern Nepal was drier than the central and western regions of Nepal.

Generally, monsoon rainfall decreases from the eastern to the western region. This study observed that the altitudinal dependency, increased monsoon rainfall up to mountainous regions and decreases in higher altitudes, especially in lesser Himalayas. Furthermore, heavy monsoon and winter rainfall have been observed in the mountainous central and eastern regions.

4.2.5.1 Quantification of Decadal Rainfall (increasing\decreasing) in Summer and Winter Seasons

In this study, we have preliminarily investigated the decadal change of winter and summer rainfall since the late 1980s. The changing pattern of the decadal seasonal rainfall was due to the frequent El Nino and possible other factors remain to be marked. The monsoon rainfall was identified wet in the decades, 1981-1990 and 1991-2000 and in the dry decade during 2001-2010 and 2011-2018. This clearly indicates the multi-decadal scale of variability of the monsoon rainfall (Table 7) and Figures 9(a, b). Similarly, the winter rainfall has followed the same patterns.

This study focuses on decadal rainfall quantification in summer and winter seasons. Multi-decadal scale variations of rainfall (summer and winter), are revealed through the bar diagram plots of decadal mean monsoon and winter rainfall for the four decades 1981-1990, 1991- 2000, 2001-2010, and 2011-2018 (Figures 9a and b). However, within a particular past decade, there were several strong and weak phases of the inter-seasonal variations. The decrease in summer rainfall is more than winter rainfall during the recent couple of decades. Based on the quantitative analysis of seasonal rainfall, during the last few decades seasonal rainfall has shown significantly varying.

In decadal analysis, we have categorized the time periods for 1981-1990, 1991-2000, 2001-2010 and 2011-2018 in the recent four decades. On the basis of decadal rainfall analysis, the monsoon rainfall trends have marked the decreasing rainfall patterns as shown in Table 7.

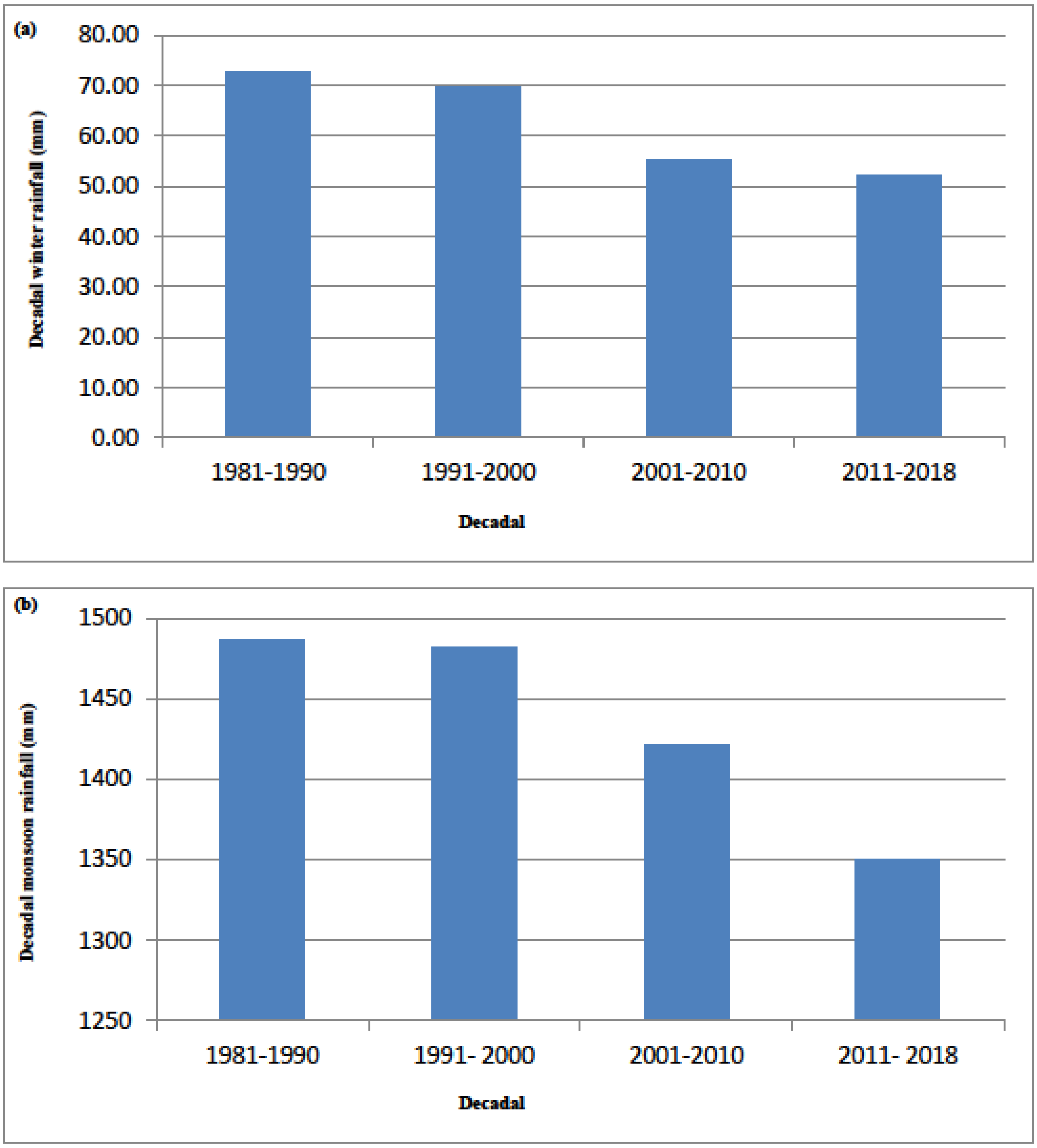

Figure 9: Decadal rainfall variability observed for winter and summer seasons.

Table 7: Decadal Seasonal Rainfall Statistics for the Past Four Decades

Decades	Average summer rainfall amounts	Average winter rainfall amounts
1981-1990	1482.76	71.89
1991-2000	1469.63	74.23
2001-2010	1428.72	56.19
2011-2018	1386.52	50.41

Actually, in the recent past decades (2001–2010) and (2011-2018) have observed a large number of dry winter episodes in the years 2001, 2006, 2008, 20009, 2016, 2017, and 2018 in Nepal. The past decade (2001-2010) shows exceptionally large deficit episodes in winter. For example, a remarkable deficit of precipitation was observed in the winters out of the episodes, 2006 and 2009, which are large dry episodes (Figure 9b).

Similarly, the second and most recent decades in 1992 and 2015 showed large dry events in summer episodes (Figure 9a). There was a decadal decreasing rainfall pattern observed in the recent past decades.

4.2.6 Nation wise Temporal Variability of Seasonal Rainfall

This study used 107 stations for average rainfall to produce the temporal variability of seasonal rainfall. The average seasonal (monsoon and winter) precipitation of Nepal was found 1433.42 and 69.67 mm/season as the long-term climatology of the period 1977–2018. Similarly, mean annual precipitation of Nepal is 1791.52 mm/annual from long-term climatology. There is a large intra-seasonal variation between summer and winter. From the statistical analysis, the monsoon rainfall records below the mean in 19 seasons and above in 23 seasons. Similarly, the winter rainfall variability is depicted in Figure 10b.

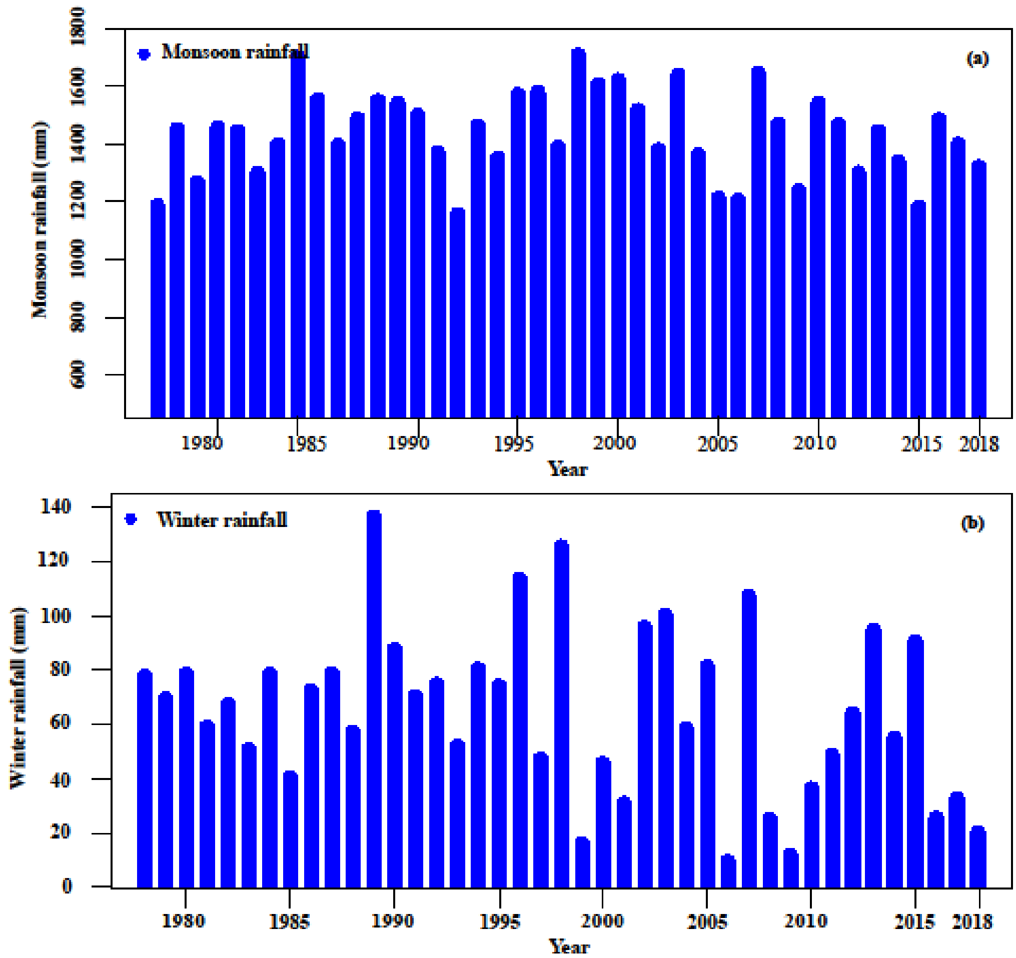

Figure 10: Temporal variability of seasonal rainfall (mm) in Nepal since 1977 to 2018, the mean from 107 stations.

During monsoon season the temporal variability varies from minimum rainfall in 1992 to maximums in 1986. A similar character was found in annual rainfall because the monsoon rainfall dominates annually in Nepal. Similarly, the variability of winter rainfall was observed as minimum in 2006 and maximums in 1989.

From Figures 10(a, b), this study found the large rainfall deficit monsoon and winter seasons in the last four decades, the details of monsoon rainfall variability was documented in the accepted manuscripts second.

4.2.6.1 Regional Temporal Variations of Monsoon and Winter Rainfall

We used mean rainfall of 28 stations for the western region, 47 stations for the central region and 32 stations for the eastern region to show the temporal variability of monsoon rainfall in respective regions (Figure 11). The regional rainfall shows that the eastern and central regions of Nepal observed more rainfall than the western region.

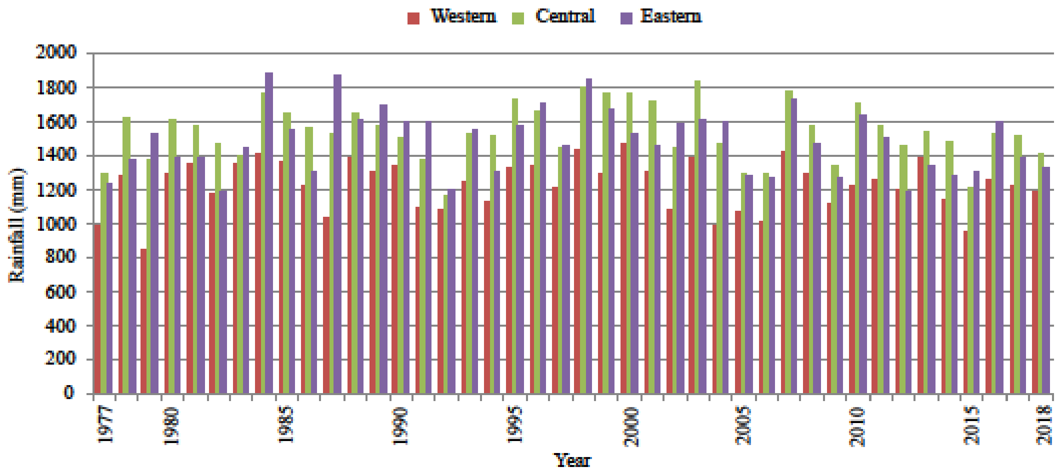

Figure 11: Temporal variability of regional monsoon rainfall from 1977 to 2018.

During the study periods, 25 seasons of high rainfall were observed in the central region as compared to the eastern region, and 17 seasons were observed having more rainfall in eastern Nepal. However, in recent years the rainfall has been decreasing in the eastern region as compared to the central region. Last 42 years show, the western region of Nepal observes low rainfall than comparing to the central and eastern regions of Nepal except in 2013. The rainfall record (Figure 11) shows a gradual decreasing rainfall values all in the western, central, and eastern regions. The total monsoon rainfall in the central region of Nepal was found more than eastern and western regions (Table 6).

4.2.6.2 Regional Temporal Variability of Winter Rainfall

For the regional analysis, we have used analyzed 28, 47 and 32 stations' rainfall for the western, central and eastern regions respectively. The average rainfall of winter in WCE regions was observed at about 92.93 mm/winter, 61.68 mm/winter and 42.75 mm/winter respectively. The fluctuation of winter rainfall in the western region ranges from 172.68 mm/winter in year 2013 and minimum of 24.28 in the dry year 1999. Similarly, the central region observes a fluctuation of winter rainfall, with a maximum of 149.44 mm/winter in 1989 and minimum of 6.27 mm/month in the year 2006. The eastern region observes a fluctuation of rainfall with a maximum of 101.38 mm/month in 2007 and a minimum of 2.18 mm/month in 2006. During the study period, 95% (40 years) was high rainfall in the western region as compared to the central region.

The rainfall variability in the WCE regions indicates that there were distinct rainfall patterns in the large deficient in winter season. In eastern Nepal, the low rainfall received in winter seasons of years 1999, 2006, 2009, 2017, and 2018 was less than 11 mm/month. Similarly, in the years 1982, 2001 and 2008 observed less than 21 mm/month. Generally, from a regional perspective, the eastern region has received less winter rainfall than the central and western regions.

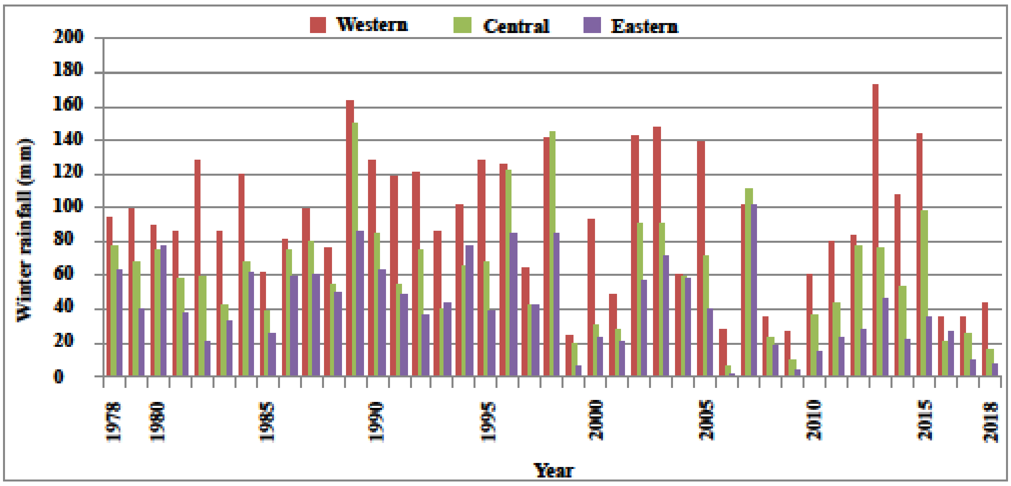

Figure 12: Temporal variability of regional winter rainfall from 1977 to 2018.

4.2.7 Spatial Distribution of Rainfall on Large Deficit Monsoon and Winter Dry Years

The spatial variability of rainfall was similar in extreme dry episodes in 2006 and 2009. In these episodes, the central and eastern regions were affected more than the western region. These dry years episodes were the worst in last four decades. Individual major drought year's rainfall magnitudes are interpolated in isohyetal maps

[Figures 13(a, b)]. The winter rainfall generally showed decreasing from west to east. There was a distinct rainfall pattern in distinct major dry seasons.

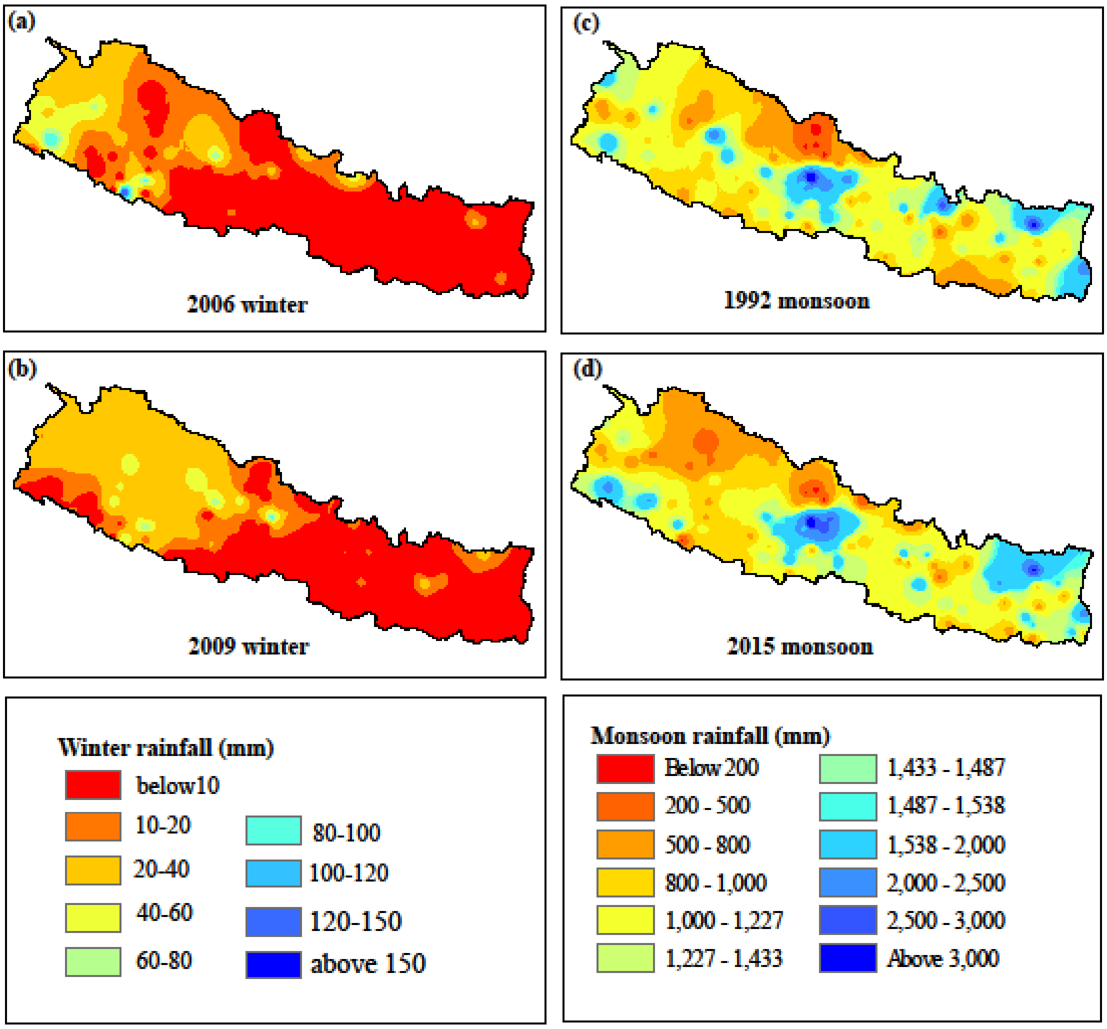

Figure 13: Spatial distributions of (a) summer rainfall 1992, (b) summer rainfall 2015, (c) winter rainfall 2006 and (d) winter rainfall 2009.

Similarly, in 1992, the country was more affected by large deficit monsoon rainfall during the last four decades. In 1992, north-central region witnessed decrement in large rainfall anomalies than the eastern and western regions (Figure 13c). In the monsoon dry year 2015, the western region of Nepal was more affected by a large rainfall deficit in comparison to the central and eastern regions (Figure 13d). In this period, the mountainous region of the central and western regions records low rainfall.

4.2.8 Spatial Distribution of Rainfall on Major Monsoon Dry Years

Nepal is a mountainous country with complex topography; it faces the leeward side with low rainfall in the Northern part of Nepal. This area of Nepal is semiarid locations as rainfall recorded < 200 mm in the monsoon season. The spatial distribution of rainfall across Nepal indicates high rainfall or pocket rainfall areas surrounding Lumle, Num, Pokhara and Gumthan. Lumle and Pokhara lie in the central region of Nepal as High and Mid Mountainous near the Annapurna region. Num and Gumthang lie in the eastern part of high mountain regions recording more than 3000 mm/month in monsoon season. The interpolated Figures 14(a-e) indicate the pockets of rainfall areas as well as dry areas in the large deficit monsoon cases.

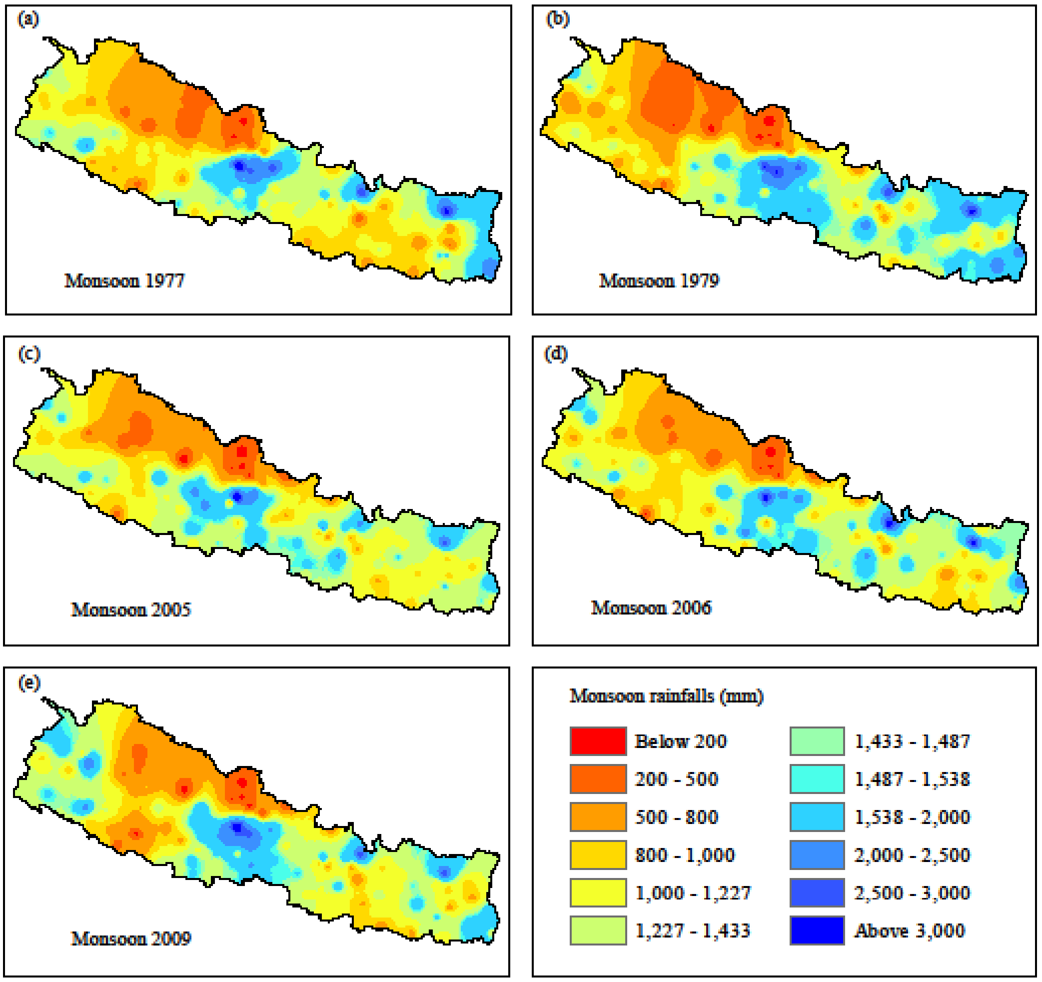

Figure 14: Spatial distributions of (a) summer rainfall in 1977, (b) summer rainfall in 1979, (d) summer rainfall in 2005, (e) summer rainfall in 2006, and (f) summer rainfall in 2009.

In the recent four decades, we calculated and analyzed the western, central, and eastern regions rainfall statistics. The large monsoon rainfall deficit recorded in 1979 in the western region as 45.09 % of the mean rainfall of the western region. Similarly, the central and eastern regions recorded large monsoon rainfall shows deficiencies in 1992. In the monsoon drought years 1977,1979, and 2006 the western region of Nepal was more affected by a large rainfall deficit in comparing to the central and eastern regions [Figures 14(a, b, and d)]. In this period the mountainous region of central and western regions recorded low rainfall. In 1979, the eastern region recorded excess rainfall whereas the western region records a large deficit in rainfall during the recent 42 years. While in the central region, rainfall anomaly decreases by 11.99 %, the eastern region increases rainfall anomaly by 2.92 %. But in 2009 the eastern region showed more affected by deficit rainfall than any region of Nepal (Figure 14e).

4.2.9 Spatial Distribution of Rainfall in Major Winter Dry Years

The winter rainfall gradually decreases from the far western to the mid-western and central and eastern regions in 1999. In 1999 and 2001, the eastern region observed low rainfall but in a similar pattern to other years. These years the far western region observed more rainfall, however years the central and eastern regions are drier. Individual major winter dry year's rainfall magnitudes are interpolated in isohyetal maps as in [Figures 15(a-f)].

The recent three consecutive winter dry years 2016, 2017 and 2018 observed deficient average rainfall of less than 27 mm/winter. The central and eastern region in 2018 was drier than 2017. The dry years 2016 and 2018 observed low winter rainfall in the eastern region and a similar pattern to other years. In those years, the far western region observed more rainfall. However, all major dry winter episodes observed mean rainfall was found less than 31.29 mm/month in the last recent four decades. Generally, in each event the rainfall decreased from the western to the eastern region however, some pocket stations lie on the central and northeast high mountains. In winter, the mountainous regions of Nepal face a crisis of drinking water, and irrigation. Generally, the major dry winter years' has experienced severe dry condition in eastern Nepal comparing to other regions. The winter rainfall dynamics are distinct in every episode. The winter rainfall plays a crucial role in the water resources recharge in an overcrowded city like Kathmandu the capital city of Nepal. Moreover, the spatial and temporal study indicates that the western region of Nepal records higher rainfall than the other regions. In major dry winter rainfall years, especially low lands of eastern regions were drier than the other areas of Nepal. Furthermore, the far western region records more winter rainfall as well as in major dry years.

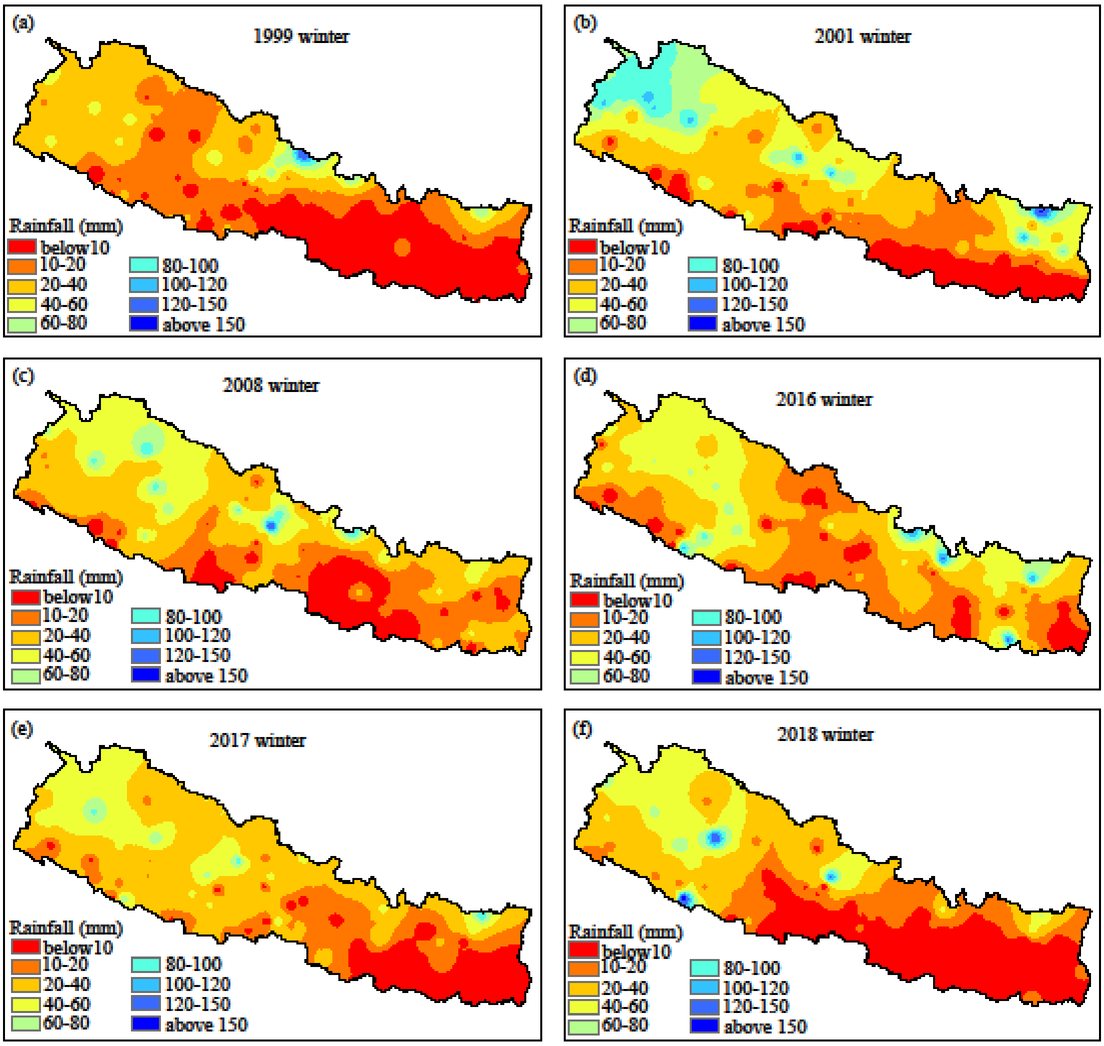

Figure 15: Spatial distributions of (a) winter rainfall of 1979, (b) winter rainfall of 1999, (c) winter rainfall of 2001, (d) winter rainfall of 2016, (e) winter rainfall of 2017, and (f) winter rainfall of 2018.

4.2.10 Quantification of Each Large Deficient Year's Rainfall from Long Term Average.

This study quantifies the major dry year's rainfall with their decreasing percent rainfall anomalies and deficit rainfall below average winter rainfall between 1977 and 2018. The average rainfall of first and second-rank dry seasons observed in the years 2006 and 2009 as 10.76 mm/month and 12.69 mm/month. Furthermore, in 2006, winter episodes observed 10.76 mm/month rainfall below 53.31 mm/month than the long-term average. Other major dry winter dries episodes of rainfall statistics are tabulated in Table 8.

Table 8: Winter dry years rainfall variability in different years over Nepal from 1977-2018

Rank	Year for mm/season	Average rainfall	Deficit rainfall below from long-term average (mm)
1	2006	10.76	53.31
2	2009	12.69	51.40
3	1999	17.02	47.10
4	2018	20.25	43.92
5	2017	22.25	41.06
6	2008	25.12	38.99
7	2016	26.47	37.64
8	2001	31.29	32.94

In eight years averaged deficit rainfall observed approximately 43.30 mm (67.69 %) below the average winter rainfall (1977 to 2018).

4.2.11 Composite of the Summer and Winter Seasons

We have analyzed the composite episodes for extreme years over Nepal; consisting of summer large deficient monsoon (drought) years 1977, 1979, 1992, 2005, 2006, 2009, and 2015. The mean anomaly sets of 5 composite large deficit monsoon years (1977, 1992, 2005, 2006, and 2015) were less than 15 %. Therefore, the composite of the 5 large deficit episodes is averaged.

The spatial distributions of the mean monsoonal of composite large deficit years are shown in Figure 16. The central part of Nepal recorded more rainfall which belongs to high and mid mountains near the Annapurna region. The rainfall pockets area of Nepal recorded > 3000 mm of rainfall during the drought years in Lumle, Pokhara, Num, and Gumthang which lie in the mountain regions of central and eastern parts of Nepal. On the other hand, the central and western parts of high lands are facing a rainfall deficit. The deficit areas in Mustang, Manang, Dunai, and Jumla stations recorded low precipitation than mean monsoonal rainfall in composite large deficit years.

Similarly, in winter composite year’s rainfall, we have evaluated the dry and wetter areas of Nepal which is useful for water resources management such as; irrigation and agricultural practices. From eight major dry years, we have chosen the driest 3 years (1999, 2006 and 2009) for composite analysis. Generally, winter rainfall is decreasing from the western-central to the eastern region though there are some pocket rainfall areas in the central and northeast mountain regions of Nepal.

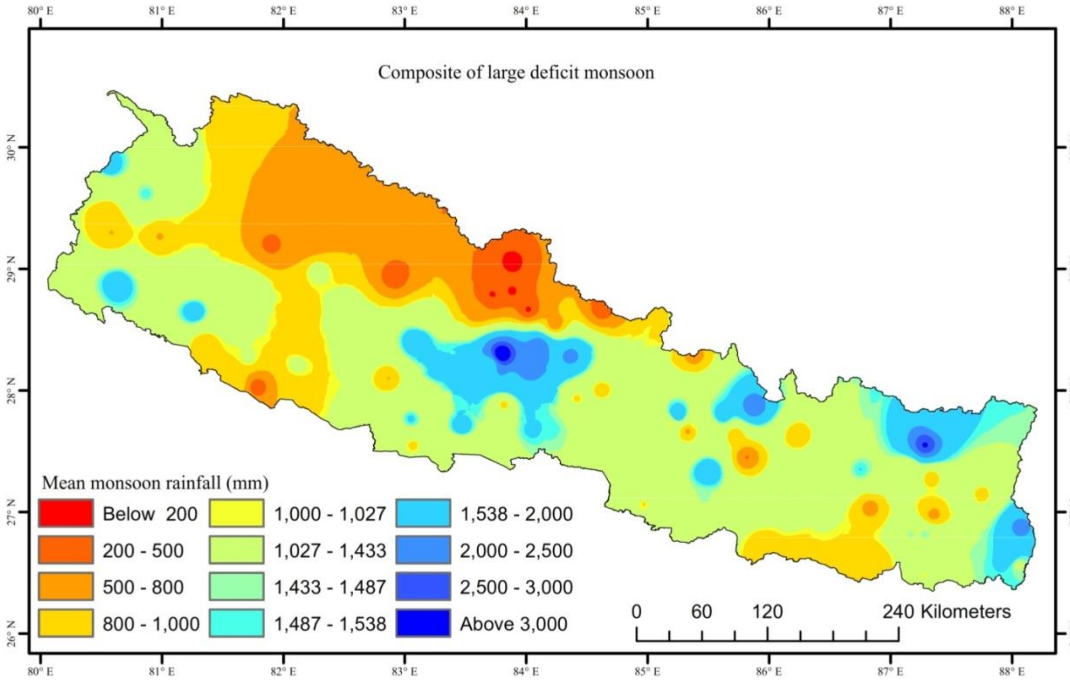

Figure 16: Spatial distributions of composite large deficit monsoon years.

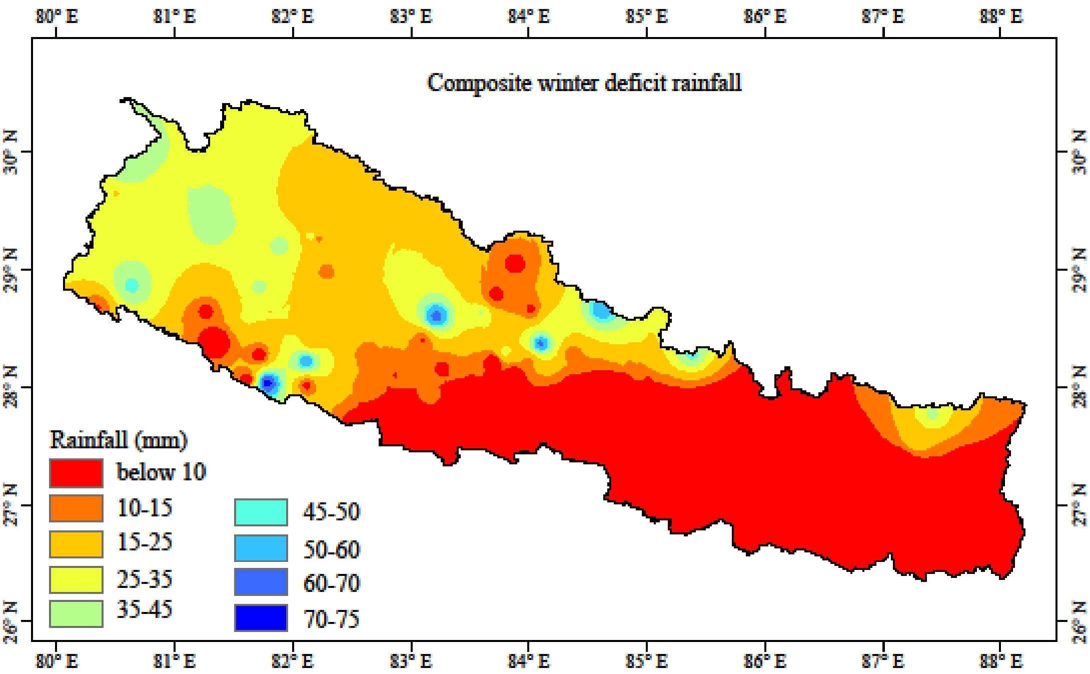

Figure 17: Spatial variability of composite winter dry years.

The north east high mountainous ranges observed heavy rainfall in comparison with the lowlands of an eastern region. The notable finding is that the central and eastern complex mountain terrain observed intricate heavy rainfall patterns. Composite rainfall analysis identified the dry and wetter zones over Nepal which has been clearly shown in the isohyetal map (Figure 17). The western region observed more average rainfall than the central and eastern regions. Comparatively, the lowlands of eastern Nepal observed minimum rainfall. The Far-western region is the wetter area among the other areas of Nepal.

4.2.12 Relation between NSMR and SOI

This study used the SOI index, which represents a large-scale fluctuation in sea level pressure between La Nina and El Niño episodes. Comparison between all Nepal summer monsoon series and SOI shows (Figure 18) the substantial correlation between SOI and NSMR records.

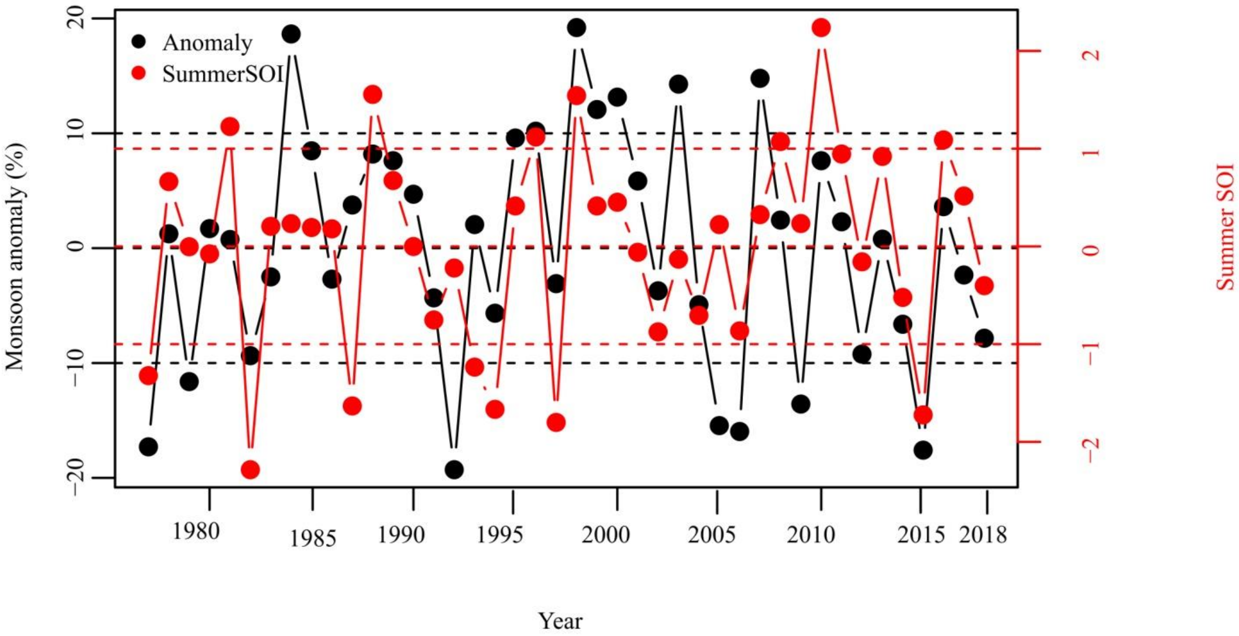

Figure 18: Relationship between Percentage Departure of NSMR and SOI.

Deficit period with (-) SOI, excess period with (+) SOI; the NSMR and SOI are 31 (about 74 %) times the phase relation (positive/negative SOI, positive/Negative NSMR (Figure 18). In 31 times phase relation 14 (about 45.16 %) times deficit and 17(about 54.84 %) times excess summer rainfall in Nepal. The correlation coefficient between NSMR and SOI is 0.52 from 1977 to 2018 as a 95 % confidence level. During the study periods, the average deficit monsoon rainfall is 8.72 % in the low phase of SOI (< -0.5), while the average excess is 7.12 % in the high phase of SOI (> 0.5). From the above-mentioned phase relation between NSMR and SOI analysis, the all-Nepal monsoon record series is highly influenced by the SOI. Such similar pattern is noticed as NSMR as large deficit (drought) years. However, during the drought/flood period, SOI and the NSMR are strong (-/+) than the normal years. The strength/weakness of the monsoon system was identified as La Nina/El Niño years for high NSMR variability. The El Niño years detected as 1982, 1983, 1987, 1991, 1992, 1997, 1998, 2002, 2004, 2009, 2015, 2016 and La Nina years as 1985, 1988, 1989, 1995, 1998, 1999, 2000, 2007, 2008, 2010, 2011, and 2015) extracted from https://origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml during study periods. The years 1998 and 2016 marked both El Niño and La Nina episodes. However, the monsoon seasons of Nepal are found dominated by excess rainfall in these years. Our findings show that Nepal's large deficit monsoon (drought) years associated with El Niño and normal both are extremely dry years. All El Niño years were found the deficit, but in the year 1987(El Niño) there was excess monsoon rainfall was observed in Nepal (Figure 2b). It is subject of further investigation. Moreover, this study quantifies the El Nino year’s rainfall with their decreasing percent rainfall anomalies and deficit rainfall below average monsoon rainfall between 1977 and 2018 (Figure 18 and Table 9).

Table 9: The rainfall variability observed in the large deficit monsoon rainfall years by El Niño events

Years	**1982**	**1983**	**1991**	**1992**	**1997**	**2002**	**2004**	**2009**	**2015**
Deficit rainfall (mm)	134.12	35.83	61.97	276.43	44.27	53.22	70.55	194.53	252.03

In 1992, summer episodes collected 1156.74 mm/month of rainfall which is below 276.43 mm/month than the long-term average. Other large deficient monsoon events rainfall deficits are tabulated in Table 9. On El Niño episode's average deficit, rainfall was observed approximately nine % below the average monsoon rainfall in period (1977 to 2018).

During the study period, this study revealed seven drought years in Nepal only three years associated with El Niño years, and four drought years are in normal years. The first and second extreme droughts in 1992 and 2015 were associated with El Niño years, and the third drought in 1977 occurred in normal years.

4.3 Results Based on SPI

4.3.1 Trend analysis of SPI3, SPI4 and SPI12 at each station

We carried out MK trend tests for SPI3, SPI4 and SPI12 over Nepal. The results of the individual station trend analysis of SPI3, SPI4 and SPI12 were examined in different regions of Nepal, which are summarized in Figure 19(a, b, c), and the SPI3, SPI4 and SPI12 trends were identified using the MAKESENS Template (Salmi *et al*., 2002); depending on the Z value of (positive, negative, and zero) for individual stations which are shown in Figure 19 (a, b, c). The Mann-Kendall trend test identified increasing, decreasing, and no trends of SPI3, SPI4 and SPI12 in the different regions. Downward red triangles and upward blue triangles represent negative and positive trends, respectively. In contrast, small downward red and upward blue triangles represent negative and positive trends, and big triangles indicate significant trends. The green circles indicate no trends. We observed that significant trends were mainly negative for SPI3, SPI4 and SPI12.

For SPI3, significant positive trends but other positive trends were observed as negligible. Out of 107 stations, 1 station showed a significant increase, and other 51 stations showed significant decreasing trends in different regions of Nepal. Figure 19a shows the overall trends of SPI3 time scale over Nepal. Many stations of the country showed a decreasing trend for SPI3 time scales in winter. However, in the eastern region, the significant decreasing trends were comparatively higher than in the central and western regions. Among the 51 significant decreasing trends, 13 were recorded in western, 10 in central, and 28 in eastern Nepal. Thus, for SPI3, significant negative trends seem to be more common in eastern region than that of central and western regions of Nepal.

For SPI4, significant positive trends and no trends were observed as negligible. Among the 107 stations, fourteen stations showed a significant decreasing trend, fifty-four stations showed a decreasing trend, thirty-two stations showed an increasing trend, five stations showed a significant increasing trend, and three stations showed no trend at all over Nepal as analyzed on SPI4. Among the fourteen significant decreasing trends, three were recorded in western, five in central, and six in eastern Nepal. Furthermore, Figure 4.18b shows the overall trends of SPI4 time scale over Nepal.

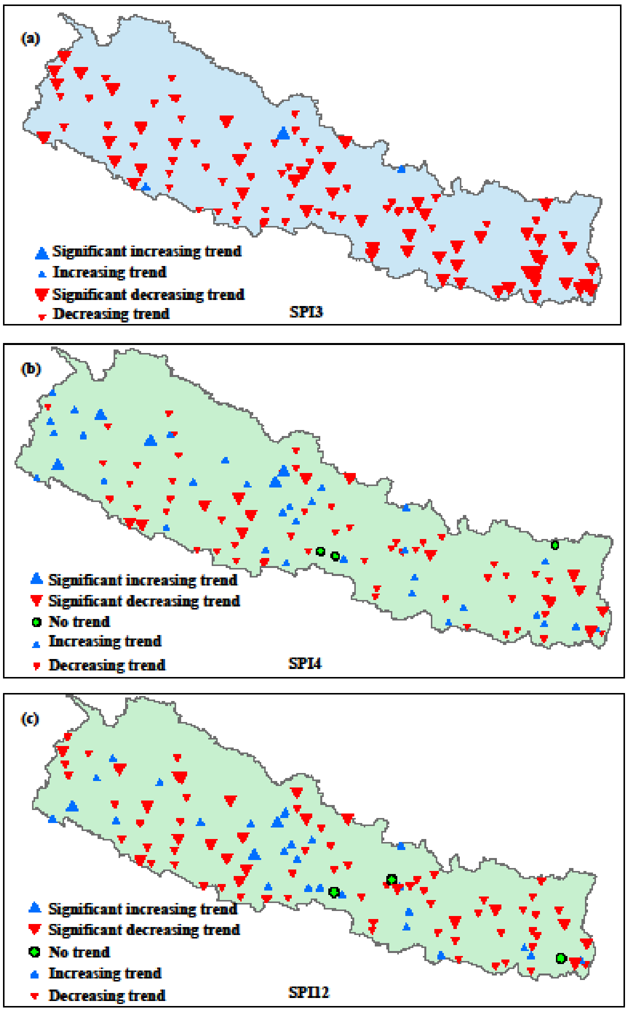

Figure 19: Station wise (a) winter, (b) summer and (c) annual trends at each station over Nepal.

Similarly, for SPI12, twenty-two stations showed a significant decreasing trend. Altogether fifty-four stations showed a decreasing trend, three stations showed a significant increasing trend, twenty-six stations showed an increasing trend, and three stations showed no trend in Nepal. Among the twenty-two significant decreasing trends, eight were recorded in the western part, eight in the central, and six in the eastern parts of Nepal, respectively. Thus, for SPI4 and SPI12, the negative trends seem to be more common in eastern, central and western regions of Nepal. The trend values of SPI3, SPI4 and SPI12 are presented in Table 10.

Table 10: Meteorological stations including the trend values of SPI3, SPI4 and SPI12

S.N	Station Name	Index No	No of years	SPI3 Z values	Trend	SPI4 Z values	Trend	SPI12 Z values	Trend
1	Belaurisantipur	106	42	**-2.03**	↓	0.39	-	0.10	-
2	Naubasta	412	42	**-1.76**	↓	-0.53	-	-0.44	-

3	Nepaljunj(Reg. off)	416	42	**-2.12**	↓	**-1.66**	↓	**-2.20**	↓
4	Ranijaruwa Nursery	417	**42**	-0.92	-	-1.20	-	-1.17	-
5	Bhairawa airport	705	42	-0.25	-	-1.00	-	-0.65	-
6	Bhairahawa (Agric)	707	42	-1.16	-	-0.23	-	-0.24	-
7	Taulihawa	716	42	-0.74	-	-1.20	-	-1.04	-
8	Bhagwanpur	723	42	-0.21	-	-1.32	-	-1.17	-
9	Simari	728	38	-0.92	-	0.03	-	-0.04	-
10	Simara airport	909	42	**-2.27**	↓	-0.27	-	-0.50	-
11	Parwanipur	911	42	**-2.38**	↓	-0.42	-	-0.44	-
12	Janakpur airport	1111	42	**-3.02**	↓	0.50	-	0.37	-
13	Karmaiya	1121	42	**-1.93**	↓	0.36	-	0.70	-
14	Siraha	1216	42	**-2.45**	↓	-0.81	-	-0.49	-
15	Rajbiraj	1223	42	**-1.95**	↓	-0.40	-	-0.16	-
16	Barmajhiya	1226	42	**-2.06**	↓	-0.99	-	-1.42	-
17	Biratnagar airport	1319	42	**-1.65**	↓	-1.04	-	-1.12	-
18	Tarahara	1320	42	**-1.83**	↓	0.76	-	0.39	-
19	Damak	1408	42	**-2.43**	↓	0.17	-	0.00	-
20	Anarmanibirta	1409	42	**-2.81**	↓	1.42	-	1.34	-
21	Chandragadhi	1412	42	**-1.85**	↓	-1.24	-	-1.18	-
22	Gaida (Kankai)	1421	35	**-2.64**	↓	**-1.75**	-	**-2.14**	-
23	Godawari (west)	215	42	-1.03	-	**1.66**	↑	**1.67**	↑
24	Chisapani (Karnali)	405	41	**-1.89**	↓	1.43	-	1.47	-
25	Kusum	407	36	-0.25	-	1.08	-	1.24	-
26	Sikta	419	41	1.08	-	**-5.01**	↓	-1.01	-
27	Nayabasti (Dang)	507	42	-1.53	-	-0.57	-	-0.63	-
28	Koilabas	510	42	-1.17	-	-0.64	-	-1.01	-
29	Butwal	703	42	-1.26	-	0.72	-	0.73	-
30	Beluwa (Girwari)	704	**42**	**-2.48**	↓	-0.08	-	0.26	-
31	Dumkauli	706	41	-0.79	-	0.00	-	0.62	-
32	Pattharkot (West)	721	42	-0.97	-	-0.94	-	**-1.69**	↓
33	Rampur	902	42	-1.62	-	0.13	-	0.28	-
34	Jhawani	903	42	-1.37	-	0.00	-	0.00	-
35	Beluwa (Manahari)	920	**42**	**-2.07**	↓	-1.21	-	-1.12	-
36	Tulsi	1110	40	**-1.72**	↓	-0.56	-	-0.70	-
37	Chisapanibazar	1112	42	**-3.36**	↓	0.39	-	-0.29	-
38	Harharpur gadhi valley	1117	41	**-1.81**	↓	0.10	-	0.22	-
39	Dharan bazar	1311	42	**-2.55**	↓	-1.22	-	-1.47	-
40	Chatara	1316	42	**-2.46**	↓	0.27	-	0.86	-
41	Kakerpakha	101	42	**-1.92**	↓	-0.98	-	**-1.65**	↓

42	Patan (west)	103	42	**-1.74**	↓	0.24	-	-0.82	-
43	Dadeldhura	104	42	-1.40	↓	0.61	-	-0.23	-
44	Pipalkot	201	42	**-2.27**	↓	1.07	-	-0.13	-
45	Silgadi doti	203	42	-1.53	↓	0.75	-	0.28	-
46	Pusma camp	401	42	-0.83	-	-0.27	-	-0.28	-
47	Dailekh	402	42	**-1.88**	↓	-0.87	-	**-1.76**	↓
48	Surkhet (Birendranagar)	406	42	-0.94	-	-0.23	-	-1.00	-
49	Libang Gaun	504	42	-1.38	-	**-2.70**	↓	**-3.09**	↓
50	Bijuwartar	505	42	-0.97	-	-1.45	-	**-2.07**	↓
51	Salyan bazar	511	42	-1.25	-	-0.81	-	**-2.09**	↓
52	Chaur jharitar	513	42	**-1.86**	↓	-0.98	-	-1.51	-
53	Kushma	614	42	-1.60	-	0.39	-	0.13	-
54	Kanchikot	715	42	**-1.85**	↓	**-2.31**	↓	**-2.54**	↓
55	Musikot	722	42	-1.18	-	**2.32**	↑	**2.99**	↑
56	Khudi bazar	802	42	**-2.71**	↓	-0.28	-	-0.64	-
57	Pokhara airport	804	42	**-2.62**	↓	-0.53	-	-0.94	-
58	Syangja	805	42	**-2.53**	↓	0.60	-	0.42	-
59	Bandipur	808	42	**-2.08**	↓	-1.09	-	-1.52	-
60	Gorkha	809	42	-1.03	-	-0.88	-	-1.28	-
61	Chapkot	810	42	-1.09	-	-0.80	-	-0.85	-
62	Kakani	1007	42	-1.06	-	-0.16	-	-0.57	-
63	Nawalpur	1008	42	**-1.86**	↓	-0.68	-	-0.70	-
64	Dolalghat	1023	42	**-1.79**	↓	**-1.80**	↓	-1.57	-
65	Khumaltar	1029	42	-1.21	-	-1.40		**-1.68**	↓
66	Kathmandu airport	1030	42	-1.07	-	1.24	-	1.51	-
67	Dhunibesi	1038	42	-0.54	-	-0.21	-	-0.57	-
68	Nagarkot	1043	42	-0.62	-	-0.23	-	-0.51	-
69	Jiri	1103	42	**-1.98**	↓	-0.57	-	0.00	-
70	Bahun tilpung	1108	42	**-2.25**	↓	-1.12	-	**-1.73**	↓
71	Nepalthok	1115	42	-1.17	-	-1.26	-	-1.19	-
72	Aisealukhark	1204	42	-0.62	-	0.75	-	**-1.94**	↓
73	Okhaldhunga	1206	42	**-2.62**	↓	-0.08	-	-0.11	-
74	Khotang bazar	1211	42	-0.54	-	-1.09	-	-0.75	-
75	Chainpur (east)	1303	42	-0.89	-	-0.95	-	-1.29	-
76	Pakhribas	1304	42	**-2.54**	↓	-1.32	-	-0.92	-
77	Dhankuta	1307	42	**-2.47**	↓	**-1.96**	↓	-1.63	-
78	Dingla	1325	**42**	**-2.55**	↓	-1.11	-	-0.79	-
79	Taplejung	1405	41	-0.96	-	**-2.41**	↓	-1.05	-
80	Kanyam tea estate	1416	42	**-4.09**	↓	**-2.41**	↓	**-3.02**	↓

81	Phidim (Panchther)	1419	41	**-1.96**	↓	**-1.90**	-	**-2.12**	↓
82	Darchula	107	42	**-2.07**	↓	0.36	-	-0.24	-
83	Chainpur (west)	202	37	-0.45	-	**2.16**	↑	1.03	-
84	Bajura	204	42	**-2.04**	↓	-1.06	-	**-1.72**	↓
85	Jumla	303	42	-0.89	-	0.38	-	**-1.83**	↓
86	Gamshree nagar	306	42	-0.99	-	-0.41	-	-0.75	-
87	Nagma	308	42	-0.55	-	**1.74**	↑	0.64	-
88	Dipalgaun	310	42	-1.02	-	-1.13	-	**-1.91**	↓
89	Dunai	312	42	**-2.22**	↓	0.72	-	**-1.87**	↓
90	Mainagaun (D.Bas)	418	42	-1.61	-	-0.37	-	-1.02	-
91	Musikot (Rukumkot)	514	42	-0.36	-	0.44	-	1.00	-
92	Bobang	615	41	**-2.61**	↓	**-2.64**	↓	**-2.85**	↓
93	Gurja Khani	616	39	-1.45	-	0.24	-	0.18	-
94	Lumle	814	42	-1.42	-	1.14	-	0.95	-
95	Siklesh	824	42	-1.44	-	0.63	-	0.54	-
96	Timure	1001	41	0.76	-	1.19	-	0.93	-
97	Gumthang	1006	42	-0.63	-	-1.59	-	-1.62	-
98	Salleri	1219	42	-1.22	-	-1.19	-	-0.82	-
99	Num	1301	42	-0.24	-	0.47	-	-0.07	-
100	Chepuwa	1317	42	**-3.27**	↓	0.00	-	-0.62	-
101	Jomsom	601	42	**1.80**	↑	**1.73**	↑	1.52	-
102	Thakmarpha	604	42	1.02	-	-0.47	-	0.57	-
103	Lete	607	42	-0.73	-	**3.08**	↑	**3.40**	↑
104	Panipauwa (M.Nath)	608	34	-0.45	-	-0.67	-	-0.44	-
105	Ghami (Musthang)	610	32	-1.02	-	-0.91	-	**-2.41**	↓
106	Larke samdo	806	41	**-2.76**	↓	**-2.61**	↓	**-3.93**	↓
107	Manang bhot	820	42	-0.99	-	**-2.58**	↓	**-3.13**	↓

Results in boldface indicate significant trends (- : No trend, ↑: upward trend, ↓: downward trend).

4.3.2 Temporal Variability of Seasonal and Annual SPI Time Scales

From 107 stations of average monthly precipitation data was generated in the timescales for SPI3, SPI 4 and SPI12 as depicted in Figure 20(a, b, c). A season is defined as a winter drought season when the SPI3 time scale thresholds are < -1. The drought seasons are categories based on the intensity of SPI3 time scale values. They are tabulated in Table 4. We used SPI3 time scale intensity for the study of the deficit/excess winter events with year-to-year variability and the plots are shown in (Fig 20a).

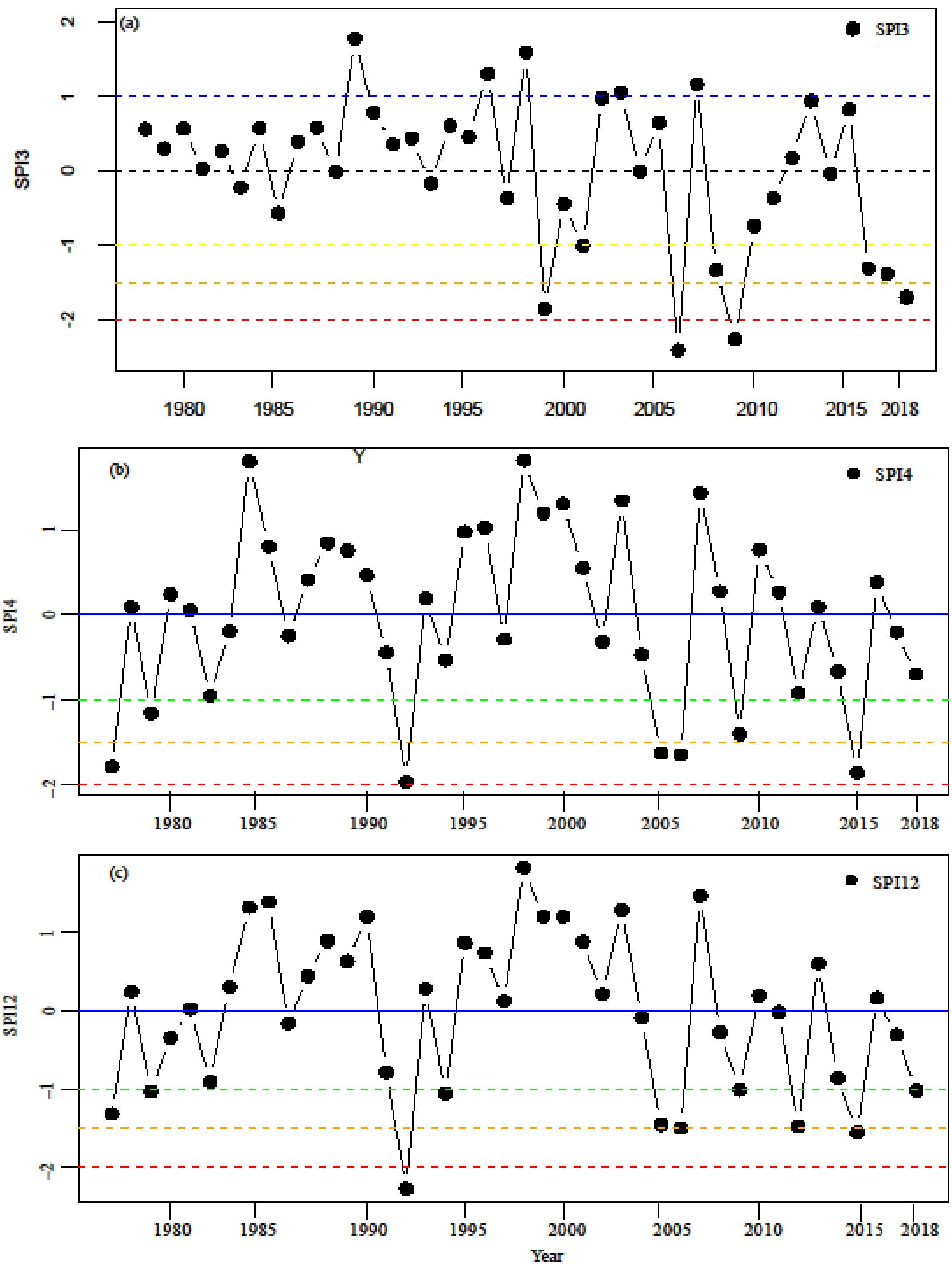

Figure 20: Temporal variability of SPI for (a) winter (SPI3), (b) summer (SPI4), and (c) annual (SPI12) during period 2017-2018.

Intensity of the SPI3 time scale values categories shows the severity of the drought and flood years. The rainfall deficit years were observed in 17 seasons, and the excess years as 24 seasons. 3-month SPI of February captured the deficiency or excess of precipitation in detecting droughts and floods in Nepal. Eight winter-drought years 2006, 2009, 1999, 2018, 2017, 2008, 2016, and 2001 with mean SPI3 time scale values are respectively -2.41, -2.26, -1.85, -1.7, -1.38, -1.33, -1.21, -1.01. And 5 winter excess years 1999, 1988, 1996, 2007 and 2003 with SPI3 average time scale values were obtained as 1.78, 1.59, 1.31, 1.17, and 1.05.

Interestingly, Nepal faced the frequent winter drought episodes in years 2008, 2009, 2016, 2017 and 2018 in the recent decade (2008-2018) as shown in (Figure 20a). Winter drought in 2006 was the worst which follows by 2009 and surplus year 1999 was followed by the year 1988 respectively during the recent 4 decades of the climatological history of Nepal. The fluctuation of SPI3 time scale values range from (-2.41) in the drought year 2006 to (1.78) in the excess year in 1999.

Similarly, summer drought seasons were identified based on the SPI4 intensity. A season is defined as a summer drought season when the SPI thresholds are < -1. The seasons are categories for the severity of the drought that depend on threshold values. They are shown in (Table. 4). Among 42 summer seasons the eight summer drought years are 1977, 1979, 1982, 1992, 2005, 2006, 2009, and 2015 as shown in (Figure 20b). The deficit SPI4 intensity is below 0 in 19 cases, and above excess SPI4 are 23 cases. The fluctuation of SPI4 was highest deficit in 1992 as (-1.96) and followed by -1.85 in 2015.

Likewise, the annual drought years were identified based on the SPI12 intensity. The Table 3 shows the ten drought years as 1977, 1979, 1992, 1994, 2005, 2006, 2009, 2012, 2015, and 2018 (Figure 20c). The SPI12 deficits are 19 cases, and excess SPI12 are 23 cases. The fluctuation of SPI12 ranges from (-2.28) in 1992 to (1.83) in 1998. Analyzing both the conditions of SPI4 and SPI12, we have identified that most of the drought years coincide with each other. The reason behind this can be the due to weightage of summer precipitation which the annual one follows.

4.3.3 Major Drought Events in Different Decades

Furthermore, variable SPI values the negative values during the last four decades in SPI time scales are shown in Table 11.

Table 11: Drought Frequency in Nepal by category for the last four decades

SPI	Time period	Drought category				Total
		Mild	Moderate	Severe	Extreme	
	1977-1980	+3,				
SPI3 Feb	1981-1990	+7,-3				
	1991-2000	+6,-3		1(1999)		

	2001-2010	+4,-2	2		2(2006,2009)
	2011-2018	+3,-2	2	1(2018)	
	total	10	4	2	2
SPI4 September	1977-1980	2	1	1 (1977)	
	1981-1990	7,+, -3			
	1991-2000	5+, -4		1(1992)	
	2001-2010	+5,-2	1	2(2005,2006)	
	2011-2018	+3,-4		1 (2015)	
	total	13	2	5	
SPI12 December	1977-1980	+1,-1	2		
	1981-1990	+8,	2		
	1991-2000	+7,-1	1		1(1992)
	2001-2010	+5,-2	2	1(2006)	
	2011-2018	+2,-3	2	1(1983)	
	total	7	9	2	1

The SPI time scale was generated as short SPI3, SPI4 and of long-term SPI12 to analyze drought impacts from monthly precipitation of 107 station rainfall data. It was used for the recognition of variability in time length and to identify drought severities. This study was based on SPI to assess and analyze the severities of droughts in the recent four decades. For this, purpose we have identified the frequency of SPI3, SPI4 and SPI12 severities. The results identified extreme (SPI < -2), severe (SPI < -1.5) and moderate droughts (SPI < -1), and deficit events occurred at different time scales. Among those, in the case of SPI4 and SPI12, two worst droughts were observed in 1992 and 2015 as shown in (Figures 20b, c). In contrast, SPI3 showed only two extreme drought events occurred in 2006 and 2009 [Figure 20(a)]. It is observed that SPI4 dominates the SPI12 because of the heavy monsoon rainfalls in June-September over Nepal which influences the annual rainfall. This may be linked to the occurrence of extreme drought during those two years. Again, the frequency of extreme drought occurrence was comparatively higher in the case of SPI12 than SPI4 [Figure 20(b, c) and Table 11] indicates high rainfall variability during the same periods. However, severe drought events occurred more frequently as indicated by SPI4 than SPI12. During the study years (1977–2018), about 50 % of the total events were struck by negative SPI intensity with different severities as shown in [Figure 20(a, b, c)]. The years 1977, 1979, 1982, 1992, 2005, 2006, 2009 and 2015 were the most drought-affected in Nepal; and 1977, 1992, and 2015 were found to be the worst years for the causes of high drought severity [Figure 20(b, c) and Table 10]. Likewise, 2006 and 2009 were the worst drought episodes in recent decades. Furthermore, [Figure 20(a, b, c)] depicts that in the last two decades, the country had a number of severe and extreme droughts that may be linked to the impact of climate change at a regional or local scales.

SPI3, SPI4 and SPI12 were used to study the winter, summer and annual drought dynamics of different regions as well as national wise. The SPI3, SPI4 and SPI12 of individual stations were investigated to examine the spatial and temporal dynamics of major drought events in Nepal.

At a glance, this study reveals that since 1977, Nepal has experienced ten high drought-affected SPI12 and eight for SPI3 and SPI4 within the recent last four decades, which detects the occurrence of extreme, severe and moderate droughts severities in different regions of the country. Thus we found the impacts of drought are increasing remarkably in Nepal since 2000.

4.3.4 Regional Variability of Seasonal and Annual SPI Time Scales

We have used average monthly precipitation of 28, 47 and 32 stations to generate the western, central and western (WCE) regional temporal variability for SPI3, SPI4 and SPI12 time scales (Figure 21, 22 and 23). The drought events with different intensities were observed in the winter season over the WCE region of Nepal.

Region wise comparative study of droughts in Nepal showed the diverse characteristics of SPI dynamics. Individual drought shows its variability due to western disturbances with distinct in nature of intensity of drought which is really crucial for the water resources planning and management in the country.

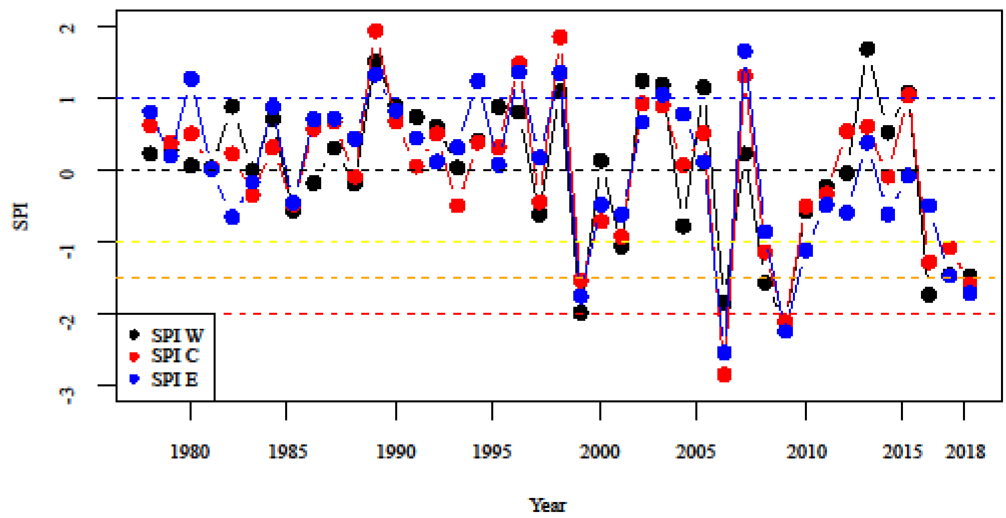

Figure 21: Regional temporal variability for SPI3 time scale on the WCE regions.

The temporal variability of winter drought/flood events in the WCE regions of Nepal are tabulated in Table 12.

Table 12: The winter drought and flood years from 1977 to 2018

	Condition	**Years**							
Western	Drought	2009	1999	2006	2016	2008	2018	2017	2001
	SPI values	-2.1	-2.0	-1.8	-1.7	-1.6	-1.5	-1.5	-1.1
	Flood	2013	1989	2002	2003	2005	1998	2015	
	SPI values	1.68	1.51	1.23	1.18	1.14	1.08	1.07	
Central	Drought	2006	2009	2018	1999	2016	2008	2017	
	SPI values	-2.8	-2.1	-1.6	-1.5	-1.3	-1.1	-1.1	
	Flood	1989	1998	1996	2007	2015			
	SPI values	1.93	1.84	1.47	1.3	1.03			
Eastern	Drought	2006	2009	1999	2018	2017	2010		
	SPI values	-2.5	-2.2	-1.8	-1.7	-1.5	-1.1		
	Flood	2007	1996	1998	1989	1980	1994	2003	
	SPI values	1.65	1.35	1.34	1.32	1.26	1.23	1.04	

Out of eight winter drought episodes, four drought episodes (1999, 2001, 2008 and 2016) were found in the western region which affected more than the central and eastern regions. Similarly, in 2006 the central region of Nepal was affected more than the eastern and western regions. And three drought episodes in (2009, 2017 and 2018) also affected more than the central and western regions of Nepal. The western and central regions observed the consecutive drought in years 2008 and 2009 and in recently years 2016, 2017 and 2018. Similarly, in the eastern region, consecutive drought years were 2009 and 2010 found in recent years 2017 and 2018. The consecutive drought years are more hazardous for environmental issues, crops and water scarcity. So, during the drought events in the hill and mountainous regions, livelihood was found more challenging than in normal years.

Similarly, the temporal variability of monsoon drought/flood events observed in the WCE regions of Nepal is shown in Figure 22 and in Table 13.

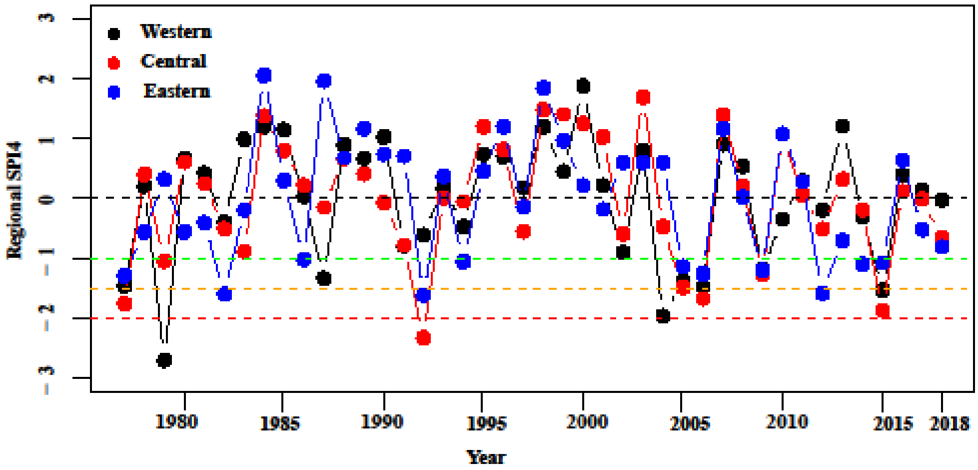

Figure 22: Regional temporal variability for SPI4 time scale on the WCE regions.

Table 13: The monsoon drought and flood years from 1977 to 2018

	Condition				**Years**				
Western	Drought	1979	2004	2015	2006	1977	2005	1987	2009
	SPI values	-2.71	-1.97	-1.53	-1.48	-1.46	-1.39	-1.34	-1.19
	Flood	2000	2013	1998	1984	1985	1990		
	SPI values	1.88	1.21	1.2	1.2	1.15	1.03		
Central	Drought	1992	2015	1977	2006	2005	2009	1979	
	SPI values	-2.33	-1.88	-1.76	-1.68	-1.49	-1.26	-1.05	
	Flood	2003	1998	1999	2007	2084	2000	1995	2010
	SPI values	1.7	1.49	1.41	1.4	1.38	1.25	1.2	1.08
Eastern	Drought	1992	1982	2012	1977	2006	2009	2005	2014
	SPI values	-1.62	-1.6	-1.59	-1.29	-1.26	-1.2	-1.14	-1.1
	Flood	2010	1989	2007	1996	1998	1987	1984	
	SPI values	2.06	1.97	1.85	1.2	1.17	1.17	1.08	

The drought and flood years are shown in Figure 22 for different regions. The intensity was different in different episodes.

The western region observed in the consecutive drought in years 2004, 2005 and 2006 and the central region observed in the years 2005 and 2006. Similarly, in the eastern region consecutive drought years were 2005 and 2006 and in the recent years

2014 and 2015. The consecutive drought years are more hazardous on environmental issues which cause crops and water scarcity. So, during the drought events in the hill and mountainous regions, livelihood is more challenging than in normal years.

Likewise, the temporal variability of annual drought/flood events observed in the WCE regions of Nepal is shown in Figure 23 and tabulated in Table 14.Similarly, drought and flood years are clearly shown in Figure (23) for different regions. The intensity is different in different episodes.

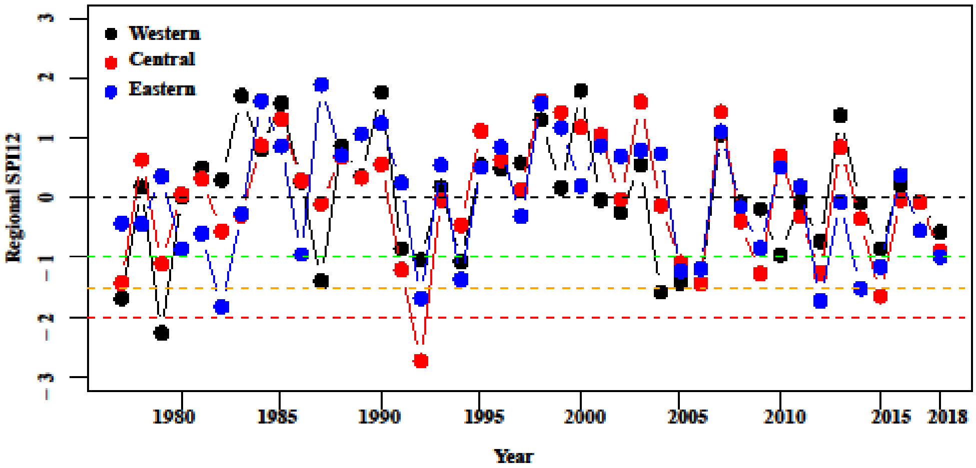

Figure 23: Regional temporal variability for SPI12 time scale on the WCE regions.

Table 14: The annual drought and flood years from 1977 to 2018

	Condition	Years							
Western	Drought	1979	1977	2004	2006	2005	1987	1994	1992
	SPI values	-2.27	-1.69	-1.58	-1.44	-1.43	-1.4	-1.07	-1.04
	Flood	2000	1990	1983	1985	2013	1998	2007	
	SPI values	1.8	1.77	1.71	1.59	1.38	1.31	1.06	
Central	Drought	1992	2015	2006	1977	2009	2012	1991	1979
	SPI values	-2.74	-1.65	-1.44	-1.43	-1.27	-1.26	-1.21	-1.11
	Flood	1998	2003	2007	1999	1985	2000	1995	2001
	SPI values	1.63	1.61	1.44	1.43	1.32	1.18	1.12	1.05
Eastern	Drought	1982	2012	1992	2014	1994	2005	2006	2015
	SPI values	-1.83	-1.73	-1.69	-1.52	-1.37	-1.23	-1.19	-1.16
	Flood	1987	1984	1998	1990	1999	2007	1989	
	SPI values	1.9	1.63	1.59	1.25	1.17	1.11	1.07	

The western region observed the consecutive drought years 2004, 2005 and 2006 however the central region observed in 1991 and 1992. Similarly, in the eastern region consecutive drought years were found in 2005 and 2006 and including years

2014 and 2015. The consecutive drought years are more hazardous to environmental issues which cause crops and water scarcity. So, during the drought events in the hill and mountainous regions, livelihood is more challenging than in normal years.

4.3.5 Spatial Variability of Major Droughts for SPI3, SPI4and SPI12

4.3.5.1 Spatial Overview of Winter Drought Episodes

Interestingly, there were severities, extreme, severe, moderate, and mild winter droughts over different regions of Nepal in each drought episode [Figure 24(a-h)]. Each event had different characteristics in Nepal. There were severities of extreme, severe, moderate, and mild droughts in winter over Nepal during the worst years in 2006 and 2009 [Figure 24(c and e)]. The worst drought episodes affected more extreme drought comparatively in the western and central regions than the eastern region. The severities of drought-affected locations are clearly depicted through spatial interpolation process which helps to identify the severities of extreme, severe, moderate, and mild drought over Nepal. Worst winter drought years 2006 and 2009 affected the larger areas of Nepal. The drought events affected particularly western and central regions of Nepal with extreme and severe drought. In winter seasons drought in 2006 and 2009; percent proportional weightage was affected by extreme, severe, moderate and mild drought conditions in different regions over Nepal which are presented in Table 14. Around 96 % of stations show negative SPI3 time scale values in the worst winter drought years (2006, 2009) so large locations of Nepal are affected by the precipitation deficit in worst drought years. Comparisons between the two worst winter drought years, in 2009 the western and central regions were affected by more extreme drought than in 2006.

The severities of drought are simply identified, and understandings are shown in Figures (24c, e). So, large locations in Nepal observed deficits in precipitation from the climatologically mean precipitation. From the point of view of drinking water and winter agricultural practices, these episodes were one of the most damaging periods over the study period. This study showed most of the western and central parts of Nepal recorded extreme and severe drought and most of the eastern part of Nepal recorded moderate drought in 2006 and 2009 with some exceptions.

The severities of drought are simply identified, and understandings are shown in Figures (24c, e). So, large locations in Nepal observed deficits in precipitation from the climatologically mean precipitation. From the point of view of drinking water and

winter agricultural practices, these episodes were one of the most damaging periods over the study period. This study showed most of the western and central parts of Nepal observed extreme and severe drought but the eastern part of Nepal observed moderate drought in 2006 and 2009.

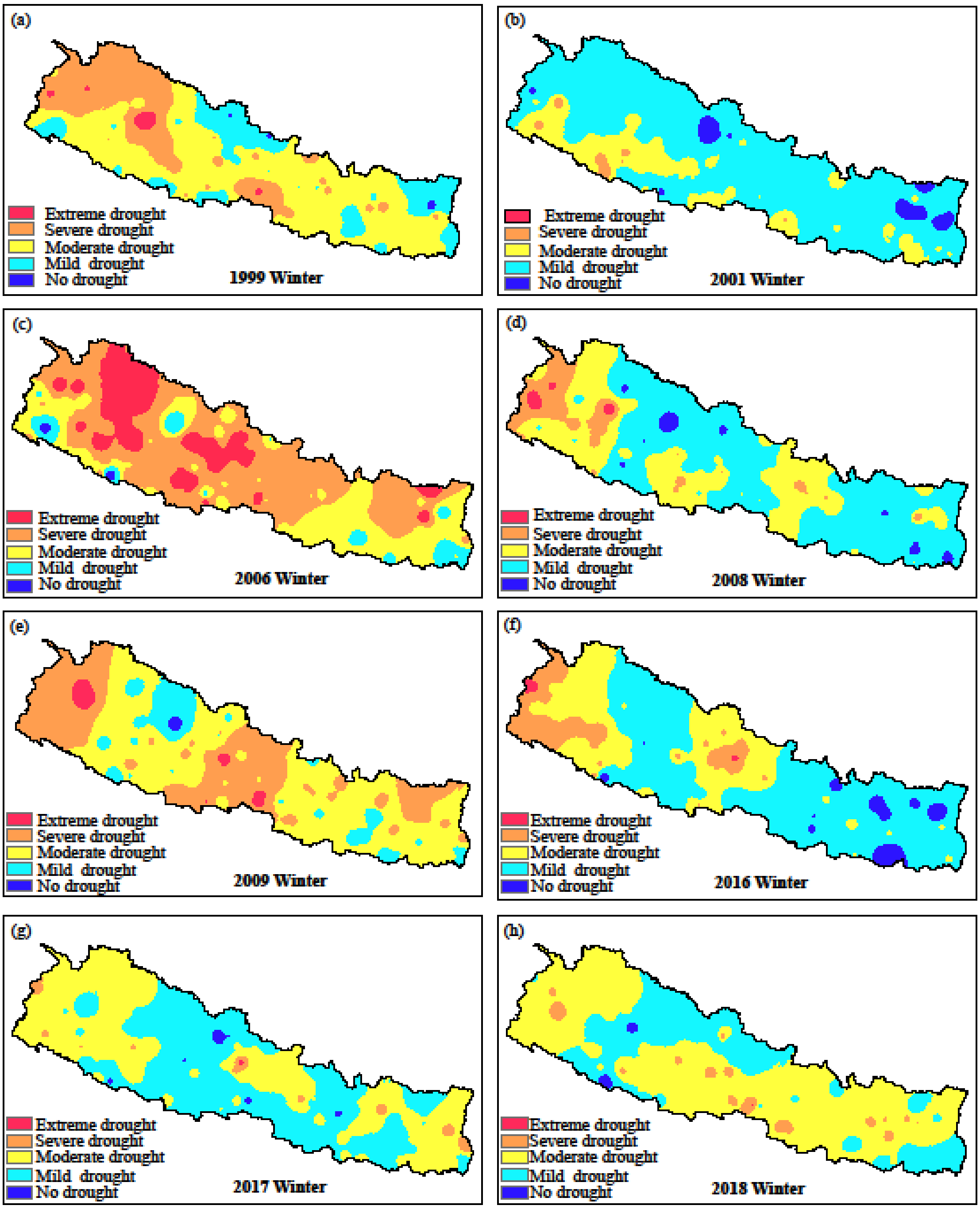

Figure 24: Spatial distributions of (a) winter (SPI3) of 1999, (b) winter (SPI3) of 2001, (c) winter (SPI3) of 2006, (d) winter (SPI3) of 2008, (e) winter (SPI3) of 2009, (f) winter (SPI3) of 2016, (g) winter (SPI3) of 2017, and (h) winter (SPI3) of 2018.

Recent winter drought events in 2017 and 2018 were interpolated through a spatial process that helped to identify the severities of drought over Nepal. In drought year 2017, the western and eastern part of Nepal was more affected by drought than the central parts of Nepal. Particularly, most of the central parts of Nepal was affected by mild drought (near normal); but the western and eastern parts of Nepal were affected by severe and moderate drought in 2017. Similarly, the far western terai and middle mountain region of central and most part of eastern region were affected by severe and moderate drought in 2018 and most of the high mountain region of the central part of Nepal by a mild drought (near normal) in 2018. Recent winter drought years in 2017 and 2018 affected drought severities (extreme, severe, moderate and mild) different locations of Nepal which has been clearly depicted in Figures 24(g, h). Drought events recorded frequently are harmful to human beings as an environmental issue. Few stations were affected by extreme, severe, moderate, and mild drought severities over the country which is tabulated in Table 15. Around 93 % of stations have negative SPI3 values in the years 2017 and 2018. So, large parts of Nepal face winter precipitation deficit. From drinking water, irrigation and agricultural point of view, this event was also crucial and damaging in period (1977-2018).

The western parts of Nepal were affected the most in terms of severities of drought in the drought years in 1999 (extreme, severe and moderate drought). Eastern parts of Nepal were affected by severe and moderate drought. In 2001 some locations in the western region of Nepal were affected by moderate drought. Large locations of the central and eastern regions of Nepal are affected by mild drought. In 2008 the western parts of Nepal were affected by drought severities more than the central and eastern parts. In this episode, the central and eastern part is affected by mild drought. In 2016 the far western parts of Nepal were affected by drought but the eastern parts of Nepal were normal and central parts of Nepal near Pokhara and Annapurna regions were affected by drought. The individual drought year’s severities extreme, severe, moderate and mild drought based on the proportional weightage of stations expressed in percent in different years is shown in Table 15. In these particular years, the different regions of Nepal have different rainfall dynamics.

Interestingly, droughts have been observed frequently since 2001 in Nepal. Drought events in recent decades were frequent in the years 2008, 2009, 2010, 2016, 2017 and 2018 in Nepal. There were different severities of drought, extreme, severe, moderate, and mild drought during the major eight winter drought episodes in Nepal (Figures 24a-h). The proportional weightage of severities of the drought episodes was tabulated in Table 15.

Table 15: Winter drought severities based on stations proportion expressed in percent in different years over Nepal

Rank	Year SPI3	Ave SPI3	Extreme	Severe	Moderate	Mild
1	2006	-2.41	17.59	38.38	33.33	9.25
2	2009	-2.26	4.63	41.67	40.74	17.59
3	1999	-1.85	3.70	25.93	41.67	26.85
4	2018	-1.7	1	15	52	23
5	2017	-1.38	0.97	11.65	39.81	42.72
6	2008	-1.33	3.70	15.74	28.70	43.52
7	2016	-1.31	1.91	14.29	27.62	28.70
8	2001	-1.01	0	6.48	28.70	56.48

The magnitudes of spatial severity of drought events were investigated from SPI3 time scale. There are severities of droughts during the recent decade in drought episodes. During the 42 years worst winter drought years were 2006 and 2009. These droughts' severity extremes, severe, moderate and mild drought show the drought dynamics over the study areas. Spatial extent of severities of SPI3 time scale values is interpolated over Nepal in Figures 24(c and e) for the worst winter drought years. Similarly, the severities of the recent drought events (2017 and 2018) are depicted in Figures 24(g and h). During the study period, eight drought episodes were observed, out of those five drought episodes were in the recent decade (2008-2018). So, we conclude that winter drought events in Nepal are increasing generally in recent years. The overview of these SPI3 dynamics over Nepal could help to know the drought characteristics of typical drought episodes. The proportional weightage of winter drought severities for extreme, severe and moderate droughts are 4, 21, 37 and 33 % during the study period 1977-2018. The proportional weightage of winter droughts severities covered about 95% of stations in Nepal.

4.3.5.2 Spatial Distribution of Summer and Annual Worst Drought Events

Based on the drought magnitude for both SPI4 and SPI12, 8 summer drought years and 10 annual drought years were identified (Tables 16 and 17). The two most widespread summer drought occurred in 1992 and 2015 which affected by drought severities. In those years, the central region of Nepal was affected more than the eastern and western regions.

Table 16: Summer drought severities based on stations' proportions expressed in percentages in different years

Rank	SPI values	year	Extreme	Severe	Moderate	Mild
1	-2.0	1992	7.5	11.2	25.2	41.1
2	-19	2015	9.7	10.7	25.2	38.8
3	-18	1977	11.3	10.3	18.6	37.1
4	-1.6	2006	7.5	10.3	15.9	42.1
5	-1.6	2005	4.7	8.4	15.9	48.6
6	-1.4	2009	6.5	3.7	15.0	57.0
7	-1.2	1079	14.4	6.7	7.7	39.4
8	-1.0	1982	3.8	2.9	16.2	44.8

Table 17: Annual drought severities based on stations' proportions expressed in percentages in different years

Rank	SPI values	year	Extreme	Severe	Moderate	Mild
1	-2.3	1992	8.4	22.4	24.3	36.4
2	-1.6	2015	6.8	8.7	23.3	37.9
3	-1.5	2006	6.5	9.3	12.1	51.4
4	-1.5	2012	8.5	11.3	17.9	40.6
5	-1.5	2005	4.7	8.4	15.9	40.2
6	-1.3	1977	8.2	10.3	11.3	36.1
7	-1.1	1994	2.8	10.3	16.3	41.1
8	-1.03	1979	7.7	4.8	16.3	36.5
9	-1.02	2018	5.1	12.2	11.2	41.8
10	-1.01	2009	4.7	2.8	16.8	46.7

For SPI4 in the year 1992, no drought condition was observed over some regions of northwestern Nepal and few areas of the eastern mountain region. For this year, moderate drought dominated from the central to eastern–southern parts, while during 2015, moderate drought dominated over mid-west and central Nepal. Approximately 8 and 10 percent of the stations were affected by extreme drought conditions in 1992 and 2015. About 11 percent of stations were affected by severe, and around 25 percent of the stations were affected by moderate drought conditions for SPI4 in the years 1992 and 2015 (Figures 25a, c). More than 76 percent of stations had negative SPI4 values; thus, large parts of Nepal faced the precipitation deficit in both worst drought years.

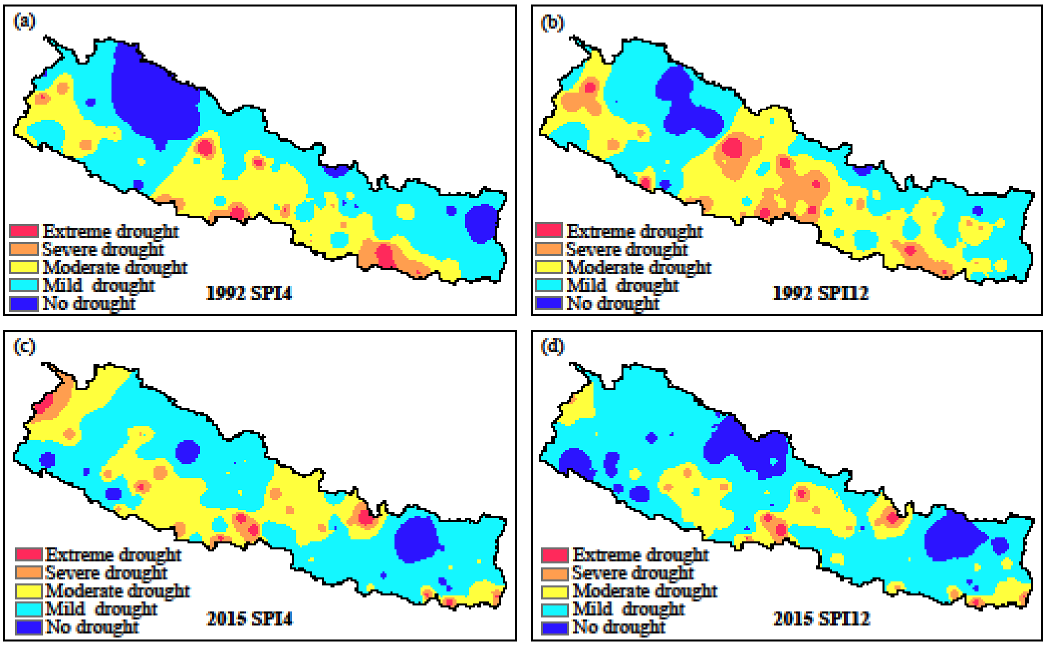

Figure 25: Spatial distributions of (a) SPI4 of 1992, (b) SPI12 of 1992, (c) SPI4 of 2015 and (d) SPI12 of 2015.

The two most widespread summer drought years were 1992 and 2015, which affected larger areas by drought severities. In those years, the central region of Nepal was affected more than the eastern and western regions. Though, the lower belt of eastern Nepal was more affected by drought severities in 1992 comparing toyear 2015. Approximately eight and ten percent of the stations were affected by extreme drought conditions in 1992 and 2015. About eleven percent of stations were affected by severe and around twenty-five percent of the stations were affected by moderate drought conditions in SPI4 of the year 1992 and 2015. Around eighty-five percent of stations have negative SPI4 values, so; large parts of Nepal have been facing the precipitation deficit in both worst years.

Similarly, we analyzed the precipitation deficits for SPI12. In the annual drought years, 1992 and 2015 larger areas of the central region were affected by drought conditions. However, in 1992 the central region was affected more by drought severities than in 2015. About ninety-three- and seventy-seven percent of stations recorded negative values of SPI12 in 1992 and 2015, respectively. So, large areas of Nepal face a precipitation deficit. The severities of drought are shown in Figures 25(b, d).

4.3.5.3 Spatial distribution of other major summer drought events

Significant summer drought intensity was also investigated over Nepal. The mean SPI4 intensity of summer drought years ranks 3rd to 8th ranging from -1.78 to -1. The percent of severities of SPI4 in stations over Nepal has been given in Table 16. The spatial severities of summer drought events are uniquely different from each other. These individual years (extreme, severe, moderate, and mid drought) intensity was interpolated, so the severities of drought are clearly shown in Figures 26(a - f). The SPI4 determinant is helpful for agricultural production, mainly rice cropping practices in Nepal.

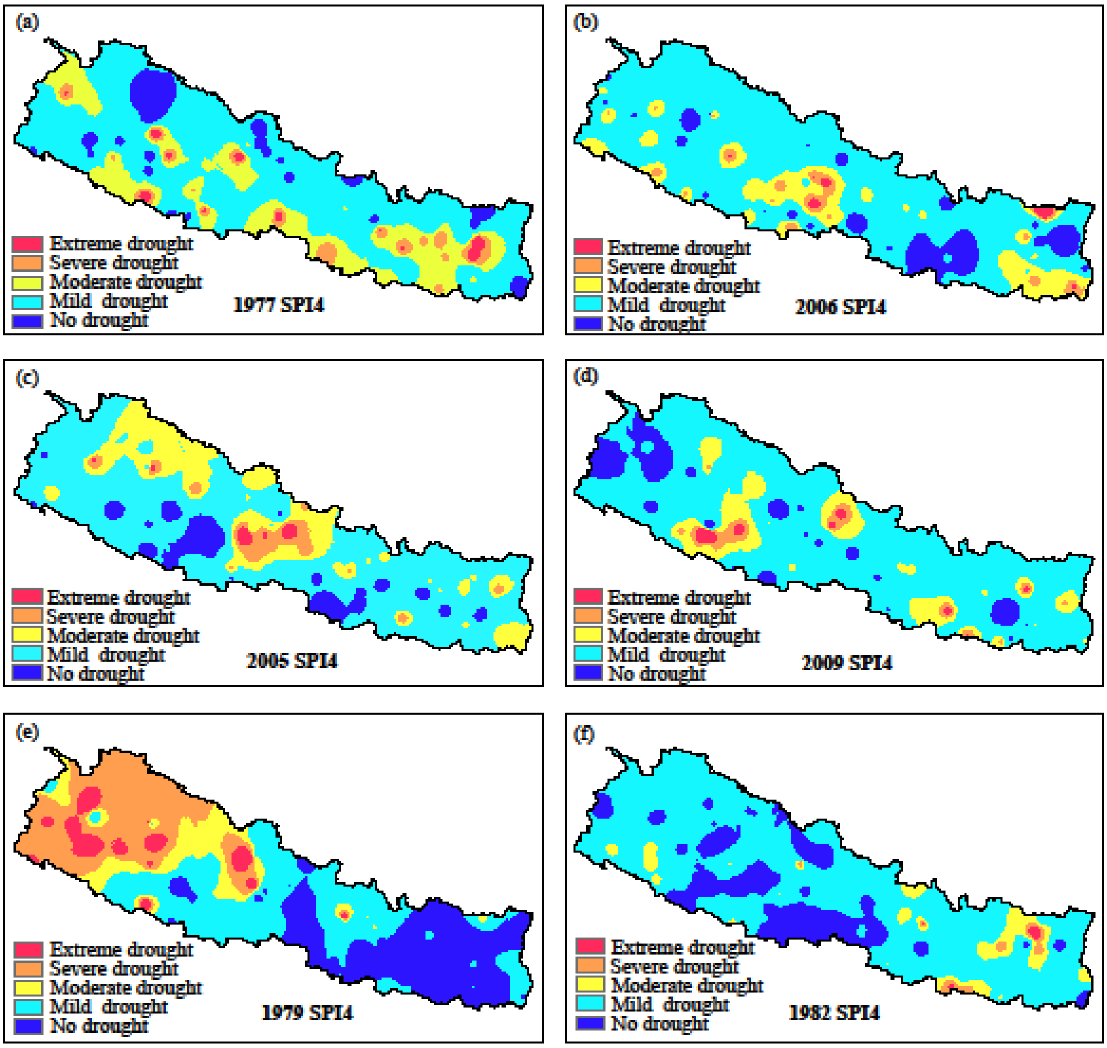

Figure 26: Spatial distributions of (a) summer (SPI4) of 1977, (b) summer (SPI4) of 2006, (c) summer (SPI4) of 2005, (d) summer (SPI4) of 2009, (e) summer (SPI4) of 1979, and (f) summer (SPI4) of 1982.

The summer drought in 1977, affected a large number of stations in the lower belts of Eastern regions and mid-mountainous areas than the central and the western region of Nepal (Figure 26a). In the year 2006, the central region was affected more by severe and moderate drought conditions than any other region. In 2005, the central region of Nepal was affected more by extreme drought and followed by upper parts of mountainous of the western region of Nepal. In this drought, low lands of Nepal were rarely affected. In 2009, drought shifted to the lower regions of Nepal. Though, the central high mountainous and the eastern region middle belt were affected by drought severities. In 1979, the only western region of Nepal was affected by drought severities. Most of the portion of the Central regions observed mild drought. There were vast differences in the western, central, and eastern regions of Nepal in monsoon dynamics. In 1982, eastern regions were affected mainly by extreme, severe, and moderate drought conditions, but the central and western regions of Nepal were in normal conditions. Moreover, drought events (SPI4) were found in year (1977, 2006, 2005, 2009, 1979, and 1982) about (37, 42, 49, 57, 39, and 45) percent of stations were affected by mild drought, which is tabulated in Table 11 and Figures 26(a-f).

Overall, the deficit of precipitation recorded in stations for third to eight rank droughts about 84 percentage stations showed negative values of SPI4, so large areas over Nepal face precipitation deficit. Mainly, the events affected Nepal's western and central regions and the lower belt of Nepal, with some exceptions. An ideal monsoon dynamic is essential to increase crop yield; therefore, it is indispensable for us to take proper crop management against extreme events to increase crop yield. Meteorological drought simultaneously affects agricultural productivity and water resources planning and creates socio-economic problems in the affected region. So, planners and hydrologists should take the necessary strategy to mitigate drought vulnerability based on the agro-climatic conditions of Nepal. Affected areas over Nepal in average summer drought indicate eight percent by extreme, nine percent by severe and eighteen percent by moderate drought.

4.3.5.4 Spatial distribution of other major annual drought events

We have analyzed the precipitation deficits in a SPI12, the events of third to tenth ranks drought mean intensity of annual drought events values varies from -1.5 to -1.01 tabulated in Table 17. The spatial severities of drought are presented in Figures 27(a-h).

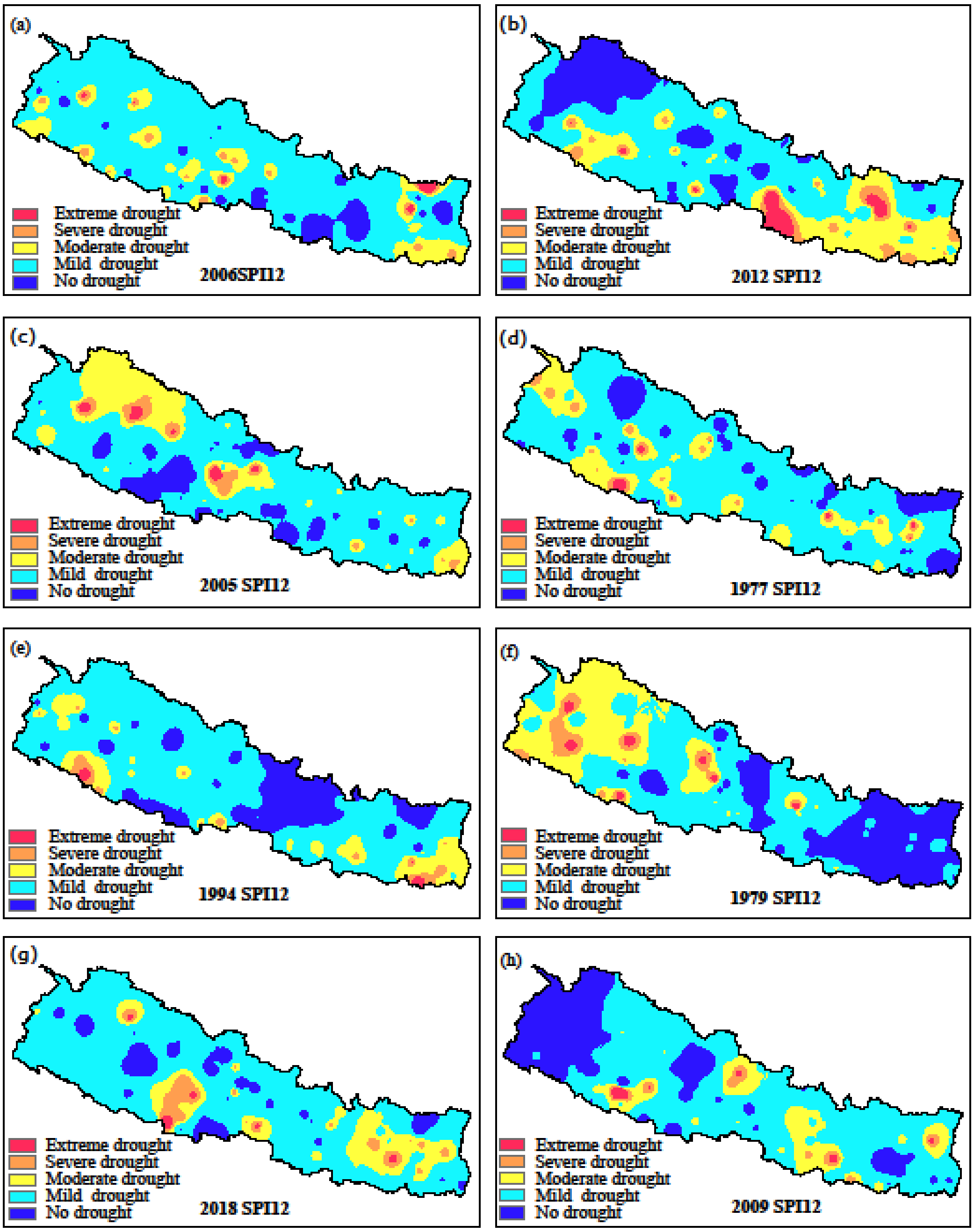

Figure 27: Spatial distributions of (a) annual (SPI12) of 2006, (b) annual (SPI12) of 2012, (c) annual (SPI12) of 2005, (d) annual (SPI12) of 1977, (e) annual (SPI12) of 1994, (f) annual (SPI12) of 1979, (g) annual (SPI12) of 2018, and (h) annual (SPI12) of 2009.

The severities of drought events are uniquely different from each to the other year. In the drought year 2006, drought was affected randomly in Nepal. Though, the lower belts of Nepal were more affected by drought severities than high lands. The eastern region recorded the drought in larger areas than the central and western regions of Nepal in the drought year 2012. About 30 percent of the territory of the country was affected by drought severities in 2005 and 1977. The western region of Nepal was more affected by extreme, severe, and moderate drought than the central and eastern regions of Nepal in 2005. However, the drought in 1977 was randomly affected by severities of extreme, severe, and moderate drought in lower regions of Nepal. In 1994, the central region of Nepal had normal but low land of the eastern and the western regions of Nepal were affected more by drought severities. In the eighth-rank drought in 1979, the western region of Nepal is more affected by drought conditions than that of the central region, and no effect was seen in the eastern region of Nepal. Drought in 2018, the eastern region of Nepal was more affected, following the central region of Nepal. However, the western region of Nepal had the usual. In 2009, small areas of lower belt of Nepal were affected by drought severities. But, large areas of Nepal were affected by mild drought. There was no drought in far western regions of Nepal in the year 2009. Furthermore, droughts event of SPI12 in the year (2006, 2012, 2005, 1977, 1994, 1979, 2018, and 2009) about (40, 41, 46, 36, 41, 32, 42, and 47) percent of the stations were affected by mild drought as shown in Figures 4.26(a-h) and Table 17. These events recorded the precipitation deficits of more than 84 percent of the study area; so, large areas of Nepal face the precipitation deficit. An affected area in Nepal in average annual drought includes seven percentages by extreme, eleven percent by severe and seventeen percent by moderate drought.

4.3.6 Relationship between SPI and climate indices

This study used SOI and ONI index to show the relation between summer and annual SPI. SOI and ONI index measure a large-scale fluctuation in sea level pressure and temperature over region 3.4. The comparison between the SPI3 and the winter SOI series shows that there were 23 events (about 56.09 %) in-phase relation (positive/negative SOI, negative/positive SPI3) and 18 (about 43.90 %) events show the phase relationship (Figure 28a).

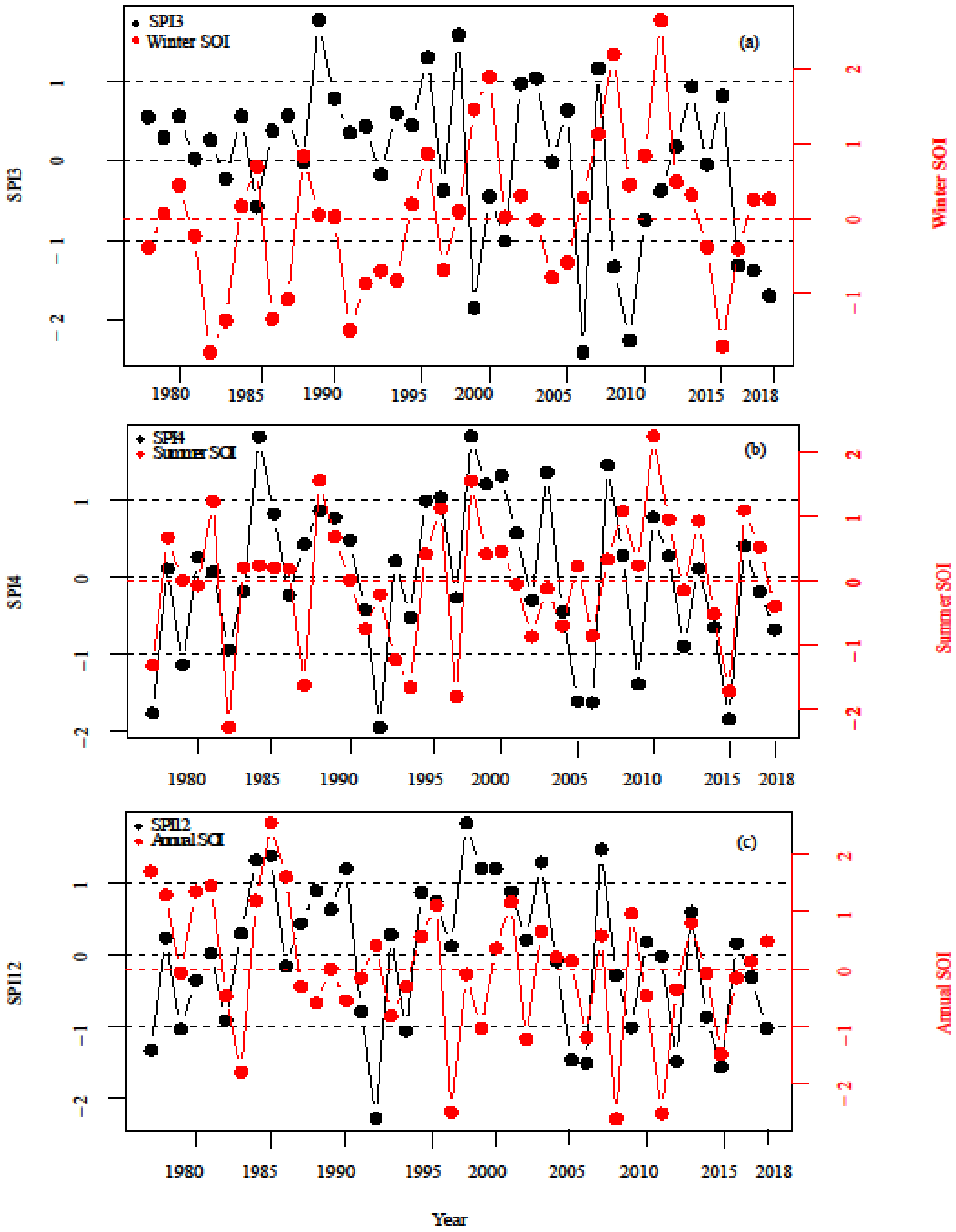

Figure 28: Relationship between SPI and SOI for (a) winter (b) summer and (c) annual.

The correlation coefficient between SPI3 and winter SOI is - 0.27 at a 95 percent confidence level. Thus, SPI3 and the winter SOI series are negatively correlated. Generally, during the drought/flood period, SOI and the SPI are (+/-). With some exceptions, during winter drought years (El Niño and non- El Niño years), high winter SOI and negative winter SPI in Nepal are in-phase relations. Deficit/excess condition from the above-mentioned relationship between SPI3 and winter SOI results; the SPI3 is influenced by the winter SOI negatively.

Similarly, the comparison between the SPI4 and the summer SOI series shows that there were 32 events (about 76.17 %) in-phase relation (positive/negative SOI, positive/Negative SPI4) and 10 (about 23.81 %) events showing the out-of-phase relationship (Figure 28b). The correlation coefficient between SPI4 and summer SOI is 0.52 at a 95 percent confidence level. Thus, SPI4 and the summer SOI series are highly correlated. Usually, during the drought/flood period, SOI and the SPI are (-/+), which is stronger than in the usual years. Generally, during drought years (El Niño and non- El Niño years), low summer SOI and negative summer SPI in Nepal are in phase relation to warm phase periods. Deficit/excess condition from the above-mentioned relationship between SPI4 and summer SOI results; the SPI4 is influenced by the summer SOI.

Likewise, a comparison between SPI12 and annual SOI analysis indicates that; there were 21 events (about 50 %) in-phase relation (positive/negative annual SOI, positive/Negative SPI12) is clearly shown in Figure 28(c). Among the 21 events, ten events were (about 47.62 %) deficit and 11 events were (about 52.38%) excess. The correlation between SPI12 and annual SOI is 0.14 at a 95 % confidence level. Deficit/excess condition shows that the SPI12 series is influenced by the annual SOI. However, during the drought/flood period, annual SOI and the SPI12 are strong (-/+) than in the usual years.

The deficit summer years ranking up to eight are summer drought years. The drought years are further linked with sea surface temperature on 3.4 regions extracted from https://origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml. When we consider an anomaly of the Nino 3.4 region of SST greater than 0.5 degrees Celsius, the years are El Niño years, and the SST less than - 0.5 degree Celsius the years are La Niña years. The El Niño and La Niña years are tabulated in Table 18.

Table 18: The El Niño and La Niña years from 1977 to 2018

Condition	Years
El Niño	1982, 1983, 1987, 1991, 1992, 1997, 1998, 2002, 2004, 2009, 2015, 2016
La Niña	1985, 1988, 1989, 1995, 1998, 1999, 2000, 2007, 2008, 2010, 2011, 2016

There were eight large excess rainfall years in Nepal which coincide with La Niña years. Out of eight summer drought years in Nepal; four years coincided with El Niño years and four drought years in non- El Niño years.

4.3.6.1 Regional Winter, and Summer SPI Relationship with SOI

The comparison between the western region's SPI3 and the winter SOI series shows that there were 25 events (about 60.98 %) in-phase relation (positive/negative SOI, positive/Negative SPI3) and 16 (about 39.02 %) events showing the out-of-phase relationship (Figure 29a). Similarly, the phase and in-phase relationship between central and eastern regions SPI3 and winter SOI are clearly shown in Figures 29(b, and c).

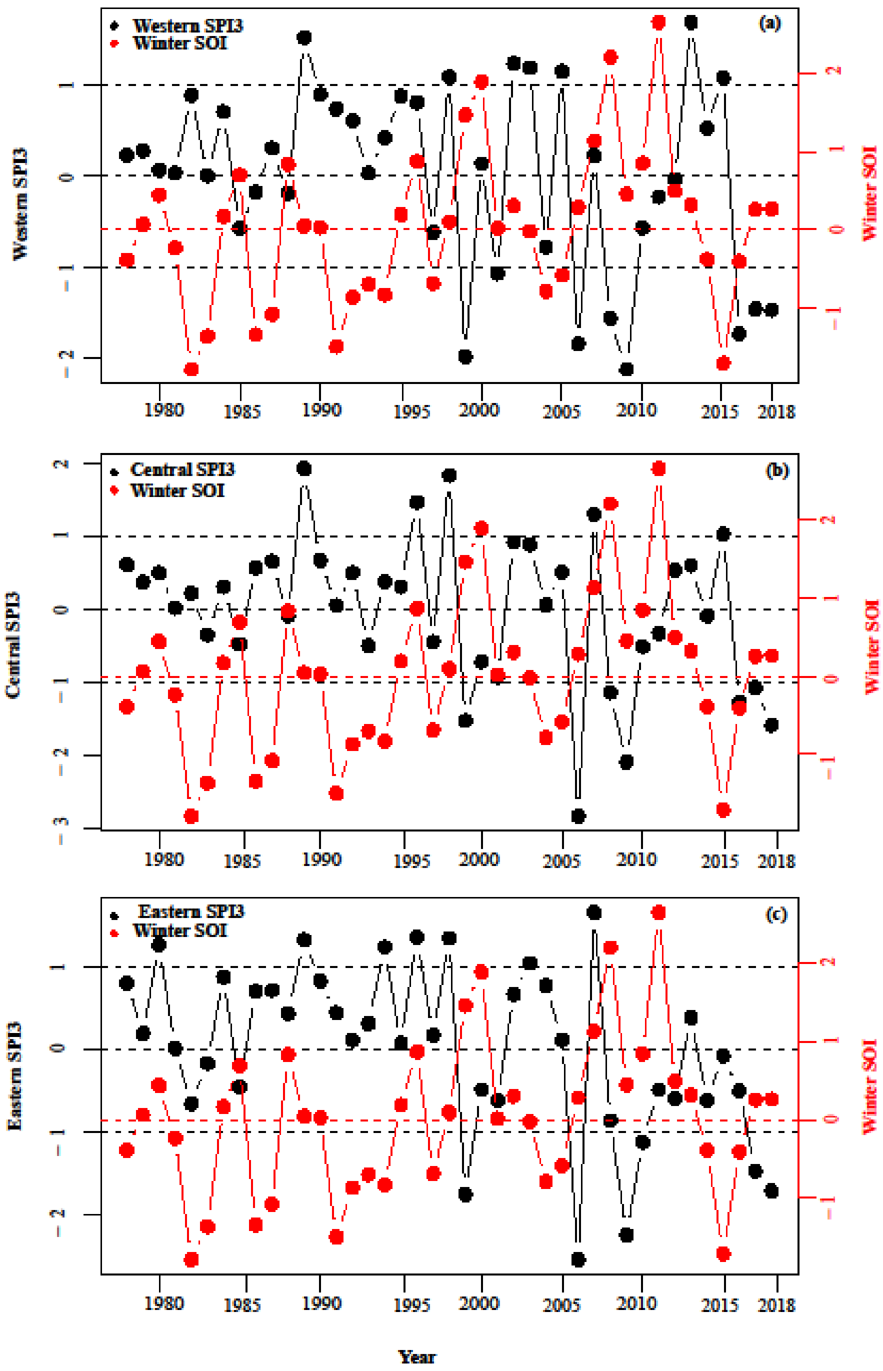

Figure 29: Relationship between winter SOI and regional SPI3 for (a) western (b) central and (c) eastern region.

The correlation coefficient between SPI3 and winter SOI is - 0.31 at a 95 percent confidence level for the western region. Similarly, the correlation coefficient between SPI3 and winter SOI is - 0.24 at a 95 percent confidence level for the central region. Likewise, the correlation coefficient between eastern region’s SPI3 and winter SOI is - 0.22 at a 95 percent confidence level. Thus, SPI3 and the winter SOI series are negatively correlated. Generally, during the drought/flood period, SOI and the SPI are (+/-).

The comparison between the western region’s SPI4 and the summer SOI series shows that there were 32 events (about 76.17 %) in-phase relation (positive/negative SOI, positive/Negative SPI4) and 10 (about 23.81 %) events showing the out-of-phase relationship Figure 4.29(a). Remaining the central and eastern region's comparisons of SPI4 and summer SOI in-phase relations are clearly shown in Figures 30(b, c). Moreover, the correlation coefficient between western region’s SPI4 and summer SOI is 0.49 at a 95 percent confidence level.

Similarly, the correlation coefficient between the central region’s SPI4 and summer SOI is 0.51 at a 95 percent confidence level. Likewise, the correlation coefficient between eastern region’s SPI4 and summer SOI is 0.36 at a 95 percent confidence level. Thus, SPI4 and the summer SOI series are highly correlated for western, central and eastern regions. Generally, during the drought/flood period, SOI and the SPI are (-/+), which is stronger than in the usual years. Generally, during drought years (El Niño and non-El Niño years), low summer SOI and negative summer SPI in Nepal are in phase relation to warm phase periods. Deficit/excess condition from the above-mentioned relationship between SPI4 and summer SOI results; the SPI4 is influenced by the summer SOI.

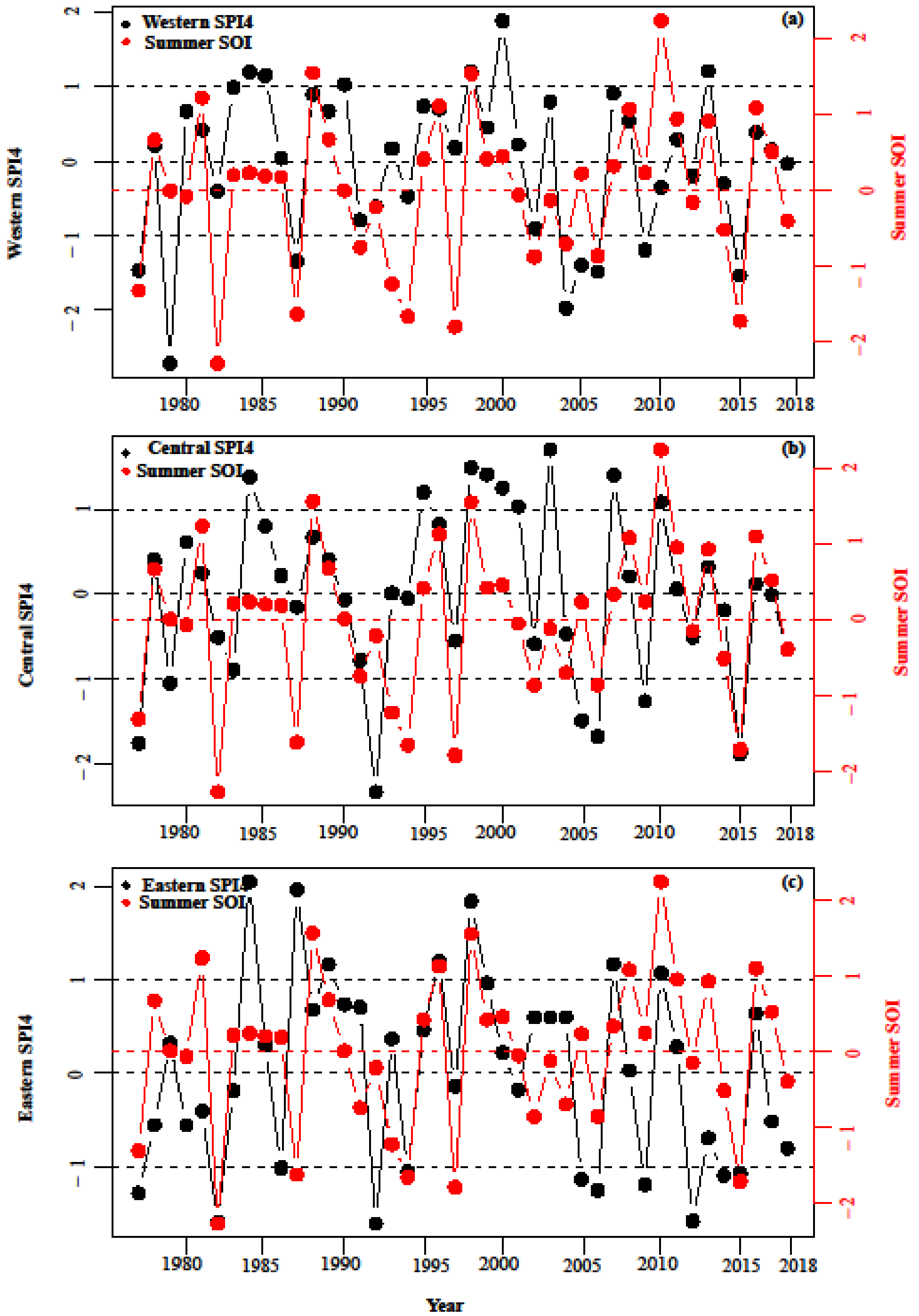

Figure 30: Relationship between summer SOI and regional SPI4 for (a) western (b) central and (c) eastern region.

4.3.7 Spatial Variability of the Frequency of SPI4 and SPI12

Moderate, severe and very severe (extreme) drought frequency maps of 4- and 12-months' time steps are prepared and shown in Figures 31(a-f).

Based on the SPI value < -1 for time scales (4 and 12), we first find the frequency of moderate drought in each station of the study area for the respective time period. Depending upon the frequency of occurrences, we divided the stations into four categories according to ≤9, 9.1-10, 10.1- 11 and ≥ 11.1. Then, the interpolation technique was used for the frequency of SPI4 with GIS from IDW method (Figure 31a) depicting the frequency of the moderate SPI values in different regions of the country. The low regions of the far eastern and mid land of central mountainous regions observed a more frequency of moderate SPI4 values.

Similarly, interpolation technique was used for the frequency of SPI12, in annual step central and far eastern regions observed more moderate frequency than other regions of Nepal (Figure 31d).

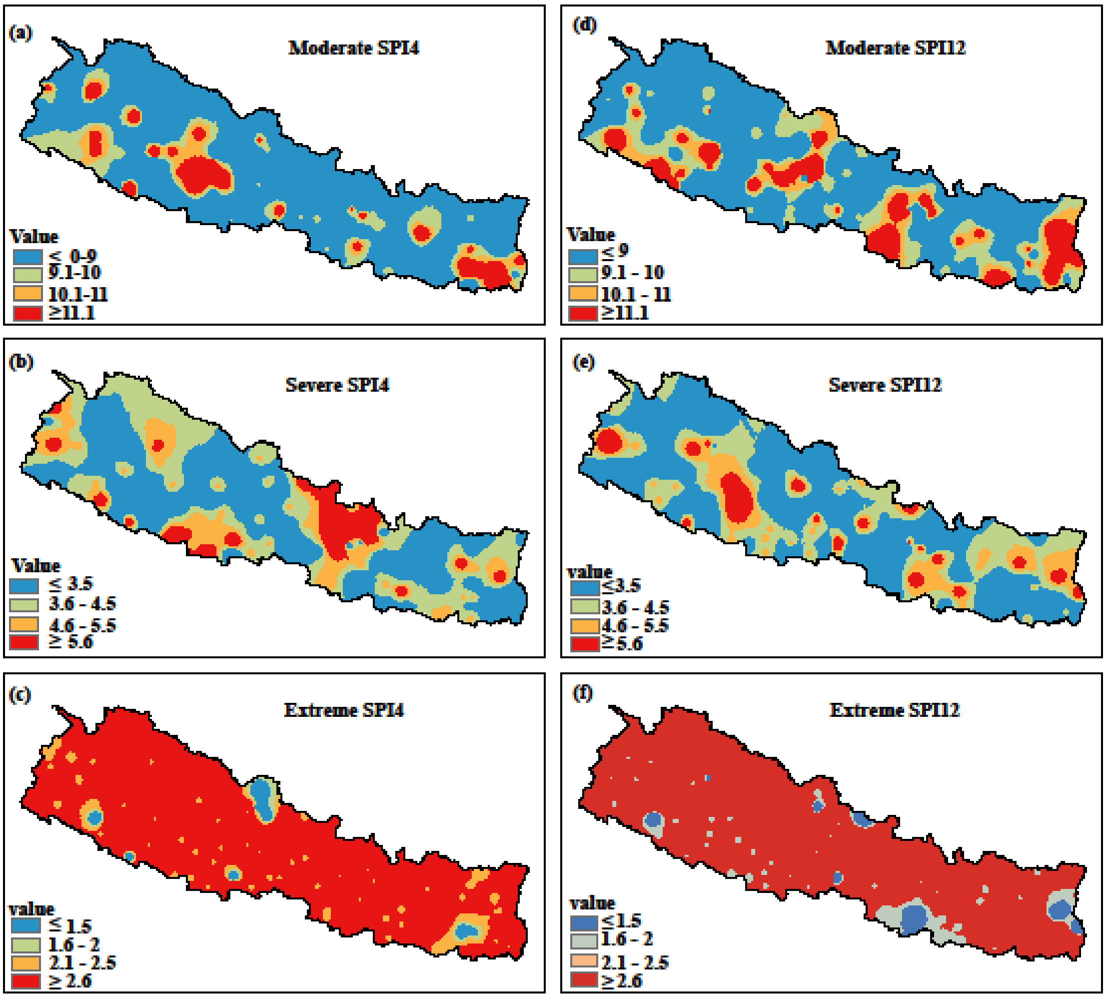

Figure 31: Spatial extent of (a, d) moderate; (b, e) severe; and (c, f) extreme; drought occurrences for SPI4 and SPI12.

Similarly, based on the SPI value < -1.5 for time scales (4 and 12), we first find the frequency of Severe drought in each station of the study area for the respective time period. Depending upon the frequency of occurrences, we divided the stations into four categories according to ≤ 3.5, 3.6 – 4.5, 4.6- 5.5 and ≥ 5.6. Then, interpolation technique was used for the frequency of SPI4 with GIS from IDW method (Figure 31b) depicting the frequency of the Severe SPI values in different regions of the country. Almost all regions of the country were affected by the low severe frequency of drought. The high mountainous regions of the central region and lowlands of the central regions observed a more frequency of severe SPI4 values. Similarly, in annual time steps the western region and eastern region observed more frequency than the central regions (Figure 31e).

Likewise, based on the SPI value < -2 for time scale 4, we first find the frequency of extreme drought in each station of the study area for the respective time period. Depending upon the frequency of occurrences, we divided the stations into four categories according to ≤ 1.5, 1.6 -2.0, 2.1- 2.5 and ≥2.6. Then, interpolation technique was used for the frequency of SPI4 and SPI12 with GIS from IDW method (Figure 31c, and f). Figures 31(c, and f) depicted the frequency of the extreme SPI4 and SPI12 values in different regions of the country. All regions of the country were affected by about 2- 4 percent of extreme SPI intensity of drought.

4.3.8 Drought Hazard Index Dataset Monitoring for Summer and Annual Time Scales.

Moderate, severe and very severe (extreme) drought maps of 4- and 12-months' time steps are prepared and then integrated separately to prepare the drought hazard index maps at 4- and 12-months' time periods. Therefore, developing a comprehensive methodology for drought hazard assessment in Nepal is important to support the preparedness and resilience for drought in the agricultural, hydropower and water resources sectors.

4.3.9 Drought Hazard Identification and Monitoring

The SPI has generated both short and long-term SPI time scales to analyze drought hazards in different regions of the country from monthly precipitation. This study was based on SPI to assess and analyze drought hazards for the recent four decades. For this, purpose we have identified the frequency of SPI4 and SPI12 severities in each station. In this study, based on the weight and rating value of SPI time scales, we have created a drought hazard map of Nepal, which represents the magnitude of drought severity and frequency for each location. The resulting drought hazard maps are presented in Figures (32a and b). High and very high drought hazardous zones were mainly concentrated in the north-western, western, south-western and some portions of the central parts of the country at all the time scales. It is noticeable that the hazardous conditions of drought were very high in the north-western part at all the time scales Figures (32a and b), indicating the most drought-prone area of the country. The Dadeldhura, Jumla and Dipalgaun stations are the most drought-hazardous locations (places) in western Nepal; which is located mainly in the north-western part, is the most drought-prone area in the country. Similarly, Timure, Kakani and Kathmandu airport and Dhulikhel stations are the drought-prone locations in central and Chainpur (East) and Biratnagar airport stations indicate the most drought-hazardous zones in eastern Nepal. This is consistent with the delineated high and very high drought hazard zones at SPI4 and SPI12.

The remarkable occurrence of mild, moderate, severe and extreme droughts depends on low seasonal and annual rainfall, high variability in rainfall and climate change impact (seasonal and annual negative trends of rainfall) greatly influence droughts in Nepal. The results were then classified into five levels: very low, low, medium, high and very high drought hazard by natural breaks classification method. The DHI map [Figures 32(a) and (b)] shows that a large part of the study area suffered from drought conditions.

Using SPI and interpolation techniques in GIS Software, over the country this study was able to identify the major drought years within the study period and drought-prone areas with drought severity. Moreover, the results of different SPI time scales show different dryness periods, which are very important for seasonal drought analysis. Therefore, the SPI, along with GIS can be applied successfully to identify the meteorological drought spatially and drought monitoring in the country.

The results were then classified into five levels: very low, low, medium, high and very high drought hazards by natural breaks classification method. The DHI map [Figures 32(a) and (b)] shows that about 30% of the study area suffered from drought hazards under high and very high levels.

The total area about 47 % was found to be under high or very high hazardous, zones of drought at the SPI4 time scale (Figure 32a). In contrast, at the SPI12 about 30% was found to be under high or very high hazardous zones of the total area (Figure 32b). Therefore, the drought hazard in Nepal exposed that, in general, the degree of hazard is high in the north-west, west and south-western parts of the country.

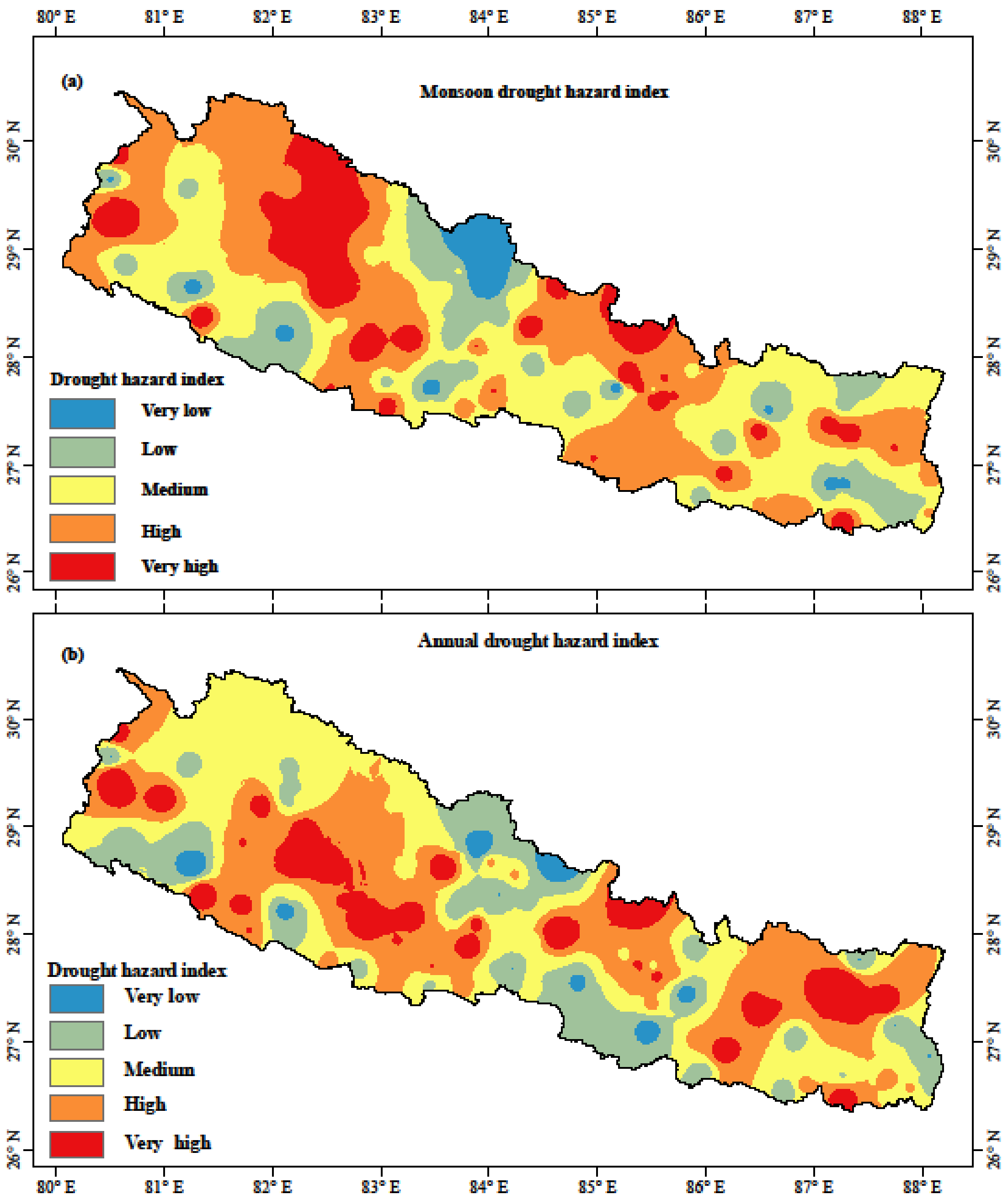

Figure 32: Spatial pattern of drought hazard in Nepal for: a) SPI4 and b) SPI12.

To minimize the drought hazards, the SPI4 and SPI12 were used for identification, monitoring, severities, duration and spatial extent of summer and annual drought events, which could be used in appropriate adaptation strategies to minimize the impacts of summer and annual droughts over Nepal directly related for the short- and long-term management of drought and its impact on agriculture and water resources in the country. As this study was involved in assessing, monitoring and hazard zoning drought areas, it is expected that this will be a useful guide towards understanding drought characteristics and assist in formulating comprehensive management strategies to overcome the drought problem effectively in Nepal.

4.4 Discussion

Approximately 80 % of the annual rainfall is received during the monsoon season, followed by the pre-monsoon 13 %, post-monsoon 4 %, and winter 3 %. This study also identified that contributions of monsoon rainfall were 74 % in the year 1992 and 86 % in 1984. The similar results presented by Shrestha *et al.* (2000) identified 1992 was the driest during the periods (1948-1994) using only 75 stations over Nepal. In that particular year, the whole Nepal recorded below-normal rainfall values which coincided with the effect of an El Nino event.

Present study shows that large monsoon-deficient episodes are extreme in El Niño and normal years. Out of seven large deficient monsoon (drought) years, only three years associated with El Niño years (1992, 2009, and 2015) and four drought years (1977, 1979, 2005, and 2006) are recorded in normal years. The year 1977 is a largest deficient monsoon year as observed in normal years. So, Nepal observed a large deficient monsoon year (drought) in El Niño and normal year. The findings of monsoon season's large deficit events from this study are also similar to other studies such as Sharma *et al*. (2020). Furthermore, a similar result was presented by Bhalme and Jadhav (1984), in India where drought is recorded in both El Niño year and normal year; however, there have been deficient monsoons over India apart from the mentioned El Niño episodes (Varikoden *et al.*, 2015). Likewise, other several studies on monsoon rainfall in India have discovered a close relationship between the monsoon and El Nino Southern Oscillation (Barnett *et al.*, 1991; Khandekar, 1991; Khandekar and Neralla, 1984). El Nino warm phases are associated with warmer sea surface temperature (SST) in the equatorial Pacific as well as in the Indian Ocean, resulting in a decreased land-ocean thermal contrast, thus reducing the strength of the monsoon (Varikoden *et al.*, 2015).

During the large monsoons deficient years the western regions of Nepal recorded comparatively low rainfall than the eastern and central regions. In the years 1979, 1992, and 2015 the central region recorded lower monsoon rainfall than comparing to the eastern region. During the years 1977, 2005, 2006, and 2009, the eastern region records low monsoon rainfall. The large monsoon deficit years have resembled with (Shrestha *et al.*, 2000). Furthermore, in recent decades some researchers (Varikoden *et al.*, 2015; Kumar *et al.*, 2013) identified the inter-decadal weakening of the South Asian Summer Monsoon frequently after 2000 both in El

Nino and Normal years over South Asian countries. Those studies support the findings of drought events frequently as reported in the present study.

The previous researchers' (Sigdel and Ikeda, 2012; Shrestha, 2000) findings support the present results that there is a strong correlation between SOI and monsoon rainfall. In this study, the correlation coefficient between NSMR and SOI is 0.52 at a 95% confidence level. Similar results were presented by Chowdhury (2003) in Bangladesh; Sein *et al.* (2015) in Myanmar and Varikoden *et al.* (2015) in India.

During the recent four decades, the patterns of decadal seasonal rainfall have decreased in Nepal. Similar results were presented by Ahasan *et al.* (2010) in Bangladesh; Sein *et al.* (2015) in Myanmar and Varikoden *et al.* (2015) in India. Furthermore, in recent decades some researchers (Varikoden *et al.*, 2015; Kumar *et al.*, 2013) identified the inter-decadal weakening of the South Asian Summer Monsoon frequently after 2000 both in El Nino and Normal years over South Asian countries. Those studies support the findings of decadal seasonal rainfall has decreased as reported in the present study.

The trend analysis of SPI3, SPI4 and SPI12 showed a decreasing trend over most of the stations, which indicates the increasing drought frequency. Similar, trend for SPI3 time scale magnitude showed a decreasing tendency, indicating increasing winter drought over Nepal which is consistent with (Karki *et al.*, 2017). Furthermore, evidence of increased occurrence of drought due to precipitation deficit is consistent with the results presented by previous researchers (Dahal *et al.*, 2016).

Our results evaluate the frequency and severities of drought episodes which have increased frequently in recent years. For SPI3, we have identified eight major drought episodes. Similarly, for SPI14, we have identified 8 major episodes, while for SPI12, 10 major drought years were identified. There were severities of percent of extreme, severe, moderate, and mild drought over different regions of Nepal during recent drought years. The results are similar to the findings presented by previous researchers (Shrestha, 2000) during the summer drought years of 1977, 1982, 1991, and 1992. Similarly, the results are similar to the findings presented by the previous researchers Sigdel and Ikeda (2010) noted that the winter drought years 1974, 1977, 1985, 1993, 1999, and 2001 from 1973 to 2003. Furthermore, similar studies by other earlier researchers (Shrestha *et al.*, 2000, Shrestha, 2000) indicates similar deficit years based on precipitation were 1957, 1972, 1977, 1982, and 1992 found in Nepal.

Drought severities depend on the intensity of SPI3, SPI4 and SPI12. Eight winter droughts, eight summer droughts and ten annual drought events have been revealed, and each drought event has unique SPI dynamics. There has been no similar drought pattern in Nepal in drought events over the past four decades. The spatial variation of SPI3, SPI4 and SPI12 indicates that every drought episode has different severities (extreme, severe, moderate, and mild drought) with differences in SPI intensities.

Nepal has experienced consecutive and worsening drought conditions in a severe drought episode in a recent decade. These events were one of the most challenging events for the mountainous country Nepal for agriculture practices and water resource management. The results are supported by some studies Kumar et al. (2013); Fan *et al.* (2017) after 2000 droughts were frequently observed in South Asian regions. These drought events were crucial for agriculture, hydropower generation, drinking purposes and water resources planning and management as well as tourism aspects.

The monsoon rainfall variability of Nepal is influenced by local effects, the regional circulation system, and large-scale circulation from the Indian and Pacific Ocean. Strengthening/weakening of the rainfall pattern has been identified and correlated with La Niña/El Niño years. The analysis revealed a relationship between the SPI4 and SPI12 with large-scale climate indices. Among them, SPI4 is well-correlated with SOI above a 95 percent confidence level (Figures 28b, c). Previous researchers were concerned with the relationship between SPI3 and SPI12 time-scales with summer and annual SOI (Sigdel and Ikeda, 2010). Similarly, the previous researchers (Shrestha *et al.*, 2000; Shrestha, 2000) focused on the relationship between summer rainfall of Nepal and SOI. The extensive circulation system affects the monsoon rainfall during the La Niña and El Niño episodes more than the average years. The drought events in El Niño years and non-El Niño years were more strongly related between SPI and SOI than the average years. The relationship between SPI and the climate indices such as the SOI and ONI anomaly over the Niño 3.4 has suggested that one of the causes for summer droughts is El Niño. Out of eight drought years, only four drought years were associated with El Niño episodes (1982,1992, 2009, and 2015), and the remaining four drought years (1977,1979, 2005, and 2006) were recorded in non-El Niño years. Similarly, annual droughts evolved in El Niño and non-El Niño years. Out of 10 drought years, only 3 drought years were associated with El Niño years (1992, 2009, and 2015) and 7 drought years (1977,1979, 1994, 2005, 2006, 2012, and 2018) were recorded in non-El Niño years.

But, the correlation coefficient between SPI3 and winter SOI is - 0.27 at a 95 percent confidence level. Thus, SPI3 and the winter SOI series are negatively correlated. Generally, during the drought/flood period, SOI and the SPI are (+/-). However, in winter the western region is negatively correlated more than other regions.

The areas of Nepal affected by the average extreme, severe and moderate summer drought were 8, 9, and 18 percent of summer drought events over the study period. Similarly, the areas of Nepal affected by the average extreme, severe and moderate annual drought were 7, 11, and 17 percent of annual drought events. Likewise, the areas of Nepal affected by extreme, severe and moderate drought in winter were 4, 21 and 37 percent. Previous researchers (Sigdel and Ikeda, 2010) noticed that the average extreme, severe, and moderate annual droughts were 5, 5, and 9 percent concerning SPI12 over the period (1971–2003). A slight difference can be observed between the severities in this study. The reason behind this is that in recent years, the worst drought events happened more frequently. On average, mild drought covered 42 percent of summer and 40 percent of annual drought events.

South Asian countries have recently been experiencing frequent drought incidents, and the Standardized Precipitation Index (SPI) has mostly been adopted in South Asian countries to quantify and monitor droughts (Chandrasekara *et al.*, 2021). Khatiwada and Pandey (2019) identified that the SPI is focused foremost on capturing the duration and intensity of drought in the Karnali river basin, Nepal. Using SPI from 1951–2015 over India, the analysis revealed that of the 34 met sub-divisions, 16 sub-divisions during the annual and monsoon season were drought-prone and showed high negative SPI values (Nandargi and Aman, 2017). Similarly, the occurrence of drought with negative SPI values is frequent in West Bengal districts in India with increasing dry events and decreasing wet and normal events (Bhunia *et al.*, 2020). The present study also showed similar patterns of SPI as the aforementioned studies. El Niño alone is not to be blamed for droughts in India. A total of 10 out of 23 droughts that India witnessed occurred during the years when El Niño was absent (Borah *et al.*, 2020). The current study is consistent with their findings too.

The study presents a comprehensive drought hazards analysis document for the first time in Nepal. The results of this document indicate that the drought-hazardous zones are higher in western and north western Nepal [Figures (4.31a and b)]. The previous researcher's findings (CBS, 2013; Wang *et al.*, 2013) indicate that the western region has observed a deficit of rainfall and creating a difficulty in livelihood due to a lack of water resources. Moreover, in South Asia, similar results presented by Chowdhury (2003) in Bangladesh; identified and categorized drought. Mooley and Balme, (1984) identified and categorized drought in India.

The DHI maps of Nepal [Figures (4.31a and b)] indicate the different types of drought-prone areas, our findings show that western Nepal has the largest area affected by high drought hazardous region. DHI monitoring of this study showed that western Nepal has been strongly suffering from drought. The results are similar to the findings of Wang *et al*. (2013). Therefore, drought response strategy should be prioritized for this region. The results were then classified into five levels: very low, low, medium, high and very high drought hazard by natural breaks classification method. The DHI monitoring of Nepal indicates that large zones of the country suffered from drought conditions.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This work is based on the climatology of the rainfall records at 107 stations from (1977-2018). Stations are homogeneously distributed in the different regions of Nepal. Based on time series data we have published three papers.

In this thesis, we have worked on monthly, annual and decadal rainfall patterns in Nepal. However, we are focused on the drought study. Using rainfall of stations; we have identified the winter, summer and annual major drought episodes and discuss the SPI dynamics in each episode of major droughts in the past four decades. Furthermore, we have monitored the drought-hazardous zones over the country. This kind of result is new in Nepal. The main conclusions of the thesis are as follows.

The three papers and some relevant topics results of the thesis parts fulfill the objectives of the thesis. Briefly, describing the drought episodes in individual SPI time scales based on extreme dry years in Nepal and its spatial variability. The spatial variability of summer and annual drought in major drought episodes and the relationship between SPI and SOI during the study periods are also sketched on paper (Bagale *et al.*, 2021), for winter documented in (Bagale *et al.*, 2023b) and the remaining results were in chapter 4.

With my drought research work, I hope I provided the major drought episodes in Nepal in different time scales. The spatial variability of SPI time scales in major drought episodes in different regions has shown the severity of drought.

I believe this research work tried to fulfill the gaps in drought work which provides new concepts and thinking in drought studies. It can guide the new research work on drought hazard analysis, vulnerability and risk analysis of the climate of Nepal.

With my research project, I hope it will provide a basic concept for the spatial and temporal variability of drought events and its connection with large-scale circulations in Nepal. It can initiate new research on drought hazardous monitoring in the field of climate science; it can give a new outlook for climate risk study in the future. However, this thesis is not exhaustive and there are many limitations in drought research, we could solve the drought-related hazard in multiple ways to extend the included studies.

In this thesis, the seasonal cycle of rainfall was investigated. It would be interesting to know monsoon dry events using SPI4 time scales on the journal paper in (Bagale et al., 2021) and the quantification of monsoon rainfall (mm) in (Bagale et al., 2023a). From these analyses, it is easy to understand the climatic variability in the monsoon season and its trends over Nepal and so on. The regional and large-scale circulation system linkage is necessary to understand the rainfall dynamics in Nepal during extreme as well as in general years.

This (Thesis) study provided concise knowledge about the temporal and spatial variability of droughts using SPI3 time-scale, SPI4 time-scale and SPI12 time-scale indices in Nepal during the past four decades (1977–2018). The SPI threshold was used to identify, categorize and monitor droughts over Nepal. For this, we investigated the frequency, duration, and severity of drought events. The SPI3, SPI4 and SPI12 month time scales were interpolated to illustrate the spatial patterns of major drought episodes and their severity. Significant droughts have occurred in the past recent decades, from the years 1977 to 2018; with ten annual, 8 winter, and summer episodes. The frequency, intensity and duration of monsoon droughts have increased due to El Nino warm phases. This study indicates that droughts are increasing frequently in a couple of decades both in winter and summer seasons.

Among the drought events, 1992 was the worst summer and annual drought year, followed by 2015. Extreme drought events of 1992 and 2015 indicated more drought signals while in winter the worst drought was observed in 2006 and 2009. Most of the study sites show a negative trend for SPI3, SPI4 and SPI12, which indicates the drought episodes are increasing and being more frequent. Moreover, the study indicates that after the year 2000 drought events evolved frequently.

The proportional weightage of winter droughts severities for extreme, severe and moderate drought was obtained at 4, 21, and 37 percent respectively. On average about 95% of the proportional weightage of winter droughts covered large locations of Nepal with negative SPI3 values so Nepal faced the winter precipitation deficit in drought years.

In the last four decades, the drought events in Nepal indicated extreme, severe, moderate, and mild categories with reference to intensity. The obtained proportional weights of summer drought severities for extreme, severe, and moderate drought were

8, 9, and 18 percent, respectively. Similarly, the obtained proportional weights of annual drought severities for extreme, severe, and moderate drought were 7, 11, and 17 percent, respectively. All drought categories were more highly affected in the western and central regions than the eastern region of Nepal, with some exceptions.

The correlation coefficient between SOI and NSMR is strong in large deficit monsoon years than normal years, the correlation coefficient between NSMR and SOI is 0.52. The present study showed that large deficit years are observed both in El Niño and normal years. With some exceptions, all El Niño years measured deficit rainfall. Deficit rainfall during the El Niño years was observed approximately nine percent below the average monsoon rainfall. The extreme episodes in particular years were different in the western, central and eastern regions of Nepal which indicates the distinct rainfall variability. In the recent four decades, both the winter and summer rainfall has decreased.

The relationship of SOI with SPI is strong in summer (SPI4) and weak in both winter (SPI3) and annual (SPI12). This study revealed that summer droughts were recorded both in El Niño and non-El Niño years. During eight summer drought years, only four drought years were associated with El Niño episodes.

The correlation coefficient between SPI3 and winter SOI is - 0.27 at a 95 percent confidence level. Thus, SPI3 and the winter SOI series are negatively correlated. Generally, during the drought/flood period, SOI and the SPI are (+/-). In the regional scale results of the relationship between SPI3 and winter, SOI indicates that the western region's winter SPI and SOI correlation is slightly strong than the central and eastern regions of the country.

The extreme, severe and moderate driest multiyear episodes were detected frequently after 2000. The north-western, western, south-western and northern parts of the country are the most hazardous in terms of drought occurrence and severity, and therefore, these areas fall under high and very high drought hazard zones.
About 47% and 30 % of the total area of Nepal falls under the high and very high drought hazard zones on SPI 4 and SPI12.

The study's findings can help make decisions for water resource management and water allocations for mitigating the impact of droughts. It is also beneficial to the researchers to study climate change in Nepal and the sustainable development of regional water resources.

5.2 Recommendations

Based on this study, several parts are identified to be improved.

Recommendations for future studies are summarized here as:

This study was completed using data from 107 stations over Nepal. In order to monitor more accurate the outcome of drought in the future it is recommended to increase the number of stations to cover comprehensively the different geographic regions of Nepal.

To reduce the impact of droughts the early warning system is essential. The intra-seasonal, inter-annual and decadal variations of climatic features govern by the atmospheric circulation such as; wind vector and magnitude, moisture flux, temperature and precipitable water, are crucible for detail understanding the seasonal to decadal atmospheric circulations. The quantitative decadal rainfall and its tracking with atmospheric circulation in a synoptic scale are urgent to identify the changing decadal rainfall patterns not only in Nepal but the whole regions of South Asia.

Comparative drought study by using different indices like (SPI, SPEI, RAI and NDVI) is recommended to evaluate meteorological, agricultural, irrigation, strategies, ultimately improving agricultural productivity and sustainability.

CHAPTER 6

SUMMARY

6.1 General Overview

Chapter 6 presents the brief summary of the thesis. In my thesis, I have created five objectives to tackle the primary research questions. This chapter presents the conclusions based summary on the two peer-reviewed research publications, and some relevant topics of the studies that I prepared during my research work and addressing each research objectives. The rainfall analysis was first carried out to determine seasonal, annual and decadal rainfall quantities from the long historical records of more than 40 years data set. However, decadal seasonal rainfall shows in decreasing in recent decades. The latter was used to investigate the spatial variability of major deficit rainfall episodes during the period 1977 - 2018. To comprehend the changing climate in developing nations like Nepal, one must have a basic awareness of drought, shifting rainfall patterns, and their effects. Thus this study was conducted to determine the frequency, severity, and occurrence of drought across various time frames across the nation. The thesis reported new findings on the spatial patterns and temporal characteristics of drought events during the winter, summer and annual periods. Furthermore, the trend part of the analysis shows drought trends in winter, summer and annual time steps.

In this thesis additionally, I have investigated major drought episodes and their linkage with large-scale circulations. The analysis took into account of available literatures, secondary rainfall data, drought thresholds from McKee *et al.* (1993); and the DHI concept from Shahid and Behrawan (2008). I used DHM rainfall data; we extracted SOI and ONI data from NOAA, for the period of 1977 to 2018. Here, a brief summary of the analysis and the findings is offered in accordance to the study objectives.

6.2 Summary Related to 'specific objective 'i' of the Study

The first objective of this study related to procedure, analysis and results of the monsoon season have been published in (Bagale *et al.*, 2023a). Historical rainfall data was used to identify the winter, summer and annual rainfall patterns for the last four decades. The large-scale circulation patterns influence the dry and wet conditions in

Nepal during the El Nino and La Nina episodes were studied. There was a strong correlation between the Nepal monsoon rainfall and southern oscillation index in summer. Generally, the large negative/positive magnitude of SOI on the Indian and Pacific Ocean has a link to both weakening/strengthening NSMR. During the last four decades, both winter and summer decadal rainfall has been decreased in Nepal. We have identified a large deficit in summer and winter years. Among the winter dry episodes, 2006 and 2009 were the worst dry conditions. Similarly, 2015 and 1992 were the worst dry conditions in summer. The eastern region frequently showed the monsoon and winter dry signals as compared to the central and western regions. Moreover, the whole Nepal indicates large deficit rainfall events after 2000.

Bagale *et al.* (2023a) picture summer monsoon rainfall based on the spatial extent, trends and correlation with SOI including the rainfall characteristic deficits and excess years. Which was evaluated using rainfall time-series data for 42 years from 1977 to 2018. We have identified the large monsoons deficient years. These years, 1992, 2009 and 2015 consisted El Niño episodes that quantified significant rainfall deficits as of 19.29, 13.6, and 17.59 % respectively from average rainfall. With some exceptions, all El Niño years observed deficit rainfall. During El Niño years averaged deficit rainfall was approximately 9 % below the average monsoon rainfall. The eastern region showed large deficient monsoon years more frequently than comparing to central and western regions of Nepal.

The study provided concise knowledge about the temporal (all-Nepal as well as regional) and spatial variability of monsoon rainfall and its anomaly over Nepal during the past four decades (1977 - 2018).

6.3 Summary Related to 'specific objective 'ii' of the Study

The second objective of this study related to procedure, analysis and results has been published in Bagale *et al.* (2021). This paper identified eight monsoon droughts and ten annual droughts during the last four decades. Among 42 summer seasons the eight summer drought years are found in 1977, 1979, 1982, 1992, 2005, 2006, 2009, and 2015. Similarly, annual ten drought years are 1977, 1979, 1992, 1994, 2005, 2006, 2009, 2012, 2015, and 2018. Analyzing both conditions of SPI4 and SPI12, we have identified that most of the drought years coincide with each other. The region behind this can be the weightage of summer precipitation with the annual one follows. The SPI threshold was identified, categorize and monitor droughts over Nepal. From this, we investigated the frequency, duration, and severity of drought events. The SPI4 and SPI12 were interpolated to illustrate the spatial patterns of major drought episodes and their severity. Furthermore, the eight winter drought years were 2006, 2009, 1999, 2018, 2017, 2008, 2016, and 2001 using SPI3 values are -2.41, -2.26, -1.85, -1.7, -1.38, -1.33, -1.21, -1.01 respectively (Bagale *et al.*, 2023b). We used SPI indices to identify the dry years during the last four decades in Nepal which depends on the station-based rainfall stations. The paper clearly mentioned the severities of drought types in different locations in Nepal for major (summer, winter and annual drought) episodes. Our results picture the robustness of the drought study using SPI time scales.

6.4 Summary Related to 'specific objective 'iii' of the Study

Droughts have been recorded more frequently in Nepal since 2005. The SPI3, SPI4 and SPI12 month time scales were interpolated to illustrate the spatial patterns of major drought episodes and their severity. The third objective of this study related to procedure, analysis and results has been also published in Bagale *et al.* (2021). In this paper relatively new findings are spatial overview of each major drought episode SPI dynamics monitoring over Nepal. Droughts were recorded during El Niño and non-El Niño years in Nepal. The drought events in El Niño years and non-El Niño years were more strongly related between SPI and SOI than the average years. The relationship between SPI and the climate indices such as the SOI and ONI anomaly over the Niño 3.4 suggest that one of the causes of summer droughts is El Niño. This study indicated that summer droughts occurred in both El Niño and non-El Niño years. Out of eight drought years, only four drought years were associated with El Niño episodes in (1982,1992, 2009, and 2015), and the remaining four drought years in (1977,1979, 2005, and 2006) were recorded in non-El Niño years. Similarly, annual droughts evolved in El Niño and non-El Niño years. Out of 10 drought years, only 3 droughts were associated with El Niño years (1992, 2009, and 2015) and 7 drought years (1977, 1979, 1994, 2005, 2006, 2012, and 2018) were recorded in non-El Niño years. Among them, 1992 was found as the worst drought year, as followed by the drought year, 2015. More than 44% of the locations of the country were showed under drought conditions during these extreme drought events. The frequency, intensity and duration of monsoon droughts have increased due to El Nino warm phases. These frequent droughts have severely stressed the water supply systems and livelihood of the communities and adversely impacted the economy by affecting primary production.

The study highlights the importance of understanding the spatiotemporal dynamics of drought events for effective drought monitoring and management in Nepal.

6.5 Summary Related to 'specific objective 'iv' of the Study

The results and relevant topics of objective 'iv' of the study were documented in the thesis. The main aim of objective 'iv' is to identify the frequency of moderate, severe and extreme drought severities over different stations of the country to identify drought-hazardous regions across Nepal. The SPI threshold was used to identify, categorize and monitor droughts over Nepal. For this, we investigated the frequency, duration, and severity of drought events. Drought is a recurring and crucial feature of climate in Nepal. The country has suffered from frequent droughts in its different regions. Precipitation is the primary factor that controls the formation and persistence of droughts and floods. The low regions of the far eastern and mid land of central mountainous regions observed a more frequency of moderate SPI4 values. Similarly, interpolation technique was used for the frequency of SPI12, in annual step central and far eastern regions observed more moderate frequency than other regions. The high mountainous parts of central region and lowlands of the central regions observed a more frequency of severe SPI4 values. Likewise, in annual time steps the western region and eastern region observed more frequency than the central regions. All regions of the country are affected by about 2- 4 percent extreme SPI4 intensity of the frequency of the extreme drought across the country. The moderate, severe and extreme droughts clearly mention the severities of drought types in different locations for major seasonal and annual drought episodes. We used SPI indices to identify the dry years during the last four decades in Nepal. Our results picture the robustness of the drought study depending on SPI time scales.

6.6 Summary Related to 'specific objective 'v' of the Study

The fifth objective of this study is to monitor the drought-hazardous regions across Nepal. Based on the rating and weights of the SPI values, a concept was applied in this thesis to produce the DHI map of Nepal which is new in Nepal. This research carried out here contributes to the existing knowledge pool by developing a methodology to construct DHI by using SPI ratings and weights to identify the probability of the risk of drought at a given geographic location. The present study categorized DHI into five divisions by applying the natural breaks method under the geographic information system (GIS). The drought-hazardous zones are highest in the western and northwest parts as comprised to the central and eastern regions on both SPI4 and SPI12 time scales. This study identified the drought hazard zones based on DHI during the recent last four decades. In this study, the SPI was used for finding out drought severity and magnitude. The extreme, severe and moderate driest multiyear episodes were detected frequently after 2000.

This study focused on the spatial variability of drought hazards in Nepal. The produced DHI map can be used to mark out drought hazard zones geographically. The hazard map can display the distribution of drought hazards with different magnitudes. The north-western, western, south-western and northern parts of the country are the most hazardous in terms of drought occurrence and severity, and therefore, these areas fall under high and very high drought hazard zones in Nepal.

About 47 and 30 percent of areas of Nepal were found to be under high and very high drought hazardous zones of the total area based on SPI4 and SPI12 time scales.

REFERENCES

Abeysingha, N. & Rajapaksha, U. (2020). SPI-based Spatiotemporal Drought Over Sri Lanka. *Advances in Meteorology*, **2020**:1-9. https://doi.org/10.1155/2020/9753279

Abubakar, I. & Yamusa, M. (2013). Recurrence of Drought in Nigeria: Causes, Effects and Mitigation. *International Journal of Agriculture and Food Science Technology*, **4**: 169-180. http://www.ripublication.com/ ijafst.htm

Adegboyega, S., Olajuyigbe, A., Balogun, I. & Olatoye, O. (2016). Monitoring Drought and Effects on Vegetation in Sokoto State, Nigeria Using Statistical and Geospatial Techniques. *Ethiopian Journal of Environmental Studies and Management*, **9**: 56-69. http://dx.doi.org/10.4314/ejesm.v9i1.6

Ahasan, M. N., Chowdhary, M. A. & Quadir, D. A. (2010). Variability and Trends of Summer Monsoon Rainfall Over Bangladesh. *Journal of Hydrology and Meteorology*, **7(1):** 1-17. https://doi.org/10.3126/jhm.v7i1.5612

Alexandersson, H. (1986). A Homogeneity Test Applied to Precipitation Data. *Journal of Climatology*, **6(6):** 661-675. https://doi.org/10.1002/joc.3370060607

Alley, W. M. (1984). The Palmer Drought Severity Index: Limitations and Assumptions. *Journal of Applied Meteorology and Climatology*, **23:** 1100-1109. https://doi.org/10.1175/1520-0450(1984)023<1100:TPDSII>2.0CO;2

Aryal, A., Maharjan, M., Talchabhadel, R. & Thapa, B. R. (2022). Characterizing Meteorological Droughts in Nepal: A Comparative Analysis of Standardized Precipitation Index and Rainfall Anomaly Index. *Earth*, **3(1):** 409-432. https://doi.org/10.3390/earth3010025

Asadi Zarch, M. 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):** 3485-3504. https://doi.org/10.1007/s11269-011-9867-1

Bagale, D., Sigdel, M. & Aryal, D. (2021). Drought Monitoring Over Nepal for the Last Four Decades and its Connection With Southern Oscillation Index. *Water*, **13:** 3411. https://doi.org/10.3390/w13233411

Bagale, D., Sigdel, M. & Aryal, D. (2023). Influence of Southern Oscillation Index on Rainfall Variability in Nepal During Large Deficient Monsoon Years. *Journal of Institute of Science and Technology*, **28(1):** 11-24. https://doi.org/10.3126/jist.v28i1.43452

Bagale, D., Sigdel, M. & Aryal, D. (2023). Winter Drought Monitoring Using Standard Precipitation Index Over Nepal. *Natural Hazards*, **2023**:1-14. https://doi.org/10.1007/s11069-023-06242-0

Baniya, B., Tang, Q., Xu, X., Haile, G. G. & Chhipi-Shrestha, G. (2019). Spatial and Temporal Variation of Drought Based on Satellite Derived Vegetation Condition Index in Nepal From 1982–2015. *Sensors*, 1**9(2):** 430. https://doi.org/10.3390/s19020430

Barnett, T., Latif, M., Kirk, E. & Roeckner, E. (1991). On ENSO Physics. *Journal of Climate*, **4:** 487-515.

Barros, A. P., Joshi, M., Putkonen, J. & Burbank, D. (2000). A Study of the 1999 Monsoon Rainfall in a Mountainous Region in Central Nepal Using TRMM Products and Rain Gauge Observations. *Geophysical Research Letters*, **27:** 3683-3686.

Barros, A. P. & Lang, T. J. (2003). Monitoring the Monsoon in the Himalayas: Observations in Central Nepal, June 2001. Mon. *Wea. Rev*., **131:** 1408-1427.

Barua, S., Ng, A. & Perera, B. (2011). Comparative evaluation of drought indexes: case study on the Yarra River catchment in Australia. *Journal of Water Resources Planning and Management*, **137(2):** 215-226. https://doi.org/10.1061/(asce)wr.1943-5452.0000105

Benn, D. I. & Owen, L. A. (1998). The Role of the Indian Summer Monsoon and the Mid-latitude Westerlies in Himalayan Glaciation: Review and Speculative

Discussion. *Journal of the Geological Society*, **155(2):** 353-363. https://doi.org/10.1144/gsjgs.155.2.0353

Bhalme, H. & Jadhav, S. (1984). The Southern Oscillation and its Relation to the Monsoon Rainfall. *Journal of Climatology,* **4:** 509-520.

Bhunia, P., Das, P. & Maiti, R. (2020). Meteorological Drought Study Through SPI in Three Drought Prone Districts of West Bengal, India. *Earth Systems and Environment*, **4(1):** 43-55. https://doi.org/10.1007/s41748-019-00137-6

Bohlinger, P., Sorteberg, A. & Sodemann, H. (2017). Synoptic Conditions and Moisture Sources Actuating Extreme Precipitation in Nepal. *Journal of Geophysical Research: Atmospheres*, **122:** 12,653-12,671. https://doi.org/10.1002/1017JDO27543

Bonaccorso, B., Bordi, I., Cancelliere, A., Rossi, G. & Sutera, A. (2003). Spatial Variability of Drought: an Analysis of the SPI in Sicily. *Water Resources Management*, **17:** 273-296.

Borah, P., Venugopal, V., Sukhatme, J., Muddebihal, P. & Goswami, B. (2020). Indian Monsoon Derailed by a North Atlantic Wavetrain. *Science*, **370(6522):** 1335-1338. https://doi.org/10.1126/science.aay6043

Buishand, T. A. (1982). Some Methods for Testing the Homogeneity of Rainfall Records. *Journal of Hydrology*, **58:** 11-27.

Cbs, N. (2013). National Sample Census of Agriculture Nepal 2011/12. *National Report.*

Chandrasekara, S. S., Kwon, H.-H., Vithanage, M., Obeysekera, J. & Kim, T.-W. (2021). Drought in South Asia: A Review of Drought Assessment and Prediction in South Asian Countries. *Atmosphere*, **12(3):** 369. https://doi.org/10.3390/atmos12030369

Chen, F.-W. & Liu, C.-W. (2012). Estimation of the Spatial Rainfall Distribution Using Inverse Distance Weighting (IDW) in the Middle of Taiwan. Paddy and Water *Environment*, **10:** 209-222. https://doi.org/10.1007/s10333-012-0319-1

Cherchi, A. & Navarra, A. (2013). Influence of ENSO and of the Indian Ocean Dipole on the Indian Summer Monsoon Variability. *Climate Dynamics*, **41:** 81-103. https://doi.org/10.1007/s00382-012-1602-y

Chowdhury, M. R. (2003). The el Niño-southern oscillation (ENSO) and Seasonal Flooding–Bangladesh. *Theoretical and Applied Climatology*, **76:** 105-124. https://doi.org/10.1007/s00704-003-0001-z

Costa, A. C. & Soares, A. (2009). Homogenization of Climate Data: Review and New Perspectives Using Geostatistics. *Mathematical Geosciences*, **41:** 291-305. https://doi.org/10.1002/joc

Dabanli, I. (2018). Drought Risk Assessment by Using Drought Hazard and Vulnerability Indexes. *Natural Hazards and Earth System Sciences Discussions*, 1-15.

Dahal, N. M., Xiong, D., Neupane, N., Yigez, B., Zhang, B., Yuan, Y., Koirala, S., Liu, L. & Fang, Y. (2021). Spatiotemporal Analysis of Drought Variability Based on the Standardized Precipitation Evapotranspiration Index in the Koshi River Basin, Nepal. *Journal of Arid Land*, **13:** 433-454. https://doi.org/10.1007/s40333-021-0065-6

Dahal, P., Shrestha, N. S., Shrestha, M. L., Krakauer, N. Y., Panthi, J., Pradhanang, S. M., Jha, A. & Lakhankar, T. (2016). Drought Risk Assessment in Central Nepal: Temporal and Spatial Analysis. *Natural Hazards*, **80:** 1913-1932. https://doi.org/10.1007/s11069-015-2055-5

De Silva M, T. & Hornberger, G. M. (2019). Identifying El Niño–Southern Oscillation Influences on Rainfall With Classification Models: Implications for Water Resource Management of Sri Lanka. *Hydrology and Earth System Sciences*, **23:** 1905-1929. https://doi.org/10.5194/hess-23-1905-2019

Di Lena, B., Vergni, L., Antenucci, F., Todisco, F. & Mannocchi, F. (2014). Analysis of Drought in the Region of Abruzzo (Central Italy) by the Standardized Precipitation Index. *Theoretical and Applied Climatology*, **115:** 41-52. https://doi.org/10.1007/s00704-013-0876-2

Dimri, A. (2006). Surface and Upper Air Fields During Extreme Winter Precipitation Over the Western Himalayas. *Pure and Applied Geophysics*, **163:** 1679-1698. https://doi.org/10.1007/s00024-006-0092-4

Dimri, A. & Mohanty, U. (2009). Simulation of Mesoscale Features Associated With Intense Western Disturbances Over Western Himalayas. Meteorological Applications: *A Journal of Forecasting, Practical Applications, Training Techniques and Modelling*, **16(8):** 289-308. https://doi.org/10.1002 met.117

Dimri, A., Niyogi, D., Barros, A., Ridley, J., Mohanty, U., Yasunari, T. & Sikka, D. (2015). Western Disturbances: a Review. *Reviews of Geophysics*, **53:** 225-246. https://doi.org/10.1002/2014RG000460

Dirks, K., Hay, J., Stow, C. & Harris, D. (1998). High-Resolution Studies of Rainfall on Norfolk Island: Part II: Interpolation of Rainfall Data. *Journal of Hydrology*, **208:** 187-193.

Dos Santos, S. R. Q., Braga, C. C., Sansigolo, C. A., Neves, T. D. a. T. & Dos Santos, A. P. P. (2017). Droughts in the Amazon: Identification, Characterization and Dynamical Mechanisms Associated. *American Journal of Climate Change*, **6(2):** 425-442. https://doi.org/10.4236/ajcc.2017.62022

Dracup, J. A., Lee, K. S. & Paulson Jr, E. G. (1980). On the Definition of Droughts. *Water Resources Research*, **16:** 297-302. https://doi.org/10.1007/BF01543134

Du, J., Fang, J., Xu, W. & Shi, P. (2013). Analysis of Dry/Wet Conditions Using the Standardized Precipitation Index and its Potential Usefulness for Drought/Flood Monitoring in Hunan Province, China. *Stochastic Environmental Research and Risk Assessment*, **27:** 377-387. https://doi.org/10.1007/s00477-012-0589-6

Du, Y., Xie, S.-P., Huang, G. & Hu, K. (2009). Role of Air–Sea Interaction in the Long Persistence of El Niño–Induced North Indian Ocean Warming. *Journal of Climate*, **22(8):** 2023-2038. https://doi.org/10.1175/2008JCLI2590.1

Fan, F., Dong, X., Fang, X., Xue, F., Zheng, F. & Zhu, J. (2017). Revisiting the Relationship Between the South Asian Summer Monsoon Drought and El

Niño Warming Pattern. *Atmospheric Science Letters*, **18:** 175-182. https://doi.org/10.1002/asl.740

Fredriksen, H. B., Berner, J., Subramanian, A. C. & Capotondi, A. (2020). How Does El Niño–Southern Oscillation Change Under Global Warming—A First Look at CMIP6. *Geophysical Research Letters*, **47(22):** e2020GL090640. https://doi.org/10.1029/2020GL090640

Frick, T. W. (1990). Analysis of Patterns in Time: A Method of Recording and Quantifying Temporal Relations in Education. *American Educational Research Journal*, **27:** https://doi.org/10.3102/00028312027001180

Gadgil, S. & Joseph, P. (2003). On Breaks of the Indian Monsoon. *Journal of Earth System Science*, **112(4):** 529-558. https://doi.org/10.1007/BF0709778

Gadgil, S., Rajeevan, M. & Nanjundiah, R. (2005). Monsoon Prediction–Why Yet Another Failure*? Current Science*, **88(9):** 1389-1400. http://www.jstor.org/stable/24110705

Ganguli, P. & Reddy, M. J. (2014). Evaluation of Trends and Multivariate Frequency Analysis of Droughts in Three Meteorological Subdivisions of Western India. *International Journal of Climatology*, **34(3):** 911-928. https://doi.org/10.1002/joc.3742

Gibbs, W. J. & J.V., M. (1967). Rainfall Deciles as Drought Indicators.

Gumus, V. & Algin, H. M. (2017). Meteorological and Hydrological Drought Analysis of the Seyhan− Ceyhan River Basins, Turkey. *Meteorological Applications*, **24(1):** 62-73. https://doi.org/10.1002/met.1605

Guttman, N. B. (1999). Accepting the Standardized Precipitation Index: a Calculation Algorithm 1. *JAWRA Journal of the American Water Resources Ass*ociation, **35(2):** 311-322. https://doi.org/10.1111/j.1752-1688.1999.tb03592.x

Hagman, G. B., M., and Wijkman,A. (1984). Report on the Manand Natural Disasters in the Third World. Prevention Better than Cure. Stockholm and Geneva: Swedish Red Cross.

Hamal, K., Sharma, S., Baniya, B., Khadka, N. & Zhou, X. (2020). Inter-Annual Variability of Winter Precipitation Over Nepal Coupled With Ocean-Atmospheric Patterns During 1987–2015. *Frontiers in Earth Science*, **8:** 161. https://doi.org/10.3389/feart.2020.00161

Hayes, M. J., Svoboda, M. D., Wiihite, D. A. & Vanyarkho, O. V. (1999). Monitoring the 1996 Drought Using the Standardized Precipitation Index. *Bulletin of the American Meteorological Society*, **80(3):** 429-438. https://doi.org/10.1175/1520-0477(1999)080<0429:MTDUTS>2.0.CO;2

Hayes, M. J., Svoboda, M. D. & Wilhite, D. A. (2000). Monitoring Drought Using the Standardized Precipitation Index. http://digitalcommons.unl.edu/drought focpub/70

Ichiyanagi, K., Yamanaka, M. D., Muraji, Y. & Vaidya, B. K. (2007). Precipitation in Nepal Between 1987 and 1996. *Int. J. Climatol.*, **27:** 1753-1762. doi:10 :1002/joc.1492

Ipcc (2007). Synthesis Report. Contribution of Working Groups I, II and III to the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC*, Geneva, Switzerland.

Kafle, H. (2016). Drought Analysis in Western,Central and Eastern Development Regions of Nepal Using Reconnaissance Drought Index. . *Journal of Hydrology and Meteorology*, **10:** 20-29.

Kafle, H. K. (2014). Spatial and Temporal Variation of Drought in Far and Mid Western Regions of Nepal: Time Series Analysis (1982-2012). *Nepal Journal of Science and Technology*, **15:** 65-76. https://doi.org/10.3126/njst.v15i2.12118

Kalsi, S. (1980). On Some Aspects of Interaction Between Middle Latitude Westerlies and Monsoon Circulation. *Mausam*, **31:** 305-308.

Kansakar, S. R., Hannah, D. M., Gerrard, J. & Rees, G. (2004). Spatial Pattern in the Precipitation Regime of Nepal. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, **24:** 1645-1659. https://doi.org/10.1002/joc.1098

Karki, R., Hasson, S. U., Schickhoff, U., Scholten, T. & Böhner, J. (2017). Rising Precipitation Extremes Across Nepal. *Climate*, **5:** 4. https://doi.org/10.3390/cli5010004

Karki, R., Talchabhadel, R., Aalto, J. & Baidya, S. K. (2016). New Climatic Classification of Nepal. *Theoretical and Applied Climatology*, **125:** 799-808. https://doi.org/10.1007/s00704-015-1549-0

Katsumoto, S., Hironori, Y., Masayoshi, N., Akiko, S., Tsutomu, K. & Yutaka, Y. (1998). Changing Surface Features of Khumbu Glacier, Nepal Himalayas Revealed by SPOT Images. *Bulletin of Glacier Research*, **16:** 33-41.

Kendall, S. B. (1975). Enhancement of Conditioned Reinforcement by Uncertainty 1. *Journal of the Experimental Analysis of Behavior*, **24:** 311-314.

Khalili, D., Farnoud, T., Jamshidi, H., Kamgar-Haghighi, A. A. & Zand-Parsa, S. (2011). Comparability Analyses of the SPI and RDI Meteorological Drought Indices in Different Climatic Zones. *Water Resources Management*, **25(6):** 1737-1757. https://doi.org/10.1007/s11269-010-9772-z

Khandekar, M. (1991). Eurasian Snow Cover, Indian Monsoon and El Niño/Southern Oscillation–a Synthesis. *Atmosphere-Ocean*, **29(4):** 636-647. https://doi.org/10.1080/07055900.1991.9649422

Khandekar, M. L. & Neralla, V. (1984). On the Relationship Between the Sea Surface Temperatures in the Equatorial Pacific and the Indian Monsoon Rainfall. *Geophysical Research Letters*, **11:** 1137-1140.

Khatiwada, K. R. & Pandey, V. P. (2019). Characterization of Hydro-Meteorological Drought in Nepal Himalaya: A Case of Karnali River Basin. *Weather and Climate Extremes*, **26:** 100239. https://doi.org/10.1016/j.wace.2019.100239

Kripalani, R. & Kulkarni, A. (1996). Assessing the Impacts of El Niño and Non-El Niño-Related Droughts Over India. *Drought Network News* (1994-2001), 24.

Krishnamurthy, V. & Goswami, B. N. (2000). Indian Monsoon–ENSO Relationship on Interdecadal Timescale. *Journal of Climate*, **13:** 579-595. https://doi.org/10.1175/1520-0442(2000)013<0579:IMEROI>2.0.CO;2

Krishnamurti, T. (1985). Summer Monsoon Experiment—A Review. *Monthly Weather Review*, **113:** 1590-1626.

Kumar, K. K., Rajagopalan, B. & Cane, M. A. (1999). On the Weakening Relationship Between the Indian Monsoon and ENSO. *Science*, **284:** 2156-2159. https://doi.org/10.1126/science.284.5423.2156

Kumar, K. N., Rajeevan, M., Pai, D., Srivastava, A. & Preethi, B. (2013). On the Observed Variability of Monsoon Droughts Over India. *Weather and Climate Extremes*, **1:** 42-50. https://doi.org/10.1016/j.wace.2013.07.006

Lang, T. J. & Barros, A. P. (2004). Winter Storms in the Central Himalayas. *Journal of the Meteorological Society of Japan*. Ser. II, **82:** 829-844.

Le, T., Sun, C., Choy, S. & Kuleshov, Y. (2021). Regional Drought Risk Assessment in the Central Highlands and the South of Vietnam. *Geomatics, Natural Hazards and Risk*, **12:** 3140-3159. https://doi.org/10.1080/19475705.2021.1998232

Li, G., Wang, Y., Lee, K. H., Diao, Y. & Zhang, R. (2008). Increased Winter Precipitation Over the North Pacific from 1984–1994 to 1995–2005 Inferred From the Global Precipitation Climatology Project. *Geophysical Research Letters*, ***35*****(13):** 1–5. https://doi.org/10.1029/2008GL034668

Mann, H. B. (1945). Nonparametric Tests Against Trend. *Econometrica*, **13(3):** 245-259. https://doi.org/10. 2307/1907187

Mckee, T. B., Doesken, N. J. & Kleist, J. The Relationship of Drought Frequency and Duration to Time Scales. *Proceedings of the 8th Conference on Applied Climatology*, (1993). California, 179-183.

Mishra, A. K. & Singh, V. P. (2010). A Review of Drought Concepts. *Journal of hydrology*, **391:** 202-216. https://doi.org/10.1016/j.jhydrol.2010.07.012

Mondol, M. a. H., Ara, I. & Das, S. C. (2017). Meteorological Drought Index Mapping in Bangladesh Using Standardized Precipitation Index During 1981–2010. *Advances in Meteorology* . https://doi.org/10.1155/2017/4642060

Mooley, D. & Parthasarathy, B. (1983). Variability of the Indian Summer Monsoon and Tropical Circulation Features. *Monthly Weather Review*, **111:** 967-978. https://doi.org/10.1175/1520-0493(1983)111<0967:VOTISM>2.0.CO;2

Morid, S., Smakhtin, V. & Moghaddasi, M. (2006). Comparison of Seven Meteorological Indices for Drought Monitoring in Iran. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, **26:** 971-985. https://doi.org/10.1002/joc.1264

Muangsong, C., Cai, B., Pumijumnong, N., Hu, C. & Cheng, H. (2014). An Annually Laminated Stalagmite Record of the Changes in Thailand Monsoon Rainfall Over the Past 387 Years and Its Relationship to IOD and ENSO. *Quaternary International*, **349:** 90-97. https://doi.org/10.1016/j.quaint.2014.08.037

Myronidis, D. & Nikolaos, T. (2021). Changes in Climatic Patterns and Tourism and Their Concomitant Effect on Drinking Water Transfers into the Region of South Aegean, Greece. *Stochastic Environmental Research and Risk Assessment*, **35(9):** 1725-1739. https://doi.org/10.1007/s00477-021-02015-y

Nalbantis, I. & Tsakiris, G. (2009). Assessment of Hydrological Drought Revisited. *Water Resources Management*, **23(5):** 881-897. https://doi.org/10.1007/s11269-008-9305-1

Nandargi, S. S. & Aman, K. (2017). Computation of the Standardized Precipitation Index (SPI) for Assessing Droughts Over India. *Int. J. Curr. Adv. Res.*, **6(12):** 8545-8557. http://dx.doi.org/10.24327/ijcar.2017.8557.1383

Nikbakht, J., Tabari, H. & Talaee, P. H. (2013). Streamflow Drought Severity Analysis by Percent of Normal Index (PNI) in Northwest Iran. *Theoretical and Applied Climatology*, **112:** 565-573. https://doi.org/10.1007/s00704-012-0750-7

Nouri, M. & Homaee, M. (2020). Drought Trend, Frequency and Extremity Across a Wide Range of Climates Over Iran. *Meteorological Applications*, **27:** e1899. https://doi.org/10.1002/met.1899

Palmer, W. C. (1965). Meteorological Drought, US Department of Commerce, *Weather Bureau*.

Panthi, J., Dahal, P., Shrestha, M. L., Aryal, S., Krakauer, N. Y., Pradhanang, S. M., Lakhankar, T., Jha, A. K., Sharma, M. & Karki, R. (2015). Spatial and Temporal Variability of Rainfall in the Gandaki River Basin of Nepal Himalaya. *Climate*, **3:** 210-226. https://doi.org/10.3390/cli3010210

Patel, N., Chopra, P. & Dadhwal, V. (2007). Analyzing Spatial Patterns of Meteorological Drought Using Standardized Precipitation Index. Meteorological Applications: *A journal of Forecasting, Practical Applications, Training Techniques and Modelling*, **14:** 329-336. https://doi.org/10.1002/met.33

Pettitt, A. N. (1979). A Non-Parametric Approach to the Change-Point Problem. *Journal of the Royal Statistical Society. Series C (Applied Statistics)*, **28:** 126-135.

Pokharel, B., Wang, S. Y. S., Meyer, J., Marahatta, S., Nepal, B., Chikamoto, Y. & Gillies, R. (2020). The East–West Division of Changing Precipitation in Nepal. *International Journal of Climatology*, **40(7):** 3348-3359. https://doi.org/10.1002/joc.6401

Portner, H. O., Roberts, D. C., Adams, H., Adler, C., Aldunce, P., Ali, E., Ara Begum, R., Betts, R., Bezner Kerr, R., Biesbroek, R., Birkmann, J., Bowen, K., Castellanos, E., Cisse, Gueladio, Constable, A., Cramer, W., Dodman, D., Eriksen, S. H., Fischlin, A., Garschagen, M., Glavovic, B., Gilmore, E., Haasnoot, M., Harper, S., Hasegawa, T., Hayward, B., Hirabayashi, Y., Howden, M., Kalaba, K., Kiessling, W., Lasco, R., Lawrence, J., Lemos, M. F., Lempert, R., Ley, D., Lissner, T., Lluch-Cota, S., Loeschke, S., Lucatello, S., Luo, Y., Mackey, B., Maharaj, S., Mendez, C., Mintenbeck, K., Moncassim Vale, M., Morecroft, M. D., Mukherji, A., Mycoo, M., Mustonen, T., Nalau, J., Okem, A., Ometto, J. P., Parmesan, C., Pelling, M., Pinho, P., Poloczanska, E., Racault, M.-F., Reckien, D., Pereira, J., Revi, A., Rose, S., Sanchez-Rodriguez, R., Schipper, E. L. F., Schmidt, D., Schoeman, D., Shaw, R., Singh, C., Solecki, W., Stringer, L., Thomas, A., Totin, E., Trisos, C., Viner, D., Aalst, M. V., Wairiu, M., Warren, R., Yanda, P. & Zaiton Ibrahim, Z. 2022. Climate change (2022): impacts, adaptation and vulnerability. Netherlands: *IPCC*.

Rahman, M. R. & Lateh, H. (2016). Meteorological Drought in Bangladesh: Assessing, Analysing and Hazard Mapping Using SPI, GIS and Monthly Rainfall Data. *Environmental Earth Sciences*, **75(12):** 1-20. https://doi.org/10.1007/s12665-016-5829-5

Rajsekhar, D., Singh, V. P. & Mishra, A. K. (2015). Integrated Drought Causality, Hazard, and Vulnerability Assessment for Future Socioeconomic Scenarios: An Information Theory Perspective. *Journal of Geophysical Research: Atmospheres*, **120(13):** 6346-6378. https://doi.org/10.org/10.1002/2014JD022670

Ramanadham, R., Visweswara Rao, P. & Patnaik, J. K. (1973). Break in the Indian Summer Monsoon. *Pure and Applied Geophysics*, **104(1):** 635-647. https://doi.org/10.1007/BF00875908

Rasmusson, E. M. & Carpenter, T. H. (1983). The Relationship Between Eastern Equatorial Pacific Sea Surface Temperatures and Rainfall Over India and Sri Lanka. *Monthly Weather Review*, **111:** 517-528. https://doi.org/10.1175/1520-0493(1983)111<0517:TRBEEP>2.0.CO;2

Raziei, T., Bordi, I. & Pereira, L. (2008). A Precipitation-Based Regionalization for Western Iran and Regional Drought Variability. *Hydrology and Earth System Sciences*, **12:** 1309-1321. https://doi.org/10.5194/hess-12-1309-2008

Raziei, T., Saghafian, B., Paulo, A. A., Pereira, L. S. & Bordi, I. (2009). Spatial Patterns and Temporal Variability of Drought in Western Iran. *Water Resources Management*, **23:** 439-455. https://doi.org/10.1007/s11269-008-9282-4

Rossi, G., Benedini, M., Tsakiris, G. & Giakoumakis, S. (1992). On Regional Drought Estimation and Analysis. *Water Resources Management*, **6(4):** 249-277. https://doi.org/10.1007/BF00872280

Salerno, F., Guyennon, N., Thakuri, S., Viviano, G., Romano, E., Vuillermoz, E., Cristofanelli, P., Stocchi, P., Agrillo, G., Ma, Y. & Tartari, G. (2015). Weak Precipitation, Warm Winters and Springs Impact Glaciers of South Slopes of

Mt. Everest (central Himalaya) in the Last 2 Decades (1994–2013). *The Cryosphere*, **9(3):** 1229-1247. https://doi.org/10.5194/tc-9-1229-2015

Santos, J. F., Portela, M. M. & Pulido-Calvo, I. (2011). Regional Frequency Analysis of Droughts in Portugal. *Water Resources Management*, **25:** 3537-3558. https://doi.org/ 10.1007/s11269-011-9869-z

Sein, Z. M. M., Ogwang, B., Ongoma, V., Ogou, F. K. & Batebana, K. (2015). Inter-Annual Variability of May-October Rainfall Over Myanmar in Relation to IOD and ENSO. *Journal of Environmental and Agricultural Sciences*, **4:** 28-36.

Sen Roy, N. & Kaur, S. (2000). Climatology of Monsoon Rains of Myanmar (Burma). International Journal of Climatology: *A Journal of the Royal Meteorological Society*, **20(8):** 913-928. https://doi.org/10.1002/1097-0088(20000630)20:8<913::AID-JOC485>3.0.CO;2-U

Shahid, S. & Behrawan, H. (2008). Drought Risk Assessment in the Western Part of Bangladesh. *Natural hazards*, **46(3):** 391-413. https://doi.org/10.1007/s11069-007-9191-5

Sharma, S., Hamal, K., Khadka, N. & Joshi, B. B. (2020). Dominant Pattern of Year-to-Year Variability of Summer Precipitation in Nepal During 1987–2015. *Theoretical and Applied Climatology*, **142(3-4):** 1071-1084. https://doi.org/10.1007/s00704-020-03359-1

Sharma, S., Hamal, K., Khadka, N., Shrestha, D., Aryal, D. & Thakuri, S. (2021). Drought Characteristics Over Nepal Himalaya and Their Relationship With Climatic Indices. *Meteorological Applications*, **28:** e1988. https://doi.org/10.1002/met.1988

Sheffield, J. & Wood, E. F. (2008). Projected Changes in Drought Occurrence Under Future Global Warming From Multi-Model, Multi-Scenario, IPCC AR4 simulations. *Climate Dynamics*, **31(1):** 79-105. https://doi.org/10.1007/s00382-007-0340-z

Shrestha, A. B., Wake, C. P., Dibb, J. E. & Mayewski, P. A. (2000). Precipitation Fluctuations in the Nepal Himalaya and its Vicinity and Relationship With

Some Large Scale Climatological Parameters. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, **20:** 317-327.

Shrestha, D., Sharma, S., Hamal, K., Jadoon, U. K. & Dawadi, B. (2021). Spatial Distribution of Extreme Precipitation Events and its Trend in Nepal. *Environmental Sciences*, **9(1):** 58-66. https://doi.org/10.12691/aees-9-1-8

Shrestha, M. (2000). Interannual Variation of Summer Monsoon Rainfall Over Nepal and Its Relation to Southern Oscillation Index. *Meteorology and Atmospheric Physics*, **75:** 21-28.

Shrestha, N. K., Qamer, F. M., Pedreros, D., Murthy, M., Wahid, S. M. & Shrestha, M. (2017). Evaluating the Accuracy of Climate Hazard Group (CHG) Satellite Rainfall Estimates for Precipitation Based Drought Monitoring in Koshi Basin, Nepal. *Journal of Hydrology: Regional Studies*, **13:** 138-151. https://doi.org/10.1016/j.ejrh.2017.08.004

Shrestha, S., Yao, T., Kattel, D. B. & Devkota, L. P. (2019). Precipitation Characteristics of Two Complex Mountain River Basins on the Southern Slopes of the Central Himalayas. *Theoretical and Applied Climatology*, **138(1-2):** 1159-1178. https://doi.org/10.1007/s00704-019-02897-7

Sigdel, M. & Ikeda, M. (2010). Spatial and Temporal Analysis of Drought in Nepal Using Standardized Precipitation Index and Its Relationship With Climate Indices. *Journal of Hydrology and Meteorology*, **7:** 59-74. https://doi.org/10.3126/jhm.v7i1.561

Sigdel, M. & Ikeda, M. (2012). Summer Monsoon Rainfall Over Nepal Related With Large-Scale Atmospheric Circulations. *J Earth Sci Clim Change*, **3:** 112. https://doi.org/10.4172/2157-7617.1000112

Sigdel, M. & Ma, Y. (2017). Variability and Trends in Daily Precipitation Extremes on the Northern and Southern Slopes of the Central Himalaya. *Theoretical and Applied Climatology*, **130(1-2):** 571-581. https://doi.org/10.1007/s00704-016-1916-5

Sikka, D. (1980). Some Aspects of the Large Scale Fluctuations of Summer Monsoon Rainfall Over India in Relation to Fluctuations in the Planetary and Regional

Scale Circulation Parameters. *Proceedings of the Indian Academy of Sciences-Earth and Planetary Sciences*, **89:** 179-195.

Sternberg, T. (2011). Regional Drought has a Global Impact. *Nature*, **472:** 169-169.

Subash, N. & Ram Mohan, H. (2011). Trend Detection in Rainfall and Evaluation of Standardized Precipitation Index as a Drought Assessment Index for Rice–Wheat Productivity Over IGR in India. *International Journal of Climatology*, **31:** 1694-1709. https://doi.org/10.1002/joc.2188

Tabari, H., Somee, B. S. & Zadeh, M. R. (2011). Testing for Long-Term Trends in Climatic Variables in Iran. *Atmospheric Research*, **100:** 132-140. https://doi.org/10.1016/j.atmosres.2011.01.005

Taxak, A. K., Murumkar, A. & Arya, D. S. (2014). Long Term Spatial and Temporal Rainfall Trends and Homogeneity Analysis in Wainganga Basin, Central India. *Weather and climate extremes*, **4:** 50-61. https://doi.org/10.1016/j.wace.2014.04.005

Tigkas, D. (2008). Drought Characterisation and Monitoring in Regions of Greece. *European water*, **23:** 29-39.

Trenberth, K. E. (1976). Spatial and Temporal Variations of the Southern Oscillation. *Quarterly Journal of the Royal Meteorological Society*, **102(433):** 639-653. https://doi.org/10.1002/qj.49710243310

Trenberth, K. E., Dai, A., Van Der Schrier, G., Jones, P. D., Barichivich, J., Briffa, K. R. & Sheffield, J. (2014). Global Warming and Changes in Drought. *Nature Climate Change*, **4:** 17-22. https://doi.org/10.1038/nclimate2067

Tsakiris, G. & Vangelis, H. (2005). Establishing a Drought Index Incorporating Evapotranspiration. *European Water*, **9:** 3-11.

Uddin, M. J., Hu, J., Islam, A. R. M. T., Eibek, K. U. & Nasrin, Z. M. (2020). A Comprehensive Statistical Assessment of Drought Indices to Monitor Drought Status in Bangladesh. *Arabian Journal of Geosciences*, **13(9):** 1-10. https://doi.org/10.1007/s12517-020-05302-0

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M. & Uijlenhoet, R. (2016). Drought in the Anthropocene. *Nature Geoscience*, **9:** 89-91.

Varikoden, H. & Babu, C. (2015). Indian Summer Monsoon Rainfall and its Relation With SST in the Equatorial Atlantic and Pacific Oceans. *International Journal of Climatology,* **35(6):** 1192-1200. https://doi.org/10.1002/joc.4056

Varikoden, H., Revadekar, J., Choudhary, Y. & Preethi, B. (2015). Droughts of Indian Summer Monsoon Associated with El Niño and Non-El Niño years. *International Journal of Climatology*, **35:** 1916-1925. https://doi.org/10.1002/joc.4097

Von Neumann, J. (1941). Distribution of the Ratio of the Mean Square Successive Difference to the Variance. *The Annals of Mathematical Statistics*, **12(4):** 367-395. https://doi.org/10.1214/aoms/1177731677

Wang, B., Luo, X. & Liu, J. (2020). How Robust is the Asian Precipitation–ENSO Relationship During the Industrial Warming Period (1901–2017)? *Journal of Climate,* **33(7):** 2779-2792. https://doi.org/10.1175/JCLI-D-19-0630.1

Wang, S.-Y., Yoon, J.-H., Gillies, R. R. & Cho, C. (2013). What Caused the Winter Drought in Western Nepal During Recent Years? *Journal of Climate*, **26(21):** 8241-8256. https://doi.org/10.1175/JCLI-D-12-00800.1

Webster, P. J., Magana, V. O., Palmer, T., Shukla, J., Tomas, R., Yanai, M. & Yasunari, T. (1998). Monsoons: Processes, Predictability, and the Prospects for Prediction.: *Journal of Geophysical Research* Oceans, **103:** 14451-14510. https://doi.org/10.1029/97jc02719

Wijngaard, J., Klein Tank, A. & Können, G. (2003). Homogeneity of 20th Century European Daily Temperature and Precipitation Series. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, **23:** 679-692. https://doi.org/10.1002/joc.906

Wilhite,D. A. (2000). Chapter 1 Droughts as a Natural Hazard;Concepts and Definations. *Drought Mitigation Center Faculty Publications*, 69. Retrieved from http://digitalcommons . unl .edu/drought facpub/69

Wilhite, D. A. & Glantz, M. H. (1985). Understanding: the Drought Phenomenon: the Role of Definitions. *Water International*, **10(3):** 111-120. https://doi.org/10.1080/02508068508686328

Wilhite, D. A., Svoboda, M. D. & Hayes, M. J. (2007). Understanding the Complex Impacts of Drought: A Key to Enhancing Drought Mitigation and Preparedness. *Water Resources Management*, **21(5):** 763-774. https://doi.org/10.1007/s11269-006-9076-5

Wmo (2012). Standardized Precipitation Index User Guide. *World Meteorological Organization*, 1090.

Wright, P. B. (1975). An Index of the Southern Oscillation, Climatic Research Unit, School of Environmental Sciences, University of East ….

Wu, B., Zhou, T. & Li, T. (2009). Seasonally Evolving Dominant Interannual Variability Modes of East Asian climate. *Journal of Climate*, **22(11):** 2992-3005. https://doi.org/10.1175/2008JCLI2710.1

Xie, H., Ringler, C., Zhu, T. & Waqas, A. (2013). Droughts in Pakistan: a Spatiotemporal Variability Analysis Using the Standardized Precipitation Index. *Water International*, **38(5):** 620-631. https://doi.org/10.1080/02508060.2013.827889

Xie, S.-P., Hu, K., Hafner, J., Tokinaga, H., Du, Y., Huang, G. & Sampe, T. (2009). Indian Ocean Capacitor Effect on Indo–Western Pacific Climate During the Summer Following El Niño. *Journal of Climate*, **22(3):** 730-747. https://doi.org/10.1175/2008JCLI2544.1

Yan, H., Sun, L., Wang, Y., Huang, W., Qiu, S. & Yang, C. (2011). A Record of the Southern Oscillation Index for the Past 2,000 Years from Precipitation Proxies. *Nature Geoscience*, **4(9):** 611-614. https://doi.org/10.1038/ngeo1231

Zargar, A., Sadiq, R., Naser, B. & Khan, F. I. (2011). A Review of Drought Indices. *Environmental Reviews*, **19(1):** 333-349. https://doi.org/10.1139/a11-013

APPENDICES

APPENDIX -1 LIST OF PUBLICATIONS

Journal Papers:

Bagale, D., Sigdel, M. & Aryal, D. (2021). Drought Monitoring Over Nepal for the Last Four Decades and its Connection With Southern Oscillation Index. *Water*, **13:** 3411. https://doi.org/10.3390/w13233411

Bagale, D., Sigdel, M. & Aryal, D. (2023). Influence of Southern Oscillation Index on Rainfall Variability in Nepal During Large Deficient Monsoon Years. *Journal of Institute of Science and Technology*, **28(1):** 11-24. https://doi.org/10.3126/jist.v28i1.43452

Bagale, D., Sigdel, M. & Aryal, D. (2023). Winter Drought Monitoring Using Standard Precipitation Index Over Nepal. *Natural Hazards*, **2023**:1-14. https://doi.org/10.1007/s11069-023-06242-0

Manuscripts ready for submission.

Meteorological drought hazard monitoring in Nepal.

Decreasing seasonal precipitation in recent four decades in Nepal.

APPENDIX -2 CONFERENCE PARTICIPITATION

1 Attending 7th WMO International workshop on Monsoons (IWM-7), 22-26 March, 2022, New Delhi, India. Oral presentation on 25 March, through online.

Title: Spatial and Temporal Variability of Monsoon Rainfall and its Trends on the Southern Slopes of Central Himalayas

By

Damodar Bagale, Deepak Aryal and Madan Sigdel

Central Department of Hydrology and Meteorology, Tribhuvan University

Kathmandu, Nepal

Email: damu.bagale@gmail.com

2 Attending 9th National Conference on Science and Technology (NAST-9), 26-28 June, 2022, Khumaltar, Lalitpur, Nepal

Title: Spatial and Temporal Variability of Winter Rainfall Over Nepal for the Recent Four Decades

By

Damodar Bagale, Deepak Aryal and Madan Sigdel
Central Department of Hydrology and Meteorology, Tribhuvan University
Kathmandu, Nepal
Email: damu.bagale@gmail.com

3 Attending First Ph.D. Festival on Institute of Science and Technology, TU, Kirtipur, Kathmandu, Nepal. Poster Presentation on October 9-10, 2023

Title: Drought Monitoring Over Nepal Associated with Southern Oscillation Index

By

Damodar Bagale, Deepak Aryal and Madan Sigdel
Central Department of Hydrology and Meteorology, Tribhuvan University
Kathmandu, Nepal
Email: damu.bagale@gmail.com

water

MDPI

Article

Drought Monitoring over Nepal for the Last Four Decades and Its Connection with Southern Oscillation Index

Damodar Bagale *, Madan Sigdel and Deepak Aryal

Central Department of Hydrology and Meteorology, Tribhuvan University, Kathmandu 44613, Nepal; sigdelbro@gmail.com (M.S.); deepak.aryal@cdhm.tu.edu.np (D.A.)
* Correspondence: damu.bagale@gmail.com

Abstract: This study identified summer and annual drought events using the Standard Precipitation Index (SPI) for 107 stations across Nepal from 1977 to 2018. For this, frequency, duration, and severity of drought events were investigated. The SPI4 and SPI12 time scales were interpolated to illustrate the spatial patterns of major drought episodes and their severity. A total of 13 and 24 percent of stations over the country showed a significant decreasing trend for SPI4 and SPI12. Droughts were recorded during El Niño and non-El Niño years in Nepal. Among them, 1992 was the worst drought year, followed by the drought year, 2015. More than 44 percent of the locations in the country were occupied under drought conditions during these extreme drought events. Droughts have been recorded more frequently in Nepal since 2005. The areas of Nepal affected by extreme, severe, and moderate drought in summer were 8, 9, and 18 percent, while during annual events they were 7, 11, and 17 percent, respectively. Generally, during the drought years, the SPI and Southern Oscillation Index (SOI) have a strong phase relation compared to the average years.

Keywords: drought; El Niño; Mann-Kendall test; Nepal; SOI; SPI

Citation: Bagale, D.; Sigdel, M.; Aryal, D. Drought Monitoring over Nepal for the Last Four Decades and Its Connection with Southern Oscillation Index. *Water* **2021**, *13*, 3411. https://doi.org/10.3390/w13233411

Academic Editor: Ana Iglesias

Received: 3 November 2021
Accepted: 23 November 2021
Published: 2 December 2021

1. Introduction

Drought is a typical natural locally or regionally recurring characteristic of the climate. It occurs in virtually all climatic regimes in areas with high and low rainfall. A universal definition of drought is an unrealistic expectation [1]. Drought is a temporary aberration, in contrast to aridity, a permanent feature of the climate, and is restricted to low rainfall areas [1]. Drought is considered by many to be the most complex but least understood of all-natural hazards, affecting more people and the environment, causing more substantial economic losses than any other hazard [2,3]. The effects of drought often accumulate slowly over a considerable time period and may linger for years after the termination of the event [4]. A combination or sequence of droughts has severe impacts on human and environmental welfare [5]. Drought can be grouped into five kinds, namely, Meteorological drought; Hydrological drought; Agricultural drought, Socio-economic drought, and Groundwater drought [6]. Meteorological drought is the consequence of a natural reduction in the amount of precipitation received over an extended period, usually a season or more in length [4]. The World Meteorological Organization (WMO) has recommended using the SPI for extensive use by all national Meteorological and Hydrological Services to ascertain Meteorological drought and complement local drought indices currently being used [7]. The Southern Oscillation Index (SOI) measures a large-scale fluctuation in sea-level pressure between La Niña and El Niño. The years of abnormally high sea surface temperature (SST) from the west coast of South America towards the equatorial mid-pacific are known as El Niño years, and the years of abnormally colder waters in the same region are known as La Nina years [8]. Most drought years are associated with El Niño episodes, followed by non-El Niño events in India [9–12]. During the El Niño years, a strong tendency for below-normal Indian monsoon rainfall spread over most parts of the country [8,12,13]. There is good agreement between the significant negative/positive value of SOI and droughts/floods; however, some exceptions are unexplained by the SOI [13]. The decrease in Indian monsoon rainfall was associated with the warm phase of ENSO due to anomalous regional Hadley circulation with decreasing motion over the Indian subcontinent [12].

Nepal observes excess rainfall in the monsoon months of a year, while there is a deficit in some other months. Almost 80% of the annual rainfall occurs during the monsoon months of June to September, and the remaining months face a deficit of water [14,15]. Summertime is dominated by a monsoonal climate, while wintertime by western disturbances. There are four seasons in Nepal, namely, pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November), and winter (December–February). Pre-monsoon is characterized by hot, dry, and westerly windy weather with mostly localized precipitation in a narrow band, whereas the monsoon is characterized by moist southeasterly monsoonal winds coming from the Bay of Bengal and occasionally from the Arabian Sea with widespread precipitation. Post-monsoon refers to a dry season with sunny days featuring the driest month, November. Winter is a cold season with precipitation mostly in the form of snow in high-altitude mountainous regions.

Many studies have been undertaken to detect rainfall variability in Nepal; however, very few studies have been conducted on drought monitoring. Although few historical drought monitoring research has been conducted, real-time drought monitoring by the national meteorological and hydrological service (NMHS) has not been carried out in Nepal. Instead, with the rainfall data, NMHS issues the seasonal precipitation analysis (above normal/normal/below normal) based on the meteorological observatories. Sigdel and Ikeda [16] analyzed the spatial and temporal variation to investigate drought patterns using the 26 stations over Nepal during 1971–2003. Similarly, Wang et al. [17] studied drought in the western region of Nepal. Likewise, Dahal et al. [18] concentrated their study on the central region of Nepal. Shrestha et al. [19] focused on the Koshi basin located in the eastern region of Nepal, while Kafle [20] focused on drought studies in Nepal's far and mid-western regions. However, drought studies using many stations and long-term data sets are still lacking.

The research hypothesis behind this study is that drought frequency and intensity is continuously increasing over Nepal in recent decades, and this could be accelerated due to large-scale atmospheric circulations, such as El Niño and Southern Oscillation. The main objective of the study was to monitor the historical drought over Nepal and its relationship with El Niño and Southern Oscillation. The specific objectives are to: (i) identify the extreme drought years during the last four decades; and (ii) study the temporal and spatial progression of drought events during El Niño and non-El Niño years.

2. Materials and Methods

2.1. Study Area

Nepal is a landlocked country located between India and China and in the southern part of the central Himalayans. It extends from 80°04′ to 88°12′ E longitude and 26°22′ to 30°27′ N latitude. It comprises 77 districts. The complex topography of Nepal ranges from the low land of Terai 60 m in the southern parts of the country, covering the fertile lands, and the high land of Mount Everest 8848 m above sea level in the Himalayan region. The northern part of Nepal has the most prominent peak worldwide. The country extends 885 km from the east to the west and varies from 130 km to 260 km in the north to the south, respectively, and covers 147,181 sq. km. Precipitation data from January 1977 to December 2018 were acquired from the Department of Hydrology and Meteorology, Government of Nepal. The spatial distributions of the 107 meteorological stations across the different regions of the country are shown in Figure 1. The amount of annual precipitation generally decreases from east to west. However, there are certain pockets with heavy annual rainfall totals, such as in central Nepal [16]. The stations measure rainfall on a daily basis and later convert it to monthly total rainfall in each station, which was applied in the present study. The stations were selected based on less than 10% of missing records, and most of the stations (95%) were lower than 3% of the total number of annual values. High-altitude stations were used for spatial coverage with 30 years' time series with 5–10% missing values.

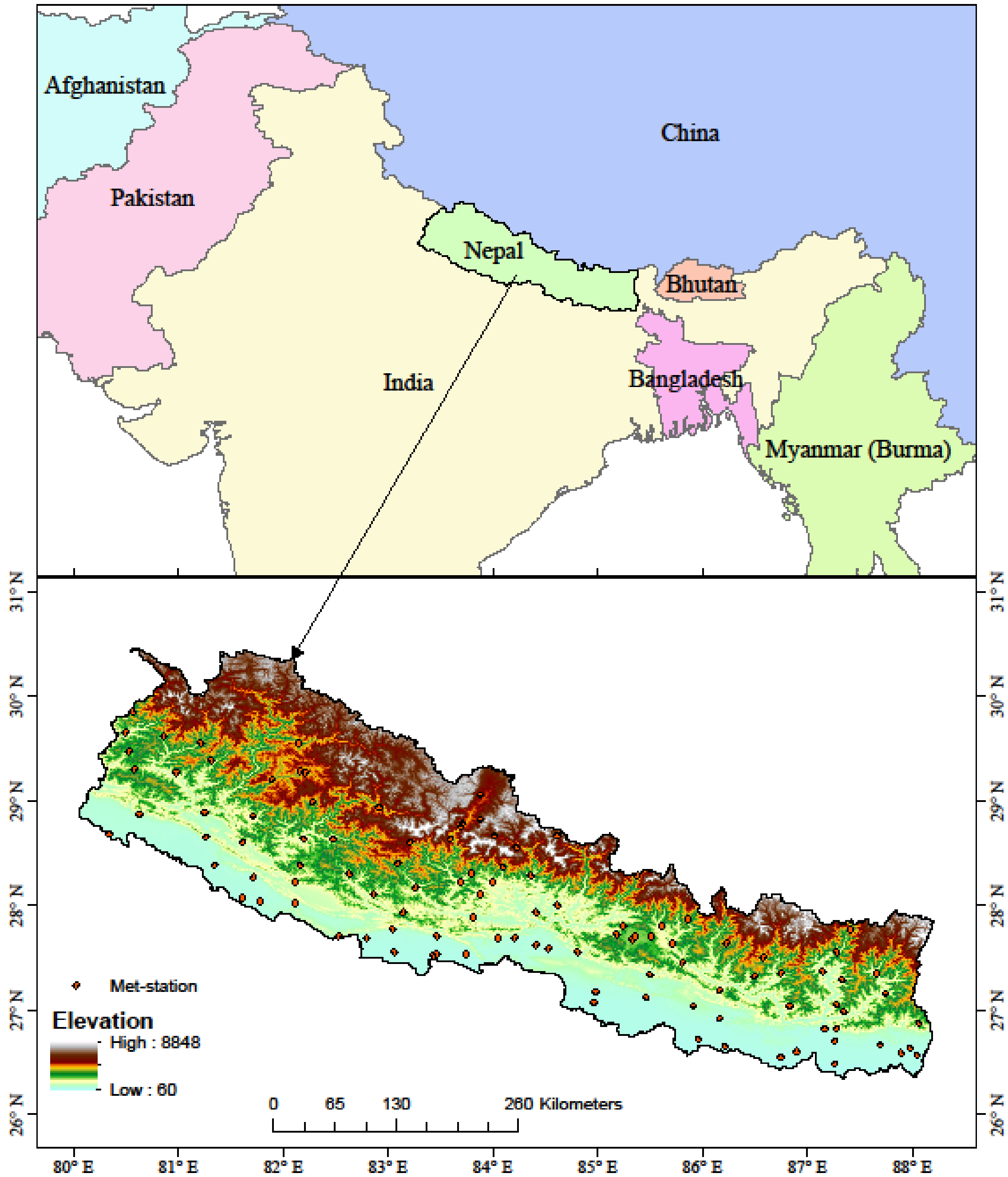

Figure 1. Location map of the study area along with rainfall stations at different elevations.

We adopted the Normal ratio method to estimate the missing rainfall values of the climate data set from three nearby weather stations [21]. Furthermore, the data selection criterion was based on the length, completeness, and reliability of the time series records of the stations as much as possible.

Monthly SOI data (1977–2018) were acquired from the climate Analysis Center of the National Oceanic and Atmospheric Administration (NOAA) available on https://www.cpc.ncep.noaa.gov/data/indices, accessed on 1 February 2020. In addition, descriptions of Changes to Ocean Niño Index (ONI) monthly SST anomalies over the Niño 3.4 region were obtained from the National Weather Service Climate Prediction Center of the NOAA, https://origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml, accessed on 1 February 2020 for the period 1977 to 2018.

2.2. Standard Precipitation Index (SPI)

SPI was developed to detect, calibrate, quantify, and monitor drought using long-term precipitation data sets [22]. SPI is normalized so that wetter and drier climates of different time scales can be represented simultaneously [23]. The duration of weeks or months and seasons can be used to apply this index to agricultural interests, and a longer duration of years can be used to apply this index to water supply and water management interests [24,25]. It has also been demonstrated in several studies in different regions of the world.

The SPI calculation method is as follows; the monthly precipitation is fitted to gamma distribution. The probability density function of Gamma distribution is defined as

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

for $x > 0$, where

$\alpha > 0$ α is a shape parameter;

$\beta > 0$ β is a scale parameter; and

$x > 0$ x is the precipitation amount.

$$\Gamma(a) = \int_0^{\infty} y^{\alpha-1} e^{-y} dy \tag{2}$$

$\Gamma(a)$ is the gamma function.

Fitting the distribution to the data requires alpha and beta to be estimated. The maximum likelihood function is given as follows:

$$\begin{gathered} \hat{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \\ \hat{\beta} = \frac{\overline{x}}{\hat{\alpha}} \end{gathered} \tag{3}$$

$$\text{where } A = \ln(\overline{x}) - \frac{\sum \ln(x)}{n} \tag{4}$$

n = number of precipitation observations.

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

$$G(x) = \int_0^x g(x)dx = \frac{1}{\hat{\beta\alpha}\Gamma\left(\hat{\alpha}\right)} \int_0^x x^{\hat{\alpha}-1} e^{-x/\hat{\beta}} dx \tag{5}$$

letting the equation $t = x/\hat{\beta}$ become

$$G(x) = \frac{1}{\Gamma\left(\hat{\alpha}\right)} \int_0^x t^{\hat{\alpha}-1} e^{-t} dt \tag{6}$$

since the gamma function is undefined for $x = 0$, and the precipitation distribution may be zero, so that the cumulative probability becomes:

$$H(x) = q + (1-q)G(x) \tag{7}$$

where q is the probability of zero. $H(x)$ is then transformed to a normal distribution with a zero mean and unit variance.

The solution of the above approach is as follows:

$$Z = SPI = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \tag{8}$$

for 0 < $H(x)$ < 0.5

$$Z = SPI = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \tag{9}$$

for 0.5 < $H(x)$ < 1.0

$$\text{where, } t = \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)} \tag{10}$$

for 0 < $H(x)$ < 0.5

$$t = \sqrt{\ln\left(\frac{1}{(1.0 - H(x))^2}\right)} \tag{11}$$

for 0.5 < $H(x)$ < 1.0

$c_0 = 2.515517$; $c_1 = 0.802853$; $c_2 = 0.010328$

$d_1 = 1.432788$; $d_2 = 0.189269$; $d_3 = 0.001308$

In this study, the SPI was computed at 4- and 12-month timescales using the "SPEI" package in R-statistical software. The index computation is simple and based on precipitation only as an input, and the outputs have multiple time scales of SPI. We defined a 4 month time-scale of SPI as SPI4 and a 12-month time-scale of SPI as SPI12 for summer and annual drought identification, respectively.

The threshold for indicating the severity of meteorological drought based on SPI was adopted [22]. First, the SPI4 and SPI12 data sets were interpolated using the inverse distance weighted (IDW) function [24]. Then, the interpolated maps were reclassified into different severity classes using the SPI threshold (Table 1). For example, the interpolated SPI4 of the months of September was reclassified because the SPI4 of September comprises the accumulated precipitation total of the rainfall received in June, July, August, and September, which is crucial to the significant cropping season in Nepal. Similarly, the interpolated SPI12 of the December months was reclassified because the SPI12 of December comprises the accumulated precipitation total of the rainfall from January to December, which is crucial for water resource planning.

Table 1. SPI classification thresholds based on the study by McKee et al. [22].

SPI Values	Drought Category
0 to –0.99	Mild drought
–1.00 to –1.49	Moderate drought
–1.50 to –1.99	Severe drought
–2.00 or less	Extreme drought

Time series of SPI for individual stations were obtained to determine the variation in SPI time length. Time series were also utilized to observe the variation in detecting the drought length of data sets. A typical drought year was detected from the average SPI time series analysis.

The nonparametric rank-based Mann-Kendall test (M.K.) was applied to assess the time series data [26,27]. Many researchers have used this method [25,28,29] to detect trends in climatic time series data in different regions of the globe.

3. Results

3.1. Trend Analysis of SPI4 and SPI12

The results of the individual station trend analysis of SPI4 and SPI12 were examined in different regions of Nepal, which are summarized in Figure 2a,b, and the SPI4 and SPI12 trends were identified using the MAKESENS Template [30], and the MAKESENS program was developed for detecting and estimating trends in the time series of annual values of atmospheric and precipitation concentrations by the Finnish Meteorological Institute depending on the Z value (positive, negative, and zero) of individual stations, which are shown in Figure 2a,b. The Mann-Kendall trend test identified increasing, decreasing, and no trends of SPI4 and SPI12 in different regions. Downward red triangles and upward blue triangles represent negative and positive trends, respectively. In contrast, small downward red and upward blue triangles represent negative and positive trends, and big triangles indicate significant trends. However, green circles indicate no trends.

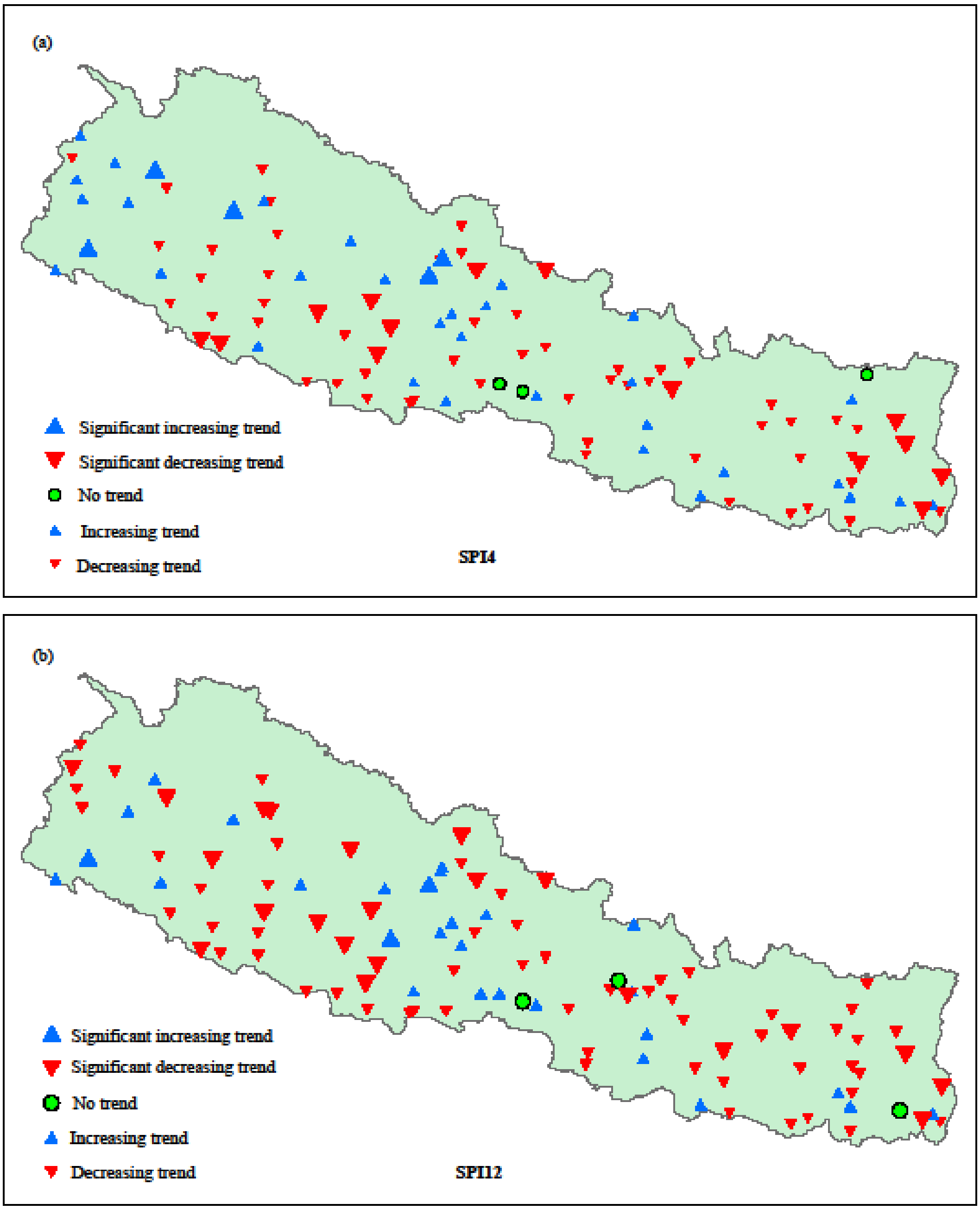

Figure 2. Station-wise (**a**) summer and (**b**) annual trends over Nepal.

For SPI4 among the 107 stations, 14 stations showed a significant decreasing trend, and five stations showed a significant increasing trend. Among the 14 significant decreasing trends, 3 were recorded in western, 5 in central, and 6 in eastern Nepal.

Similarly, for SPI12, 22 stations showed a significant decreasing trend, and three stations showed a significant increasing trend. Among the 22 significant decreasing trends, 8 were recorded in the western region, 8 in the central region, and 6 in the eastern region of Nepal, respectively. In summary, for SPI4 and SPI12, negative trends seem to be more common for Nepal's eastern region than the central and western regions of Nepal.

3.2. Temporal Variability of SPI4 and SPI12

We applied stations' average monthly precipitations to generate the temporal pattern for SPI4 and SPI12, which is depicted in Figure 3a,b. Summer drought seasons were identified based on the SPI4 intensity. A season is defined as a drought season when the SPI thresholds are <−1. The seasons are categories for the severity of the drought that depend on threshold values. They are shown in Table 1. Among 42 summer seasons, the eight summer drought years are 1977, 1979, 1982, 1992, 2005, 2006, 2009, and 2015 (Figure 3a). The SPI4 intensity is below 0 in 19 cases, and above for 23 cases. The magnitude of SPI4 was about −1.96 in 1992, and followed in 2015 at about −1.85.

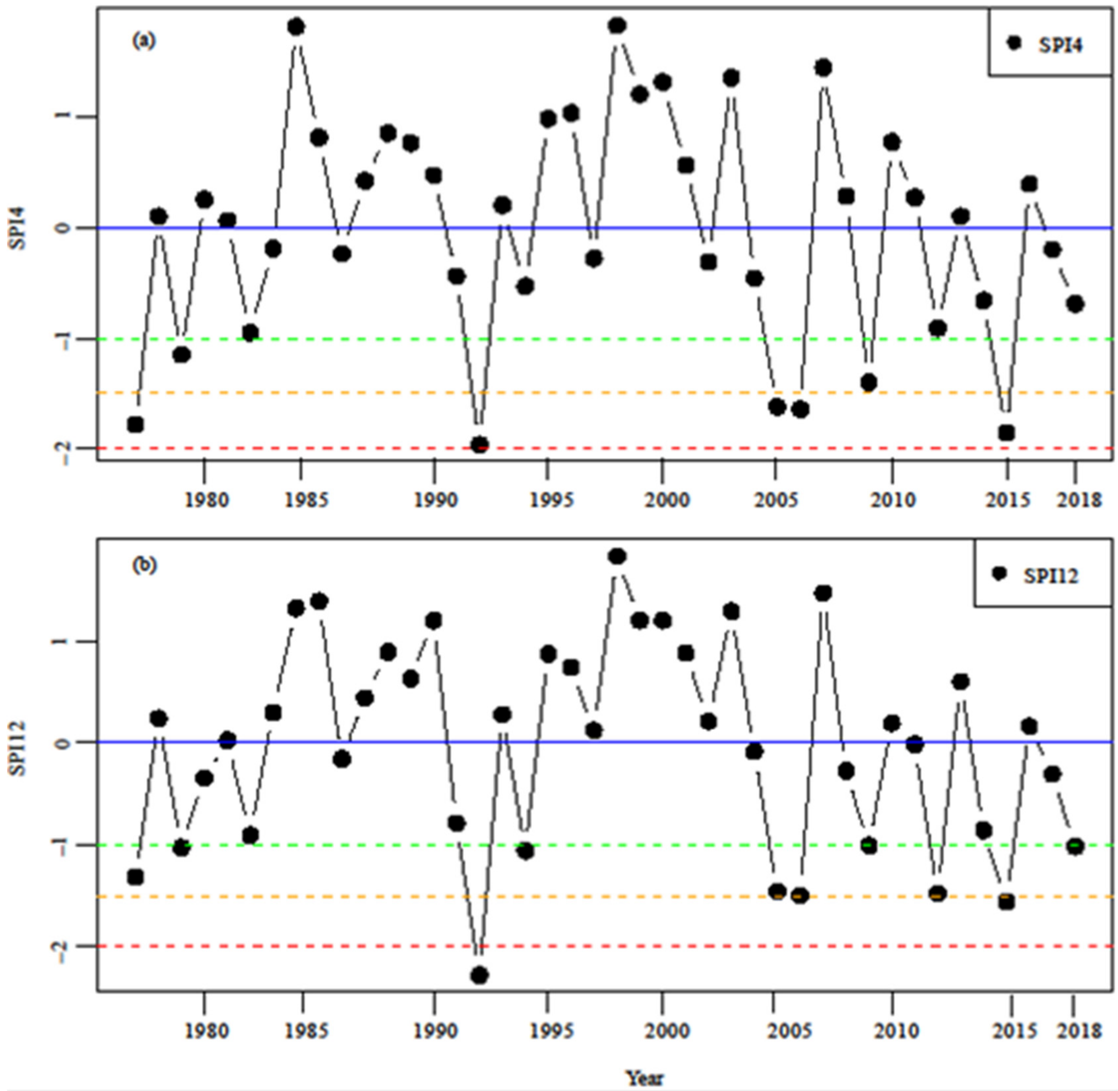

Figure 3. Temporal variability of SPI for (**a**) summer (SPI4), (**b**) annual (SPI12).

Similarly, the annual drought years were identified based on the SPI12 intensity. Based on the threshold value of Table 1, the 10 identified drought years were (1977, 1979, 1992, 1994, 2005, 2006, 2009, 2012, 2015, and 2018) (Figure 3b). The precipitation deficits were observed for 19 cases, and in excess for 23 cases. The magnitude of SPI12 ranges from −2.28 in 1992 and 1.83 in 1998. Analyzing both time-scales of SPI4 and SPI12, we have identified that most of the drought years coincide between the time-scales. The region behind this can be the weightage of summer precipitation which the annual one follows.

3.3. Spatial Distribution of Worst Drought Events

Based on the drought magnitude for both SPI4 and SPI12, 8 summer drought years and 10 annual drought years were identified (Tables 2 and 3). The two most widespread summer drought years were 1992 and 2015, where larger areas were affected by drought severities. In those years, the central region of Nepal was affected more than the eastern and western regions of Nepal.

Table 2. Summer drought severities based on stations' proportions expressed in percentages in different years.

Rank	SPI4 Values	Year	Extreme	Severe	Moderate	Mild
1	−2.0	1992	7.5	11.2	25.2	41.1
2	−1.9	2015	9.7	10.7	25.2	38.8
3	−1.8	1977	11.3	10.3	18.6	37.1
4	−1.6	2006	7.5	10.3	15.9	42.1
5	−1.6	2005	4.7	8.4	15.9	48.6
6	−1.4	2009	6.5	3.7	15.0	57.0
7	−1.2	1979	14.4	6.7	7.7	39.4
8	−1.0	1982	3.8	2.9	16.2	44.8

Table 3. Annual drought severities based on stations' proportions expressed in percentages in different years.

Rank	SPI12 Values	Year	Extreme	Severe	Moderate	Mild
1	−2.3	1992	8.4	22.4	24.3	36.4
2	−1.6	2015	6.8	8.7	23.3	37.9
3	−1.5	2006	6.5	9.3	12.1	51.6
4	−1.5	2012	8.5	11.3	17.9	40.6
5	−1.5	2005	4.7	8.4	15.9	40.2
6	−1.3	1977	8.2	10.3	11.3	36.1
7	−1.1	1994	2.8	10.3	16.8	41.1
8	−1.03	1979	7.7	4.8	16.3	36.5
9	−1.02	2018	5.1	12.2	11.2	41.8
10	−1.01	2009	4.7	2.8	16.8	46.7

For SPI4 in the year 1992, no drought condition was observed over some regions of northwestern Nepal and for a few areas of the eastern mountain. For this year, moderate drought dominated from the central to eastern–southern parts, while during 2015, moderate drought dominated over mid-west and central Nepal. Approximately 8 and 10 percent of the stations were affected by extreme drought conditions in 1992 and 2015. About 11 percent of stations were affected by severe, and around 25 percent of the stations were affected by moderate drought conditions for SPI4 in the years 1992 and 2015 (Figure 4a,c). More than 76 percent of stations had negative SPI4 values; thus, large parts of Nepal faced the precipitation deficit in both worst years.

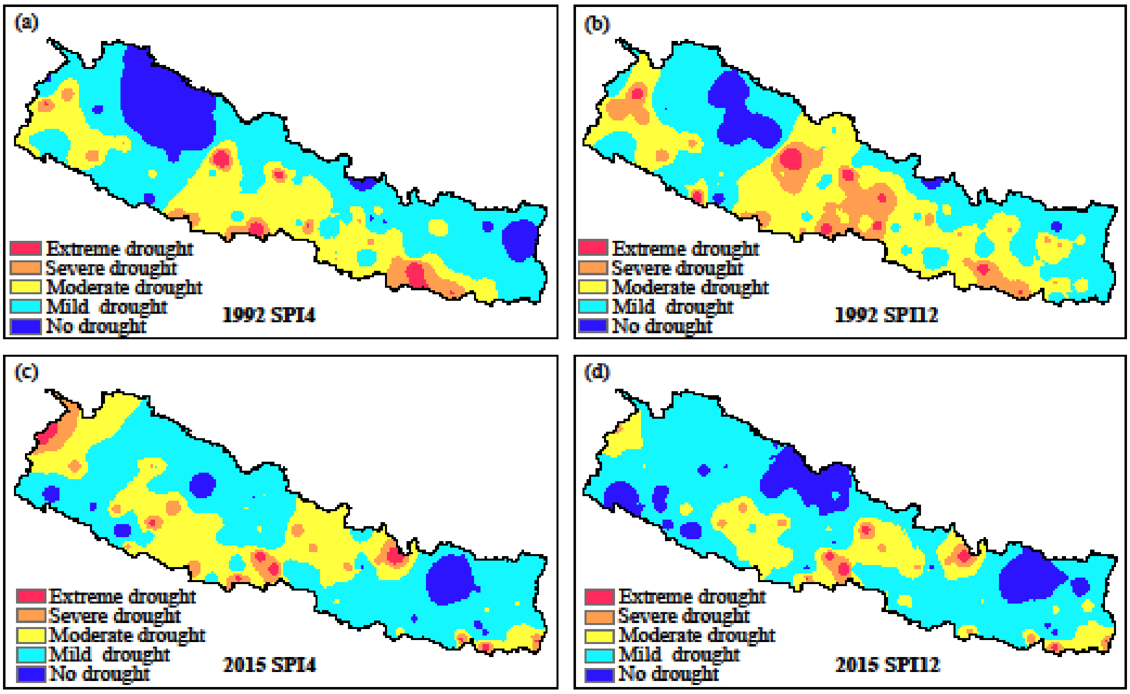

Figure 4. Spatial distributions of (**a**) SPI4 of 1992, (**b**) SPI12 of 1992, (**c**) SPI4 of 2015, and (**d**) SPI12 of 2015.

Similarly, for SPI12 during the drought years of 1992 and 2015, larger areas of the central region were affected by dry conditions. In the year 1992, the central region was highly affected by the dryness than the 2015. Almost the entire area was dominated by drought conditions, except a certain region of northwestern Nepal in 1992. About 93 and 78 percent of stations recorded negative values of SPI12 in 1992 and 2015, respectively (Figure 4b,d). Therefore, large areas of Nepal faced a precipitation deficit.

3.4. Spatial Distribution of Other Major Summer Drought Events

The spatial variation of severities of summer drought events was uniquely different among the different drought categories. The severities of drought are clearly shown in Figure 5a–f. The mean SPI4 intensity of the summer drought years ranked from 3rd to 8th ranges from −1.78, to −1.

In the year 1977, a large area in the lower belts of the eastern region and mid-mountain areas were more affected by the summer drought than the central and the western regions of Nepal (Figure 5a). In the year 2006, the central region was affected more by the severe and moderate drought conditions than any of the other regions. Similarly for the year 2005, the central region of Nepal was highly affected by extreme drought and followed in the upper parts of the mountains of western Nepal; however, low lands of Nepal were rarely affected. In 2009, drought shifted to the lower regions of Nepal. However, the central high mountain and the mid belt of the eastern region were affected. In 1979, the only western region of Nepal was affected by dryness; however, the eastern regions of Nepal had no drought situation. During 1982, the eastern regions were mainly affected by extreme, severe, and moderate drought conditions, but the central and western regions of Nepal were in normal conditions. Drought events during different years for SPI4 with the percent coverage are tabulated in Table 2.

3.5. Spatial Distribution of Other Major Annual Drought Events

For SPI12, the 3rd to 10th ranks of drought mean intensity varies from −1.5 to −1.01 (Table 3). The spatial variation of drought severities is shown in Figure 6a–h. In the drought year 2006, drought was randomly affected in Nepal. However, the lower belts of Nepal were more affected by drought severities than high lands. The eastern region recorded the drought in larger areas than the central and western regions of Nepal in the drought year 2012. About 30 percent of the country was affected by drought severities in 2005 and 1977. The western region of Nepal was highly affected by extreme, severe, and moderate drought than the central and eastern regions of Nepal in the year 2005. In 1994, the central region of Nepal had normal conditions, but the low land of the eastern and the western regions of Nepal were highly affected. For the year 2018, the eastern region of Nepal was more affected, following the central region of Nepal. However, the western region of Nepal had a usual condition. In 2009, small areas of the lower belt of Nepal were affected by higher drought severities instead of the large areas of Nepal that were affected by mild drought. There was no drought in the far western regions of Nepal in the year 2009. The details of drought categories during different years for SPI12 with the percent coverage are tabulated in Table 3.

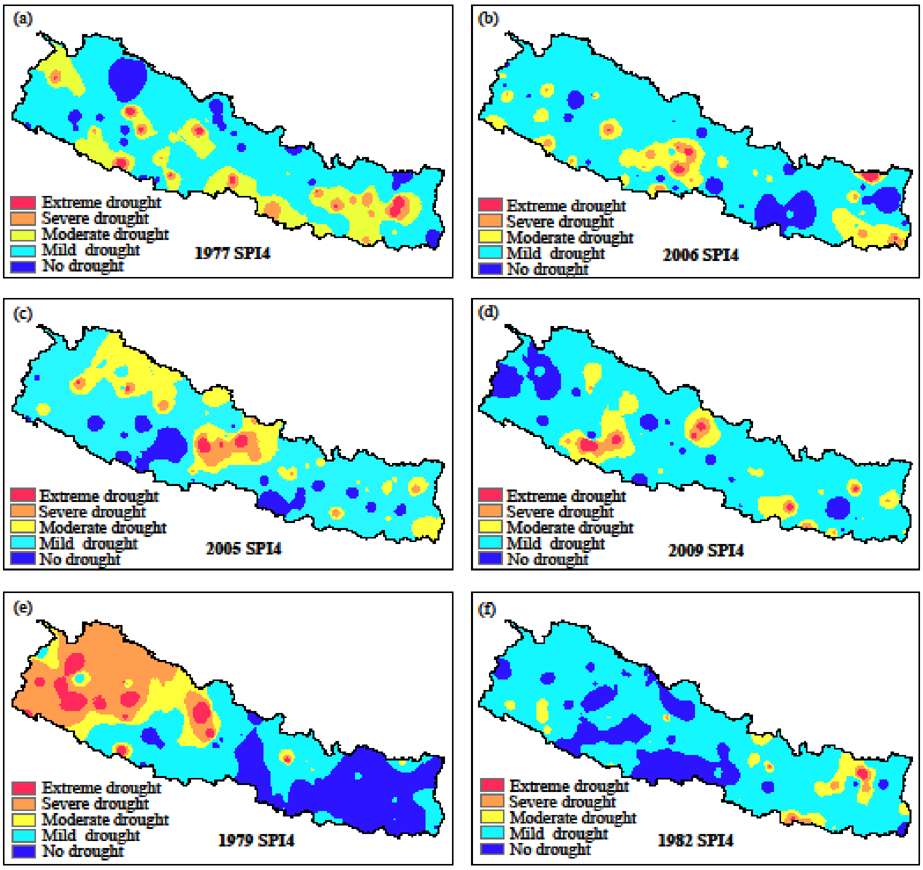

Figure 5. Spatial distributions of (**a**) summer (SPI4) of 1977, (**b**) summer (SPI4) of 2006, (**c**) summer (SPI4) of 2005, (**d**) summer (SPI4) of 2009, (**e**) summer (SPI4) of 1979, and (**f**) summer (SPI4) of 1982.

3.6. Relationship between SPI and Climate Indices

This study used the SOI and ONI index to show the relationship with summer and annual SPI. The SOI and ONI index measure large-scale fluctuations in sea level pressure and temperature over region 3.4. Similar studies have been conducted around the globe [31].

The comparison between the SPI4 and the summer SOI series shows that there were 32 events (76.17%) phase relation (positive/negative SOI, positive/negative SPI4), and 10 (23.81%) events show the in-phase relationship in Figure 7a. The correlation coefficient between SPI4 and summer SOI was 0.52 at a 95 percent confidence level. Thus, SPI4 and the summer SOI series are highly correlated. Generally, during the drought/flood period, SOI and the SPI are (−/+), which is stronger than the usual years. Generally, during the drought years (El Niño and non- El Niño years), low summer SOI and negative summer SPI in Nepal are in phase relations on warm phase periods. Deficit/excess conditions from the above-mentioned relationship between SPI4 and summer SOI results; the SPI4 is influenced from the summer SOI.

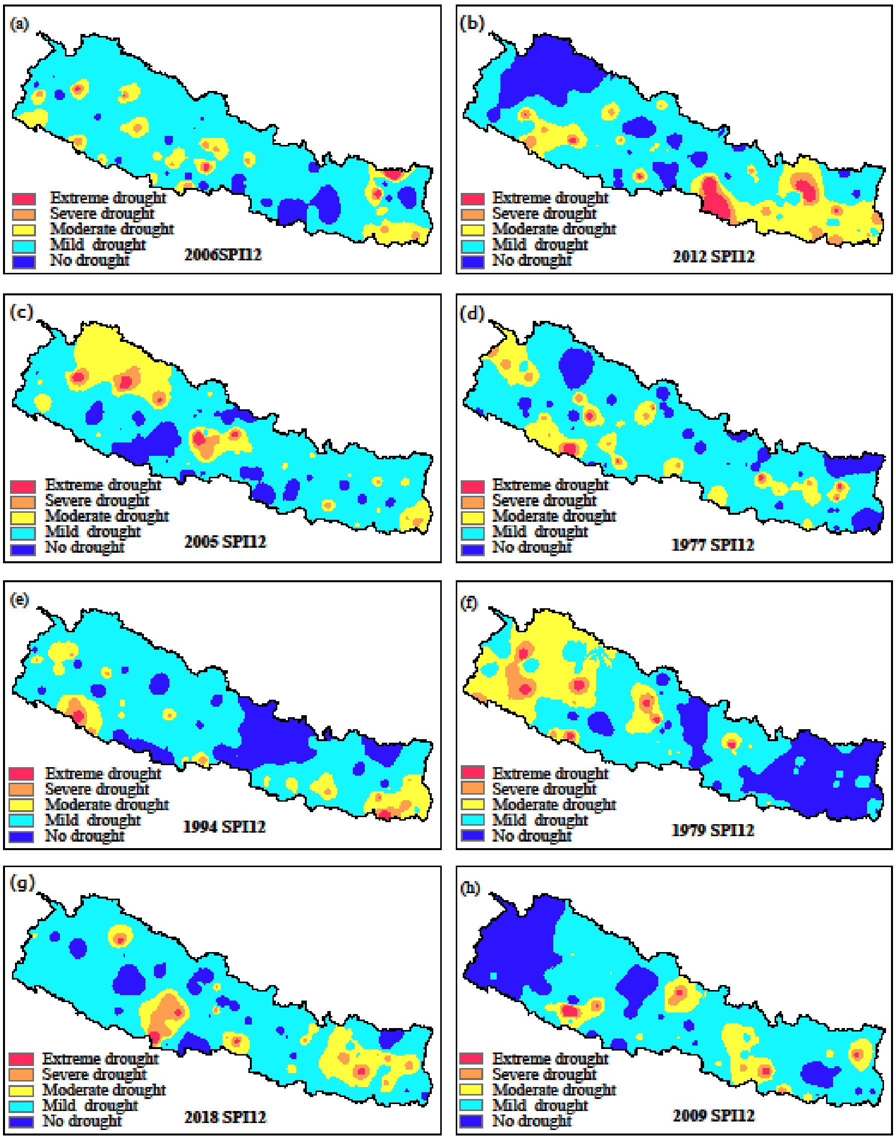

Figure 6. Spatial distributions of (**a**) annual (SPI12) of 2006, (**b**) annual (SPI12) of 2012, (**c**) annual (SPI12) of 2005, (**d**) annual (SPI12) of 1977, (**e**) annual (SPI12) of 1994, (**f**) annual (SPI12) of 1979, (**g**) annual (SPI12) of 2018, and (**h**) annual (SPI12) of 2009.

Similarly, a comparison between SPI12 and annual SOI analysis indicates that there were 21 events (about 50%) and the phase relation (positive/negative annual SOI, positive/negative SPI12) is clearly shown in Figure 7b. Among the 21 events, 10 events (47.62%) were in deficit and 11 events (52.38%) were in excess. The correlation between SPI12 and annual SOI is 0.14 at a 95% confidence level. The deficit/excess condition shows that the SPI12 series is influenced from the annual SOI. However, during the drought/flood period, annual SOI and the SPI12 are stronger (−/+)than the usual years.

The summer drought years were also further linked with ONI (El Niño and La Niña episode) which was extracted from https://origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml, accessed on 1 February 2020. The El Niño and La Niña years are tabulated in Table 4.

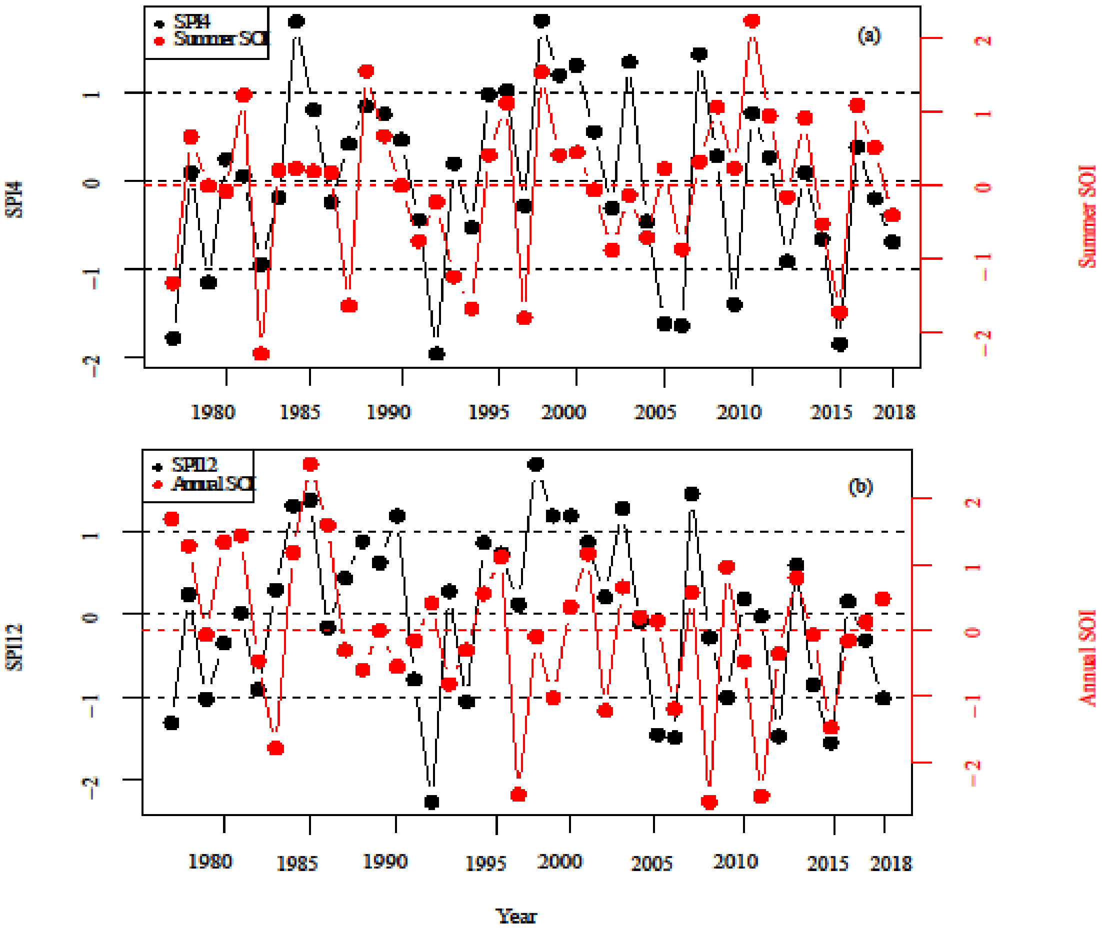

Figure 7. Relationship between SPI and SOI: (**a**) summer, (**b**) annual.

Table 4. The El Niño and La Niña years from 1977 to 2018.

Condition	Years
El Niño	1982, 1983, 1987, 1991, 1992, 1997, 1998, 2002, 2004, 2009, 2015, 2016
La Niña	1985, 1988, 1989, 1995, 1998, 1999, 2000, 2007, 2008, 2010, 2011, 2016

There were eight excess rainfall years in Nepal that coincided with La Niña years. Out of eight summer drought years in Nepal, four years coincided with El Niño years and the other four drought years were marked in non-El Niño years.

4. Discussions

The trend analysis of SPI4 and SPI12 showed a decreasing trend over most of the stations, which indicates the increasing drought frequency. The negative trends are steady for both time-scales among a majority of the stations, which was caused because monsoon (4 months JJAS) rainfall dominated the annual. The results are consistent with the Ref. [18].

Our results depict the fact that the frequency and intensity of drought events increased in recent years. For SPI12, we have identified 10 major years, while for SPI4, 8 major drought years were identified. The result is similar to the findings presented by previous researchers [15] during the summer drought years of 1977, 1982, 1991, and 1992. Furthermore, the study by the Refs. [15,32] indicates the deficit years based on precipitation were 1957, 1972, 1977, 1982, and 1992 in Nepal.

Drought severities depend on the intensity of SPI4 and SPI12. Eight summer droughts and ten annual drought events have been revealed, and each drought event has unique SPI dynamics. There has been no similar drought pattern over Nepal in drought events over the past four decades. The spatial variation of SPI4 and SPI12 indicates that every drought episode has different severities (extreme, severe, moderate, and mild drought) with differences in SPI intensities.

The areas of Nepal affected by the average extreme, severe and moderate summer drought were 8, 9, and 18 percent on summer drought events over the study period. Similarly, the areas of Nepal affected by the average extreme, severe and moderate annual drought were 7, 11, and 17 percent on annual drought events. Previous researchers [16] noticed that the average extreme, severe, and moderate annual droughts were 5, 5, and 9 percent concerning SPI12 over the period (1971–2003). A slight difference can be observed in between the severities in this study. The reason behind this is that in recent years, the worst drought events happened more frequently. On average, mild drought covered 42 percent in summer and 40 percent in annual drought events. On average, Nepal's dry areas were found to be 77 percent in summer events and 75 percent in annual drought events.

The monsoon rainfall variability of Nepal is influenced by local effect, the regional circulation system, and large-scale circulation from the Indian and Pacific Ocean. Strengthening/weakening of the rainfall pattern has been identified and correlated with La Niña/El Niño years. The analysis revealed a relationship between the SPI4 and SPI12 with large-scale climate indices. Among them, SPI4 is well-correlated with SOI above a 95 percent confidence level. Previous researchers were concerned with the relationship between SPI3 and SPI12 time-scales with summer and annual SOI [16]. Similarly, the Refs. [15,32] focused on the relationship between summer rainfall of Nepal and SOI. The extensive circulation system affects the monsoon rainfall during the La Niña and El Niño episodes more than the average years. The drought events on El Niño years and non-El Niño years were strongly related between SPI and SOI than the average years. The relationship between SPI and the climate indices such as the SOI and ONI anomaly over the Niño 3.4 has suggested that one of the causes for summer droughts is El Niño.

This study indicated that summer droughts occurred in both El Niño and non-El Niño years. Out of eight drought years, only four drought years were associated with El Niño episodes (1982,1992, 2009, and 2015), and the remaining four drought years (1977,1979, 2005, and 2006) were recorded in non-El Niño years. Similarly, annual droughts evolved in El Niño and non-El Niño years. Out of 10 drought years, only 3 drought years were associated with El Niño years (1992, 2009, and 2015) and 7 drought years (1977,1979, 1994, 2005, 2006, 2012, and 2018) were recorded in non-El Niño years. Each drought event also had distinct SPI dynamics.

South Asian countries have recently been experiencing frequent drought incidents, and the Standardized Precipitation Index (SPI) has mostly been adopted in South Asian countries to quantify and monitor droughts [33]. Khatiwada and Pandey [34] identified that the SPI is focused foremost on capturing the duration and intensity of drought in the Karnali river basin, Nepal. Using SPI from 1951–2015 over India, the analysis revealed that of the 34 met sub-divisions, 16 sub-divisions during the annual and monsoon season were drought-prone and showing high negative SPI values [35]. Similarly, the occurrence of drought with negative SPI values is frequent in West Bengal districts in India with increasing dry events and decreasing wet and normal events [36]. The present study also showed similar patterns of SPI as aforementioned studies. El Niño alone is not to be blamed for droughts in India. A total of 10 out of 23 droughts that India witnessed have occurred during years when El Niño was absent [37]. The current study is consistent with their findings too.

Nepal has experienced consecutive and worsening drought conditions in a severe drought episode during 2005–2006. These events were one of the most challenging events for the mountainous country Nepal for agriculture practices and water resource management. Since drought directly affects crops leading to economic losses, countries like Nepal, where people are primarily dependent on rain-fed agriculture for their livelihoods, are very vulnerable due to drought [38]. The livelihoods of around 60 percent of the total Nepalese population are directly dependent on agriculture [39]. Extreme droughts negatively impact both cash and cereal crops [40]. Therefore, impact assessment studies of drought events are essential. These outputs help make decisions for water resource management and water allocations for mitigating the impacts of drought.

5. Conclusions

This study provided concise knowledge about the temporal and spatial variability of meteorological droughts using a SPI4 time-scale and SPI12 time-scale over Nepal during the past four decades (1977–2018). Among the drought events, 1992 was the worst summer and annual drought year, followed by 2015. Extreme drought events of 1992 and 2015 indicated more drought signals in the central region than any other regions of Nepal. Most of the study sites show a negative trend for SPI4 and SPI12, which indicates the drought episodes are increasing and being more frequent.

In the last four decades, the drought events in Nepal indicated extreme, severe, moderate, and mild categories with reference to the intensity. The obtained proportional weightages of summer drought severities for extreme, severe, and moderate drought were 8, 9, and 18 percent, respectively. Similarly, the obtained proportional weightages of annual drought severities for extreme, severe, and moderate drought were 7, 11, and 17 percent, respectively. All drought categories were more highly affected in the western and central regions than the eastern region of Nepal, with some exceptions.

The relationship of SOI with SPI is strong in summer (SPI4) and weak in annual (SPI12). This study revealed that summer droughts were recorded both in El Niño and non-El Niño years. During eight summer drought years, only four drought years were associated with El Niño episodes.

The study's findings can help make decisions for water resource management and water allocations for mitigating the impact of droughts. It is also beneficial to the researchers to study climate change in Nepal and the sustainable development of regional water resources.

Author Contributions: Conceptualization, D.B., D.A. and M.S.; Data analysis and original draft preparation, D.B.; Review and editing, M.S.; Supervision, D.A.All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Nepal Government's Department of Hydrology and Meteorology is acknowledged for providing observed rain gauge data, and University Grant Commission, Kathmandu Nepal for financial support (U.G.C. Award No: PhD-75/76-S&T-11) was provided to the first author. Climate index data were taken from the National Oceanic and Atmospheric Administration (NOAA).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wilhite, D.A.; Glantz, M.H. Understanding: The Drought Phenomena: The role of Defintions. *Water Int.* **1985**, *10*, 111–120. [CrossRef]
2. Hagman, G.; Beer, M.; Wijkman, A. *Prevention Better Than Cure: Report on the Human and Natural Disasters in the Third World*; Swedish Red Cross: Stockholm, Sweden, 1984.
3. Wilhite, D.A.; Svoboda, M.D.; Hayes, M.J. Understanding the complex impacts of drought: A key to enhancing drought mitigation and preparedness. *Water Resour. Manag.* **2007**, *21*, 763–774. [CrossRef]
4. Wilhite, D.A. *Chapter 1 Droughts as a Natural Hazard; Concepts and Definations*; Drought Mitigation Center Faculty Publications; University of Nebraska-Lincoln: Lincoln, NE, USA, 2000; pp. 1–22. Available online: http://digitalcommons.unl.edu/droughtfacpub/69 (accessed on 5 December 2020).

5. Sheffield, J.; Wood, E.F. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Clim. Dyn.* **2008**, *31*, 79–105. [CrossRef]
6. Mishra, A.K.; Singh, V.P. A review of drought concepts. *J. Hydrol.* **2010**, *391*, 202–216. [CrossRef]
7. World Meteorological Organization (WMO). *Standard Precipitation Index User Guide*; WMO-No. 1090; WMO: Genava, Switzerland, 2012; 16p, ISBN 978-92-63-11-0-91-6.
8. Sikka, D. Some aspects of the large scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary and regional scale circulation parameters. *Indian Acad. Sci. Earth Planet Sci.* **1980**, *89*, 179–195. [CrossRef]
9. Moleey, D.A.; Parthasarathy, B. Variability of the Indian Monsoon and Tropical Circulation Features. *J. Mon. Weather Rev.* **1983**, *111*, 967–978. [CrossRef]
10. Krishnamurthy, V.; Goswami, B.N. Indin Monsoon-ENSO Relationship on Interdecadal Time Scale. *J. Clim.* **2000**, *17*, 579–595. [CrossRef]
11. Kripalani, R.H.; Kulkarni, A. Assessing the Impacts of El Niño and Non-El Niño-Related Droughts over India Assessing the Impacts of El Niño and Non-El Niño-Related Droughts over India. *Drought Network News (1994–2001)*. 1996, p. 24. Available online: https://digitalcommons.unl.edu.droughtnews/24 (accessed on 1 December 2020).
12. Varikoden, H.; Revadekar, J.V.; Choudhary, Y.; Preethi, B. Droughts of Indian summer monsoon associated with El Niño and Non-El Niño years. *Int. J. Climatol.* **2015**, *1925*, 1916–1925. [CrossRef]
13. Bhalme, H.N.; Jadhav, S.K. The southern Oscillation and its relation to the monsoon rainfall. *J. Climatol.* **1984**, *4*, 509–520. [CrossRef]
14. Ichiyanagi, K.; Yamanaka, M.D.; Muraji, Y.; Vaidya, B.K. Precipitation in Nepal Between 1987 to 1996. *Int. J. Climatol.* **2007**, *27*, 1753–1762. [CrossRef]
15. Shrestha, M.L. Interannual variation of Summer monsoon rinfall over Nepal and its relation to Southern Oscillation Index. *Meteorol. Atmos. Phys.* **2000**, *75*, 21–28. [CrossRef]
16. Sigdel, M.; Ikeda, M. Spatial and Temporal Analysis of Drought in Nepal Using Standrdized Precipitation Index and its Reltionship with Climate Indices. *J. Hydrol. Meteorol.* **2010**, *7*, 59–74. [CrossRef]
17. Wang, S.Y.; Yoon, J.H.; Gillies, R.R.; Cho, C. What caused the winter drought in western Nepal during recent years? *J. Clim.* **2013**, *26*, 8241–8256. [CrossRef]
18. Dahal, P.; Shrestha, N.S.; Shrestha, M.L.; Krakauer, N.Y.; Panthi, J.; Pradhanang, S.M.; Jha, A.; Lakhankar, T. Drought risk assessment in central Nepal: Temporal and spatial analysis. *Nat. Hazards* **2016**, *80*, 1913–1932. [CrossRef]
19. Shrestha, N.K.; Qamer, F.M.; Pedreros, D.; Murthy, M.S.R.; Wahid, S.M.; Shrestha, M. Evaluating the accuracy of Climate Hazard Group (CHG) satellite rainfall estimates for precipitation based drought monitoring in Koshi basin, Nepal. *J. Hydrol. Reg. Stud.* **2017**, *13*, 138–151. [CrossRef]
20. Kafle, H.K. Spatial and Temporal Variation of Drought in Far and Mid Western Regions of Nepal: Time Series Analysis (1982–2012). *Nepal J. Sci. Technol.* **2015**, *15*, 65–76. [CrossRef]
21. Myronidis, D.; Nikolaos, T. Changes in climatic patterns and tourism and their concomitant effect on drinking water transfers into the region of South Aegean, Greece. *Stochastic Environ. Res. Risk Assess.* **2021**, *35*, 1725–1739. [CrossRef]
22. McKee, T.B.; Doesken, N.J.; Kleist, J. The relationship of Drought Frequency and Duration to Time Scales. In Proceedings of the Eighth Conference on Applied Climatology, Anaheim, CA, USA, 17–22 January 1993; p. 6.
23. Hayes, M.J.; Svoboda, M.D.; Wilhite, D.A.; Vanyarkho, O.V. Monitoring Drought Using the Standardized Precipitation Index. In *Bulletin of the American Meteorological Society*; University of Nebraska-Lincoln: Lincoln, NE, USA, 1999; Volume 80, pp. 429–438. [CrossRef]
24. Patel, N.R.; Chopra, P.; Dadhwal, V.K. Analyzing spatial patterns of meteorological drought using stndard precipitation index. *Meteorol. Appl.* **2007**, *14*, 329–336. [CrossRef]
25. Di Lena, B.; Vergni, L.; Antenucci, F. Analysis of drought inthe region of bruzzo (central Italy) by the standarized Precipitation Index. *Theor. Appl. Climatol.* **2014**, *115*, 41–52. [CrossRef]
26. Kendall, S. Enhancement of Conditional Reinforcement by uncertainty. *J. Exp. Anal. Behav.* **1975**, *24*, 311–314. [CrossRef]
27. Mann, H.B. Nonparametric tests against trend. *J. Econom. Soc.* **1945**, *13*, 245–259. Available online: http://www.jstor.org (accessed on 12 May 2020). [CrossRef]
28. dos Santos, S.R.Q.; Braga, C.C.; Sansigolo, C.A.; de Araujo Tiburtino Neves, T.T.; dos Santos, A.P.P. Droughts in the Amazon: Identification, Characterization and Dynamical Mechanisms Associated. *Am. J. Clim. Chang.* **2017**, *6*, 425–442. [CrossRef]
29. Nouri, M.; Homaee, M. Drought trend, frequency and extremity across a wide range of climates over Iran. *Meteorol. Appl.* **2020**, *27*, e1899. [CrossRef]
30. Salmi, T.; Matta, A.; Anttila, P.; Ruoho-Airolo, T.; Amnell, T. *Detecting Trends Annul Values of Atmospheric Pollutants by the Mann-Kendall Test and Sen's Slope Estimates—The Excel Template Application MAKESENS*; Finnish Meteorological Institute: Helsinki, Finland, 2002.
31. Myronidis, D.; Fotakis, D.; Ioannou, K.; Sgouropoulou, K. Comparison of ten notable meteorological drought indices on tracking the effect of drought on streamflow. *Hydrol. Sci. J.* **2018**, *63*, 2005–2019. [CrossRef]
32. Shrestha, A.B.; Wake, C.P.; Dibb, J.E.; Mayewski, P.A. Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatology parameters. *Int. J. Climatol.* **2000**, *20*, 317–327. [CrossRef]

33. Chandrasekara, S.S.K.; Kwon, H.-H.; Vithanage, M.; Obeysekera, J.; Kim, T.-W. Drought in South Asia: A Review of Drought Assessment and Prediction in South Asian Countries. *Atmosphere* **2021**, *12*, 369. [CrossRef]
34. Khatiwada, K.R.; Pandey, V.P. Characterization of hydro-meteorological drought in Nepal Himalaya: A case of Karnali river basin. *Weather Clim. Extrem.* **2019**, *26*, 100239. [CrossRef]
35. Nandargi, S.S.; Aman, K. Computation of the Standardized Precipitation Index (Spi) for Assessing Droughts over India. *Int. J. Curr. Adv. Res.* **2017**, *6*, 8545–8557. [CrossRef]
36. Bhunia, P.; Das, P.; Maiti, R. Meteorological Drought Study through SPI in Three Drought Prone Districts of West Bengal, India. *Earth Syst. Environ.* **2019**, *4*, 43–55. [CrossRef]
37. Borah, P.J.; Venugopal, V.; Sukhatme, J.; Muddebihal, P.; Goswami, B.N. Indian monsoon derailed by a North Atlantic wavetrain. *Science* **2020**, *370*, 1335–1338. [CrossRef]
38. Gentle, P.; Maraseni, T.N. Climate change, poverty and livelihoods: Adaptation practices by rural mountain communities in Nepal. *Environ. Sci. Policy* **2012**, *21*, 24–34. [CrossRef]
39. Central Bureau of Statistics. *National Sample Census of Agriculture Nepal 2011/12*; National Report; Government of Nepal, National Planning Commission Secretariat, Central Bureau of Statistics: Kathmandu, Nepal, 2013; p. 114.
40. Revadekar, J.V.; Preethi, B. Statistical analysis of the relationship between summer monsoon precipitation extremes and food grain yield over India. *Int. J. Climatol.* **2012**, *32*, 419–429. [CrossRef]

Journal of Institute of Science and Technology, 28(1), 11-24 (2023)
ISSN: 2467-9062 (print), e-ISSN: 2467-9240
https://doi.org/10.3126/jist.v28i1.43452

Research Article

INFLUENCE OF SOUTHERN OSCILLATION INDEX ON RAINFALL VARIABILITY IN NEPAL DURING LARGE DEFICIENT MONSOON YEARS

Damodar Bagale*, Madan Sigdel, Deepak Aryal
Central Department of Hydrology and Meteorology, Tribhuvan University, Kathmandu 44613, Nepal
** Correspondence: damu.bagale@gmail.com*
(***Received***: *March 02, 2022;* ***Final Revision***: *March 01, 2023;* ***Accepted***: *March 19, 2023)*

ABSTRACT

The study was conducted using rainfall time-series data for 42 years from 1977 to 2018.We have identified seven large monsoon deficient years. Among these years, 1992, 2009, and 2015 consisted of El Niño episodes which quantify significant rainfall deficits 19.29, 13.6, and 17.59 % respectively from an average rainfall. With some exceptions, all El Niño years observed deficit rainfall. On El Niño years averaged deficit rainfall was approximately nine percent below than the average monsoon rainfall. The eastern region observed the large deficient monsoon years frequently than the central and western regions of Nepal. The central region recorded large spatial variability of average summer rainfall ranging from less than 200 mm/months in lesser Himalayans to more than 3,000 mm/months in mid-mountainous region. The western region had observed a large deficient summer monsoon anomaly 45 % in the year 1979. Similarly, the central region had 31 % deficient summer monsoon anomalies in 1992, and the eastern region observed 25 % deficient anomalies in 1982. There was a strong correlation between the Nepal Summer Monsoon Rainfall (NSMR) and Southern Oscillation Index (SOI). Generally, large negative/positive magnitude of SOI on the Indian and Pacific Ocean has link to weakening/strengthening NSMR.

Keywords: Anomalies, deficit monsoon years, El Niño, Nepal

INTRODUCTION

The Asian monsoon circulation system of the annual cycle has been divided into two different wet and dry phases, which undergo a periodic and high amplitude variation on intra-seasonal, annual and inter-annual timescales (Webster *et al*., 1998). The active and break period of the monsoon is characterized by precipitation maxima and minima over South-Asia (Ramanadham *et al*., 1973). The atmosphere is highly complex, and it cannot be expected that the Southern Oscillation could account for most of the monsoon variability (Bhalme and Jadhav, 1984). Although large positive/negative value of SOI signifying strengthening/weakening of the Walker circulation coincides with a large excess/deficient monsoon rainfall in India (Rasmusson and Carpenter, 1983; Bhalme and Jadhav, 1984). Generally, there is a good correlation between a large negative/positive value of SOI and droughts/floods in India, however, there are some exceptions unexplained by the SOI (Mooley and Parthasarathy, 1983; Bhalme and Jadhav, 1984). The Southern Oscillation has an irregular period, ranging from 2 to 6 years, usually averaging between 2 and 3 years (Wright, 1975; Trenberth, 1976; Fredriksen *et al*., 2020). During the El Niño year in India there is a strong tendency for a below-normal Indian monsoon rainfall over most parts of India (Sikka, 1980; Varikoden *et al*., 2015; Bhalme and Jadhav, 1984). Similarly, during the El Niño/La Nina phenomena there is a good correlation between a large negative/positive value of SOI and droughts/floods in Nepal (Shrestha *et al*., 2000; Sigdel and Ikeda, 2012). El Niño Southern Oscillation (ENSO) develops the weaker monsoon rainfall in South Asian countries Nepal, India, Bangladesh, and Sri Lanka described in detail by the researchers (Shrestha *et al*., 2000; Varikoden *et al*., 2015; Chowdhury, 2003; Silva and Hornberger, 2019). The effect of ENSO and Indian Ocean Dipole (IOD) events on the rainfall variability is still undefined and unclear (Muangsong *et al*., 2014; Cherchi and Navar, 2013).The influence of SOI on monsoon rainfall over Myanmar was significant than the linkage with IOD (Sien *et al*., 2015). Similarly, the influence of SOI on monsoon rainfall over Nepal was more significant than the effect of IOD (Sigdel and Ikeda, 2012). Shrestha, (2000) identified that there is a strong correlation between SOI and summer rainfall over Nepal. Strong El Niño episodes develop to weaker monsoons and droughts in South Asian region (Fan *et al*., 2017). El Niño characterized by warming of surface temperatures in the Pacific Ocean, is associated with lower than normal monsoon rainfall in the South Asian region (Varikoden and Babu, 2015; Wang *et al*., 2020).

The record of the annual cycle of the monsoon system shows that most of the rainfall occur from June to September as the southwest Indian monsoon enters Nepal. Southeasterly circulation brings abundant rainfall (moisture) from the Bay of Bengal and occasionally from the Arabian Sea (Bohlinger *et al*., 2017). The winter season is dominated by westerly circulation originating from the Mediterranean Sea and Siberia (Kanskar *et al*., 2004). The influence of these two circulation systems is heterogeneously distributed over Nepal; summer rainfall greater in the central and eastern regions cause southeasterly and westerly derived winter rainfall most significant in the western region of Nepal (Kanskar *et al*., 2004). Moreover, Wang *et al*. (2013) studied the drought over the western region of Nepal to investigate the winter deficit rainfall. Rainfall is the only primary source of both surface and groundwater in Nepal. It is essential to understand large-scale atmospheric circulation system connections to monsoonal variability over Nepal from a socioeconomic aspect, such as drought risk, flood damage, effect on hydropower generation, and crop production practices.

Many studies had concentrated on rainfall variability in Nepal, (Kanskar *et al*., 2004; Ichiyanagi *et al*., 2007; Salerno *et al*., 2015; Karki *et al*., 2017; Shrestha *et al*., 2019; Sigdel and Ma, 2017; Pokharel *et al*., 2020). However, few authors have researched monsoon rainfall connecting with large-scale atmospheric circulation (Shrestha *et al*., 2000; Sigdel and Ikeda, 2012; Sharma *et al*., 2020). Shrestha *et al*. (2000) identified that strong El Niño episodes develop to weaker monsoons and deficit rainfall in Nepal. Sigdel and Ikeda, (2012) concluded main large-scale pattern influential on the monsoon rainfall variability was explained by ENSO as a significant correlation with SOI. Sharma *et al*. (2020) identified the year-to-year dominant variability of summer rainfall in Nepal which corresponds with ENSO. However, there is still a gap in identifying the large deficient monsoon years and its spatial variability relating with SOI across the country.

The main objective of this research is to investigate the large monsoon deficient years associated with El Niño and normal years during the last 42 years (1977-2018). Similarly, this research focused on rainfall variability in the western, central, and eastern regions during the monsoon period.

MATERIALS AND METHODS

Study Area

Nepal is a landlocked mountainous country situated in the central Himalayas of South Asian territory. The northern side is situated in Highland Tibet of China, and the remaining sides surround India. It extends from 80° 04' to 88° 12' E in longitude and 26° 22'to 30° 27' N in latitude (Sigdel and Ikeda, 2010). The country extends 885 km from east to west, varies from 130 km to 260 km in the North to the south (Karki *et al*., 2017), and covers 147516 sq. km (Shrestha *et al*., 2020).The complex topography of Nepal ranges from the low land of Terai 60 meters in south to Mount Everest 8848.86 m above sea level in the Himalayan region towards the North. The climate of Nepal is sub-tropical, with most of the rainfall concentrated in the monsoon season (Karki *et al*., 2015). We have further classified the country into the western, central, and eastern regions to identify the differences of the spatial variations of NSMR.

Data and Methods

Data (Methods of Data Collection)

The daily rainfall data of 107 weather stations acquired from the Department of Hydrology and Meteorology, Government of Nepal. Monthly total rainfall values were obtained by summing up daily rainfall data. Similarly, the annual total rainfall data were calculated by adding monthly total rainfall data from January to December, and for summer monsoon (June–September), total annual rainfall at each station was computed after completing the missing data. The distribution of the meteorological stations is shown in Fig.1. Available observed rainfall data covering the year between 1977 to 2018. Time range was determined by evaluating the records of the stations as possible as more stations. Annual, seasonal, and monthly means were calculated for all stations using the arithmetic mean method. The annual mean is averaged over January-December. After data collection and study of climate datasets, stations were selected based on less than 10 % missing records, and most of the stations (95 %) were lower than 3 % of the total number of annual values. Some high-altitude stations are used for spatial coverage having 30 years' time series with 5-10 % missing values. We have adopted the Normal ratio method to estimate missing rainfall values of climate datasets from nearby three weather stations (Myrondis, D & Nikolaos, T., 2021, Bagale *et al*., 2021). Monsoon rainfall was interpolated and visualized by using inverse distance weighted (IDW) technique (Patel *et al*., 2007).

The SOI is one measure of the large-scale fluctuations in air pressure observed between the western and eastern tropical Pacific during El Niño and La Niña episodes (Yan *et al*., 2011).The negative phase of the SOI represents below-normal air pressure at Tahiti and above-normal air pressure at Darwin. Monthly Southern Oscillation Index (SOI) data and Ocean Nino Index (ONI) monthly sea surface temperature (SST) anomaly over the Nino-3.4 regions were acquired from the National Weather Service Climate Prediction Centre of National Oceanic and Atmospheric Administration (NOAA) available on https://origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml, accessed 5 January 2020 for the time 1977 to 2018. The ONI defined by three months running mean SST anomalies in the Nino-3.4 regions, which is also known as the Nino-3.4 index.

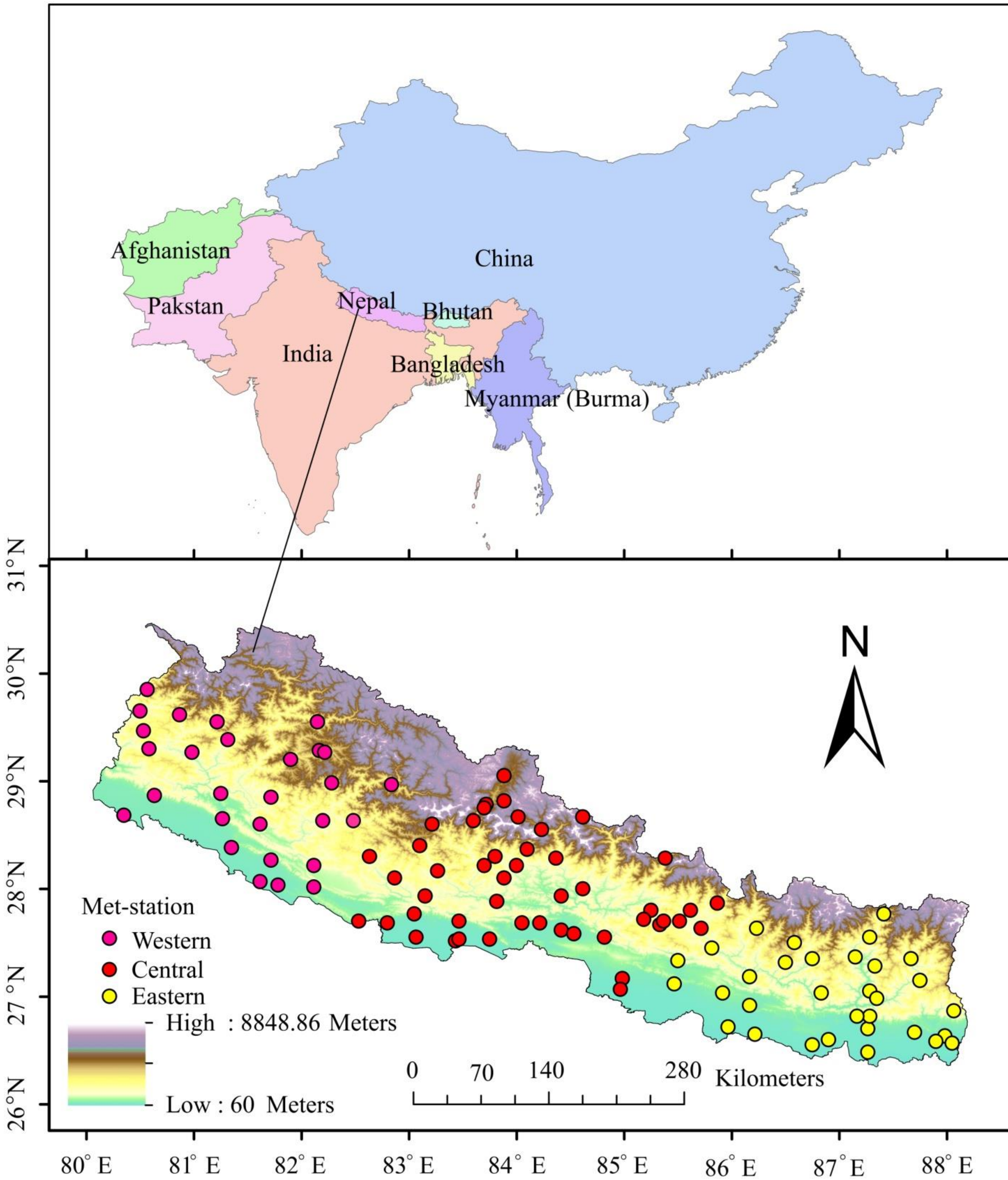

Figure 1. Location map of the study area along with rainfall stations used in this study; pink, red and yellow color respectively represents the stations for the western, central, and eastern regions between 1977 and 2018.

Methodology for Identification Departure of Deficit and Excess Years

Bhalme and Jadhav (1984) and Varikoden *et al.* (2015) used the ±10 % departure from long-term mean to excess /deficit Indian Summer Monsoon Rainfall climatology was identified as severe flood/drought years in India. Flood/Drought document in Nepal using anomalies is limited; it is new; this study used ± 10 % departure from long term mean monsoonal rainfall to identify the severe extreme events. Percent Departure Nepal Summer Monsoon Rainfall (PDNSMRi) is easily calculated.

$$PDNSMR_i = \frac{R_i - \bar{R}}{\bar{R}} * 100\ \%$$

Where R_i and $\bar{R}$ denote all Nepal summer monsoon rainfall and means all Nepal monsoon rainfall for 42 years datasets, the Percent Departure Summer Monsoon Rainfall of each 107 stations was calculated the same.

The Student's t test is used to check statistically significant test for monsoon rainfall anomalies. Furthermore, Gumus and Algin, (2017) defined stations proportion is the number of stations relative to the total number of stations used.

The El Niño years were identified based on the three-month running average SST anomalies over the Nino-3.4 regions. We considered a year as El Niño when the value of Nino 3.4 SST anomaly is greater than 0.5 degree Celsius and a year as La Niña when the value of Nino 3.4 SST anomaly is lower than 0.5 degree Celsius in any five consecutive overlapping months. The detail information of El Niño episodes was obtained from NOAA (Website) URL, https:/origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml.

RESULTS

Rainfall Statistics

The monthly rainfall statics of 1977 to 2018 revealed that the precipitation strongly increased from May (7 %), with the highest in July (27 %) due to the influence of summer monsoon while the lowest recorded in November (Fig. 2a) below 1 %. Approximately 50 % of the annual rainfall was recorded during July and August in two months, and 80 % of the annual rainfall occurs, during the monsoon season, followed by the pre-monsoon 13 %, post-monsoon 4 %, and winters 3 %. Monsoon rainfall variability with respective year to year varied from 74 % in 1992 to 86 % in 1984 (Fig. 2b).

Table 1. Regional rainfall (mm) statistics

Region	Western	Central	Eastern
Winter	91.40	61.46	40.28
Pre-monsoon	171.41	229.42	281.94
Monsoon	1239.36	1515.31	1491.19
Post-monsoon	51.50	74.92	98.12
Annual	1553.68	1881.11	1911.53

Summer rainfall observed greater in the central region with comparisons to the eastern and western regions of Nepal. However, the western region observed low annual rainfall but high amount of Westerly derived winter rainfall in winter season than other regions of Nepal (Table 1). Pre- and post-monsoon rainfall increases from the western to eastern Nepal. Though, the annual rainfall decreases from eastern to western Nepal.

Monsoon Rainfall

During the 42 years the mean monsoon rainfall is 1,433.2 mm/month. Monsoon rainfall widely varies over different parts of the country with lowest over Northwest part (< 200 mm) and highest over central mid-mountainous part (> 3000 mm) of the country followed by Northeast part. The spatial variations of monsoon rainfall have clearly observed the dry areas as well as wet areas in different regions over the country in the isohyetal map. Low rainfall observed in Mustang region lies on lesser Himalayans and high in Lumle region lies on the mountainous region of central Nepal (Fig. 3).

Generally, the amount of mean monsoon rainfall observed decreases from the east to west region. However, in the central region of Nepal there are certain pockets with heavy monsoon rainfall totals.

Temporal Variability of Monsoon Anomaly in Nepal

We have used an average rainfall of 107 stations for the monsoon anomaly (Fig. 3). Excess/deficit years were identified based on the percent departure of NSMR (anomalies). Anomalies are prepared based on climatology for the period 1977–2018. A season is defined as a large excess (flood)/ large deficient (drought) season when the departure percent is ±10 % from the mean NSMR. From this statistical analysis the seven flood/drought years were 1984, 1996, 1998, 1999, 2000, 2003, 2007 and 1977, 1979, 1992, 2005, 2006, 2009, 2015 respectively. The rainfall anomalies observed below the mean is 19 seasons and above is 23 seasons.

The deficit fluctuation of rainfall anomalies was about 19.29 % in 1992 and followed 2015 at about 17.59 %. Similarly, the excess fluctuation of rainfall anomalies was 19.21 % in 1998 and followed 2007 at about 14.79 % (Fig. 4). Furthermore, the deficit and excess monsoon anomalies and rainfall are clearly depicted in Table S1.

Regional Temporal Variations of Monsoon Rainfall

We used average rainfall of 28 stations for the western region, 47 stations for the central region and 32 stations for the eastern region to show the temporal variability of rainfall in respective regions as depicted in Fig. 5a. The regional rainfall shows that the eastern and central regions of Nepal observed more rainfall than the western region.

During the study periods, 25 seasons of high rainfall were observed in the central region compared with the eastern region, and 17 seasons observed more rainfall in eastern Nepal. However, in recent years the rainfall has been decreasing in the eastern region compared to the central region. In all 42 years, the western region of Nepal observed low rainfall than the central and eastern regions of Nepal except in 2013. The rainfall record (Fig. 5a) shows the decreasing and increasing rainfall characteristics in the western, central, and eastern regions. The average monsoon rainfall totals in the central region of Nepal observed more than eastern and western regions (Table 1).

The variability of an anomaly of the western, central, and eastern regions is in different characteristics each year. For example, the large deficient monsoon (drought) year percent departure of rainfall in the western region was about -45 % in 1979. Similarly, in the central region, the large deficient monsoon year percent departure of monsoon rainfall was 31.37 % in 1992, and in the eastern region about 25.27 % percent departure monsoon rainfall was in 1982. The decreases of anomalies (percent departure monsoon rainfall) in these regions on deficit rainfall years are shown in Fig. 5b.

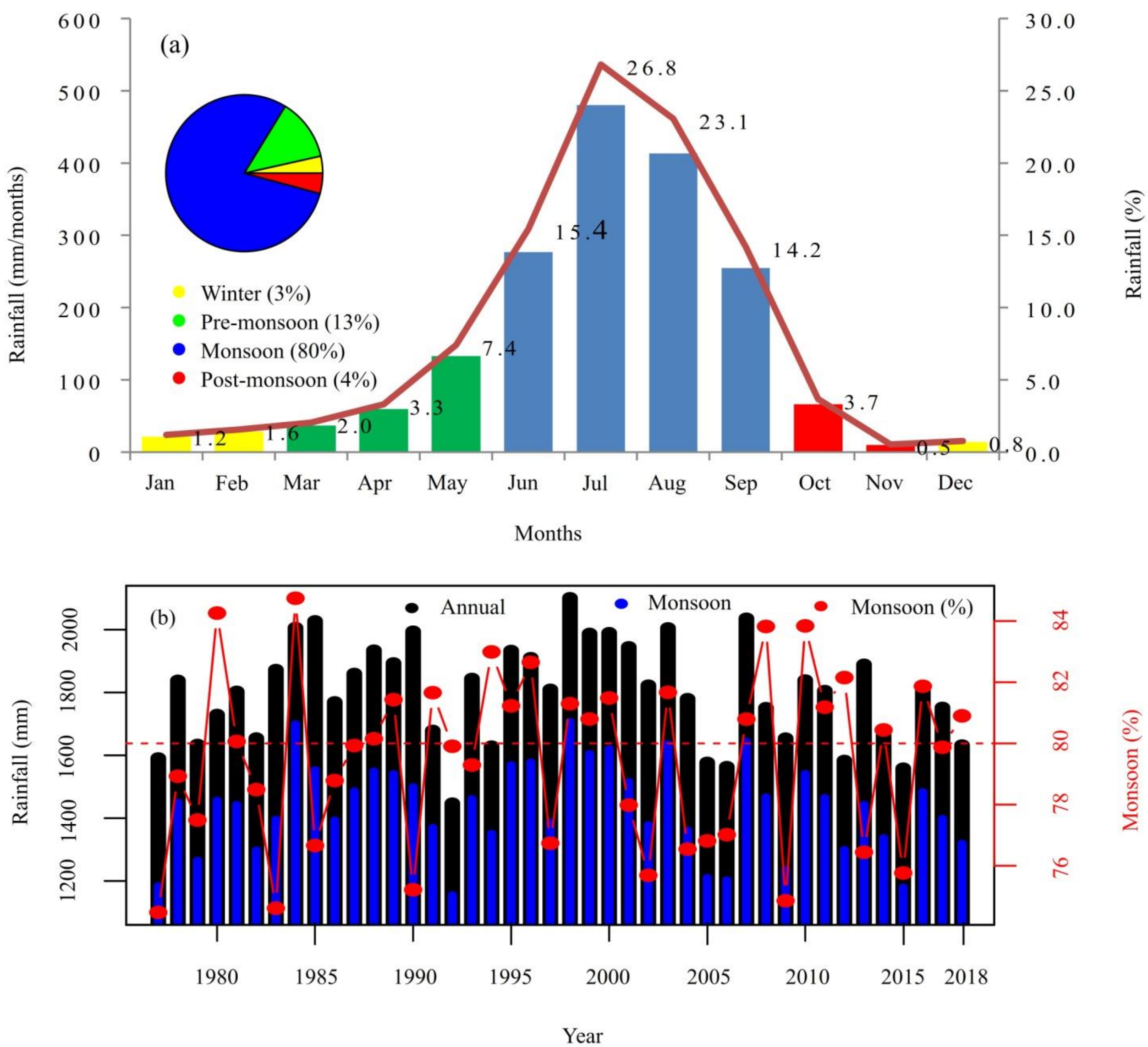

Figure 2. Variability of (a) Monthly rainfall statistics averaged from 1977 to 2018 and Pie chart shows the seasonal amount of rainfall (%). (b) annual monsoon rainfall variability and percent monsoon rainfall for the period 1977-2018

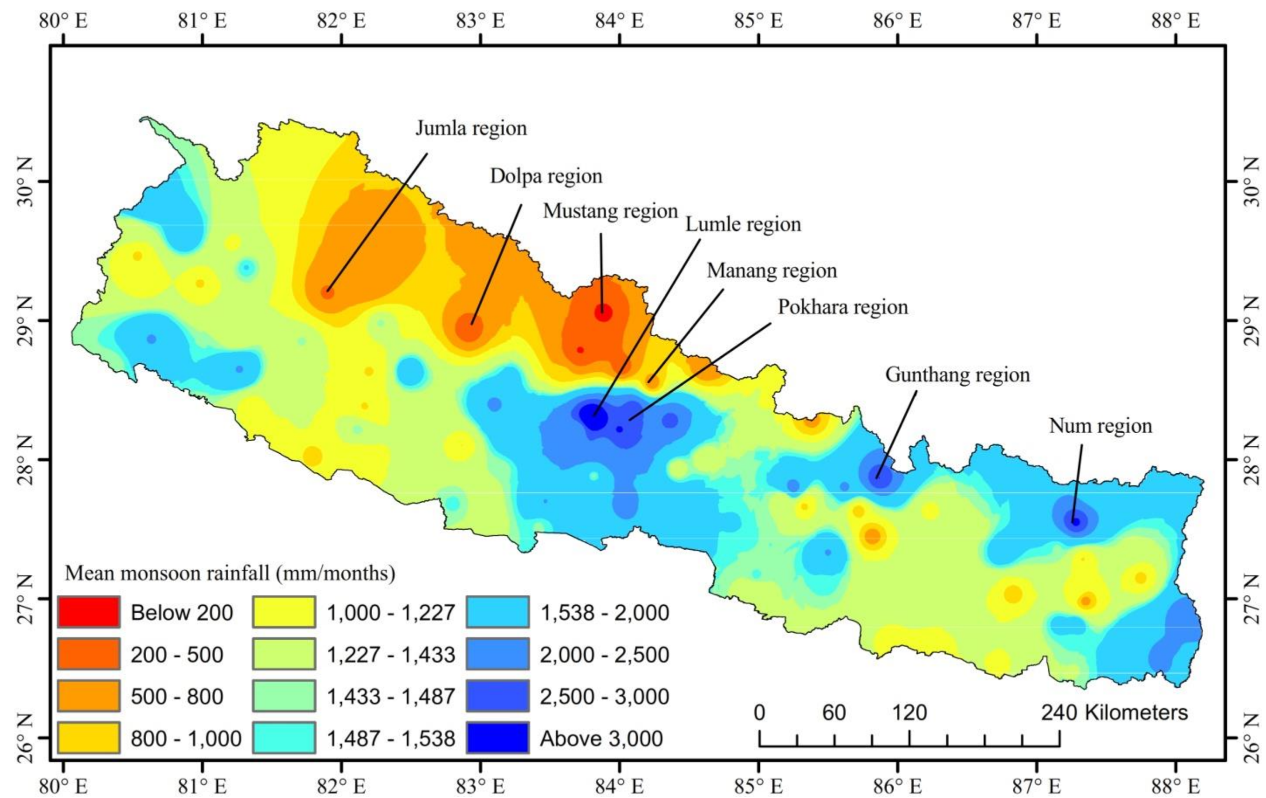

Figure 3. Spatial distributions of mean Monsoon rainfall over Nepal from 1977 to 2018

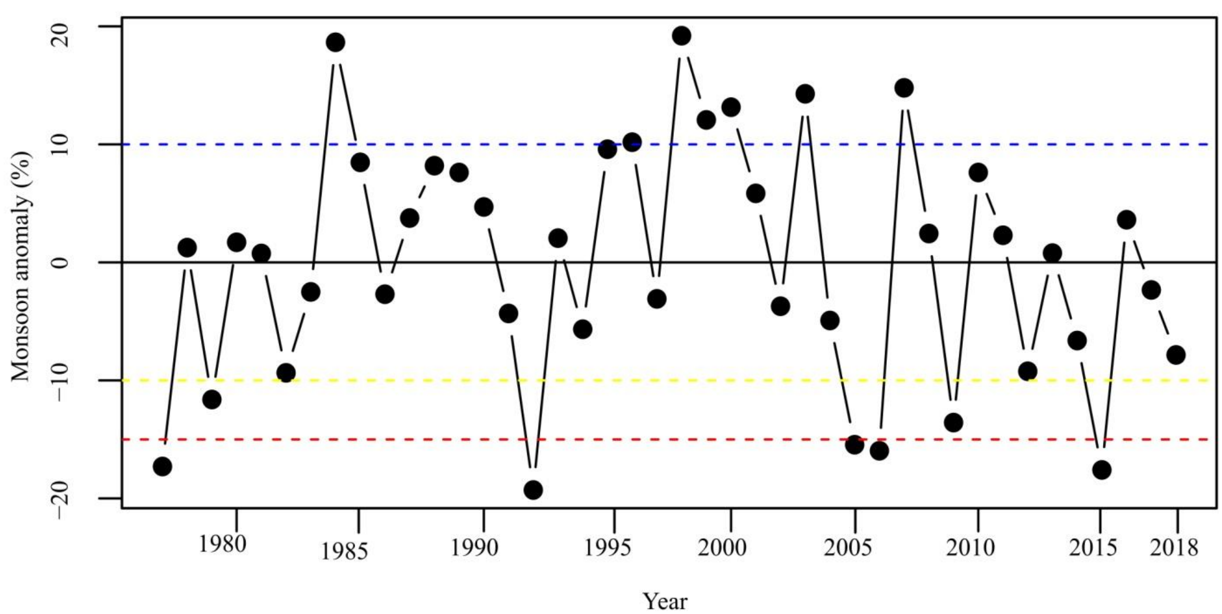

Figure 4. Temporal Variability of Monsoon Anomalies from 1977 to 2018

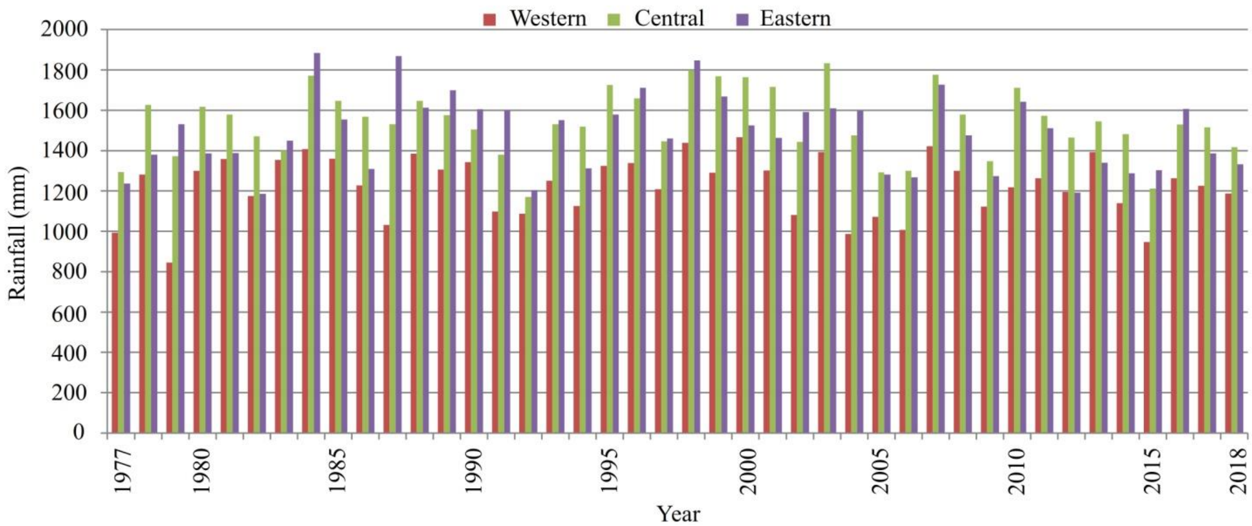

Figure 5a. Temporal Variability of Regional Monsoon Rainfall from 1977 to 2018

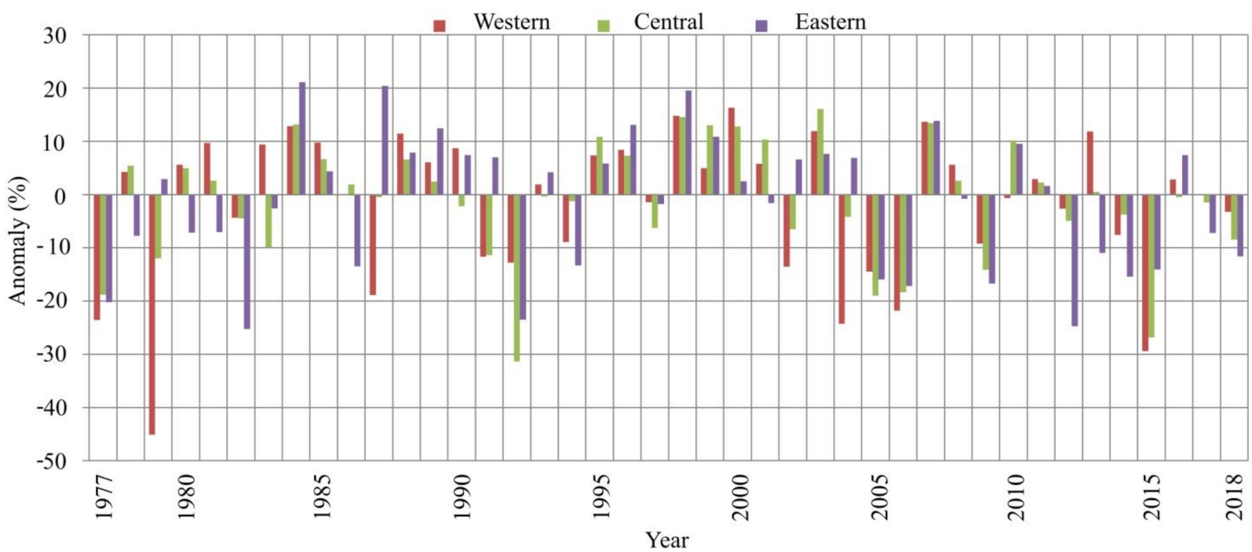

Figure 5b. Temporal Variability of Regional Monsoon Anomalies from 1977 to 2018

The western, central, and eastern regions of Nepal recorded ten, seven, and thirteen seasons of large deficient monsoon (drought) years respectively. The regional deficient monsoon years and its rank are shown in Table 2. Moreover, the western region of Nepal recorded seven seasons of large excess monsoon (flood) years in recent 42 years. The flood years were 2000, 1998, 2007, 1984, 2003, 2013, and 1988. Similarly, the central region recorded nine seasons of large excess monsoon (flood) years. The flood years are 2003, 1998, 2007, 1984, 1989, 2000, 1995, 2001, and 2010. While in the eastern region recorded 7 seasons as large excess monsoon (flood) years. The flood years are 1984, 1987, 1998, 2007, 1996, 1989, and 1999. Comparing the results region-wise, the eastern region of Nepal faced more dry conditions frequently than the central and western regions of Nepal are shown in Table 2.

Relative Frequency of Monsoon Rainfall in Large Deficient Monsoon Episodes

This study quantifies the seven large deficient monsoon year's stations proportion expressed in percent which are depicted in table 3 and we also present large deficient year's deficit rainfall in each drought episodes from long term average. Spatial extents of the variability of rainfall are interpolated over Nepal in Fig. 6 (a-g).

Table 2. Regional Large Deficit Percent Departure Monsoon Rainfall in Nepal from 1977 to 2018

Rank	Eastern			Western			Central		
	year	Monsoon Rainfall mm	Percent departure	year	Monsoon Rainfall mm	Percent departure	year	Monsoon Rainfall mm	Percent departure
1	1982	1186.70	-25.3	1979	845.37	-45.1	1992	1170.61	-31.4
2	2012	1191.80	-24.7	2015	947.73	-29.4	2015	1212.20	-26.9
3	1992	1203.68	-23.5	2004	987.13	-24.3	2005	1292.27	-19.0
4	1977	1236.39	-20.2	1977	992.66	-23.6	1977	1293.97	-18.8
5	2006	1268.35	-17.2	2006	1006.98	-21.8	2006	1299.30	-18.4
6	2009	1273.35	-16.7	1987	1031.64	-18.9	2009	1347.04	-14.2
7	2005	1282.04	-16.0	2005	1071.61	-14.5	1979	1373.19	-12.0
8	2014	1288.21	-15.4	2002	1080.41	-13.5	1991	1380.82	-11.4
9	2015	1302.82	-14.1	1992	1087.77	-12.8			
10	1986	1309.75	-13.5	1991	1098.22	-11.7			
11	1994	1311.76	-13.3						
12	2018	1331.78	-11.6						
13	2013	1339.59	-11.0						

Table 3. Large deficient monsoon rainfall statistics based on stations proportion expressed in percent in different years

Rank	Year	<Average monsoon rainfall mm	<10% monsoon rainfall mm	Deficit rainfall below from long term average (mm)
1	1992	73	66	276.26
2	2015	72	63	251.86
3	1977	72	48	247.72
4	2006	70	65	228.59
5	2005	68	55	221.26
6	2009	66	56	194.37
7	1979	62	51	166.35

Large deficient summer monsoon was in 1992. In this episode 66 % stations observed below 10 % monsoon rainfall anomalies and more than 73 % stations are observed below from mean monsoon rainfall. Large deficit monsoon years ranking from first to seventh is tabulated in Table 3 with rainfall statistics.

Spatial Distribution of Monsoon Rainfall Variability on Large Monsoon Deficit Years

Nepal is a mountainous country with complex topography; Nepal faces the leeward side with low rainfall in the Northern part of Nepal. This area of Nepal is semiarid; low monsoon rainfall areas are Mustang, Dunai and Manang located in the lesser Himalayans regions. These locations recorded < 200 mm in the monsoon season. The spatial distribution of rainfall across Nepal indicates high rainfall or pocket rainfall areas surrounding Lumle, Num, Pokhara, and Gumthan. Lumle and Pokhara lie in the central region of Nepal on High and Mid Mountainous near the Annapurna region. Num and Gumthang lie on the eastern part of high mountain regions record more than 3000 mm/months in the monsoon season. The interpolated Fig. 6(a-g) indicates the pockets rainfall areas as well as dry areas in the seven large deficient monsoon cases.

In the recent four decades, we observed and analyzed the western, central, and eastern regions rainfall statistics. The large monsoon rainfall deficit recorded in 1979 on western region which was 45.09 % from the mean rainfall of the western region. Similarly, the central region and eastern region have recorded large monsoon rainfall deficient in year 1992. In this year, central and eastern regions have measured rainfall anomalies decreases 37.37 % and 23.50 % respectively. In the monsoon drought years 1979, 2015, 1977, and 2006 the western region of Nepal was more affected by large rainfall deficit in comparisons to the central and eastern regions [Fig. 6 (b, c, e and g)]. In these years the mountainous region of the central and western region recorded low rainfall. In the particular year 1979, the eastern region recorded excess rainfall, but the western region recorded a large deficit rainfall during the recent 42 years. While in the central region, rainfall anomaly decreases by 11.99 %, but the eastern region increases rainfall anomaly by 2.92 %. Similarly, in the year 1992 the central region was more affected by a large deficit monsoon rainfall in comparison to eastern and western regions followed by the year 2005. In the year 1992, the central region witnessed a decrease in larger rainfall anomalies than the eastern and western regions (Table 2). But in 2009 the eastern region was more affected by deficit rainfall than any regions of Nepal (Fig. 6f).

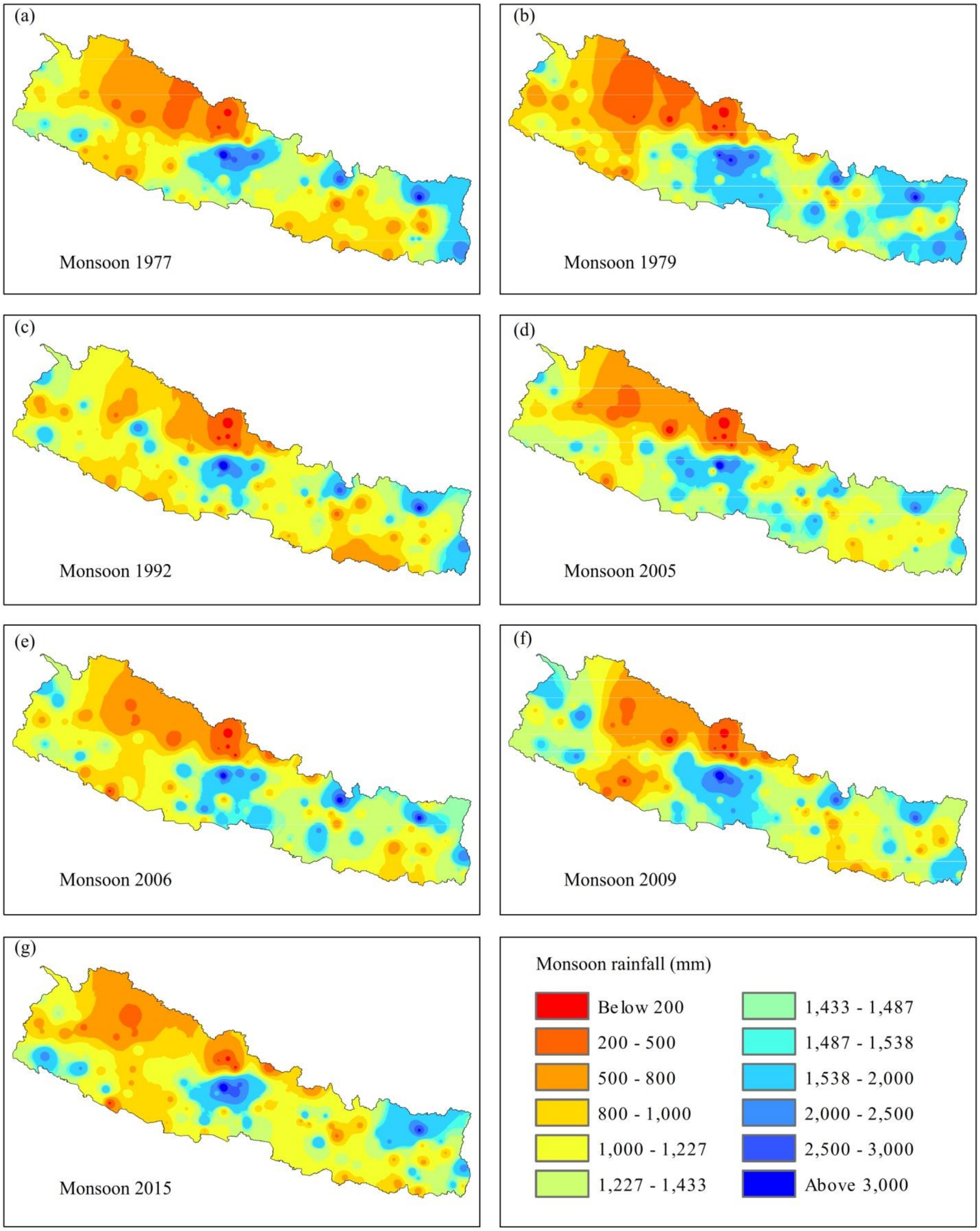

Figure 6. Spatial distributions of (a) monsoon rainfall 1977, (b) monsoon rainfall 1979, (c) monsoon rainfall 1992, (d) monsoon rainfall 2005, (e) monsoon rainfall 2006, (f) monsoon rainfall 2009, and (g) monsoon rainfall 2015

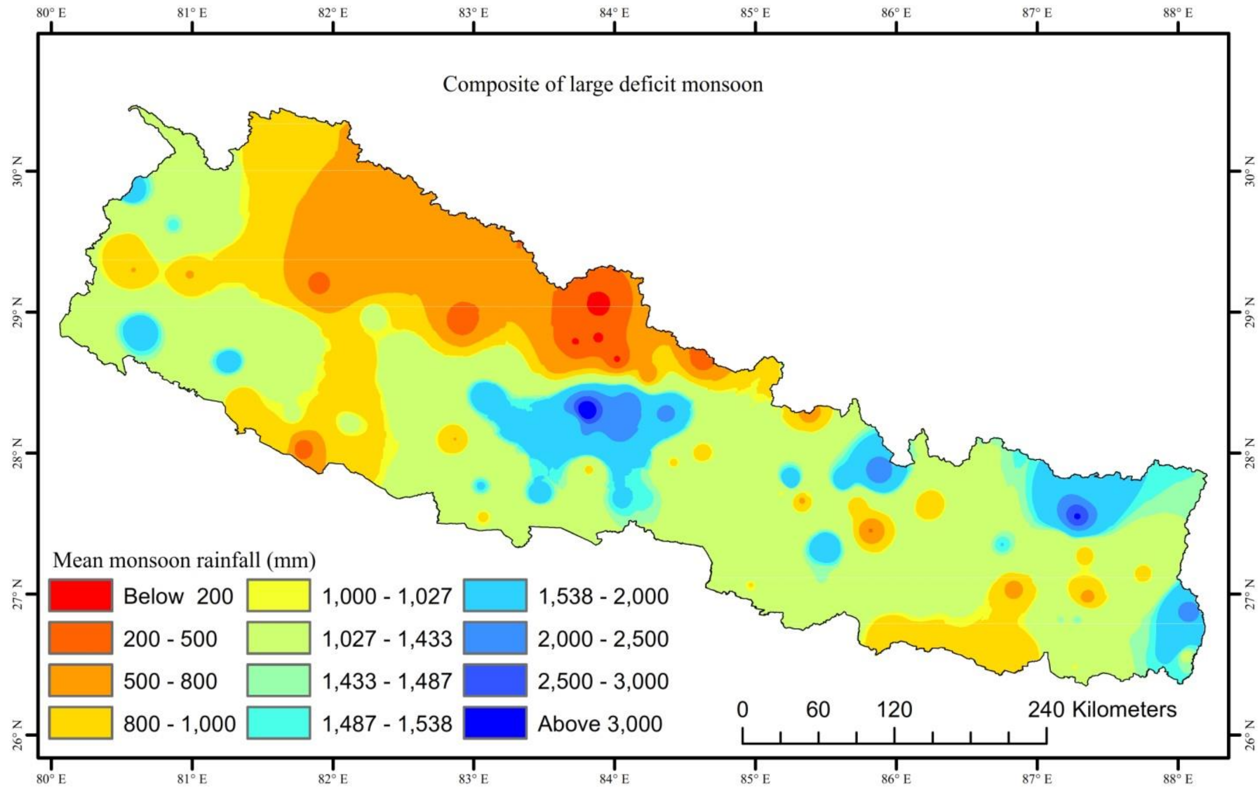

Figure 7. Spatial distributions of composite large deficit monsoon years

Composite of Large Deficit Years

We have analyzed the composite episodes for extreme years over Nepal; consisting of summer large deficient monsoon (drought) years are 1977, 1979, 1992, 2005, 2006, 2009, and 2015. The mean anomaly sets of 5 composite large deficit episodes were less than 15 %. Therefore, the composite of the 5 large deficit episodes is averaged.

The spatial distributions of the mean monsoonal of composite large deficit years are shown in Fig. 7. The central part of Nepal recorded more rainfall which belongs to the high and mid mountains near the Annapurna region. The rainfall pockets area of Nepal recorded > 3000 mm rainfall during the drought years in Lumle, Pokhara, Num, and Gumthang which lie on the mountain regions of central and eastern parts of Nepal. On the other hand, the central and western parts of high lands are facing a rainfall deficit. The deficit areas are in Mustang, Manang, Dunai, and Jumla station recorded low precipitation than mean monsoonal rainfall in composite large deficit years.

Relation between NSMR and SOI

This study used the SOI index, which measures a large-scale fluctuation in sea level pressure between La Nina and El Niño episodes. Comparison between all Nepal summer monsoon series and SOI shows (Fig. 8) the substantial correlation between SOI and NSMR records.

Deficit period with SOI (-), excess period with SOI (+); the NSMR and SOI are 31 (about 74 %) times the phase relation (positive/negative SOI, positive/Negative NSMR (Fig. 8). In 31 times phase relation 14 (about 45.16 %) times deficit and 17(about 54.84 %) times excess summer rainfall in Nepal. The correlation coefficient between NSMR and SOI is 0.52 from 1977 to 2018 at a 95 % confidence level. During the study periods, the average deficit monsoon rainfall is 8.72 percent in the low phase of SOI (< -0.5), while the average excess is 7.12 percent in the high phase of SOI (> 0.5). From the above-mentioned phase relation between NSMR and SOI analysis, the all-Nepal monsoon record series is highly influenced by the SOI. Such a similar pattern is noticed in NSMR in large deficit (drought) years. However, during the drought/flood period SOI and the NSMR are strong (-/+) more than the normal years. The strength/weakness of the monsoon system was identified as La Nina/El Niño years for high NSMR variability. The El Niño years are 1982, 1983, 1987, 1991, 1992, 1997, 1998, 2002, 2004, 2009, 2015, 2016 and La Nina years are 1985, 1988, 1989, 1995, 1998, 1999, 2000, 2007, 2008, 2010, 2011, 2015) during study periods extracted from https://origin.cpc.ncep.noaa.gov/products/precip/CWli nk/MJO/enso.shtml.The years 1998 and 2016 marked both El Niño and La Nina episodes. However, monsoon seasons of Nepal dominated by excess rainfall in these years. Our findings show that Nepal's large deficit monsoon (drought) years associated with El Niño and normal both are extreme dry years. All El Niño years were the deficit, but in year 1987(El Niño) there was excess monsoon rainfall observed in Nepal (Fig. 2b). It is a need to further investigation for the justification causes. Moreover, this study quantifies the El Nino year's rainfall with their decreasing percent rainfall anomalies and deficit rainfall below average monsoon rainfall between 1977 and 2018 in (Table S1 and Table 4).

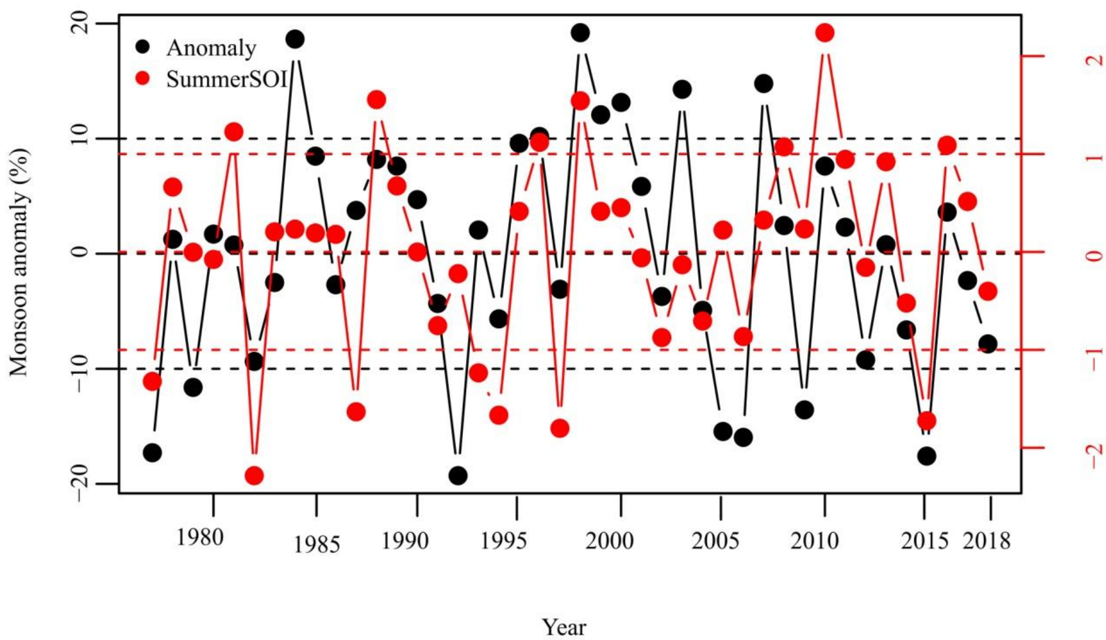

Figure 8. Relationship between Percentage Departure of NSMR and SOI

Table 4. The rainfall variability observed in the large deficit monsoon rainfall years by El Niño events

Years	1982	1983	1991	1992	1997	2002	2004	2009	2015
Deficit rainfall (mm)	134.12	35.83	61.97	276.43	44.27	53.22	70.55	194.53	252.03

In 1992, summer episodes collected 1156.74 mm/months rainfall below 252.03 mm/months than the long-term average. Other large deficient monsoon events rainfall deficits are tabulated in table 4. On El Niño episodes averaged deficit rainfall observed approximately nine percent below from an average monsoon rainfall (1977 to 2018).

During the study period, this study observed seven drought years in Nepal only three years associated with El Niño years, and four drought years are in normal years. The first and second extreme drought in 1992 and 2015 were associated with El Niño years, and the third drought in 1977 occurred in normal year.

DISCUSSION

Approximately 80 % of the annual rainfall is received during the monsoon season (Kanskar *et al.*, 2004; Sigdel and ikeda, 2012; Karki *et al.*, 2017). This study also identified that contributions of monsoon rainfall was 74 % in year 1992 and 86 % in year 1984. The similar results presented by Shrestha *et al.* (2000) identified the year 1992 was the driest during the periods (1948-1994) using 75 stations over Nepal. In that particular year, whole Nepal recorded below normal rainfall which coincided with an El Nino event.

Present study shows that large monsoon deficient episodes are extreme in El Niño and normal years. Out of seven large deficient monsoons (drought) years, only three drought years associated with El Niño years (1992, 2009, and 2015) and four drought years (1977, 1979, 2005, and 2006) are recorded in normal years. The year 1977 is a large deficient monsoon year observed on normal year. So, Nepal observed a large deficient monsoon (drought) year on El Niño and normal year. The findings of monsoon seasons large deficit events from this study are also similar with other studies such as Sharma *et al*., 2020. Furthermore, A similar result presented by Balme and Jadhav, (1984), in India where drought is recorded in both El Niño year and normal year; however, there have been deficient monsoons over India apart from the mentioned El Niño episodes (Varikoden *et al*., 2015).

During the seven large monsoons deficient years' western regions of Nepal recorded comparatively low rainfall than eastern and central regions. In the year 1979, 1992, and 2015 the central region recorded low monsoon rainfall than the eastern region, and in the year 1977, 2005, 2006, 2009, the eastern region records low monsoon rainfall (Fig. 5a). The large monsoon deficient years have resembled Shrestha *et al*. (2000) and Shrestha (2000). Furthermore, in the recent decades some researchers (Wang *et al*., 2019; Varikoedal *et al*., 2015; Kumar *et al*., 2013) identified the inter-decadal weakening of the South Asian Summer Monsoon frequently after 2000 both on El Nino and Normal years over the South Asian countries. Those studies support the findings of drought events frequently as reported in the present study.

The previous researchers' (Sigdel and Ikeda, 2012; Shrestha, 2000) findings supports the present results that there a strong correlation between SOI and monsoon rainfall. In this study the correlation coefficient between NSMR and SOI is 0.52 at a 95% confidence level. Similar results were presented by Chudhary *et al*. (2003) in Bangladesh; Sien *et al*. (2015) in Myanmar and Varikoedal *et al*. (2015) in India.

CONCLUSIONS

The study provided concise knowledge about the temporal (all-Nepal as well as regional) and spatial variability of monsoon seasons using a rainfall anomaly over Nepal during the past four decades (1977- 2018). There were seven large deficit monsoon years 1977, 1979, 1992, 2005, 2006, 2009, and 2015 with deficit percent of rainfall 17.30, 11.62, 19.29, 15.45, 15.96, 13.57 and 17.59 respectively from long term average on corresponding monsoon episodes. The eastern region frequently showed the monsoon dry signals compared with the central and western regions. Moreover, whole Nepal indicates that after the year 2000 large deficit rainfall events evolved frequently. The average deficit monsoon rainfall is 8.72 percent in the low phase of SOI (< - 0.5). The correlation coefficient between SOI and NSMR is strong on large deficit monsoon years than normal years, the correlation coefficient between NSMR and SOI is 0.52. Present study showed that large deficient years are observed both in El Niño and normal years. Out of seven drought years, only three years associated with El Niño years. With some exceptions, all El Niño years measured deficit rainfall. Deficit rainfall during the El Niño years observed approximately nine percent below the average monsoon rainfall.

ACKNOWLEDGEMENTS

Nepal Government's Department of Hydrology and Meteorology is acknowledged for providing observed rain gauge data, and University Grant Commission, Kathmandu Nepal for providing financial support to the first author. In addition, climate index data were taken from the National Oceanic and Atmospheric Administration (NOAA).

AUTHOR CONTRIBUTIONS

Damodar Bagale designed the study, data analysis and original draft preparation. Deepak Aryal and Madan Sigdel prepared the paper with significant input.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

REFERENCES

Bagale, D., Sigdel, M., & Aryal, D. (2021). Drought monitoring over Nepal for the last four decades and its connection with southern oscillation index. *Water*, *13*(23), 3411. https://doi.org/10.3390/w13233411

Bhalme, H.N., & Jadhav, S.K. (1984). The Southern Oscillation and its relation to the monsoon rainfall. *Journal of Climatology*, *4,* 509-520.

Bohlinger, P., Sorteberg, A., & Sodemann, H. (2017). Synoptic conditions and moisture sources actuating extreme precipitation in Nepal. *Journal of Geophysical Research: Atmospheres*, *122*(23), 12653-12671. https://doi.org/10.1002/2017JD027543.

Cherchi, A., & Navarra, A. (2013). Influence of ENSO and of the Indian Ocean Dipole on the Indian summer monsoon variability. *Climate Dynamics, 41*(1), 81–103. https://doi.org/10.1007/s00382-012-1602-y.

Chowdhury, M.R. (2003). The El Niño-Southern Oscillation (ENSO) and seasonal flooding-Bangladesh. *Theoretical and Applied Climatology*, *76*(1–2), 105–124. https://doi.org/10.1007/s00704-003-0001-z

De Silva, T.M., & Hornberger, G.M. (2019). Identifying El Niño-Southern Oscillation influences on rainfall with classification models: Implications for water resource management of Sri Lanka. *Hydrology and Earth System Sciences, 23*(4), 1905–1929. https://doi.org/10.5.

194/hess-23-1905-2019

Fan, F., Dong, X., Fang, X., Xue, F., Zheng, F., & Zhu, J. (2017). Revisiting the relationship between the South Asian summer monsoon drought and El Niño warming pattern. *Atmospheric Science Letters,* 18(4), 175–182. https://doi.org/10.1002/asl.740

Fredriksen, H.B., Berner, J., Subramanian, A.C., & Capotondi, A. (2020). How does El Niño–Southern Oscillation change under global warming? A first look at CMIP6. *Geophysical Research Letters*, 47(22). https://doi.org/10.1029/2020GL090640

Gumus, V., & Algin, H.M. (2017). Meteorological and hydrological drought analysis of the Seyhan−Ceyhan River Basins, Turkey. *Meteorological Applications*, 24(1), 62–73. https://doi.org/10.1002/met.1605

Ichiyanagi, K., Yamanaka, M.D., Muraji, Y., & Vaidya, B.K. (2007). Precipitation in Nepal between 1987 to 1996. *International Journal of Climatology*, 27(13), 1753-1762. https://doi.org/10 :1002/joc.1492

Kansakar, S.R., Hannah, D.M., Gerrard, J., & Rees, G. (2004). Spatial pattern in the precipitation regime of Nepal. *International Journal of Climatology*, 24(3), 1645–1659. https://doi.org/10.1002/joc.1098

Karki, R., Hasson, S., Schickhoff, U., & Scholten, T. (2017). Rising precipitation extremes across Nepal. *Journal of Climate*, 5(1), 4. https://doi.org/10.3390/cli5010004

Karki, R., Talchabhadel, R., Aalto, J., & Baidya, S.K. (2015). New climatic classification of Nepal. *Theoretical and Applied Climatology,* 125(3–4), 799–808. https://doi.org/10.1007/s00704-015-1549-0

Mooley, D.A., & Parthasarathy, B. (1983). Variability of the Indian summer monsoon and tropical circulation features. *Monthly Weather Review*, 111(5), 967-978. https://doi.org/10.1175/1520-0493(1983)111

Muangsong, C., Cai, B., Pumijumnong, N., Hu, C., & Cheng, H. (2014). An annually laminated stalagmite record of the changes in Thailand monsoon rainfall over the past 387 years and its relationship to IOD and ENSO. *Quaternary International,* 349, 90–97. https://doi.org/10.1016/j.quaint.2014.08.037

Myronidis, D., & Nikolaos, T. (2021). Changes in climatic patterns and tourism and their concomitant effect on drinking water transfers into the region of South Aegean, Greece. *Stochastic Environmental Research and Risk Assessment*, 35(9), 1725–1739. https://doi.org/10.1007/s00477-021-02015-y

Niranjan Kumar, K., Rajeevan, M., Pai, D. S., Srivastava, A.K., & Preethi, B. (2013). On the observed variability of monsoon droughts over India. *Weather and Climate Extremes*, 1, 42–50. https://doi.org/10.1016/j.wace.2013.07.006

Patel, N.R., Chopra, P., & Dadhwal, V.K. (2007). Analyzing spatial patterns of meteorological drought using stndard precipitation index. *Meteorological Applications*, 14(4), 329-336. https://doi.org/10.1002/met.33

Pokharel, B., Wang, S.Y.S., Meyer, J., Marahatta, S., Nepal, B., Chikamoto, Y., & Gillies, R. (2020). The east–west division of changing precipitation in Nepal. *International Journal of Climatology*, *40*(7), 3348–3359. https://doi.org/10.1002/joc.6401

Ramanadham, R., Visweswara Rao, P., & Patnaik, J.K. (1973). Break in the Indian summer monsoon. *Pure and Applied Geophysics*, *104*(1), 635–647. https://doi.org/10.1007/BF00875908.

Rasmusson, E.M., & Carpenter, T.H. (1983). The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka, *Monthly Weather Review, 111*(3), 517-528.

Salerno, F., Guyennon, N., Thakuri, S., Viviano, G., Romano, E., Vuillermoz, E., Cristofanelli, P., Stocchi, P., Agrillo, G., Ma, Y., & Tartari, G. (2015). Weak precipitation, warm winters and springs impact glaciers of south slopes of Mt. Everest (central Himalaya) in the last 2 decades (1994-2013). *The Cryosphere*, *9*(3), 1229–1247. https://doi.org/10.5194/tc-9-1229-2015

Sein, Z.M.M., Ogwang, B., Ongoma, V., Ogou, F.K., & Batebana, K. (2015). Inter-annual variability of May-October rainfall over Myanmar in relation to IOD and ENSO. *Journal of Environmental and Agricultural Sciences, 4*, 28–36.

Sharma, S., Hamal, K., Khadka, N., & Joshi, B.B. (2020). Dominant pattern of year-to-year variability of summer precipitation in Nepal during 1987–2015. *Theoretical and Applied Climatology, 142*(3–4), 1071–1084. https://doi.org/10.1007/s00704-020-03359-1

Shrestha, A.B., Wake, C.P., Dibb, J.E., & Mayewski, P.A. (2000). Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale, *International Journal of Climatology*, *20*(3), 317–327.

Shrestha, D., Sharma, S., Hamal, K., Khan Jadoon, U., & Dawadi, B. (2020). Spatial Distribution of Extreme Precipitation Events and Its Trend in Nepal. *Applied Ecology and Environmental Sciences*, *9*(1), 58–66. https://doi.org/10.12691/aees-9-1-8

Shrestha, M.L. (2000). Interannual variation of Summer monsoon rinfall over Nepal and its relation to Southern Oscillation Index. *Meteorology and Atmospheric Physics*, *75*, 21-28.

Shrestha, S., Yao, T., Kattel, D.B., & Devkota, L.P. (2019). Precipitation characteristics of two complex mountain river basins on the southern slopes of the central Himalayas. *Theoretical and Applied Climatology*, *138*(1–2), 1159–1178. https://doi.org/10.1007/s00704-019-02897-7.

Sigdel, M., & Ikeda, M. (2010). Spatial and temporal analysis of drought in Nepal using standardized precipitation index and its relationship with climate indices. *Journal of Hydrology and Meteorology, 7*(1), 59–74. https://doi.org/10.3126/jhm.v7i1.5617.

Sigdel, M., & Ikeda, M. (2012). Summer monsoon rainfall over Nepal related with large-scale atmospheric circulations. *Earth Science & Climatic Change*, *3*(2), 112. https://doi.org/10.4172/2157-7617.1000112.

Sigdel, M., & Ma, Y. (2017). Variability and trends in daily precipitation extremes on the northern and southern slopes of the central Himalaya. *Theoretical and Applied Climatology*, *130*(1–2), 571–581. https://doi.org/10.1007/s00704-016-1916-5.

Sikka, D. (1980). Some aspects of the large-scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary and regional scale circulation parameters. *Indian Academy of Sciences-Earth and Planetary Sciences, 89,* 179-195.

Trenberth, K.E. (1976). Spatial and temporal variations of the Southern Oscillation. *Quarterly Journal of the Royal Meteorological Society*, *102*(433), 639–653. https://doi.org/10.1002/qj.49710243310.

Varikoden, H., & Babu, C.A. (2015). Indian summer monsoon rainfall and its relation with SST in the equatorial Atlantic and Pacific Oceans. *International Journal of Climatology, 35*(6), 1192–1200. https://doi.org/10.1002/joc.4056.

Varikoden, H., Revadekar, J.V., Choudhary, Y., & Preethi, B. (2015). Droughts of Indian summer monsoon associated with El Niño and Non-El Niño years, *International Journal of Climatology*, *35*(8), 1916–1925. https://doi.org/10.1002/joc.4097.

Wang, B., Luo, X., & Liu, J. (2020). How robust is the asian precipitation-ENSO relationship during the industrial warming period (1901-2017)? *Journal of Climate, 33*(7), 2779–2792. https://doi.org/10.1175/JCLI-D-19-0630.1.

Wang, S.Y., Yoon, J.H., Gillies, R.R., & Cho, C. (2013). What caused the winter drought in western Nepal during recent years? *Journal of Climate*, *26*(21), 8241–8256. https://doi.org/10.1175/JCLI-D-12-00800.1

Webster, P.J., Magaña, V.O., Palmer, T.N., Shukla, J., Tomas, R.A., Yanai, M., & Yasunari, T. (1998). Monsoons: processes, predictability, and the prospects for prediction. *Journal of Geophysical Research: Oceans*, *103*(C7), 14451–14510. https://doi.org/10.1029/97jc02719.

Wright, P.B. (1975). *An index of the Southern Oscillation*. Climatic Research Unit School of Environmental Sciences University of East Anglia. Climatic Research Unit, Publications series, 4.

Yan, H., Sun, L., Wang, Y., Huang, W., Qiu, S., & Yang, C. (2011). A record of the Southern Oscillation Index for the past 2,000 years from precipitation proxies. *Nature Geoscience*, *4*(9), 611–614. https://doi.org/10.1038/ngeo1231.

Natural Hazards
https://doi.org/10.1007/s11069-023-06242-0

REVIEW ARTICLE

Winter drought monitoring using standard precipitation index over Nepal

Damodar Bagale[1] · Madan Sigdel[1] · Deepak Aryal[1]

Received: 21 September 2022 / Accepted: 27 September 2023

Abstract
The frequency of winter drought episodes has been marked frequently in the recent decades. This study examines the time series indices of drought variability over Nepal using historical data of 42 years (1977–2018) from 107 stations using the standardized precipitation index (SPI). Monthly rainfall was used as an input variable to generate the output for SPI time scales of each station. SPI threshold was used to identify severity, frequency, duration, and spatial extent of the drought episodes. The SPI3 output showed occurrence of major eight drought episodes. Among these years, dryness signals identified 2006 as the worst drought episode year. However, from regional perspective, the western region observed extreme drought episodes in 2009. There were distinct drought dynamics in each major drought event over the western, central and eastern Nepal. Spatial variability for SPI3 time scale was interpolated to depict spatial patterns of major drought episodes with their severities. The areas of Nepal affected by extreme, severe and moderate drought in winter were 4, 21 and 37%.

Keywords Drought · Man-Kendall test · Nepal · SPI · Variability

1 Introduction

Drought is considered the most complex of all natural hazards (Wilhite 2007); it is insidious, slow-onset that produces a complex web of impacts that ripple through many sectors of the economy (Hagman 1984; Wilhite 2007). The effects of drought often accumulate slowly over a considerable period of time and many linger for years after the termination of the event, the onset and end of drought are difficult to determine (Wilhite 2007). The characteristics and quantification of drought are really useful for enabling both severities

✉ Damodar Bagale
damu.bagale@gmail.com

Madan Sigdel
sigdelbro@gmail.com

Deepak Aryal
deepak.aryal@cdhm.tu.edu.np

1 Present Address: Central Department of Hydrology and Meteorology, Tribhuvan University, Kathmandu 44613, Nepal

Published online: 17 October 2023

versus impacts analysis and risk assessment (Zargar et al. 2011). Drought and flood years of summer season are generally linked between atmospheric large circulations with correspond to El Niño and La Niña episodes in South Asia (Keshavamurty and Goswami 2000; Varikoden et al. 2015; Chowdhury 2003). There was a strong correlation between negative/positive values of SOI and summer drought/flood years than the normal years in Nepal, in the central Himalayan region (Bagale et al. 2021). But, there was a poor correlation between SOI and rainfall in winter seasons in Nepal (Shrestha et al. 2000; Sigdel and Ikeda 2010).

Synoptic weather disturbances are the main causes of winter precipitation in Nepal which is dynamically different from monsoon circulations (Lang and Barros 2002, 2004). However, winter precipitation (December–February) is significant as it accounts for approximately 3% of Nepal's annual precipitation total (Sigdel and Ikeda 2012). The frequency of winter rainfall has been observed high in the western regions, trend of which is decreasing from the western-central to eastern regions in Nepal. Precipitation plays a major role in the mass balance of glaciers in the western region while playing a secondary role in the glaciers of eastern and central Nepal (Seko and Takahashi 1991). The major factor for the study of drought evolution over Nepal is the lack of precipitation analysis linked with (westerly) circulations. An adequate understanding of drought dynamics and subsequent impacts is required in Nepal. Major rivers of Nepal originate from Himalayas throughout the year. These rivers flow toward the Gangetic plain regions of India.

There were very limited winter drought studies concerning Nepal. Sigdel and Ikeda (2010) study and point out drought events over Nepal. There are few regional and basin-wise studies concerned with winter drought events. The study of Wang et al. (2013) studied only for the western region of Nepal using different rainfall sources. Also the study indicates the worst winter deficit episodes were in the years 2006 and 2009 in the western Nepal. Similarly, winter drought study by Khatiwada and Pandey (2019) has been conducted over the Karnali region of western Nepal, using different indices. Dahal et al. (2015) concentrated on a drought study in central Nepal and pointed out that droughts have a crucial effect on livelihood of the villagers. Dahal et al. (2021) examined the spatiotemporal variability of drought episodes in Koshi river basin located in eastern Nepal. There are no adequate studies of spatial coverage of extreme drought effects in recent winter episodes over Nepal. There is a clear research gap in winter spatial drought variability across the country. This study reviews spatial variability of winter drought across the country. So this study has tried to study the overall drought statistics in winter deficit events in the last 42 years (1977–2018). The study of winter drought variability over Nepal is essential for the climatological and socioeconomic perspectives.

The main objective of this study is to quantify the winter drought events in Nepal during the last four decades. Similarly, this study has focused on the temporal and spatial progression of the major winter drought events.

2 Materials and methods

2.1 Study area

Nepal is a landlocked mountainous country situated in the central Himalayas of South Asian territory. To the northern side lies the Highland of Tibet China and the remaining sides are surrounded by India. It extends from 80° 04´ to 88° 12´E in longitude and 26°

22´to 30° 27´ N in latitude (Fig. 3). The complex topography of Nepal ranges from low land of Terai 60 m in southern plain to High land Mount Everest 8848 m above sea level in Himalayan region toward North and the country extends 885 km from east to west and varies from 130 to 260 km in north to south and covers an area of 147,181 km^2 (Bagale et al. 2021). Approximately 86% of the total land comprises hilly and mountainous regions and the remaining 14% is flatland. The climate of Nepal varies from tropical in the southern part to cold arid steppe in the northern part (Karki et al. 2016). Furthermore, the country has been divided into the western, central and eastern regions to study comparative regional drought variability. We have used 28, 47 and 32 stations precipitation time series data for regional (western, central and eastern) study depicted in Fig. 1.

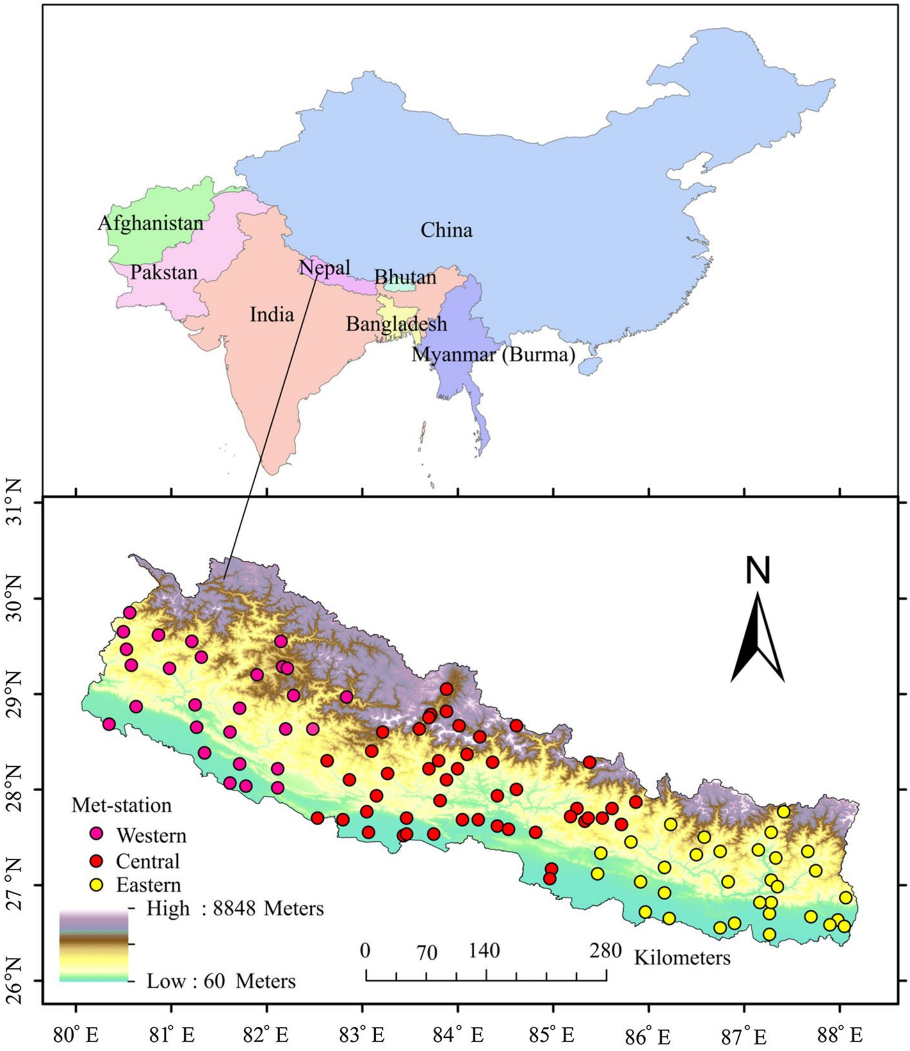

Fig. 1 Location map of the study area along with rainfall stations at different elevation

2.2 Data and methodology

The precipitation data were acquired from the Department of Hydrology and Meteorology, Government of Nepal. The Spatial distribution of the meteorological stations across the different regions of the study area is shown in Fig. 1. Stations were selected based on less than 3% missing records of the total number of annual values. Some high-altitude stations are used for spatial coverage being 30 year time series with 5–10% missing values. This study adopted the normal ratio method to estimate missing rainfall values of climate datasets from nearby 3 weather stations (Myronidis and Nikolaos 2021). Observed precipitation data selection criterion is based on the length, completeness and quality of the time series and records of the stations as possible as more enabling to identification 107 stations covering the years (1977–2018). Such strict criteria have been tested for continuous, homogeneous and consistent, high-quality rainfall data of used stations for further analysis.

2.3 Standard precipitation index (SPI)

SPI was developed for detecting, calibrating, quantifying and monitoring drought by using the long-term precipitation datasets (McKee et al. 1993). The SPI is uniquely related to probability and normalized so that wetter and drier climates of different time scales can be represented simultaneously (Hayes 2000). The index computation is simple and is based on precipitation only as an input. For this, a monthly precipitation dataset was prepared for a continuous period of at least 30 years. The outputs have multiple time scales of SPI (McKee et al. 1993). Previous researchers (McKee et al. 1993; Naresh Kumar et al. 2009; Sigdel and Ikeda 2010; Bagale et al. 2021) described SPI methodology in detail. SPI is simply a drought monitoring tool, frequently used in South Asia and widely accepted over the globe. In South Asia, it has been demonstrated by several researchers for drought monitoring in recent decades (Xie et al. 2013; Mondol et al. 2017; Khatiwada and Pandey 2019; Abeysingha, and Rajapaksha 2020; Uddin et al. 2020, Bagale et al. 2021).

In this study, the SPI was computed at 3-month time scales using "SPEI" package in R-statistical software. We define a 3-month time scale of SPI as SPI3. We generated the SPI data of 3-month scales for each 107 stations using monthly rainfall data (1977–2018). The threshold for indicating severity, extreme, severe, moderate, and mild drought of meteorological drought based on SPI has been adopted from (McKee et al. 1993) and tabulated in Table 1. Major drought episodes in the recent four decades were documented through spatial interpolations and were performed by the IDW algorithms (Patel et al. 2007). The interpolated maps of SPI3 have been presented using severities of SPI threshold (Table 1). For example, the interpolated 3-month SPI of February months was accumulated precipitation which is the total of the rainfall received in December, January and February.

Table 1 SPI classification thresholds based on McKee et al. (1993)

SPI values	Drought category
0 to −0.99	Mild drought
−1.00 to −1.49	Moderate drought
−1.50 to −1.99	Severe drought
−2.00 or less	Extreme drought

Individual station series of SPI3 time scales are used to recognize the variability for time length and also used to identify drought severities from SPI3 intensity. The SPI3 time scale index was used to identify and monitor, the severities, duration and spatial extent of winter drought events, which could be used in appropriate adaptation strategies to minimize the impacts of winter drought over Nepal. SPI3 time scale February was used to study the winter drought dynamics over different regions. The SPI3 time scale series of individual stations are investigated to examine the spatial and temporal SPI dynamics of major drought events over Nepal.

The nonparametric rank-based Mann–Kendall test (MK) was used to evaluate the time series data (Kendal 1975; Mann 1945; Salmi et al. 2002). Many researchers have used this method (Bagale et al. 2021; Nouri and Homaee 2020; Santos et al. 2017; Lena et al. 2013) to evaluate drought trends for SPI time scale over various countries of the world.

3 Results

3.1 Trend analysis of SPI3

We carried out MK trend test for winter SPI3 time scale over the country. The trends were identified using MAKESENS Template (Salmi et al. 2002), which depends on the Z value of individual stations; the increasing/decreasing trends were identified with reference to the positive/negative value of Z.

Station-wise significant trends were examined in different regions of Nepal for SPI3 time scale from 1977 to 2018. Out of the overall 107 stations, 1 station showed a significant increase, and 51 stations showed significant decreasing trends in different regions over Nepal.

Figure 2 shows the overall trends of SPI3 time scale over Nepal. Many of the stations of the country showed a decreasing trend for SPI3 time scales in winter. However, in the

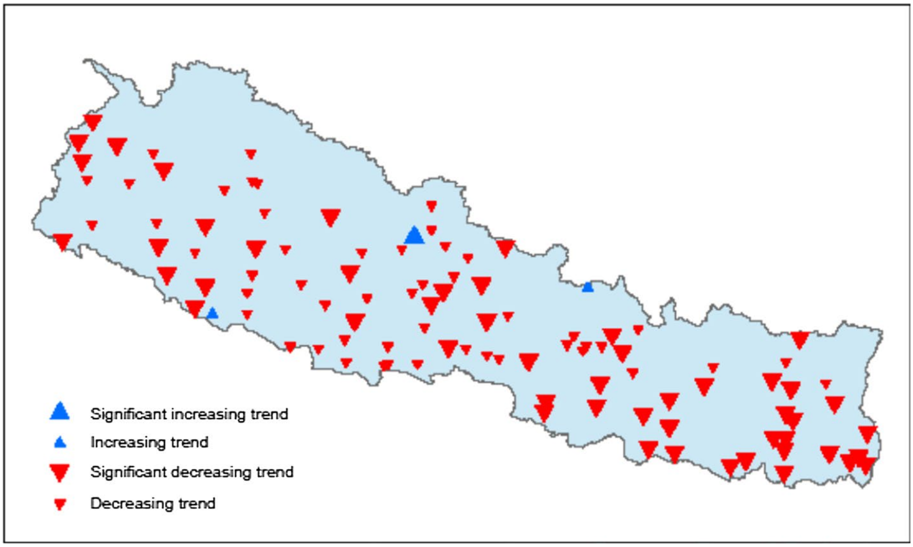

Fig. 2 Trends for SPI3 at each station over Nepal

eastern region, the significant decreasing trends were comparatively higher than in the central and western regions.

3.2 Temporal variability for SPI3 time scale

This study has used average monthly precipitation of 107 stations to generate the temporal variability for SPI3 time scale (Fig. 3). A season is defined as a winter drought season when the SPI3 time scale thresholds are < -1. The drought seasons are categorized based on the intensity of SPI3 time scale values. They are tabulated in Table 1.

We used SPI3 time scale intensity for the study of the deficit/excess winter events with year-to-year variability. The intensity of the SPI3 time scale values the categories and the severity of the drought and flood years. The deficit years were observed in 17 seasons, and the excess years were 24 seasons. Three-month SPI of February captured the deficiency or excess of precipitation for detecting drought and flood in Nepal. Eight winter drought years were 2006, 2009, 1999, 2018, 2017, 2008, 2016, and 2001 with average SPI3 time scale values which are −2.41, −2.26, −1.85, −1.7, −1.38, −1.33, −1.21, −1.01, respectively. And 5 winter excess years were 1989, 1998, 1996, 2007 and 2003 with SPI3 average time scale values were 1.78, 1.59, 1.31, 1.17, and 1.05.

Interestingly, in the recent decade (2008–2018) Nepal faced frequent winter drought episodes in the years 2008, 2009, 2016, 2017 and 2018 (Fig. 3). Winter drought of 2006 was the worst drought and followed by the 2009 and surplus year 1989 follower by year 1998, respectively, in the recent 4 decades' climatologically history of Nepal. The fluctuation of SPI3 time scale values ranges from (−2.41) in the drought year 2006 and (1.78) in the excess year 1989. Furthermore, from the Man-Kendell test we have identified an increasing trend of drought while carrying out the statistical test for SPI3 time series, which is at 95 percent confidence level (Fig. 3).

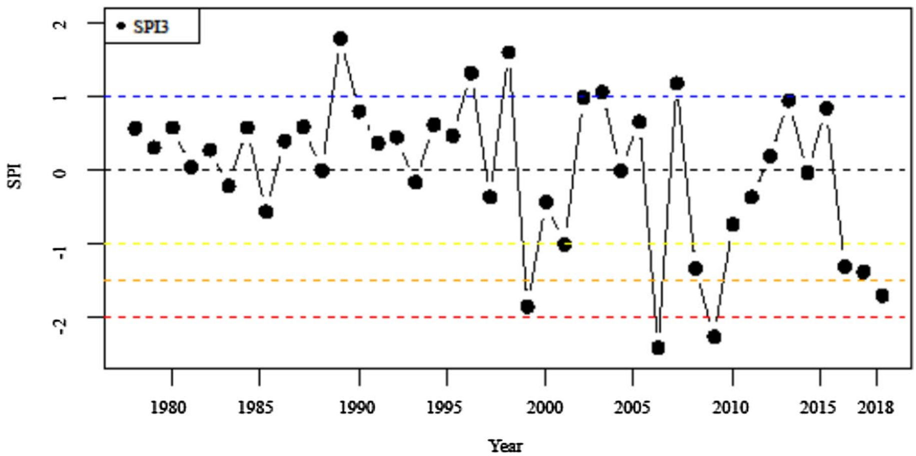

Fig. 3 Temporal variability for SPI3 during 1978–2018

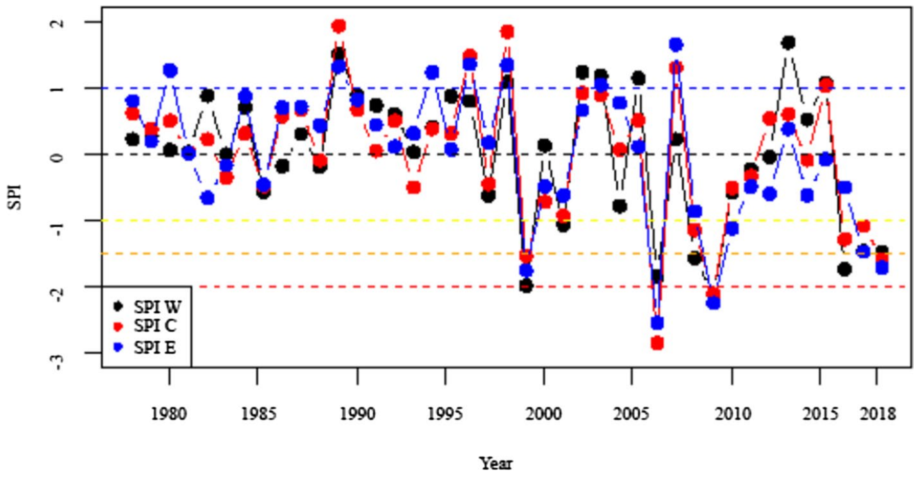

Fig. 4 Regional temporal variability for SPI3 time scale on the WCE regions

Table 2 The drought and flood years from 1977 to 2018

	Condition	Years							
	Drought	2009	1999	2006	2016	2008	2018	2017	2001
Western	SPI3 values	−2.1	−2.0	−1.8	−1.7	−1.6	−1.5	−1.5	−1.1
	Flood	2013	1989	2002	2003	2005	1998	2015	
	SPI3 values	1.68	1.51	1.23	1.18	1.14	1.08	1.07	
Central	Drought	2006	2009	2018	1999	2016	2008	2017	
	SPI3 values	−2.8	−2.1	−1.6	−1.5	−1.3	−1.1	−1.1	
	Flood	1989	1998	1996	2007	2015			
	SPI3 values	1.93	1.84	1.47	1.3	1.03			
Eastern	Drought	2006	2009	1999	2018	2017	2010		
	SPI3 values	−2.5	−2.2	−1.8	−1.7	−1.5	−1.1		
	Flood	2007	1996	1998	1989	1980	1994	2003	
	SPI3 values	1.65	1.35	1.34	1.32	1.26	1.23	1.04	

3.3 Regional temporal variability for SPI3 time scale

We have used average monthly precipitation of 28, 47 and 32 stations to generate the western, central and eastern (WCE) regional temporal variability for SPI3 time scale (Fig. 4). The drought events observed in winter season over the WCE regions of Nepal had different intensities. A regional comparative study of droughts in Nepal showed the diverse characteristics of SPI dynamics.

The temporal variability of winter drought/flood events observed in the WCE regions of Nepal is tabulated in Table 2.

Out of eight winter drought episodes, four drought episodes (1999, 2001, 2008 and 2016) of the western region affected more than the central and eastern regions. Similarly, in 2006 the central region of Nepal was affected more than in the eastern and western regions. The eastern region was affected more by the three drought episodes (2009, 2017 and 2018) than the central and western regions of Nepal. The western and central regions observed consecutive droughts in years 2008 and 2009 and in recent years 2016, 2017 and 2018. Similarly, in the eastern region, consecutive drought years were 2009 and 2010 and in the recent years 2017 and 2018. From Fig. 4, it has been identified that the western, central and eastern regions have increasing trend of drought while carrying out the statistical test for the trends of the western, central and eastern regions have the confidence level at 95 percent. The consecutive drought years are more hazardous on environmental issues causing crops and water scarcity. So, during the drought events in the hill and mountainous region livelihood is more challenging in these years than in the normal years.

3.4 Spatial overview of winter drought episodes

Interestingly, there were extreme, severe, moderate, and mild severities, of winter droughts over different regions of Nepal in each drought episode Fig. 5a–h. Each event had different characteristics over Nepal. There were severities of extreme, severe, moderate, and mild droughts in winter over Nepal during worst years in 2006 and 2009 Fig. 5c and e. From the Table 2 (Figs. 4 and 5), it has been observed that the drought intensity is generally severe-extreme in the western, central and eastern regions. The severities of drought-affected locations are clearly depicted through the spatial interpolation process which helps to identify the severities of extreme, severe, moderate, and mild drought over Nepal. The worst winter drought years 2006 and 2009 affected the larger areas of Nepal. In the winter seasons drought in 2006 and 2009; the percent proportional weightage was affected by extreme, severe, moderate and mild drought conditions in different regions over Nepal which are presented in Table 3. Around 96% of stations are negative SPI3 time scale values in worst winter drought years (2006, 2009) so large locations of Nepal affect the precipitation deficit in worst drought years. In comparison between the two worst winter drought years, in 2009, the western and central regions were affected by more extreme drought than in 2006. The severities of drought are simply identified, and understandings are shown in Fig. 5c, e. So, large locations in Nepal observed deficits in precipitation from the climatologically mean precipitation. Drinking water and winter agricultural practices point of view, these episodes were one of the most damaging periods over the study period. This study showed most of the western and central parts of Nepal recorded extreme and severe drought and most of the eastern part of Nepal recorded moderate drought in 2006 and 2009 with some exceptions.

Recent winter drought events in 2017 and 2018 interpolated through spatial processes which help to identify the severities of drought over Nepal which indicates that the drought events affected with severities of drought in the different regions of the nation. In drought year 2017, the western and eastern part of Nepal was affected by drought more than the central parts of Nepal. Particularly, most of the central part of Nepal was affected by mild drought (near normal), but the western and eastern parts of Nepal were affected by severe and moderate drought in 2017. Similarly, 2018 drought year affected far western Terai and the middle mountain region of central and most part of the eastern region, with severe and moderate drought and most of the high mountain region of the central part of Nepal was affected by mild drought (near normal) in 2018. Recent winter drought years of 2017 and 2018 affected drought severities (extreme, severe, moderate and mild) in different locations of Nepal, which is clearly depicted in Fig. 5g, h. Drought events recorded frequently are harmful to human beings from environmental aspects. Percentages of the stations that were

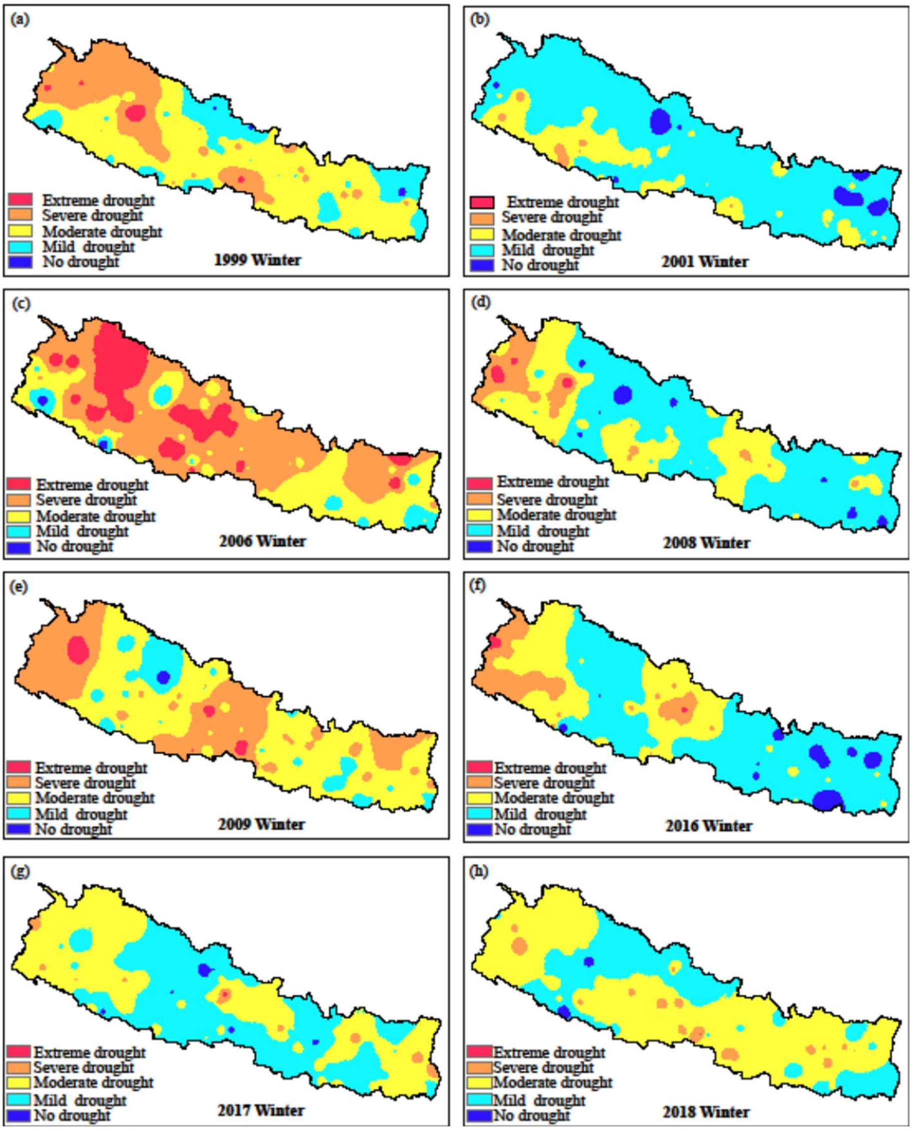

Fig. 5 Spatial distributions of (**a**) winter (SPI3) of 1999, (**b**) winter (SPI3) of 2001, (**c**) winter (SPI3) of 2006, (**d**) winter (SPI3) of 2008, (**e**) winter (SPI3) of 2009, (**f**) winter (SPI3) of 2016, (**g**) winter (SPI3) of 2017, and (**h**) winter (SPI3) of 2018

affected by extreme, severe, moderate, and mild drought severities over the country are tabulated in Table 3. Around 93% of stations have negative SPI3 values in the years 2017 and 2018. So, large parts of Nepal face the winter precipitation deficits. Drinking water, irrigation and agricultural and point of view, this event was also crucial and damaging to the study period (1977–2018).

The western part of Nepal was affected in most of the locations by severities of drought (extreme, severe and moderate drought) in the drought year, 1999. Eastern parts of Nepal were

Table 3 Winter drought severities based on stations proportion expressed in percent in different years over Nepal

Rank	Year	Ave SPI3	Extreme	Severe	Moderate	Mild
1	2006	−2.41	17.59	38.38	33.33	9.25
2	2009	−2.26	4.63	41.67	40.74	17.59
3	1999	−1.85	3.70	25.93	41.67	26.85
4	2018	−1.7	1	15	52	23
5	2017	−1.38	0.97	11.65	39.81	42.72
6	2008	−1.33	3.70	15.74	28.70	43.52
7	2016	−1.31	1.91	14.29	27.62	28.70
8	2001	−1.01	0	6.48	28.70	56.48

affected by severe and moderate drought. In 2001, some locations of the western region of Nepal were affected by moderate drought. Large numbers of locations in the central and eastern regions of Nepal were affected by the mild drought. In 2008, the western part of Nepal was affected by drought severities more than the central and eastern parts. In this episode, the central and eastern part is affected by mild drought. In 2016, the far western part of Nepal was affected by drought but the eastern part of Nepal is normal and central parts of Nepal near Pokhara and Annapurna regions were affected by drought. The individual drought year's severities extreme, severe, moderate and mild drought based on the proportional weightage of stations expressed in percent in different years is shown in Table 3. In these particular years, the different regions of Nepal have different rainfall dynamics.

Interestingly, droughts have been observed frequently since 2001 in Nepal. Drought events in recent decades were seen frequently in the years 2008, 2009, 2010, 2016, 2017 and 2018 in Nepal. There were different severities of drought, extreme, severe, moderate, and mild drought during major eight winter drought episodes in Nepal (Fig. 5a–h). The proportional weightage of severities of the drought episodes is tabulated in Table 3.

The magnitude and spatial severity of drought events were investigated from SPI3 time scale. There have been severe droughts during recent decades in drought episodes. During the 42 years, worst winter drought years were 2006 and 2009. These droughts severe extremes, severe, moderate and mild drought show the drought dynamics over the study areas. Spatial extent of severities of SPI3 time scale values is interpolated over Nepal in Fig. 5c and e for worst winter drought years. Similarly, the severities of the recent drought events (2017 and 2018) are depicted in Fig. 5g and h. During the study period, observed eight drought episodes out of which five drought episodes were in the recent decade (2008–2018). So we conclude that winter drought events in Nepal have increased generally in recent years. The overview of these SPI3 dynamics over Nepal could help to know the drought characteristics of typical drought episodes. The proportional weightage of winter drought severities for extreme, severe, and moderate drought are 4, 21 and 37%, respectively, during the study period 1977–2018. The proportional weightage of winter drought severities covered about 95% locations of in Nepal with negative SPI3 values.

4 Discussions

Trend analysis for SPI3 time scale showed a decreasing trend in Nepal. The Negative trends were steady for SPI3 time-scale in Nepal which is caused due to the reason that winter rainfall is dominated by the westerly. The trend for SPI3 time scale magnitude showed a decreasing tendency, indicating increasing winter drought over Nepal consistent with Karki et al. (2017).

Our results evaluate the frequency and severities of drought episodes which have increased in recent years. The winter, SPI3 time scales have identified eight major drought years. There were severities of percent of extreme, severe, moderate, and mild drought over different regions of Nepal during recent drought years. The results are similar to the findings presented by the previous researchers Sigdel and Ikeda (2010) who noted that the winter drought years 1974, 1977, 1985, 1993, 1999, and 2001 are from 1973 to 2003.

In recent years, Nepal has experienced consecutive and worsening drought episodes in years 2008–09 and 2016–2018. Drought events in Nepal have been increasing generally in recent years. The results are supported by some studies by Kumar et al. (2013), Fan et al. (2017) after 2000 droughts were frequently observed in South Asian regions. These drought events were crucial for agriculture, hydropower generation, drinking purposes and water resources planning and management as well as tourism aspects.

The regional study showed that the western region of Nepal was affected by drought for 8 years during the study period. Similarly, the central and eastern regions of Nepal were affected by drought in seven years (Table 2). When we studied the region-wise drought characteristics, there were distinguishing conditions due to winter rainfall-induced SPI3 dynamics over Nepal. The results of this research resemble those of a previous researcher (Wang et al. 2013) for western Nepal. They identified the worst winter drought years are 2006, 2008, 2009 and 2011. Similarly, Dahal et al. (2015) concentrated on a drought study in central Nepal and pointed the widespread winter drought years were 2006, 2008 and 2009.

The impact assessment of drought, drought hazard studies and risk analysis of drought events are very crucial for Nepal because nearly 60 percent of Nepalese people's livelihoods depend on agriculture (CBS 2013). Due to the worst winter drought observed in 2008–2009 reduced the yield of agricultural products such as wheat and barley by 14% and 17%, respectively, which created severe food scarcity in far- and mid-western hill and mountain regions (MoAC 2009). Extreme droughts impact negatively the yield of cash and cereal crops (Revadekar and Preethi 2012). This study showed that drought episodes in 2006 and 2009 were the worst during the last four decades. In these years' drought intensity and severity have been distinct in different regions over Nepal.

In worst drought first to third rank in the years 2006, 2009 and 1999, almost all locations of the country were affected by severity of drought. In the fifth rank drought episode, 2017 affected the western and eastern regions more than the central region. In the fourth rank, drought 2018 affected the eastern and far western part of the western region more than the central region. In 2008 and 2016, the far western region was more affected than other regions. In 2001, low lands and mid-mountains of the western region were affected by drought and almost all of the country was affected by mild drought. Also, the fluctuation of precipitation patterns has affected the drinking water, agriculture productivity and livelihood of the community. During the winter's worst drought years and recent events, the western and central parts of Nepal were more affected than the eastern parts with some exceptions.

5 Conclusion

This study designed SPI3 time-scale indices to provide concrete knowledge of winter droughts in Nepal. Among the drought episodes, the years 2006 and 2009 were extreme drought events in the country during the last four decades.

The country showed a negative trend for SPI3 time scale on many stations indicating that the drought episodes are increasing and becoming more frequent. Eight winter drought episodes were revealed and each episode has unique SPI3 time scale dynamics. Furthermore, three drought episodes in years 2009, 2017 and 2018 affected more on the eastern region with comparisons to other regions. Similarly, in 2006 the central region was more affected by the drought. The western region observed strong drought signals in the years 1999 2001, 2008 and 2016 than the central and eastern regions.

In the recent decade, Nepal has been observing more frequent winter droughts than in other decades. Moreover, the regional study showed that the western region of Nepal has been affected by droughts frequently in comparison with the central and eastern regions.

The proportional weightage of winter drought severities for extreme, severe, and moderate drought was obtained at 4, 21, and 37 percent, respectively. On average about 95% of the proportional weightage of winter droughts covered large locations of Nepal with the negative SPI3 values so Nepal faced the winter precipitation deficit in drought years.

These outputs are useful for water resource practices, design, and water allocations for mitigating the impact of winter drought hazards. Furthermore, these results are important for the assessment of drought impacts over the country.

Acknowledgements Nepal Government's Department of Hydrology and Meteorology is acknowledged for providing observed rain gauge data, and University Grant Commission, Kathmandu, Nepal, for financial support (U.G.C. Award No: PhD-75/76-S&T-11) was provided to the first author.

Funding The authors have not disclosed any funding.

Declarations

Conflicts of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abeysingha NS, Rajapaksha URLN (2020) SPI-based spatiotemporal drought over Sri Lanka. Adv Meteorol. https://doi.org/10.1155/2020/9753279

Bagale D, Sigdel M, Aryal D (2021) Drought monitoring over Nepal for the last four decades and its connection with Southern Oscillation Index. J Water 13:3411. https://doi.org/10.3390/w13233411

CBS N (2013) National Sample Census of Agriculture Nepal 2011/12, National Report

Chowdhury MR (2003) The el Niño-southern oscillation (ENSO) and seasonal flooding–Bangladesh. Theor Appl climatol 76:105–124. https://doi.org/10.1007/s00704-003-0001-z

Dahal P, Shrestha NS, Shrestha ML, Krakauer NY, Panthi J, Pradhanang SM, Lakhankar T (2015) Drought risk assessment in central Nepal: temporal and spatial analysis. Nat Hazards 80(3):1913–1932. https://doi.org/10.1007/s11069-015-2055-5

Dahal NM, Xiong D, Neupane N, Belayneh Y, Fang Y (2021) Spatiotemporal analysis of drought variability based on the standardized precipitation evapotranspiration index in the Koshi River Basin, Nepal. J Arid Land 13(5):433–454. https://doi.org/10.1007/s40333-021-0065-6

Fan F, Dong X, Fang X, Xue F, Zheng F, Zhu J (2017) Revisiting the relationship between the South Asian summer monsoon drought and El Niño warming pattern. Atmos Sci Lett 18(4):175–182. https://doi.org/10.1002/asl.740

Di Lena B, Vergni L, Antenucci F, Mannocchi F (2013) Analysis of drought inthe region of bruzzo (Central Italy) by the standarized Precipitation Index. Theoret Appl Climatol 115(1–2):41–52. https://doi.org/10.1007/s00704-013-0876-2

dos Santos SRQ, Braga CC, Sansigolo CA, de Araujo Tiburtino Neves TT, dos Santos APP (2017) Droughts in the Amazon: identification, characterization and dynamical mechanisms associated. Am J Clim Change 06(02):425–442. https://doi.org/10.4236/ajcc.2017.62022

Hagman G, Beer M, and Wijkman A (1984) Prevention better than cure: report on the manand natural disasters in the third world. Stockholm: Swedish Red Cross

Hayes MJ, Svoboda MD, Wilhite DA (2000) Monitoring Drought Using the Standardized Precipitation Index. http://digitalcommons.unl.edu/drought focpub/70

Karki R, Talchabhadel R, Aalto J, Baidya SK (2016) New climatic classification of Nepal. Theoret Appl Climatol 125(3–4):799–808. https://doi.org/10.1007/s00704-015-1549-0

Karki R, Hasson S, Schickhoff U, Scholten T, Bohner J (2017) Rising precipitation extremes across Nepal. Climate. https://doi.org/10.3390/cli5010004

Kendall S (1975) Enhancement of conditional reinforcement by uncertainty. Jexp Anal Behav 24(3):311–314

Khatiwada KR, Pandey VP (2019) Characterization of hydro-meteorological drought in Nepal Himalaya: a case of Karnali River Basin. Weather Clim Extr. https://doi.org/10.1016/j.wace.2019.100239

Kumar KN, Rajeevan M, Pai D, Srivastava A, Preethi B (2013) On the observed variability of monsoon droughts over India. Weather Clim Extremes 1:42–50. https://doi.org/10.1016/j.wace.2013.07.006

Lang TJ, Barros AP (2002) An investigation of the onsets of the 1999 and 2000 monsoons in central Nepal. Mon Weather Rev 130(5):1299–1316. https://doi.org/10.1175/1520-0493(2002)130<1299:AIOTOO>2.0.CO;2

Lang TJ, Barros AP (2004) Winter storms in the Central Himalayas. J Meterol Soc Jpn 82(3):829–844

Mann HB (1945) Nonparametric tests against trend. Econometrica 13(3):245–259. https://doi.org/10.2307/1907187

McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. In: Paper presented at the proceedings of the 8th Conference on Applied Climatology

MoAC WFP, Fao (2009) Crop and food security assessment: Joint assessment report. Retrieved from https://documents.wfp.org/stellent/groups/publicldocuments/ena/wfp202832.pdf, microdata.cbs.gov.np

Mondol MAH, Ara I, Das SC (2017) Meteorological drought index mapping in Bangladesh using standardized precipitation index during 1981–2010. Adv Meteorol. https://doi.org/10.1155/2017/4642060

Myronidis D, Nikolaos T (2021) Changes in climatic patterns and tourism and their concomitant effect on drinking water transfers into the region of South Aegean. Greece Stoch Environ Res Risk Assess 35:1725–1739

Naresh Kumar M, Murthy CS, Sai MVR, Roy PS (2009) On the use of standarized precipitation index for drought intensity assessment. Meteorol Appl: A J Forecast Pract Appl Train Techniq Model 16(3):381–389

Nouri M, Homaee M (2020) Drought trend, frequency and extremity across a wide range of climates over Iran. Meteorol Appl 27(2):1–19. https://doi.org/10.1002/met.1899

Patel NR, Chopra P, Dadhwal VK (2007) Analyzing spatial patterns of meteorological drought using stndard precipitation index. Meteorol Appl. https://doi.org/10.1002/met.33

Revadekar JV, Preethi B (2012) Statistical analysis of the relationship between summer monsoon precipitation extremes and foodgrain yield over India. Int J Climatol 32(3):419–429. https://doi.org/10.1002/joc.2282

Salmi T, Matta A, Anttila P, Ruoho-Airolo T, Amnell T (2002) Detecting trends annul values of atmospheric pollutants by the Mann-Kendall test and sen's slope estimates- the excel template application MAKESENS. Helsinki: Finnish Meteorological Institute. Retrieved Aug 2002

Seko, K, Takahashi T (1991) Glacier inventory of the Langtang valley, Nepal Himalayas. In: Contribution from the institute of low temperature science series A, vol 50. pp 47–72

Shrestha AB, Wake CP, Dibb JE, Mayewski PA (2000) Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale. Int J Climatol 317–327

Sigdel M, Ikeda M (2010) Spatial and temporal analysis of drought in Nepal using standrdized precipitation index and its reltionship with climate indices. J Hydrol Meteorol 7(1):59–74. https://doi.org/10.3126/jhm.v7i1.561

Sigdel M, Ikeda M (2012) Summer monsoon rainfall over Nepal related with large-scale atmospheric circulations. Earth SciClim Change. https://doi.org/10.4172/2157-7617.1000112

Uddin MJ, Hu J, Islam ARMT, Eibek KU, Nasrin ZM (2020) A comprehensive statistical assessment of drought indices to monitor drought status in Bangladesh. Arab J Geosci. https://doi.org/10.1007/s12517-020-05302-0

Varikoden H, Revadekar J, Choudhary Y, Preethi B (2015) Droughts of Indian summer monsoon associated with El Niño and Non-El Niño years. Int J Climatol 35:1916–1925. https://doi.org/10.1002/joc.4097

Wang SY, Yoon JH, Gillies RR, Cho C (2013) What caused the winter drought in Western Nepal during recent years? J Clim 26(21):8241–8256. https://doi.org/10.1175/JCLI-D-12-00800.1

Wilhite DA, Svoboda MD, Hayes MJ (2007) Understanding the complex impacts of drought: a key to enhancing drought mitigation and preparedness. Water Resour Manage 21(5):763–774. https://doi.org/10.1007/s11269-006-9076-5

Xie H, Ringler C, Zhu T, Waqas A (2013) Droughts in Pakistan: a spatiotemporal variability analysis using the Standardized Precipitation Index. Water Int 38(5):620–631. https://doi.org/10.1080/02508060.2013.827889

Zargar A, Sadiq R, Naser B, Khan FI (2011) A review of drought indices. Environ Rev 19(1):333–349. https://doi.org/10.1139/a11-013