Winter drought monitoring using Standard Precipitation Index over Nepal

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Research Article

Keywords: Drought, Man-Kendall test, Nepal, SPI, Variability

Posted Date: September 28th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2074322/v1

Version of Record: A version of this preprint was published at Natural Hazards on October 17th, 2023. See the published version at https://doi.org/10.1007/s11069-023-06242-0.

Abstract

The frequency of winter drought episodes marked frequently in the recent decade. This study examined the time series indices of drought variability over Nepal using historical data of 42-years (1977–2018) for 107 stations using Standardized Precipitation Index (SPI). Monthly rainfall was used as 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 the worst drought episode in the year 2006. However, in regional prospective the western region observed extreme drought episode in 2009. There was 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%.

1. Introduction

Drought is considered by many to 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, et al., 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 is difficult to determine (Donald A Wilhite, 2000). The characteristics and quantify of drought is 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 linkage between atmospheric large circulations with corresponds to El Niño and La Niña episodes in South Asia (Keshavamurty and Goswami, 2000; Varikoden et al., 2015; Chaudhry et al.,2003). 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). But, there was 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 for the winter precipitation in Nepal which is dynamically different from monsoon circulations (Barlow et al., 2002, 2005). However, winter precipitation (December to February) is significant as it accounts approximately about 3% of Nepal's annual precipitation total (Sigdel and Ikeda, 2012). The winter rainfall 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 the eastern and central Nepal (Seko and Takahashi, 1991). The major factor for drought evolution over Nepal is the lack of precipitation linked (westerly) circulations. Adequate understanding drought dynamics and subsequent impacts are required in Nepal. Major rivers of Nepal originated from Himalayans throughout the year. These rivers flow towards the Gangetic plain regions of India.

There were very limited winter drought studies concerned over Nepal. Sigdel and Ikeda, (2010) studied and point out drought events over Nepal. There are few regional and basin wise study concerned on winter drought events. Wang et al. (2013) has studied only for 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 the western Nepal. Similarly, winter drought study by Khatiwada and Pandey, (2019) has conducted over the Karnali region of the western Nepal; using different indices. Dahal et al. (2015) concentrated on drought study in the central Nepal and pointed that droughts have a crucial effects on livelihood of villager's people. Dahal et al. (2021) examined the spatio-temporal variability of drought episodes in Koshi river basin located in the eastern Nepal. Though, there is not any document 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 winter spatial drought variability on winter drought across the country. So this study has tried to study the overall drought statistics in winter deficit events in recent 42 years (1977–2018). The study of winter drought variability over Nepal is essential for the climatologically as well as socioeconomic prospective.

The main objective of this study is to quantify the winter drought events in Nepal during the recent 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 landlocked mountainous country situated in the central Himalayans of south Asian territory. The northern side situated Highland Tibet of china and remaining side's surroundings 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 low land of Terai 60 meters in southern plain to High land Mount Everest 8848 meters above sea level in Himalayans region towards North and the country extends 885 km from east to west and varies from130 km to 260 Km in north to south and covers an area of 147181 sq km (Bagale et al., 2021). Approximately 86% comprises of hilly and mountainous regions and the remaining 14% is flatland. The climate of Nepal varies tropical in the southern part to the cold arid steppe in the northern part (Karki et al., 2015). Furthermore, the country divided as 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.

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 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 years time series with 5–10% missing values were used. This study adopted Normal ratio method to estimate missing rainfall values of climate dataset from nearby 3 weather stations (Myronidis and Nikolaos, 2021). Observed precipitation data selection criterion based on the length, completeness and quality of the time series records of the stations as possible as more enabled to identify 107 stations covering the year (1977 to 2018). Such strict criteria have tested for continuous, homogeneous and consistency, high quality of rainfall data of used stations for further analysis.

2.2 Standard Precipitation Index (SPI)

SPI was developed to detecting, calibrating, quantify and monitoring of drought by using the long term precipitation data sets (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, et al., 1999l). The index computation is simple and is based on precipitation only as an input. For this, a monthly precipitation data set 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; Kumar et al., 2009; Sigdel and Ikeda. 2010; Bagale et al., 2021) were described SPI methodology in detail. SPI simply understands 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; Rupakheti and Pandey, 2017; Abeysingha, and Rajapaksha, 2020; Uddin et al., 2020, Bagale et al., 2021).

In this study, the SPI was computed at 3-month timescales using “SPEI” package in R-statistical software. We define a 3-month time-scale of SPI as SPI3. We were 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) tabulated on Table 1. Major drought episodes in recent four decades were documented through the spatial interpolations was 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 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 scale are used to recognition the variability for time length and also used to identify drought severities from SPI3 intensity. The SPI3 time scale index was used to identification, monitoring, 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 (M.K.) was used for 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., 2014) to evaluate drought trends for SPI time scale over various countries of the world.

3. Results

3.1. Trend analysis of SPI3

We were carried out MK trend test for winter SPI3 time scale over the country. The trends were identified Using MAKESENS Template (Salmi et al., 2002), depend on the Z value of individual stations; the increasing/decreasing trends were identified with reference 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. Overall 107 stations, 1 station showed significant increasing, and 51 stations showed significant decreasing trends in different regions over Nepal.

Figure 2 shows 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 eastern region the significant decreasing trends were comparatively high than 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 categories 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. Intensity of the SPI3 time scale values categories the severity of the drought and flood years. The deficit years were observed 17 seasons, and excess years were 24 seasons. 3-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 are − 2.41,-2.26,-1.85,-1.7,-1.38,-1.33,-1.21,-1.01 respectively. And 5 winter excess years were 1999, 1988, 1996, 2007 and 2003 with SPI3 average time scale values were 1.78, 1.59, 1.31, 1.17, and 1.05.

Interestingly, the recent decade (2008–2018) Nepal faced the frequently winter drought episodes in years 2008, 2009, 2016, 2017 and 2018 (Fig. 3). Winter drought 2006 was the worst drought and followed by the 2009 and surplus year 1999 followed by year 1988 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 1999.

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. Regional comparative study of droughts in Nepal showed the diverse characteristics of SPI dynamics. Individual drought year's drought variability due to western disturbances is distinct nature and intensity of drought is crucial for the water resources planning and management.

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

Table 2
The 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) the western region affected more than the central and eastern regions. Similarly, in 2006 the central region of Nepal affected more than in the eastern and western regions. And three drought episodes (2009, 2017 and

2018) the eastern region affected more than the central and western region of Nepal. The western and central regions observed the consecutive drought 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. The consecutive drought years are more hazardous on environmental issues causes the crops and water scarcity. So, during the drought events in the hill and mountainous region livelihood is more challenging than normal years.

3.4. Spatial overview of winter drought episodes

Interestingly, there were severities, extreme, severe, moderate, and mild of winter drought over different regions of Nepal in each drought episodes {Fig. 5 (a-h)}. Each event had different characteristics over Nepal. There were severities of extreme, severe, moderate, and mild drought in winter over Nepal during worst years in 2006 and 2009 {Fig. 5(c and e)}. The worst drought episodes affected more extreme drought comparatively in the western and central regions than 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 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. Comparisons between two worst winter drought years, in 2009 the western and central region affected more extreme drought than in 2006. The severities of drought are simply identified, and understandings are shown in Fig. 5(c, e). So, large locations of Nepal observed the deficits precipitation from the climatologically mean precipitation. Drinking water and winter agricultural practices point of view, these episodes were one of the most damaging period over the study period. This study showed most of the western and central part of Nepal recorded the extreme and severe drought and most of eastern part of Nepal recorded the moderate drought in 2006 and 2009 with some exceptions.

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

Around 93% of stations are negative SPI3 values in 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 of the study period (1977–2018).

The drought years in 1999 the western part of Nepal affected most of locations by severities of drought (extreme, severe and moderate drought). Eastern parts of Nepal affected by severe and moderate drought. In 2001 some locations of the western region of Nepal affected by moderate drought. Large locations of the central and eastern region of Nepal affected under mild drought. In 2008 the western part of Nepal affected by drought severities more than 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 affected by drought but the eastern part of Nepal is normal and central parts of Nepal near Pokhara and Annapurna regions 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 the recent decades were frequently in 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. 5 (a-h)}. The proportional weightage of severities of the drought episodes were tabulated in Table 3.

Table 3
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 magnitude and spatial severity of drought events were investigated from SPI3 time scale. There are severities of drought during recent decade in drought episodes. During the 42 years worst winter drought years were 2006 and 2009. These droughts severities extremes, severe, moderate and mild drought shows the drought dynamics over the study areas. Spatial extent of severities of SPI3 time scale values are interpolated over Nepal in Fig. 5(c and e) for worst winter drought years. Similarly, the severities of the recent drought events (2017 and 2018) are depicted in Fig. 5(g and h). During study period observed eight drought episodes out of those five drought episodes are in the recent decade (2008–2018). So we conclude winter drought events in Nepal are increasing generally in the recent years. With the overview of these SPI3 dynamics over Nepal could help to know the drought characteristics of typical drought episodes. The proportional weightage of winter droughts severities for extreme, severe, moderate drought are 4, 21, 37 and 33% during study period 1977–2018. The proportional weightage of winter droughts severities covered about 95% locations of Nepal with the negative SPI3 values.

4. Discussions

Trend analysis for SPI3 time scale showed decreasing 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 frequency and severities of drought episodes have increased frequently 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 with 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.

The recent years, Nepal has experienced consecutive and worsening drought episodes in years 2008-09 and 2016 to 2018. Drought events in Nepal were increasing generally in the recent years. The results are supported by some studies Kumar et al., (2013); Fan et al., (2013) after 2000 the droughts were frequently observed on 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 affected by drought in 8 years during the study period. Similarly, the central and eastern regions of Nepal affected through drought in seven years (Table 2). When we study the regional-wise drought characteristics, there were distinguishing conditions due to winter rainfall induced SPI3 dynamics over Nepal. The results of this research are resembled with a previous researcher (Wang et al., 2013) for western Nepal. They identified worst winter drought years are 2006, 2008, 2009 and 2011. Similarly, Dahal et al., (2015) concentrated on 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 livelihoods are depending on agriculture (CBS, 2013). Due to the worst winter drought observed in 2008–2009 reduced yield of agriculture products such as wheat and barley by14% and 17%, respectively which creates to severe food scarcity in far- and mid-western hill and mountain regions (MoAC, 2009). Extreme droughts impact negatively 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 are distinct in different regions over Nepal.

In worst drought first to third rank in years 2006, 2009 and 1999 all most all locations of country affected by severity of drought. In fifth rank drought 2017 the western and eastern region affected more than the central region. In forth rank drought 2018 the eastern and far western part of western region are more affected than central region. In 2008 and 2016 the far western region were more affected more than other regions. In 2001, low lands and mid-mountainous of the western region affected by drought and all most all of the country affected from mild drought. Also, the fluctuation of precipitation pattern has affected the drinking water, agriculture productivity and livelihood of the community. During the winter drought years of worst and recent events, the western and the central part of Nepal was more affected than the eastern parts with some exceptions.

5. Conclusion

This study designed SPI3 time-scale indices to provide conscience knowledge of winter droughts in Nepal. Among the drought episodes, the years 2006 and 2009 were extreme drought events of the country during the recent four decades.

The country showed a negative trend for SPI3 time scale on many of stations indicate the drought episodes are increasing and being 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 affected more drought signals. The western region observed strong drought signals in years 1999 2001, 2008 and 2016 than central and eastern regions.

In the recent decade Nepal observed frequently winter droughts than other decades. Moreover, the regional study showed that the western region of Nepal affected by droughts frequently in comparisons to the central and eastern regions.

The proportional weightage of winter droughts severities for extreme, severe, moderate drought was obtained 4, 21, and 37 percent respectively. In average about 95% 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 resources 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 country.

Declarations

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.

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.

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Figures

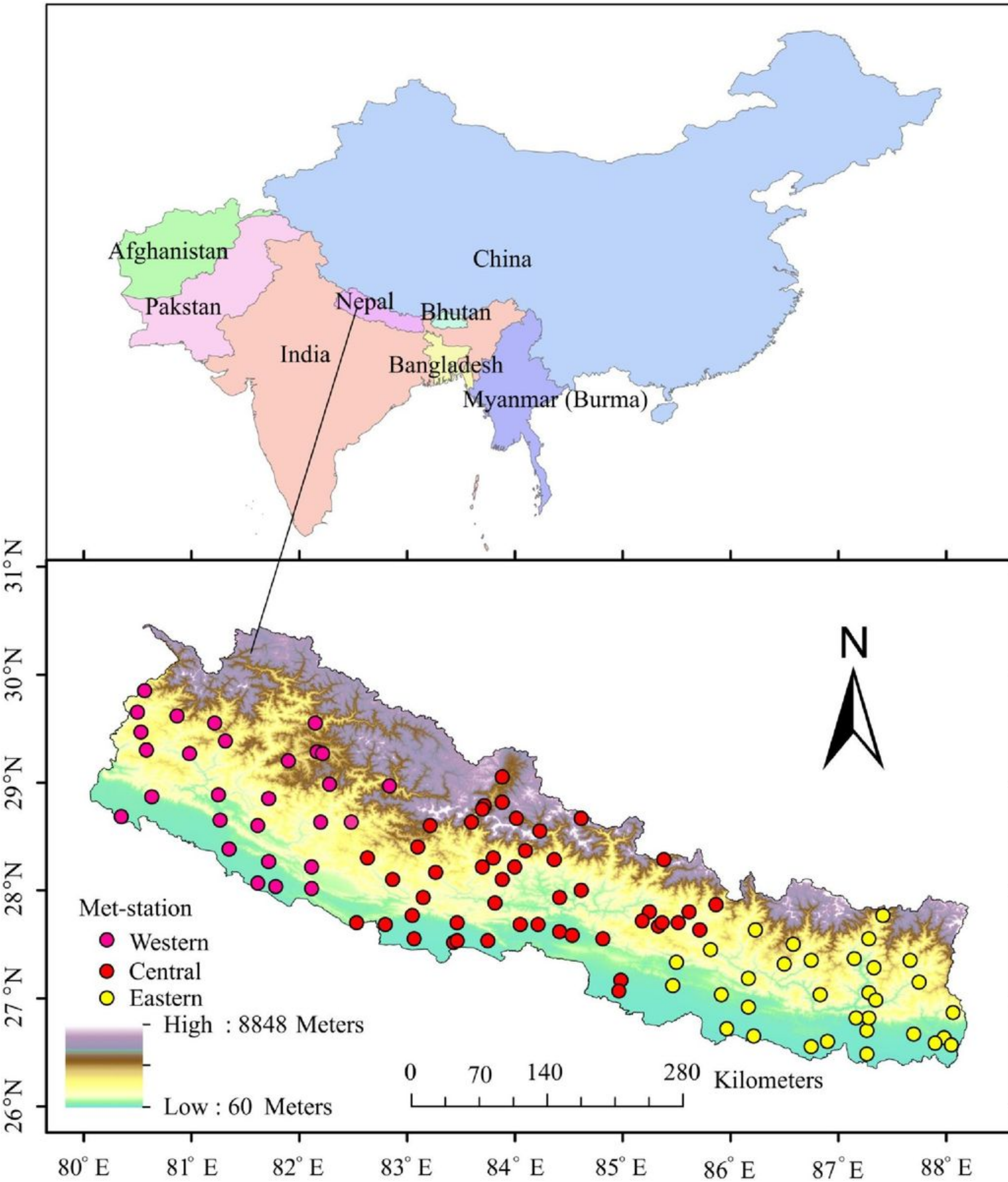

Figure 1

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

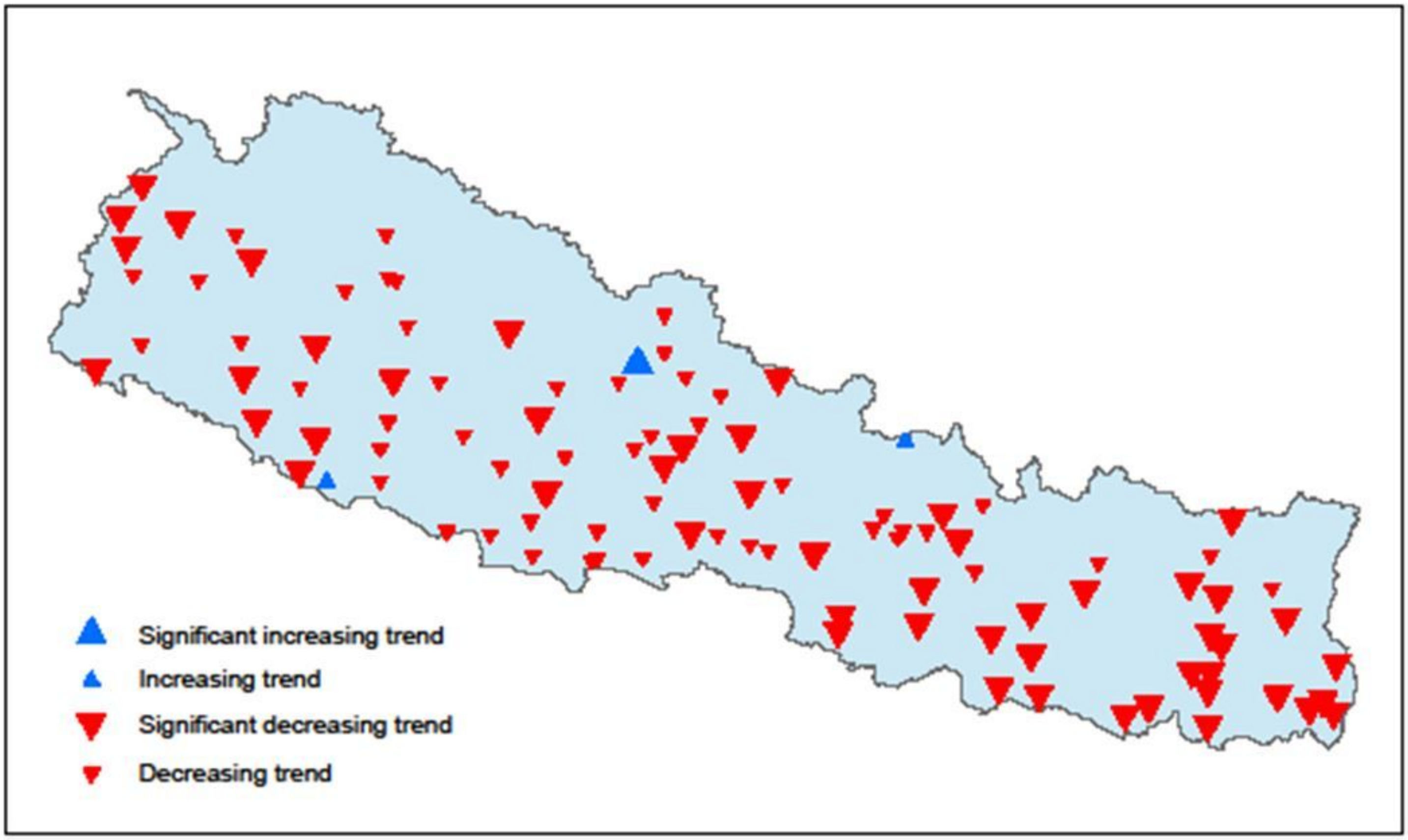

Figure 2

Trends for SPI3 at each station over Nepal

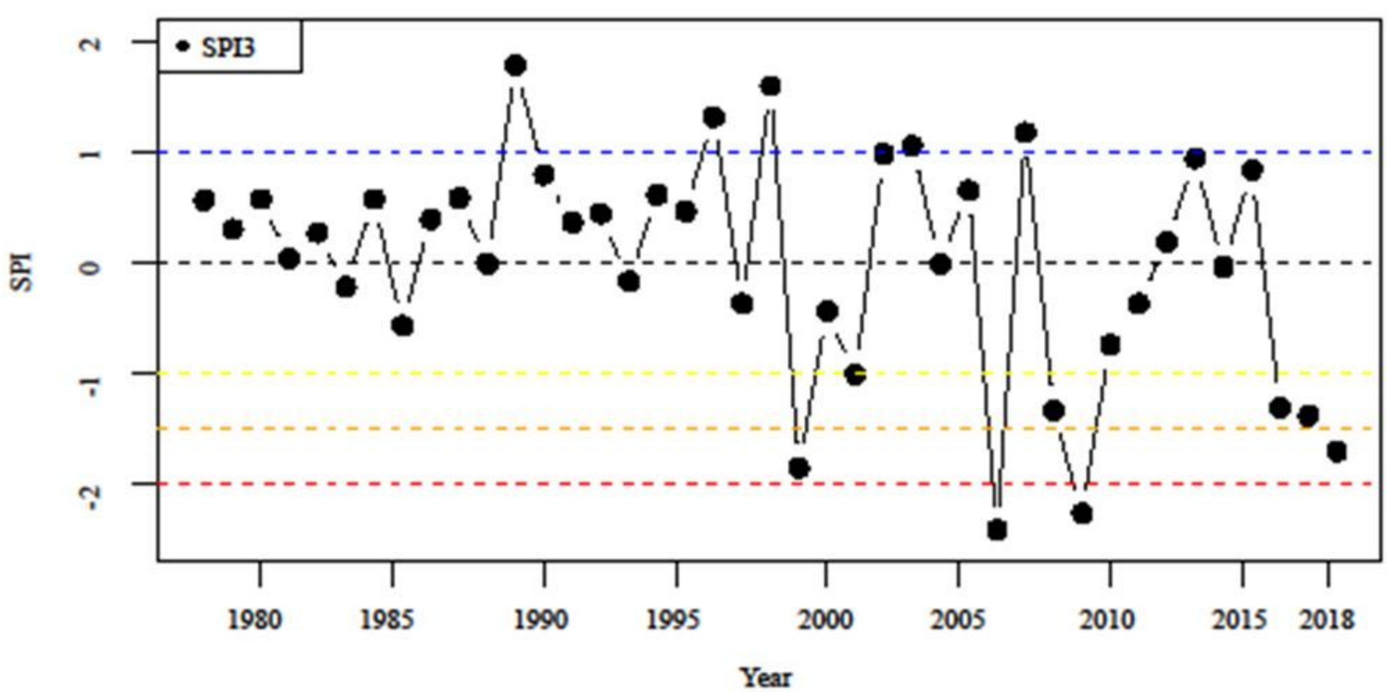

Figure 3

Temporal variability for SPI3 during 2017-2018

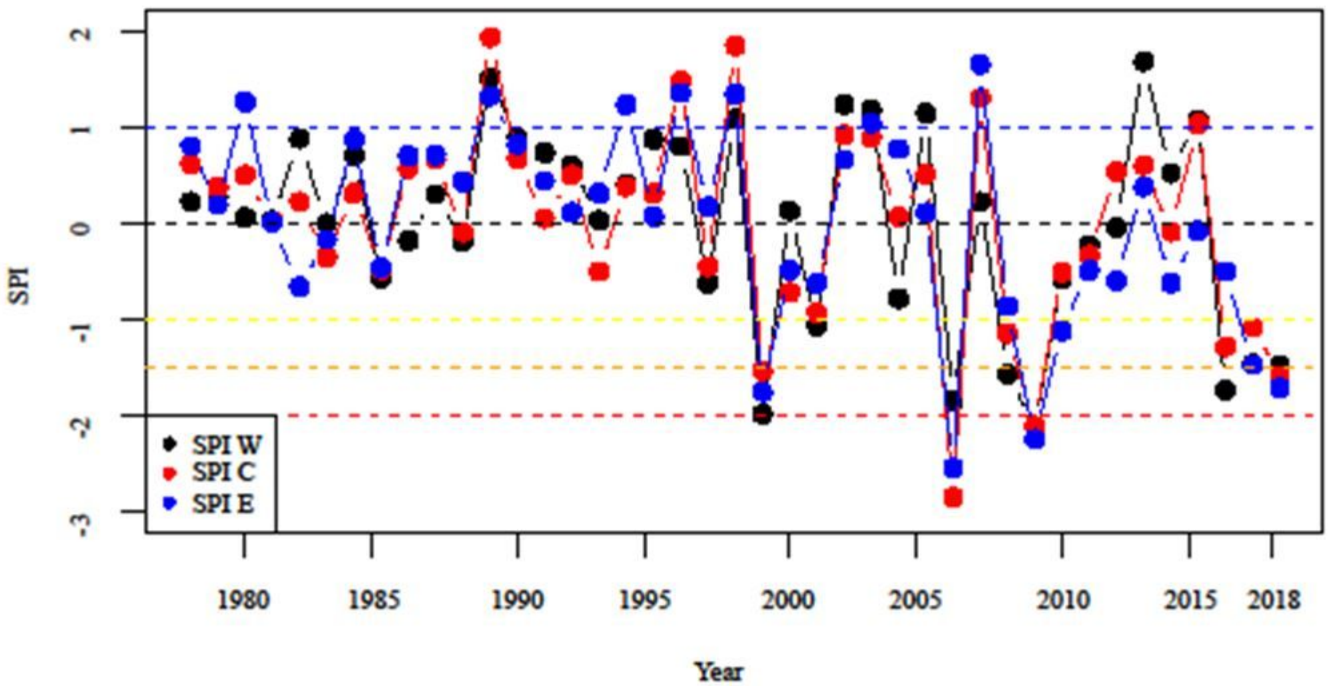

Figure 4

Regional temporal variability for SPI3 time scale on the WCE regions

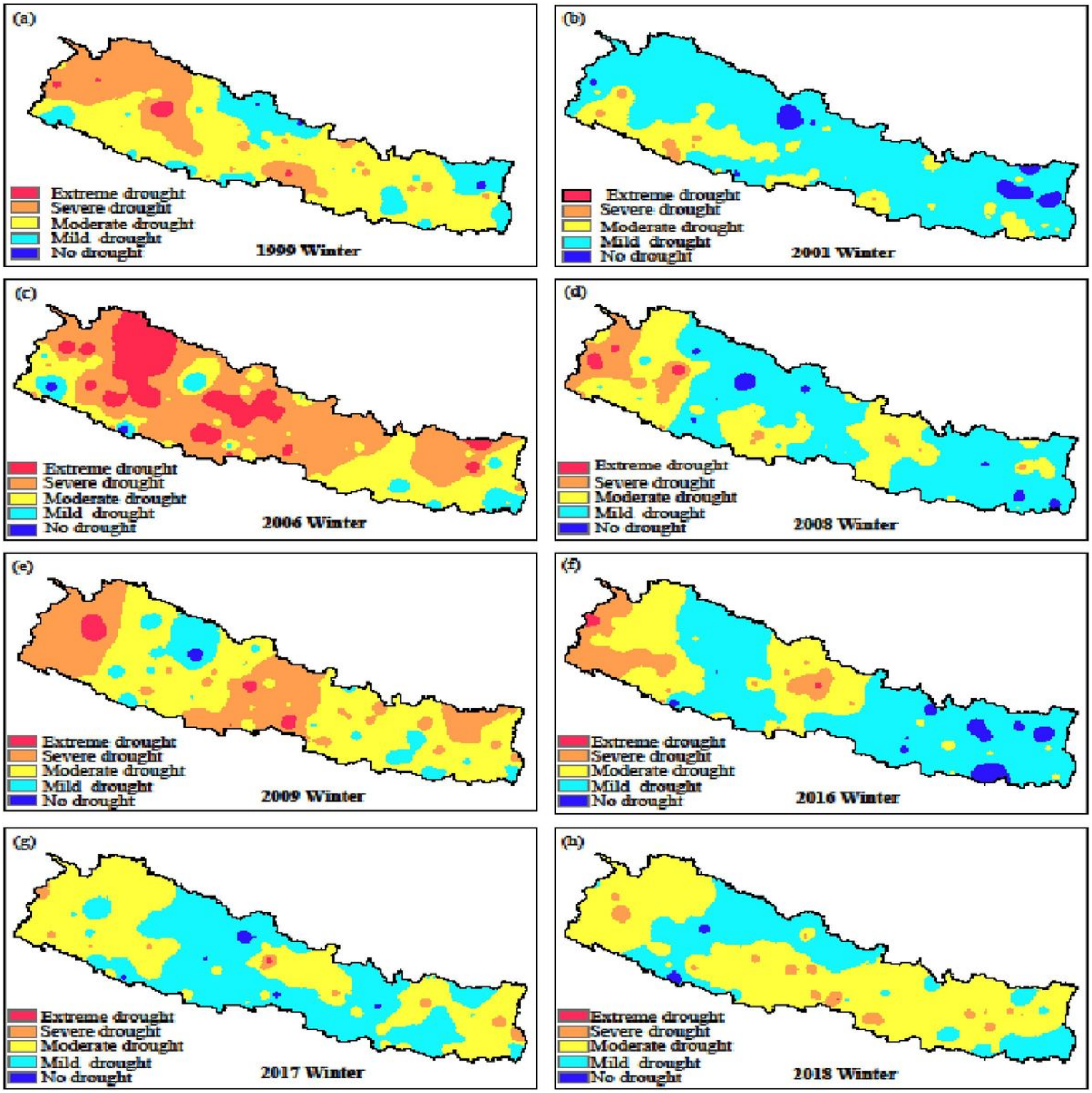

Figure 5

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.