CHAPTER 6

Evaluation of Spatiotemporal Drought Characteristics using SPI and SPEI

6.1 Overview

Prolonged and repeated drought, as seen in India and other parts of South Asia, is a symptom of climate change, which is partially the result of human interventions. This study addresses the need to assess drought characteristics in Uttar Pradesh, India's most populous state with a significant agricultural sector. Severe droughts in recent years have resulted in substantial losses to crops, animals, and property, making it imperative to understand the dynamics and variability of drought in the region. The chapter evaluates the regional variability of drought characteristics based on intensity, duration, and frequency at different severity levels. Using a single drought index to assess drought conditions can lead to uncertainties due to different indices giving different results, limited coverage and resolution, limited information about meteorological factors, and the inability to capture short-term droughts. The performance of widely used drought indices Standardized Precipitation Index (SPI), and Standardized Precipitation Evapotranspiration Index (SPEI) are evaluated and compared for 18 synoptic locations in Uttar Pradesh state for the period 1971 to 2018. In addition, station proportion is estimated at a different timescale, providing a better insight into temporal variability of the spatial extent of drought events of the specific category. Spatiotemporal trend variability of SPEI and SPI was investigated at a significance level of 0.05 using the non-parametric Mann- Kendall (MK) test. The

study provides valuable insights into the temporal variability of drought events and their relationship with climate change, with a focus on the spatiotemporal variability of the drought characteristics of different categories.

6.1.1 Temporal evaluation of SPI and SPEI at different timescales

The SPI and SPEI time series were estimated at the timescale of 3, 6, 9, and 12-months between 1971 to 2018 for the entire region. Noticeably, the evolution of drought characteristics changes with timescale with both indices. The negative value of SPI and SPEI output depict the drying condition from the normal condition, whereas the positive value is referred to the wet condition (Figure 6.1). A significant increase in drying events was observed after 2000, whereas from 1971 to 2000, wet conditions dominated. Figure 6.1 displays the difference between SPI and SPEI output time series at various timescales. At a shorter timescale (3-month, 6-month), both the indices SPI and SPEI occur with higher frequency drying events with wet alteration, which demarcates the seasonal fluctuation of water balance, directly impacting agriculture of the study region (Figures 6.1, a & b). At longer timescales (9-month and 12-month), the frequency of dry and wet alteration decreased, and drought events occurred with higher severity and longer duration. This shows that drought indices at a longer timescale are reflected in the annual variation of water balance, which is relevant for the hydrological assessment (Figures 6.1, c & d). The SPEI and SPI time series depicts a similar pattern of drought characteristics with different magnitude of drought severity. Whereas SPEI accounts drought characteristics that occur with higher magnitude.

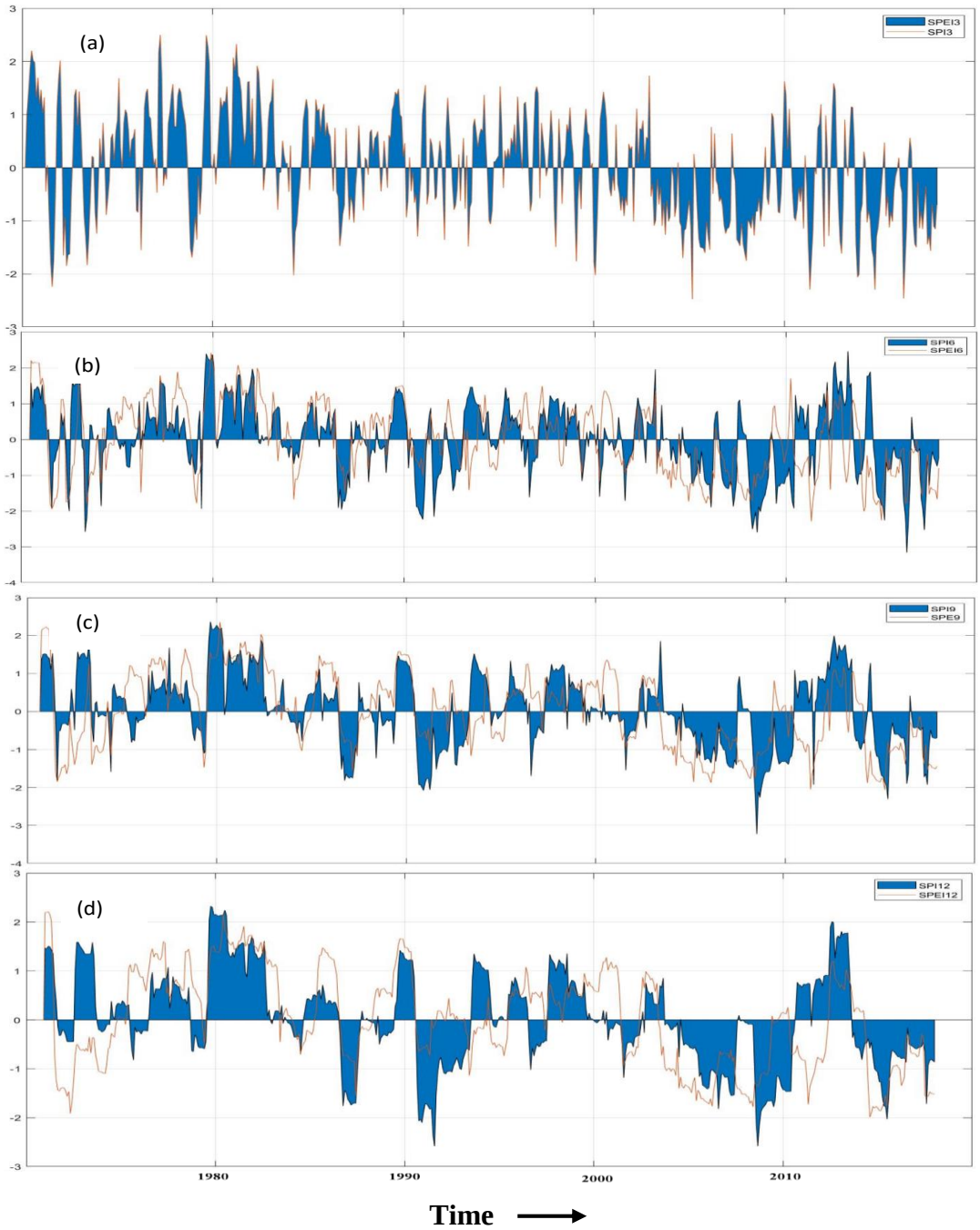


Figure 6.1 Temporal variation of SPI and SPEI time series between 1971 to 2018 at timescale (a) 3-month (b) 6-month (c) 9- month, and (d) 12-month

6.1.2 Decadal change in the drought event

Decadal variability of meteorological drought episodes over Uttar Pradesh was assessed using SPEI and SPI at various timescales (3-month, 6-month, 9-month, and 12-month) for five decades 1970s, 1980s, 1990s, 2000, and 2010s. At threshold

SPI/SPEI = -1, number of drought events is calculated for several categories ("Moderate," "Severe," and "Extreme"). Figure 6.2 depicts the decadal shift in the occurrences of drought events of various categories, highlighting the greater number of drought occurrences reported during the 1970s, followed by the 2000s. Compared to SPI, SPEI accounted higher number of meteorological drought events during the study period (SPEI-3=89, SPEI-6=87, SPEI-9=85, SPEI-12=87), except at 12-month (SPI-3=72, SPI-6=73, SPI-9=81, SPI-12=93). The decadal review of drought occurrence shows that SPEI indices account for a higher number of moderate and severe drought events throughout the 1970s, and both indices show a considerable increase in drought events after the 2000s (Figure 6.2). During the 2000s, both indices accounted for a higher number of moderate and severe drought events. As the decades progressed, drought occurrences increased, indicating moderate to severe drying-up conditions over the study region. Both drought indices have not documented any extreme droughts at the state level, prompting the author to investigate drought occurrences at a spatial scale across the study region.

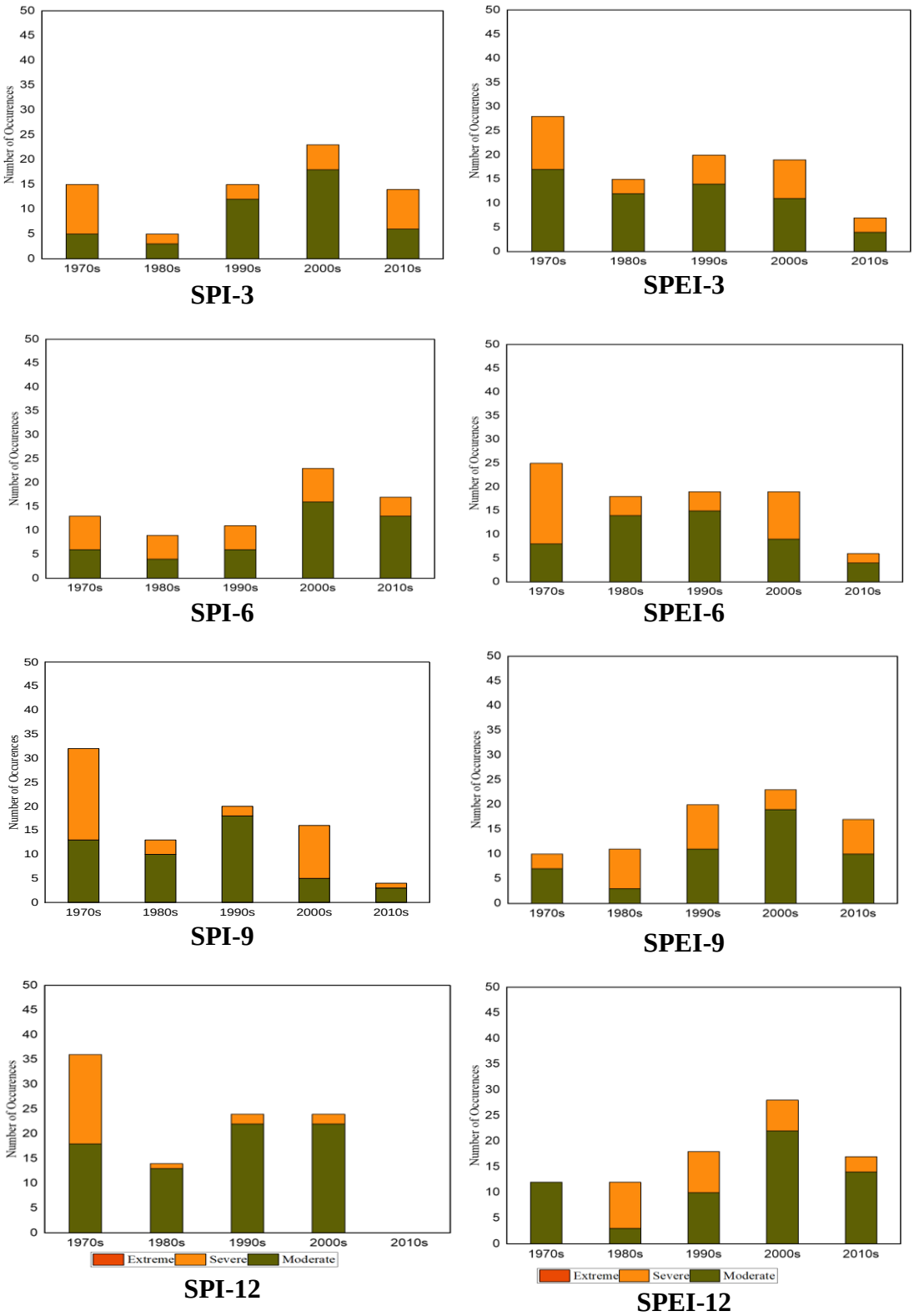


Figure 6.2 The number of occurrences of drought occurrences of different categories (Extreme, Severe, moderate) estimated from SPI and SPEI at the timescale of 3-month, 6-month, 9-month, and 12-month during the last five decades i.e.,1970s, 1980s,1990s, 2000s, and 2010s

6.1.3 Spatiotemporal evaluation of drought trend

Assessing drought trends is essential for evaluating climate change and identifying potential strategies for managing water supplies in the future. MK test (Z_{MK}) has been used to analyze the trend of drought severity time-series estimated using SPI and SPEI at a timescale of 3, 6, 9, and 12-month from 1971 to 2018. The positive Z_{MK} indicate an increase in the trend of drought which implies decrease in drying events over the period, whereas the negative Z_{MK} value indicate the drying event increases. Figure 6.3 demonstrates the spatial pattern of trend distribution of SPI and SPEI drought severity time series over the study area at the timescale of 3-month, 6-month, 9-month, and 12-months. As the timescale lengthens, the magnitude of the trend becomes increasingly negative, reflecting an increase in drying conditions over time. The drying condition trend pattern changes as the timescale changes for both indices, as illustrated in Figure 6.3. For the SPEI time series, except Saharanpur and Aligarh, the majority of locations are experiencing an increase in dryness conditions at a significance level of ($p>0.05$), whereas, at a longer timescale, Meerut, Bareilly, and Mirzapur are experiencing wetness conditions with a drying trend at timescale of 3-month, 6-months. At shorter timescales of SPI, all the stations tend towards the drying conditions, whereas with the increase in timescale, Bareilly and Moradabad experience an increase in wetness conditions over the year. Interestingly, the drying condition spread over the region with the SPI time series compared to the SPEI time series, with stations Aligarh, Saharanpur, and Meerut showing drying conditions with SPI but not with SPEI. The difference in the magnitude of the Z_{MK} value of SPI and SPEI at various timescales was observed. In the SPEI time series, drying conditions stretched throughout the central region compared to SPI. They occurred with greater magnitude, whereas in the SPI time

series, drying conditions expanded with greater magnitude in the studied area's eastern part. So, utilizing only one drought index, particularly the SPI, should be evaluated with caution. The result of trend analysis illustrate that both the indices SPI and SPEI at various scales tended towards the drying condition recently over the entire study area.

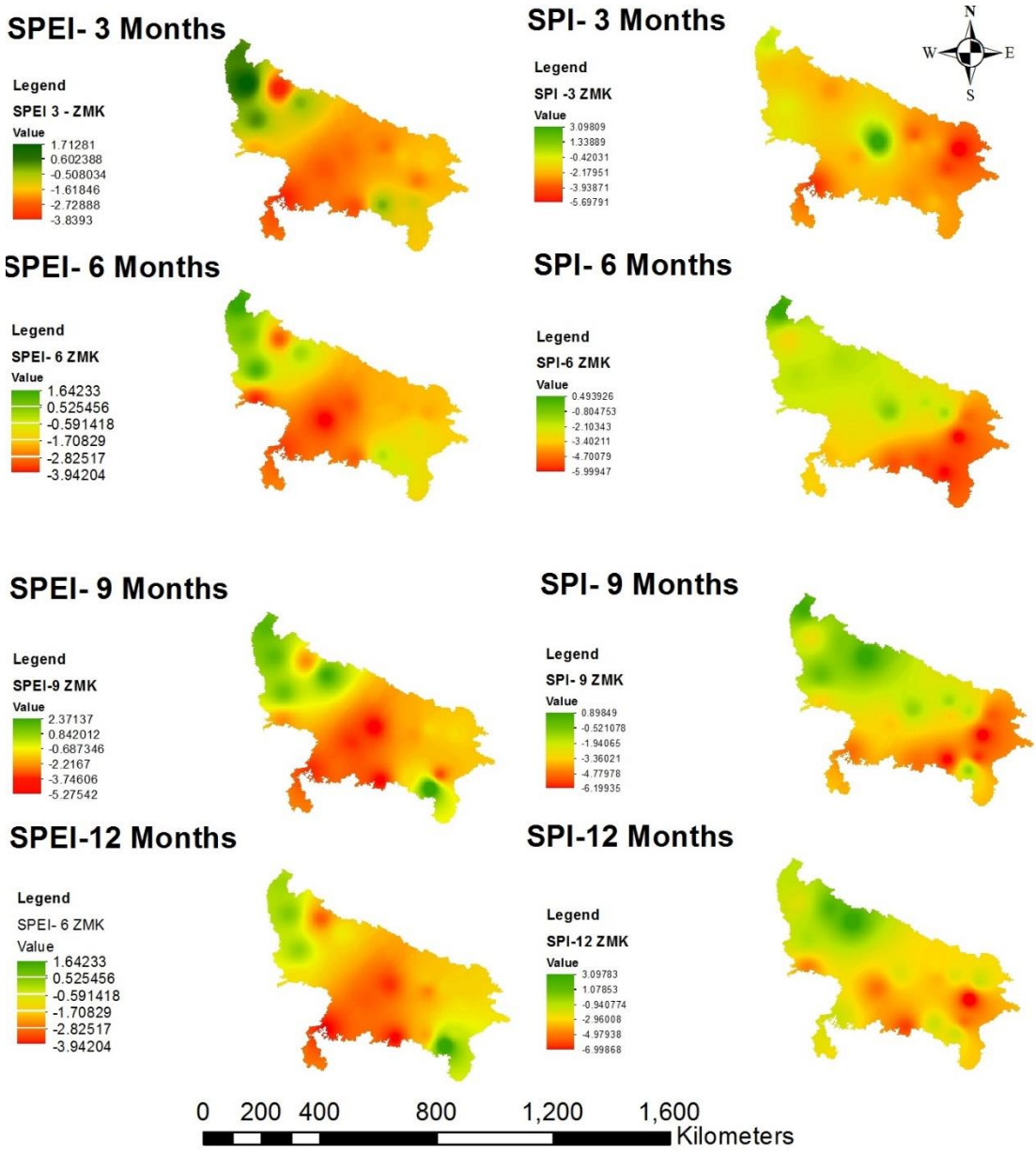


Figure 6.3 Spatial distribution of the drought trend (ZMK) of SPI and SPEI time series at a scale of 3-month, 6-month, 9-month, and 12-month for the period of 1971 to 2018

6.1.4 Spatiotemporal assessment of drought intensity

Drought Intensity (*I*) of SPI and SPEI time series were estimated by employing run theory at the threshold of (<-1) for timescale 3-month, 6-month, 9-month, and 12-month from 1971 to 2018 over Uttar Pradesh. The spatial distribution of drought Intensity (*I*) for SPI and SPEI in the study area is illustrated in Figure 6.4, where the change in color reflects the change in the magnitude of drought intensity. The spatial distribution of drought Intensity (*I*) for SPI and SPEI in the study area is illustrated in Figure 6.4, where the change in color reflects the change magnitude of drought intensity. There were differences in the distribution of drought intensity represented by the SPI and SPEI at all timescales. SPI time series accounts for a slightly higher magnitude of drought intensity at every timescale than SPEI. During 48 years, the SPI time series, at the timescale of 3, 6, 9, and 12-month, the average drought intensity for the entire studied area is 1.52, 1.50, 1.40, and 1.30. For the SPEI time series, the average drought intensity is 1.30, 1.30, 1.30, and 1.20. Drought intensity expansion diminishes for both indices with an increase in timescale. The spatial map indicate that all of the studied stations experience nearly the same intensity of drought events over the study area at a shorter scale. Figure 6.4 demonstrate the spatial distribution of drought intensity estimated from SPI and SPEI time series for every scale. The SPI and SPEI time series account for the same pattern of increase in the duration of drought events with increasing timescale with the difference in magnitude. Results demonstrate that SPEI accounts lengthier duration of drought events than SPI at every scale. The study area records average drought duration is 3, 6, 9, and 12-month for SPEI is 2.30, 3.50, 4.60, and 7.90 & SPI is 2.20, 3.07, 4.09, and 7.02. The spatial distribution drought duration shows that the eastern and northernmost part of the study area record drought

event of relatively shorter duration for the SPEI time series. Whereas, the SPI time series records the longer duration of drought in Prayagraj, Gorakhpur, Basti, and Azamgarh in the eastern region of Uttar Pradesh. It's worth noting that the area with high drought intensity hasn't extended with the increase of timescale, implying that this region was primarily affected by short-term drought.

6.1.5 Spatiotemporal assessment of drought duration.

Drought duration (*D*) of SPI and SPEI time series were estimated by employing run theory at the threshold of (<-1) for timescale of 3-month, 6-month, 9-month, and 12-months from 1971 to 2018 over Uttar Pradesh. Figure 6.5 demonstrates the spatial distribution of drought duration estimated from SPI and SPEI time series for every scale. The SPI and SPEI time series account for the pattern of increase in the duration of drought events with increasing timescale with the difference in magnitude. Results demonstrate that SPEI accounts lengthier duration of drought events than SPI at every scale. The study area experienced drought events of average duration of 3, 6, 9, and 12-month timescale for SPEI is 2.3, 3.5, 4.6, and 7.9 & SPI is 2.2, 3.07, 4.09, and 7.02. The spatial distribution drought duration indicates that the eastern and northernmost part of the study area record drought event of relatively shorter duration for SPEI time series, whereas SPI time series records the higher duration of drought in Prayagraj, Gorakhpur, Basti, and Azamgarh in the eastern region of Uttar Pradesh. In conclusion, due to differences in the values of the SPI and SPEI, their drought characteristics varied substantially spatially and temporally.

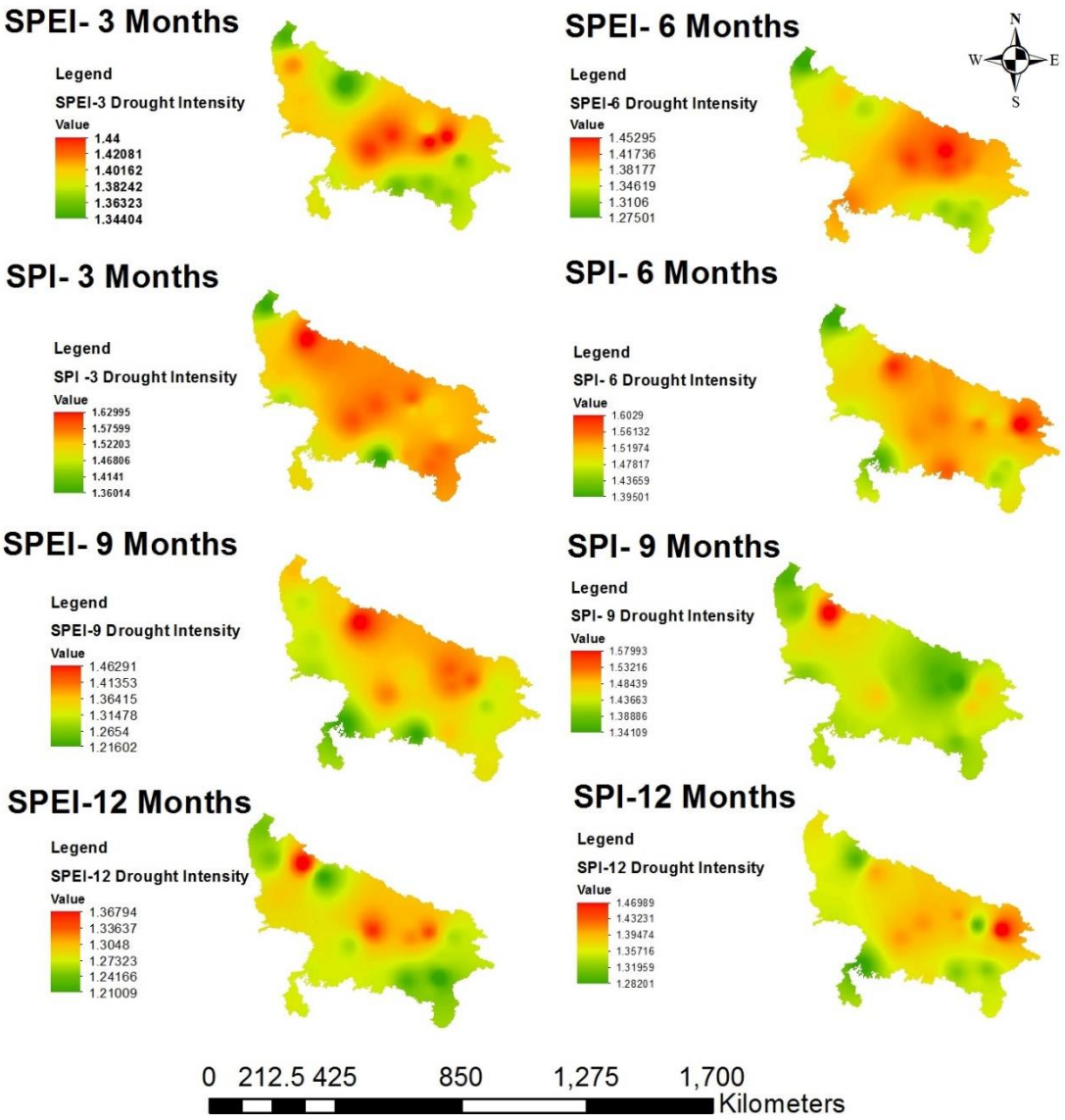


Figure 6.4 Spatial distribution of the drought intensity of SPI and SPEI time series at scale of 3-month, 6-month, 9-month, and 12-month for the period of 1971 to 2018

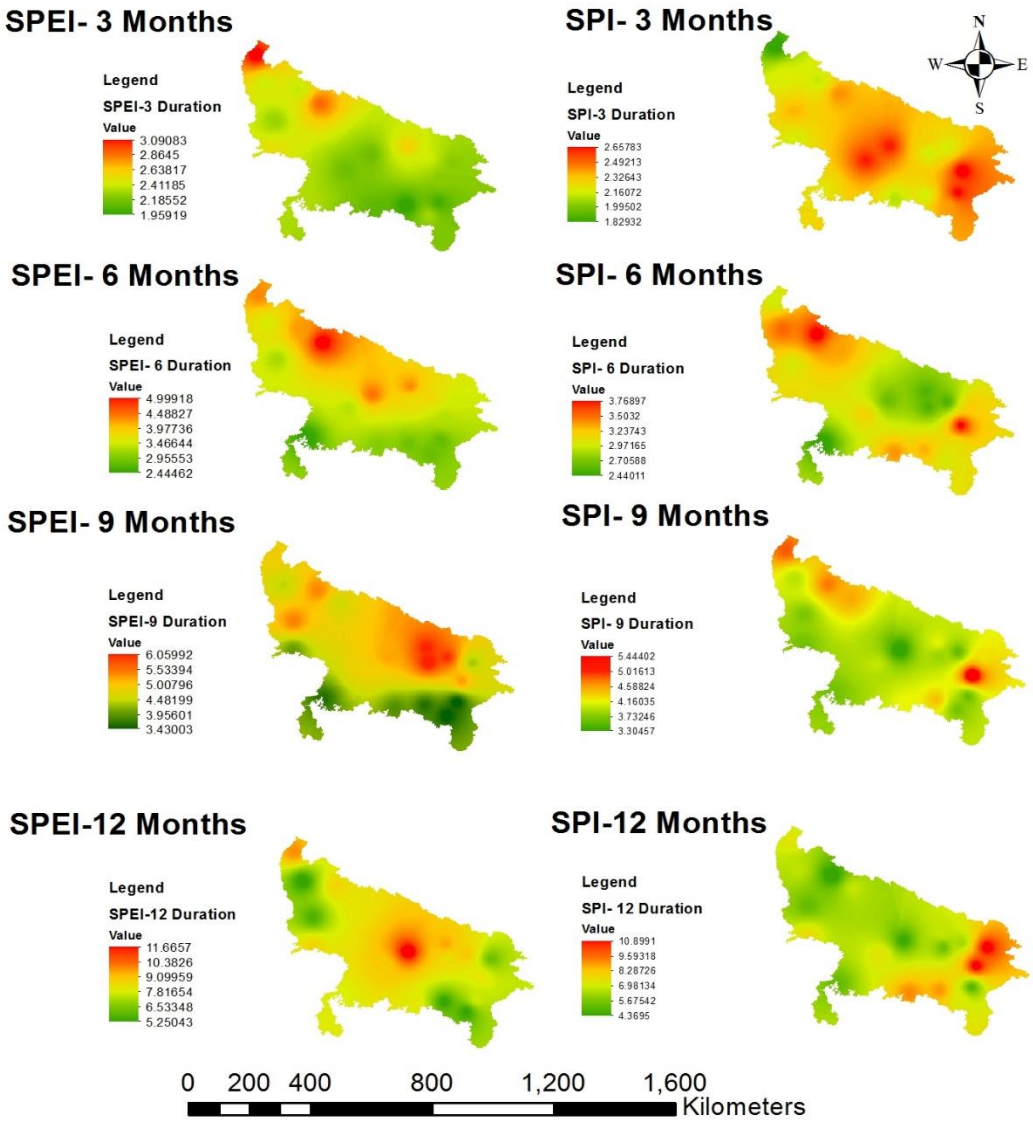


Figure 6.5 Spatial distribution of the drought duration of SPI and SPEI time series at scale of 3-month, 6-month, 9-month, and 12-month for the period of 1971 to 2018

6.1.6 Spatiotemporal assessment of frequency of occurrence

Figure 6.6 (a to c) demonstrates the spatial variation frequency of occurrence of drought events of different severity, i.e., moderate, severe, and extreme estimated for SPI and SPEI time series at a timescale of 3-month, 6-month, 9-month, and 12-months for the observed period from 1971 to 2018. The result demonstrates the higher occurrence of moderate category drought at all timescales of 3, 6, 9, and 12-months for

both the indices over the study area. The spatial map reflects the change in the magnitude of the frequency of occurrence by both indices SPI and SPEI over the study area and the variation in the pattern of drought occurrence of different severities of frequency drought with timescale. With the increase in timescale, the extent of drought incidence diminished. At a shorter timescale, for SPEI, the moderate drought frequency spans with higher values in the western and southern parts of Uttar Pradesh. In contrast, the frequency of extreme drought is significantly higher for the SPI time series. At longer timescale, the drought frequency for different severity significantly decreases for both SPEI and SPI time series where the frequency of moderate severity drought is greater at stations Agra, Jhansi, Prayagraj, Bareilly, Saharanpur, Lucknow, and Aligarh (F >10%) whereas the frequency of extreme drought severity decreases up to 0.5 and 0.9 percent both the Indices SPI and SPEI. Spatial distribution of frequency of different severity demonstrates that SPEI accounts for a higher frequency of drought of different severity than SPI, except at the higher frequency of extreme severity observed with SPI-3 and SPI-6 time series. SPEI responds increasingly slowly over a longer timescale and is consistent with monthly rainfall and temperature changes, exhibiting different annual and multi-year dry period events. As a result, lengthier periods are better suited for evaluating the situation. Shorter periods allow the discovery of historically significant occurrences that demonstrate the seasonal and inter-annual fluctuations that often occur (Łabędzki, 2007).

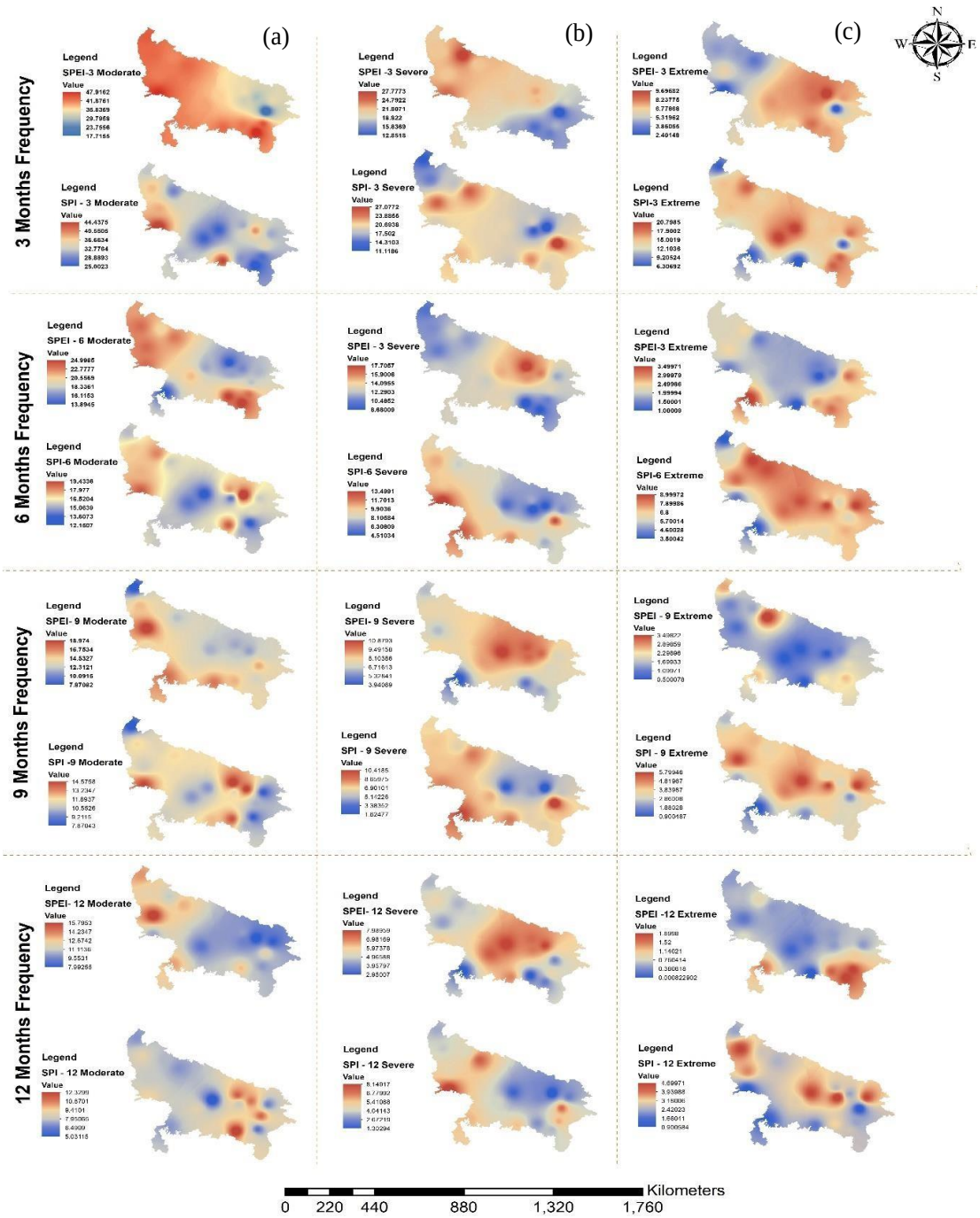
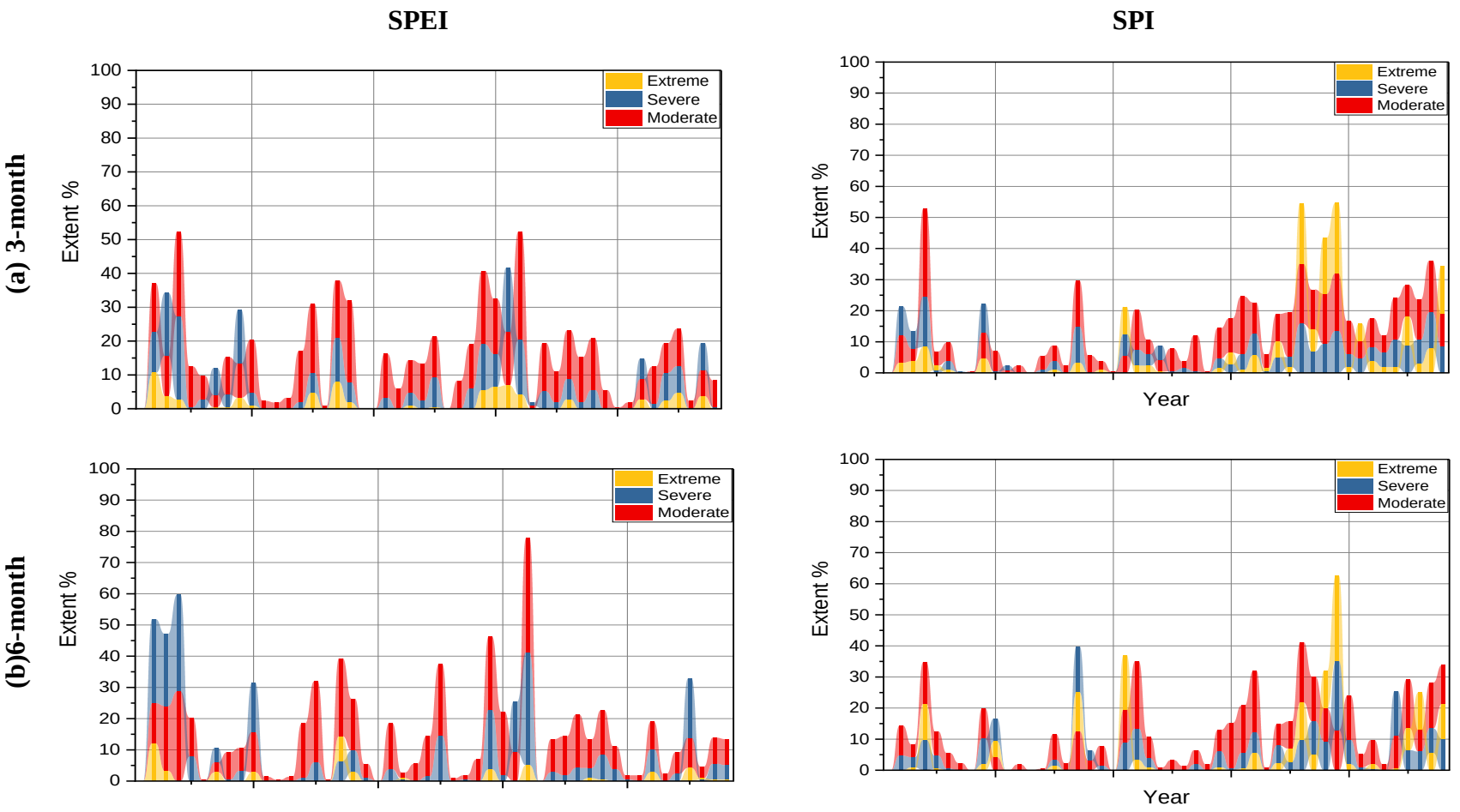


Figure 6.6 Spatial distribution of the frequency of drought of different severity of SPI and SPEI time series at timescale of 3-month, 6-month, 9-month, and 12-month for the period of 1971 to 2018

6.1.7 Temporal variations of drought station proportion

The annual variation of spatial expansion drought of different categories of moderate (SPI/SPEI = - 1 to - 1.49), severe (SPI/SPEI = -1.5 to -1.99), and extreme

(SPI/SPEI = <-2) was studied for the period 48 years, from 1971 to 2018. The drought station proportion was estimated for SPI and SPEI indices at a timescale of 3, 6, 9, and 12-month for the study area. The annual station proportion was calculated by averaging the monthly drought station proportion over the entire year. Figure 6.7 (a-d) depicts the study area's vulnerability to droughts of different severity. At a 3-month scale for SPEI, the spatial extent of drought in moderate categories extends from 0% to 24%, severe (0 to 18%), and extreme (0 to 10%), while SPI droughts run from (0 to 19%) for moderate category, severe (0 to 16%), and extreme (0 to 15 %). At 6-month timescale, SPEI droughts vary from moderate (0 to 36%), severe (0 to 26%), and extreme (0 to 12%), whereas SPI droughts range from moderate (0 to 21%), severe (0 to 22%), and extreme (0 to 17%). At 9-month timescale, SPEI droughts vary from moderate (0 to 43%), severe (0 to 23%), and extreme (0 to 13%), whereas SPI droughts range from moderate (0 to 32%), severe (0 to 15%), and extreme (0 to 11%). At 12-month timescale, SPEI droughts are moderate (0 to 25%), severe (0 to 14%), and extreme (0 to 22%), whereas SPI droughts are moderate (0 to 45%), severe (0 to 31%), and extreme (0 to 22%). This study shows that the majority of the studied region was affected by moderate drought at all timescales. The findings show that drought events of the extreme category are less likely to occur or are more likely to be localized to a specific location. However, a simple comparison of the two indices revealed that the SPEI was better suited to presenting an overall picture of drought expansion over the study area. The average spatial extent of the drought of different categories every decade is higher than the SPI except from 2010 to 2018.


SPEI
SPI
(a) 3-month
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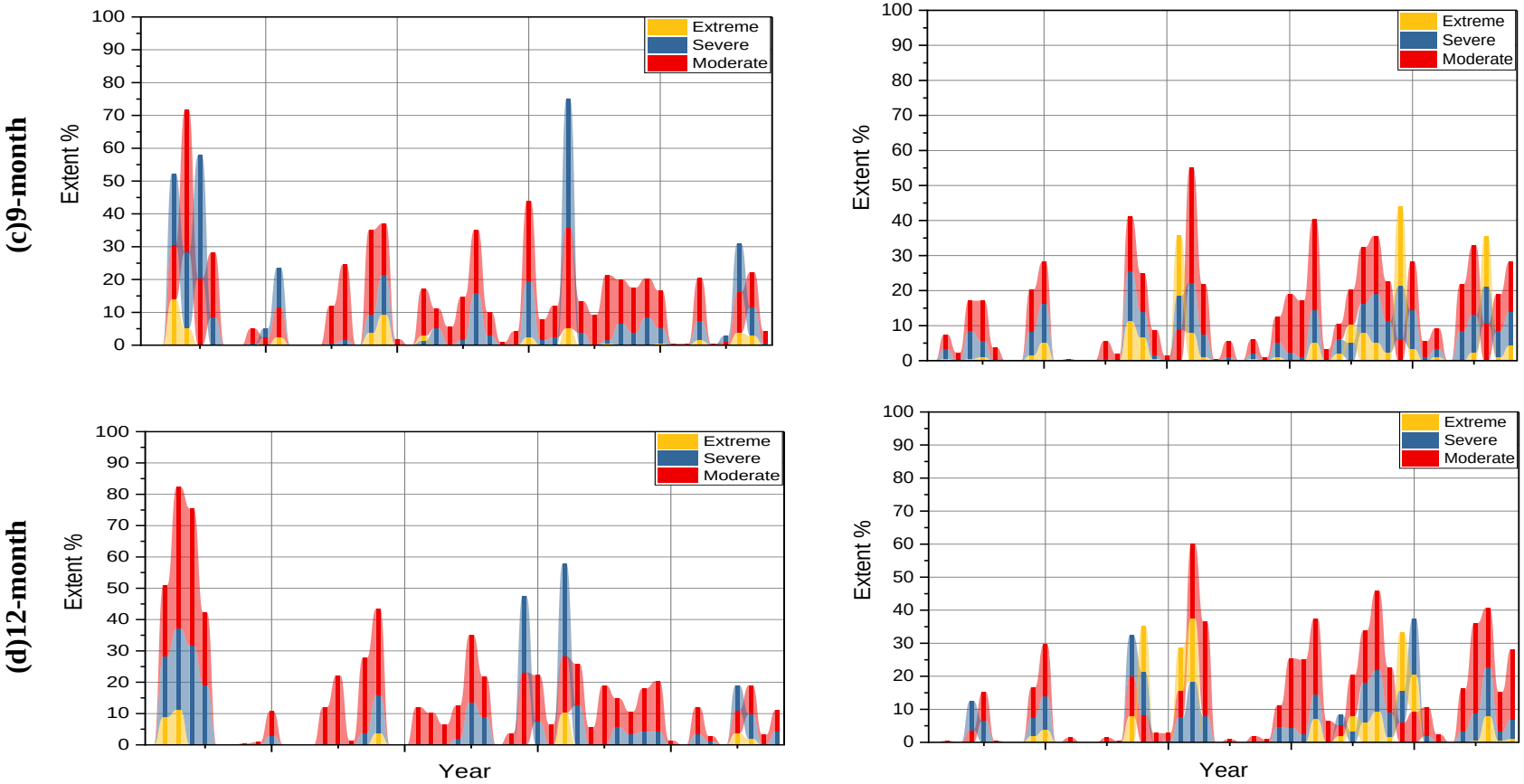

Figure 6.7 The station proportion estimated from SPI and SPEI timeseries at timescale (a) 3-month (b) 6-month (c) 9-month and (d) 12-month for the period of 1971 to 2018

6.1.8 Consistency of monthly SPI and SPEI

Pearson correlation coefficient ($r_{spi/spei}$) is estimated to test the strength of the linear relationship between monthly SPI and SPEI at a scale of 3-month, 6-month, 9-month, and 12-month. It's been used in numerous studies to demonstrate the association between SPI and SPEI (Byakatonda et al., 2018; Wang et al., 2017) The $r_{spi/spei}$ plotted as a heatmap (Figure 6.8) to demonstrate the temporal and spatial variation of the strength of consistency between SPI and SPEI at various scales, where the change in magnitude $r_{spi/spei}$ corresponds to the change in color, where the higher intensity of brown color denotes the excellent correlation between the SPI and SPEI. There was a noticeable change in each station's correlation coefficient at every scale as the months changed. The SPI and SPEI monthly show a positive correlation for the entire region except at station Azamgarh. However, at a shorter timescale, $r_{spi/spei}$ is relatively high ($r_{spi/spei}>0.5$) for August to November and February, whereas at a larger scale, $r_{spi/spei}$ increase in the magnitude of $r_{spi/spei}$ for March to July noticed. The correlation coefficient significantly varies across the region where Saharanpur denotes the most significant strong correlation between the SPEI and SPI at every timescale. In contrast, Azamgarh indicates a weak or negative correlation, which may be due to different climates over the state.

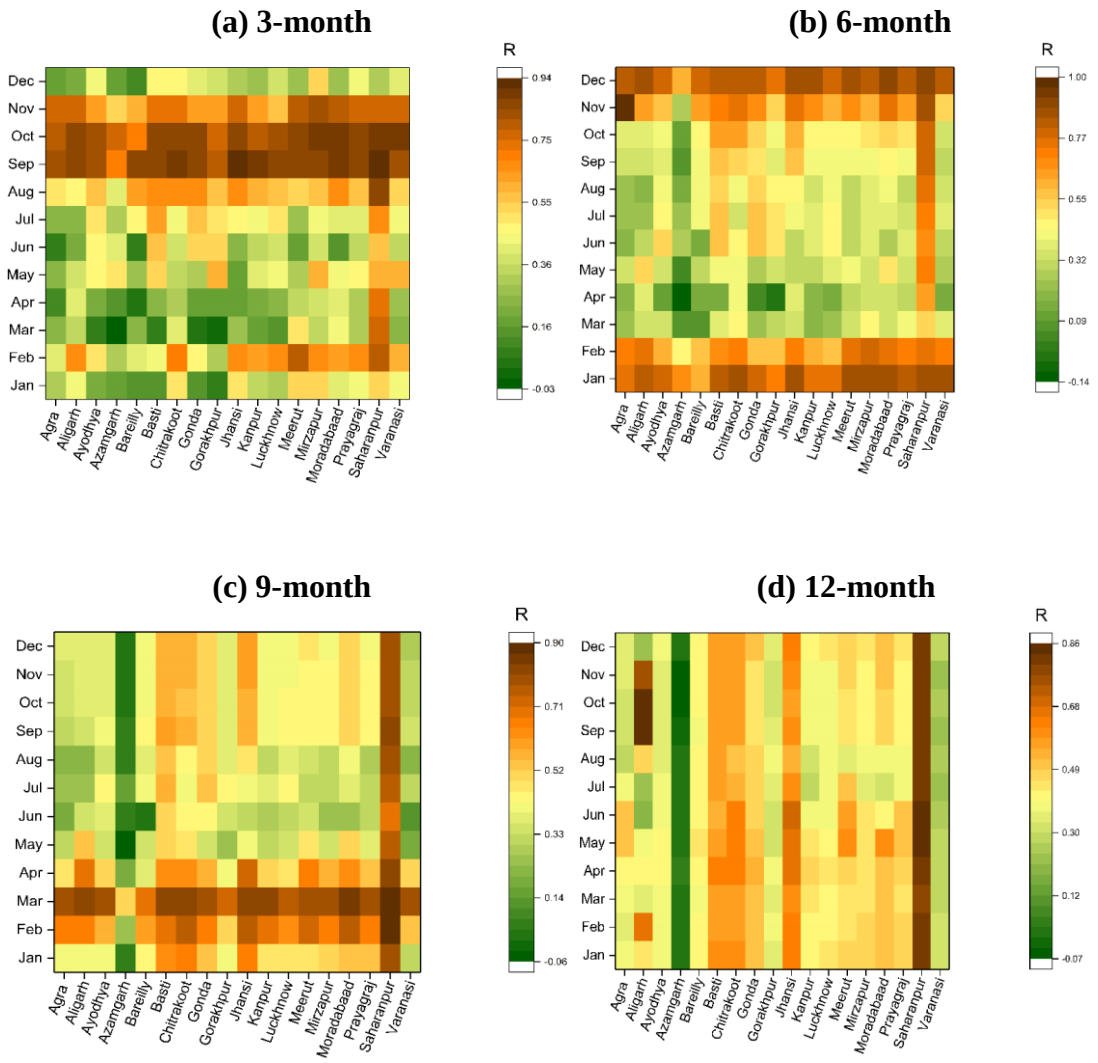

Figure 6.8 The correlation coefficient ($r_{spi/spei}$) between SPEI and SPI time series at timescale of (a) 3-month, (b) 6-month, (c) 9-month, and (d) 12-month

6.2 Summary

Uttar Pradesh is India's most populated state, with a population of 20 crore people. Approximately 47% of the population is dependent on agriculture for a living. Recent years saw severe droughts in 2002 and 2004, which resulted in losses to crops, animals, and property estimated at Rs.7540 crores and Rs.7292 crores, respectively. This necessitates the assessment of drought characteristics over Uttar Pradesh. Number of studies focused on understanding the dynamics and variability of drought on India

whereas drought of various categories hits in southern and eastern part (drought prone area with variable severity) of Uttar Pradesh is yet scanty. As a result, the drought characteristics for the chosen study area have been examined. Previously, drought assessment was primarily focused on the assessment of drought based on a single drought index, which could result in an uncertainty in drought assessment over spatially varied climate over the research area. Previously, most studies focused on drought evaluation based on trend assessment, drought severity, or drought duration. Over this study region, no study offered a complete assessment of drought characteristics taking into account all of the evaluation parameters that measure drought characteristics. The regional variability of the drought characteristics was measured in this study based on the intensity, duration, and occurrence of occurrence in three different classes (Moderate, Severe, and Extreme). Temporal variability over a half-decade was investigated using trend analysis. The spatial extent of drought occurrence of various severity levels is assessed using station proportion. This regional assessment of drought characteristics provides a comprehensive framework for evaluating drought in any study region. The present research work provides a detailed assessment of drought characteristics estimated based on the standard drought indices SPI and SPEI at the scale of 3-month, 6-month, 9-month, and 12-month from 1971 to 2018 across Uttar Pradesh (India). This study explores the respective assessment of meteorological drought characteristics based on SPI and SPEI and takes Uttar Pradesh in northern India as a study region. Drought has recently been more severe in several parts of the northern India plains, raising concerns about its effects on agricultural output in general, particularly crop yield (Gupta et al., 2022). Some research conducted in various parts of the study region showed that drought occurrence has become prevalent due to the

reasons of rainfall deficit during the monsoon season and positive temperature change (Nath et al., 2017; Saharwardi et al., 2021). The significant variability in the climate-induced by topography, the heterogeneous spatiotemporal distribution of rainfall, temperature increase, and global oscillation (ENSO event) are the critical parameter of frequent occurrence of metrological drought over Uttar Pradesh. According to findings of this study, meteorological drought occurs frequently over Uttar Pradesh, but its severity ranges from moderate to severe category depending on the timescale and methodologies used to determine drought episodes. The topography and semi-arid climate of the western and southern parts of Uttar Pradesh made drought condition more likely to be severe than rest of the study area. The observed discrepancies in values between SPEI and SPI may be due to differences in input variables and computation methods (Potopová et al., 2015). It's worth noting that both indices have positive and negative points. The SPI has the drawback of including only the average precipitation and neglecting the effect of temperature over drought characteristics. Moreover, the SPEI also has several disadvantages, such as the Thornthwaite equation used in calculating PET, which only takes average temperature into account, and heat waves might be misinterpreted for meteorological dryness (Spinoni et al., 2013). In this study, drought characteristics (Intensity, duration, and frequency) were calculated using various statistical methodologies and portrayed through a spatial distribution map to understand the drought vulnerability over Uttar Pradesh. The different researchers reported the difference in the drought characteristics estimated from SPI and SPEI at a regional scale (Danandeh Mehr & Vaheddoost, 2020; Labudová et al., 2017). Both the Indices follow the same pattern of the temporal evolution of dry and wet events, where SPEI accounts for the higher records and the higher severity of a drying event. The

more significant number of drying events accounted at a timescale of 3 and 6-month, which reflects the higher variability of the seasonal fluctuation of water balance over the state. At 9 and 12-month timescales, SPI and SPEI fluctuate gradually with considerable differences between the severity and duration of drought events. This study concludes that during the last two decades (2000 to 2018), a substantial number of drought events has increased over the state. Investigations conducted over the study region indicate a drop in precipitation over northern India, which has resulted to a decline in PET over the study region (Cook et al., 2015; Paul et al., 2016). Bhatt et al. (2019) documented that there is an increase in temperature in every zone of Uttar Pradesh, India. A decrease in trend of rainfall and increasing temperature are the two major factor that causes an increase in drying event over most of the synoptic location across Uttar Pradesh. Spatiotemporal trend assessment of drought severity time series for both indices indicate nearly 85% percent of the districts of the state experienced a negative trend at a significance level of ($p>0.05$), which implies an increase in the severity of drought events. In addition, a higher magnitude of negative trend is associated with the SPEI time series. The spatial pattern of decreasing trend occupied the central and western part of the state for SPEI, whereas for SPI time series eastern part occupied decreasing trend. The difference in spatial pattern for both time series identified may occur due to variations of different climatic zones across Uttar Pradesh. Compared to SPI, SPEI accounts for a longer duration of drought events at all timescales. Drought intensity was observed to be almost nearly same for all the districts of the State. A comparison of the spatial distribution of drought events of three severity classes ('Moderate,' 'Severe,' and 'Extreme') shows that the moderate class has a much greater prevalence over the region. SPEI time series records the higher frequency of

drought of 'Moderate' and 'Severe' severity whereas SPI accounts for the greater frequency of extreme severity drought events. The station proportion investigates the year-wise spatial extent of drought of specific severity class (moderate, severe, and extreme). It provides insight into the percentage of the area hit by the drought of a particular severity. The state is experiencing a drought of moderate severity that is affecting greater spatial extent, as indicated by both the SPI and SPEI indices. Due to the difference in the magnitude of SPI and SPEI time series variability in the drought characteristics observed across the region. In conclusion, the study area experiences drought of a short timescale of moderate severity and has vulnerability to increased. Due to differences in the climatic condition across the study area experience difference in the drought characteristics for SPI and SPEI where SPI only considers the precipitation deficit as an input variable for the drought estimation, which can lead to the inaccurate estimation of drought characteristics for the arid and semi-arid region. The SPEI index records the effect of temperature on the severity of the drought characteristics, which is reflected in the result of the above discussion. This observation inferences that the study area is at risk of erratic meteorological drought conditions, whereas the western part of the study is severely affected in comparison with the eastern part of Uttar Pradesh (India).