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RESEARCH ARTICLE

DROUGHT MONITORING USING STANDARD PRECIPITATION INDEX IN WESTERN NEPAL

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ABSTRACT

This study used 28 meteorological stations' monthly precipitation data for 42 years (1977 - 2018) as input to generate a standardized precipitation index (SPI) for winter and monsoon. SPI3 and SPI4 are used in winter and monsoon droughts to investigate frequency, duration, and severity. This study identified monsoon droughts in 1977, 1979, 1987, 2004, 2005, 2006, 2009, and 2015. The 1979 was an extreme monsoon drought event. It has been revealed that extreme and severe droughts dominated western Nepal in 1979. Similarly, winter droughts were identified in 1999, 2001, 2006, 2008, 2009, 2016, 2017, and 2018. The winter drought event of 1999 is an extreme drought. This episode is dominated by extreme and severe drought in western Nepal. Eight (winter and monsoon) major droughts have diverse natures in different areas. The drought dynamics in each episode are different at various altitudes. Winter and monsoon droughts have been observed frequently since 2000. SPI and Southern Oscillation Index (SOI) correlation patterns indicate that extreme drought and SOI are comparatively stronger than general events. Furthermore, the relationship between seasonal rainfall and SOI is strong in monsoon and weak in winter.

KEYWORDS

Drought, Precipitation, Severity, SPI, Western Nepal.

1. INTRODUCTION

Drought is a prolonged period of dry conditions that impacts communities, in drinking water, agriculture, and livestock (Wilhite and Glantz, 1985). Low rainfall, high temperatures, strong winds, and increased evaporation temporarily cause drought. Human activities like deforestation and overgrazing can worsen drought conditions by decreasing the soil's ability to hold water (Abubakar and Yamusa, 2013; Adegboyega et al., 2016). Drought is a complex natural hazard, affecting millions and causing significant economic and environmental damage (Wilhite et al., 2007). It can result from climatic changes and poor land management practices. Drought impacts can be severe, especially when multiple droughts occur in sequence, affecting human welfare and the environment (Wilhite et al., 2007). Droughts have become more common and severe in recent years, impacting agricultural productivity (Gentle and Maraseni, 2012; Wang et al., 2013). Generally, drought types are meteorological, hydrological, agricultural, socioeconomic, and groundwater (Mishra and Singh, 2010).

Meteorological drought occurs when rainfall is significantly lower than usual. The SPI is applied to measure and monitor meteorological droughts. The SPI helps assess precipitation deficits over short and long periods and is critical for understanding their impact on agriculture and water resources. It is commonly used in South Asia to monitor drought (Chandrasekara et al., 2021). The SPI in Nepal accurately reflects drought duration and intensity (Khatiwada and Pandey, 2018). SPI has become a widely used tool for comparing droughts globally.

Warmer phases of large-scale circulations, ENSO influence drought in South Asia. During El Niño episodes, the drought in India becomes stronger than normal episodes (Balme and Jadhav, 1984). A group researcher examined the extreme events study in the Ganga plains of India and identified the extreme events increasing in recent years (Sharma et al., 2024). Nepal experienced similar conditions during the El Niño years, with strong monsoon droughts occurring in 1992 and 2015 (Bagale et al., 2021). Similarly, this region observed the worst winter drought in 2006 and 2009 (Bagale et al., 2024).

In Nepal, most research has concentrated on rainfall trends, with few previous studies addressing drought trends (Bagale et al., 2021; Dahal et al., 2016). According to a study, droughts are more frequent in the northwestern part for short-term drought (SPI3) and the northeastern part hit by long-term drought (SPI12), examined drought severity across Nepal (Sigdel and Ikeda, 2010). A studied drought in Central Nepal, identified 2006 and 2009 as extreme drought events from 1981- 2012 (Dahal et al., 2015). A studied drought in western Nepal indicated drought is caused due to weak westerlies in winter (Wang et al., 2013). Western Nepal is a drought-affected zone in Nepal compared to other regions (Bagale et al., 2021). The effect on livelihood and controlling migration of people from drought is challenging. The assessment of drought in this region is essential for better livelihood. The SPI trends showed an increasing drought pattern, especially at longer timescales (Bagale et al., 2021).

This study, covering 1977-2018, used the SPI index to analyze drought variations in terms of space and time in Western Nepal. It identified extreme winter and monsoon drought events and compared drought severities across physiographical regions.

2. MATERIALS AND METHODS

2.1 Study Area

Western Nepal extends from 27º 68'-30º 48' N in latitude and 80º 05'-83º 68' E in longitude; the altitudinal variation is from about 95 m in the southern plain (Terai) to 7750 m in the north. The western area extends topographically from the low to the northern high Himalayas. The met stations were used for the study (Figure 1).

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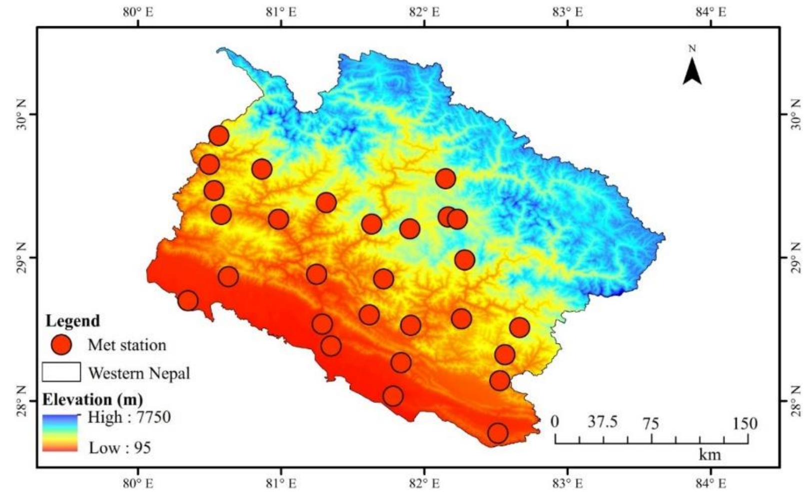

Figure 1: Location map of western Nepal, along with rainfall stations.

2.2 Data

Daily rainfall data for 42 years (1977–2018) was carried out by the Department of Hydrology and Meteorology (DHM), the Government of Nepal. This study adopted the Normal ratio method to estimate missing rainfall values of climate datasets from nearby weather stations (Bagale et al., 2023b). The data management process was adopted from (Bagale et al., 2023a).

Monthly SOI data sourced for the period 1977 to 2018 from the https://origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.

2.3 Standard Precipitation Index (SPI)

This study used the Standardized Precipitation Index to examine drought occurrence's temporal and spatial extents and severity (Mckee et al., 1993). SPI is simple and WMO-recommended software used by many researchers in South Asia and Nepal (Chandrasekara et al., 2021; Khatiwada and Pandey, 2018; Bagale et al., 2024). The detailed methodology is retained in previous studies (Mckee et al., 1993; Guttman, 1999; Hayes et al., 1999; Bagale et al., 2021; Dalina et al., 2013). This study followed the above-mentioned studies for SPI generation.

This study calculated the SPI for 3-month and 4-month periods using SPEI packages in R-Statistical software. The calculation relies only on precipitation data, and the results include SPI for different time scales. We referred to the 3-month SPI as SPI3 and the 4-month SPI as SPI4, which were used to identify droughts in winter and monsoon seasons respectively. A drought starts when the SPI falls below zero after reaching -1 or less, the threshold for severity based on the SPI values in Table 1, ends when the SPI becomes positive.

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

The Man-Kendal test was used to perform a trend of SPI3 and SPI4. Man-Kendal test has been utilized to find trends in climate time series data from various parts of the world (Dalina et al., 2013; Bagale et al., 2021).

3. Results

The SPI is used to assess drought conditions based on precipitation. It involves calculating SPI values, which represent the deviation of rainfall from its climatology, normalized by the long-term variability. SPI3 and SPI4 are used for winter and monsoon drought identification and monitoring in Western Nepal.

3.1 Trends of SPI3 and SPI4

Many of the used stations showed decreasing trends of SPI3 and SPI4 (Figure 2a and b). In SPI3, only three stations showed a significant decrease. Similarly, in SPI4, only two stations show significant decreasing trends. The decreasing trends of SPI3 and SPI4 indicate that in Western Nepal drought episodes are increasing.

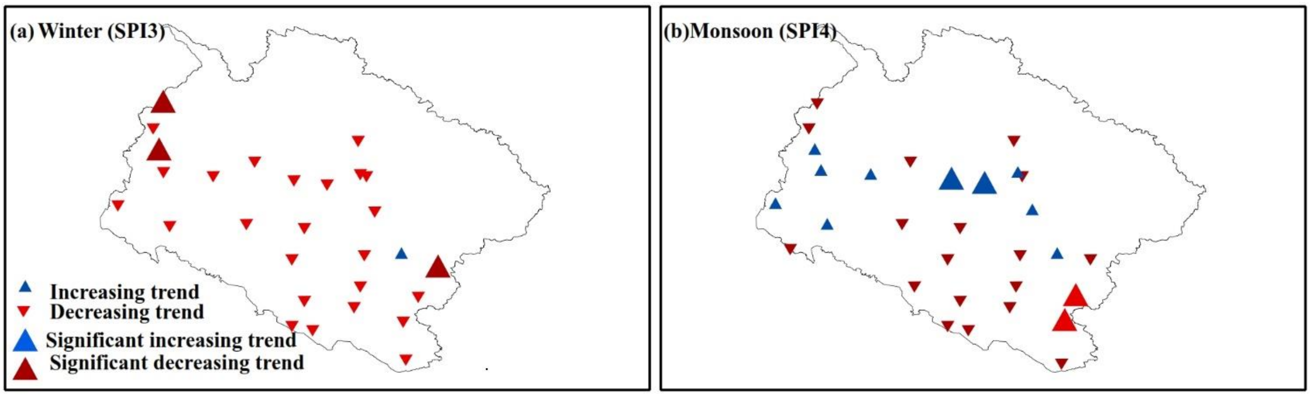

Figure 2: Station-wise (a) winter and (b) monsoon SPI trends in the western region from 1977-2018.

3.2 Temporal Variability of SPI3 and SPI4

The temporal pattern for SPI3 and SPI4 was produced using monthly precipitation of 28 stations, which is shown (Figure 3a and b). The variability of SPI3 was minimum in 2009 and maximum in 2013 (Figure 3a). Eight drought episodes have been observed in the years (1999, 2001, 2006, 2008, 2009, 2016, 2017, and 2018). The major winter drought episodes have different intensities. The intensities are tabulated in Table 2.

Table 2: The major drought years and the SPI3 values.		
Rank	**Year**	**SPI3**
1	2009	-2.12
2	1999	-1.98
3	2006	-1.84
4	2016	-1.73
5	2008	-1.56
6	2018	-1.47
7	2017	-1.46
8	2001	-1.07

In the winter season, 2009 experienced extreme drought, while 1999, 2006, 2016, and 2008 experienced severe drought. Similarly, 2018, 2017, and 2001 experienced moderate drought. The remaining years' SPI3 intensities are shown in Figure 3a.

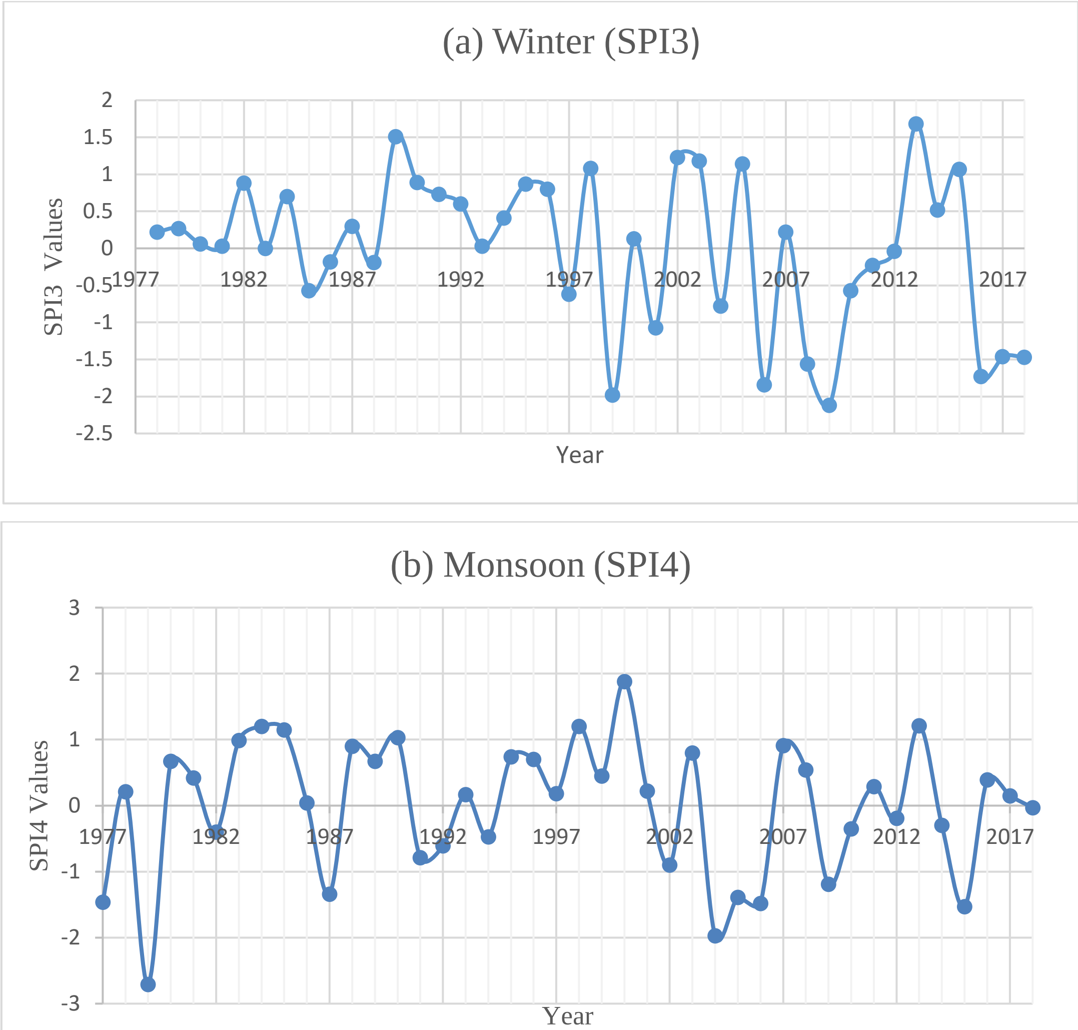

Figure 3: Temporal Variability of (a) SPI3 and (b) SPI4 from 1977-2018.

Similarly, the temporal pattern for SPI4 was produced using monthly precipitation, which is shown (Figure 3b). Based on SPI4 thresholds, 8 drought episodes were identified in the years (1977, 1979, 1987, 2004, 2005, 2006, 2009, and 2015). The magnitude of SPI4 ranges from -2.71 in 1979 to 1.89 in 2000. The major monsoon drought episodes have different intensities. The intensity of the major droughts is shown in Table 3.

Table 3: The major drought years and the SPI4 values.		
Rank	**Year**	**SPI4**
1	1979	-2.71
2	2004	-1.97
3	2015	-1.53
4	2006	-1.50
5	1977	-1.46
6	2005	-1.39
7	1987	-1.34
8	2009	-1.19

In the monsoon season, 1979 experienced extreme drought, while 2004, 2006, and 2015 experienced severe drought. Similarly, 1977, 2005, 1987, and 2009 experienced moderate drought. The extreme episodes have different intensities. The remaining years' SPI4 intensities are shown in Figure 3b.

3.3 Worst Winter Drought Episodes

The severities of the worst winter droughts in years (2009, 1999, 2006, and 2016) are shown in Figures 4a to 4d. In 2009, far western areas faced severe and extreme drought, while western Nepal dominated moderate drought. In 1999, northern regions had a severe drought, and the south had a moderate drought. Western Nepal was mostly affected by severe drought. In 2006, the upper areas faced extreme and severe drought, while western Nepal experienced extreme drought. In 2016, severe and moderate droughts affected far western areas, while eastern parts of western Nepal experienced mild drought.

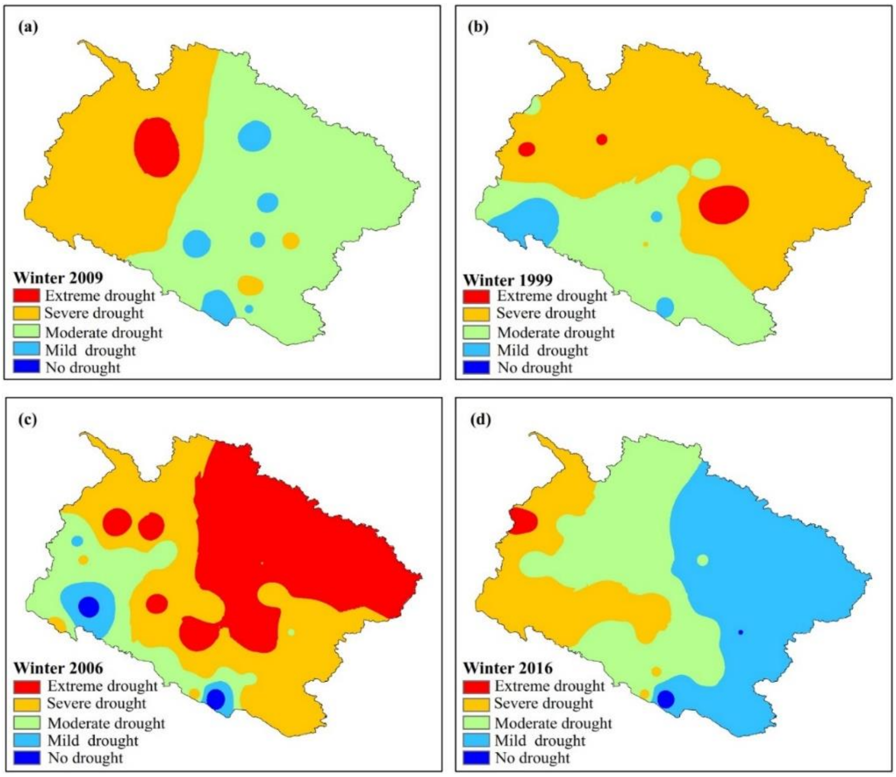

Figure 4: Spatial distributions of SPI3 for 2009, 1999, 2006, and 2016.

3.4 Major Winter Drought Episodes

The severities of the worst monsoon droughts in years (2008, 2018, 2017, and 2001) are shown in Figures 5a to 5d. In 2008, the Far West faced severe drought, the central western region had moderate drought, and the East experienced mild drought (Figure 5a). In 2018, western Nepal was mainly affected by moderate and mild drought in both the west and east experiencing these conditions (Figure 5b). In 2017, western Nepal had moderate drought (Figure 5c). In 2001, the lower areas faced moderate drought, and most regions had mild drought (Figure 5d).

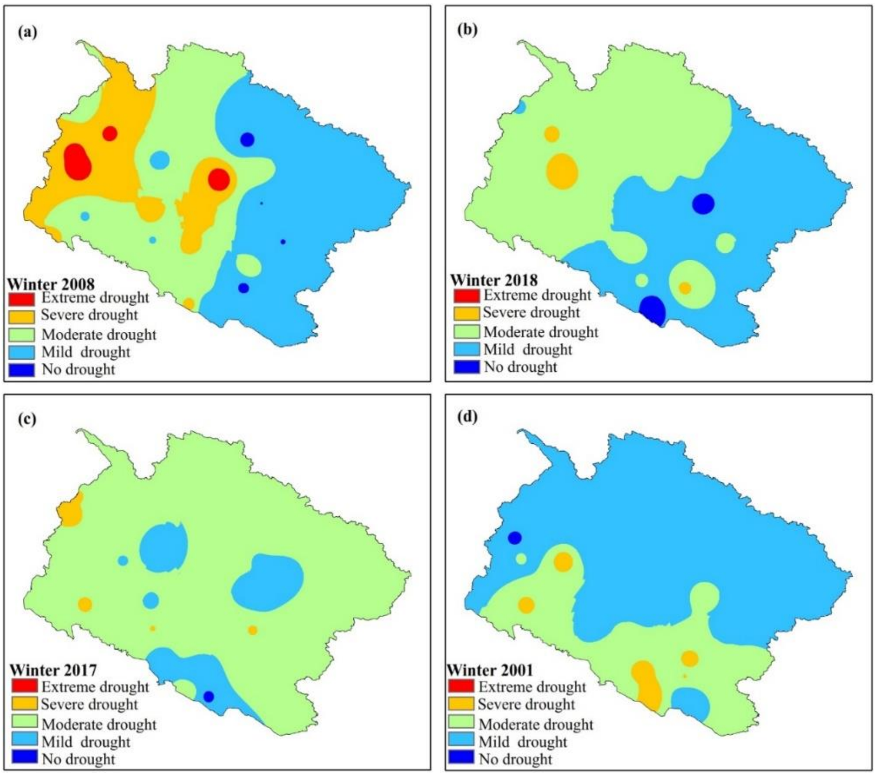

Figure 5: Spatial distributions of SPI4 for 2008, 2018, 2017, and 2001.

3.5 Spatial Distributions of Worst Monsoon Droughts

Droughts occurred during the monsoon episodes in 1979, 2015, 2006, and 2004. In 1979, western Nepal was affected by drought severities dominated by severe and extreme droughts (Figure 6a).

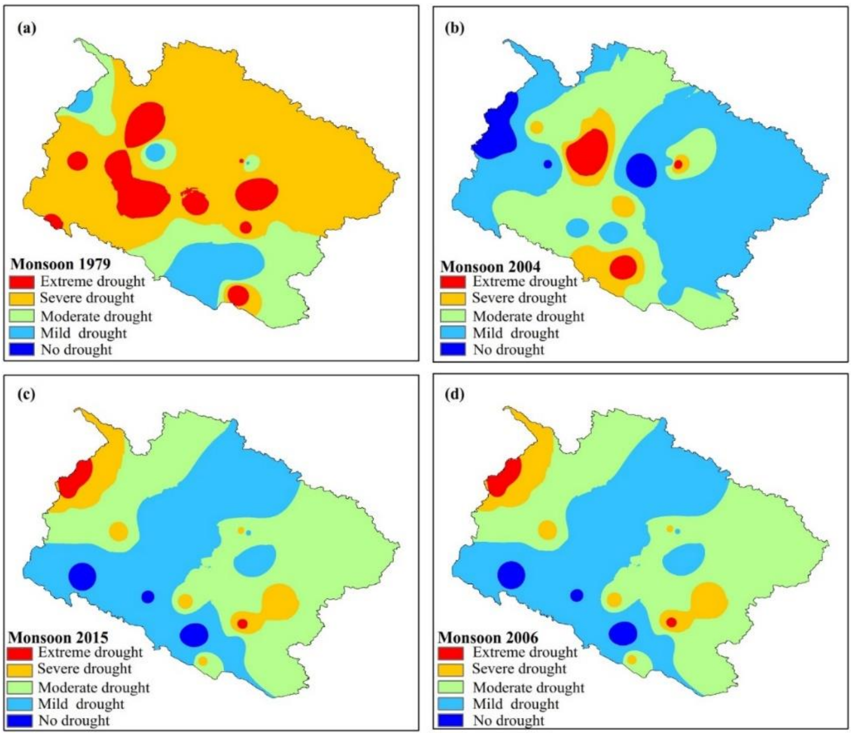

Figure 6: Spatial distributions of SPI4 for 1979, 2004, 2015, and 2006.

In 2004, extreme, severe, and moderate droughts affected the western region, with moderate and mild droughts widespread in various areas of western Nepal (Figure 6b). In 2015, Western Nepal experienced moderate drought, while the northern and eastern parts were hit by extreme and severe drought (Figure 6c). In 2006, far Western areas were dominated by extreme and severe conditions. However, moderate and mild droughts dominated the Western locations in 2006 (Figure 6d).

3.6 Spatial Distributions of Major Monsoon Droughts

In 1977, the western region mostly experienced mild drought and no drought conditions, with some lower areas affected by extreme and severe droughts (Figure 7a). In 2005, the western region was mainly affected by mild drought, while some upper parts faced severe, moderate, and extreme drought (Figure 7b). In 1987, lower areas of the lowlands were affected by extreme and severe droughts (Figure 7c). 2009 was dominated by the mild and moderate in the western region, although a severe drought afflicted the lower parts (Figure 7d).

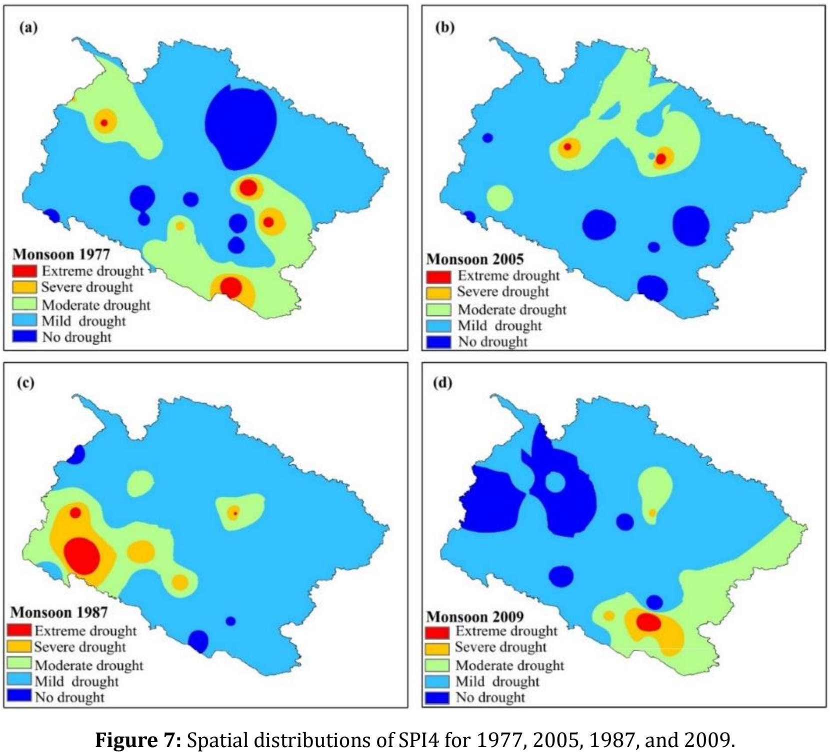

Figure 7: Spatial distributions of SPI4 for 1977, 2005, 1987, and 2009.

3.7 Relationship between SPI Scales and Climate Indices

The comparison between SPI4 and summer SOI shows a 76.17% in-phase relationship and 23.81% out-of-phase events. The correlation coefficient between SPI4 and summer SOI is 0.49 at a 95% confidence level. The relationship between SOI and SPI is stronger during the study period than in normal years. Typically, during drought, low summer SOI and negative SPI in Nepal are in phase, indicating that the SPI4 is influenced by the summer SOI. Similarly, during flood years, high SOI and the SPI are positive. Generally, during drought years, low summer SOI and negative summer SPI in western Nepal are in phase relation to warm phase periods.

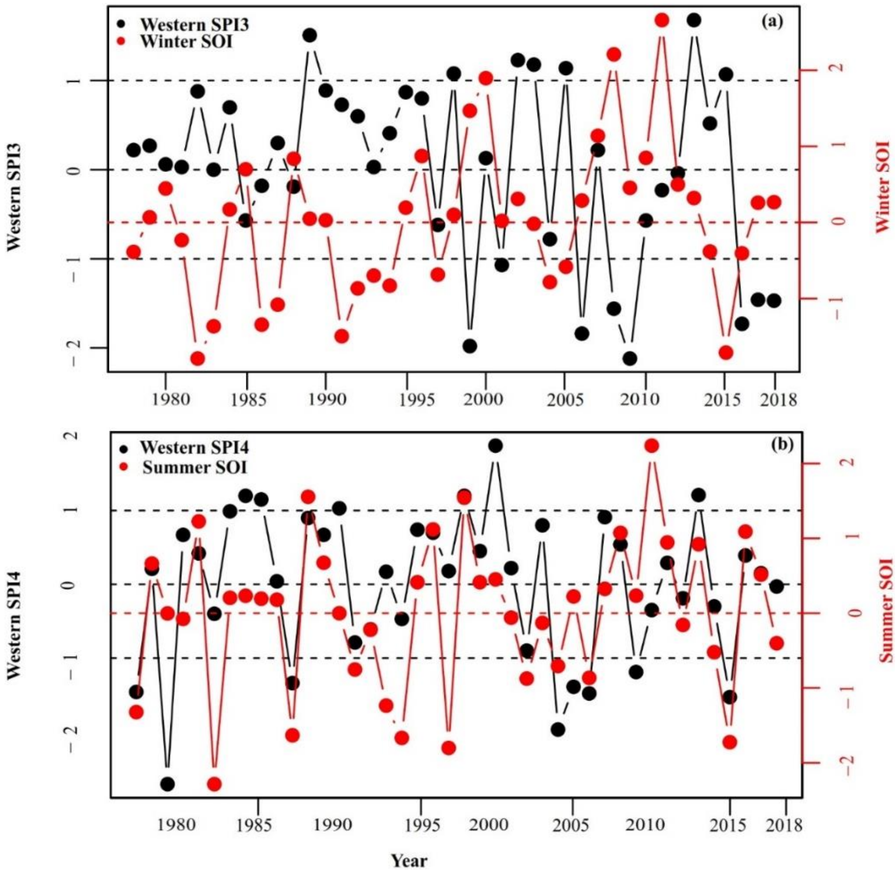

Figure 8: Relationship between SPI and SOI for winter and summer seasons in western Nepal.

The comparison between the western regions' SPI3 and the winter SOI shows a 60.98 % in-phase relationship and 39.02 % out-of-phase events (Figure 8a). The correlation coefficient between SPI3 and winter SOI is -0.31 at a 95 % confidence level. SPI3 and the winter SOI series are negatively correlated. Generally, during the drought/flood period, SOI and the SPI are (+/-).

Figures 8a and b show the phase relationships between SPI and SOI in winter and monsoon seasons. During the monsoon season, drought events have low SOI and SPI, while floods correspond to high values of both. Similarly, in the winter phase, the relation between SPI and SOI is displayed in Figure 8b.

Figures (8a and b) indicate drought/flood episodes in western Nepal. The eight winter drought episodes are presented in Table 2. The flood episodes are in the years (1989, 1988, 2003, 2004, 2014, and 2016) (Figure 8a). The monsoon droughts are presented in Table 3. The flood episodes are in the years (1984, 1985,1990,1998,2000, and 2013) (Figure 8b). Figures (8a and b) show that the extreme episodes have been more frequent since 2000.

4. Discussion

The SPI3 and SPI4 time scales decreased at many stations in Western Nepal, indicating rising drought frequency due to decreasing winter and monsoon rainfall. This pattern aligns with previous studies (Karki et al., 2017; Bagale et al., 2021). Similar results are observed in central Nepal (Dahal et al., 2015). According to a study, the frequency and severity of seasonal and annual drought episodes have increased frequently in recent years (Bagale et al., 2021). For SPI4 and SPI3, studies have identified eight major drought episodes in monsoon and eight winters in Nepal. The earlier study supports the results of the present study, which determined the eight summer and eight winter drought episodes in western Nepal. The main cause of the drought formation is the deficit of precipitation. According to a study in drought years, the monsoon systems are weaker than usual in tropical oceans (Fan et al., 2017). A group researcher remarked in India, monsoon droughts exposed to El Niño are characterized by tropical sea surface temperature (Krishna Kumar et al., 2013).

Our findings show that recent years' monsoon droughts occurred in 1977, 1979, 2004, 2005, 2006, and 2015 in western Nepal. The 1977 and 1979 were extreme events due to monsoon droughts during the last four decades. Similarly, winter droughts have been observed over the years (1999, 2001, 2006, 2008, 2009, 2016, 2017, and 2018). This trend toward drier circumstances is in line with the findings of previous researchers, drought performed in various regions of Western Nepal (Bagale et al., 2021; Wang et al., 2013). Anthropogenic global warming has caused deficit monsoons and droughts in India (Krishna Kumar et al., 1999). The favorable conditions of drought have been influenced by the El Niño in South Asia (Fan et al., 2017). Furthermore, according to most of study, these dry spells have a significant negative influence on agriculture productivity (Gentle and Maraseni, 2012; Wang et al., 2013).

The study identified eight major monsoon drought episodes from 1977 to 2015, varying severity levels, including extreme droughts in 1977 and 1979. These findings are consistent with earlier research (Bagale et al., 2021; Bangladesh Chaudhary, 2003). In recent years, the dry episodes have increased due to the changing climate in South Asia (Fan et al., 2017). Due to dry episodes, the livelihood of western Nepal has become challenging nowadays due to water scarcity, so drought assessment work is necessary in Western Nepal, for a better livelihood (Wang et al., 2013).

5. Conclusion

This study used the SPI3 and SPI4 time scales for winter and monsoon drought severity, duration, and frequency in western Nepal during the past 4 decades. Many stations across western Nepal displayed a negative trend for the SPI3 and SPI4 time scales. The frequency and severity of drought episodes are rising. Eight monsoon and eight winter droughts have been observed in years (1977, 1979, 1987, 2004, 2005, 2006, 2009, and 2015) and (1999, 2001, 2006, 2008, 2009, 2016, 2017, and 2018) respectively. Out of them, 2009 and 1999 are the first and second ranks of the winter drought. Similarly, in monsoon 1979, it was an extreme event that was followed by 2004. The drought events have become more frequent after 2000. There is a unique pattern of drought in each drought episode. The connection between SPI and climatic indices for SOI is strong in monsoon and weak in winter in western Nepal. These findings are important for better management of water-related projects. The study recommended further study that a tropical atmospheric circulation system is important for extreme climatic events.

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Conflicts of Interest

The authors declare no conflicts of interest.

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