https://doi.org/10.5194/nhess-2021-249
Preprint. Discussion started: 24 August 2021

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Hydrological Drought across Peninsular Malaysia: Implication of Drought Index

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Abstract. Drought is considered a damaging natural disaster causing significant economic, social, and environmental impacts. The challenge of drought is to determine the characteristics of drought, its frequency, duration, and severity, which are critical for controlling the effects of drought and mitigation strategies. The objective of this study is to identify the drought characteristics and temporal assessment of drought using Streamflow Drought Index (SDI) and theory of runs (ToR). It also highlights the need and methods for selecting the most appropriate time scale for drought assessment, especially in tropical countries. Malaysia experiences tropical weather and monsoon seasons throughout the year with typically humid temperatures ranging from 20 °C to 30 °C. The different spatial patterns of SDI for three-, six-, nine-, and 12-month were adopted throughout Peninsular Malaysia, using 40 years of daily streamflow data from 42 gauging stations. The area under drought stress at different time scales during the study period is stable and accounts for about 24% of the total area. The years 1997-1999, 2002 and 2016-2018 mark the most critical drought years, when more than 48% of the total area of the basin was affected by hydrological drought. Spatial evaluation of drought characteristics shows that short-term droughts are common in most regions, with relatively high severity and frequency in the northeast and southeast of Peninsular Malaysia, where the maximum frequency reached 35.7% and 42.8%, respectively. The shortest scale (3-month) recorded more mild and moderate events. Since the most extensive time scale (12-month) includes more dry and wet periods, its high value may lead to misleading information for the early warning system. Using the results of this multi-scale SDI analysis, hydrologists, water managers, and policy makers can better understand the time scale selected for hydrological drought analysis. Short-term drought conditions show high interannual variability with the predominant pattern. It was shown that among the SDI time scales, the SDI for 3-month is the most suitable for effectively tracking hydrological droughts in tropical regions.

1 Introduction

Drought can be considered a widespread phenomenon due to climatic changes that may be exacerbated by anthropogenic influences. In recent years, the focus has been on the global drought scenario caused by increased water demand and climate

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change. Droughts in the region differ from other natural disasters in their slow onset and long duration, which can last up to months or years (Yang et al., 2017). All continents of the world are affected by the consequences of droughts. Droughts are expected to become more frequent, intense, and prolonged over time in different places around the world (Leta et al., 2018). As these characteristics increase, the global proportion of extreme droughts is expected to increase from 1% to 30% in the 21st century. This means that the number of severe drought events and their duration are expected to increase. (Siderius et al., 2018).

Droughts can have significant impacts on a wide range of socio-economic activities, including agriculture, water supply, wildlife, aquaculture, tourism and transport, and hydropower generation. Due to the frequency and duration of droughts, it is necessary to consider the development of a comprehensive drought monitoring system capable of providing early notification of the onset and termination of droughts. Severity, duration, frequency and spatial extent of droughts are the most valuable indicators for assessing the spatio-temporal characteristics of droughts in a given region, which is considered one of the most important aspects in mitigating drought disasters (Hasan et al., 2019). This information can be used to minimize the economic, social, and environmental impacts of droughts.

Drought is a natural feature of climate that is usually associated with dry and warm weather over an extended period of time, resulting in less water available at the land surface than average. The development of a drought is a slow process, and it is often difficult to detect it early. The difficulty lies in determining when a drought begins and when it ends. Drought is a complex phenomenon that can be divided into meteorological, hydrological, agricultural and socioeconomic phenomena (Barella-Ortiz and Quintana-Seguí, 2019). In brief, a meteorological drought occurs due to the absence or lack of precipitation compared to the average precipitation over a long period of time; an agricultural drought occurs due to the unavailability of water at different stages of crop development to sustain production; a hydrological drought occurs when water supplies in storage systems such as aquifers, reservoirs and rivers fall below the level required for their operational and environmental use; and a socio-economic drought occurs when water scarcity affects the supply of an economic good or service or has an impact on the economy in general (Choi et al., 2018; Li et al., 2020; Wang et al., 2016). Among these classifications, hydrological drought assessment is more important for water resources management.

Hydrologic drought refers to events that result in inadequate water supply from rivers, reservoirs, and aquifers under a given water resource management system (Barker et al., 2016), including streamflow drought and groundwater drought. Although precipitation deficiency is the primary cause of hydrological drought, it takes longer for the deficiency to become apparent in streamflow or groundwater levels. Hydrological drought is best characterized by hydrological parameters such as streamflow. Understanding this parameter is necessary to develop measures to mitigate the effects of drought. The simplest method for monitoring drought conditions is to use a drought index. The index is a quantitative method of determining the onset and end of drought conditions in order to minimize the severity of the drought (Ward, 2013). Drought indices allow for

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the identification of drought characteristics such as timing, duration, intensity, and spatial distribution to assist decision makers in managing drought mitigation strategies.

Several hydrological drought indices have been developed over the years to assess hydrological drought. The indices developed under the hydrological approach rely heavily on streamflow, runoff, reservoir, and groundwater level data. This approach aims to quantify the lagged effects of drought in the hydrological system to capture a lack of water resources over a period of time. However, several indices use only streamflow data, namely the Regional Streamflow Deficiency Index (RSDI), the Standardized Streamflow Index (SSFI), the Streamflow Drought Index (SDI), the Base Flow Index (BFI), and the Regional Drought Area Index (RDAI) (Niemeyer, 2008).

In recent years, several researchers have applied the Streamflow Drought Index (SDI) methodology to study streamflow drought (Akbari et al., 2015; Barker et al., 2016; Hong et al., 2015; Tigkas et al., 2012). SDI is estimated using continuous streamflow values. This index has been used to assess hydrological droughts in several countries, including the United States, India, Iraq, and Iran. Tabari et al. (2013) used SDI to characterise hydrological drought occurrences in West Azerbaijan, which is located in northwestern Iran using streamflow data of over 34 years. Four overlapping periods were used within each hydrological year. They concluded that almost all sites experienced significant drought during the last 12 years. Manikandan and Tamilmani (2015) conducted a study using SDI and theory of runs (ToR) assessments in Aliyar sub-basin, India to determine hydrological drought characteristics, namely duration, severity, intensity, and frequency of drought. These studies have shown that SDI is capable of determining hydrological drought at spatial and temporal scales. However, there have been few quantitative analyses of the relationship between sample size and different time scales.

Recently, climate change has led to severe consequences around the world such as exceptional flooding, extreme drought, snowfall, heat waves and natural disasters. For example, the occurrence of El Nino is due to the increase in surface temperature of sea water and has a cumulative effect on global warming. Records show that the El Nino event occurred in 1997-1998 and caused severe damage worldwide (Frappart et al., 2018). During an El Nino event, temperatures in Malaysia increased that lead to forest fires throughout the country, resulting in severe haze conditions in 1997-1998. At that time, rainfall decreased, leading to more extreme dry seasons in Malaysia (Bong and Richard, 2019; Tan et al., 2019). Malaysia experiences tropical weather throughout the year, with typically humid temperatures ranging from 20 °C to 30 °C throughout the year due to its proximity to the sea. Nevertheless, the weather is rarely excessively hot. The weather and climate in Malaysia is also affedted by monsoon seasons, known as southwest monsoon which occurs from May to September, while northeast monsoon usually resulted in rainy season lasts from November to March. In 2016, El Nino occurred again and caused a hydrological drought in Malaysia. This resulted in less than half of the water reserves being stored in seven dams, namely Timah Tasoh (Perlis), Bukit Kwong (Kelantan), Beris Padang Saga, Muda (Kedah), Bukit Merak (Perak) and Labong (Johor)(Tan et al., 2019). Hydrological drought leads to a water crisis and consequently a decline in crop production.

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Given the severity of historical drought in Malaysia, particularly on water supply, it is necessary to have an effective hydrological analysis and management. Therefore, in this study, SDI and ToR were used for a long-term analysis of the distribution of hydrological drought events using streamflow data collected from 42 gauging stations throughout Peninsular Malaysia.

Since drought has massive impacts, drought indices should be used as an indicator to study the characteristics of a drought event. Therefore, drought indices are important for making strategic water management decisions during a drought. Previous researchers, e.g. Khan et al. (2017); Yusof et al. (2014); Zin et al. (2014), have studied meteorological and agricultural droughts in Peninsular Malaysia. However, few studies have been conducted on hydrological drought based on SDI in Peninsular Malaysia. There is only one study related to the application of SDI, namely the study by Khan et al. (2017), but the study is a case study in the state of Selangor (which covers only 6% of the area of Peninsular Malaysia). In contrast, the present an extensive work on SDI, which focused on the spatial and temporal distribution of hydrological drought throughout Peninsular Malaysia.

Appropriate water resources planning, and management must be preceded by a comprehensive drought assessment, which requires a thorough understanding of past drought episodes as well as the effects of drought at a particular site. In developing models to study drought events and their impacts, it is important to thoroughly understand the various concepts of drought. Drought assessment requires the selection of an appropriate time scale. The choice of an appropriate time scale is therefore crucial in developing a drought mitigation strategy (Pathak et al., 2016; Zamani et al., 2015). Therefore, this study was conducted to determine the method for determining the best time scale for identifying hydrological drought throughout Peninsular Malaysia. To further investigate the statistical properties of the observed samples of hydrological variables, this study examined the relationship between a limited sample size and multiple time scales. In addition, the different time scales of SDI series were used to analyse the transition frequency of SDI values at different time durations.

Streamflow is the most important part of the hydrological cycle. Analysis of historical drought periods provides information for effective drought monitoring in the future (Hasan et al., 2021). Researchers have used various methods to characterise drought periods. One technique widely used in the study of drought is the use of drought indices. The Streamflow Drought Index (SDI) is a practical and straightforward index for assessing hydrological drought. Because there is limited research on hydrological drought monitoring using the SDI in Malaysia, this study focused on hydrological drought assessment using the SDI for historical streamflow data. To our knowledge, this is the first comprehensive study to examine the different time scales of observed streamflow at 42 stations in Peninsular Malaysia.

The aim of this study is to investigate hydrological drought at different time scales (three-, six-, nine- and 12-month) for Peninsular Malaysia from 1978 to 2018 (40 years) with the following objectives: (i) identify and characterise hydrological

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drought using Streamflow Drought Index (SDI) and ToR; and (ii) determine the temporal and spatial patterns of hydrological drought based on short- and long-term duration for each 10-year interval. This study also highlights the need and methods for selecting the most appropriate time scale for drought assessment, especially in tropical countries. The results of this study can be used to assess water resources at the regional level and to prepare drought management planning. Planning authorities need to identify the temporal and spatial patterns of identified droughts, prepare a drought forecast, and publicly report the results to enable better planning for mitigation and preparation for droughts.

2 Methodology

Hydrological droughts at Peninsular Malaysia were determined using the SDI based on 40 years of streamflow data. These data were then analysed in four major steps. The first step was to analyse the SDI using monthly streamflow data. The second step was to evaluate the frequency of the SDI for each classification. Then, the hydrological drought characteristics determined for each station were further analysed using the theory of runs (ToR). Finally, the Inverse Distance Weighting (IDW) method was applied to perform the temporal and spatial analysis of hydrological drought characteristics through Peninsular Malaysia.

2.1 Study area

Peninsular Malaysia lies between 1° and 6° north latitude and between 100° and 103° east longitude. Peninsular Malaysia is a tropical country with two distinct rainy seasons, southwest and northeast Monsoons (Mamun et al., 2010). The southwest monsoon, often referred to as the summer monsoon, lasts from May to September, while northeast Monsoon lasts from November to March. April and October are known as inter-monsoon months. This annual monsoon results in rainy and dry seasons in Malaysia (Muhammad et al., 2016; Yusof et al., 2014). Southwest Monsoon, which originates from the deserts of Australia, leads to a dry monsoon season in northern of Peninsular Malaysia with lower rainfall due to blockage by the high mountain ranges in Sumatra. On the other hand, northeast Monsoon, which originates from China, tends to bring more rainfall to Malaysia due to its currents along North Pacific (Amin et al., 2017; Syafrina et al., 2015).

Peninsular Malaysia consists of 12 states, namely Johor, Melaka, Negeri Sembilan, Wilayah Persekutuan, Selangor, Pahang, Perak, Kelantan, Terengganu, Pulau Pinang, Kedah and Perlis. There are 42 discharge stations in this study area with 40 years of continuous historical streamflow data as shown in Figure 1.

Figure 1: The location of streamflow stations in Peninsular Malaysia.

For this study, the monthly streamflow data was collected from the Department of Irrigation and Drainage (DID), Malaysia from 1978 to 2018. As mentioned earlier, there are 42 well-functioning streamflow stations for Peninsular Malaysia, and the details of each station are given in Table 1. About 17 of the 42 stations have less than 40 years of streamflow data because their installation date is less than 40 years ago.

Table 1 Information on Streamflow Stations in Peninsular Malaysia

2.2 Streamflow Drought Index (SDI)

The Streamflow Drought Index (SDI) proposed by Nalbantis and Tsakiris (2009) has been used to assess the extent of hydrological drought in Peninsular Malaysia at different time scales. Streamflow data is the only crucial variable in the construction of the SDI. The main advantage of the SDI is that it requires less data than other indices, such as the Palmer Hydrological Drought Index, which requires streamflow and precipitation data. The reason for choosing the SDI is the availability of streamflow data.

The SDI indicates droughts of different durations within a region at different time intervals and thus has the advantage of monitoring hydrological drought and water supply in the short, medium, and long term. For example, the three-month drought index (SDI-3) reflects the seasonal water situation and provides important information for agricultural irrigation (Akbari et al., 2015). The six-month drought index (SDI-6) can represent drought conditions over a six-month period (Wambua, 2019). The 12-month drought index (SDI-12) is ideal for assessing the impact of climate change on regional water supply (Sardou and Bahremand, 2014; Tabari et al., 2013). The time series of monthly streamflow volumes ($Q_{i,j}$) are continuously accumulated based on their duration (k) within the hydrological year. The cumulative streamflow volumes can be calculated according to Eq. (1):

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j} \ , \tag{1}$$

where $Q_{i,j}$ denotes the monthly streamflow volumes, i the hydrological year, j the month of that year, k the period length, and $V_{i,k}$ the cumulative streamflow volume for an i-th hydrological year with a period length of k. i = 1, 2, ..., 40 (hydrological year); j = 1, 2, ..., 12 (where j = 1 for January and j = 12 for December); k = 1, 2, 3, 4 (k = 1 for January to March, k = 2 for January to June, k = 3 for January to September and k = 4 for January to December). Then the long-term mean ($\overline{V}_k$) and standard deviation (s_k) of the cumulative streamflow volume ($V_{i,k}$) are calculated to define the SDI for the kth reference period within the i-th hydrological year as follows in Eq. (2):

$$SDI_{i,k} = \frac{V_{i,k} - \overline{V}_k}{s_k} \ , \tag{2}$$

where k = 1, 2, 3, 4; and i = 1, 2, 3, ..., N. The hydrological drought categories are determined based on the calculated SDI. SDI values have been classified into categories ranging from extremely wet to extremely drought (Nalbantis and Tsakiris, 2009). Wet conditions are defined as values greater than 0, while drought conditions are defined as values less than 0. Table 2 contains descriptions of the Streamflow Drought Index (SDI) values.

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Table 2 Hydrological Drought Classification by SDI

In this study, the ongoing three-, six-, nine- and 12-month total streamflow series were used to derive the SDI series. In this way, minor drought or dependent droughts can be accounted for. The 12-month time scale simplifies the comparison between the long-term variation of the dry climate and the corresponding hydrological variation.

2.3 Identification of drought events

When defining drought characteristics, it is difficult to determine the beginning and end of a drought event. However, the drought index can be used to monitor drought and analyse drought characteristics. After calculating the drought index based on the streamflow data series, it is necessary to apply specific criteria to detect drought events. In this study, the ToR originally proposed by Yevjevich (1967) was used to determine the hydrological drought characteristics (Razmkhah, 2017). Following Nalbantis and Tsakiris (2009), the successive sequence of months with SDI values (X_t) below the threshold (X_{-1}) is defined as a hydrological drought event (Figure 2).

Figure 2: Determination of hydrological drought characteristics using the theory of runs.

A drought event can be defined if the index is smaller than -1.0 in at least one period, as shown in Table 2. Otherwise, it is neglected as it is only a minor drought event (Hong et al., 2015). The drought onset period is the month when SDI values fall below -1.0, indicating the beginning of a drought episode. The drought duration is the period between the occurrence of the drought and the time of its end. The cumulative drought index defines the severity of the drought during a drought event. The onset of the drought was determined at the beginning of the period when the SDI was negative for an extended period. The end of the drought was expected for the first month in which the SDI became positive.

Usually, the frequency of each SDI category is estimated using the following Eq. (3):

$$F_{m,k} = \frac{n_{m,k}}{N}, \tag{3}$$

where $F_{m,k}$ is the frequency of each SDI classification m in the reference period k (with k = 1, 2, 3, 4); N is the total number of recording periods (years); and $n_{m,k}$ is the number of drought events for each m within the k reference periods. However, in this study, the frequency of hydrological drought was expressed as a percentage terms as suggested by Hong et al. (2015) to understand and interpret the spatio-temporal expression of hydrological drought in Peninsular Malaysia. The percentage of hydrological drought frequency at different time scales can be derived from the following Eq. (4):

$$\text{Hydrological drought frequency (\%)} = \frac{\text{Total number of months with SDI} \leq -1}{\text{Total number of months}} \times 100\,\%, \tag{4}$$

Where the total number of months with SDI ≤ -1 is based on the respective drought category and the total number of months on the respective time scale, which is 10 years (120 months).

2.4 Hydrological drought zoning

By minimising the distance effect of its sample location, Inverse Distance Weighting (IDW) evaluates the neighbourhoods of the selected locations where the variable is displayed (Jahangir and Yarahmadi, 2020). As shown in Eq. (5), the Inverse Distance Weighting (IDW) approach was used in this study to interpolate and analyse the spatial variations of hydrological drought characteristics throughout Peninsular Malaysia.

$$\hat{Z} = \frac{\sum_{i=1}^{n} \frac{z_i}{d_i^k}}{\sum_{i=1}^{n} \frac{1}{d_i^k}}, \quad (5)$$

Where $\hat{Z}$ is the estimated value at an unsampled point, n is the number of control points used for the estimation, k is the power by which the distance is increased, d is the distance between each control point and an unsampled point.

The hydrological drought characteristics throughout Peninsular Malaysia were spatially interpolated to illustrate the spatial variability of the SDI. To assess the accuracy and correlation of the interpolated values with the original recorded data in the region, the IDW interpolation method was cross-validated with standard statistical tests, including root mean square error (RMSE) and correlation coefficient (R) (Aghelpour and Varshavian, 2020). For zoning by drought, the SDI index was used, which was calculated over 12-month. Then the station names, Universal Transverse Mercator (UTM) coordinates and SDI data were entered into the software Arc Map software. Then the IDW approach was used for drought zoning.

3 Result and discussion

3.1 SDI analysis

The analytical results are compared with the standard drought criterion in Table 2 to assess hydrological drought. Figure 3 shows the SDI-12 over 40 years. Positive numbers indicate wet conditions, while negative values indicate drought.

Figure 3: Colour-coded SDI-12 table for 40-year time series

Figure 3 shows that all streamflow stations have experienced at least one severe drought in 40 years (-2.0 SDI -1.5). After 2010, about 22 stations experienced severe and extreme droughts for SDI-12 (January-December). The most severe drought was recorded at station S28 at Perak River from 2012 to 2018. In addition, all extreme drought events occurred in the last

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nine years from 2012. In general, the driest years were 1996 - 1998 with four stations in Selangor (S14, S17, S20 and S21) and one station in Pahang (S18), 2002 - 2003 with a total of five stations (three stations in Selangor - S11, S13, S20; one station in Perak - S25; and one station in Kedah - S33) and 2012 - 2018 with 15 stations. The 15 stations in Johor (S01, S02 and S06), Melaka (S05), Negeri Sembilan (S10 and S12), Selangor (S21), Wilayah Persekutuan (S15 and S16), Pahang (S18), Terengganu (S23 and S35), Perak (S27 and S28) and Perlis (S40). Some stations where extreme hydrological drought occurred repeatedly during the study period (40 years) are S21 (Selangor), S18 (Pahang) and S28 (Perak). In other words, the most severe hydrological drought occurred in the hydrological years 1996 - 1998, 2002 - 2003 and 2012 - 2018. The most severe hydrological drought occurred at station S21 along Bernam River in Selangor in 1997-1998 and 2014-2016. This findings is consistent with to the results reported by Shaaban and Low (2003), which concluded that Peninsular Malaysia was severely affected by the 1997/1998 El-Nino drought, especially in Selangor and central region, and the impact lasted until September 1998. Comparing the 1997/1998 El-Nino drought with the 2015/2016 El-Nino drought, Fung et al. (2020) found that high temperatures affected the dry months during these periods.

SDI results in the study region show that moderate and severe drought events follow each other for more than one year on average. For example, moderate drought occurred in 2012 and 2013. The following year, 2014 and 2015, severe drought conditions were observed. In the following years, 2015 to 2018, extreme drought conditions were recorded. The results from each station at Peninsular Malaysia were classified into drought categories, events, and frequency. Visual interpretations were then created for each region by plotting the characteristics on a spatial grid map to analyse spatial variation (Figures 4 to 6).

3.2 Spatial and temporal SDI analysis

Drought zonation was also assessed as most streamflow stations experienced prolonged drought periods with more than two consecutive drought episodes throughout the study period. Drought zonation in the study region was examined using IDW over periods of 3, 6, 9 and 12 months. Figure 4 shows the spatial and temporal zonation for SDI-3, SD -6, SDI-9, and SDI-12 for every interval of 10 years.

Figure 4: Spatial and temporal distribution of SDI-3, SD-6, SDI-9, and SDI-12 for 10-year intervals.

A three-month SDI represents short-term hydrological drought and provides seasonal streamflow estimates. The six- and nine-month SDIs reflect medium-term trends in streamflow and can be used to compare streamflow between seasons. A six-month SDI can also be associated with anomalous streamflow and reservoir situations. The SDI reflects long-term streamflow patterns in 12 months. Figure 4 shows that the 1980s to 1990s and the 2010s are the years when more than half of the total area of the catchment is affected by drought (SDI < -1). Drought severity was calculated at ten-year intervals in

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the 1980s, 1990s, 2000s and 2010s to determine changes in the region over time. Drought severity increased over time, rising from 1.05 to 10.50 (SDI-3), 1.45 to 23.80 (SDI-6), 3.32 to 25.12 (SDI-9) and 3.74 to 28.90 (SDI-12).

On the time scale of SDI-3, moderate hydrological drought was recorded in the 1980s with a major drought area of 28.57%, followed by severe hydrological drought with 4.76% area. In the 1990s, the catchment area of Peninsular Malaysia generally experienced severe hydrological drought with a moderate drought area of 44.64%. Moreover, the areas of hydrological drought in SDI-3 accounted for 42.86% of the total area. On the time scale of SDI-6, moderate hydrological drought decreased to 23.81% of the drought areas. Severe drought also declined from the 1980s to the 1990s to 2.38% of the total area. The pattern is the same as in SDI-9. In SDI-12, moderate hydrological drought accounts for the same percentage of drought areas at 42.86% of the total area. No severe or extreme hydrological drought was recorded in SDI-12 from 1980s to 1990s. No extreme hydrological drought in the 1990s.

There was no hydrological drought in the entire catchment of Peninsular Malaysia in the 2000s, except in the northern region. Moderate hydrological drought areas (SDI-3, SDI-6, SDI-9, and SDI-12) accounted for 33.33%, 35.71%, 33.33% and 26.19% of the total area respectively. The most significant drought years across the basin occurred in the last decade (the 2010s), with more than 75% of the entire basin affected by drought (Peninsular Malaysia), coinciding with the El Nino event. The worst year was 2016, when 85% of the entire catchment was affected by drought, followed by the drought years of 1997 and 1998, when 80% of the entire catchment was affected. For the different time scales, there are 2559 hydrological drought events for each drought category. For SDI-3, there are 505, 265 and 152 drought events for moderate, severe, and extreme drought, respectively. The total number of drought events for SDI-6 is 351 (moderate), 196 (severe) and 105 (extreme). On the 9-month time scale, there are 291 drought events (moderate), 171 drought events (severe) and 83 drought events (extreme). Finally, for SDI-12, there are about 231, 133 and 76 drought events for moderate, severe, and extreme drought respectively. The area under drought stress at different time scales during the study period is stable and accounts for about 24% of the total area as the time scale increases.

In the 1980s, the spatial distribution of hydrological drought based on SDI-3 to SDI-12 generally changed from southeast to northeast from Peninsular Malaysia. However, in the 1990s, the spatial distribution shows mainly the east and west coasts of Peninsular Malaysia. The spatial distribution of hydrological drought in the 2000s is mainly concentrated in the northwest of the northern region of Peninsular Malaysia. In the 2010s, the spatial distribution of hydrological drought was relatively complex. The spatial distribution pattern has changed compared to 2000. SDI-3 shows a north-eastern distribution; SDI-6 shows a specific south-eastern distribution; SDI-9 shows a scattered distribution in the northwest, and SDI-12 shows southwestern distribution areas.

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Moderate hydrological drought is tilted to the northeast and is most widespread on the west coast Peninsular Malaysia. The spatial distribution from the 1980s to the 2010s is mainly distributed in the southeast and northwest Peninsular Malaysia at a severe level. At the extreme level of hydrological drought, the spatial distribution of the 1990s is in the northwest and the 2010s in the southeast and northeast. Thus, the area of drought in the catchment of Peninsular Malaysia increases with increasing time scale. The spatial and temporal SDI analysis revealed that the SDI-3 and SDI-6 could be misleading in the regions that are normally dry for six months. The SDI-3 can be used to determine when the dry season begins and ends. However, a drought index for longer periods is essential. For example, a three-month drought may occur in the middle of a prolonged drought, but this would only be noticeable over longer periods such as 12 months.

3.3 Hydrological drought events

The drought indices simplify the complicated relationships between hydrometeorological parameters and allow the characteristics of drought propagation to be effectively identified. By combining the determined SDI and ToR, the drought events and important characteristic variables can be determined. As shown in Figure 2, a drought event is a series of events where the SDI value falls below a certain threshold, which in this case is set at -1. The total number of drought events with SDI ≤ -1 for all reference periods (SDI-3, SDI-6, SDI-9, SDI-12) is presented in Figure 5. Almost all stations show a surprising number of drought events. It was also found that in the first two reference periods (SDI-3 and SDI-6), each station experienced more drought events. The results show that almost every station has the same number of drought events. Based on the ToR and SDI, Peninsular Malaysia identified 391, 439, 408 and 392 drought events between 1978 and 2018 for SDI-3, SDI-6, SDI-9, and SDI-12 respectively.

Figure 5: Spatial and temporal distribution of number of hydrological drought events for 10-year intervals.

The hydrological drought of all historical drought events (1980s, 1990s, 2000s and 2010s) with different durations are shown in Figure 5. The analysis revealed that hydrological drought occurred mainly in the central and eastern coastal region of Peninsular Malaysia during the first decades of the study period. Due to the location of the study in a humid tropical climate, it is also assumed that groundwater recharge occurred during the early stages of the drought events. The shorter duration of the event can be explained by the results, which suggest that the main cause of the event was higher water demand during the dry period (Mussá et al., 2015).

In the 1980s, the spatial distribution (SDI-3 and SDI-6) of hydrological drought events on Peninsular Malaysia in the last 40 years showed a high number in the northeast and southwest. For SDI-9 and SDI-12, the spatial pattern shows the same trends, with the maximum number of hydrological droughts being 5 to 6 events in 10 years. In the 1990s, hydrological drought events decreased compared to the total number of events recorded in the 1980s. SDI-3 and SDI-6 show that the

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maximum number of drought events is 7 to 8, mainly in the northwest of Peninsular Malaysia. For SDI-9, the maximum number of drought events is 3 to 4 events for Peninsular Malaysia. SDI-12, on the other hand, shows that the maximum number of drought events is 5 to 6 in the northwest and southwest.

In the 2000s, the spatial distribution of drought events for SDI-3 and SDI-6 is mainly found in the northeast and southeast, with 7 to 10 maximum drought events. However, for SDI-9 and SDI-12, the spatial distribution is the same, but the number of drought events is slightly less than 5 to 6. The same patterns were found for SDI-6 and SDI-9. However, the maximum number of drought events for SDI-9 is 5 to 6. For SDI-12, the distribution pattern of the southeast with the number of drought events is 5 to 6 events. Figure 5 shows that the number of drought events increased steadily from the 1980s to the 2010s, indicating an increasing frequency of droughts throughout the Peninsular Malaysia catchment. In the 2010s, Peninsular Malaysia experienced hydrological drought up to 10 times based on SDI-3. According to SDI, a total of 2559 hydrological drought events were recorded for the 42 stations, namely 922 drought events over three months (SDI-3), 652 drought events over six months (SDI-6), 545 events over nine months (SDI-9) and 440 drought events over one year (SDI-12). On the time scale (three to 12 months), the hydrological drought events are mainly distributed in the north-east and southeast and in some areas in the north-west and southwest of Peninsular Malaysia.

Figure 5 shows the spatial and temporal variation of SDI values calculated for long periods of nine and 12 months. Hydrological droughts for 9- and 12-month events occurred mainly in the 2010s. These were mainly found in the East Coast region and in the north of the southern region of west coast of Peninsular Malaysia. Between 1980 and 2010, drought events changed drastically in most regions of the river basin. The south-eastern region is more prone to drought events than any other region. Most hydrological drought events in the late 21st century occurred in the southern and northern regions of Peninsular Malaysia. In addition, short-term drought events (a drought of less than six months) were distributed throughout the region Peninsular Malaysia. The interannual variability in short-term drought events is considerable.

3.4 Hydrological drought frequency

To identify drought-prone regions on Peninsular Malaysia, drought events were analysed based on three-month, six-month, nine-month and 12-month time scale. The frequency of drought events classified as moderate, severe, or extreme is assessed for each station. The aim of this analysis is to identify which regions are most affected by droughts over comparable periods of time, based on the percentage frequency of occurrence.

The frequency of droughts in Peninsular Malaysia is assessed at different time scales based on the percentage occurrence of each event at each station relative to the total number of observations in the same category and time scale in the region. Figure 6 shows the spatial distribution of the different drought frequencies during the last 40 years at different time scales based on Equation (4). As shown in Figure 6, the frequency values of four drought categories (in percentage) are divided into five frequencies: 0 - 20%, 20 - 40%, 40 - 60%, 60 - 80% and 80 - 100%.

Figure 6: Spatial and temporal distribution of hydrological drought frequency for 10-year intervals.

Table 3 shows the percentage of drought events based on drought frequency categories. For SDI-3, the drought frequency in the 1980s was 85.72% and for Peninsular Malaysia, 14.28% for SDI-6, 78.57% and 21.43% (rare and less frequent, respectively). In SDI-9, areas of rare and less frequent occurrence accounted for 83.33% and 9.52% of drought events, respectively, while areas of often occurrence accounted for 7.14% of drought events. In SDI-12, the rare and less frequent hydrological droughts accounted for 61.91% and 26.19% of the drought events in the entire basin, respectively, while the often occurrence accounted for 11.90% of the drought events. In SDI-3, rare and less frequent drought events accounted for 35.71% and 47.62% of the drought events in the 1990s, respectively. In 16.67% of the time, drought events occurred often in different parts of Peninsular Malaysia. On the time scale of 9 months (SDI-9), there was no frequent hydrological drought in the entire catchment. The frequency of drought was 33.33%, 54.76% and 11.90% for rare, less, and often, respectively. However, SDI-12 showed increased frequency of often drought events with 23.81% compared to 30.95% and 45.24% for rare and less frequent hydrological drought respectively.

The rare and less frequent SDI-3 events accounted for 14.28% and 85.71% of the drought events in the entire basin in the 2000s. However, the rare occurrence doubled to 30.95%, while the drought events over six months (SDI-6) decreased to 69.04%. The often occurrence of SDI-9 and SDI-12 accounted for 11.90% and 21.43% of the drought events respectively, while the less frequent occurrence accounted for 59.52% and 52.38% and the rare occurrence accounted for 28.57% and 26.19% of the drought events respectively. The rare, less often, and frequent occurrences of hydrological drought in the 2010s were 38.10%, 52.38%, 7.14% and 2.38%, respectively, on a three-month time scale (SDI-3). On the nine-month scale (SDI-9), there is a significant shift above the level of often occurrence (23.81% and 4.76%, respectively), while rare and less frequent drought events accounted for 23.81% and 47.62%, respectively. The often occurrence of drought events did not differ significantly between SDI-12 and SDI-9 (23.81% and 4.76%, respectively), while the rare and less occurrences remained the same (35.72%).

Table 3 Percentage of drought occurrence with different time scales.

Overall, areas of frequent occurrence have tended to increase on a time scale of three to 12 months, with a marked increase in frequency in the 1990s and 2010s. However, frequent droughts did not occur in the 1980s and 2000s. The frequency of hydrological drought was highest in the 1990s and 2010s. The frequency of hydrological droughts in a given area is 25.30% and 24.60% for frequent and extremely frequent droughts, respectively. Based on the three-month and six-month time scales

(SDI-3 and SDI-6), droughts occurred rare and less frequently in the 1980s and 2000s. In the 1990s and 2010s (SDI-3 and SDI-6), there are often frequent droughts in the northern and central regions of west coast of Peninsular Malaysia. Looking at the hydrological drought category on the 12-month scale, the regions where droughts occurred are extremely frequent in two stations (S13 and S28, Selangor and Perak, respectively). Short-term drought conditions show high interannual variability. Short-term drought variability is found to be in the predominant pattern.

Spatial analysis of drought characteristics also revealed that most areas in Peninsular Malaysia are prone to short-term droughts, with relatively high frequency in the northeast and southeast, especially in the central and southern regions, where frequency reached 35.7% and 42.8%, respectively. The temporal analysis of SDI-3 shows that it is beneficial to identify hydrological droughts when there are short-term changes, especially due to human factors. In other words, since drought is a natural hazard caused by various factors, SDI-3 seems to be an appropriate index since the streamflow used takes into account the impact of each drought-causing factor and affects the water supply for domestic or irrigation purposes. In summary, the results show that the frequency of droughts decreases as the severity of the drought increases. The result shows that on a given time scale, moderate, severe, and extreme droughts are most common as predicted for the last decade. It became clear that a significant proportion of historical droughts are due to hydrological droughts and that drought areas cover most of the basin, while they occur less frequently (20-40%). It should be noted that the percentage of drought events in a given category varies by location and SDI time scale. SDI-12 is more suitable for water management applications. The spatial and temporal distribution in Figure 6 shows the complexity of hydrological drought, where individual drought episodes can have very different spatial patterns in terms of onset, intensity, spatial spread, and area. When moving from a 6-month to a 9-month period, the differences are generally small, but they disappear when moving from a 9-month to a 12-month hydrological year. This illustrates that as the length of the period increases, the number and intensity of dry years increases.

4 Conclusion

The Streamflow Drought Index (SDI) was used to assess the spatial and temporal variations of hydrological droughts throughout Peninsular Malaysia from 1978 to 2018. Analysis of hydrological drought using the SDI revealed that almost all stations suffered from hydrological drought throughout the study period. Therefore, the calculation of SDI from the different time scales in this paper are able to reflect the spatial and temporal distribution characteristics of hydrological drought in Peninsular Malaysia. Extreme drought events occurred mainly in the last two decades, from 1997 to 1998 and 2001 to 2002, with 2011 to 2018 being the driest years.

The years 1997-1999, 2002 and 2016-2018 are the most critical drought years in the basin, with more than 48% of the total area of the basin affected by hydrological drought. According to the SDI, a total of 2559 hydrological drought events were

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recorded during the 40-year study period, of which 36.03% were drought events over three months (SDI-3), 25.48% were drought events over six months (SDI-6), 21.30% were events over nine months (SDI-9) and 17.19% were drought events over one year (SDI-12). On time scales (3 to 12 months), hydrological drought events are mainly found in the northeast and southeast and in a few areas in the northwest and southwest of Peninsular Malaysia. The highest percentage of drought events is mostly rare and less occurrences of hydrological drought events on Peninsular Malaysia is lower. Most of the areas in the northeast and southeast of Peninsular Malaysia have relatively high frequency, especially in the central and southern regions where the frequency reached 35.7% and 42.8%, respectively.

The following results were obtained:

(1) From the 1980s to the 2010s, the intensity of hydrological drought at Peninsular Malaysia gradually weakened in the 1980s to 1990s and became stronger in the 2000s to 2010s. Moreover, the 1990s and 2010s were the most severe hydrological droughts, followed by the 1980s and 2000s. Drought spread with increasing time scale, while severe drought regions decreased and shifted to the centre of Peninsular Malaysia.

(2) From the 1980s to the 2010s, the number of drought events gradually increased, meaning that the frequency of droughts increased throughout the Peninsular Malaysia catchment. On the time scale (three to 12 months), hydrological drought events were mainly distributed in the northeast and southeast, and in a few areas in the northwest and southwest of Peninsular Malaysia.

(3) The frequency of occurrence increased dramatically between the 1990s and 2010s at the SDI-3, SDI-6, SDI-9 and SDI-12-time scales. This was not the case between the 1980s and 2000s. The spatio-temporal distribution of the frequency of hydrological droughts on Peninsular Malaysia corresponds to the severity of the hydrological drought. In the 1990s and 2010s, the frequency of hydrological drought was highest with frequent occurrence during this period.

This study highlights the need and methods for selecting an appropriate time scale for drought assessment. Furthermore, the average duration of a drought varied depending on the time scale chosen for the analysis. A longer scale indicates droughts with a longer duration, while a shorter scale indicates droughts with a shorter duration. More extreme drought events were recorded on the longest time scale (12 months) than on the shortest time scale (3 months). On the shortest scale (3 months), more mild and moderate events were recorded. As the longest time scale (12 months) tends to include dry and wet periods, its high value can lead to misleading information for the early warning system. The 12-month time scale simplifies the comparison between the long-term variations in dry climate and the corresponding hydrological variations. Therefore, the choice of an appropriate time scale is crucial for the development of an effective drought mitigation strategy. Among the SDI time scales, SDI-3 is the most suitable for effectively tracking hydrological drought. For tropical regions, this is the scale that is most sensitive to changes in streamflow.

Author contribution

Hasrul Hazman Hasan : Conceptualisation, writing the original draft, conceptualisation, methodology, formal analysis, validation, investigation. Siti Fatin Mohd Razali : Funding acquisition, supervision, conceptualisation, drafting, review and editing, review of analysis, validation. Nur Shazwani Muhammad : Supervision, conceptualisation, writing, review and editing, review of analysis, validation. Asmadi Ahmad : writing, reviewing, and editing. Hasrul Hazman Hasan prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

The authors would like to thank the Ministry of Education Malaysia for financial support for this research through Research Grant No. FRGS/1/2018/TK01/UKM/02/2. The authors would also like to acknowledge their gratitude to the Department of Irrigation and Drainage Malaysia for providing data. We would like to thank the Ministry of Education (MOE) Malaysia and Universiti Kebangsaan Malaysia (UKM) for their support which contributed to the success of this study.

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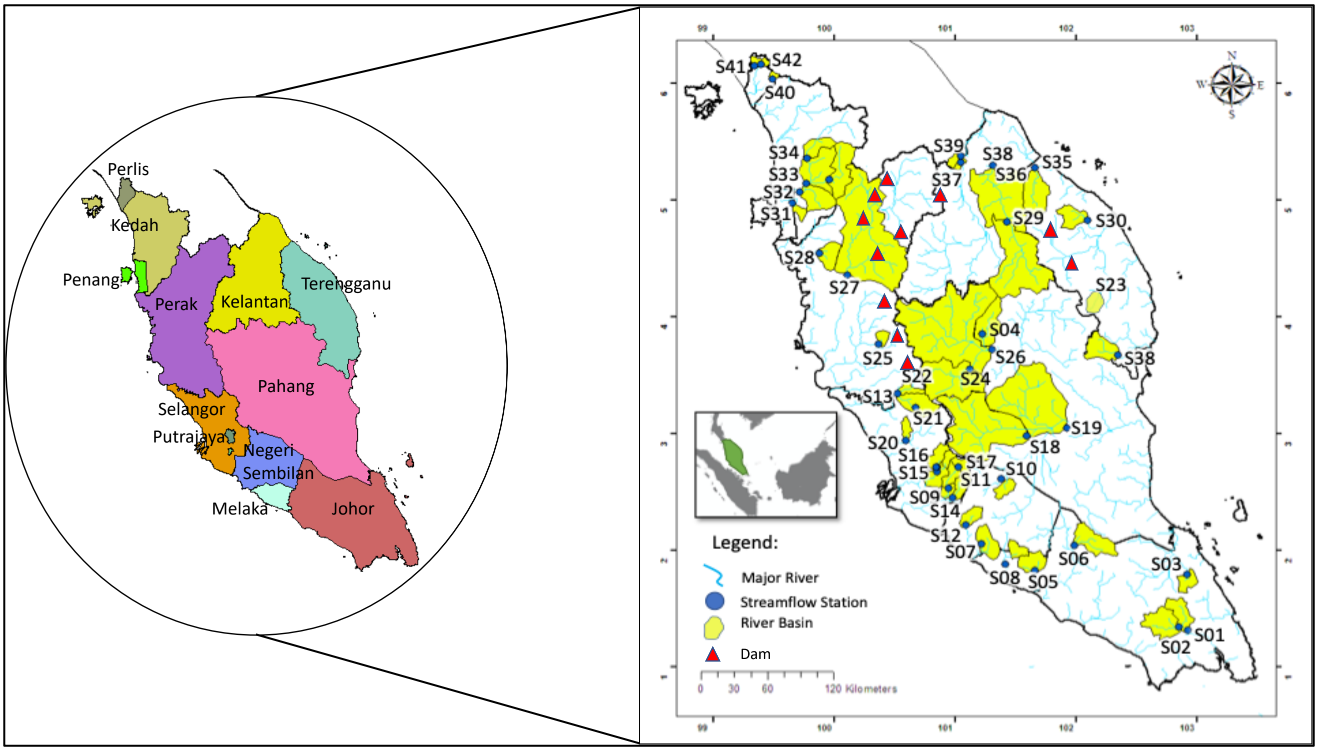
590 

Figure 1: The location of streamflow stations in Peninsular Malaysia.

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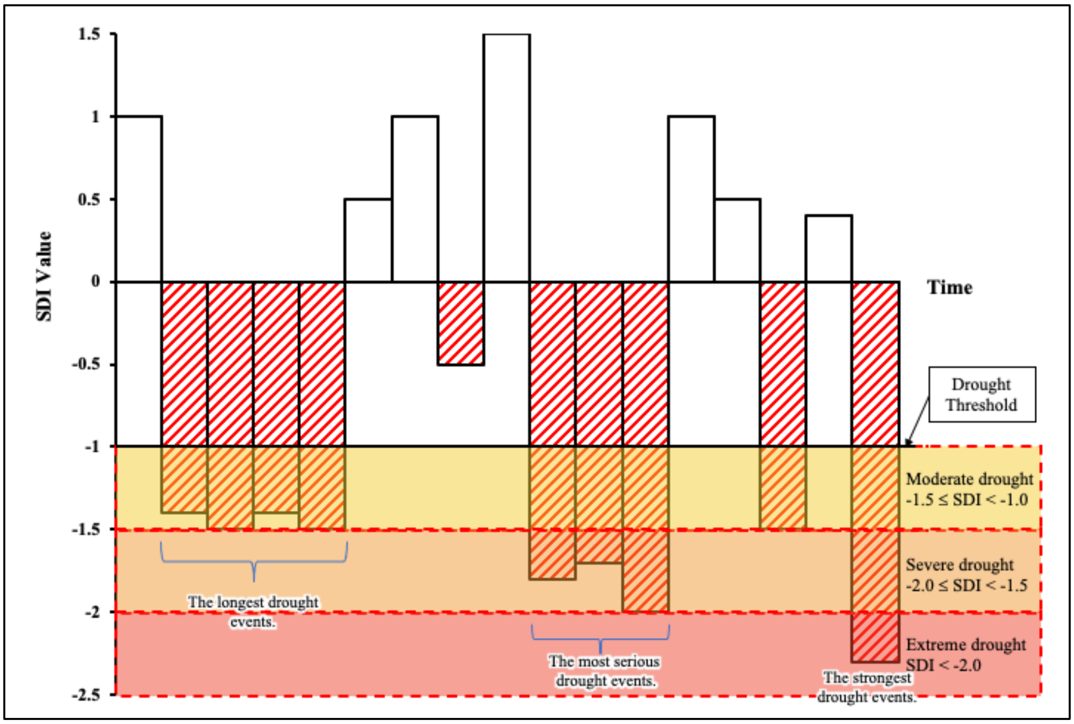

Figure 2: Determination of hydrological drought characteristics using the theory of runs.

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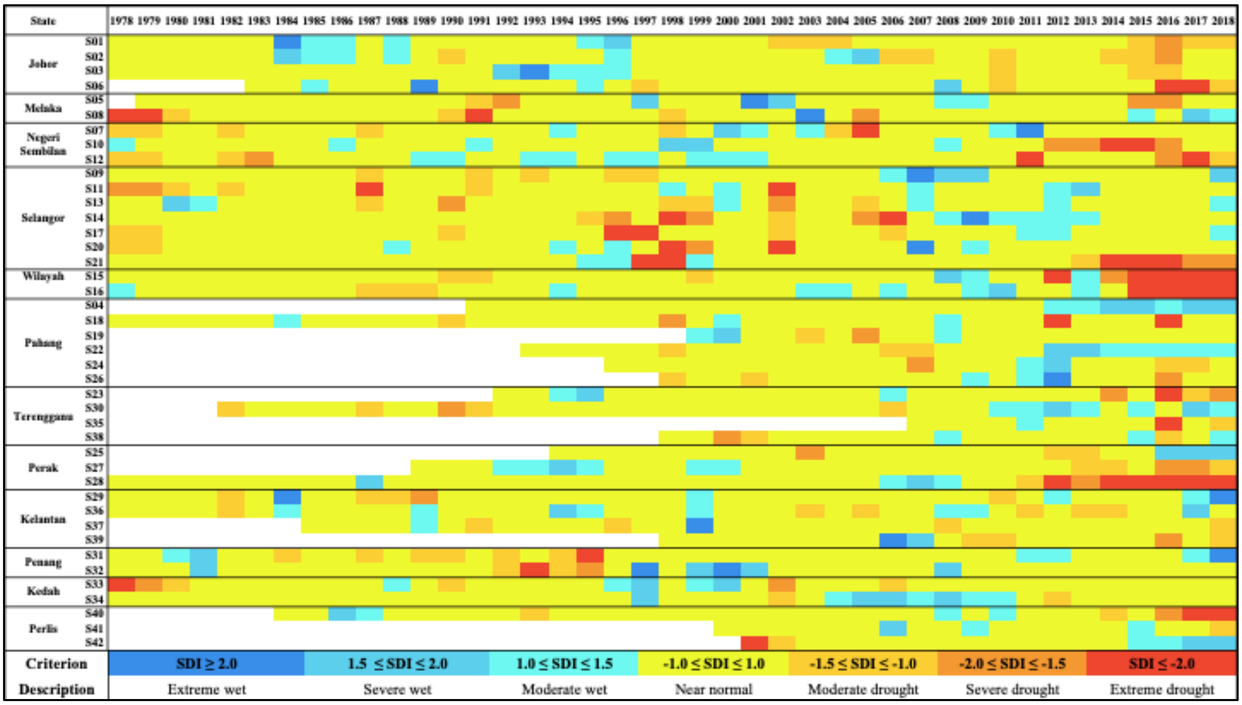

Figure 3: Colour-coded table of SDI-12 for 40-year time series.

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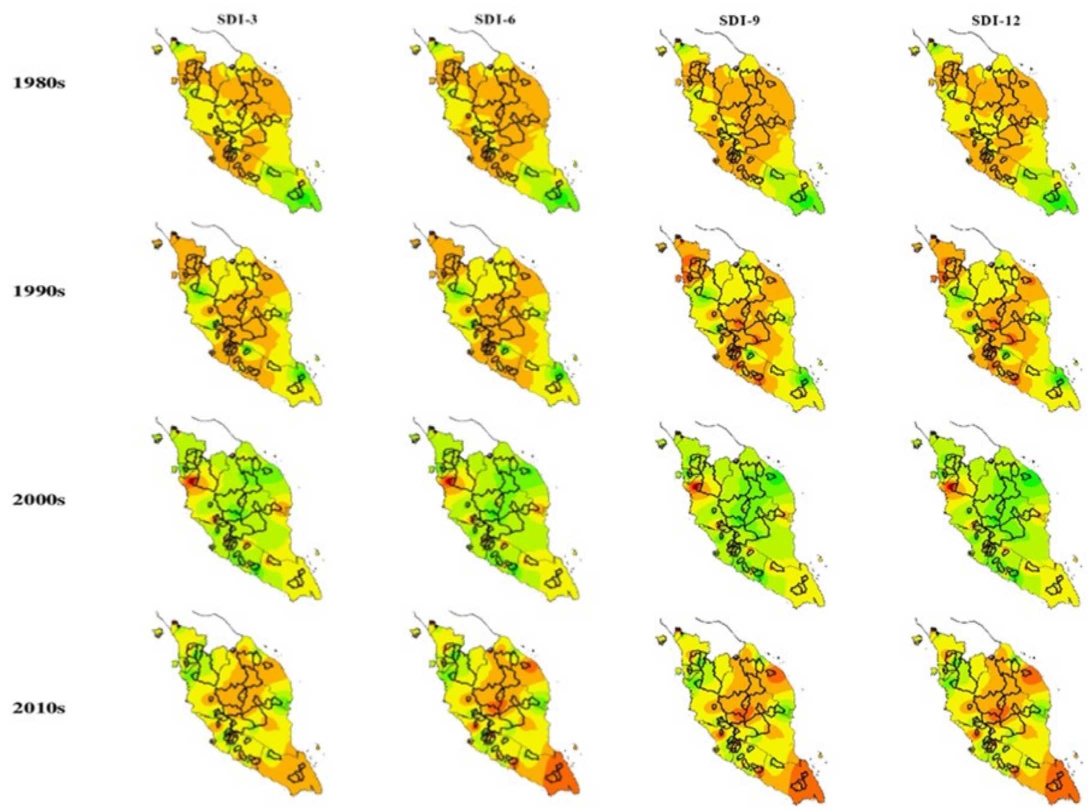

Criterion	SDI ≥ 2.0	1.5 ≤ SDI < 2.0	1.0 ≤ SDI < 1.5	-1.0 ≤ SDI < 1.0	-1.5 ≤ SDI < -1.0	-2.0 ≤ SDI < -1.5	SDI < -2.0
Description	Extreme wet	Severe wet	Moderate wet	Near normal	Moderate drought	Severe drought	Extreme drought

Figure 4: Spatial and temporal distribution of SDI-3, SD-6, SDI-9 and SDI-12 for 10-year intervals.

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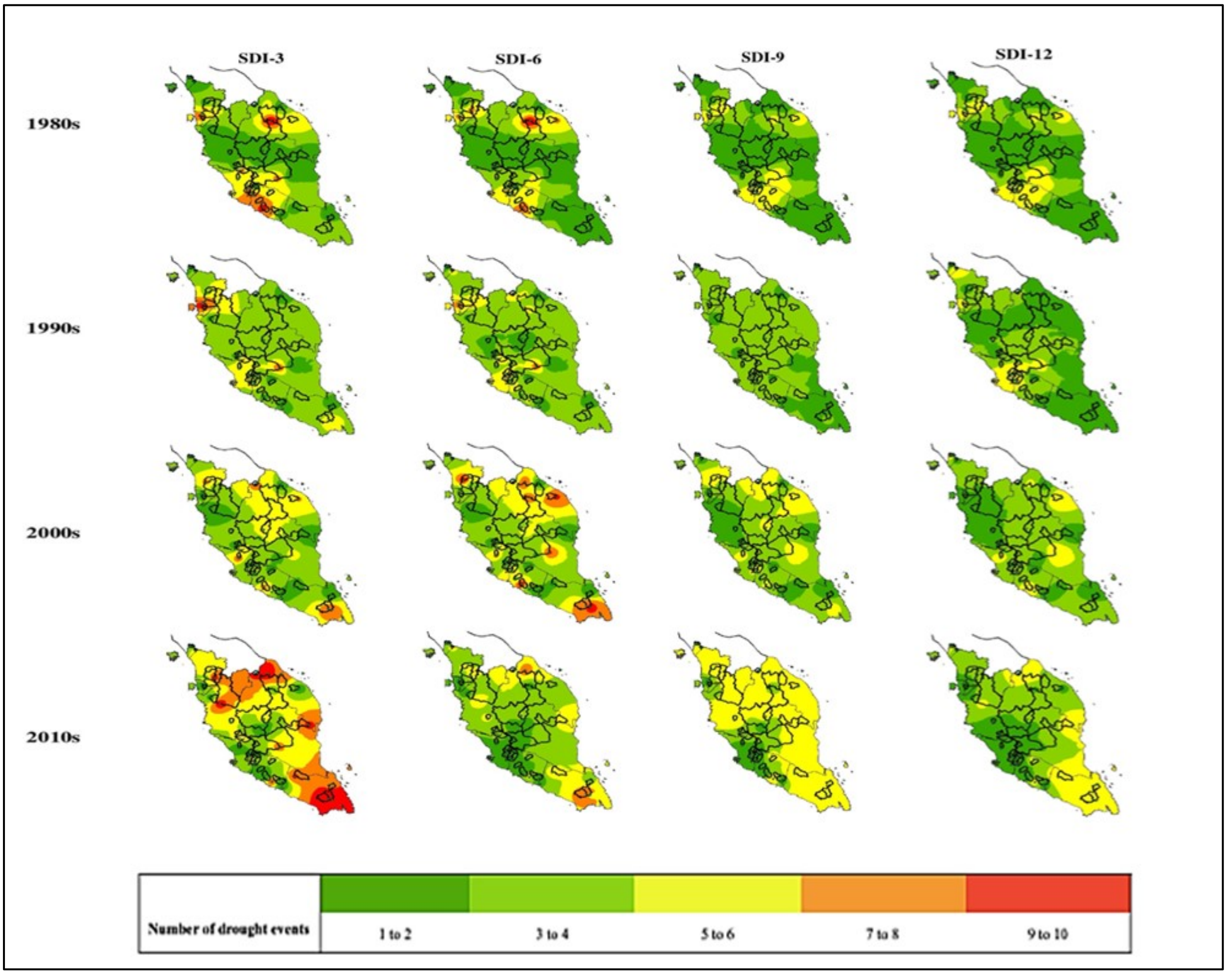

Figure 5: Spatial and temporal distribution of number of hydrological drought events for 10-year intervals.

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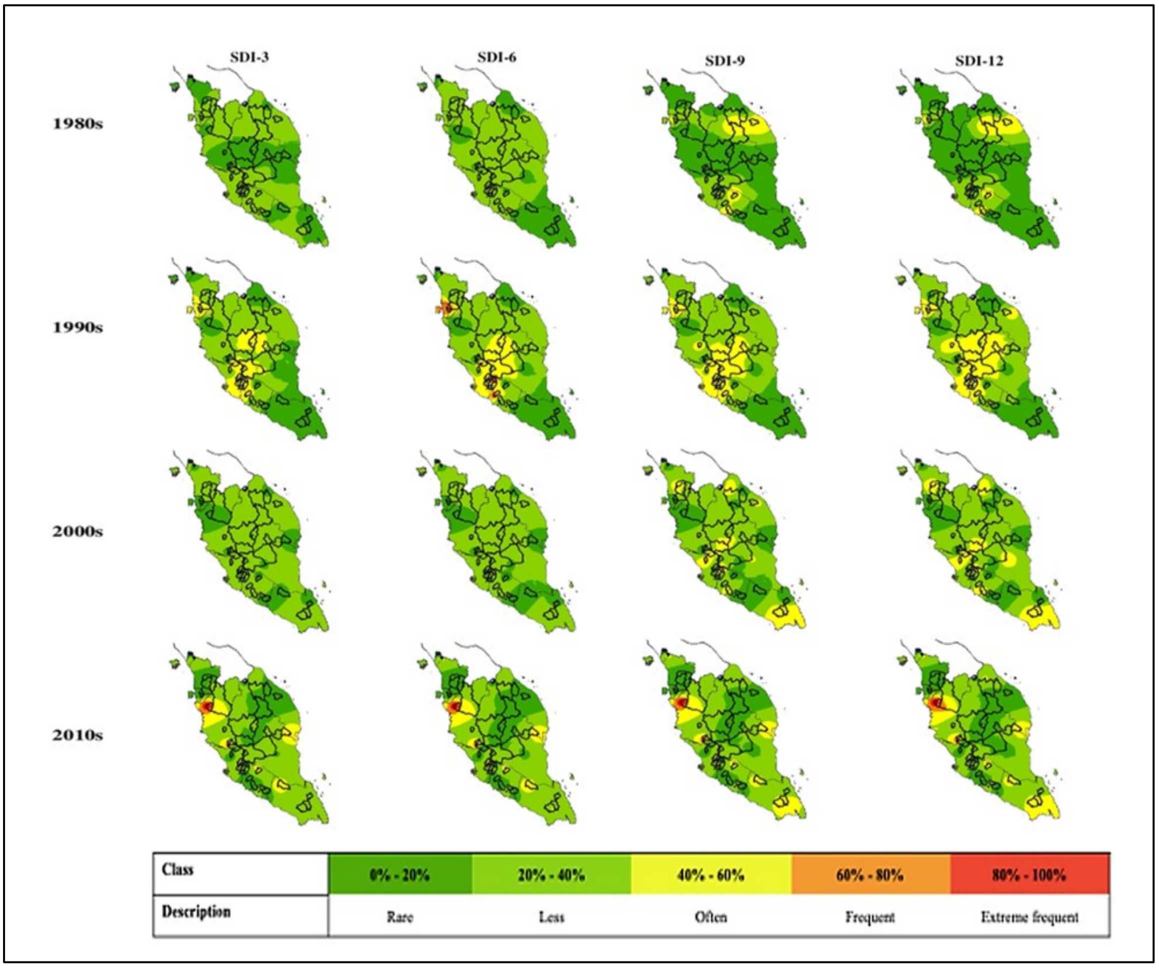

Figure 6: Spatial and temporal distribution of hydrological drought frequency for 10-year intervals.

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Table 1. Information on streamflow stations in Peninsular Malaysia

Station ID	Gauging Station	River	State	Area (km^2)	Coordinate		Record Duration, N (Year)	Start and End Year
					Latitude (N)	Longitude (E)		
S01	1737451	Johor River	Johor	1130	1° 46' 50.002" N	103° 44' 44.999" E	40	1978-2018
S02	1836402	Sayong River	Johor	624	1° 48' 15.001" N	103° 40' 09.998" E	40	1978-2018
S03	2237471	Lenggor River	Johor	207	2° 15' 29.999" N	103° 44' 10.000" E	40	1978-2018
S04	4320401	Kecau River	Pahang	497	2° 17' 25.001" N	102° 29' 35.002" E	28	1990-2018
S05	2224432	Kesang River	Melaka	161	2° 20' 35.002" N	102° 15' 10.001" E	40	1978-2018
S06	2528414	Segamat River	Johor	658	2° 30' 24.998" N	102° 49' 05.002" E	25	1993-2018
S07	2519421	Linggi River	Negeri Sembilan	523	2° 31' 00.001" N	102° 03' 29.999" E	40	1978-2018
S08	2322413	Melaka River	Melaka	350	2° 40' 52.000" N	101° 55' 39.000" E	40	1978-2018
S09	2917401	Langat River	Selangor	380	2° 54' 55.001" N	101° 49' 25.000" E	40	1978-2018
S10	3022431	Triang River	Negeri Sembilan	904	2° 59' 34.001" N	101° 47' 12.998" E	40	1978-2018
S11	2816441	Langat River	Selangor	1240	2° 59' 39.998" N	101° 47' 10.000" E	40	1978-2018
S12	2920432	Triang River	Negeri Sembilan	228	3° 04' 30.000" N	102° 13' 05.002" E	40	1978-2018
S13	3813411	Bernam River	Selangor	1090	3° 08' 20.000" N	101° 41' 49.999" E	40	1978-2018
S14	2918401	Semenyih River	Selangor	225	3° 10' 25.000" N	101° 52' 19.999" E	40	1978-2018
S15	3116433	Gombak River	Wilayah Persekutuan	122	3° 10' 25.000" N	101° 41' 49.999" E	40	1978-2018
S16	3116434	Batu River	Wilayah Persekutuan	145	3° 10' 35.000" N	101° 41' 15.000" E	40	1978-2018
S17	3118445	Lui River	Selangor	68	3° 24' 10.001" N	101° 26' 35.002" E	40	1978-2018
S18	3424411	Pahang River	Pahang	19000	3° 26' 39.998" N	102° 25' 45.001" E	40	1978-2018
S19	3527410	Pahang River	Pahang	25600	3° 30' 45.000" N	102° 45' 29.999" E	20	1998-2018
S20	3414421	Selangor River	Selangor	1450	3° 41' 07.001" N	101° 31' 23.999" E	40	1978-2018
S21	3615412	Bernam River	Selangor	186	3° 48' 27.000" N	101° 22' 09.998" E	40	1978-2018
S22	4019462	Lipis River	Pahang	1670	4° 01' 05.002" N	101° 57' 55.001" E	26	1992-2018
S23	4930401	Berang River	Terengganu	140	4° 08' 00.000" N	103° 10' 30.000" E	27	1991-2018
S24	4121413	Jelai River	Pahang	7320	4° 11' 10.000" N	102° 08' 39.998" E	23	1995-2018

https://doi.org/10.5194/nhess-2021-249
Preprint. Discussion started: 24 August 2021

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Station ID	Gauging Station	River	State	Area (km^2)	Coordinate		Record Duration, N (Year)	Start and End Year
					Latitude (N)	Longitude (E)		
S25	4212467	Chendering River	Perak	119	4° 13' 54.998" N	101° 13' 09.998" E	25	1993-2018
S26	4223450	Tembeling River	Pahang	5050	4° 19' 14.999" N	102° 03' 40.000" E	21	1997-2018
S27	4809443	Perak River	Perak	7770	4° 49' 09.998" N	100° 57' 55.001" E	30	1988-2018
S28	5007421	Kurau River	Perak	337	5° 00' 45.000" N	100° 43' 54.998" E	40	1978-2018
S29	5222452	Lebir River	Kelantan	2430	5° 16' 30.000" N	102° 16' 00.001" E	40	1978-2018
S30	5229436	Nerus River	Terengganu	393	5° 17' 30.001" N	102° 55' 19.999" E	37	1981-2018
S31	5405421	Kulim River	Penang	129	5° 26' 10.000" N	100° 30' 50.000" E	40	1978-2018
S32	5505412	Muda River	Penang	4010	5° 31' 54.998" N	100° 34' 19.999" E	40	1978-2018
S33	5606410	Muda River	Kedah	3330	5° 36' 34.999" N	100° 37' 35.000" E	40	1978-2018
S34	5806414	Muda River	Kedah	1710	5° 38' 20.000" N	100° 48' 45.000" E	40	1978-2018
S35	5724411	Besut River	Terengganu	787	5° 44' 20.000" N	102° 29' 35.002" E	12	2006-2018
S36	5721442	Kelantan River	Kelantan	11900	5° 45' 45.000" N	102° 09' 00.000" E	40	1978-2018
S37	5718401	Golok River	Kelantan	80	5° 47' 10.000" N	101° 53' 30.001" E	34	1984-2018
S38	4131453	Cherul River	Terengganu	505	5° 49' 09.998" N	100° 37' 54.998" E	21	1997-2018
S39	5818401	Lanas River	Kelantan	216	5° 50' 25.001" N	101° 53' 30.001" E	21	1997-2018
S40	6503401	Arau River	Perlis	21	6° 30' 10.001" N	100° 21' 05.000" E	35	1983-2018
S41	6602402	Pelarit River	Perlis	21	6° 36' 45.000" N	100° 12' 24.998" E	19	1999-2018
S42	6602403	Jarum River	Perlis	22	6° 37' 30.000" N	100° 15' 37.001" E	18	2000-2018

Table 2 Hydrological drought classification by SDI

SDI values	Classification
SDI ≥ 2.0	Extreme wet
1.5 ≤ SDI < 2.0	Severe wet
1.0 ≤ SDI < 1.5	Moderate wet
-1.0 ≤ SDI < 1.0	Near normal
-1.5 ≤ SDI < -1.0	Moderate drought
-2.0 ≤ SDI < -1.5	Severe drought
SDI < -2.0	Extreme drought

Table 3. Percentage of drought occurrence with different time scales

Year	Drought Frequency Category (DFC)	Drought Occurrences (%)			
		SDI-3	SDI-6	SDI-9	SDI-12
1980s	Rare	85.72	78.57	83.34	61.91
	Less	14.28	21.43	9.52	26.19
	Often	-	-	7.14	11.90
	Frequent	-	-	-	-
	Extremely frequent	-	-	-	-
1990s	Rare	35.71	35.71	33.34	30.95
	Less	47.62	40.58	54.76	45.24
	Often	16.67	21.32	11.90	23.81
	Frequent	-	2.39	-	-
	Extremely frequent	-	-	-	-
2000s	Rare	14.28	30.95	28.57	26.19
	Less	85.72	69.05	59.53	52.38
	Often	-	-	11.90	21.43
	Frequent	-	-	-	-
	Extremely frequent	-	-	-	-
2010s	Rare	38.10	38.09	23.81	35.71
	Less	52.38	47.20	47.62	35.72
	Often	9.52	11.90	23.81	23.81
	Frequent	-	2.81	4.76	4.76
	Extremely frequent	-	-	-	-