Spatiotemporal analysis of drought variability based on the standardized precipitation evapotranspiration index in the Koshi River Basin, Nepal (Postprint)

Authors: Nirmal M DAHAL, XIONG Donghong, Nilhari NEUPANE, Belayneh YIGEZ, ZHANG Baojun, Yong Yuan, Saroj KOIRALA, LIU Lin, FANG Yiping, Donghong Xiong

Date: 2021-06-04T00:00:00+00:00

Abstract

Drought is an inevitable condition with negative impacts in the agricultural and climatic sectors, especially in developing countries. This study attempts to examine the spatial and temporal characteristics of drought and its trends in the Koshi River Basin (KRB) in Nepal, using the standardized precipitation evapotranspiration index (SPEI) over the period from 1987 to 2017. The Mann-Kendall test was used to explore the trends of the SPEI values. The study illustrated the increasing annual and seasonal drought trends in the KRB over the study period. Spatially, the hill region of the KRB showed substantial increasing drought trends at the annual and seasonal scales, especially in summer and winter. The mountain region also showed a significant increasing drought trend in winter. The drought characteristic analysis indicated that the maximum duration, intensity, and severity of drought events were observed in the KRB after 2000. The Terai region presented the highest drought frequency and intensity, while the hill region presented the longest maximum drought duration. Moreover, the spatial extent of drought showed a significant increasing trend in the hill region at the monthly (drought station proportion of 7.6%/10a in August), seasonal (drought station proportion of 7.2%/10a in summer), and annual (drought station proportion of 6.7%/10a) scales. The findings of this study can assist local governments, planners, and project implementers in understanding drought and developing appropriate mitigation strategies to cope with its impacts.

Full Text

Preamble

Nirmal M. DAHAL[1,2], XIONG Donghong[1,3,4*], Nilhari NEUPANE[5], Belayneh YIGEZ[1,2], ZHANG Baojun[1,3,4], YUAN Yong[1,2], Saroj KOIRALA[1,2], LIU Lin[1,2], FANG Yiping[1]

[1]Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Branch of Sustainable Mountain Development, Kathmandu Center for Research and Education, CAS-TU, Kathmandu 44600, Nepal
[4]International Centre for Integrated Mountain Development (ICIMOD), Lalitpur, GPO 3226, Nepal

*Corresponding author: XIONG Donghong (E-mail: dhxiong@imde.ac.cn)

Received 2020-06-01; revised 2021-01-08; accepted 2021-01-18

Abstract

Drought is an inevitable condition with negative impacts on the agricultural and climatic sectors, especially in developing countries. This study examines the spatial and temporal characteristics of drought and its trends in the Koshi River Basin (KRB) in Nepal using the Standardized Precipitation Evapotranspiration Index (SPEI) over the period from 1987 to 2017. The Mann-Kendall test was used to explore trends in SPEI values. The study reveals increasing annual and seasonal drought trends in the KRB over the study period. Spatially, the hill region of the KRB showed substantial increasing drought trends at annual and seasonal scales, particularly in summer and winter. The mountain region also exhibited a significant increasing drought trend in winter. Drought characteristic analysis indicated that the maximum duration, intensity, and severity of drought events were observed in the KRB after 2000. The Terai region presented the highest drought frequency and intensity, while the hill region presented the longest maximum drought duration. Moreover, the spatial extent of drought showed a significant increasing trend in the hill region at monthly (drought station proportion of 7.6%/10a in August), seasonal (drought station proportion of 7.2%/10a in summer), and annual (drought station proportion of 6.7%/10a) scales. These findings can assist local governments, planners, and project implementers in understanding drought and developing appropriate mitigation strategies to cope with its impacts.

Keywords: drought duration; drought intensity; drought severity; standardized precipitation evapotranspiration index; mountains; hills; Terai

1. Introduction

Drought is a recurrent climate phenomenon that occurs due to a reduction in normal precipitation amount and/or delays in the rainy season in a region for a specific time [?, ?]. This phenomenon can last for months to years and presents a larger spatial extent than any other climatic hazard [?]. Droughts may cause significant water supply shortages and reduce agricultural production. Wilhite and Glantz (1985) categorized drought as meteorological, agricultural, hydrological, and socioeconomic phenomena based on precipitation deficit over time. The causal effects of drought can be recognized at spatial and temporal scales through intensity, duration, frequency, and severity characteristics [?, ?, ?]. Sheffield and Wood (2007) studied increasing drought duration from 1950 to 2000 at different latitudes globally. Similarly, Trenberth et al. (2011) reported that the magnitude, intensity, frequency, and spatial extent of drought have doubled since the 1970s in different parts of the world, including South and East Asia.

The Hindu Kush Himalayan region is the largest mountain range in the world, serving as freshwater towers for South Asia and parts of Southeast Asia that provide water to more than one billion people [?]. This region is highly susceptible to natural hazards with significant impacts on livelihoods [?]. Nepal is one of the hazard-prone countries in the Hindu Kush Himalayan region, along with its large neighboring countries China and India [?, ?, ?]. Transboundary river basins in Nepal, such as Koshi, Gandaki, and Karnali, originate from the high Himalayas to the plains and sustain livelihoods in mountain, hill, and lowland areas facing extreme climate events [?]. The South Asian monsoon climate, together with strong interactions with extreme topographic variations within short south-north distances, predominantly affects precipitation patterns in Nepal [?]. The horizontal extension of hill and mountain ranges results in moist conditions on south- and west-facing slopes and rain shadow effects on northern slopes [?]. The Intergovernmental Panel on Climate Change (IPCC) reported that increasing global temperature has substantially impacted precipitation patterns worldwide [?]. Manton et al. (2001) observed increasing numbers of annual hot days and warm nights and decreasing numbers of rainy days in the Asian region. Several studies have shown evidence of erratic precipitation patterns [?] and increasing maximum temperatures (0.06°C/a–0.12°C/a) in Nepal [?]. Agrawala et al. (2003) projected that Nepal will experience temperature increases of 1.2°C and 3.0°C by 2050 and 2100, respectively. Increasing temperature may increase evapotranspiration and reduce soil moisture, accelerating high-risk climatic hazards in Nepalese river basins, particularly associated with extreme climatic events such as drought [?, ?, ?]. Since drought occurrence is primarily related to precipitation (decreasing) and temperature (increasing) factors, drought intensity, duration, and frequency at spatial and temporal scales vary with the magnitude of these changing factors [?, ?, ?, ?]. Therefore, studying drought at spatial and temporal scales in Nepal is essential.

Drought indices are often used to study and monitor drought phenomena. Several indices have been developed for drought studies that can define and analyze drought at spatial and temporal scales [?]. These include the Palmer Drought Severity Index (PDSI) [?], Rainfall Anomaly Index [?], Crop Moisture Index [?], Surface Water Supply Index [?], and Standardized Precipitation Index (SPI) [?]. The PDSI is considered a milestone in drought studies and is commonly used, but its major limitations are inability to capture short-term drought and lack of multiscalar features in assessing drought [?, ?, ?]. To overcome these limitations, researchers widely use SPI for drought studies [?, ?] because it is simple to calculate and can quantify precipitation deficit for multiple time scales that reflect drought impact on water resource availability [?]. However, because SPI is based only on precipitation data, it is especially suited for studying meteorological drought [?, ?]. Many studies indicate that temperature and evapotranspiration are also influencing factors for drought but are not considered in SPI; therefore, this method is not suitable for studying drought in the context of climate change [?, ?, ?]. Thus, Vicente-Serrano et al. (2010) proposed the Standardized Precipitation Evapotranspiration Index (SPEI), which incorporates the merits of SPI and PDSI, such as multitemporal scales, climate water balance, influence of climate change on drought and evapotranspiration, and can reflect these factors [?, ?]. Therefore, this study adopted SPEI for drought analysis.

Drought studies are relatively recent in Nepal. Ghimire et al. (2010) conducted qualitative assessments of climate-induced drought vulnerability at the household level in hill agriculture. Kafle (2014) studied spatial and temporal drought assessments from 1982 to 2012 in western Nepal using the Standardized Reconnaissance Drought Index. Adhikari (2018) reviewed climate-induced drought hazards in mid-hill farming systems in western Nepal. Baniya et al. (2019) analyzed spatial and temporal drought patterns in Nepal for 1982–2015 using SPI and vegetation condition index. Hamal et al. (2020) studied drought impacts on crop yields across Nepal using SPEI. There are three major river basins in Nepal: Gandaki, Karnali, and Koshi. Dahal et al. (2016) conducted drought risk assessment in the Gandaki River Basin of central Nepal from 1981 to 2012. Khatiwada and Pandey (2019) characterized hydro-meteorological drought in the Karnali River Basin of western Nepal from 1981 to 2014. These studies used several drought indices and revealed that SPI correlates with other indices and captures hydro-meteorological drought, indicating that in the Karnali River Basin, other drought factors are negligible and drought is mostly contributed by precipitation variations [?]. Nevertheless, several studies have shown the role of warming-induced drought in the context of climate change [?, ?] and impacts of drought on agriculture [?, ?, ?].

A wide range of water-related hazards have affected the Koshi River Basin

(KRB), and among these hazards, drought has affected large areas [?]. The river basin receives approximately 900.0–1200.0 mm of annual precipitation, with annual mean evapotranspiration of approximately 1500.0–2000.0 mm [?]. Therefore, this river basin always experiences water shortage. The basin shows increasing weather extremes [?], and seasonal precipitation is unevenly distributed. Approximately 75% of annual precipitation occurs during the summer monsoon (June to September), 10% occurs during October and November, and 15% occurs during winter and spring seasons [?]. Daily minimum and maximum temperatures have increased by 0.3°C/10a and 0.1°C/10a, respectively, and consecutive dry days are increasing [?]. Monthly average maximum and minimum temperatures range from 27.0°C to 32.0°C and from 0.0°C to 5.0°C, respectively. Studies project that annual and seasonal minimum and maximum temperatures will show increasing trends throughout the basin. Approximately 70% of the population relies on rainfed agriculture for their livelihood; therefore, uneven precipitation distribution and increasing temperatures cause water stress in the basin [?].

Several studies have examined precipitation variations [?], temperature [?], water resources [?], climate change, and agricultural production [?, ?] in the KRB. Bharati et al. (2014) mentioned future climate change impacts and the need to include extreme climate events such as drought in planning processes. Wu et al. (2019) conducted a basin-wide study (including transboundary regions) on drought using satellite-based crop water shortage index from 2000 to 2014. Shrestha et al. (2017) estimated SPI values in the KRB (Nepal' s part) to compare precipitation-based drought severity and assess the accuracy of two climate hazard group satellite precipitation estimates. As increasing temperature also affects drought occurrence and the KRB is already facing increasing weather extremes, studying drought in the context of climate change based on meteorological indices is essential. Thus, this study aims to (1) examine spatial and temporal variations in drought in different ecological regions of the KRB from 1987 to 2017; and (2) analyze drought characteristics using SPEI at a three-month time scale from 1987 to 2017.

This study evaluated drought characteristics using SPEI based on ground station meteorological data over 31 years in the KRB, Nepal. Investigating the spatial and temporal variability of drought can provide valuable information for decision-makers to devise plausible policies, make climate-smart decisions, and implement these policies effectively.

2.1 Study Area

The study area is located at 26°49 -27°59 N latitude and 86°55 -87°10 E longitude within the KRB in central and eastern Nepal. The KRB is a transboundary river system with a total area of 8.73$×10^{4}$ km^2, covering five counties in China, 27 districts in Nepal, and 16 districts in India [?]. In Nepal, the basin covers three distinct ecological regions—mountains, hills, and Terai—from north to south, with elevations ranging from 60 to 8849 m a.s.l. (Fig. 1 [Figure 1: see original paper]) [?]. Climate within the KRB (Nepal) varies from tropical in the Terai to alpine in high mountains, with subtropical warm temperate climate in the hills [?]. Generally, temperature decreases from south to north, although topography causes spatial variations. Annual mean temperatures are 16.0°C, 20.0°C, and 25.0°C in the mountains, hills, and Terai, respectively. Annual precipitation decreases from 1931.0 to 536.0 mm. Among the 27 districts in the KRB (Nepal), we selected 16 districts based on data availability: three in the mountains, seven in the hills, and six in the Terai ecological zone (Fig. 1). Major climatic features of these regions estimated from available data (1987-2017) are illustrated in Table 1 [?, ?].

2.2 Data Sources

This study employed monthly precipitation and minimum and maximum temperature data collected from the Department of Hydrology and Meteorology, Government of Nepal. We considered the longest period of climate data available from the maximum number of weather stations. Altogether, 31 years of data from 23 weather stations between 1987 and 2017 were collected. The 23 weather stations are located within 16 districts of the KRB (Nepal): three in the mountain region, 11 in the hill region, and nine in the Terai region. Details of weather stations are provided in Table 2 . For basin- and regional-level drought distributions, we calculated average climate data values at multiple time scales from all weather stations in the basin and respective regions (mountain, hill, and Terai) and obtained SPEI values [?, ?, ?]. We assumed that using the longest period of data from the maximum available stations would help minimize uncertainties regarding spatial variation in drought.

2.3 Methods

This study used the SPEI index and Mann-Kendall (M-K) test to quantify drought and detect trends in the KRB. SPEI is considered an improved drought index for studying drought conditions [?]. Similarly, the M-K test is a widely used nonparametric approach for detecting trends in time series data [?]. Details of these methods are described below.

2.3.1 Standardized Precipitation Evapotranspiration Index (SPEI)

SPEI is a drought index developed by Vicente-Serrano et al. (2010) that uses precipitation and temperature components. Its strength lies in including temperature components along with precipitation to account for temperature effects on drought. SPEI uses the "climatic water balance" component—the difference between precipitation and potential evapotranspiration rather than precipitation alone as the input variable. This approach compares water availability with atmospheric evaporative demand, providing reliable drought severity measurements [?]. SPEI output is applicable for all climate regimes, and results are comparable because they are standardized [?]. SPEI can be calculated at different time scales, enabling detection of both short- and long-term drought [?].

The SPEI package version 1.7 in R software calculated monthly SPEI values. Negative SPEI values indicate drought conditions, with lower negative values representing worse conditions. Multiscale features of SPEI values at a 3-month time scale (May for spring, August for summer, November for autumn, and February for winter) provide seasonal drought context. Similarly, 12-month time scale SPEI values (December SPEI of each year) indicate whole-year water conditions caused by drought. The 3-month and 12-month time scales reflect agricultural and hydrological drought conditions, respectively. The 3-month time scale also describes short- and medium-term soil moisture and seasonal precipitation estimation, while the 12-month time scale observes long-term precipitation patterns over a period, providing annual moisture conditions [?, ?]. This study examined annual and seasonal drought characteristics in the KRB, focusing on moderate, severe, and extreme drought events based on SPEI values (Table 3) [?, ?].

Based on this classification, we extracted 3-month (seasonal) and 12-month (annual) SPEI values from 1987 to 2017. Livelihoods in the KRB depend on agriculture [?]; thus, studying drought at seasonal scales is essential [?]. Monthly SPEI values at the 3-month time scale were used to calculate drought event characteristics (intensity, duration, severity, and frequency). Annual SPEI was indicated by December SPEI of each year, while seasonal SPEI was obtained for May (spring), August (summer), November (autumn), and February (winter).

2.3.2 Estimation of Potential Evapotranspiration

Calculating SPEI requires estimating potential evapotranspiration (PET) from available climate data. Several methods exist, including the Thornthwaite [?], Hargreaves [?], and Penman-Monteith methods [?, ?]. Each method requires different data inputs. Studies have used these methods based on data availability: Tan et al. (2015) and Mohsenipour et al. (2018) used Thornthwaite; Prabnakorn et al. (2018) and Bisht et al. (2019) used Hargreaves; and Gao et al. (2017) and Huang et al. (2018) used Penman-Monteith.

The Penman-Monteith method (FAO-56) is recommended by the Food and Agriculture Organization (FAO) because it accurately estimates PET across wide climate ranges [?]. However, this method requires wind speed, net radiation, temperature, and relative humidity data, which are not readily available in developing countries [?]. Alternative methods requiring fewer data—Thornthwaite and Hargreaves—are widely used for PET estimation [?, ?].

Thornthwaite and Hargreaves methods are temperature-based approaches. Thornthwaite requires average temperature and latitude (calculated sunshine duration), while Hargreaves uses minimum and maximum temperatures and extraterrestrial radiation [?]. Hargreaves is recommended as the standard method for computing PET when only temperature data are available [?, ?, ?] and is recommended by FAO as an alternative method [?]. Studies show Hargreaves is comparable to Penman-Monteith [?]. Stagge et al. (2014) studied SPEI sensitivity to PET estimation methods, including Thornthwaite, Hargreaves, Penman-Monteith Hargreaves, Priestley-Taylor, and Penman-Monteith FAO-56. SPEI estimates from Hargreaves and three other methods were more internally consistent than those from Thornthwaite. Therefore, Hargreaves is the most useful and consistent method for estimating PET in data-scarce areas [?].

Our study adopted the Hargreaves method to estimate PET due to data limitations. This method has been successfully applied in Nepal: Bhatt et al. (2014) estimated PET for the KRB; Dahal et al. (2016) studied climate change impacts on water availability in the Bagmati River Basin; Penton et al. (2016) used it for hydroclimate and streamflow modeling in the KRB; Aadhar and Mishra (2017) conducted real-time drought analysis in South Asia (including Nepal); and Hamal et al. (2020) assessed drought impacts on crop yields in Nepal.

The Hargreaves method equation is:

$$ET_0 = 0.0023 \times RA \times (T_{avg} + 17.8) \times \sqrt{TD}$$

where ET_0 is mean monthly reference or potential evapotranspiration (mm/month); RA is extraterrestrial radiation (MJ/(m^2 • month)) estimated from latitude and month; T_{avg} is average monthly temperature (°C); TD is mean monthly temperature range (°C) (difference between mean maximum and mean minimum temperatures); and 0.0023 is the coefficient proposed by Hargreaves and Samani (1985).

2.3.3 Definition of Drought Characteristics

A drought event is defined as a period when the drought index value is continuously negative and reaches -1.00 or less. Drought starts when the value falls below zero and ends when it reaches a positive value following -1.00 or less [?].

Drought frequency is defined as the number of drought events relative to total study years, calculated as:

$$F_s = \frac{n_s}{N_s} \times 100\%$$

where F_s is drought frequency (%); n_s is number of drought events; N_s is total years in the study period; and s is the station.

Drought duration is the number of months between drought start and end, with the start month included and end month excluded [?].

Severity is the sum of all absolute SPEI values during a drought event:

$$S_e = \sum_{j=1}^{m} |SPEI_j|$$

where e is the drought event; j is the month; m is duration; and S_e is severity.

Drought intensity (DI_e) is obtained by dividing severity by duration:

$$DI_e = \frac{S_e}{m}$$

Larger intensity indicates greater drought severity.

Drought station proportion is the number of drought stations at a time scale relative to total stations studied, providing spatial extent of drought events:

$$P_j = \frac{n_j}{N_j} \times 100\%$$

where P_j is drought station proportion at a given time scale (%); j is the time scale; n_j is number of droughts in the given time scale; and N_j is total number of stations.

2.3.4 Trend Analysis

The M-K test and Sen' s slope methods [?] were used for trend analysis. These methods are widely used for detecting trends in hydrometeorological data series [?, ?], including drought index series [?]. The M-K test is nonparametric and does not require specific data distribution. Sen' s slope method is not highly affected by single data errors or outliers [?]. These tools help obtain magnitude and trend significance in time series data.

The M-K test uses hypothesis testing for monotonic trends. It tests the null hypothesis (H_0) of no trend versus the alternative hypothesis of a trend at 0.001, 0.01, and 0.05 significance levels. The M-K test statistic S is:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k)$$

where x_j and x_k are annual values in years j and k ($j > k$), and sgn is the sign function.

When $n \leq 9$, the absolute S value is compared directly to the theoretical distribution. When $n \geq 10$, normal approximation is used, and variance of S is:

$$\mathrm{VAR}(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)}{18}$$

where VAR(S) is variance of S; q is number of tied groups; and t_p is number of data values in the pth group.

The test statistic Z is:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{VAR}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\mathrm{VAR}(S)}} & \text{if } S < 0 \end{cases}$$

Positive and negative Z values indicate increasing and decreasing trends, respectively. H_0 is rejected if $|Z| > Z_{1-\alpha/2}$ from the standard normal distribution. We tested significance at 0.001, 0.01, and 0.05 levels.

Trend magnitude (Q) is quantified by Sen' s slope:

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

where j and k are data series with n values. Slope observations (N) are calculated as $N = n(n-1)/2$. The median of N slope values gives Sen' s estimator Q_i. After ranking N values of Q_i from ascending to descending order, Sen' s estimator is:

$$Q = \begin{cases} Q_{(N+1)/2} & \text{if } N \text{ is odd} \\ \frac{Q_{N/2} + Q_{(N/2)+1}}{2} & \text{if } N \text{ is even} \end{cases}$$

Finally, Q is tested by a two-sided hypothesis at 100% (1-α) confidence interval. If the slope is significant at 95% confidence interval using a nonparametric technique based on normal distribution, then C_α is computed. We used the Microsoft Excel program MAKESENS 1.0 developed by the Finnish Meteorological Institute in 2002 for analysis [?].

3.1 Spatial and Temporal Variations in the SPEI

Annual SPEI variation showed decreasing trends at regional and basin levels in the KRB from 1987 to 2017 (Fig. 2 [Figure 2: see original paper]). Negative SPEI values represent drought conditions. Temporal variation revealed moderate drought in the mountain region in 1992, 2011, 2014, and 2015, with severe drought in 2005 and 2009. In the hill region, moderate drought occurred in 1992, 2008, 2009, 2015, and 2017, with severe drought in 2012. The Terai region experienced moderate drought in 2009 and 2015 and severe drought in 1992, 1994, and 2012.

Spatially, annual moderate drought variation occurred across mountains, hills, and Terai during recent years (e.g., 2015). In 1992, drought was moderate in mountains and hills but severe in Terai. In 2009, drought was severe in mountains and moderate in hills and Terai. Severe drought occurred in hills and Terai in 2012. Drought conditions in mountain, hill, and Terai regions are generally independent, though some years showed related occurrences that were not consistent throughout 1987–2017.

Overall results indicated frequent drought occurrence after 2000. Moderate drought was relatively higher in the hill region, while severe drought was higher in the Terai region. Spatial consistency in annual drought occurrence was higher within hills and Terai. Annual SPEI values showed significant decreasing trends per decade in the hills, indicating high probability of increasing drought tendency in the future.

Seasonal SPEI variation also showed decreasing trends at regional and basin levels from 1987 to 2017 (Fig. 3 [Figure 3: see original paper]). In the mountain region, extreme drought occurred in autumn (2009); severe drought in spring (1992, 2011), summer (1993, 2009), and winter (1999, 2006); and moderate drought in spring (2005, 2007, 2014, 2016), summer (1992, 2005, 2011), autumn (1994, 2000, 2002, 2005, 2015), and winter (2008, 2009, 2014, 2017).

In the hill region, severe drought occurred in spring (1996), summer (2006, 2017), autumn (2000), and winter (2006, 2009); moderate drought in spring (1992, 1995, 1999, 2012, 2014), summer (2008, 2009, 2012), autumn (1988, 1997, 2008, 2009, 2012, 2015, 2017), and winter (1999, 2001, 2017).

In the Terai region, extreme autumn drought occurred in 2009. Severe drought was observed in spring (1995, 1996), summer (1992, 1994, 2012), autumn (2005), and winter (2006, 2017); moderate drought in spring (1991, 1992, 1994, 2012), summer (2006, 2013, 2015), autumn (2008, 2012, 2015), and winter (1999, 2001). SPEI values showed decreasing trends in all four seasons, but trends were only significant during summer in the hill region and winter in mountain and hill regions.

Spatially, seasonal drought showed variations during the study period. Some years exhibited similar seasonal drought patterns across all regions. For instance, severe winter drought occurred in 2006 and moderate autumn drought in 2012 across mountain, hill, and Terai regions. In some years, seasonal drought patterns were consistent in at least two regions. In 1992, moderate spring drought occurred in hills and Terai while severe drought occurred in mountains. A similar pattern was observed for winter drought in 1999. In 2009, extreme autumn drought occurred in mountains and Terai while moderate drought occurred in hills. In 2017, moderate winter drought occurred in mountain and hill regions while severe drought occurred in Terai.

Drought occurred in at least two regions each season. Drought severity was similar in some cases (mostly in hill and Terai) but different in others. For example, hill and Terai regions showed severe spring drought in 1996, moderate winter drought in 2001, moderate autumn drought in 2008 and 2015, and moderate spring drought in 2012. Similarly, moderate summer drought occurred in mountain and hill regions in 2011 and moderate spring drought in 2014.

Different drought severities were observed between regions in some years. During autumn 2000, moderate drought occurred in mountains while severe drought occurred in hills. In autumn 2005, mountains showed moderate drought while Terai showed severe drought. In 1995, moderate spring drought occurred in mountains and severe drought in Terai. During summer 1992, moderate and severe drought occurred in mountains and Terai, respectively. In summers 2006 and 2009, severe drought occurred in hills and mountains while moderate drought occurred in Terai and hills. During winter 2009, moderate drought occurred in mountains and severe drought in hills.

Overall seasonal variation indicated that both moderate (most common) and severe drought occurred in all KRB regions. Higher spatial consistency in seasonal drought was sometimes observed in two regions rather than all three. Significant decreasing SPEI trends occurred in hill region summer and mountain and hill region winters. Across the entire KRB, significant decreasing seasonal SPEI trends were observed in summer and winter.

3.2.1 Duration and Severity of Drought Events

Average drought duration calculated from SPEI for the KRB during 1987–2017 was 5.8 months. Maximum drought duration (approximately 15.0 months) occurred during 2009–2010. Spatially, substantial differences in average drought duration were not observed between mountain and hill regions, though values were relatively lower (by one month) in the Terai region. Maximum drought duration (2007–2009) was greatest in the hill region. Maximum duration occurred twice from 2005 to 2013 in the mountain region but only in the mid-1990s in the Terai region (Table 4).

Average and maximum severity values of drought events in the KRB from 1987 to 2017 were 5.80 and 16.05, respectively. Spatially, average drought severity was highest in the hill region and lowest in the Terai region, though maximum severity magnitude was highest in the Terai region and lowest in the mountain region. The longest duration of maximum severity occurred in the mid-1990s in the Terai region but in the mid-2000s and late 2000s in mountains and hills.

3.2.2 Intensity and Frequency of Drought Events

Average and maximum drought intensities calculated from SPEI in the KRB during 1987-2017 were 1.00 and 1.59, respectively. Maximum intensity occurred over a 3-month duration in 2006. Spatially, the Terai region showed the highest magnitude of average and maximum drought intensity compared to mountain and hill regions. The highest drought intensity in the Terai region was observed in a single month duration (November) of 2005. Average drought intensity magnitude in mountain and hill regions was 0.94, while maximum intensity was higher in the mountain region (1.74). Maximum intensity duration in mountain, hill, and Terai regions was six, three, and one months, respectively.

Drought event frequency in the KRB from 1987 to 2017 was 71%. Spatially, drought frequency was 74% in the mountain region, 77% in the hill region, and 81% in the Terai region, indicating a general increase in drought frequency from mountain to Terai region.

Overall results indicated that maximum duration, intensity, and severity of drought events were mainly observed after 2000 in the KRB. Spatially, onset of maximum duration and severity occurred either in winter or spring of the current year and ended mostly in spring of the next year across all regions. Maximum drought intensity was observed in summer and late autumn in the mountain region, mid-winter and early spring in the hill region and entire KRB, and late autumn in the Terai region.

3.3 Variation in Drought Station Proportion

Monthly drought station proportion was calculated from monthly SPEI values using Equation 5 for 1987-2017. Annual and seasonal proportions were calculated by averaging monthly proportions for each year and season. M-K trends of these proportions at monthly, interannual, and interseasonal scales are shown in Table 5 .

In the mountain region, monthly proportions showed no trends, but interseasonal and interannual scales showed significant increasing trends of 4.1%/10a and 5.8%/10a ($P<0.05$), respectively. In the hill region, significant increasing trends occurred in January (5.3%/10a; $P<0.05$), March (3.0%/10a; $P<0.05$), July (5.1%/10a; $P<0.05$), August (7.6%/10a; $P<0.05$), and September (7.0%/10a; $P<0.01$). At interseasonal scale, proportions increased in all seasons but were only significant in summer (7.2%/10a; $P<0.05$), autumn (4.5%/10a;

P<0.05), and winter (5.7%/10a; P<0.05). At interannual scale, a significant increasing trend (6.7%/10a; P<0.01) was observed.

In the Terai region, proportion showed a significant decreasing trend (-4.8%/10a; P<0.05) in June and no trends in other months. At interseasonal scale, positive trends occurred in spring and autumn, negative trend in winter, and no trend in summer. At interannual scale, no trend was observed.

Overall results indicated that spatial extent of drought has significant increasing trends in summer, autumn, and winter in the hill region. Across the entire KRB, drought station proportion showed increasing trends in January, February, and July–November; no trends were observed March–June and December. Only trends in February, August, and September were statistically significant (P<0.05; Table 5). At interseasonal scale, drought station proportion increased in all seasons but was not statistically significant. However, annual drought station proportion showed a significant increasing trend (4.2%/10a; P<0.05) from 1987 to 2017.

---

4 Discussion

Our study showed that drought and its characteristics exhibited significant spatial and temporal variations in the KRB from 1987 to 2017. These variations are directly and indirectly influenced by precipitation, temperature, and topography. Decreasing precipitation and increasing temperature contribute to drought events, leading to differences in drought intensity and duration [**?**, **?**]. Global drought studies revealed increasing drought tendency since the mid-1980s due to increasing temperature through evapotranspiration mechanisms [**?**, **?**]. Reduced precipitation frequency triggers and enhances drought [**?**]. Topographic diversity can also create rain shadow regions with low precipitation that reinforce drought [**?**]. Our results exhibited more significant increasing trends in annual and seasonal temperatures in the hill region than other regions (Table 6). Winter precipitation showed significant decreasing trends in all regions, while annual trends were only observed in hills. To better understand drought conditions at spatial and temporal scales, we discuss influencing factors and their implications below.

4.1 Spatial and Temporal Drought Trend Variations in the KRB

This study scrutinized spatial and temporal drought variations based on SPEI. Findings revealed increasing drought trends spatially and temporally in the basin. Significant increasing drought trends were observed at annual and seasonal (summer and winter) scales in hills and in winter in mountains. This increasing trend indicates drought occurrence will likely become more frequent, negatively impacting water resources, agriculture, and livelihoods in the KRB. Hill region drought findings resemble quantitative and qualitative studies conducted in Nepal' s hill region. Ghimire et al. (2010) identified that 63% of farms in Nepal' s hills are highly vulnerable to drought. Kafle (2014) identified extreme drought events from five meteorological stations in mid- and far-western hill regions. Sapkota et al. (2016) mentioned severe drought-affected areas in Kavre District in the KRB hills and explored climate change vulnerability. Adhikari (2018) studied drought occurrence and impacts on rainfed agriculture in western Nepal hills.

Several studies explain that increasing temperature and decreasing precipitation are directly linked to drought variations [?, ?, ?, ?]. Variations in these climatic variables create higher atmospheric evaporative demand and long dry spell durations, increasing drought dynamics and magnitude [?, ?, ?]. Based on these facts, annual and seasonal precipitation and temperature trends for the three topographic regions (mountain, hill, and Terai) and entire KRB from 1987 to 2017 are shown in Table 6. Our analysis is consistent with Baniya et al. (2018), who found annual precipitation decreased at 5.12 mm/a and temperature increased at 0.03°C/a from 1982 to 2015 in Nepal. Increasing temperature and decreasing trends at both annual and seasonal scales fit with respective SPEI trends from our findings (Figs. 2 and 3), indicating high drought risk. Other causes of drought variations may include KRB geographical features. As elevation increases from Terai (south) to mountains (north), climate varies from tropical to warm temperate [?]. South Asian monsoon influences southern and northern parts that lie in rain shadow areas. Precipitation patterns are linked with summer monsoon-southeasterly and winter monsoon-westerly circulations [?].

Due to substantial topographic differences, spatial and temporal precipitation variations occur within short distances. In mountains, north-facing slopes maintain relatively higher humidity than south-facing slopes after monsoon due to diffuse solar radiation. On hills, sudden cloudbursts can cause intense precipitation within a day, while rain shadow areas of the Tibetan Plateau remain dry [?]. Therefore, local geographical features, orography, and complex terrain produce varied microclimates that may cause drought conditions in the basin [?, ?, ?].

4.2 Variation of Drought Characteristics in the KRB

This study detected drought characteristic variations in the KRB using SPEI values. Analysis showed highest frequency and intensity (average and maximum) of drought in the Terai region, while the longest maximum drought duration occurred in the hill region. Saravi et al. (2009) indicated that the longest duration drought event may not necessarily be intense enough to cause greatest impacts. In our case, the Terai region had only 1-month drought duration in 2005 with maximum intensity of 1.84, while mountain and hill regions had relatively longer durations (Table 4).

Our study found highest drought intensity magnitude in the Terai region, which might have impacted winter crop growth, especially wheat. This finding aligns with Wu et al. (2019), who reported severe drought in the KRB downstream from 2000 to 2014. Their transboundary KRB study revealed that highest drought intensity is directly related to higher drought severity, significantly impacting crops and water facilities. Our study observed drought in different seasons, particularly winter and spring in hills and summer, winter, and spring in mountains, Terai, and entire KRB. These seasons are crucial for producing major cereal crops such as wheat, maize, and rice; therefore, any drought conditions might affect production. These findings support Joshi (2018), cited by Adhikari (2018), who revealed that eastern and central Nepal faced droughts in 1992, 1994, 1997, 2002, 2008, 2009, 2012, and 2013 due to inadequate and poorly distributed precipitation, causing major crop losses of approximately 3.85$×10^{5}$ t. Seasonal drought occurrence is also consistent with Baniya et al. (2019), who found several severe and moderate droughts during the 1990s, 2000s, and 2010s at annual and seasonal scales. A Nepal study also showed moderate to extreme drought intensity from 1972 to 2003 [?]. Other findings revealed that western Nepal experiences extreme drought conditions, especially in summer and winter [?, ?]. A SPI-based study (1981–2012) in Nepal' s Gandaki River Basin showed severe drought in 2004, 2005, 2006, and 2009 [?]. These results indicate that different regions and river basins in Nepal, including KRB, experienced drought from the 1980s to 2010s.

4.3 Implications of Drought Variations in the KRB

Drought occurrence implications at any location and time can be determined by climate features and biophysical conditions [?]. These conditions can evaluate seasonal and annual drought in the KRB. The 3-month time scale highlights soil moisture conditions, while the 12-month time scale reflects water levels in source regions; these scales are most effective in agricultural regions.

Our findings revealed increasing annual and seasonal drought trends in the KRB from 1987 to 2017 (Figs. 2 and 3), which can reduce soil moisture and decrease water source levels and availability [?, ?, ?]. Increased intensity, duration, and frequency of drought can affect water sources and agricultural productivity [?, ?]. Adhikari (2018) reviewed that climate-induced drought profoundly affects agricultural systems in Nepal hills. The KRB has significant arable land and is therefore more sensitive to drought. Aryal (2012) noted that crops are sensitive to water requirements during their lifecycle. During growth and development stages, crops have high water demand, and any delay in water supply affects growth and decreases production potential [?]. Bhatt et al. (2014) mentioned that rice, maize, and wheat cultivated below 1100, 1350, and 1700 m a.s.l. in the KRB suffer from drought caused by increasing temperatures during flowering and yield formation phases. Thus, delay in fulfilling water demand at growth stages ultimately affects yield. Malla (2008) revealed that rainy days are decreasing in Nepal and are highly intense followed by prolonged drought. In the KRB, sectoral water demand increases from mountain to Terai region, highest in agriculture (92%), followed by domestic (6%) and industrial (2%) sectors [?].

Temporally, water demand is higher in dry season than wet season. Our results imply that drought may decrease water availability for all sectors in the future; therefore, necessary policies and plans for water management, such as increasing water storage capacity and other drought mitigation strategies, should be adopted.

---

5 Conclusions

This study assessed spatial and temporal drought characteristics in the KRB from 1987 to 2017. SPEI value variations indicated more frequent drought occurrence after 2000. Moderate and severe drought occurrences were relatively higher in hill and Terai regions, respectively. Annual SPEI values showed significant decreasing trends per decade in the hill region and entire KRB, implying increasing drought tendency in the future, potentially exacerbated by climate change. The magnitude rank of drought trends was hills > mountains > Terai. Seasonal SPEI variation indicated both moderate (most common) and severe droughts occurred in all KRB regions, with significant increasing trends in winter over mountain and hill regions and in summer and winter over the hill region. The magnitude rank of spring drought trend was Terai > mountains > hills; summer was hills > mountains > Terai; winter was mountains > hills > Terai; and autumn was hills and Terai > mountains. Regions more likely affected by seasonal drought should focus on essential mitigation measures.

Drought characteristic analysis indicated that maximum duration, intensity, and severity were observed after 2000 in the KRB. These characteristics mainly appeared in winter or spring of the current year and mostly ended in spring of the next year across the entire KRB. The Terai region had the highest drought frequency (81%) and average intensity (1.01), while the hill region had the highest average severity (5.60) and duration (5.9 months). The hill region also had the longest maximum drought duration (17.0 months), and the Terai region had maximum drought severity (17.28). Drought station proportion from SPEI at 3-month time scale showed the highest significant increasing trend in the hill region at monthly (7.6%/10a in August), seasonal (7.2%/10a in summer), and annual (6.7%/10a) scales. Spatial extent of drought decreased only in the Terai in June during summer ($P<0.05$), autumn, and winter throughout the study period.

This study observed drought conditions in different ecological regions of the KRB using SPEI values. Overall findings revealed significant drought in the KRB, providing a basis for long-term future drought monitoring. This study provides resource planners and policy-makers with information on drought conditions under changing climate, helping them make informed climate decisions and implement appropriate measures. Further detailed studies should investigate drought impacts at district level and examine detailed effects of increasing drought trends during crop growth phases and water demand under population growth scenarios.

Acknowledgements

This study was funded by the CAS (Chinese Academy of Sciences) Overseas Institutions Platform Project (Grant No. 131C11KYSB20200033) and the NSFC-ICIMOD Joint Research Project (Grant No. 41661144038). We express gratitude to the Department of Hydrology and Meteorology (Government of Nepal) for providing original data. We also thank Dr. Bikram PANDEY and Mr. Javed HASSAN for valuable suggestions and support during revision.

References

Aadhar S, Mishra V. 2017. High-resolution near real-time drought monitoring in South Asia. *Scientific Data*, 4: 170145, doi: 10.1038/sdata.2017.145.

Adhikari S. 2018. Drought impact and adaptation strategies in the mid-hill farming system of western Nepal. *Environments*, 5(9): 101, doi: 10.3390/environments5090101.

Adnan S, Ullah K, Khan A H. 2017. Meteorological impacts on evapotranspiration in different climatic zones of Pakistan. *Journal of Arid Land*, 9(6): 938–952.

Agarwal A, Babel M S, Maskey S. 2014. Analysis of future precipitation in the Koshi river basin, Nepal. *Journal of Hydrology*, 513: 422–434.

Agarwal A, Babel M S, Maskey S, et al. 2016. Analysis of temperature projections in the Koshi River Basin, Nepal. *International Journal of Climatology*, 36(1): 266–279.

Agrawala S, Raksakulthai V, Aalst M, et al. 2003. *Development and climate change in Nepal: Focus on water resources and hydropower*. Environment Directorate Development Co-operation Directorate. Paris: Organization for Economic Co-operation and Development, 64.

Allen R G, Smith M, Pereira L S, et al. 1994. An update for the calculation of reference evapotranspiration. *ICID Bulletin*, 43(2): 1–13.

Allen R G, Pereira L S, Raes D, et al. 1998. *Crop evapotranspiration-Guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper 56. Rome: FAO, 300(9): D05109.

Alley W M. 1984. The Palmer drought severity index: limitations and assumptions. *Journal of Climate and Applied Meteorology*, 23(7): 1100–1109.

Amrit K, Pandey R P, Mishra S K. 2018. Characteristics of meteorological droughts in northwestern India. *Natural Hazards*, 94(2): 665-682.

Aryal S. 2012. Rainfall and water requirement of rice during growing period. *The Journal of Agriculture and Environment*, 13: 1-14.

Bandyopadhyay A, Bhadra A, Raghuwanshi N, et al. 2009. Temporal trends in estimates of reference evapotranspiration over India. *Journal of Hydrologic Engineering*, 14(5): 508-515.

Baniya B, Tang Q, Xu X, et al. 2019. Spatial and temporal variation of drought based on satellite derived vegetation condition index in Nepal from 1982-2015. *Sensors*, 19(2): 430, doi: 10.3390/s19020430.

Beguería S, Vicente-Serrano S M, Reig F, et al. 2014. Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *International Journal of Climatology*, 34(10): 3001-3023.

Bharati L, Gurung P, Jayakody P, et al. 2014. The projected impact of climate change on water availability and development in the Koshi Basin, Nepal. *Mountain Research and Development*, 34(2): 118-130.

Bharati L, Bhattarai U, Khadka A, et al. 2019. *From the mountains to the plains: Impact of climate change on water resources in the Koshi River Basin.* Colombo: International Water Management Institute (IWMI), 49.

Bhatt D, Maskey S, Babel M S, et al. 2014. Climate trends and impacts on crop production in the Koshi River basin of Nepal. *Regional Environment Change*, 14(4): 1291-1301.

Bisht D S, Sridhar V, Mishra A, et al. 2019. Drought characterization over India under projected climate scenario. *International Journal of Climatology*, 39(4): 1889-1911.

Bolch T, Kulkarni A, Kääb A, et al. 2012. The state and fate of Himalayan glaciers. *Science*, 336(6079): 310-314.

Burke E J, Brown S J, Christidis N. 2006. Modeling the recent evolution of global drought and projections for the twenty-first century with the Hadley Centre climate model. *Journal of Hydrometeorology*, 7(5): 1113-1125.

Burn D H, Elnur M A H. 2002. Detection of hydrologic trends and variability. *Journal of Hydrology*, 255(1-4): 107-122.

Challinor A J, Ewert F, Arnold S, et al. 2009. Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation. *Journal of Experimental Botany*, 60(10): 2775-2789.

Chen N S, Hu G S, Deng W, et al. 2013. On the water hazards in the trans-boundary Kosi River basin. *Natural Hazards & Earth System Sciences*, 13(3): 795-808.

Chen T, Xia G, Liu T, et al. 2016. Assessment of drought impact on main cereal crops using a standardized precipitation evapotranspiration index in Liaoning Province, China. *Sustainability*, 8(10): 1069, doi: 10.3390/su8101069.

Chinnasamy P, Bharati L, Bhattarai U, et al. 2015. Impact of planned water resource development on current and future water demand in the Koshi River basin, Nepal. *Water International*, 40(7): 1004–1020.

Dabanli I. 2018. Drought risk assessment by using drought hazard and vulnerability indexes. *Natural Hazards and Earth System Sciences*, 18(5): 1451–1468.

Dahal P, Shrestha N S, Shrestha M L, et al. 2016. Drought risk assessment in central Nepal: temporal and spatial analysis. *Natural Hazards*, 80(3): 1913–1932.

Dahal V, Shakya N M, Bhattarai R. 2016. Estimating the impact of climate change on water availability in Bagmati Basin, Nepal. *Environmental Processes*, 3(1): 1–17.

Dai A. 2011. Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900–2008. *Journal of Geophysical Research: Atmospheres*, 116(D12), doi: 10.1029/2010JD015541.

Damberg L, AghaKouchak A. 2014. Global trends and patterns of drought from space. *Theoretical and Applied Climatology*, 117(3–4): 441–448.

Das P K, Dutta D, Sharma J, et al. 2016. Trends and behaviour of meteorological drought (1901–2008) over Indian region using standardized precipitation-evapotranspiration index. *International Journal of Climatology*, 36(2): 909–916.

Dehghan S, Salehnia N, Sayari N, et al. 2020. Prediction of meteorological drought in arid and semi-arid regions using PDSI and SDSM: a case study in Fars Province, Iran. *Journal of Arid Land*, 12(2): 318–330.

di Lena B, Vergni L, Antenucci F, et al. 2014. Analysis of drought in the region of Abruzzo (Central Italy) by the standardized precipitation index. *Theoretical and Applied Climatology*, 115(1–2): 41–52.

Dixit A, Upadhya M, Dixit K, et al. 2009. *Living with Water Stress in the Hills of the Koshi Basin, Nepal*. Kathmandu: International Centre for Integrated Mountain Development, 31.

Droogers P, Allen R G. 2002. Estimating reference evapotranspiration under inaccurate data conditions. *Irrigation and Drainage Systems*, 16(1): 33–45.

Duan K, Mei Y. 2014. Comparison of meteorological, hydrological and agricultural drought responses to climate change and uncertainty assessment. *Water Resources Management*, 28(14): 5039–5054.

Easterling D R, Meehl G A, Parmesan C, et al. 2000. Climate extremes: observations, modeling, and impacts. *Science*, 289(5487): 2068–2074.

Farmer W, Strzepek K, Schlosser C A, et al. 2011. A method for calculating reference evapotranspiration on daily time scales. MIT Joint Program on the Science and Policy of Global Change. Cambridge: Massachusetts Institute of Technology, 21.

Gao X, Zhao Q, Zhao X, et al. 2017. Temporal and spatial evolution of the standardized precipitation evapotranspiration index (SPEI) in the Loess Plateau under climate change from 2001 to 2050. *Science of the Total Environment*, 595: 191–200.

Ghimire Y N, Shivakoti G P, 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.

Gilbert R O. 1987. *Statistical Methods for Environmental Pollution Monitoring*. New York: John Wiley & Sons, 320.

Gumus V, Algin H M. 2017. Meteorological and hydrological drought analysis of the Seyhan−Ceyhan River Basins, Turkey. *Meteorological Applications*, 24(1): 62–73.

Hamal K, Sharma S, Khadka N, et al. 2020. Assessment of drought impacts on crop yields across Nepal during 1987–2017. *Meteorological Applications*, 27(5): 1–18.

Hargreaves G H, Samani Z A. 1985. Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture*, 1(2): 96–99.

Huang J, Zhai J, Jiang T, et al. 2018. Analysis of future drought characteristics in China using the regional climate model CCLM. *Climate Dynamics*, 50(1–2): 507–525.

IPCC (Intergovernmental Panel on Climate Change). 2018. *Global warming of 1.5°C*. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Geneva: Intergovernmental Panel on Climate Change, 616.

Jamro S, Dars G H, Ansari K, et al. 2019. Spatio-temporal variability of drought in Pakistan using standardized precipitation evapotranspiration index. *Applied Sciences*, 9(21): 4588, doi: 10.3390/app9214588.

Joshi G R. 2018. *Agricultural economy of Nepal: Development challenges & opportunities*. Kathmandu: Sustainable Research & Development Center, 374.

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(2): 65–76.

Kansakar S R, Hannah D M, Gerrard J, et al. 2004. Spatial pattern in the precipitation regime of Nepal. *International Journal of Climatology*, 24(13): 1645-1659.

Karki M, Mool P, Shrestha A. 2009. Climate change and its increasing impacts in Nepal. *The Initiation*, 3: 30-37.

Khan J U, Islam A S, Das M K, et al. 2020. Future changes in meteorological drought characteristics over Bangladesh projected by the CMIP5 multi-model ensemble. *Climatic Change*, 162: 667-685.

Khanal U, Wilson C, Hoang V-N, et al. 2018. Farmers' adaptation to climate change, its determinants and impacts on rice yield in Nepal. *Ecological Economics*, 144: 139-147.

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, doi: 10.1016/j.wace.2019.100239.

Li L, She D, Zheng H, et al. 2020. Elucidating diverse drought characteristics from two meteorological drought indices (SPI and SPEI) in China. *Journal of Hydrometeorology*, 21(7): 1513-1530.

Liu X, Wang S, Zhou Y, et al. 2015. Regionalization and spatiotemporal variation of drought in China based on standardized precipitation evapotranspiration index (1961-2013). *Advances in Meteorology*, 2015, doi: 10.1155/2015/950262.

Liu X, Pan Y, Zhu X, et al. 2018. Drought evolution and its impact on the crop yield in the North China Plain. *Journal of Hydrology*, 564: 984-996.

Livada I, Assimakopoulos V. 2007. Spatial and temporal analysis of drought in Greece using the Standardized Precipitation Index (SPI). *Theoretical and Applied Climatology*, 89(3-4): 143-153.

Malla G. 2008. Climate change and its impact on Nepalese agriculture. *Journal of Agriculture and Environment*, 9: 62-71.

Manton M J, Della-Marta P M, Haylock M R, et al. 2001. Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1961-1998. *International Journal of Climatology*, 21(3): 269-284.

McKee T B, Doesken N, Kleist J. 1993. The relationship of drought frequency and duration to time scales. In: *Proceedings of the 8th Conference on Applied Climatology*. Anaheim: American Meteorological Society, 179-183.

Mishra A K, Singh V P. 2010. A review of drought concepts. *Journal of Hydrology*, 391(1-2): 202-216.

Mohsenipour M, Shahid S, Chung E, et al. 2018. Changing pattern of droughts during cropping seasons of Bangladesh. *Water Resources Management*, 32(5): 1555-1568.

NCVST (Nepal Climate Vulnerability Study Team). 2009. *Vulnerability through the eyes of vulnerable: Climate change induced uncertainties and Nepal' s development predicaments*. Kathmandu: Institute for Social and Environmental Transition-Nepal, 95.

Neupane N, Murthy M S R, Rasul G, et al. 2013. Integrated biophysical and socioeconomic model for adaptation to climate change for agriculture and water in the Koshi Basin. In: Leal Filho W. *Handbook of Climate Change Adaptation*. Berlin: Springer, 1–77.

Nijssen B, O' Donnell G M, Hamlet A F, et al. 2001. Hydrologic sensitivity of global rivers to climate change. *Climatic Change*, 50(1–2): 143–175.

Norbu N. 2004. *Invasion success of Chromolaena odorata in the Terai of Nepal*. Enschede: Geo-Information Science, International Institute for Geo-information and Earth Observation (ITC), 41.

Pai D, Sridhar L, Guhathakurta P, et al. 2011. District-wide drought climatology of the southwest monsoon season over India based on standardized precipitation index (SPI). *Natural Hazards*, 59(3): 1797–1813.

Palmer W C. 1965. *Meteorological Drought*, Research Paper No. 45. Washington, DC: Office of Climatology, US Weather Bureau, 58.

Palmer W C. 1968. Keeping track of crop moisture conditions, nationwide: The New Crop Moisture Index. *Weatherwise*, 21(4): 156–161.

Paudyal K R, Ransom J K, Adhikari K, et al. 2001. *Maize in Nepal: Production Systems, Constraints, and Priorities for Research*. Kathmandu: Nepal Agricultural Research Council, International Maize and Wheat Improvement Center, 48.

Pei Z, Fang S, Wang L, et al. 2020. Comparative analysis of drought indicated by the SPI and SPEI at various timescales in Inner Mongolia, China. *Water*, 12(7): 1925, doi: 10.3390/w12071925.

Penton D, Neumann L, Doody T, et al. 2016. Preliminary analysis of hydroclimate and stream flow modelling in the Koshi Basin: Climate, hydrology, ecology and institutional setting. In: *Sustainable Development Investment Portfolio (SDIP) Project*. Canberra: CSIRO, 68.

Peterson T C, Stott P A, Herring S. 2012. Explaining extreme events of 2011 from a climate perspective. *Bulletin of the American Meteorological Society*, 93(7): 1041–1067.

Portela M, Silva A, Santos J, et al. 2017. Assessing the use of SPI in detecting agricultural and hydrological droughts and their temporal cyclicity: some Slovakian case studies. *European Water*, 60: 233–239.

Potop V, Boroneanţ C, Možný M, et al. 2014. Observed spatiotemporal characteristics of drought over the Czech Republic. *Theoretical and Applied Climatology*, 115(3–4): 563–581.

Prabnakorn S, Maskey S, Suryadi F, et al. 2018. Rice yield in response to climate trends and drought index in the Mun River Basin, Thailand. *Science of the Total Environment*, 621: 108-119.

Salmi T, Määttä A, Anttila P, et al. 2002. Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen' s slope estimates-the excel template application MAKESENS. Helsinki: Finnish Meteorological Institute, 35.

Sapkota P, Keenan R J, Paschen J A, et al. 2016. Social production of vulnerability to climate change in the rural middle hills of Nepal. *Journal of Rural Studies*, 48: 53-64.

Saravi M M, Safdari A, Malekian A. 2009. Intensity-duration-frequency and spatial analysis of droughts using the standardized precipitation index. *Hydrology & Earth System Sciences Discussions*, 6(2), doi: 10.5194/hessd-6-1347-2009.

Shafer B, Dezman L. 1982. Development of a surface water supply index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. In: *Proceeding of the Western Snow Conference*. Reno, NV: Colorado State University, 164-175.

Sharma E, Molden D, Rahman A, et al. 2019. Introduction to the Hindu Kush Himalaya assessment. In: Wester P, Mishra A, Mukherji A, et al. *The Hindu Kush Himalaya Assessment*. Switzerland: Spring Nature, 1-16.

Sheffield J, Wood E F. 2007. Characteristics of global and regional drought, 1950-2000: Analysis of soil moisture data from off-line simulation of the terrestrial hydrologic cycle. *Journal of Geophysical Research: Atmospheres*, 112(D17), doi: 10.1029/2006JD008288.

Shrestha A B, Wake C P, Mayewski P A, et al. 1999. Maximum temperature trends in the Himalaya and its vicinity: an analysis based on temperature records from Nepal for the period 1971-94. *Journal of Climate*, 12(9): 2775-2786.

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

Shrestha A B, Bajracharya S R, Sharma A R, et al. 2017. Observed trends and changes in daily temperature and precipitation extremes over the Koshi river basin 1975-2010. *International Journal of Climatology*, 37(2): 1066-1083.

Shrestha N K, Qamer F M, Pedreros D, et al. 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: 138-153.

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.

Sigdel M, Ikeda M. 2012. Seasonal contrast in precipitation mechanisms over Nepal deduced from relationship with large-scale climate patterns. *Nepal Journal of Science and Technology*, 13(1): 115–123.

Spinoni J, Naumann G, Carrao H, et al. 2014. World drought frequency, duration, and severity for 1951–2010. *International Journal of Climatology*, 34(8): 2792–2804.

Stagge J H, Tallaksen L M, Xu C Y, et al. 2014. Standardized precipitation-evapotranspiration index (SPEI): Sensitivity to potential evapotranspiration model and parameters. In: *Hydrology in a Changing World*. Montpellier: International Association of Hydrological Sciences, 367–373.

Tam B Y, Szeto K, Bonsal B, et al. 2019. CMIP5 drought projections in Canada based on the Standardized Precipitation Evapotranspiration Index. *Canadian Water Resources Journal*, 44(1): 90–107.

Tan C, Yang J, Li M. 2015. Temporal-spatial variation of drought indicated by SPI and SPEI in Ningxia Hui Autonomous Region, China. *Atmosphere*, 6(10): 1399–1421.

Thornthwaite C W. 1948. An approach toward a rational classification of climate. *Geographical Review*, 38(1): 55–94.

Touma D, Ashfaq M, Nayak M A, et al. 2015. A multi-model and multi-index evaluation of drought characteristics in the 21st century. *Journal of Hydrology*, 526: 196–207.

Trenberth K, Meehl J, Masters J, et al. 2011. *Current Extreme Weather and Climate Change*. Colorado: Climate Communication Science and Outreach, 28.

Trenberth K E. 2011. Changes in precipitation with climate change. *Climate Research*, 47(1–2): 123–138.

van Rooy M. 1965. A rainfall anomaly index independent of time and space. *Notos*, 14: 43–48.

Vicente-Serrano S M, Beguería S, López-Moreno J I. 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *Journal of Climate*, 23(7): 1696–1718.

Vicente-Serrano S M, Beguería S, Lopez-Moreno J I. 2011. Comment on "Characteristics and trends in various forms of the Palmer Drought Severity Index (PDSI) during 1900–2008" by Aiguo Dai. *Atmosphere*, 116(D19), doi: 10.1029/2010JD015541.

Vicente-Serrano S M, Beguería S, Lorenzo-Lacruz J, et al. 2012. Performance of drought indices for ecological, agricultural, and hydrological applications. *Earth Interactions*, 16(10): 1–27.

Vicente-Serrano S M, Lopez-Moreno J I, Beguería S, et al. 2014. Evidence of increasing drought severity caused by temperature rise in southern Europe. *Environmental Research Letters*, 9(4): 044001, doi: 10.1088/1748-9326/9/4/044001.

Wanders N, Wada Y. 2015. Human and climate impacts on the 21st century hydrological drought. *Journal of Hydrology*, 526: 208–220.

Wang H, Vicente-Serrano S M, Tao F, et al. 2016. Monitoring winter wheat drought threat in Northern China using multiple climate-based drought indices and soil moisture during 2000–2013. *Agricultural and Forest Meteorology*, 228–229: 1–12.

Wang J, Lin H, Huang J, et al. 2019. Variations of drought tendency, frequency, and characteristics and their responses to climate change under CMIP5 RCP scenarios in Huai River Basin, China. *Water*, 11(10): 2174, doi: 10.3390/w11102174.

Wang Q, Wu J, Lei T, et al. 2014. Temporal-spatial characteristics of severe drought events and their impact on agriculture on a global scale. *Quaternary International*, 349: 10–21.

Wang S Y, Yoon J H, Gillies R R, et al. 2013. What caused the winter drought in western Nepal during recent years? *Journal of Climate*, 26(21): 8241–8256.

Wang Y, Quan Q, Shen B. 2019. Spatio-temporal variability of drought and effect of large scale climate in the source region of Yellow River. *Geomatics, Natural Hazards and Risk*, 10(1): 678–698.

Wilhite D A, Glantz M H. 1985. Understanding the drought phenomenon: the role of definitions. *Water International*, 10(3): 111–120.

Wilhite D A. 2000. Drought as a natural hazard: Concepts and definitions. In: Wilhite D A. *Drought: A Global Assessment*. London: Routledge, 3–18.

Wilhite D A. 2005. *Drought and Water Crises: Science, Technology, and Management Issues*. Boca Raton: Taylor & Francis Group, 432.

WMO (World Meteorological Organization). 2012. *Standardized Precipitation Index User Guide*. WMO-No. 1090. Geneva: WMO, 16.

WMO (World Meteorological Organization), GWP (Global Water Partnership). 2016. *Handbook of Drought Indicators and Indices*. WMO/GWP Integrated Drought Management Programme (IDMP). WMO-No. 1173. Geneva, Switzerland: WMO, and Stockholm, Sweden: GWP.

Wu H, Xiong D, Liu B, et al. 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): 3100, doi: 10.3390/ijerph16173100.

Xu C Y, Singh V P. 2001. Evaluation and generalization of temperature-based methods for calculating evaporation. *Hydrological Processes*, 15(2): 305–319.

Yang M J, Yan D H, Yu Y D, et al. 2016. SPEI-based spatiotemporal analysis of drought in Haihe River Basin from 1961 to 2010. *Advances in Meteorology*, 2016: 7658015, doi: 10.1155/2016/7658015.

Zuo D, Cai S, Xu Z, et al. 2018. Spatiotemporal patterns of drought at various time scales in Shandong Province of Eastern China. *Theoretical and Applied Climatology*, 131(1-2): 271-284.

Note: Figure translations are in progress. See original paper for figures.