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Space–time heterogeneity of drought characteristics in Sabah and Sarawak, East Malaysia: implications for developing effective drought monitoring and mitigation strategies

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Abstract

Natural calamities like droughts have harmed not just humanity throughout history but also the economy, food, agricultural production, flora, animal habitat, etc. A drought monitoring system must incorporate a study of the geographical and temporal fluctuation of the drought characteristics to function effectively. This study investigated the space–time heterogeneity of drought features across Sabah and Sarawak, East Malaysia. The Standardized Precipitation Index (SPIs) at timescales of 1-month, 3-months, and 6-months was selected to determine the spatial distribution of drought characteristics. Rainfall hydrographs for the area for 30 years between 1988 and 2017 have been used in this study. A total of six five-year sub-periods were studied, with an emphasis on the lowest and highest drought occurrence. The sub-periods were a division of the 30 years over an arbitrary continual division for convenience. The results showed that the sub-periods 1993–1997 and 2008–2012 had the highest and lowest comparative drought events. The drought conditions were particularly severe in Central and Eastern parts of East Malaysia, owing to El Nino events and the country's hilly terrain. Understanding how and when drought occurs can aid in establishing and developing drought mitigation strategies for the region.

Keywords Drought · Standardized precipitation index · Rainfall · East Malaysia

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Introduction

Drought is one of the more significant threats to humanity (Thanh et al. 2023). According to the 1994 World Disasters Report, droughts have the highest number of casualties in modern history, accounting for half of all deaths from natural disasters. Changes in water quality are one of the impacted factors, which are compounded by intensive agriculture or other human activities in the region (El-Magd et al. 2022). It is vital to have a greater awareness of the features of impending droughts, along with the techniques for tracking rainfall data, looking for patterns, and foreseeing drought events sooner to limit their effects (Hina et al. 2021). Some criteria for assessing the drought are moisture availability, such as rainfall intensity, and the demands needed for productivity.

During the 1900s, significant attention was given to the study and monitoring of drought, including the development of drought indicators (Afzal and Ragab 2020; Keyantash and Dracup 2002) (Keyantash and Dracup 2002). The Standardized Precipitation Index (SPI) (McKee et al. 1993), the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010), and the Palmer Drought Severity Index (PDSI) (Palmer 1965) are three common drought indicators. These drought indicators (or indices) are calculated analytically and differ based on the hydrological factors used to derive them. SPI, for example, differs from SPEI in that it is computed without the temperature variable. The SPI drought index is significant because it gives a standardized assessment of meteorological drought across many periods (Salimi et al. 2021). It enables the comparison of drought situations across locations with vastly varied climates. The SPI may also be used to characterize aberrant wetness at various time scales that correlate to the temporal availability of various water resources. The obtained data may be used to design mitigation plans to mitigate the effects of droughts on various industries. There are some limitations to the SPI drought index. It does not account for evapotranspiration as a metric of water supply, limiting its capacity to reflect the influence of rising temperatures (related to climate change) on moisture demand and availability (Chong et al. 2022). It is also sensitive to the amount and consistency of data used to fit the distribution; 30–50 years is suggested. The SPI does not take into account precipitation intensity and its possible effects on runoff, streamflow, and water availability within the system of interest.

One of the studies which utilized SPI can be found in He et al. (2015). They analysed the Huai River Basin's spatial–temporal patterns of drought conditions based on a 3-month SPI for seasonal analysis. The drought cycle experienced positive trends in the summer and winter, whereas negative trends were in the spring and fall. They also noticed that summer has more distinct patterns than any other season due to unusual shifts in the precipitation upstream. SPEI, on the other hand, provides more geographical coverage of drought than SPI due to the addition of temperature variables (or potential evapotranspiration (PET)), ascribed to higher evaporation rate brought on by a period of little rain and intense heat (Wang et al. 2015). Byakatonda et al. (2018) demonstrated the impact of temperature factors in determining drought evolutions at Francistown using SPEI, contradicting the findings of the SPI, which did not consider temperature as a variable. With current global warming, SPEI is more effective than SPI as a drought indicator. However, the variability of water vapour density, air humidity, surface temperature, and other factors makes it challenging to calculate potential evapotranspiration (PET), limiting the potential of SPEI, as demonstrated in the study of (Wang et al. 2015), where SPEI of comparable time scale was unable to follow the drought trend any better than SPI.

The Palmer Drought Severity Index (PDSI) is another prominent measure for analysing drought features. It is more suited to forecasting longer-lasting droughts, albeit this element has received less attention. It uses the obtained temperature and precipitation data to estimate relative dryness, outputting values that ranges between − 10 (dry) and + 10 (wet) (Ghosh et al. 2020). When a region lacks water resources, the PDSI can assess the severity of the drought for a specific period. PDSI has some drawbacks, such as the significant influence of the calibration length, its limited usefulness across regions, and issues with geographic comparability. The PDSI is a helpful but sophisticated drought monitoring approach that necessitates a large amount of data and processing capacity (Balti et al. 2020). However, a time scale lower than 12 months was not utilized in PDSI, rendering its usefulness in detecting the onset of drought. Furthermore, due to the differences in hydroclimatic conditions in Sabah and Sarawak, the PDSI may not perform well in regions with different hydroclimatic conditions from those for which it was originally designed if not calibrated. As a result, the PDSI has consistently been refined by numerous researchers. The self-calibrating PDSI (SC-PDSI), developed by Yu et al. (2019), enhances the spatial comparability of PDSI. Zhao et al. (2017) proved that this index is appropriate for mid and long-term drought monitoring, especially monitoring changes in groundwater level and river discharge. Additionally, when compared to SPI, the PDSI showed higher variability in agricultural yield and natural vegetative propagation.

The states of Sabah and Sarawak were chosen for this study due to their tropical environment and lack of seasonal change. Over the previous 30 years, Sabah and Sarawak have experienced dry spells. Since the late 1960s, droughts have statistically increased in severity and frequency. Historical data indicate that two periods of extreme drought, lasting at least four months each, occurred between 1877 and 1915 and 1968 and 1992, followed by a nearly drought-free 52 years. The government has always been concerned about drought events, and drought contingency plans have been set in motion in case droughts do occur, particularly along the coastal areas.

Methodology

Case area

On the island of Borneo, Malaysia has two states: Sabah and Sarawak. Sabah has a 1,743-km coastline and less seasonal change than other tropical regions. There is no clearly defined wet or dry season, and temperatures hardly ever get over the middle to high 90 s Fahrenheit. 2500–3500 mm of precipitation fall in Sabah annually. The biggest state in Malaysia, Sarawak, accounts for 37.5% of the nation's total land area. Its tropical environment has high humidity and temperatures that range from 23 to 32 °C. Its annual rainfall ranges from 3,300 to 4,600 mm.

In Sarawak, severe droughts caused by strong El Nino events in 1998 and 2014 impacted the irrigation-based agriculture and water supply. Similarly, research on the effects of a severe drought environment on North Borneo's water security discovered that the Northeast Monsoon's extreme drought climate influenced water levels in dams on Borneo's North and Northeast Coasts. At the turn of the century, Sabah and Sarawak are experiencing rapid and dramatic transformation. At the turn of this new century, Sabah and Sarawak of today a place of rapid and dynamic change. Continued fast population expansion, dependency on natural resources, conversion of land to agriculture, and the advent of urbanization and industrialization are all factors. These events make Sabah and Sarawak relevant case studies for understanding the impacts of droughts and for planning and formulating drought strategies to reduce and mitigate their adverse effects.

The terrain and geographical location of rainfall stations can impact the studies of drought and climate change in Sabah and Sarawak. Because of orographic influences and regional winds, Sabah and Sarawak's predominantly mountainous and hilly landscape produces variances in rainfall patterns. Particularly in rural or difficult-to-access locations, this might lead to gaps or biases in the data. Therefore, the locations of the rainfall stations vary among the states, with some stations covering the coastal up to the hilly regions while accounting for the above conditions. The topography of the research region and the placements of the rainfall stations are depicted in Fig. 1. An overview of the methodology flowchart is depicted in Fig. 2.

Standardized precipitation indices (SPI)

Choosing the right indicators or indices for drought management can be challenging, especially when they are used to trigger actions in a comprehensive drought plan, which vary depending on the type of location, area, basin, or region, necessitating a process of trial and error (Ndayiragije and Li 2022). In recent years, composite indicators have emerged as a way to combine multiple indicators and indices, either weighted or unweighted, or in a modelled fashion, with aims to provide as much information as possible through various inputs (Karagiannis and Karagiannis 2020).

The Standardized Precipitation Index (SPI) indicator computation is simple since it is the only one used to track drought features over a wide variety of periods and is purely based on precipitation data. The SPI can be compared across regions with markedly different climates and can be created for differing periods of 1-to-36 months, using monthly input data. The SPI values can be interpreted as the number of standard deviations by which the observed anomaly deviates from the long-term mean. For the operational community, the strength of SPI has been recognized as the standard index that should be available worldwide for quantifying and reporting meteorological drought. However, concerns have been raised about the utility of the SPI as a measure of changes in drought associated with climate change, as it does not deal with changes in evapotranspiration. Although ground-based observations and remote retrieval are the main methods used in Malaysia to measure meteorological and hydrological data, the topography, remoteness of some areas, and dense jungle vegetation prevent plans to cover the meteorological data collection of entire regions because it would be a tedious and error-filled task (García Chevesich et al. 2017). The historical precipitation data from 1988 to 2017 were used to calculate the 1-, 3- and 6-month SPIs intervals. The SPI is calculated using the following steps (Bhunia et al. 2020):

Based on the preceding *j* months—*j* might be 1, 3, 6, or 12 months—a series of j average periods can be computed. The connection between probability and rainfall is then determined by fitting the data to a gamma function. The gamma distribution's probability density function is defined.

$$g(x) = \frac{1}{\beta^{\alpha} T(\alpha)} x^{\alpha-1} e^{-x/\beta}, \text{for } x > 0 \tag{1}$$

where x is the rainfall; $T(\alpha)$ represents the gamma function; α and β form the structure of the gamma distribution and can be defined as follows:

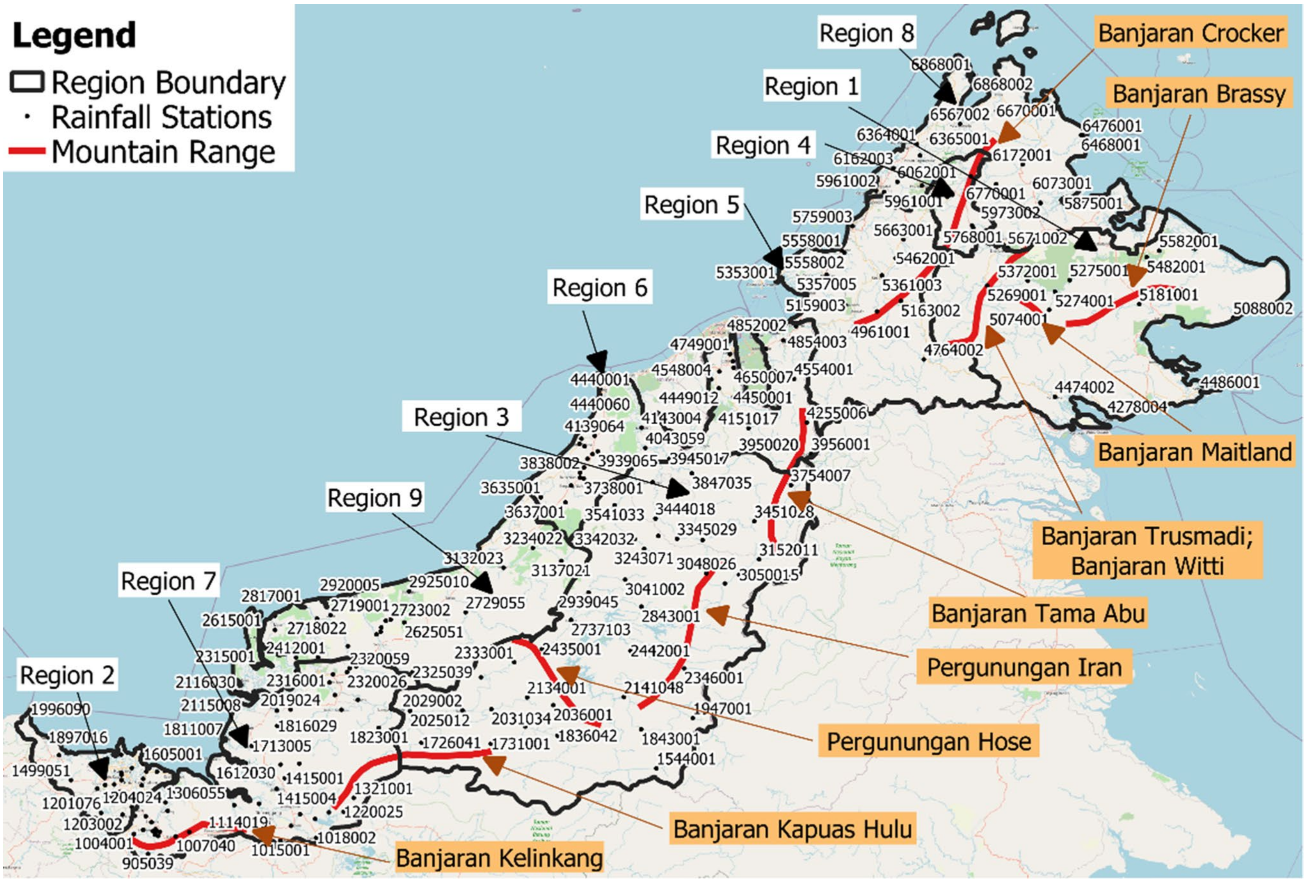

Fig. 1 Rainfall stations, regional sections and mountain ranges in Sabah and Sarawak

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \quad (2)$$

And

$$\beta = \frac{\bar{x}}{\alpha} \quad (3)$$

With

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \quad (4)$$

where x and $\bar{x}$ represent the current and average precipitation, respectively; n denotes the length of the dataset. The following step uses the equation to calculate the cumulative probility of an observed amount of precipitation:

$$G(x) = \int_0^x g(x)dx = g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} dx \quad (5)$$

Given that the gamma distribution is undefined at $x=0$, the following adaptation is required:

$$H(x) = q + (1-q)G(x) \quad (6)$$

After estimating the adjusted cumulative probability, the SPI index may be approximated as follows:

$$\mathrm{SPI} = \left\{ -\left[t - \frac{C0+C1t+C2t^2}{1+d1t+d2t^2+d3t^3} \right] \; 0 < H(x) \le 0.5 \right. \quad (7)$$

$$\mathrm{SPI} = \left\{ +\left[t - \frac{C0+C1t+C2t^2}{1+d1t+d2t^2+d3t^3} \right] \; 0.5 < H(x) < 1 \right. \quad (8)$$

where,

$$t = \left\{ \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)} \; 0 < H(x) \le 0.5 \right. \quad (9)$$

$$t = \left\{ \sqrt{\ln\left(\frac{1}{(1-H(x))^2}\right)} \; 0.5 < H(x) \le 1 \right. \quad (10)$$

And $C0, C1, C2, d1, d2,$ and $d3$ are coefficients whose values are:

$C0 = 2.515517$, $C1 = 0.802853$, $C2 = 0.010328$, $d1 = 1.432788$, $d2 = 0.189269$ $d3 = 0.001308$.

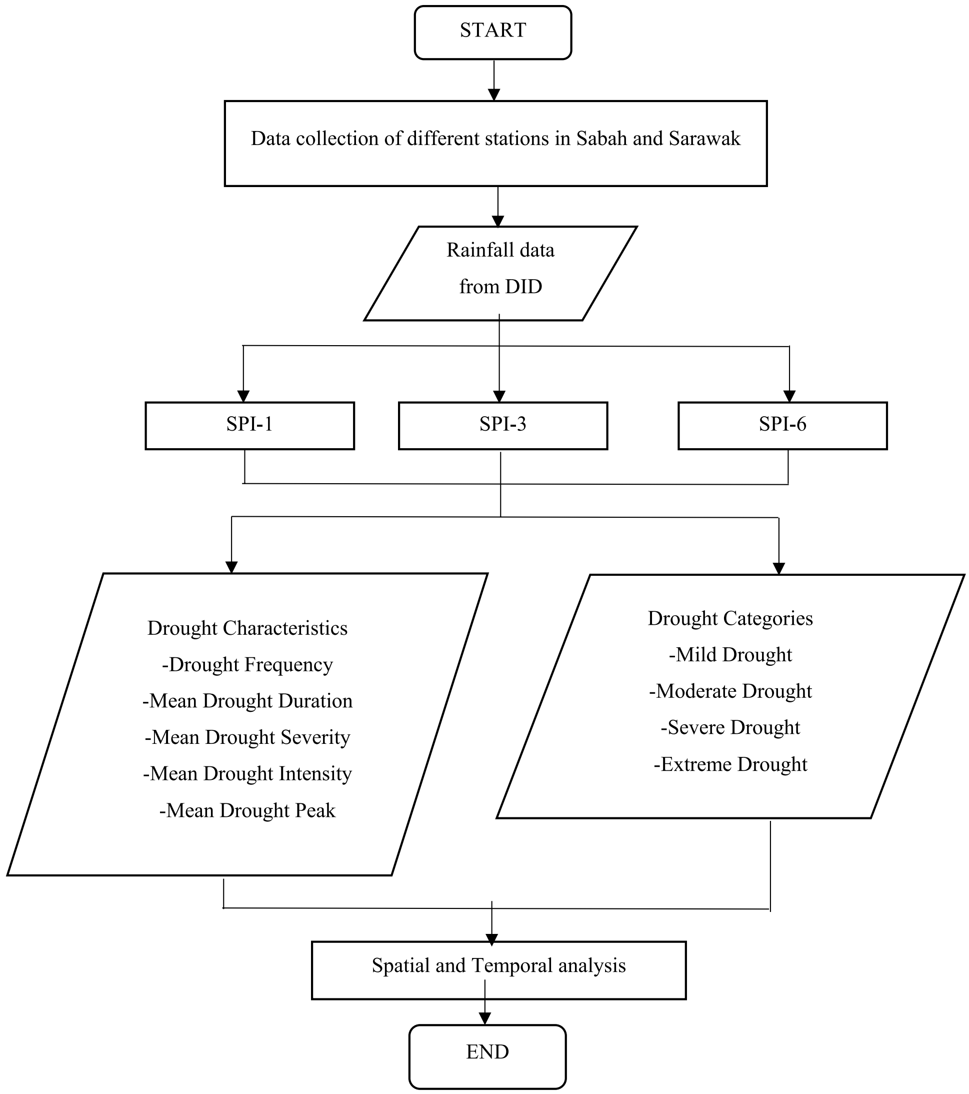

Fig. 2 The Methodology of the study

Drought categories

The investigation resulted in an assessment of regional and temporal changes to compare the features of the drought in East Malaysian regions. In order to have the possibility to separate the drought features in greater detail, the 30 years (1988–2017) of the research periods were effectively, arbitrarily, and sequentially separated into six 5-year sub-periods for three different timescales, SP1-1, SPI-3, and SPI-6. Drought occurrences were also classified as mild (0, − 0.99), moderate (− 1.00, − 1.47), severe (− 1.50, − 1.99), or extreme drought (< − 2.00) (Paulo, 2006) as can be seen in Table 1. Drought maps for each category were also developed and studied.

Drought characteristics

Several drought indices were evaluated to establish the characteristics of the drought in Sabah and Sarawak. Knowing the drought characteristics allows for early warning to improve readiness and avoid potential repercussions, such as agricultural disaster, avoid or mitigate associated famines, and cope with heightened fire danger. The following factors were taken into consideration: the Mean Drought Duration (MDD), Mean Drought Severity (MDS), Mean Drought Peak (MDP), and Mean Drought Intensity (MDI), which each offer a different perspective (Fung et al. 2020; Guo et al. 2022):

1. Drought Frequency is calculated based on the occurrence of drought occurrences, with a negative computed number indicating the sign of drought, as follows:

$$\text{Drought frequency} = \sum \text{Number of drought event} \tag{11}$$

2. Mean Drought Duration is the interval of the occurrence of drought events. The following calculation may be used to calculate the mean drought length by integrating the cumulative drought period for the entire research timeframe across the drought frequency:

$$\text{Mean drought duration} = \frac{\sum \text{Drought duration}}{\text{Drought frequency}} \tag{12}$$

3. Mean Drought Severity refers to the consequences of a lack of rainfall. The amount of moisture lacking in the air, how long the drought has been going on, and how big the research region is may all affect how extreme the droughts are. Guo, et al. (2022) claimed that the drought severity is calculated using the actual drought index value and may be written as the following equation:

$$\text{Mean drought severity} = \frac{\sum \text{Negative drought index}}{\sum \text{Drought duration}} \tag{13}$$

4. Drought Intensity refers to the drought severity as the average drought magnitude during the drought:

$$\text{Drought Intensity} = \frac{\sum \text{Negative drought index of a drought event}}{\text{Drought duration of a drought event}} \tag{14}$$

whereas the mean drought intensity was calculated as follows by summing up the overall drought intensity across the frequency of drought:

$$\text{Mean drought intensity} = \frac{\sum \text{Drought intensity}}{\text{Drought frequency}} \tag{15}$$

5. Mean Drought Peak is the lowest value on the drought index, calculated by dividing the total drought peak of a drought event by its respective frequency. The equation is computed as follows:

$$\text{Mean drought peak} = \frac{\sum \text{Drought peak of a drought event}}{\text{Drought frequency}} \tag{16}$$

Results and discussion

The topography of East Malaysia and the El-Nino occurrences depicted in Table 2 were both used to support the drought features that occurred during the 6 subperiods.

Table 1 Classification of SPI values

SPI value	Class
2.0 or greater	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
– 0.99 to 0.99	Near normal
– 1.00 to – 1.49	Moderately dry
– 1.50 to – 1.99	Severely dry
– 2.0 or lesser	Extremely dry

The rise in sea surface temperature in the presence of the El Nino event reduces the rainfall amount. In addition, East Malaysia's rugged geography may block the effect either from the South-West Monsoon or the North-East Monsoon, leading to the occurrence of drought.

Drought frequency (DF)

The colour depth changes from bright yellow to deeper red, as seen in Fig. 3, signifying the severity level of DF in ascending order. Tables 3 indicate the values of Drought Frequency for each timescale of 1-month (SPI-1), 3-month (SPI-3), and 6-month (SPI-6) for each of the nine regions (Regions 1 to Region 9) in each of the six corresponding 5-year sub-periods.

Among all the sub-periods for the SPI-1, the DF had the lesser incidence during the sub-period of 1988–1992. This sub-peak period's DF varied from 16.2 to 18.9 and occurred in practically all areas, with the maximum over Regions 2 and 3, which are thought to be caused by their hilly topography. The region experienced DF throughout the sub-periods of 1993–1997 and 1998–2002, with the peak DF primarily falling between 15.5 and 17.6; 15.3 and 17.4, respectively (Table 3). Peak DF was recorded to be 15.4–17.66 in Region 1 for the sub-period 2003–2007, with the high DF induced by El-Nino occurrences that had occurred historically owing to the coastal area. The subsequent era (sub-period 2008–2012) has seen a reduced peak DF (DF = 13.6 in all regions except region 8, which had a DF of 16.0). Except for Regions 3 and 6, where it peaked at 17.7 during the sub-period 2013–2017, all regions experienced a peak DF of 15.0. Overall, the SPI-1 revealed that the Eastern and Central regions of East Malaysia experienced peak DF more frequently. Peak DF was generated primarily by hilly topography instead of prior El Nino occurrences. The highest DF for the last 30 years was 18.9.

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During the earliest sub-periods (1988–1992 and 1993–1997), the DF occurrence was one of the highest, with Region 3 being the highest, reaching a DF value of > = 10. Peak DF ranged from 9.3 to 10.6 for 2003–2007, with Regions 1, 3, and 8 recording the highest values owing to the mountainous topography. Peak DF of 7.9–9.0 for 2008–2012, with Region 3 recording the highest values (mountainous topography). From 2013 to 2017, Region 3 remained the highest DF value. In general, the Central region of East Malaysia experienced frequent SPI-3 DF peaks. Additionally, Region 3 had the highest peak DF occurrence. Mountainous terrain, rather than El Nino periods, was the cause of Peak DF. Over the 30 years, the highest DR was 10.4.

Around 1988–1992, the SPI-6 had a high DF of 7.0 (Regions 1 and 7) in the coastal area. In 1998–2002, the peak DF was shifted to the mountainous region (Regions 2, 8, and 9), with DF values between 7.2 and 7.6. For the subsequent period, Region 3 was the most impacted by drought (similar to the findings from SPI-3). The highest recorded during 30 years was 8.6. From SPI-1 to SPI-6, a declining trend of drought frequency can be observed.

Table 2 El-Niño incidents from 1951 through 2020 (Oceanic Niño Index 2020)

Weak–12	Moderate–7	Strong–5	Very Strong–3
El-Niño incidents			
1952–1953	1951–1952	1957–1958	1982 – 1983
1953–1954	1963–1964	1956–1957	1997–1998
1958–1959	1968–1969	1972–1973	2015–2016
1969–1970	1986–1987	1987–1988	
1976–1977	1994–1995	1991–1992	
1977–1978	2002–2003		
1979–1980	2009–2010		
2004–2005			
2006–2007			
2014–2015			
2018–2019			
2019–2020			

Mean drought duration (MDD)

Figure 4 depicts the use of SPIs at 1-month (SPI-1), 3-month (SPI-3), and 6-month (SPI-6) timeframes to explore the spatiotemporal variations of MDD. Yellow to red is the spectrum of colour depth used to represent the severity of MDD, from moderate to severe. Table 4 shows the values of Mean Drought Length for each timescale for the 1-month (SPI-1), 3-month (SPI-3), and 6-month (SPI-6) respective timescales for each of the nine regions (Region 1 to Region 9) in each of the six 5-year sub-periods.

Peak MDD for 1988–1992 varied from 6.120 to 7.210, with the peak occurring in Region 3. Over 1993–1997, the Peak MDD ranged from 4.200 to 4.428, with the largest occurring in Region 9. In descending order, the highest MDD was reported to be in range of 2.605 to 3.428 in 1998–2002 but increased from 3.550 to 5.167 the following year (2003–2007). Following that year, the MDD value grew from 3.789–4.407 in 2008–2012 to 4.772–5.5661 in 2013–2017, continuing the fluctuating. Over the 30 years of research, one consistent finding was that Region 2 had the highest prevalence of peak MDD. With potent Regions such as Regions 2 and 9, the Peninsula's southwest was the most impacted.

There is not much of a difference between SPI-1 and SPI-3. Regions of mountainous topography (Regions 1 and 2) and proximity to the sea (Region 9) were the areas with the highest peak MDD. In the longer timescale, Region 1, unaffected in SPI-1, appeared to be one of the areas with a high MDD value. The highest MMD during the entire 30-year period was 15.931.

Peak MDD for SPI-6 was 40.121 (Region 9), 14.841 (Region 1), 11.912 (Region 1), 13.621 (Region 1), 15.560 (Region 1), and 14.951 (Region 1) for the following 5-year sub-periods. Based on Table 4, Region 1 (located in the eastern half of Sabah) has the highest Peak MDD incidence rate. The highest for the 30 years appears to be 15.560 in 2008–2012. According to the findings, using a higher MMD corresponds to a longer period.

Mean drought severity (MDS)

Figure 5 depicts the use of SPIs at 1-month (SPI-1), 3-month (SPI-3), and 6-month (SPI-6) timeframes to explore the spatiotemporal variations of MDS. Yellow to red is the spectrum of colour depth used to represent the severity of MDS, from

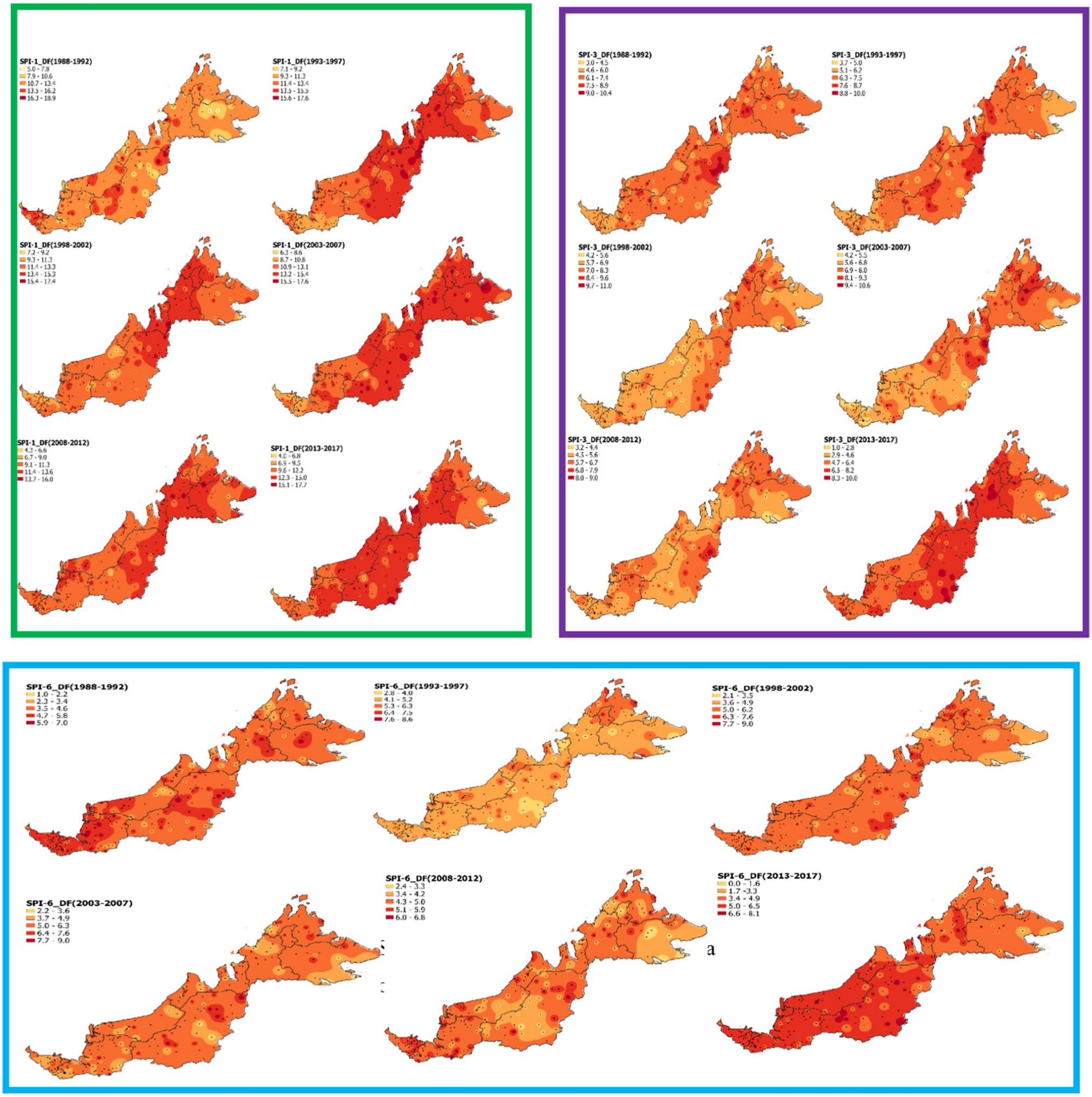

Fig. 3 **a** Drought frequency maps for SPI-1, SPI-3, and SPI-6 for each 5-year sub-period from 1988 to 2017. SPI-1 is in the top left corner, SPI-3 is in the top right, and SPI-6 is at the bottom. **b** Drought Frequency maps of SPI-1 (green border-box, top left), SPI-3 (violet border box, top right), and SPI-6 (blue border box, bottom) for each of the 5-years sub-period from 1988 to 2017

moderate to severe. Table 5 shows the values of MDS for each timescale, including 1-month (SPI-1), 3-month (SPI-3), and 6-month (SPI-6) for each of the nine regions (Regions 1 to Region 9) in each of the six 5-year sub-periods.

The highest Peak MDS values for the SPI-1and SPI-6 for the 30 years were − 1.293 and − 1.519, which occurred in Region 3 (mountainous) during 1988–1992 and 2008–2012, respectively. Also, Region 3 exhibited the highest prevalence of peak MDS in these sub-periods. As for the intermediate period, SPI-3, as shown in Table 5, the highest MDS throughout the 30 years, occurred in Regions 1 and 5, with an MDS value of − 1.415. These studies demonstrated that peak MDS was primarily driven by mountainous terrain rather than El Nino influences.

Table 3 Drought frequency: (a) SPI-1, (b) SPI-3, and (c) SPI-6

Sub-period	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7	Region 8	Region 9
(a) Drought frequency (SPI-1)									
1988–1992	5.0–13.4	7.9–18.9	5.0–18.9	10.7–16.2	10.7–16.2	7.9–16.2	7.9–16.2	7.9–16.2	5.0–16.2
1993–1997	9.3–15.5	7.1–13.4	9.3–17.6	11.4–15.5	11.4–15.5	11.4–17.6	7.1–13.5	9.3–15.5	9.3–15.5
1998–2002	7.2–15.3	7.2–13.3	7.2–17.4	13.4–15.3	13.4–15.3	9.3–17.4	9.3–15.3	11.4–15.3	7.2–15.3
2003–2007	8.7–17.6	6.3–13.1	10.9–17.6	13.2–17.6	13.2–17.6	10.9–17.6	8.7–15.4	10.9–15.4	10.9–15.4
2008–2012	6.7–13.6	6.7–13.6	6.7–13.6	6.7–13.6	6.7–13.6	6.7–13.6	6.7–13.6	9.1–16.0	6.7–13.6
2013–2017	4.0–15.0	6.9–15.0	4.0–17.7	12.3–15.0	12.3–15.0	9.6–17.7	6.9–15.0	6.9–15.0	6.9–15.0
(b) Drought frequency (SPI-3)									
1988–1992	4.6–8.9	4.6–7.4	3.0–10.4	4.6–8.9	4.6–8.9	4.6–8.9	3.0–7.4	4.6–8.9	4.6–8.9
1993–1997	3.7–7.5	5.1–7.5	3.7–10.0	5.1–8.7	5.1–8.7	5.1–10.0	5.1–7.5	5.1–8.7	5.1–8.7
1998–2002	4.2–8.3	4.2–6.9	4.2–6.9	5.7–9.6	5.7–9.6	5.7–9.6	4.2–8.3	4.2–9.6	4.2–8.3
2003–2007	5.6–10.6	4.2–6.8	4.2–10.6	6.9–9.3	5.6–9.3	5.6–9.3	4.2–9.3	5.6–10.6	4.2–9.3
2008–2012	3.2–6.7	3.2–5.6	3.2–9.0	4.5–6.7		4.5–7.9	3.2–7.9	3.2–7.9	3.2–6.7
2013–2017	1.0–8.2	4.7–8.2	4.7–10.0	6.5–8.2		4.7–8.2	4.7–8.2	2.9–8.2	4.7–8.2
(c) Drought frequency (SPI-6)									
1988–1992	2.3–7.0	3.5–5.8	2.3–7.0	2.3–4.6	2.3–5.8	1.0–4.6	2.3–7.0	2.3–5.8	1.0–5.8
1993–1997	2.8–7.5	4.1–5.2	2.8–6.3	5.3–7.5	2.8–5.2	2.8–6.3	2.8–6.3	4.1–8.6	2.8–6.3
1998–2002	2.1–6.2	5.0–7.6	3.6–7.6	5.0–7.6	2.1–6.2	3.6–7.2	3.6–6.2	3.6–7.6	3.6–7.6
2003–2007	2.2–7.6	3.7–6.3	2.2–9.0	5.0–7.6	2.2–6.3	3.7–6.3	3.7–6.3	3.7–6.3	3.7–7.6
2008–2012	2.4–5.9	4.3–5.9	2.4–6.8	2.4–5.9	3.4–5.9	3.4–5.9	3.4–6.8	2.4–5.9	3.4–5.9
2013–2017	0.0–4.9	3.4–6.5	1.7–8.1	3.4–4.9	1.7–6.5	3.4–8.1	3.4–6.5	1.7–6.5	5.0–8.1

Mean drought intensity (MDI)

Figure 6 depicts the use of SPIs at 1-month (SPI-1), 3-month (SPI-3), and 6-month (SPI-6) timeframes to explore the spatiotemporal variations of MDI. Yellow to red is the spectrum of colour depth used to represent the severity of MDI, from moderate to severe. Tables 6 show the values of MDI for each timescale, including 1-month (SPI-1), 3-month (SPI-3), and 6-month (SPI-6) for each of the nine regions (Regions 1 to Region 9) in each of the six 5-year sub-periods.

The highest MDI regardless of the timescale was observed in 1988–1992 compared to other sub-periods. Although the afflicted region changed throughout time, these places were nonetheless classified as hilly terrain. In terms of location, peak MDI was mostly driven by high terrain rather than El Nino events.

Mean drought peak (MDP)

Figure 7 depicts the use of SPIs at 1-month (SPI-1), 3-month (SPI-3), and 6-month (SPI-6) timeframes to explore the spatiotemporal variations of MDP. Yellow to red is the spectrum of colour depth used to represent the severity of MDP, from moderate to severe. Tables 7 show the values of MDP for each timescale, including 1-month (SPI-1), 3-month (SPI-3), and 6-month (SPI-6) for each of the nine regions (Regions 1 to Region 9) in each of the six 5-year sub-periods.

According to the findings, MDP is similar to other drought characteristics, such as MDI and MDS, and was also influenced by mountainous topography rather than El-Niño events. Apart from that, the temporal was also seen from the earliest period, 1988–1992, and was gradually reduced in the subsequent years.

Drought categories

Table 8 illustrates the variations between the four types of drought (mild, moderate, severe, and extreme). Figure 8 demonstrates a more in-depth knowledge of the distinctions between the various drought categories. A total number of 251 stations classified as part of each drought category has been recorded in three timescale, SPI-1, SPI-3, and SPI-6 between 1988 and 2017.

The most common form of drought in SPI-1 is mild, followed by moderate, severe, and extreme droughts. For the Mild Drought category, almost all of the stations (251) display a very steady trend. In contrast to the Severe Drought, where the number of stations fluctuated between 16 and 161, the Moderate Drought saw station counts fluctuate between 76 and 196. With the exception of the Extreme Drought category, none of the stations for the aforementioned categories surpassed the others during the course of 30 years. The number of stations for the Extreme Drought varied from 13 to 129 stations.

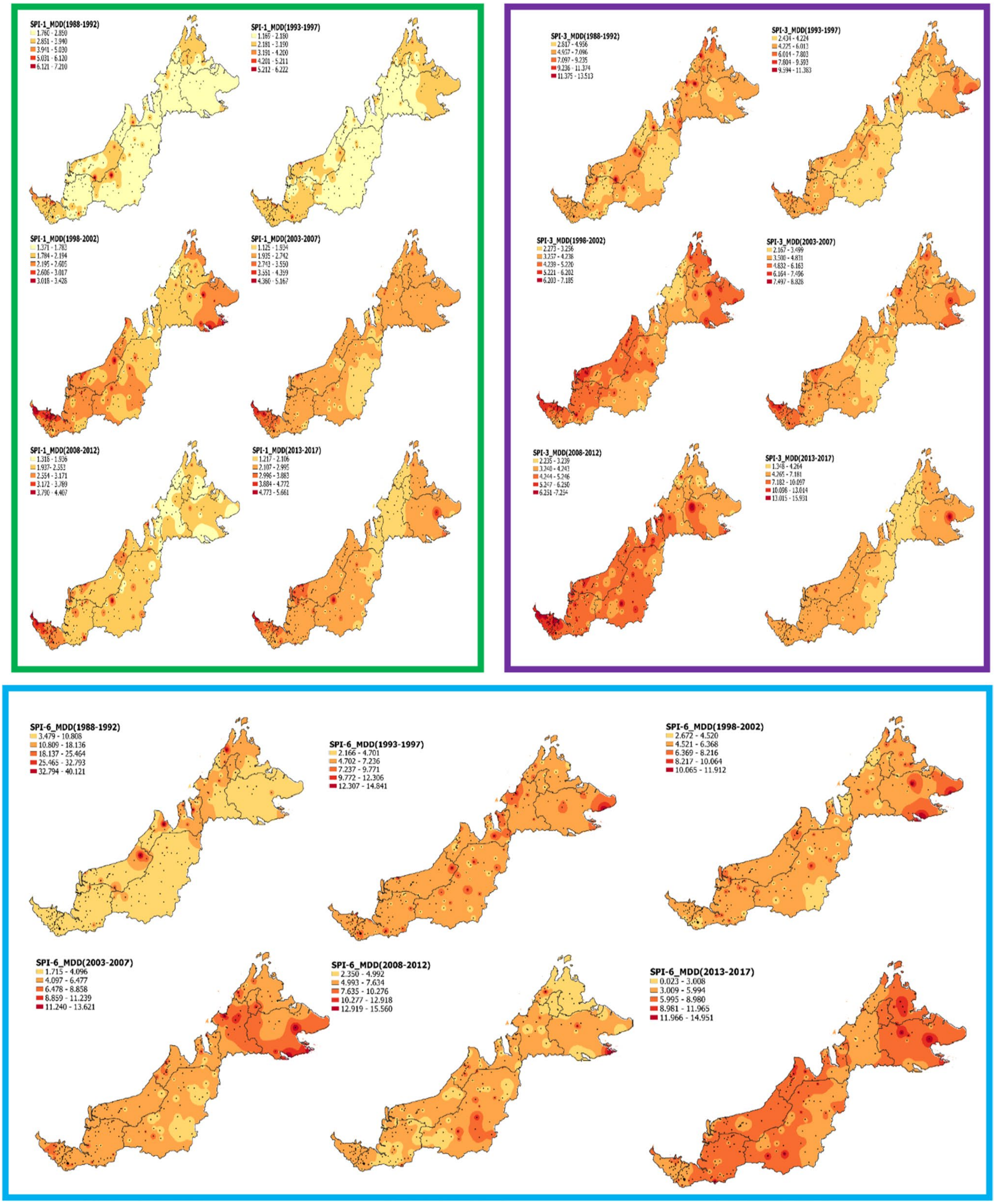

Fig. 4 Mean Drought Duration maps of SPI-1 (green border-box, top left), SPI-3 (violet border box, top right), and SPI-6 (blue border box, bottom) for each of the 5-years sub-period from 1988 to 2017

Table 4 Mean drought duration: (a) SPI-1, (b) SPI-3, and (c) SPI-6

Sub-period	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7	Region 8	Region 9
(a) Mean drought duration (SPI-1)									
1988–1992	1.760–3.940	2.851–6.120	1.760–7.210	1.760–5.030	1.760–3.940	1.760–5.030	1.760–5.030	1.760–3.94	1.169–4.200
1993–1997	1.169–3.190	1.169–4.200	1.371–3.017	1.169–3.190	1.169–3.190	1.169–3.190	1.169–4.200	1.169–4.200	1.784–4.428
1998–2002	1.371–3.428	2.195–3.428	1.371–3.017	1.371–2.605	1.371–2.605	1.371–3.017	1.748–3.017	1.371–3.017	1.784–3.428
2003–2007	1.125–3.550	1.935–5.167	1.935–4.359	2.743–3.550	1.125–3.550	1.935–4.359	1.935–4.359	1.935–4.359	1.935–4.359
2008–2012	1.318–3.171	1.937–4.407	1.318–4.407	1.318–2.553	1.318–2.553	1.935–4.359	1.318–3.789	1.318–3.171	1.318–3.789
2013–2017	1.217–4.772	2.107–4.772	2.107–5.661	2.107–3.883	2.107–3.883	2.107–3.883	2.107–4.772	2.107–4.772	1.217–4.772
(b) Mean drought duration (SPI-3)									
1988–1992	2.817–7.096	4.597–7.096	2.817–9.235	2.817–9.235	2.817–11.374	2.817–11.374	2.817–7.096	2.817–11.374	2.817–13.513
1993–1997	2.434–9.593	4.225–7.803	2.434–4.224	2.434–6.013	2.434–6.013	2.434–7.803	2.434–7.803	2.434–7.803	2.434–7.803
1998–2002	2.273–7.185	4.239–6.202	2.273–6.202	2.273–5.220	2.273–4.238	2.273–6.202	2.273–6.202	2.273–6.202	4.239–7.185
2003–2007	2.167–7.496	3.500–7.496	2.167–6.163	3.500–6.163	3.500–6.163	2.167–6.163	2.167–6.163	2.167–6.163	2.167–6.163
2008–2012	2.235–7.254	4.244–7.254	2.235–7.254	2.235–5.246	2.235–5.246	3.240–6.250	3.240–6.250	2.235–5.246	3.240–6.250
2013–2017	1.348–15.931	4.265–10.097	1.348–10.097	1.348–7.181	1.348–7.181	1.348–7.181	1.348–7.181	1.348–10.097	4.265–10.097
(c) Mean drought duration (SPI-6)									
1988–1992	3.479–18.136	3.479–10.808	3.479–18.136	3.479–18.136	3.479–18.136	3.479–40.121	3.479–18.136	3.479–32.793	3.479–40.121
1993–1997	4.702–14.841	4.702–7.236	2.166–9.771	2.166–7.236	4.702–9.771	2.166–9.771	2.166–9.771	2.166–9.771	7.237–12.306
1998–2002	4.521–11.912	4.521–6.368	2.672–8.216	2.672–6.368	2.672–8.216	2.672–8.216	2.672–8.216	2.672–8.216	4.521–8.216
2003–2007	4.097–13.621	4.097–8.858	1.715–8.858	4.097–8.858	4.097–11.239	1.715–8.858	4.097–8.858	4.097–8.858	1.715–6.477
2008–2012	2.350–15.560	4.993–7.634	2.350–12.918	2.350–4.992	2.350–10.276	2.350–10.276	2.350–7.634	2.350–10.276	2.350–10.276
2013–2017	3.009–14.951	3.009–8.980	3.009–11.965	5.995–8.980	0.023–8.980	3.009–8.980	3.009–8.980	3.009–11.965	3.009–8.980

It is worth noting that the presence of extreme EI-Nino events in 1997–1998 and 2009–2010 has caused the number of Extreme Drought occurrence exceeded the Severe Drought. It is probably due to limiting factor exhibits on the rainfall due to the rise in sea surface temperature. Comparatively, apart from more stations fluctuated in SPI-3 than in SPI-1 according to Fig. 8, the characteristics of SPI-3 is almost the same as SPI-1. The SPI-6 experienced the highest station volatility, but a notable difference is that the SPI-6 did not display the impacts of Extreme Drought beyond Severe Drought in 1997–1998, as clearly illustrated by the other SPIs. It might be attributed to the sensitivity of SPI-6, which was previously thought to be a less accurate indicator of monthly precipitation for a single site. Figure 9 shows maps of numerous drought categories that were generated to further investigate the regional variance.

Mild droughts

According to the SPI-1, peak mild droughts occurred periodically in East Malaysia's Eastern and South-Western areas. Also, Region 2 had the highest frequency of peak Mild Drought. Depending on where it happens, peak mild drought can be caused by both high geography and El Nino events. Moreover, Fig. 9 shows that the Eastern and South-West parts of East Malaysia regularly had Mild Drought maxima for SPI-3. The most severe Mild Droughts has occurred in Region 2. Peak moderate droughts, according to the area of the drought, were brought on by El-Nino events instead of just high topography.

Moderate droughts

Figure 10 from the study demonstrates how frequently the Central region of East Malaysia had Moderate Drought peaks with SPI-1. The highest number of Moderate

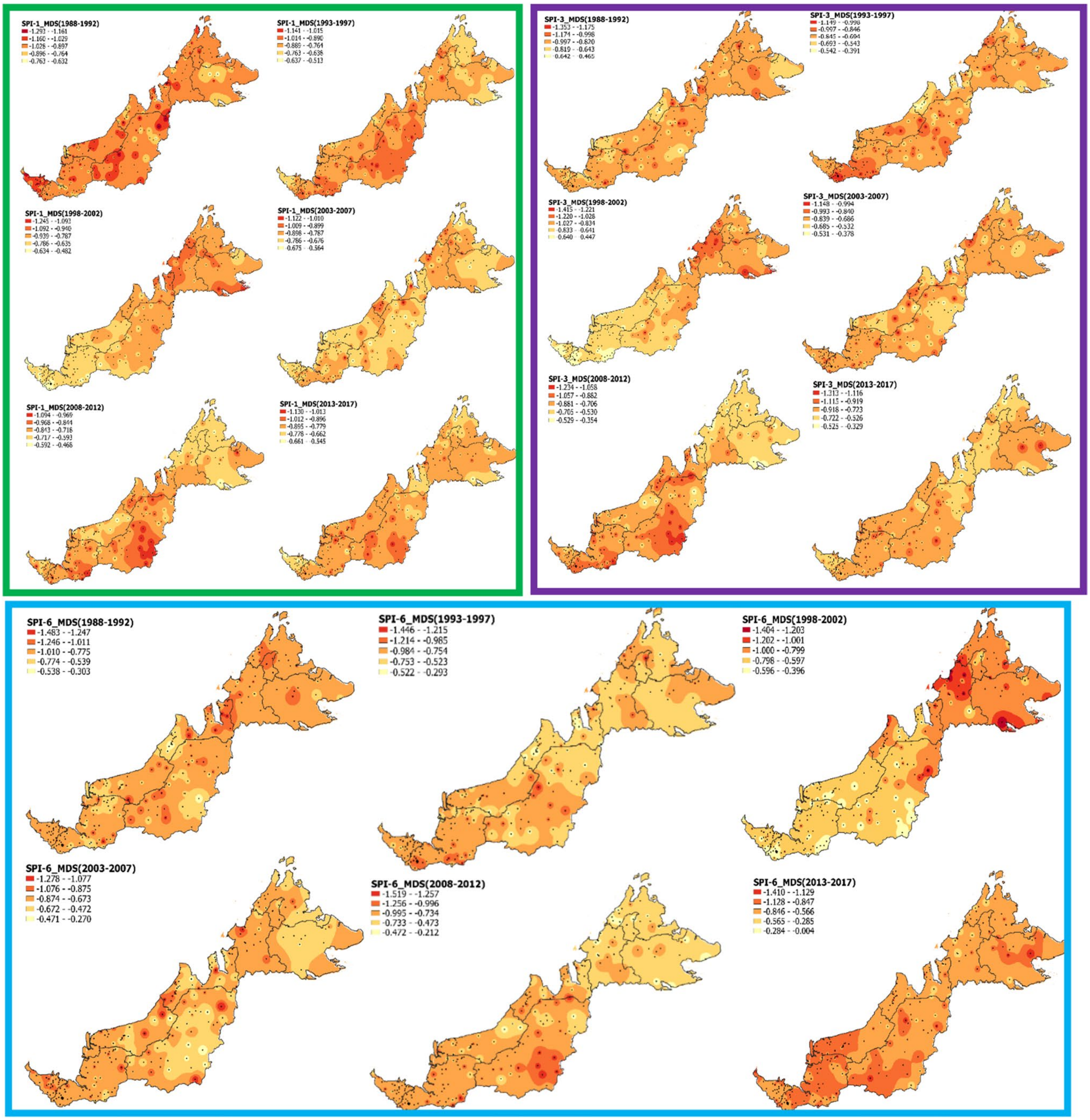

Fig. 5 Mean Drought Severity maps of SPI-1 (green border box, top left), SPI-3 (violet border box, top right), and SPI-6 (blue border box, bottom) for each of the 5-years sub-period from 1988 to 2017

Drought occurred was in Region 1, where the drought events are mostly driven by the mountainous topography rather than El Nino events. A longer timescale analysis, SPI-3, has revealed that the South-West parts of East Malaysia experienced peak Moderate Drought frequently, occurring the most in Region 2. Most moderate drought peak occurrences had been seen in Region 2. SPI-6 has the similar findings as SPI-1, where SPI-6 demonstrated the slow and varying drought also occurred the most in Region 1 (Fig. 11).

Severe droughts

Region 3 in Central Malaysia experienced Peak Severe Drought more frequently than any other region, according to the SPI-1. Longer timescales, such as SPI-3 and SPI-6,

Table 5 Mean drought severity: (a)SPI-1, (b) SPI-3, and (c) SPI-6

Sub-period	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7	Region 8	Region 9
(a) Mean drought severity (SPI-1)									
1988–1992	− 1.160 to − 0.632	− 1.293 to − 0.764	− 1.293 to − 0.632	− 1.160 to − 0.897	− 1.160 to − 0.764	− 1.160 to − 0.764	− 1.160 to − 0.764	− 1.014 to − 0.638	− 1.160 to − 0.764
1993–1997	− 0.889 to − 0.513	− 0.889 to − 0.513	− 1.141 to − 0.638	− 0.889 to − 0.638	− 1.141 to − 0.638	− 1.014 to − 0.638	− 1.014 to − 0.638	− 1.092 to − 0.635	− 1.014 to − 0.638
1998–2002	− 1.245 to − 0.482	− 0.786 to − 0.482	− 1.092 to − 0.482	− 1.092 to − 0.787	− 1.092 to − 0.635	− 1.092 to − 0.635	− 0.939 to − 0.482	− 1.092 to − 0.635	− 0.939 to − 0.635
2003–2007	− 0.898 to − 0.564	− 0.898 to − 0.564	− 1.009 to − 0.564	− 1.009 to − 0.676	− 1.009 to − 0.676	− 1.122 to − 0.564	− 1.122 to − 0.676	− 1.009 to − 0.564	− 1.009 to − 0.564
2008–2012	− 0.968 to − 0.468	− 1.094 to − 0.593	− 1.094 to − 0.593	− 0.717 to − 0.593	− 0.843 to − 0.468	− 0.968 to − 0.593	− 1.094 to − 0.593	− 0.843 to − 0.468	− 0.843 to − 0.468
2013–2017	− 1.012 to − 0.545	− 0.895 to − 0.545	− 1.012 to − 0.545	− 0.895 to − 0.662	− 0.895 to − 0.662	− 1.012 to − 0.662	− 1.012 to − 0.545	− 0.895 to − 0.545	− 1.012 to − 0.662
(b) Mean drought severity (SPI-3)									
1988–1992	− 1.174 to − 0.643	− 0.997 to − 0.643	− 1.353 to − 0.465	− 1.174 to − 0.820	− 1.174 to − 0.643	− 1.353 to − 0.465	− 1.174 to − 0.643	− 1.174 to − 0.643	− 1.353 to − 0.643
1993–1997	− 0.997 to − 0.391	− 0.845 to − 0.543	− 0.997 to − 0.391	− 0.997 to − 0.694	− 0.997 to − 0.543	− 0.845 to − 0.391	− 1.149 to − 0.694	− 0.997 to − 0.543	− 1.149 to − 0.543
1998–2002	− 1.415 to − 0.641	− 0.833 to − 0.447	− 1.220 to − 0.447	− 1.027 to − 0.641	− 1.415 to − 0.641	− 1.220 to − 0.641	− 0.883 to − 0.447	− 1.220 to − 0.641	− 1.027 to − 0.447
2003–2007	− 0.993 to − 0.532	− 0.993 to − 0.532	− 0.993 to − 0.378	− 0.839 to − 0.532	− 0.993 to − 0.532	− 1.148 to − 0.532	− 0.993 to − 0.532	− 0.993 to − 0.532	− 1.148 to − 0.378
2008–2012	− 0.881 to − 0.354	− 0.881 to − 0.354	− 1.234 to − 0.354	− 0.705 to − 0.354	− 0.881 to − 0.354	− 1.234 to − 0.530	− 1.234 to − 0.530	− 0.881 to − 0.354	− 0.881 to − 0.354
2013–2017	− 1.313 to − 0.329	− 0.918 to − 0.329	− 1.115 to − 0.526	− 0.918 to − 0.526	− 0.918 to − 0.526	− 0.918 to − 0.329	− 1.115 to − 0.526	− 0.918 to − 0.329	− 1.115 to − 0.526
(c) Mean drought severity (SPI-6)									
1988–1992	− 1.246 to − 0.539	− 1.246–− 0.775	− 1.246–− 0.303	− 1.246 to − 0.775	− 1.246–− 0.539	− 1.483–− 0.303	− 1.246–− 0.539	− 1.246–− 0.775	− 1.246 to − 0.539
1993–1997	− 0.984 to − 0.523	− 0.984 to − 0.523	− 1.446 to − 0.293	− 1.446 to − 0.523	− 1.214 to − 0.523	− 0.984 to − 0.293	− 1.214 to − 0.523	− 1.214 to − 0.523	− 1.214 to − 0.523
1998–2002	− 1.404 to − 0.597	− 0.798 to − 0.396	− 1.202 to − 0.396	− 1.000 to − 0.597	− 1.404 to − 0.396	− 1.202 to − 0.597	− 1.000 to − 0.396	− 1.202 to − 0.597	− 0.789 to − 0.396
2003–2007	− 0.874 to − 0.472	− 1.076 to − 0.673	− 1.278 to − 0.270	− 0.874 to − 0.472	− 1.076 to − 0.472	− 1.278 to − 0.472	− 1.076 to − 0.472	− 1.076 to − 0.472	− 1.076 to − 0.270
2008–2012	− 0.995 to − 0.212	− 1.256 to − 0.473	− 1.519 to − 0.212	− 0.733 to − 0.212	− 0.9995 to − 0.212	− 1.256 to − 0.473	− 1.256 to − 0.473	− 0.995 to − 0.212	− 0.995 to − 0.212
2013–2017	− 1.128 to − 0.004	− 1.128 to − 0.566	− 1.410 to − 0.285	− 0.846 to − 0.566	− 0.846 to − 0.285	− 0.846 to − 0.285	− 1.128 to − 0.566	− 0.846 to − 0.285	− 1.128 to − 0.566

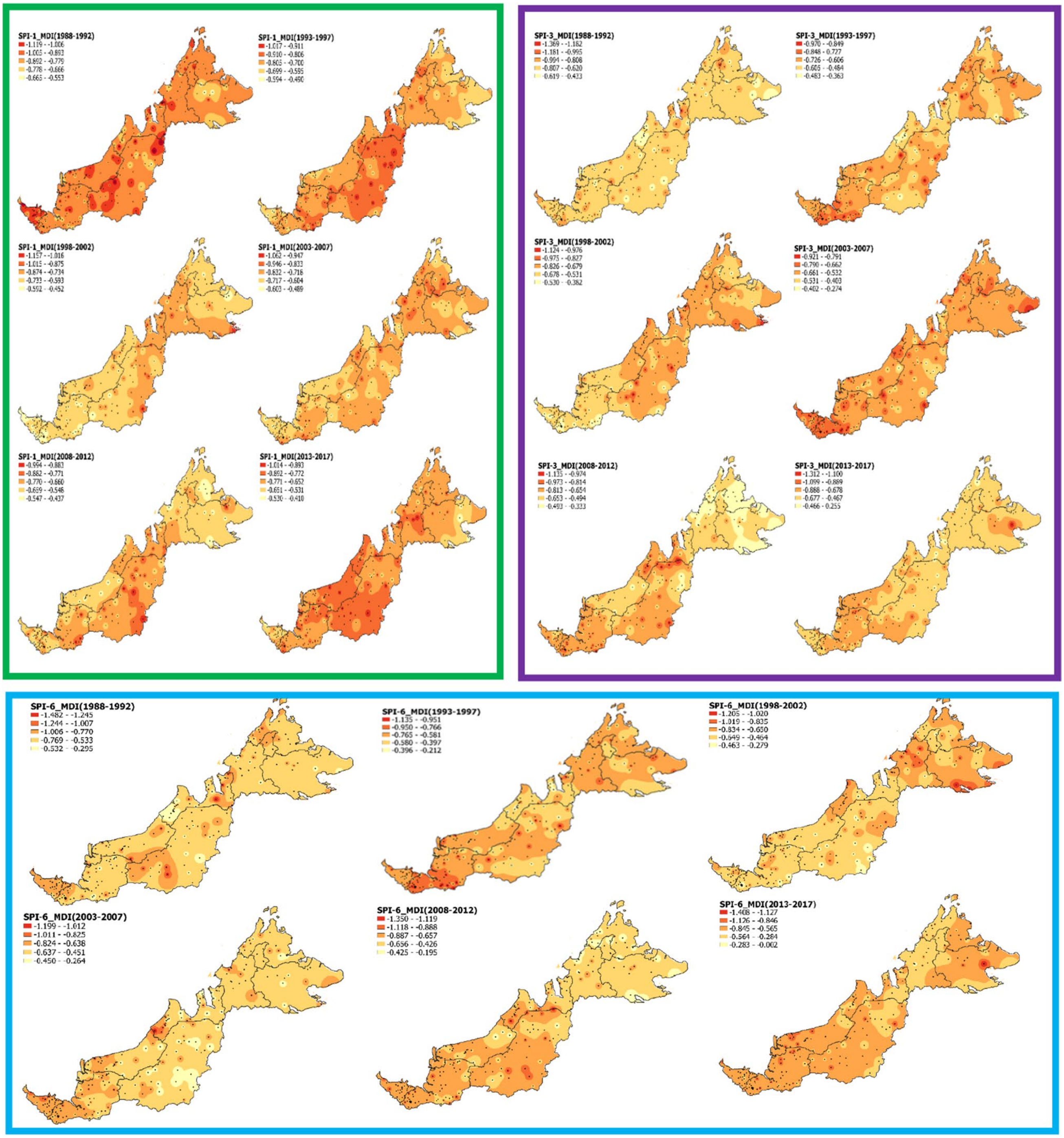

Fig. 6 Mean drought intensity maps for SPI-1, SPI-3, and SPI-6 for each 5-year sub-period from 1988 to 2017. SPI-1 is shown in green in the top left corner, SPI-3 in the top right, and SPI-6 is shown in blue in the bottom

showed that the Severe Droughts significantly affected the Peninsula's eastern half more than other regions, particularly in Regions 1 and 3 for SPI-3 and Region 5 for SPI-6 (Fig. 11).

Extreme droughts

Overall, SPI-1 results (Fig. 12) demonstrated that the Central and Eastern parts of East Malaysia commonly experienced peak Extreme Drought Meanwhile, SPI-3 and SPI-6 results suggested that only the Central region of East Malaysia

Table 6 Mean drought intensity: (a) SPI-1, (b) SPI-3, and (c) SPI-6

Sub-period	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7	Region 8	Region 9
Mean drought intensity (SPI-1)									
1988–1992	− 1.005 to − 0.553	− 1.005 to − 0.779	− 1.119 to − 0.553	− 1.005 to − 0.779	− 1.005 to − 0.666	− 1.005 to − 0.666	− 1.005 to − 0.666	− 1.005 to − 0.666	− 1.005 to − 0.666
1993–1997	− 0.805 to − 0.490	− 0.805 to − 0.490	− 1.017 to − 0.595	− 0.805 to − 0.595	− 0.910 to − 0.595	− 0.910 to − 0.595	− 0.910 to − 0.595	− 0.910 to − 0.595	− 0.910 to − 0.595
1998–2002	− 1.157 to − 0.452	− 0.733 to − 0.452	− 1.015 to − 0.452	− 0.874 to − 0.593	− 1.015 to − 0.593	− 1.015 to − 0.593	− 0.874 to − 0.452	− 0.874 to − 0.452	− 0.874 to − 0.452
2003–2007	− 0.946 to − 0.604	− 0.832 to − 0.489	− 0.946 to − 0.489	− 0.946 to − 0.718	− 1.062 to − 0.718	− 0.946 to − 0.489	− 0.946 to − 0.604	− 1.062 to − 0.604	− 0.946 to − 0.604
2008–2012	− 0.882 to − 0.437	− 0.882 to − 0.437	− 0.994 to − 0.548	− 0.770 to − 0.548	− 0.882 to − 0.548	− 0.882 to − 0.548	− 0.882 to − 0.548	− 0.770 to − 0.437	− 0.770 to − 0.437
2013–2017	− 0.892 to − 0.410	− 0.892 to − 0.410	− 1.014 to − 0.531	− 0.892 to − 0.652	− 1.014 to − 0.531	− 0.892 to − 0.531	− 0.892 to − 0.531	− 0.892 to − 0.531	− 1.014 to − 0.652
Mean Drought intensity (SPI-3)									
1988–1992	− 0.994 to − 0.433	− 0.994 to − 0.620	− 0.994 to − 0.433	− 1.369 to − 0.808	− 0.994 to − 0.433	− 1.181 to − 0.433	− 0.994 to − 0.433	− 0.994 to − 0.433	− 0.994 to − 0.433
1993–1997	− 0.848 to − 0.363	− 0.726 to − 0.484	− 0.970 to − 0.363	− 0.726 to − 0.484	− 0.970 to − 0.484	− 0.848 to − 0.363	− 0.848 to − 0.484	− 0.848 to − 0.484	− 0.970 to − 0.606
1998–2002	− 0.975 to − 0.531	− 0.678 to − 0.382	− 0.978 to − 0.382	− 0.826 to − 0.382	− 0.975 to − 0.531	− 0.975 to − 0.531	− 0.826 to − 0.382	− 0.826 to − 0.382	− 0.826 to − 0.382
2003–2007	− 0.921 to − 0.403	− 0.790 to − 0.403	− 0.921 to − 0.274	− 0790 to − 0.532	− 0790 to − 0.403	− 0.790 to − 0.403	− 0.921 to − 0.532	− 0.790 to − 0.403	− 0.790 to − 0.274
2008–2012	− 0.813 to − 0.333	− 0.813 to − 0.494	− 1.135 to − 0.333	− 0.653 to − 0.333	− 0.831 to − 0.333	− 1.135 to − 0.494	− 0.973 to − 0.494	− 0.653 to − 0.333	− 0.813 to − 0.333
2013–2017	− 1.312 to − 0.467	− 0.888 to − 0.467	− 0.888 to − 0.255	− 0.888 to − 0.467	− 0.677 to − 0.255	− 0.888 to − 0.255	− 1.099 to − 0.467	− 0.888 to − 0.255	− 0.888 to − 0.255
Mean drought intesity (SPI-6)									
1988–1992	− 1.006 to − 0.295	− 1.006 to − − 0.533	− 1.244 to − 0.295	− 1.006 to − 0.533	− 1.006 to − 0.295	− 1.482 to − 0.295	− 1.006 to − 0.295	− 1.006 to − 0.533	− 1.244 to − 0.533
1993–1997	− 0.950 to − 0.212	− 0.950 to − 0.581	− 0.950 to − 0.212	− 0.950 to − 0.397	− 0.950 to − 0.397	− 0.950 to − 0.212	− 1.135 to − 0.397	− 0.950 to − 0.581	− 0.950 to − 0.397
1998–2002	− 1.205 to − 0.464	− 0.834 to − 0.464	− 0.834 to − 0.279	− 0.834 to − 0.279	− 1.019 to − 0.464	− 1.019 to − − 0.279	− 0.834 to − 0.297	− 0.834 to − 0.464	− 0.834 to − 0.279
2003–2007	− 0.824 to − 0.264	− 1.011 to − 0.638	− 0.824 to − 0.264	− 0.637 to − 0.451	− 0.824 to − 0.451	− 1.011 to − 0.264	− 0.824 to − 0.451	− 0.824 to − 0.264	− 0.824 to − 0.264
2008–2012	− 0.887 to − 0.195	− 1.118 to − 0.657	− 1.118 to − 0.195	− 0.656 to − 0.195	− 0.887 to − 0.195	− 1.118 to − 0.426	− 1.118 to − 0.426	− 0.656 to − 0.195	− 0.887 to − 0.195
2013–2017	− 1.408 to − 0.284	− 0.845 to − 0.284	− 1.126 to − 0.284	− 0.845 to − 0.284	− 0.845 to − 0.002	− 0.845 to − 0.284	− 1.126 to − 0.284	− 0.845 to − 0.284	− 1.126 to − 0.284

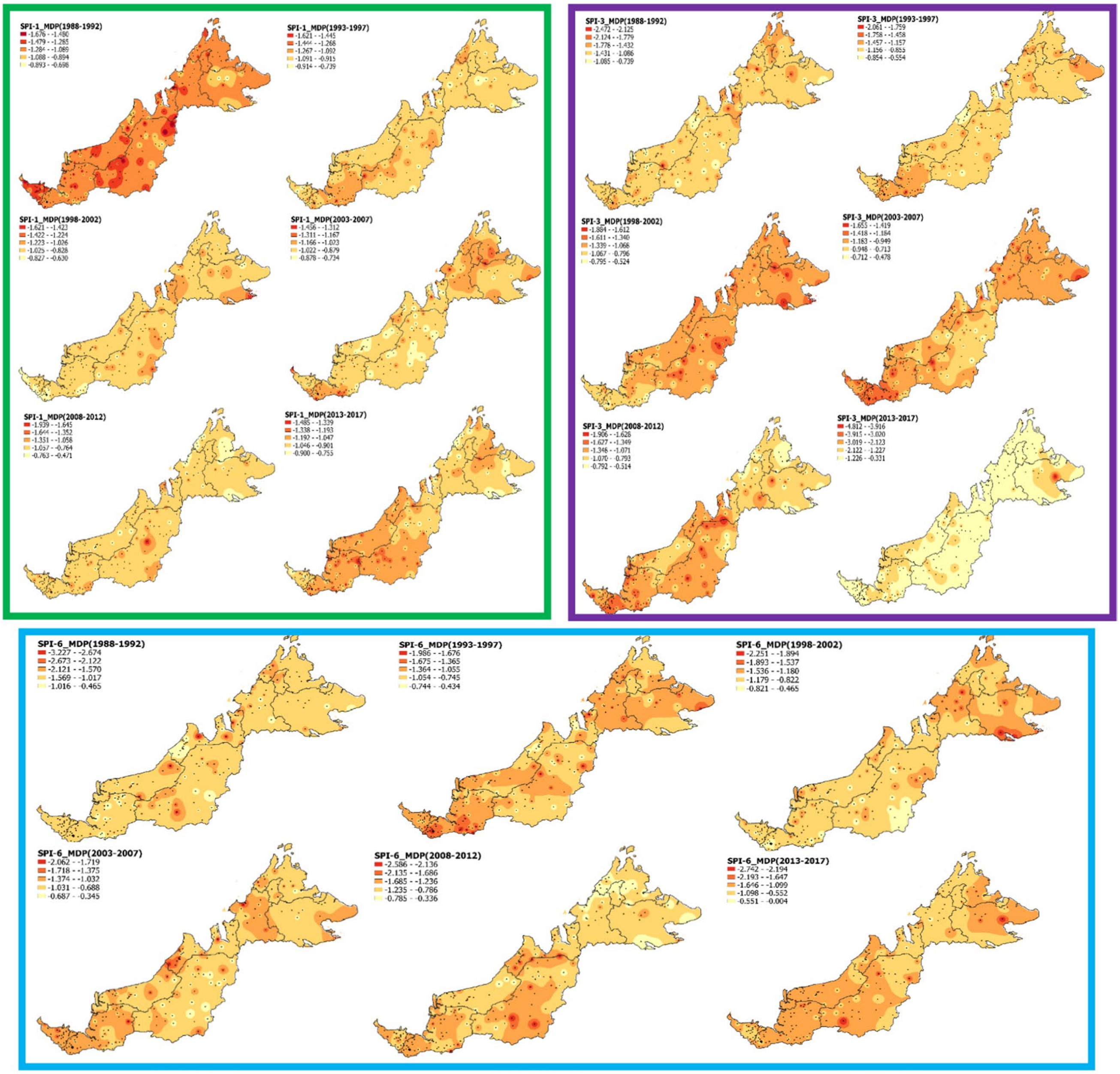

Fig. 7 Mean Drought Peak maps for SPI-1, SPI-3, and SPI-6 for each 5-year sub-period from 1988 to 2017. SPI-1 is shown in green (top left), SPI-3 is shown in violet (top right), and SPI-6 is shown in blue (bottom)

frequently experienced peak Extreme Drought. Region 3, with its mountainous topography, accounted for the majority of the peak Extreme Drought occurrences, which frequently occurred in the Central region of East Malaysia.

Drought response strategies to be considered

With the aids of drought assessment conducted, several drought response strategies could be considered.

More efficient irrigation systems can strengthen and expand agricultural diversification plans to match weather conditions. Malaysia is under pressure to become more efficient due to drought stress and its low water use efficiency (Rahman et al. 2019). One practical improvement could be to reduce distribution losses by modernizing existing schemes and adopting drip and sprinkler irrigation systems. These systems are more water-efficient and avoid losses due to deep percolation, surface runoff, and transmission caused

Table 7 Mean drought peak: (a) SPI-1, (b) SPI-3, and (c) SPI-6

Sub-period	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7	Region 8	Region 9
Mean drought peak (SPI-1)									
1988–1992	−1.479 to −0.698	−1.479 to −0.894	−1.676 to −0.698	−1.479 to −1.089	−1.479 to −0.894	−1.479 to −0.894	−1.479 to −0.894	−1.479 to −0.894	−1.479 to −0.894
1993–1997	−1.267 to −0.739	−1.267 to −0.739	−1.444 to −0.739	−1.267 to −0.915	−1.267 to −0.739	−1.267 to −0.739	−1.267 to −0.739	−1.267 to −0.739	−1.267 to −0.739
1998–2002	−1.621 to −0.630	−1.025 to −0.630	−1.422 to −0.630	−1.223 to −0.630	−1.223 to −0.828	−1.223 to −0.828	−1.223 to −0.630	−1.025 to −0.630	−1.223 to −0.630
2003–2007	−1.311 to −0.734	−1.311 to −0.734	−1.166 to −0.734	−1.311 to −0.879	−1.311 to −0.879	−1.311 to −0.734	−1.311 to −0.734	−1.311 to −0.734	−1.166 to −0.734
2008–2012	−1.351 to −0.471	−1.351 to −0.764	−1.393 to −0.764	−1.057 to −0.764	−1.351 to −0.471	−1.351 to −0.764	−1.351 to −0.471	−1.057 to −0.471	−1.057 to −0.471
2013–2017	−1.192 to −0.755	−1.192 to −0.755	−1.338 to −0.755	−1.192 to −0.901	−1.192 to −0.755	−1.338 to −0.755	−1.338 to −0.755	−1.192 to −0.755	−1.338 to −0.901
Mean drought peak (SPI-3)									
1988–1992	−2.124 to −0.739	−1.431 to −1.086	−1.778 to −0.739	−2.124 to −1.086	−2.124 to −0.739	−2.124 to −0.739	−1.778 to −0.739	−2.124 to −0.739	−2.472 to −0.739
1993–1997	−1.758 to −0.554	−1.457 to −0.855	−1.457 to −0.554	−1.457 to −0.554	−1.457 to −0.554	−2.061 to −0.554	−1.758 to −0.855	−1.457 to −0.855	−1.457 to −0.855
1998–2002	−1.884 to −0.796	−1.339 to −0.796	−1.884 to −0.524	−1.611 to −0.796	−1.611 to −0.796	−1.611 to −0.796	−1.339 to −0.524	−1.611 to −0.796	−1.611 to −0.796
2003–2007	−1.655 to −0.713	−1.418 to −0.949	−1.418 to −0.478	−1.418 to −0.713	−1.418 to −0.713	−1.418 to −0.478	−1.655 to −0.713	−1.418 to −0.713	−1.418 to −0.478
2008–2012	−1.627 to −0.514	−1.627 to −0.793	−1.906 to −0.514	−1.348 to −0.793	−1.627 to −0.514	−1.906 to −0.793	−1.906 to −0.793	−1.070 to −0.514	−1.348 to −0.514
2013–2017	−2.122 to −0.331	−2.122 to −0.331	−2.122 to −0.331	−2.122 to −0.331	−2.122 to −0.331	−2.122 to −0.331	−2.122 to −0.331	−2.122 to −0.331	−2.122 to −0.331
Mean drought peak (SPI-6)									
1988–1992	−2.121 to −0.465	−2.121 to −1.017	−2.673 to −0.465	−2.121 to −1.017	−2.121 to −0.465	−3.227 to −0.465	−2.121 to −0.465	−2.121 to −0.465	−2.673 to −0.465
1993–1997	−1.675 to −0.434	−1.364 to −0.745	−1.675 to −0.434	−1.364 to −0.745	−1.675 to −0.745	−1.675 to −0.434	−1.986 to −0.745	−1.675 to −0.434	−1.675 to −0.745
1998–2002	−2.251 to −0.822	−1.536 to −0.465	−1.536 to −0.465	−1.536 to −0.465	−1.893 to −0.465	−1.536 to −0.465	−1.536 to −0.465	−1.536 to −0.882	−1.536 to −0.465
2003–2007	−1.374 to −0.345	−1.718 to −1.032	−1.374 to −0.345	−1.374 to −0.688	−2.062 to −0.345	−2.062 to −0.345	−1.718 to −0.688	−1.374 to −0.345	−1.718 to −0.345
2008–2012	−1.685 to −0.336	−1.685 to −0.786	−2.586 to −0.336	−1.235 to −0.336	−1.685 to −0.336	−2.135 to −0.336	−2.135 to −0.336	−1.235 to −0.336	−1.685 to −0.336
2013–2017	−2.742 to −0.552	−1.646 to −0.552	−2.742 to −0.552	−1.098 to −0.552	−1.646 to −0.004	−1.646 to −0.004	−2.193 to −0.552	−1.646 to −0.552	−1.646 to −0.552

Table 8 The Number of stations in each drought category

Year	SPI-1				SPI-3				SPI-6			
	Mild	Moderate	Severe	Extreme	Mild	Moderate	Severe	Extreme	Mild	Moderate	Severe	Extreme
1988	245	122	85	48	251	93	42	29	251	57	26	21
1989	249	154	83	59	248	137	80	55	240	143	56	34
1990	250	196	128	98	247	191	110	81	245	185	112	59
1991	251	191	149	109	249	201	160	99	239	195	122	67
1992	251	170	136	88	247	160	92	95	242	169	99	58
1993	249	177	102	55	247	143	70	33	244	130	54	22
1994	246	155	127	108	248	174	94	60	243	143	77	34
1995	245	123	67	28	238	76	39	13	220	72	29	16
1996	249	148	71	28	236	97	37	19	200	76	27	12
1997	250	183	161	129	250	194	146	93	247	193	145	94
1998	245	120	83	112	243	117	82	117	239	148	116	98
1999	250	136	59	21	243	101	26	7	233	76	27	7
2000	248	152	79	29	247	108	40	9	233	84	32	8
2001	248	168	102	38	248	146	73	20	236	111	42	9
2002	250	171	98	40	251	180	87	41	247	171	62	21
2003	248	167	86	58	248	164	74	37	245	153	53	19
2004	248	177	129	80	249	165	94	32	244	139	55	18
2005	250	163	75	47	249	128	61	38	236	115	57	17
2006	248	155	115	61	246	148	96	60	235	126	90	47
2007	249	98	48	16	234	60	23	19	213	39	14	14
2008	247	76	16	13	218	45	9	14	191	39	15	14
2009	246	179	115	61	250	177	115	68	238	170	107	56
2010	239	90	54	80	224	77	56	46	207	73	42	26
2011	250	139	90	41	245	144	61	28	236	119	54	23
2012	247	155	114	75	246	160	80	48	238	159	101	49
2013	250	143	71	50	246	124	57	22	234	129	49	23
2014	248	172	147	120	243	186	106	59	238	174	113	78
2015	248	185	121	92	250	182	115	54	241	175	105	48
2016	249	144	120	80	250	159	87	71	248	160	81	44
2017	245	104	49	25	232	56	18	11	208	63	24	9

by drought. Climate-proofing methods can also be used to make it easier to implement plans and policies that are resilient to changing weather conditions (Juschten et al. 2021). However, funding that scales to the size of the project is a major challenge for these strategies. Examples of climate-proofed projects include road-building infrastructure and the design of breakwaters for water basins (Storbjörk and Hjerpe 2021).

Dam building remains an effective strategy, despite being one of the oldest drought-management measures (Marengo et al. 2022). Dams function as water reservoirs, storing water during seasons of heavy rainfall and releasing it during periods of low precipitation. It aids in water supply regulation and guarantees that adequate water is accessible for diverse needs such as irrigation, drinking water, and industrial activities (McNabb and Swenson 2023). In addition to providing a reliable water supply, dams can also serve other purposes. A dam, for instance, may control flooding, provide hydroelectric power, and offer recreational possibilities (Ehteram et al. 2022). However, building new dams may be a laborious and expensive endeavour since it requires careful planning and analysis of environmental and socioeconomic effects (Nikonow et al. 2019).

Potential impacts of drought on water availability, biodiversity, and human health

This section explores the potential impacts of drought on sectors beyond agriculture and the economy by reviewing several case studies in selected respective areas.

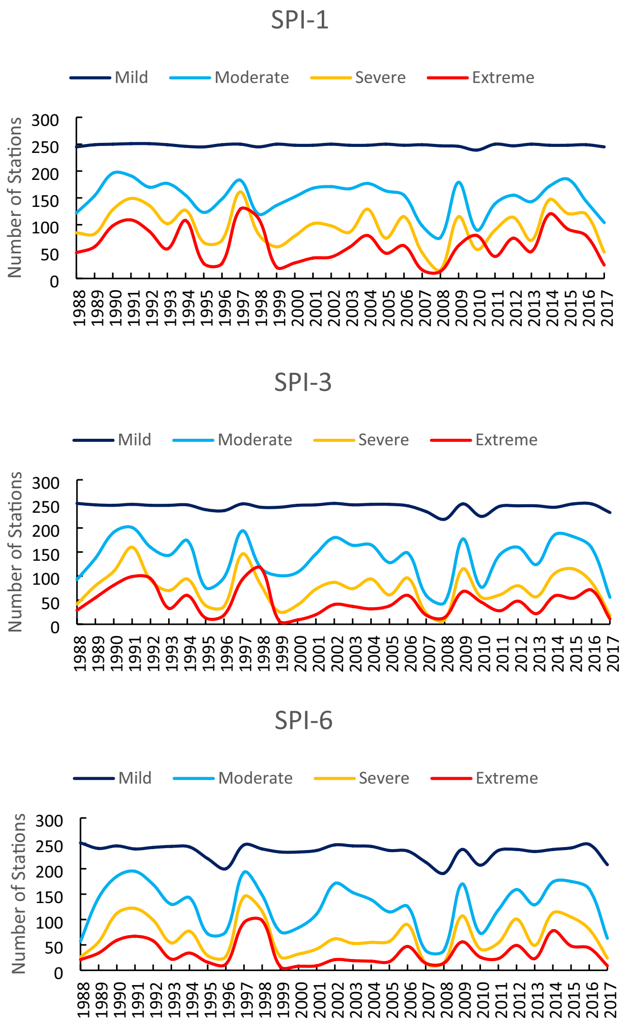

Fig. 8 Number of stations that showed different drought categories in SPI-1 (top chart), SPI-3 (middle chart), and SPI-6 (bottom chart)

Water availability

Prolonged drought can impact the balance of water supply and demand significantly (Achite et al. 2023). It can reduce water availability and increase the vulnerability of regions to adverse consequences. While several drought events over the years, one notable impact on water availability occurred in 2019. During this time, over 3,000 residents from 20 villages in Sabah suffered water shortages due to the drought. Despite six dams operating at approximately 80%, the state Infrastructure Development Minister, Datuk Peter Anthony, warned that the water would only last a few more months. Eight main rivers had reached critical levels, while nine had reached alert levels. The drought had an impact on both residential and industrial regions, in addition to hospitals and government hospitals. Its impact on water availability reached a level where cloud seeding was needed as an immediate action to increase water levels. For instance, the Sungai Papar plant stopped working due to low water levels, affecting over 19,000 residents from 33 villages who depended on its 10 million litres of clean water. Sarawak's rivers were no exception. The EI Nino effect reduced river flow in Sungai Sarawak Kiri, KWB's primary raw water supply. Also, dry weather nearly dried out Sungai Lichok's adjacent water treatment plants.

Biodiversity

The forested hills and mountain in Malaysia serve as water catchments that supply freshwater to communities, while wetlands and coastal ecosystems provide fishing supplies. However, the fact that droughts can destroy biodiversity has put these ecosystems in danger. Mangroves are crucial components of coastal ecosystems all around the world, including Sabah, yet they are underestimated and in danger. Mangrove forests, home to several coastal species, may also be harmed by fluctuations in water levels and salinity due to climate change. These factors can impact breeding habitats and disrupt the food chain. According to study by Mohamed Shaffril et al. (2017), they demonstrated that fishing activities are severely impacted by the fluctuation in the climate change. Besides, the climate change also impacted the aquaculture in the coastal areas of Sabah and Sarawak due to intoxicated of water by the algae bloom due to oxygen depletion (Maulu et al. 2021).

Due to the combination of global warming and intense Ei Nino occurrences, rising sea levels may potentially damage coral reefs by lowering the amount of light that reaches them, preventing their growth and survival (Bylund and Jonsson 2020). Besides, increasing precipitation can cause soil erosion and siltation in coastal locations, potentially disrupting seagrass meadows and coral reefs critical to preserving the ecosystem and maintaining marine life. Being a Coral Triangle nation, Malaysia has one of the most ecologically varied coral reef ecosystems, and additional precautions should be taken to reduce losses.

Human health

A drought is a complex event that results from a lack of precipitation and can have significant impacts on water resources and human livelihoods (El-Magd et al. 2022). Heat waves and droughts can cause dehydration and heat-related illnesses such as heat exhaustion and heatstroke, which reduces the water body level through perspiration. In May 2023, the Health Ministry in Sabah recorded a considerable heat strokes cases per day.

Rising temperatures may also accelerate the growth and proliferation of these pathogens. A study published by Leizeaga et al. (2022) found that bacterial growth responds to re-wetting in two ways: either with a resilient response

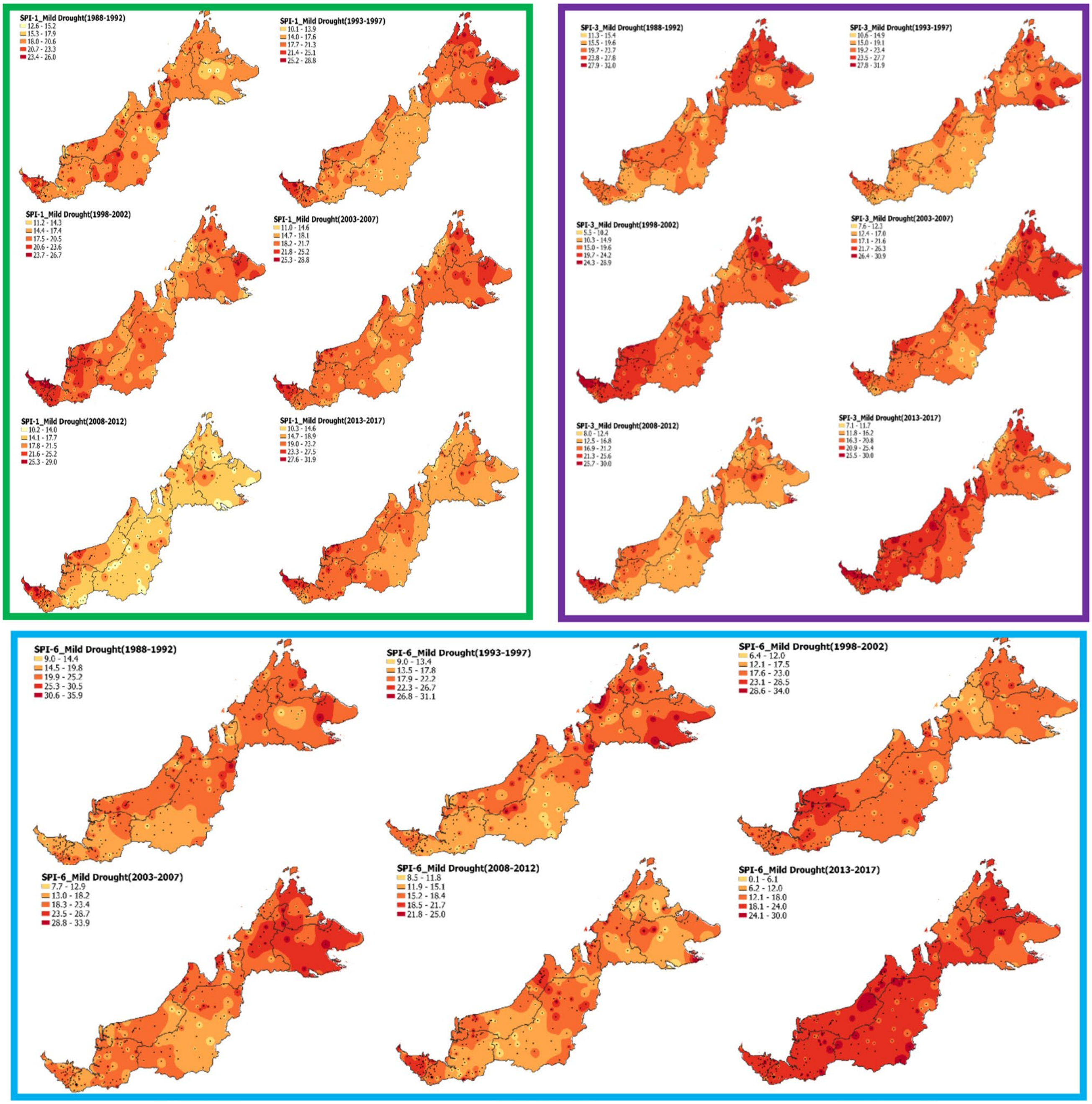

Fig. 9 Maps of mild drought for each 5-year sub-period from 1988 to 2017 for SPI-1 (green border box, top left), SPI-3 (violet border-box, top right), and SPI-6 (blue border box, bottom)

where growth rates rise linearly and immediately ("type 1") or with a less resilient response where there is a lag period of no growth for up to 24 h before rates rise exponentially ("type 2"). The study also discovered that bacterial growth was more resistant and tolerant to drought in rainforest soils than in oil palm plantation soils. These polluted rivers and other water sources become breeding grounds for disease-carrying pathogens, with several events impacting human health. Given that rivers are the primary supply of water, drinking polluted river water and consuming contaminated river fish can affect human health. With the recently reported deaths, the Department of Meteorology Malaysia (METMalaysia) has issued a warning for some areas in the peninsula and Sabah.

Another drought-related issue is that increasing sea levels due to climate change has increased the salinity of coastal aquifers in Malaysia (ESCAP 2019). As a result, saltwater infiltrated freshwater sources, leaving them unfit for human

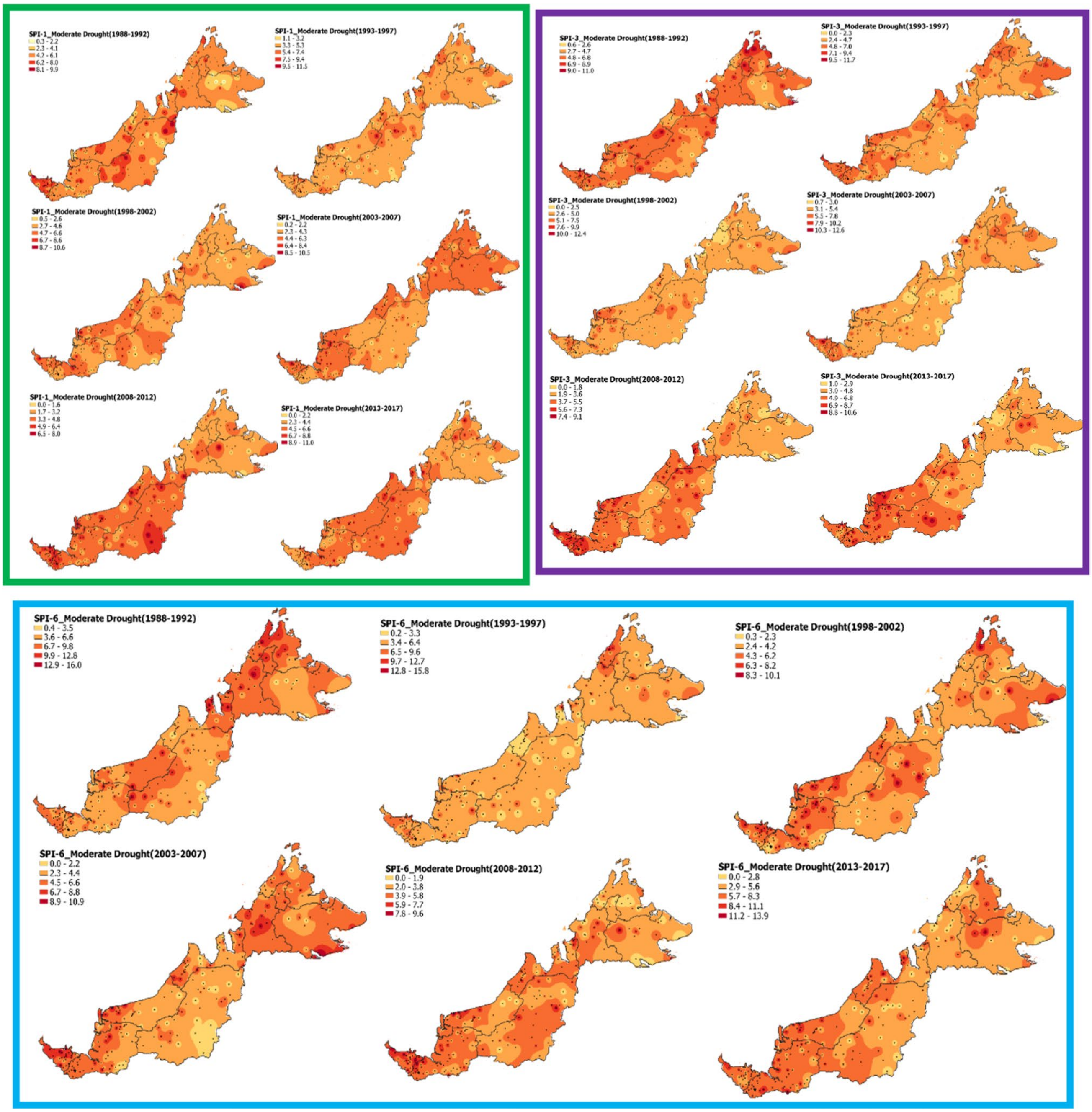

Fig. 10 Maps of moderate drought for each of the 5-year sub-periods from 1988 to 2017 for SPI-1 (green border box, top left), SPI-3 (violet border-box, top right), and SPI-6 (blue border box, bottom)

consumption or agricultural use. Coastal towns that rely on these freshwater supplies have suffered as a result.

Conclusions

This research showed how drought patterns vary over time. Droughts were most common in the years 1993–1997 and 2008–2012. Nonetheless, from 2003 to 2007, drought periods were at their lowest. El-Nino events in 1994–1995, 1997–1998, and 2009–2010 may have played a role in the occurrence. Droughts were most widespread in the Central (Region 3) and Eastern (Region 1) regions of East Malaysia. The drought in the Central area was caused by the rugged geography of East Malaysia since the stations in Region 3 are bordered by the mountainous regions of Pergunungan Iran and Pergunungan Hose, which hinder the North-East and South-West

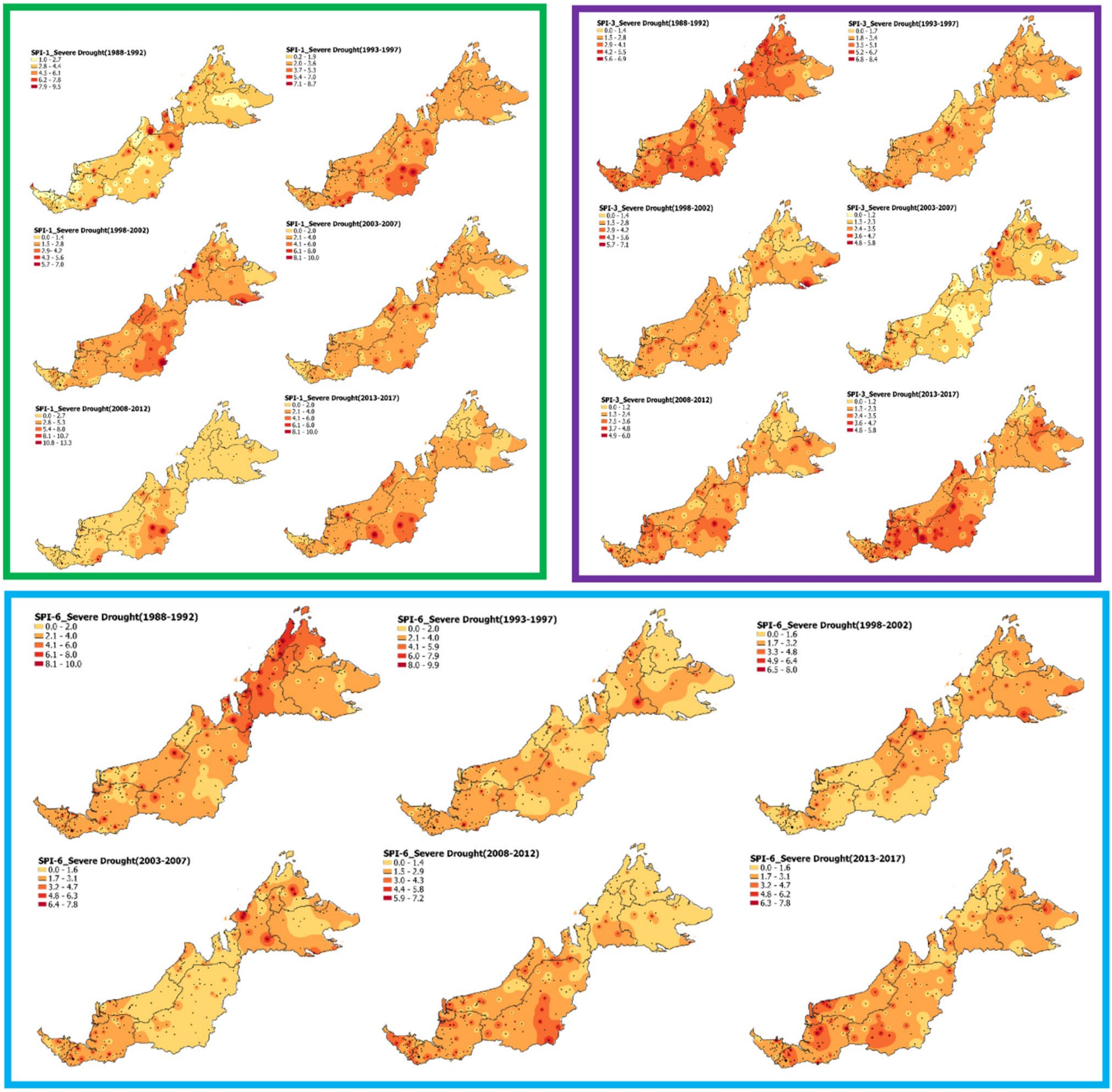

Fig. 11 Severe Drought maps of SPI-1 (green border box, top left), SPI-3 (violet border box, top right), and SPI-6 (blue border box, bottom) for each of the 5-years sub-period from 1988 to 2017

Monsoons from reaching the stations, respectively. The features of the drought in the Eastern region were influenced by earlier El Nino experiences, which caused a rise in sea surface temperature and a lack of rainfall in areas near coastal stations. Also, based on the lessons acquired from past events have demonstrated that future responses must be proactive, improving the early warning systems to reduce the impact of drought.

Drought characteristics in numerous locations of Sabah and Sarawak, were studied at 251 stations between 1988 and 2017 on 1-month, 3-month, and 6-month timeframes. Due to its adaptability across the temporal scale and its capacity to depict the anomaly of precipitation, SPI analysis can efficiently extract the spatiotemporal pattern of dry and wet circumstances. With its simple computation, multiscale drought indicators, and low input requirements,

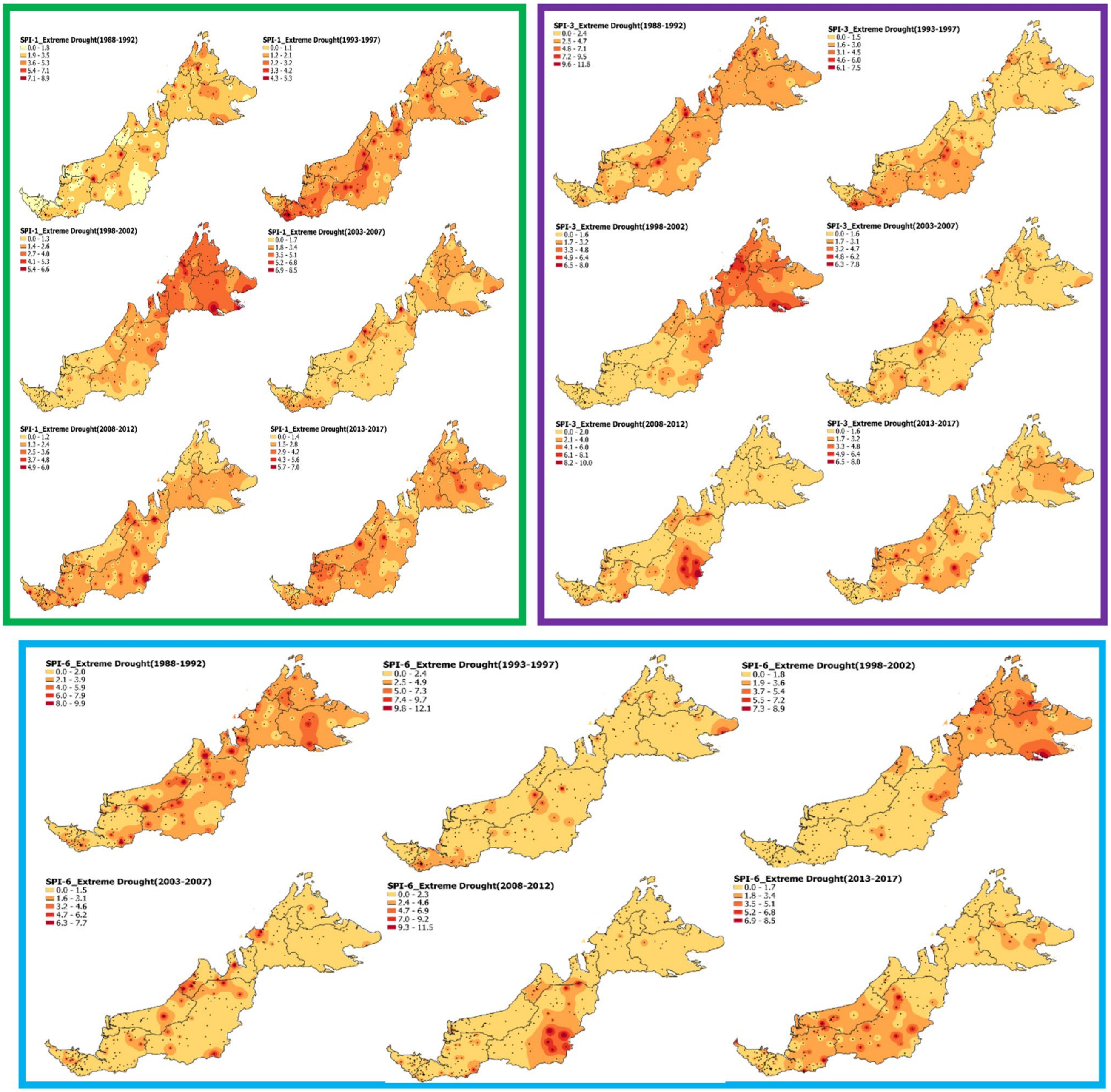

Fig. 12 Maps of extreme drought over the 5-year sub-period from 1988 to 2017 for SPI-1 (green border box, top left), SPI-3 (violet border, top right), and SPI-6 (blue border box, bottom)

the SPI sets the foundation for describing the whims of droughts (only precipitation data). Three scenarios were examined, each with relation to distinct drought timelines (short-, medium-, or long-term trends). First off, the SPI-1 represents monthly precipitation more accurately by using typical precipitation for each month. Second, the SPI-3 reflects seasonal estimation of precipitation as well as short- to medium-term moisture conditions of 3 months. The SPI-6, which displays precipitation over six-month seasons, also illustrates medium-term trends in precipitation. Precipitation data were evaluated in this work to explore drought features, which included computing the DF, MDD, MDS, MDI, and MDP. Droughts were classified as mild, moderate, severe, or extreme.

The findings of the study can serve as a pre-requisite drought assessment plan for the authorities. Authorities may better understand and respond to drought conditions by applying the study's information and methodologies, potentially decreasing their consequences on people and ecosystems. Drought evaluation can give useful information for the creation of early warning systems, mitigation techniques, and damage relief operations. The following changes to this drought feature study might be implemented in the future to compensate the lacking of the current study:

(1) Other drought indices, such as the SPEI and PDSI, can be examined to assess additional drought aspects while taking into consideration diverse data inputs, such as temperature, streamflow, and other parameters.
(2) The SPI may be extended to other periods, such as 9-, 12-, 24-, or even 48 months, to understand better the additional drought features. By prolonging the SPI period, computed based on a moving window of n months ($n >$ nine months) can be performed, operations such as reservoir monitoring and groundwater replenishment are possible. The longer timeline may be ineffectual, given that Malaysia is less likely to experience mid- and long-term drought due to its tropical climate.
(3) Various factors impacting rainfall occurrence, such as land use, soil qualities, and moisture-carrying winds, can be explored in other Peninsular Malaysian locations. It is possible to measure the soil loss of different land use types under varied rainfall patterns by analysing the paramaters through statistical tests. One of the analyses is to determine the mean value of soil erosion modulus, which is a measure of the average rate of soil erosion in a given area. It is calculated by dividing the total amount of soil loss by the area of the land surface and the period over which the erosion occurred. The purpose of calculating the mean value of the soil erosion modulus is to provide a quantitative measure of soil erosion that can be used to assess the severity of erosion in a given area and to compare erosion rates between different areas or over time.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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