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Spatiotemporal characteristics of hydro-meteorological droughts and their connections to large-scale atmospheric circulations in the Kelantan River Basin, Malaysia

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ABSTRACT

Climate change exacerbates dry seasons in Southeast Asia, leading to water supply shortage. However, the link between hydro-meteorological droughts and large-scale atmospheric circulations, such as the El Nino Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Madden–Julian oscillation (MJO), has received very little attention. Therefore, this study aims to analyse the hydro-meteorological droughts that occurred in the Kelantan River Basin (KRB) between 1985 and 2020 using the Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) as well as their connections to ENSO, IOD, and MJO. Sen's slope and Mann–Kendall test were employed to evaluate the trends and magnitude changes of the historical droughts, respectively. In addition, the response rate of SSI to SPI was considered to understand how precipitation affects streamflow. The results show that extremely dry events occurred in 1986, 1987, 1989, 1990, 1992, 1997–1998, 2015–2016, and 2020. Based on the SSI results, more than 70% of extremely dry periods last 6 months or longer. Interestingly, from January to May, when there was low precipitation, SSI had a higher response rate to SPI. The ENSO, as opposed to the IOD and MJO, had a stronger impact on the dry conditions over the KRB.

Key words: climate change, drought, ENSO, precipitation, SPI, tropical

HIGHLIGHTS

- An in-depth analysis of hydro-meteorological droughts in a tropical basin.
- Moderate response rate of SSI to SPI due to the high withdrawal of groundwater.
- About half of the stations experienced more than 10 extremely dry events.
- ENSO has a larger impact on tropical droughts than IOD and MJO.
- Major drought events have occurred during the strong El Nino years.

1. INTRODUCTION

Droughts have significantly impacted a wide variety of socioeconomic activities such as water supply, agriculture, aquaculture, industry, and hydropower generation (Munyasya *et al.* 2022). In Southeast Asia, droughts have frequently destroyed crops, caused forest fires and depleted water supplies. According to the International Disaster Database, 52 drought episodes have affected more than 77 million people in Southeast Asia since 1996 (EM-DAT 2018). Drought is defined as water deficiencies when compared to normal circumstances, where it can be classified as hydrological, agricultural, meteorological, and socioeconomic, depending on the impact. According to Leta (2018), droughts will become more frequent, severe, and persistent in many parts of the world. While Siderius *et al.* (2018) also stated that the frequency and duration of severe drought events are predicted to increase in the future. This is because, based on the United Nations, the human population

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will increase by 2 billion in the next 30 years, and the population growth leads to more resources extraction and consumption that accelerate climate change.

In Malaysia, precipitation characteristics are influenced by two monsoon seasons, the northeast monsoon (NEM) from November to March and the southwest monsoon (SWM) from May to September. While the inter-monsoon normally occurred in April and October. During these monsoon seasons, total annual precipitation between 2,000 and 4,000 mm with 150–200 wet days, falls over the nation (Suhaila & Aziz 2007). However, a reduction in total precipitation and the number of precipitation days during the SWM season in Peninsular Malaysia, which might potentially cause issues in the agricultural, industrial, water supply, public health and energy sectors (Suhaila *et al.* 2010). Other than that, Hasan *et al.* (2021) applied Streamflow Drought Index (SDI) to study the spatiotemporal pattern of drought in Peninsular Malaysia across 3, 6, 9, and 12 months. They found that 1997–1999, 2002, and 2016–2018 were severe drought periods in Peninsular Malaysia. Short-term droughts are commonly occurred in most areas, while more severe droughts can be found in the northeast and southeast regions. For instance, a severe drought in 2014 impacted paddy productivity in Kelantan located in the northeastern part of Peninsular Malaysia, resulting in approximately USD$22 million losses in agricultural industry (Tan *et al.* 2017). In addition, Tew *et al.* (2022) also reported rapidly rising temperatures and high variability rainfall patterns in Kelantan, which could eventually cause severe droughts. For example, some severe droughts were found in 1997, 1998, 2002, 2003, 2005, 2006, 2007, 2009, and 2010 (Yusof *et al.* 2013; Hashim *et al.* 2016).

Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) have been utilized to determine the severity, duration, and intensity of basin-scale drought using precipitation and streamflow data, respectively (Tan *et al.* 2019). SPI was created to define and track droughts by McKee *et al.* (1993). SPI is simple to apply since requires only monthly precipitation data and is able to compute various timeframes and widely used by other researchers. For example, Luhaim *et al.* (2021) utilized SPI-3 to study the characteristics of drought events in the Muda River Basin, where they found the basin was affected by severe droughts in 1991–1992, 1995, 1998, 2002–2003, 2005–2006, 2008, 2012–2013, and 2016. Other than that, they also found the SPI values decreased throughout the three time periods, which is indicative of an increasing trend of drought events across the basin. Climate change may also account for the increase in the amount of dry months at most of the rainfall stations in the Sarawak River basin during the last decade compared to the preceding 30–40 years (Bong & Richard 2020). Almost all the stations had at least 5 very dry periods, and most of the stations endured roughly 10 severely dry droughts. Eventually, information may assist enhance the system for early warning of drought and drought mitigation techniques. Salimi *et al.* (2021) have utilized SPI, SSI, and Standardized Precipitation Evapotranspiration Index (SPEI) to analyse the dry and wet periods across three basins in Iran. Moreover, Lee *et al.* (2017) due to climate change, droughts were more severe between the years 1995 and 2085 in Hwanghae Plain, North Korea. The SPIs revealed that future 1-month droughts would be more severe than future 6-month droughts, whereas the SPEI showed the reverse. The findings demonstrate that the association between the meteorological and hydrological dryness is substantial at 99% in all three basins. However, an in-depth analysis of correlation between meteorological and hydrological droughts as well as their relationship with large-scale atmospheric circulation is relatively limited.

This study aims to assess the spatiotemporal characteristics of droughts in the KRB from 1985 to 2020. The specific objectives of this study include: (1) to quantify the hydro-meteorological drought characteristic, i.e., duration, peak, severity, and intensity; (2) to evaluate the response rate of SSI to SPI; and (3) to analyse the impact of large-scale atmospheric circulations on the drought formation in the KRB. The findings are important for local stakeholders to formulate regional water resources management and disaster reduction plans. For a stronger preventive measures and readiness, planning authorities must identify temporal and geographical patterns of existing droughts for forecasting future droughts. Lastly, the findings could contribute to improve the current literature on the tropical droughts and how large-scale atmospheric circulation, i.e., El Niño Southern Oscillation (ENSO) affect the drought formation.

2. STUDY AREA AND MATERIALS

2.1. Study area

The KRB lies between 4°–6°N latitudes and 101°–102°E longitudes as shown in Figure 1. The basin receives about 2,700 mm/year of total precipitation annually, with higher precipitation amount falls during the early NEM from November to January. The average annual temperature ranges from 23 to 34.8 °C. Based on the European Space Agency (ESA) global land use map improved by Tew *et al.* (2022), the basin is covered by 68% of forest and 27.5% of agricultural land in 2018. The agricultural

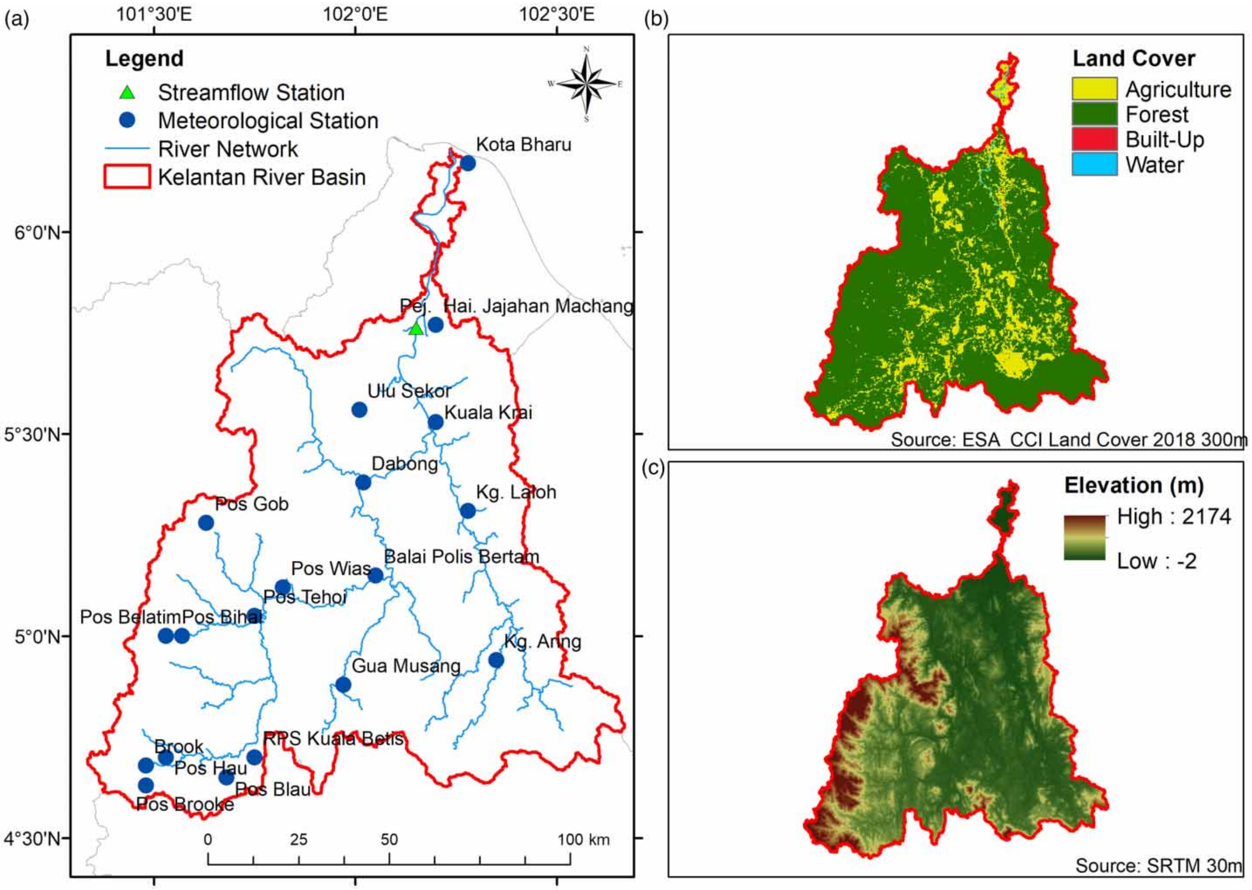

Figure 1 | The distribution of (a) hydro-climatic stations, (b) land use, and (c) elevation of the Kelantan River Basin (KRB), Malaysia.

land can be found in the middle, lower, and southeastern parts of the basin. The basin is surrounded by high mountain-level ranges to the east, west, and south (Figure 1(c)).

2.2. Observed data

Monthly precipitation data from 1985 to 2020 at 21 meteorological stations installed in the basin were collected from the Malaysian Meteorological Department (MMD). Monthly streamflow data for the same period at the Jambatan Guillemard was collected from the Department of Irrigation and Drainage (DID) Malaysia. Basic information and distribution of the meteorological and hydrological stations is shown in Figure 1.

2.3. Drought indices

World Meteorological Organization (WMO) suggests the use of SPI for characterizing droughts. SPI values below −1 indicate severe precipitation shortages, whereas values above 1 indicate severe precipitation excesses. Table 1 lists the several types of wetness and dryness based on the SPI values. For example, a severely dry condition is defined when the SPI value is less than −2.00. In Malaysia, relatively dry periods typically last for not longer than 3 months (Tan *et al.* 2019), so SPI three-month time scale (SPI-3) was selected for the drought assessment in this study. The key advantage of SPI established by McKee *et al.* (1993) is that it can study drought at multiple time scales for different forms of drought. In this study, SPI-3 was calculated using the SPI tool created by the National Drought Mitigation Centre (NDMC). SPI-3 is suitable to analyse the moisture conditions for short and medium-term time scales and, therefore, accessible to offer a seasonal estimate of precipitation (Haroon *et al.* 2016).

While SPI uses monthly precipitation data, SSI uses data on monthly streamflow. SSI is computed based on the cumulative flow values estimated separately for each month, which is based on the terminology of SPI developed by McKee *et al.* (1993).

Table 1 | Drought category based on the SPI value by McKee *et al.* (1993)

SPI value	Drought classes
≥ 2.00	Extremely wet
1.50 to 1.99	Severely wet
1.00 to 1.49	Moderately wet
$-$ 0.99 to 0.99	Near normal
$-$ 1.49 to $-$1.0	Moderately dry
$-$ 1.99 to $-$1.50	Severely dry
≤ -2.00	Extremely dry

SSI has been used in basin-scale drought study in Malaysia, i.e., Luhaim *et al.* (2021) to detect hydrological drought in the Muda River Basin, where most of the severe droughts endure at least 5 months. Types of droughts based on the SSI can be referred to in Table 1 as well.

2.4. Large-scale atmospheric circulation indices

ENSO is a major climatic phenomenon that influences severe weather conditions all over the globe. ENSO occurs every 5–7 years and is characterized by the warming of the seas caused by winds, resulting in the spread of heat over the planet. In this study, the National Oceanic and Atmospheric Administration (NOAA) model Nino 3.4 was employed to reflect ENSO fluctuation. It is a five-phase-averaged measure that identifies El Niño or La Niña occurrences. The index can freely be accessed from the NOAA website at https://www.cpc.ncep.noaa.gov/data/indices (accessed 20 August 2022).

The MJO is the dominant mode of intra-seasonal fluctuation in tropical regions. Generally, it flows to the east at around 4–8 ms1, entering the tropics in 30–90 days. Consequently, the MJO influences the intra-seasonal variability of monsoon precipitation. Past and present MJO activities can be quantified based on the outgoing longwave radiation (OLR) MJO Index (OMI), which is accessible at https://psl.noaa.gov/mjo/mjoindex/ (accessed 20 August 2022).

IOD is also known as the Indian Nino, occurs due to the difference in sea surface temperature between the eastern Indian Ocean and the Arabian Sea (Yue *et al.* 2021). Similar to ENSO, positive IOD values are associated with El Niño, while negative IOD values are associated with La Niña. The Dipole Mode Index (DMI), which can be retrieved from https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/ (accessed 20 August 2022), is generally used to represent the IOD.

2.5. Trend analysis

To examine the temporal changes and trends of SPI and SSI, the Mann–Kendall (MK) test was employed in this study. Drought trend indices are defined as a significant level when the result is in a 95% significance level and Z absolute values more than ± 1.96, with the positive value showing the increasing trend and the negative value indicating the decreasing trend. Furthermore, Sen's slope estimator calculated the magnitude of the detection in the trend. ArcMap 10.8 software was then used to map the Sen's slope values and spatially evaluate the magnitude change. While the significance level by following the MK test results. Equation (1) is used to compute the MK Z value:

$$z = \begin{cases} \dfrac{S-1}{\sigma^2}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \dfrac{S+1}{\sigma^2}, & \text{if } S < 0 \end{cases} \tag{1}$$

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{Sign}\,(x_j - x_k) = \begin{cases} 1, & \text{if } x > 0 \\ 0, & \text{if } x = 0 \\ -1, & \text{if } x < 0 \end{cases} \tag{2}$$

where x_j and x_k are the annualized values in years' j and k $(j > k)$, accordingly, and n is the data series period.

$$\sigma^2 = \frac{(n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)}{18} \tag{3}$$

where t_p represents the number of ties for the pth value and q represents the number of ties value. The mean variance for sample sizes is greater. Sen's non-parametric technique generates slope estimates for N pairs of predicted values, as does Sen's estimator.

$$Q_i = \frac{x_j - x_k}{j - k}, \quad i = 1, \ldots, n \tag{4}$$

where N refers to the number of slope values sorted from smallest to maximum. Sen's slope is determined the following way if N is odd.

$$Q_{\text{median}} = \frac{Q(N+1)}{2} \quad \begin{matrix} N \text{ is odd} \\ N \text{ is even} \end{matrix} \tag{5}$$

2.6. Drought characteristics

Drought characteristics such as drought duration (DD), drought intensity (DI), drought severity (DS), and drought peak (DP) of the KRB were defined in this study. The lowest SPI value during a drought occurrence is called DP (Spinoni *et al.* 2014), while the time between the start of the drought and its end is called DD (Misnawati & Ramdhani 2021). DS refers to the accumulation of the SPI values within a particular drought event, while DI indicates the division of DS with DD. This should not be confused with intensity, which refers to the drought event's lowest SPI number. The equation below shows:

$$\text{Drought severity (DS)} = \sum_{j=1}^{\text{DD}} \text{SPI}(j) \tag{6}$$

$$\text{Drought intensity (DI)} = \frac{\text{DS}}{\text{DD}} \tag{7}$$

where j is shown as a month, and SPI (j) shows a value of SPI in a month.

2.7. Response rate

The response rate was applied to evaluate the relationship between SPI and SSI (Tan *et al.* 2019; Luhaim *et al.* 2021). Response rates indicate the percentage of SSI that affected by SPI. Higher the response rate, greater the influence of precipitation on streamflow. By contrast, a lower percentage value shows that the effect is low. The response rate equation is shown below:

$$R_r = \frac{n}{m} \times 100\% \tag{8}$$

where m is the occurrences of drought that occurred in SPI <0 from 1985 until 2020, while n is the number of droughts that responded to the SSI <0 and SPI <0.

2.8. Correlation analysis

Spearman's correlation method, a non-parametric test used to evaluate the correlation of two different variables (Spearman 1904). It can be used in this study to determine the correlation of SPI or SSI with large-scale atmospheric circulations. In addition, since the test can be used to measure variables with relationships between -1 and 1, it was modified to identify the variables with strong relationships. This method can have either positive or negative correlations, with a strong correlation indicating two variables increasing together. The negative correlation, on the other hand, indicates that one variable is increasing while the others are decreasing in a logical way. R_s denotes the Spearman rank correlation.

$$R_s = 1 - \frac{6\sum_{i=1}^{n} D^2}{n(n^2 - 1)} \tag{9}$$

D is the difference between the object's two rankings (drought index), and n indicates the sum of measurements.

3. RESULTS AND DISCUSSION

3.1. Standardized Precipitation Index

SPI has an intensity scale with both positive and negative values that connect directly to wet and dry events. Figures 2 and 3 show the temporal variability of SPI at meteorological stations from 1985 until 2020. The result shows that many meteorological stations, i.e., Pos Blau, Pos Bihai, Pos Wias, Pos Belatim, Kota Bharu, etc., were experienced extremely dry periods in 1998, where SPI values greater than −2, especially from March until June. Gua Musang was also experienced extreme droughts every few years, particularly in 2020. Extremely dry events of Pos Wias were reported in 1985, 1986, 1991, 1995, 1998, 2000, 2001, 2007, 2016, and 2019. Additionally, several extreme dry periods of the basin occurred in 2020 over other years, followed by 1998, 1990, and 1985. Meanwhile, relatively limited extreme droughts appeared in 1993, 2006, 2009, 2010, 2013, 2014, and 2018.

Extreme dry events occurred in Gua Musang, Station Dabong, Kampung Laloh, and Ulu Sekor, at least 4 months a year. Besides, at least three extreme dry events were recorded in all stations from 1985 until 2020. Meanwhile, Balai Polis Bertam, Kampung Aring, and Brook experienced the most severe droughts, where the SPI values were less than −1.50, especially in 1987, 1989, and 2020. For example, Kampung Aring experienced severe dry spell from March to December 1989 and 2020. By the time, throughout the period, in 1986, 1987, 1989, 2008, and 2020, KRB had hit the highest number of occurrences of severe dry events. However, most of the stations experienced moderate drought for other years, for example, Kuala Krai in 1986 (March until June), 1995 (February, May, June, and December), and 2002 (March, June, October, and November). As a result, the highest number of dry events mainly occurred in 1986 and 2020.

At stations with a 95% confidence level, a considerable upward trend in SPI-3 was seen from January to March (Figures 4 and 5), with some of the stations showed a significant change at 95% confidence level, i.e., Pej Hai Jajahan Machang, Ulu Sekor, Kuala Krai, and Kota Bharu. Furthermore, both increasing and decreasing trends were observed from April to December. Most of the stations in the upper and middle parts of the basin were experienced a significant decreasing trend of SPI, i.e., Balai Polis Bertam, Pos Wias, Kuala Krai, and Kampung Aring, particularly from September to November.

3.2. Standardized Streamflow Index

Table 2 shows that between 1985 and 2020, the KRB experienced 13 dry spells based on SSI. More than 70% of dry spells last 6 months or longer. The longest drought (18 months) was seen between January 1997 and July 1998, followed by a 13-month period between November 2013 and December 2014 and from March 2005 until February 2006 (11 months). Even though the DP was the longest during events, the severity was only −11.36 in 1997/1998, while the highest severity was −13.87 in 2013/2014. There were only four extremely dry events, each with a peak of −2 or even less. Meanwhile, from October 1992 until November 1992, Jambatan Guillemard only had a lesser dry duration, with only one-month duration. Extremely dry periods, as defined by the SSI-3 with intensity level more than −1, were recorded in 1992, 1995–1996, 2004, 2005–2006, 2010–2011, 2012–2013, and 2013–2014. The most intense dry period was recorded from May 2010 to March 2011, with the intensity value of −1.28. The water level had decreased by over 2 m during the dry season in Kelantan, and to irrigate farms affected by drought, the Kelantan Drainage and Irrigation Department has released water from the Bukit Kwong dam (New Straits Time 2019). In fact, dam can effectively capture precipitation for storage and usage in the dry season (Chen *et al.* 2022; Wang *et al.* 2022; Zhu *et al.* 2022).

3.3. Drought characteristics

Figure 6 depicts the total of dry months that happened in the KRB in the past few decades. We have classified them into three categories based on the SPI values to help further study the drought occurrence in the KRB. Whenever the SPI

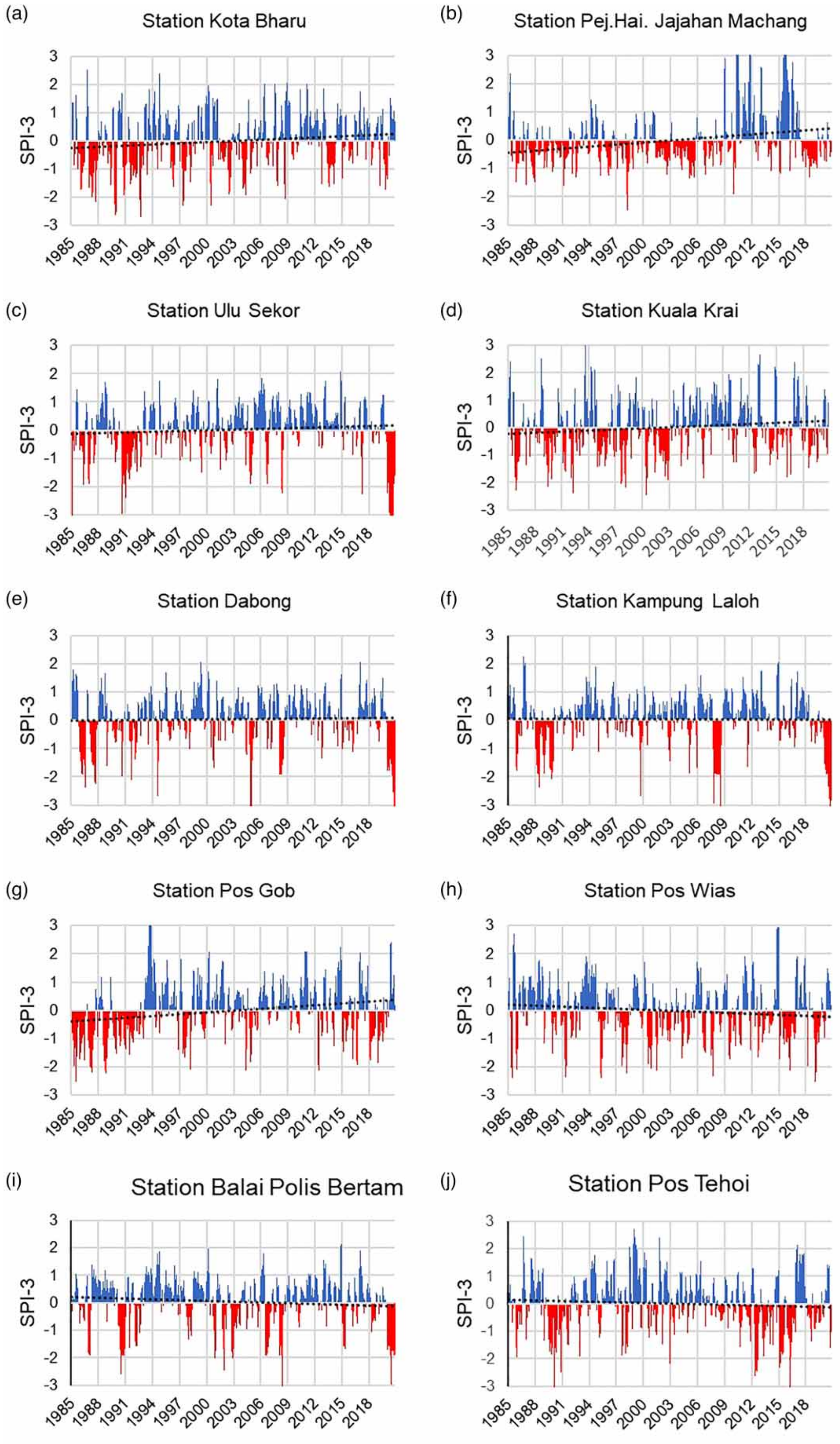

Figure 2 | Spatial temporal SPI-3 in (a) Kota Bharu, (b) Jajahan Machang, (c) Ulu Sekor, (d) Kuala Krai, (e) Dabong, (f) Kampung Laloh, (g) Pos Gob, (h) Pos Wias, (i) Balai Polis Bertam, and (j) Pos Tehoi.

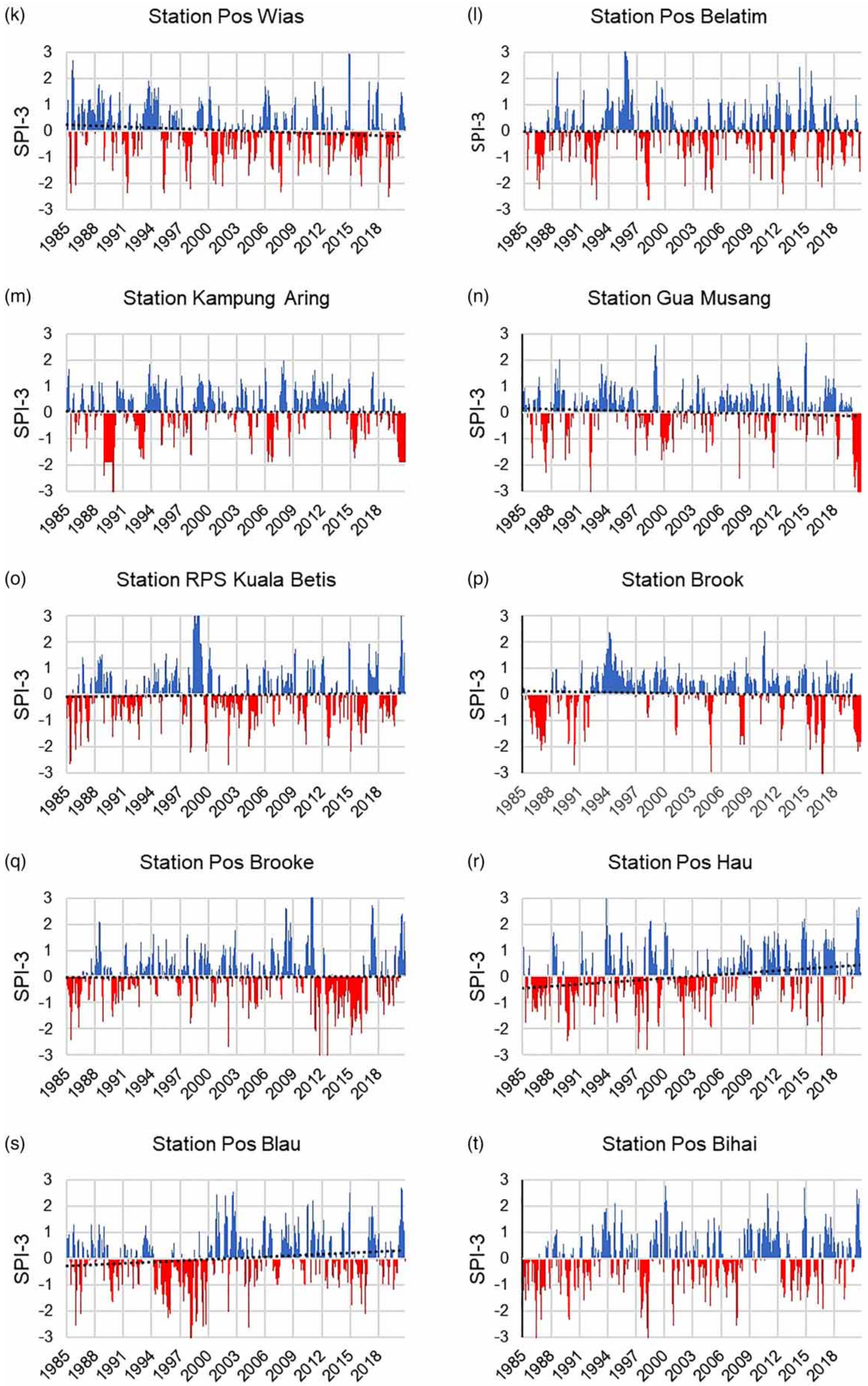

Figure 3 | Continued spatial temporal SPI-3 in (k) Pos Wias, (l) Pos Belatim, (m) Kampung Aring, (n) Gua Musang, (o) RPS Kuala Betis, (p) Brook, (q) Pos Brooke, (r) Pos Hau, (s) Pos Blau, and (t) Pos Bihai.

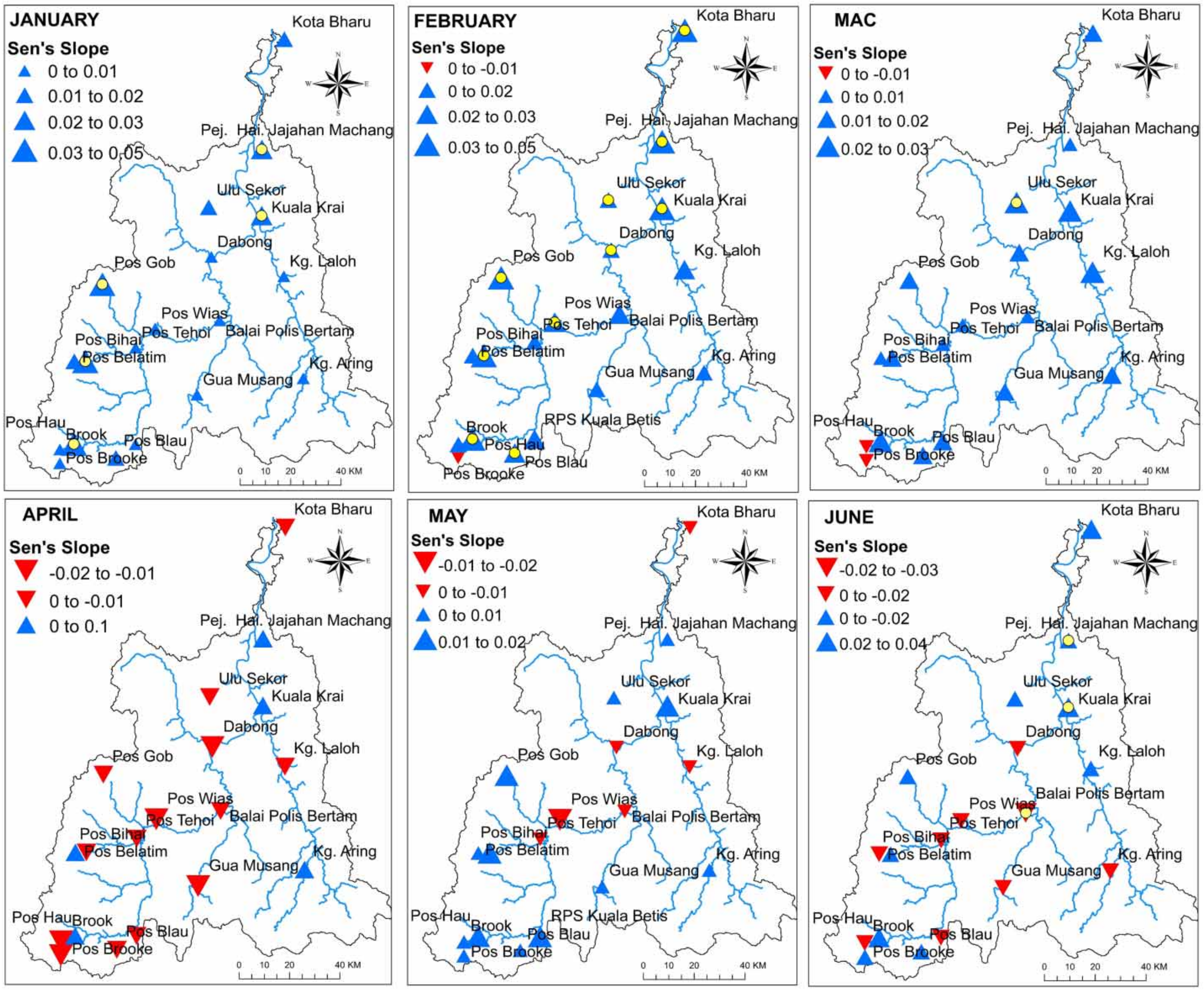

Figure 4 | Sen's slope of SPI for January, February, March, April, May, and June (positive = increase, negative = fall, dotted = significant).

time series of each station was shown, it was discovered that all 19 stations experienced moderate, severe, and extreme dry events throughout the research period. More than 25 moderately dry months were encountered by almost 58% of the stations in the KRB. Meanwhile, from 1985 to 2020, 89% of the stations suffered more than 15 severe drought months, and 10 stations have seen more than 10 extremely dry months. In addition, it clearly shows that Pos Blau, Gua Musang, Pos Wias, Ulu Sekor, and Belatim have the highest number of extremely dry months as compared to other stations. However, Pej Hai Jajahan Machang and Kampung Aring experienced the lowest number of extremely dry months, with only 1 and 3 months, respectively.

Other than that, Balai Polis Bertam and Kampung Aring had taken a place in the leading the occurrences of severely dry months, respectively. In contrast, moderately dry months have happened in most of the stations. Still, Kuala Krai had the highest number of moderately dry months compared to the extremely dry months. Besides that, Pej Jajahan Machang experienced a major variance among these three types of droughts. For example, the station had a higher number in moderately dry months, while only experienced one extreme dry month and four severely dry months. On the other hand, Balai Polis Bertam also faced a major difference between moderate, severe, and extreme drought months, e.g., in severe drought, the station experienced the more severely dry months than extremely and moderately dry months.

Figure 7 shows the spatial distribution of the maximum peak, maximum duration, maximum severity, and maximum intensity of droughts over KRB. According to Figure 7(d), higher drought intensities can be found in Kota Bharu, Dabong,

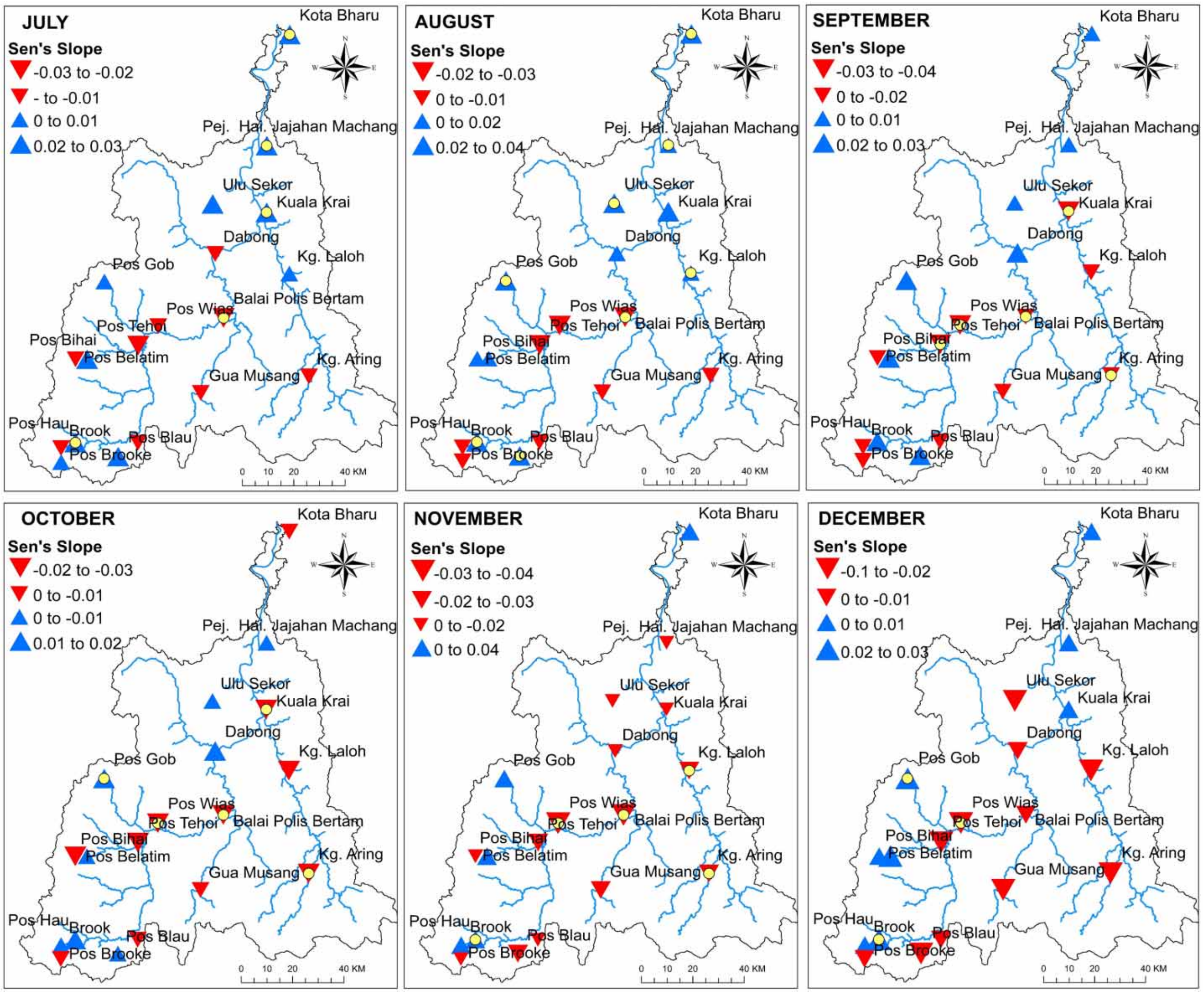

Figure 5 | Sen's slope of SPI for July, August, September, October, November, and December (positive = increase, negative = fall, dotted = significant).

Kampung Laloh, Balai Polis Bertam, Gua Musang, Kampung Aring, and Pos Blau that located in southern, southeastern, and northern parts of the basin. The highest peak level of drought was at the Brook station with −4.28 from October 2016 to March 2017. Furthermore, the second highest peak level of drought was at the Balai Polis Bertam station occurred from March to September 2008, with a SPI-3 value of −3.92. In general, most of the stations in the KRB's middle and upper reaches were affected by more intense droughts than those in the lower reaches.

3.4. Analysis of response rate

Figure 8 illustrates the annual, seasonal, and monthly response rates of streamflow (SSI) to precipitation (SPI) from 1985 to 2020. Higher response rates between SPI-3 and SSI-3 can be found in DJF and MAM than JJA and SON, which is 64% for both seasons. In fact, the monthly result shows that starting from January until April, the percentage of the response of SSI to SPI was the greater influence. The result started declining from May until August and inconsistently rated from October until December. At the same time, JJA and SON seasons have a lower rating which is only 50 and 53%, respectively. Meanwhile, for the annual result, only an average range in the relationship between meteorological drought and hydrological drought resulted from only 58% of the response. A possible explanation for the moderate response rate is that groundwater is the major freshwater source in the KRB, where about 75% of the total population in Kelantan are relied on groundwater. Annual precipitation might be contributed to the recharge of groundwater in the

Table 2 | The KRB experienced hydrological drought conditions in SSI-3

Start	End	Duration	Peak	Severity	Intensity
Jan 1990	Sept 1990	8	– 1.64	– 5.34	– 0.67
May 1991	Dec 1991	7	– 2.1	– 6.6	– 0.94
Oct 1992	Nov 1992	1	– 1.02	– 1.02	– 1.02
Nov 1995	March 1996	4	– 1.38	– 4.08	– 1.02
Jan 1997	Jul 1998	18	– 1.62	– 11.36	– 0.63
Jan 2003	Oct 2003	9	– 1.2	– 5.08	– 0.56
Jul 2004	Oct 2004	3	– 1.22	– 3.16	– 1.05
March 2005	Feb 2006	11	– 2.13	– 11.09	– 1.01
Dec 2006	March 2007	3	– 1.14	– 1.89	– 0.63
May 2010	March 2011	10	– 3.02	– 12.76	– 1.28
June 2011	Jan 2012	7	– 2.1	– 6.56	– 0.94
Aug 2012	Feb 2013	6	– 1.65	– 7.32	– 1.22
Nov 2013	Dec 2014	13	– 1.74	– 13.87	– 1.07

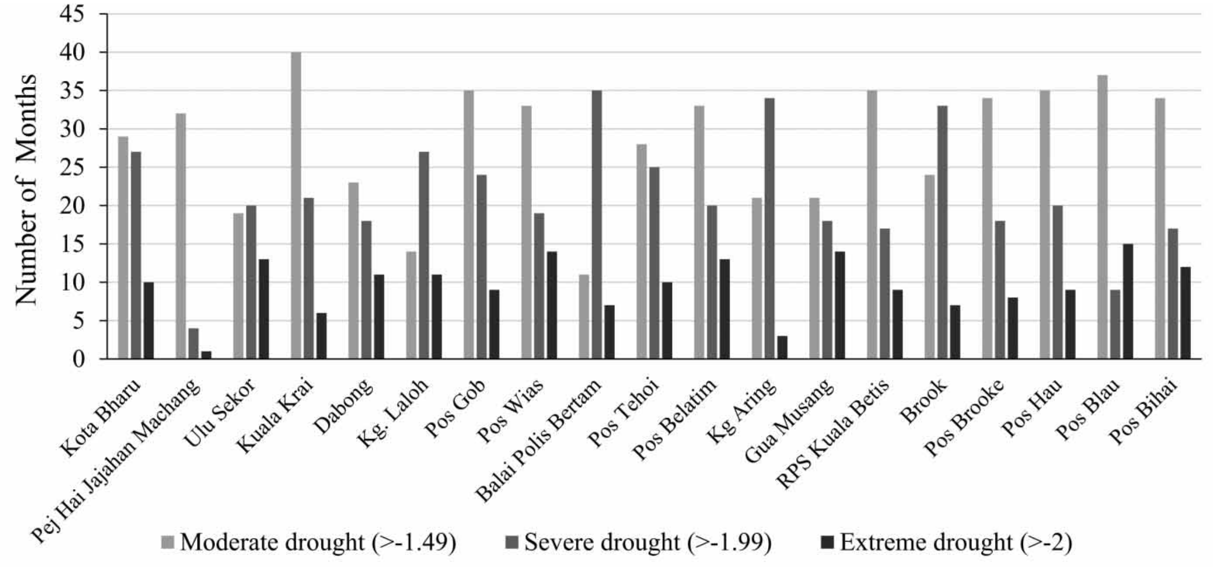

Figure 6 | Drought conditions in all stations in KRB.

basin. Since groundwater may take months to years to reach the river; thus, the response rate of SSI to SPI in the KRB is moderate.

3.5. Large-scale atmospheric circulation

For further investigation, Spearman correlation analysis was utilized to measure the association between the annual series of monsoon indexes. The correlation values of the relationship between drought indices (SPI-3 and SSI-3) and large-scale atmospheric circulation (ENSO, MJO, and IOD) from 1985 to 2019 are listed in Table 3. In general, ENSO had a bigger impact on the meteorological and hydrological dryness in the KRB than IOD and MJO. ENSO showed a significant connection with SPI-3 in March (0.62), April (0.67), May (0.34), and June (0.36) at a 95% confidence level, showing ENSO encountered a favourable effect in the emergence of dryness in KRB during the dry season. Similarly, the response rate results show that DJF and MAM seasonal have the highest relationship. In fact, Kelantan receives low precipitation amount from February

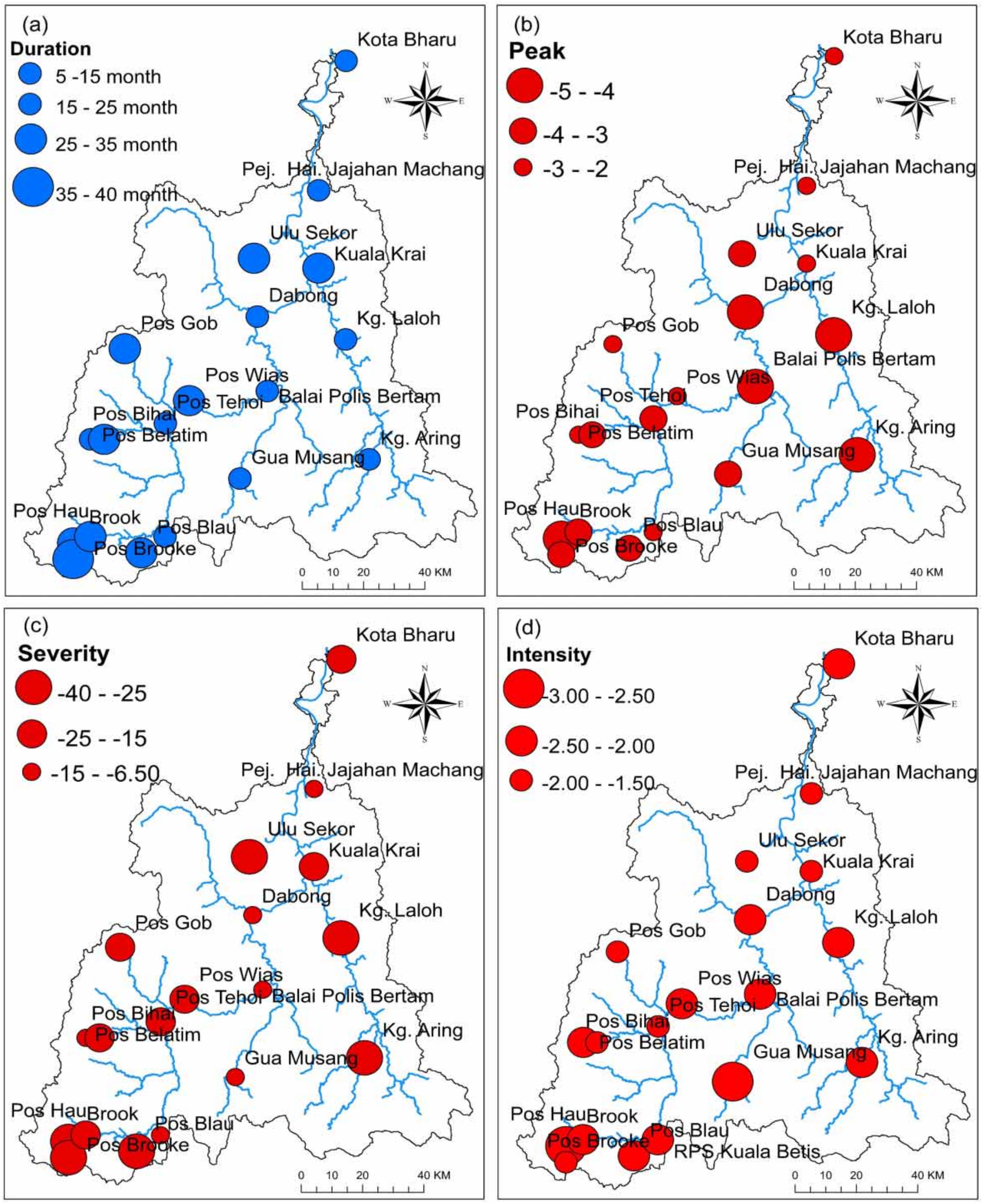

Figure 7 | Characteristics of the drought (a) maximum duration, (b) maximum peak, (c) maximum severity, and (d) maximum intensity in the KRB from 1985 to 2020.

to April (Tan *et al.* 2017), where the impact on water supply could take part in the following months. Hence, the agricultural sector in this region was affected badly during the strong big El Niño years such as 1997–1998 and 2015–2016.

During the SWM phase, the eastern regions might be the driest and vice versa for the northwestern area (Suhaila *et al.* 2010). This is because the influence of the SWM is less than that of the NEM since Sumatra Island conceals by Peninsular Malaysia. Therefore, ENSO and SSI-3 demonstrated a significant correlation in February (0.32) and March (0.39), April (–0.55), and May (–0.43), which showed related to the dryness of that month. ENSO occurrences usually last between 9 and 12 months, whereas droughts in Malaysia often range between 2 and 6 months (Luhaim *et al.* 2021). Shaaban *et al.* (2011) stated that for the future intervals 2025–2034 and 2041–2050, the mean and maximum monthly streamflow at the same station will increase by a stated amount, but mostly during the months with high precipitation. By contrast, during 2015–2044, the monthly streamflow is anticipated to decline from June to October by a range of 1.1–9.1%, showing a drier condition might happen in the future.

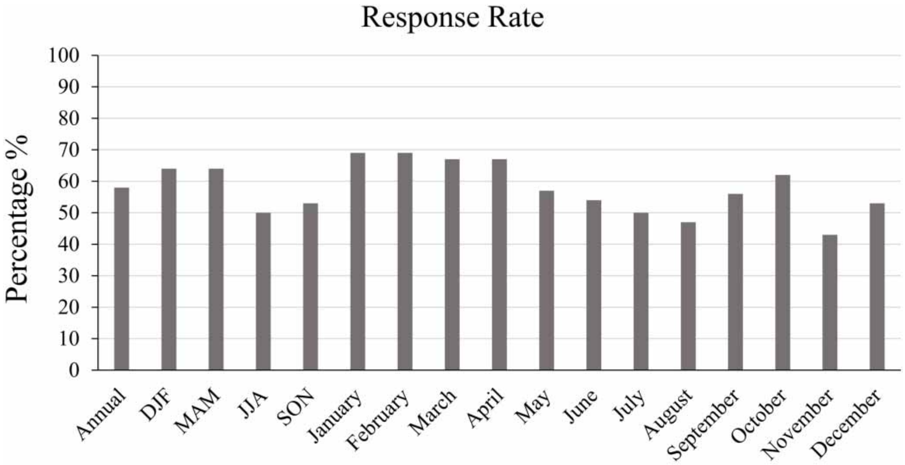

Figure 8 | Response rate of SSI to SPI in the Kelantan River Basin from 1985 to 2020.

Table 3 | Association of ENSO, MJO, and IOD with dry episodes

	SPI-3			SSI-3		
Month	**ENSO**	**MJO**	**IOD**	**ENSO**	**MJO**	**IOD**
January	– 0.10	– 0.27	0.01	– 0.15	0.13	0.11
February	– 0.20	0.07	0.14	– **0.32**	0.10	– 0.07
March	– **0.62**	– 0.05	**0.46**	– **0.39**	0.02	**0.44**
April	– **0.67**	0.41	0.22	– **0.55**	0.11	**0.40**
May	– **0.34**	– 0.28	0.20	– **0.43**	– **0.40**	0.16
June	– **0.36**	0.17	0.05	– 0.26	– 0.16	0.20
July	– 0.12	0.26	– 0.15	– 0.30	0.00	0.27
August	– 0.10	– **0.35**	– 0.04	0.19	– 0.19	0.52
September	– 0.08	– 0.15	– 0.11	0.22	– 0.09	0.26
October	– 0.08	– 0.06	– 0.17	0.13	– 0.13	0.13
November	0.02	– 0.10	0.00	– 0.35	0.13	0.00
December	– 0.05	– 0.17	– 0.20	– 0.28	0.04	– 0.03

At a confidence level of 95%, the MJO was linked with SPI-3 only in August (0.35), indicating that the phenomenon influences the meteorological drought creation during the middle phase of the SWM. With the correlation values of 0.46, 0.44, and 0.40, respectively, the IOD was connected to SPI-3 in March and SSI-3 in March and April at a 95% confidence level. This shows the dryness of the KRB in March influenced by both ENSO and IOD, which is consistent with the findings reported by Luhaim *et al.* (2021) in the Muda River Basin that located besides the KRB. Meanwhile, Tan *et al.* (2017) found that during 1985–2014, both consecutive wet days and consecutive dry days have decreased by 0.15 and 0.96 days/decade, respectively. In addition, the maximum 1-day and 5-day precipitation amount were also decreased from May to July and September to November. Similarly, they concluded that ENSO plays a crucial role in the climate system of Malaysia, and could bring prolonged drought events in the KRB.

4. DISCUSSION

Over the previous several decades, the KRB has experienced numerous severe dry events. For instance, the Kota Bharu and Kuala Krai stations experienced severe droughts most often. However, as Kelantan is identified as the Peninsular state with the highest flood risk, so lesser attention is given to the impact of dry spells in this region. Moreover, in this study, a similar result within Fung *et al.* (2020) experiment reported that in the East Coast and Northern areas, where precipitation and temperature have risen over the years. This clearly shows that KRB is still in a mild drought, and as a result, in SPI also, most of the stations are only in mild dry and more sensitive to brief periods of insufficient precipitation (dry spells). This is because Peninsular Malaysia has a tropical climate zone and is situated close to the equator, which may be the reason of the short-term dry events. The high temperatures and excessive precipitation are also a contributing factor. According to Adnan & Atkinson (2011), there could be seasonal fluctuation in the intensity of monsoon season rainfall in the Kelantan catchment. This study has proven that the seasonal fluctuation, particularly from February to May, could affect the water supply in the basin.

The agricultural sector in the KRB, particularly paddy, affected the most during the El Niño years due to insufficient water supply for irrigation. This has been further proven by the hydrological drought conditions as measured by SSI-3 using the observed streamflow data. These extreme weathers have significantly impacted the paddy farmers' income and livelihoods (Firdaus *et al.* 2020), affecting the national food security as rice is the staple food of Asia. To tackle the issue, more water treatment plants can be constructed in the regions that affected by less intense drought, i.e., along the Lebir River in the south-eastern part and in the middle part of the basin such as Kula Krai and Tanah Merah. In addition, construction of new storage reservoirs, either elevated or ground reservoirs, particularly in the lower part of the basin is required, since most of the paddy fields are located in this region.

5. CONCLUSION

This study focuses on the quantification of hydro-meteorological droughts, the response rate analysis of SSI to SPI and the impact of the large-scale atmospheric circulation on the dry periods in the Kelantan River Basin (KRB) between 1985 and 2020. The main findings of the study are summarized as follows:

- KRB had experienced extremely dry events vary across the stations, but most of the stations were affected in 1986, 1987, 1989, 1990, 1992, 1997–1998, 2015–2016, and 2020. From January to March, there was a noticeable increasing trend in SPI-3, and some stations like Pej Hai Jajahan Machang, Ulu Sekor, Kuala Krai, and Kota Bharu showed a significant change at 95% confidence level. Furthermore, from April to December, both increasing and decreasing trends were seen. Most of the stations in the upper and middle parts of the basin, including Balai Polis Bertam, Pos WIas, Kuala Krai, and Kampung Aring, had a significant decreasing trend of SPI-3, especially from September to November, threatening the water supply of the KRB.
- The majority of the stations in the middle and upper parts of the KRB experienced more intense droughts than those in the lower part. The response rates of SSI-3 to SPI-3 were higher in December–February and March–May than in June–August and September–November, ranging from 50 to 64%. The moderate response rate may be contributed by the extraction of groundwater as the main freshwater supply in the KRB, where part of the rainwater has recharged the shallow groundwater.
- In general, ENSO played a more crucial role than IOD and MJO on the hydro-meteorological droughts formation in the KRB, especially from February to June. At a 95% confidence level, IOD was also correlated with the SPI-3 in March and SSI-3 in March and April. Hence, more attention should be paid by the local authorities and water supply company during the El Nino years.
- In the KRB, the paddy field was most negatively impacted during the dry spells due to the low water supplies for irrigation. Hence, more water treatment plants should be constructed in the areas that are less impacted by intense drought, i.e., in the middle part of the basin and along the Sungai Lebir (Figure 7(d)). In addition, since most of the paddy fields are in the lower part of the basin, building new storage reservoirs are essential to reduce the impact of drought on the agricultural sector.

Future studies should look at ways to enhance SPI drought monitoring, such as application of satellite products, development of a new satellite-based drought index and hydrological modelling (Li & Zhang 2008; Liu *et al.* 2020). In addition, recent studies have shown an interest in forecasting evaporation and soil moisture (Zhang *et al.* 2019; Zhao *et al.* 2022), which might be included in drought indices for even more accurate drought monitoring in Kelantan.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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