Meteorological Drought Assessment in Koshi and Sudurpaschim Provinces, Nepal

Isha KC[1]*, Brinda Adhikari[1], and Rijan Bhakta Kayastha[2]

[1]*Department of Environmental Science and Engineering, School of Science, Kathmandu University, Bakhundol, Ward No. 4, Dhulikhel Municipality, Kavrepalanchowk district 45200, Bagmati Province.*

[2]*Department of Environmental Science and Engineering, Himalayan Cryosphere, Climate and Disaster Research Center (HiCCDRC), School of Science, Kathmandu University, Bakhundol, Ward No.4, Dhulikhel Municipality, Kavrepalanchowk district 45200, Bagmati Province.*

(Received 06 August 2024; Accepted 01 December 2024)

ABSTRACT

Drought, characterized by prolonged periods of reduced precipitation and water scarcity, poses significant challenges as a creeping disaster. This study focuses on assessing meteorological drought patterns using the Standard Precipitation Index (SPI) in the Koshi and Sudurpaschim provinces of Nepal from 1980 to 2023. Additionally, it incorporates climate change considerations in drought analysis and utilizes projected precipitation data for the period of 2025-2060 which are bias-corrected ensembles of thirteen GCMs of CMIP6 Project. The findings indicate a consistent trend of dry conditions in the Koshi region since 2005, marked by extreme fluctuations. In contrast, Sudurpaschim has experienced increased precipitation and demonstrated a more stable pattern over the years. Projections suggest heightened drought conditions in both provinces during 2026/2027, 2032/2033, 2045/2046, and 2058, highlighting the need for proactive measures. However, there is a notable trend towards increased precipitation in the far future for both regions. Particularly concerning is the occurrence of winter drought in both provinces across all regions, emphasizing the urgency for targeted strategies to mitigate water scarcity during this critical season.

Keywords: Meteorological Drought Assessment, Climate change, Sudurpaschim province, Koshi province and Standard Precipitation Index

1. Introduction

Drought is a natural disaster that occurs gradually and is caused by a lack of precipitation, which is worsened by climate change and human activities (Eriyagama et al., 2009). Drought impacts water resources, agriculture, biodiversity, and livelihoods reducing crop production, increasing food insecurity, and heightening the risk of wildfires (Wu et al., 2019; Sidiropoulos et al., 2021; Stirling et al., 2020; Bista et al., 2020). In Nepal, where agriculture is vital, drought manifests through delayed monsoons and insufficient rainfall, aggravating food insecurity. Nepal's diverse topography results in varied precipitation patterns across regions. In the western region, shorter and less intense summer monsoons make it prone to pre-monsoonal and monsoonal droughts. Conversely, the eastern region, while receiving early summer rain, faces pre-monsoonal droughts in certain leeward areas due to orographic relief. Moreover, the eastern region is vulnerable to winter drought, impacting winter wheat production. To comprehensively capture these variations, our study focuses on Sudurpaschim in the far west and Koshi in the east. Meteorological drought serves as a precursor to agricultural and hydrological drought, although the progression is nonlinear. Understanding meteorological drought is crucial in grasping the broader drought phenomenon. Drought Indices (DIs) serve as proxies for quantifying and monitoring drought conditions, with over a hundred indices developed for this purpose. Among these, the Standardized Precipitation Index (SPI) stands out due to its versatility and reliance solely on precipitation data, making it the standard for assessing meteorological drought.

Numerous studies have been conducted using SPI to assess meteorological drought globally and nationally. Spinoni et al. (2020) found that around 15% of the world's area is predicted to experience more frequent and severe droughts between 2071 and 2100 compared to 1981 to 2010 based solely on precipitation. Similarly, many studies have reported an overall global tendency toward more frequent and severe meteorological drought events (Dai, 2011; Duffy et al., 2015; Kotikot and Omitaomu, 2021; Zeng et al., 2021).

DOI: https://doi.org/10.3126/jhm.v12i1.72655

Corresponding author: Isha KC, ishbsh01@gmail.com

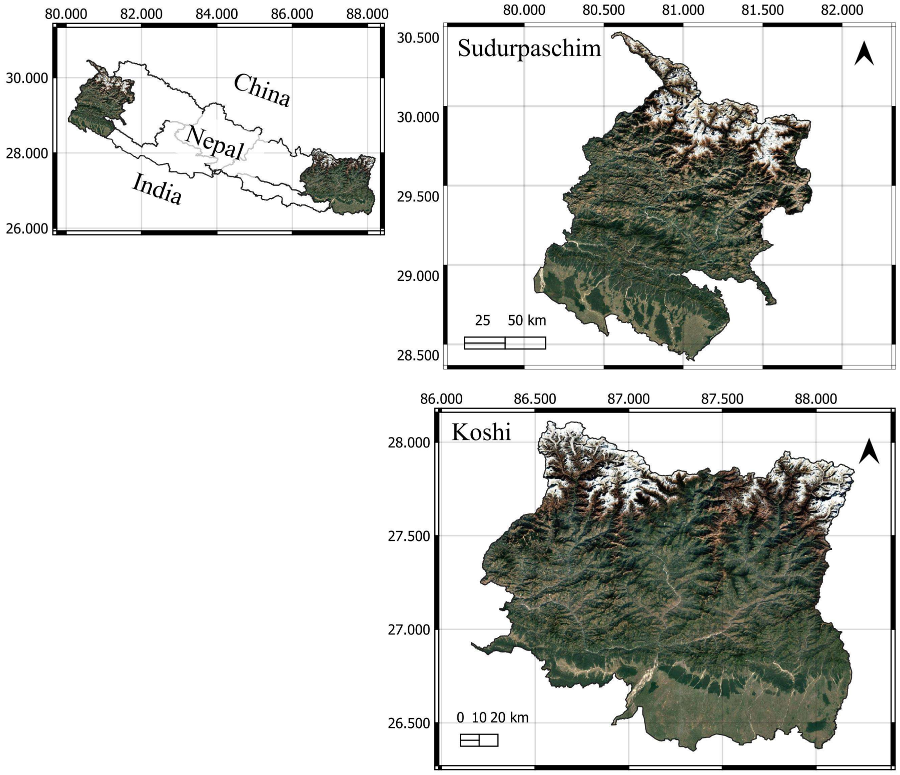

Figure 1. Location map of study areas, Sudurpaschim and Koshi Provinces with Nepal inset map.

In Nepal, various studies have been carried out to characterize drought events, their historical occurrences, and their impacts on agriculture and socioeconomic sectors. Drought events were identified in the years 1982, 1985, 1991–1992, 1994, 2005–2006, 2008–2009, 2012, 2013, and 2015 (Ghimire et al., 2010; Dahal et al., 2016; Bagale et al., 2021; Sharma et al., 2021a; Aryal et al., 2022). Ghimire et al. (2010) observed significant disruptions in rural livelihoods due to drought, emphasizing its adverse effects on rainfed subsistence agriculture.

Dahal et al. (2016) conducted a temporal and spatial analysis spanning 1981 to 2012, revealing no significant extended trends in annual mean precipitation but identifying notable year-to-year fluctuations and periods of deficient rainfall. Studies by Khatiwada and Pandey (2019), and Sharma et al. (2021a) spanning various periods from 1975 to 2018 highlighted increasing occurrences of drought events, particularly post-2004 (Aryal et al., 2022), necessitating focused drought management interventions. These studies also connected drought events to the Southern Oscillation Index, identifying severe drought years like 1992 and 2015, particularly impacting the central region (Bagale et al., 2021). Sigdel and Ikeda (2010) observed that drought patterns in Nepal are closely linked to climate indices, particularly the El Niño-Southern Oscillation, which exacerbates summer droughts, and the Indian Ocean Dipole Mode Index influencing winter drought conditions. Despite a historical focus, recent studies like those by Sharma et al. (2021b) and Shah et al. (2022) have started considering the influence of climate change on drought occurrences. Sharma et al. (2021b) highlighted an anticipated increase in drought frequency, especially in the near future, while Shah et al. (2022) projected concerning scenarios for specific terai regions, necessitating proactive adaptation measures. Notably, these studies underscore the importance of considering climate change impacts in drought analysis. Henceforth, this study not only conducts a drought assessment based on past observed precipitation data in two distinct regions, Sudurpaschim and Koshi respectively but also investigates the impact of climate change on drought occurrences by utilizing multimodel ensemble mean of the projected precipitation output of thirteen General Circulation Models (GCMs) from Coupled Model Intercomparison Project-6 (CMIP6) and evaluates its specific influence on drought patterns at SSP370 scenario.

2. Study Area

Koshi Province is situated between 86°11′ to 88° 3′ East longitude and 28°2′ to 26°3′ North latitude and encompasses an extensive land area spanning 25,905 square kilo-

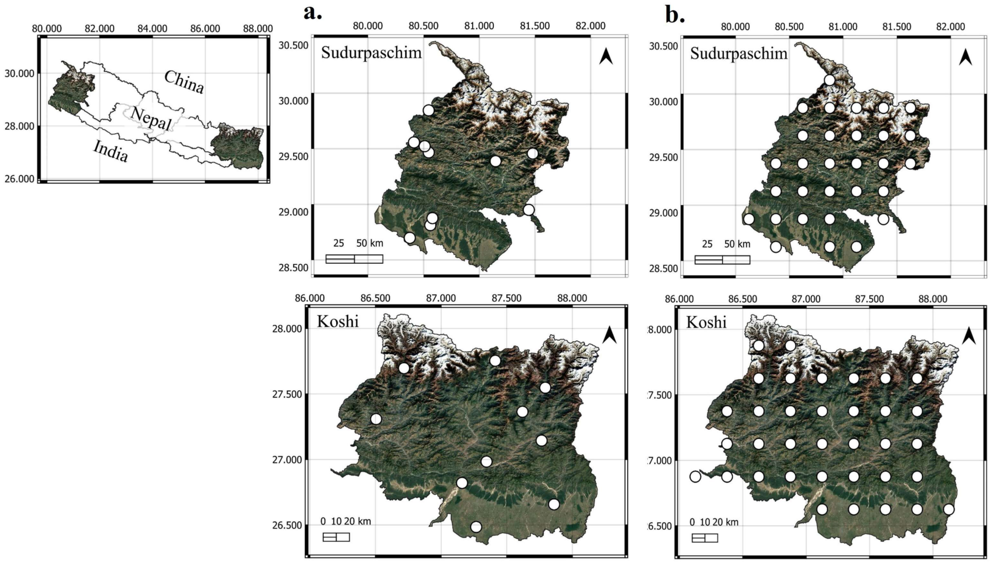

Figure 2. Meteorological stations and projected rainfall data for Koshi and Sudurpaschim provinces (1980–2060): a) Observed stations (1980–2023) b) Projected data points (2025–2060) under SSP370.

meters, accounting for 17.5% of the total land area of the country. Likewise, Sudurpaschim Province is situated within the geographical coordinates of 80°03′ to 81°25′ East longitude and 28°22′ to 30°09′ North latitude. It encompasses an area spanning 15,539 square kilometers, accounting for 13.27% of the total land area of the country. Both study areas are shown in Fig. 1. Koshi Province exhibits significant variations in climate due to the province's diverse topography and varying altitudes, leading to distinct dry and wet monsoon seasons. Climatically, the province can be categorized into three main types namely subtropical, temperate, and alpine. Precipitation levels vary throughout the province, with the Terai and Inner Terai receiving an average rainfall between 110 and 300 mm, the mid and high mountains experiencing 27.5 to 230 mm, and the Himalayan region receiving 15-20 mm of rainfall. Sudurpaschim Province exhibits a diverse range of climates due to its varied topography. The Terai region experiences hot summers, mild winters, and heavy monsoon rains. In the hilly areas, the climate is temperate with warm summers and colder winters, while the mountain regions have short, cool summers, and cold winters with snowfall, and are affected by the monsoon season.

3. Data and Methods

3.1. Data Collection

3.1.1) Observed meteorological data

Meteorological Data (rainfall data) from 10 meteorological stations for each province, from 1980 to 2023 were collected from the Department of Hydrology and Meteorology, Babarmahal, Kathmandu, Nepal.

The names and indices of these stations are listed in Table 1, and their locations are illustrated in Fig. 2 a. This figure shows the stations across the Koshi and Sudurpaschim provinces.

3.1.2) Future (projected) data

Daily bias-corrected precipitation projections at 0.25° spatial resolution are obtained from the multimodel ensemble mean of the projected output of thirteen General Circulation Models (GCMs) from Coupled Model Intercomparison Project-6 (CMIP6). These bias-corrected datasets from CMIP6-GCMs were developed using Empirical Quantile Mapping (EQM) by Mishra et al. for the historical (1951–2014) and projected (2015–2100) climate for the four scenarios (SSP126, SSP245, SSP370, SSP585). The monthly correlation between observed and CMIP6-simulated historical Standardized Precipitation Evapotranspiration Index (SPEI) is 0.23 ($p<0.01$), suggesting that the CMIP6 model ensemble effectively replicates drought characteristics in Nepal and can be used for climate change impact assessment (Mishra et al., 2020; Sharma et al., 2021b). These CMIP6 model future projections consider the specific changes in societal development indicators, such as the population and economy, thus named Shared Socioeconomic Pathways (SSP) (O'Neill et al., 2017). These SSPs focus on radiative forcing ranging from low to high-emission scenarios. This study adopted SSP3 (Regional Rivalry – A Rocky Road) which is the medium-to-high end of future emissions and temperature scenarios

Table 1. The meteorological stations from the study area.

S.N	Province	Station name	Station Index	Physiographic region
1	Koshi	Chepuwa	1317	High Mountain
2		Lungthung	1403	High Mountain
3		Chaurikharka	1202	High Mountain
4		Dovan	1420	High Mountain
5		Phidim	1419	Middle Hill
6		Okhaldhunga	1206	Middle hill
7		Dhankuta	1307	Middle hill
8		Saptakoshi at Chatara	1316	Siwalik Hill
9		Gaida (Kankai)	1421	Terai
10		Biratnagar airport	1319	Terai
11	Sudurpaschim	Darchula	107	High mountain
12		Khaptad	211	High mountain
13		Patan (West)	103	Middle hill
14		Bajura	204	Middle hill
15		Satbanjh	108	Middle hill
16		Asaraghat	206	Middle hill
17		Baitadi	102	Middle hill
18		Godavari	215	Siwalik hill
19		Dhangadi	209	Terai
20		Belauri Shantipur	106	Terai

and it offers a framework for evaluating the repercussions of resurgent nationalism, regional conflicts, and an emphasis on domestic or regional issues on socio-economic development. This pathway is particularly relevant in the context of addressing challenges related to mitigation and adaptation amidst sluggish economic growth, material-intensive consumption, and potential environmental degradation (Meinshausen et al., 2019). Climatic precipitation simulations encompassing the CMIP6 historical period (1980–2014) and projected period (2020–2100) are acquired from Bias Corrected Climate Projections from CMIP6 Models for South Asia. Subsequently, the coordinates for the Koshi and Sudurpaschim regions were extracted for the SSP370 scenario data using R code, and daily precipitation data were then aggregated to generate monthly datasets for the period of 2025 to 2060, for further analysis. This involved gathering 30 coordinate points from Sudurpaschim and 35 from Koshi as shown in Fig. 2b. Following this, daily precipitation data were aggregated to generate monthly datasets, enabling further analysis.

3.2. Data Analysis

3.2.1) INTERPOLATION OF MISSING DATA

The Inverse Distance Method (IDW) was employed to address missing rainfall data at various weather stations in our study. This technique was valuable in estimating and filling the gaps in precipitation records with a spatially weighted approach. By utilizing the principle that points closer to the target location had a greater influence on the estimated values, the IDW method was used to interpolate missing rainfall values based on the inverse of their distances from neighboring stations using the equation (1). This approach helped in producing a more comprehensive and representative dataset of rainfall across the study area.

$$Z_p = \frac{\sum_{i=1}^{n}\left(\frac{z_i}{d_i^p}\right)}{\sum_{i=1}^{n}\left(\frac{1}{d_i^p}\right)} \tag{1}$$

where,
Z_p = the estimated precipitation
z_i = the known precipitation of nearby station
d_i^p = the distance between the two stations

3.2.2) GAMMA DISTRIBUTION

The rainfall record at a desired station was fitted to a probability distribution, which was then transformed into a normal distribution so that the mean is zero. If x is a precipitation data series of a desired time scale, then its probability density function satisfying gamma distribution is given by the equation (2):

$$f(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{a-1} e^{\frac{-x}{\beta}} \qquad for x > 0 \tag{2}$$

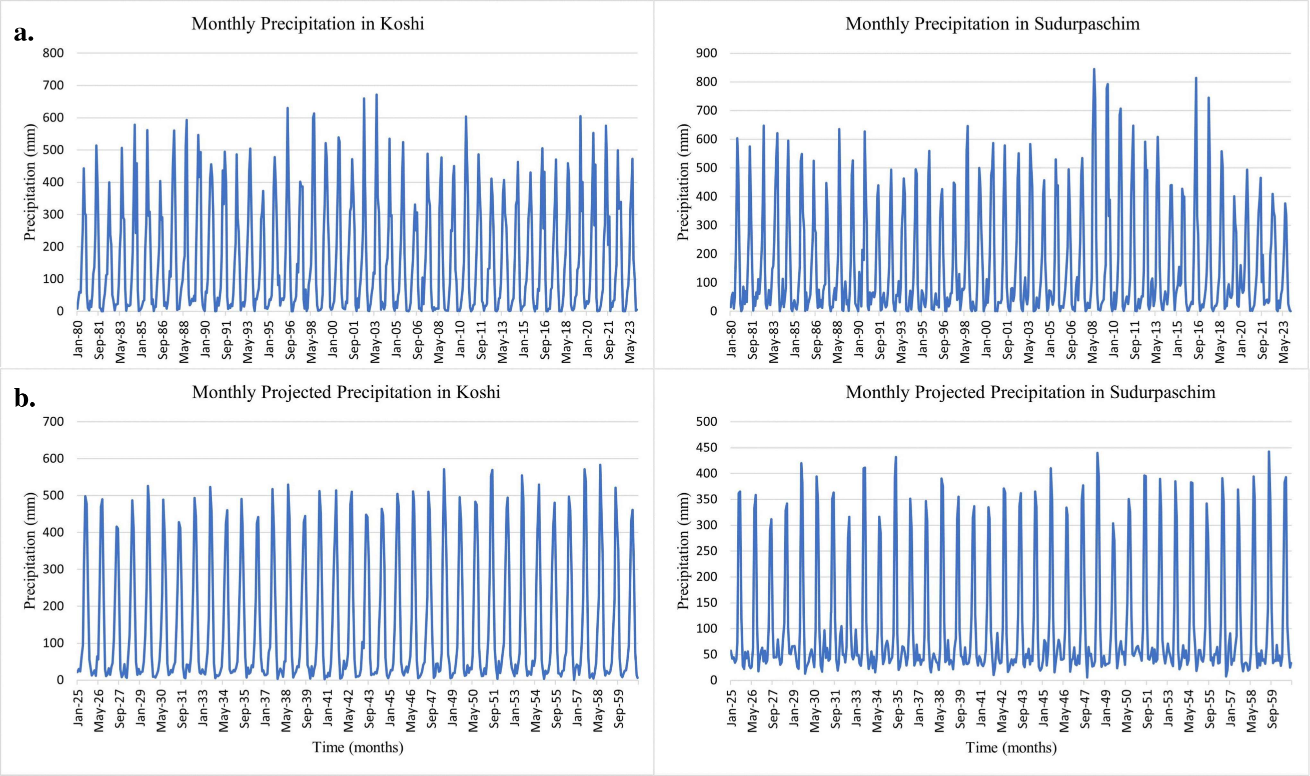

Figure 3. Monthly precipitation time series for Sudurpaschim and Koshi provinces. (a) Observed data (1980–2023) and (b) projected data (2025–2060).

where,
$\alpha > 0 = \alpha$ is a shape parameter
$\beta > 0 = \beta$ is a scale parameter
$x > 0 =$ x is a precipitation amount
$\Gamma(\alpha) = \int_0^\infty y^{\alpha-1} e^{-y} dy = \alpha$ is a shape parameter

The gamma cumulative distribution function (cdf) was calculated for each value of x by inserting the estimated values of a and b and integrating the probability density function for x. The shape and scale parameters are evaluated using the greatest likelihood technique. After that, the cdf is converted to the conventional normal distribution to produce SPI (Dahal et al., 2016)

3.2.3) Standardized Precipitation Index

The Standardized Precipitation Index (SPI) was used to analyze meteorological drought in this study. It was developed by McKee et al. (1993) at Colorado State University, United States. The goal of the SPI was to give precipitation a single numerical value that may be used to compare different places with notably differing climates. SPI was inscribed as a primary meteorological drought index by the World Meteorological Organisation (WMO), in 2009 (Hayes et al., 2011) and is widely used for early drought detection. Standardized precipitation is simply the difference of precipitation from the mean for a specified time period divided by the standard deviation where the mean and standard deviation are determined from past records (McKee et al., 1993). SPI is computed using equation (3):

$$SPI = \frac{Xi - Xm}{\sigma} \tag{3}$$

where,
X_i = precipitation at i^{th} month or season and year
X_m = mean monthly, seasonal, or annual precipitation
σ = standard deviation of the recorded precipitation

Using monthly precipitation data as the input parameter, the index can be computed over a range of time scales, which includes 1, 3, 4, 6, 9, 12, and 24 months. We used SPI3, SPI4, and SPI12 for the available meteorological data of the study area. The 3-month and 4-month timescale reflects short and medium moisture conditions and provides a seasonal estimation of precipitation. While a 12-month time scale reflects long-term precipitation patterns (Wu et al., 2001). For any time scale, a quantitative and functional definition of drought can be established by using the SPI as the indicator. A period of drought for time scale i refers to the time frame during which the SPI is continuously negative and eventually hits a value of -1.0

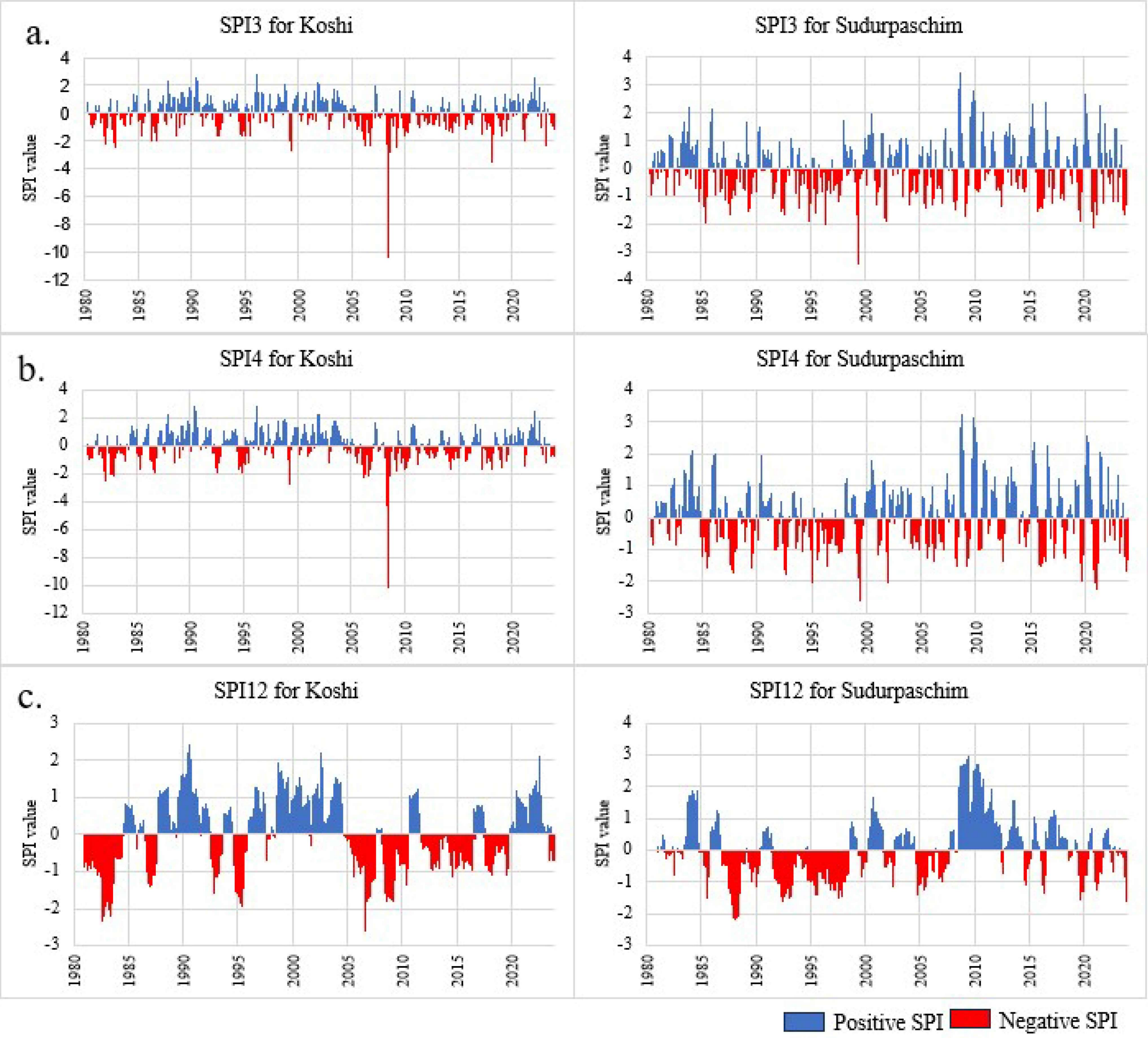

Figure 4. SPI values plotted from average monthly precipitation for Koshi and Sudurpaschim Provinces.

or less. The drought begins when its value drops below zero for the first time, and it ends when its value rises to a value of 1.0 or less (McKee et al., 1993). The definition of drought intensity is arbitrary for SPI values falling within the categories as shown in Table 2.

3.2.4) SPI Calculation using Rstudio

In this study, the SPI was computed at 3, 4, and 12-month timescales using the SPEI package version 1.8.1, (Begueria and Vicente-Serrano, 2017) in R-statistical software to capture short-term and longer-term precipitation anomalies, respectively. The calculation of SPI followed the gamma distribution for the probability density function in the precipitation time series.

3.2.5) Trend Analysis using Mann- Kendall test

Meteorological trends can be analyzed using various methods, such as statistical approaches and rank-based tests. The non-parametric Mann-Kendall test is the most popular technique for identifying trends in a time series (Mann, 1945; Kendall, 1948). In this study, we utilized the 'trend' package developed by Pohlert (2023) in R for conducting the Mann-Kendall (MK) test to assess the trend in SPI values for both observed and projected scenarios. The SPI 3 values of February were analyzed to assess winter drought trends, the SPI 4 values of September were analyzed for summer drought, and the SPI 12 values of December were used to assess annual drought trends (Dahal et al., 2016). The Tau value provided insights into the trend, indicating

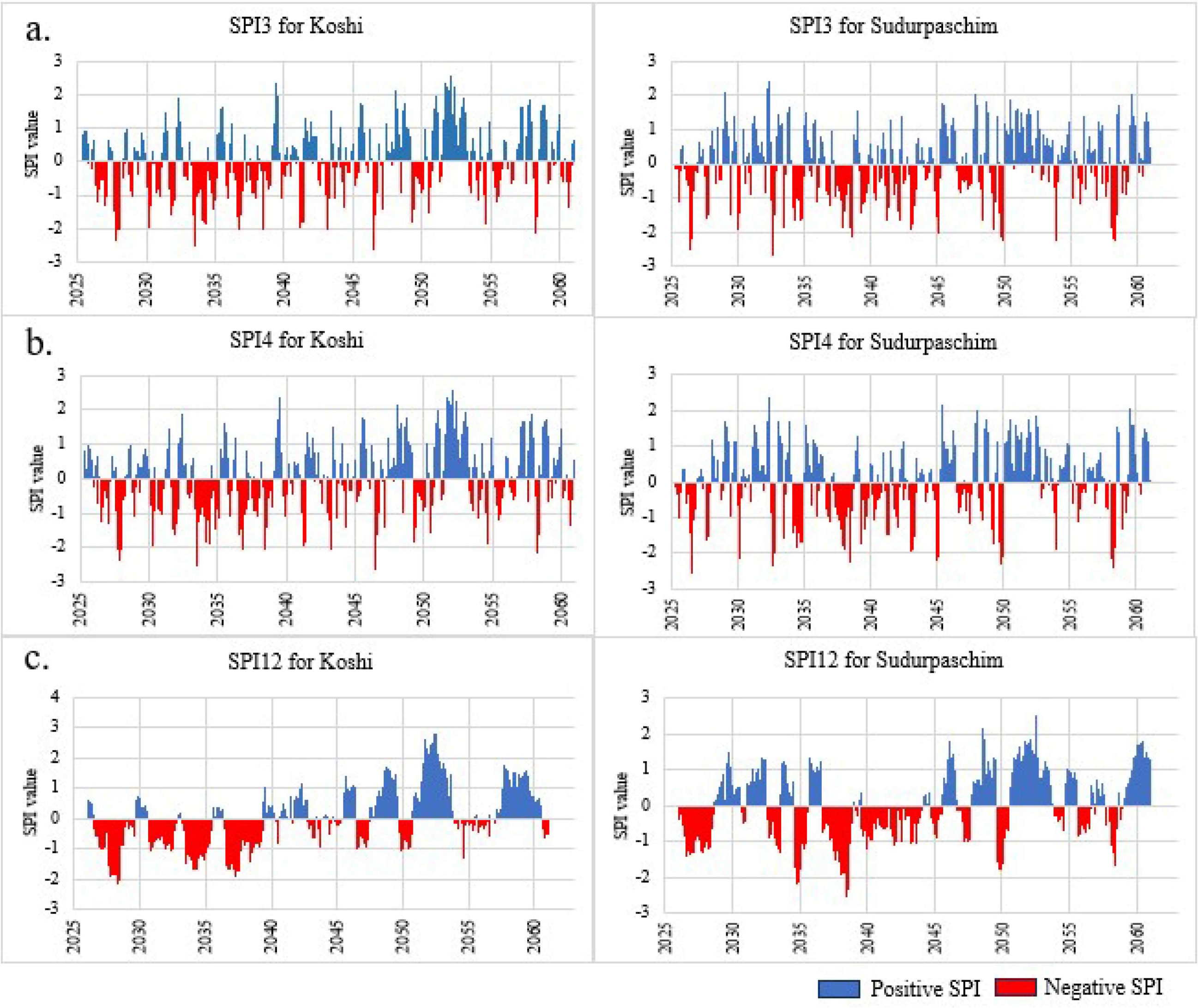

Figure 5. SPI values plotted from average monthly precipitation for Koshi and Sudurpaschim Province.

Table 2. SPI Classification.

SPI Category	SPI Values
Extremely wet	2.00
Severely wet	1.50–1.99
Moderately wet	1.00–1.49
Mildly wet	0.00–0.99
Mild drought	-0.99–0.00
Moderate drought	-1.49– -1.00
Severe drought	-1.99– -1.50
Extreme drought	-2.00

Source: (McKee et al., 1993).

whether SPI values are increasing, decreasing, or showing no trend, with positive and negative values. The significance of these trends was determined by the p-value, with values below 0.05 considered statistically significant.

4. Results and Discussion

4.1. Monthly Rainfall Time Series Distribution for Sudurpaschim and Koshi Provinces

The temporal distribution of monthly rainfall for Sudurpaschim and Koshi provinces was analyzed over two scenarios: the observed precipitation from 1980 to 2023 and the projected future rainfall patterns as shown in Fig. 3a-b. In the historical context, Koshi province, typically characterized by a wetter climate, shows lower precipitation values in our dataset compared to Sudurpaschim. This deviation can be attributed to the selection of weather stations, as many are located in the hill areas of Sudurpaschim, where orographic factors likely influence the precipitation patterns, making it appear wetter. The rainfall variability is prominent in both regions, with notable peaks during the monsoon season. Furthermore, recent research shows that the spatial patterns of high-intensity precipitation extremes in Nepal differ from those of annual or monsoonal precipitation. Specifically, the western middle hills, where many of our stations are located, experience increasing trends in monsoonal precipitation. This may have contributed to the observed higher precipitation levels in Sudurpaschim, despite its overall drier climate compared to Koshi (Karki et al., 2017). In contrast, the projected precipitation scenario of time period 2025 to 2060 indicates significant differences. Sudurpaschim is expected to experience generally lower rainfall, with monthly precipitation ranging from 50 mm to 450 mm. On the other hand, Koshi province is projected to receive higher rainfall, with values nearly reaching 600 mm during multiple months. This shift suggests that future climate patterns will likely intensify regional differences in precipitation, with Sudurpaschim experiencing drier conditions relative to Koshi.

4.2. Temporal Distribution of SPI3, SPI4 and SPI12

We applied average monthly observed precipitation values between 1980 and 2023, for 10 selected meteorological stations in each of both Koshi and Sudurpaschim provinces to obtain a regional average of each province. These values were then used to calculate SPI values at different time scales to generate the temporal pattern for SPI3, SPI4, and SPI12, which is depicted in Figs. 4a-c, respectively.

The observed SPI3 for Koshi Province showcases the region's volatile weather patterns, characterized by erratic shifts between intense wet spells and severe droughts. Notable instances of extreme drought include 1999 with a staggering SPI value of -2.99 and the unprecedented severity of 2018, registering at -3.56. The driest year, according to the SPI4 plot, was 2008, with an SPI value of -5.196, and another extreme drought occurred in 1999, with a value of -2.83. The SPI12 analysis reveals a history of prolonged droughts, notably from 1982 to 1984, with the SPI value plummeting below -2.0, and consistent severity observed from 2005 onwards, culminating in the driest year of 2006 with a value of -2.7. Similar observations of increased drought severity in eastern Nepal were made by Aryal et al. (2022) and Bagale et al. (2021), who confirmed these prolonged drought events beyond 2005.

Conversely, the observed SPI for Sudurpaschim Province presents a more predictable pattern, with uniform seasonal fluctuations between wet and dry periods. While Koshi experienced more short-term droughts, with 15 instances of SPI3 and 16 of SPI4 below -2, Sudurpaschim, had fewer occurrences, with 4 instances of SPI3 and 5 of SPI4 values below -2. This suggests that while Sudurpaschim has relatively frequent droughts, the drought intensity is more pronounced in Koshi. Notable droughts include 1999, marked by an SPI value of -3.46. In both SPI3 and SPI4 plots, 1999 and 2020 experienced very extreme drought conditions. Since 2000, both the frequency and severity of droughts in Sudurpaschim have declined, with occurrences now mostly mild to moderate. This is consistent with the findings of Aryal et al. (2022), who reported reduced drought severity in the far west region after 2005. The relatively higher precipitation recorded at the Khaptad station, situated in a high-elevation area of the province, has inadvertently skewed the region's depiction towards overall wetter conditions.

Precipitation values for the projected period of 2025-2060 were extracted from 35 meteorological stations in Koshi province and 30 stations in Sudurpaschim province. These values were utilized to calculate the regional average precipitation for each province. These values were then used to calculate SPI values at different time scales to generate the temporal pattern for SPI3, SPI4, and SPI12, which is depicted in Figs. 5a-c, respectively.

The projected SPI for Koshi Province reveals changes in severity and frequency for both SPI3 and SPI4, with high precipitation levels in the 50s and 60s. The forecast anticipates drought in 2027, 2033, 2046, and 2058. Meanwhile, the SPI12 indicates dry periods between 2025 and 2040, followed by an increase in precipitation. Koshi is expected to experience extremely prolonged spells, both wet and dry. In Sudurpaschim Province, SPI3 shows consistently fluctuating values, with the years 2026, 2032, 2045, 2049, 2053, and 2058 exceeding -2 values. SPI4 points to dry periods in 2026, 2030, 2032, 2038, 2044, 2049, and 2058. The SPI12 projection reveals prolonged dry periods between 2026-2028 and 2036-2045, with extreme conditions in 2034 and 2038. Despite this, there is a notable shift towards greater precipitation in the far future when compared to the near future across both regions, as was observed by Sharma et al. (2021b) in his study.

4.2.1) Trend Analysis of SPI3, SPI4, and SPI12

The Mann-Kendall trend test identifies increasing, decreasing, and no trends of these time scales in different regions. Downward red triangles and upward blue triangles represent increasing dry and increasing wet scenarios, respectively. Similarly, the solid-filled triangles represent significant trends. The results of observed individual trend analysis of SPI3, SPI4, and SPI12 for the period of 1980-2023 have been examined in both Koshi and Sudurpaschim provinces which depicted the Winter drought, Summer drought, and Annual drought trends, which are summarized in Figs. 6a-c.

The SPI3 map of Sudurpaschim indicates a rising trend of winter drought in the area, with 9 out of 10 stations demonstrating increased drought, notably Gothalapani showing higher significance. Conversely, Khaptad

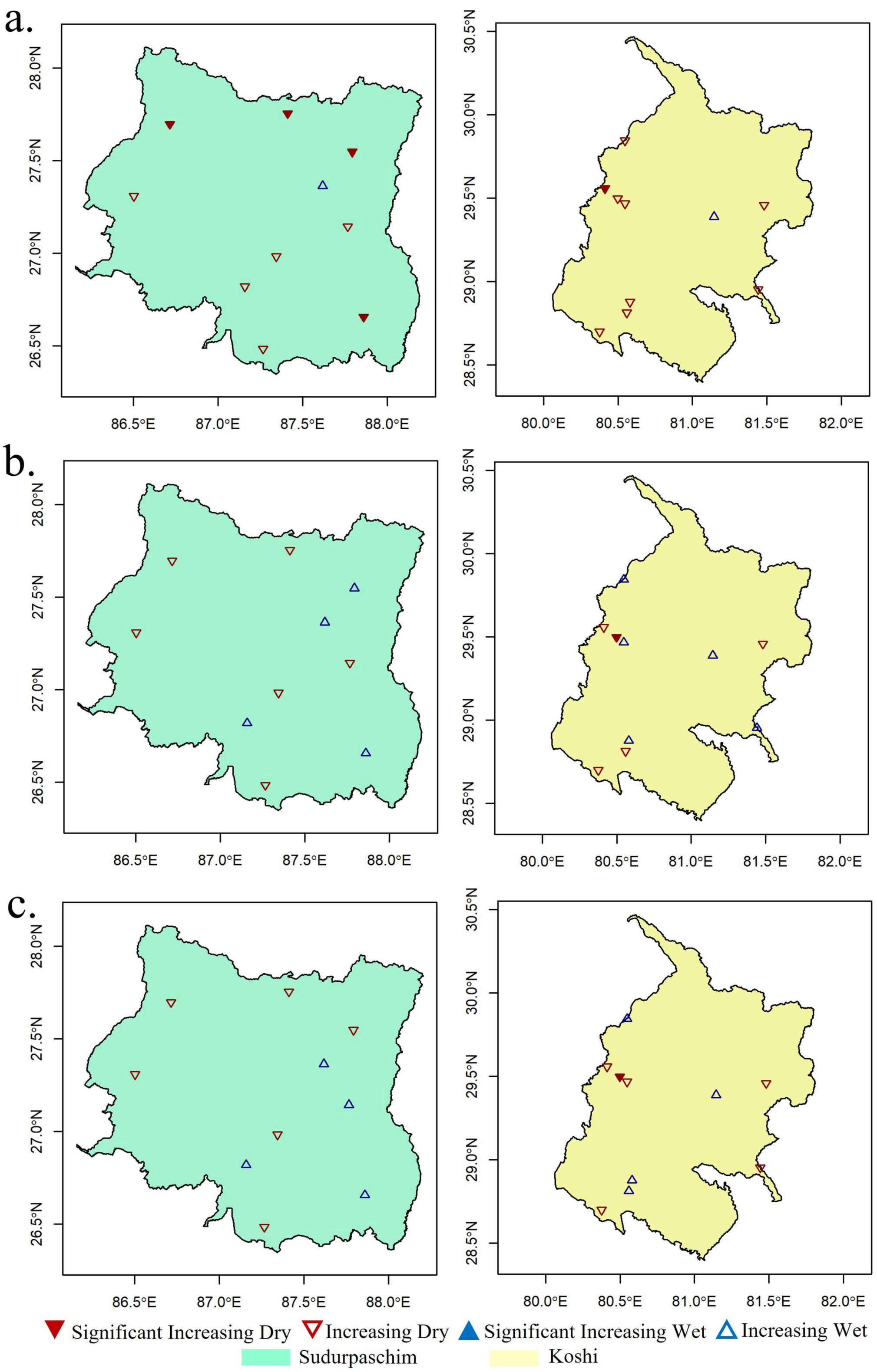

Figure 6. Observed drought trends (a) winter (b) summer (c) annual.

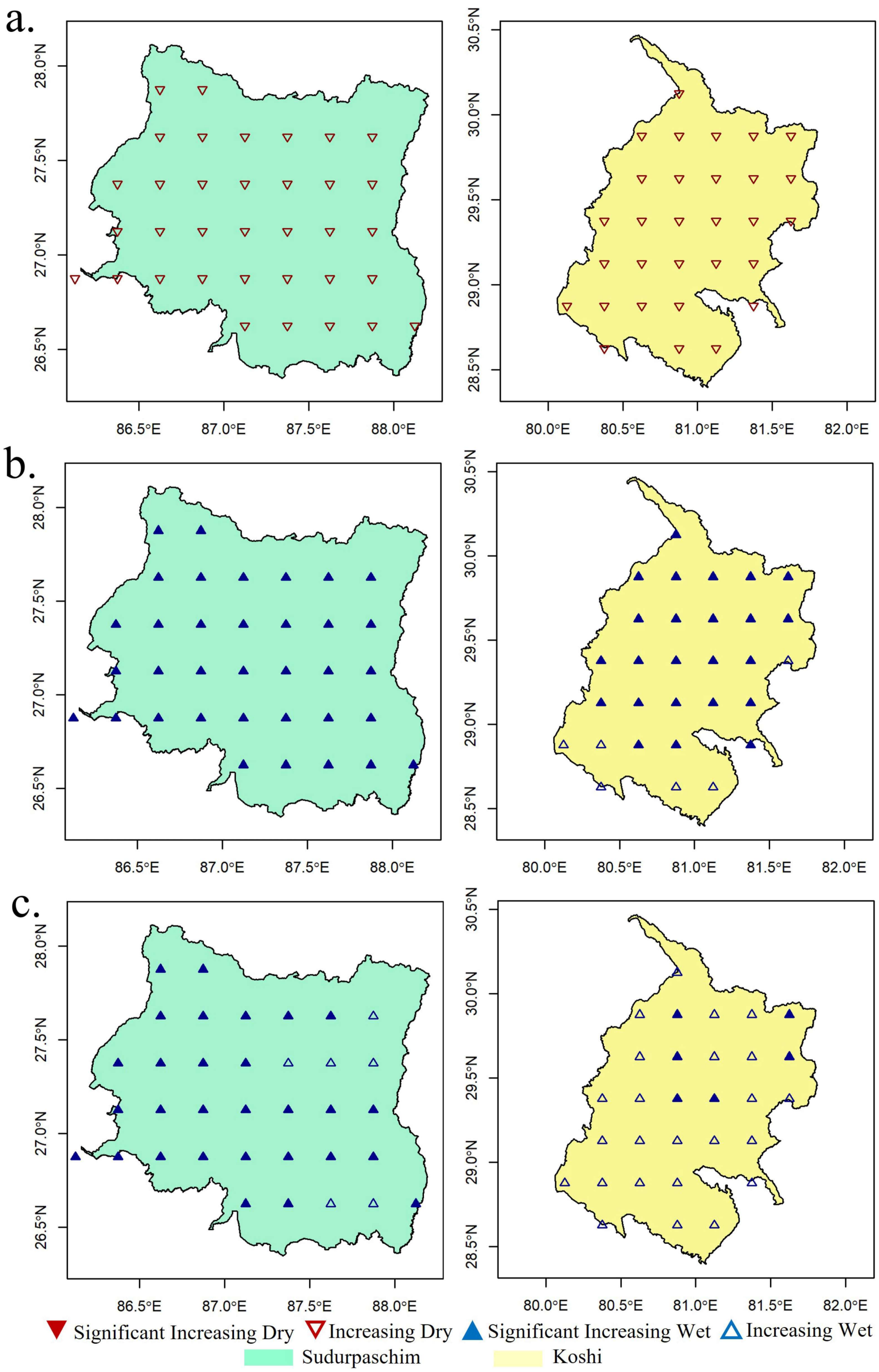

Figure 7. Projected drought trends (a) winter (b) summer (c) annual.

exhibited a trend towards wetter conditions. Similarly, the SPI3 map of Koshi depicts a similar trend with 9 out of 10 stations experiencing drier conditions, particularly noticeable in high mountain regions. However, Dovan displayed a contrasting trend towards wetter conditions, with less significance. In Sudurpaschim's SPI4, which indicates summer drought, we see diverse trends. Five out of ten stations show a trend towards wetter conditions, while the rest indicate increasing dryness. Notably, Santbanjh station experiences significant summer drought. Meanwhile, in the SPI4 plot Koshi region, although none of the stations show a significant trend, six out of ten stations depict an increasingly dry scenario.

The SPI12 map indicates annual drought patterns. In Sudurpaschim, the SPI12 plot reveals Khaptad consistently experiencing wet conditions across all time scales, while Santbanjh consistently faces dry conditions, with higher significance. In the Koshi region, the SPI12 plot highlights the dominance of summer monsoons in annual drought trends. Stations at higher elevations such as Chepwa, Okhaldhunga, and Chaurikharka consistently show drought across all time scales. Similarly, the results of projected individual trend analysis of SPI3, SPI4, and SPI12 for the period of 2025-2060 have been examined in both Koshi and Sudurpaschim provinces which depicted the Winter drought, Summer drought, and Annual drought trends, which are summarized in Figs. 7a-c.

In the projected winter drought trends for Sudurpaschim and Koshi, the prominence of winter drought is evident. These findings are supported by studies that also observed winter drought as a growing concern in the future for Nepal, attributed to factors such as declining winter precipitation, increased climate variability, and projected warming (Wang et al., 2013; Sharma et al., 2021b; Bagale et al., 2024). This observation underscores the necessity for proactive measures to mitigate the challenges posed by prolonged dry conditions during the winter season. When we examine the projected data for summer drought trends, we observe increasingly wetter conditions with higher significance in both provinces. However, the significance decreases for the Terai region of Sudurpaschim. In annual drought trends, Sudurpaschim exhibits increased wet conditions, but only 20% of stations show high significance, while Koshi experiences an overall increase in wetter conditions, with approximately 83% of stations indicating higher significance.

5. Conclusion

This study provided a comprehensive examination of meteorological drought assessment in the Koshi and Sudurpaschim Provinces using the SPI over the period from 1980 to 2023 The analysis revealed significant regional variations in drought patterns, with Koshi Province exhibiting extreme fluctuations in both wet and dry spells with increased drought spells beyond 2005, while Sudurpaschim demonstrated a more stable pattern. Projected SPI values for the period from 2025 to 2060 indicate that both regions are likely to experience more frequent and intense droughts, particularly in the mid-term (2026-2046). Koshi Province is expected to witness a sharp increase in extreme drought events, while Sudurpaschim shows less volatility but continues to exhibit dry conditions. Winter drought, in particular, was found to be a consistent concern across all temporal scales, with the potential to significantly impact both regions, emphasizing the need for targeted strategies to address water scarcity issues. These results highlight the distinct drought dynamics in the Koshi and Sudurpaschim Provinces, emphasizing the importance of understanding regional variability in drought occurrences. The use of SPI at multiple timescales has provided valuable insights into both the historical and future trends of drought in these regions, offering a clear picture of evolving drought conditions driven by climatic variability.

Acknowledgments

We are thankful to the Department of Hydrology and Meteorology, Government of Nepal for kindly providing us with meteorological data. Additionally, we are grateful to the Department of Environmental Science and Engineering, Kathmandu University for providing the necessary resources and conducive environment for conducting this study.

References

Aryal, A., Maharjan, M., Talchabhadel, R., and Thapa, B. R., 2022. Characterizing Meteorological Droughts in Nepal: A Comparative Analysis of Standardized Precipitation Index and Rainfall Anomaly Index. *Earth*, 3 (1), Article 1.

Bagale, D., Sigdel, M., and Aryal, D., 2021. Drought monitoring over Nepal for the last four decades and its connection with southern oscillation index. *Water*, 13 (23), 3411.

Bagale, D., Sigdel, M., and Aryal, D., 2024. Winter drought monitoring using standard precipitation index over Nepal. *Natural Hazards*, 120 (2), 975–988.

Begueria, S., and Vicente-Serrano, S. M., 2017. SPEI: calculation of the standardized precipitation-evapotranspiration index. R package version, 1(7).

Bista, D. R., Heckathorn, S. A., Jayawardena, D. M., and Boldt, J. K., 2020. Effect of drought and carbon dioxide on nutrient uptake and levels of nutrient-uptake proteins in roots of barley. *American Journal of Botany*, 107 (10), 1401–1409.

Dahal, P., Shrestha, N. S., Shrestha, M. L., Krakauer, N. Y., Panthi, J., Pradhanang, S. M., Jha, A., and Lakhankar, T., 2016. Drought risk assessment in central Nepal: Temporal and spatial analysis. *Natural Hazards*, 80 (3), 1913–1932.

Dai, A., 2011. Drought under global warming: A review. *WIREs Climate Change*, 2 (1), 45–65.

Duffy, P. B., Brando, P., Asner, G. P., and Field, C. B., 2015. Projections of future meteorological drought and wet periods in the Amazon.

Proceedings of the National Academy of Sciences, 112 (43), 13 172–13 177.

Eriyagama, N., Smakhtin, V. Y., and Gamage, N., 2009. Mapping drought patterns and impacts: a global perspective. International Water Management Institute, 133.

Ghimire, Y. N., Shivakoti, G. P., and Perret, S. R., 2010. Household-level vulnerability to drought in hill agriculture of Nepal: implications for adaptation planning. *International Journal of Sustainable Development & World Ecology*, 17 (3), 225–230.

Hayes, M. J., Svoboda, M., Wall, N., and Widhalm, M., 2011. The Lincoln declaration on drought indices: Universal Meteorological Drought Index Recommended. *Bulletin of the American Meteorological Society*, 92 (4), 485–488.

Karki, R., Hasson, S. U., Schickhoff, U., Scholten, T., and Böhner, J., 2017. Rising precipitation extremes across Nepal. *Climate*, 5 (1), 4.

Kendall, M. G., 1948. Rank correlation methods.

Khatiwada, K. R., and Pandey, V. P., 2019. Characterization of hydro-meteorological drought in Nepal Himalaya: A case of Karnali River Basin. *Weather and Climate Extremes*, 26, 100 239.

Kotikot, S. M., and Omitaomu, O. A., 2021. Spatial–Temporal Patterns of Historical, Near-Term, and Projected Drought in the Conterminous United States. *Hydrology*, 8 (3), Article 3.

Mann, H. B., 1945. Nonparametric Tests Against Trend. *Econometrica*, 13 (3), 245–259.

McKee, T. B., Doesken, N. J., and Kleist, J., 1993. The relationship of drought frequency and duration to time scales. *Proceedings of the 8th Conference on Applied Climatology*, 179–183.

Meinshausen, M., Nicholls, Z., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., and Wang, H. J., 2019. The SSP greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development Discussions*, 1–77.

Mishra, V., Bhatia, U., and Tiwari, A. D., 2020. Bias-corrected climate projections for South Asia from Coupled Model Intercomparison Project-6. *Scientific Data*, 7 (1), 1.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., Van Ruijven, B. J., Van Vuuren, D. P., Birkmann, J., Kok, K., and Coauthors, 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global environmental change*, 42, 169–180.

Pohlert, T., 2023. Non-Parametric Trend Tests and Change-Point Detection.

Shah, S., Tiwari, A., Song, X., Talchabahdel, R., Habiyakare, T., and Adhikari, A., 2022. Drought index predictability for historical and future periods across the Southern plain of Nepal Himalaya. *Environmental Monitoring and Assessment*, 194 (9), 642.

Sharma, S., Hamal, K., Khadka, N., Shrestha, D., Aryal, D., and Thakuri, S., 2021a. Drought characteristics over Nepal Himalaya and their relationship with climatic indices. *Meteorological Applications*, 28 (2), e1988.

Sharma, S., Hamal, K., Khadka, N., Ali, M., Subedi, M., Hussain, G., Ehsan, M. A., Saeed, S., and Dawadi, B., 2021b. Projected Drought Conditions over Southern Slope of the Central Himalaya Using CMIP6 Models. *Earth Systems and Environment*, 5 (4), 849–859.

Sidiropoulos, P., Dalezios, N. R., Loukas, A., Mylopoulos, N., Spiliotopoulos, M., Faraslis, I. N., and Sakellariou, S., 2021. Quantitative classification of desertification severity for degraded aquifer based on remotely sensed drought assessment. *Hydrology*, 8 (1), 47.

Sigdel, M., and 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.

Spinoni, J., and Coauthors, 2020. Future Global Meteorological Drought Hot Spots: A Study Based on CORDEX Data. *Journal of Climate*, 33 (9), 3635–3661.

Stirling, E., Fitzpatrick, R. W., and Mosley, L. M., 2020. Drought effects on wet soils in inland wetlands and peatlands. *Earth-Science Reviews*, 210, 103 387.

Wang, S.-Y., Yoon, J.-H., Gillies, R. R., and Cho, C., 2013. What Caused the Winter Drought in Western Nepal during Recent Years? *Journal of Climate*, 26 (21), 8241–8256.

Wu, H., Hayes, M. J., Weiss, A., and Hu, Q., 2001. An evaluation of the Standardized Precipitation Index, the China-Z Index and the statistical Z-Score. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 21 (6), 745–758.

Wu, H., Xiong, D., Liu, B., Zhang, S., Yuan, Y., Fang, Y., Chidi, C. L., and Dahal, N. M., 2019. Spatio-Temporal Analysis of Drought Variability Using CWSI in the Koshi River Basin (KRB). *International Journal of Environmental Research and Public Health*, 16 (17), 17.

Zeng, P., Sun, F., Liu, Y., Wang, Y., Li, G., and Che, Y., 2021. Mapping future droughts under global warming across China: A combined multi-timescale meteorological drought index and SOM-Kmeans approach. *Weather and Climate Extremes*, 31, 100 304.