Investigation of streamflow as a seasonal hydrological drought indicator for a tropical region

Kit Fai Fung, Yuk Feng Huang and Chai Hoon Koo

ABSTRACT

Understanding the operational definition of drought is important for alleviating the negative impacts of droughts. This study investigates the use of streamflows to indicate seasonal hydrological droughts in the Northern Region of Peninsular Malaysia. The seasonal 3-month Streamflow Drought Index (SDI-3) was used to analyse drought characteristics in 2003–2017. The occurrences of all three reported droughts were successfully identified with the SDI-3, with the identified events having a 3-month earlier onset with a 6-month longer duration; a 1-month delayed onset with a 5-month longer duration; and a 1-month delayed onset with a 1-month shorter duration, respectively compared to their actual onset and duration. Along with justifications such as the increase in evaporation and evapotranspiration due to temperature increase, losses for groundwater replenishment and human factors, the SDI-3 was concluded to be suitable for hydrological drought monitoring. Drought characteristics were spatially interpolated using the Inverse Distance Weighting (IDW) method, which was cross-validated for applicability with average root mean squared error (RMSE) and R equal to 0.630 and 0.586, respectively. It was found that most of the areas are more prone to short-term droughts with mean severity up to the mild category, except for the central zone which showed more severe droughts, albeit being less likely to occur.

Key words | drought characteristics, hydrological drought, Inverse Distance Weighting, spatial interpolation analysis, Streamflow Drought Index

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INTRODUCTION

Droughts can cause immeasurable damage to economies, societies and also the environment. Evaluation and prediction of drought duration, frequency, intensity, severity, peak, and geographic extent is therefore important for impact control and mitigation. This is especially true for the hydrological cycle, water management and crop production sectors. Thus, accurate quantitative measurement techniques are required for the monitoring of drought events. Malaysia is a humid tropical country with two rainy seasons. One of them is the southwest monsoon (SWM), also known as the summer monsoon, which occurs from June to September. The other is the northeast monsoon (NEM), the winter monsoon, which occurs between November and March. These annual monsoon seasons, together with the inter-monsoon seasons, result in rainy and dry periods. Therefore, flood seasons, flash flood seasons, and the dry and hazy seasons are inevitable in Malaysia (Abdulah *et al.* 2014).

The Northern Region is the driest region during the SWM season, due to the SWM that originates from the deserts of Australia. The SWM is largely blocked by the high mountain ranges in Sumatra before it reaches Malaysia. The rainfall brought by the SWM is low (Tan *et al.* 2015). The NEM, which originates in China, flows

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over the north Pacific and tends to bring more rainfall to Malaysia. However, the Titiwangsa Range that runs down Peninsular Malaysia blocks the NEM and thus rain falls mainly onto the Eastern Region (Tan *et al.* 2015) and is minimal for the Northern Region of Malaysia (Syafrina *et al.* 2015).

The Northern Region of Peninsular Malaysia consists of Penang, Perlis, Kedah, and Perak. These few states make up the territory covered by the Northern Corridor Economic Region (NCER) that occupies about 7% of the area of Malaysia. This region contributes over 20% of GDP, 30%-plus of tourism income and, importantly, in excess of 45% of exports, as well as being more than 60% of the total agricultural area for rice growing (Oxford Business Group 2012). With this in mind, attention should be paid to the occurrence of hydrological droughts, which represents insufficient water flows, as they may impact the aforementioned industries and cause losses to the country's GDP.

Over the past decades, lots of efforts have been devoted to defining and monitoring droughts, and a series of drought indices have been developed, e.g. the Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Crop Moisture Index (CMI), Reconnaissance Drought Index (RDI), Normalized Difference Vegetation Index (NDVI), Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano *et al.* 2010; Zargar *et al.* 2011). Based on their ability to identify the operational definition (starting and ending dates, severity and duration) of droughts, drought indices have been used widely for drought monitoring and mitigation (Huang *et al.* 2016; Soh *et al.* 2018; Fung *et al.* 2019a, 2019b).

Among the indicators, streamflow is an important and direct indicator for hydrological drought monitoring. Therefore, various studies on drought forecasting have also been carried out using streamflow as the input variable (Fung *et al.* 2019c). For hydrological droughts, the existing indices include the Palmer Hydrological Drought index (PHDI), the Surface Water Supply Index (SWSI), the Streamflow Drought Index (SDI) (Nalbantis & Tsakiris 2009; Zargar *et al.* 2011) among others. Of these, the SDI has the advantages of requiring the least data input and having lower computational requirements. Hence, this study investigated the SDI in characterizing and identifying seasonal hydrological droughts for the Northern Region of Peninsular Malaysia. Among the timescales available for the SDI, the smallest cumulative streamflow calculation period (i.e. 3 months) was selected to track droughts as closely as possible because it is the most sensitive to the streamflow variations. Furthermore, the 3-month timescale has proven its capability in reflecting seasonal changes in humid or semi-humid tropical regions (Zhao *et al.* 2016).

The main contributing factor to drought events in Malaysia is the very uneven temporal and spatial distribution of rainfall amounts. These variations in rainfall pattern result in reduced streamflow due to insufficient replenishment after a period of water deficit. Given the more frequent occurrences of droughts in the last 15 years, the aim of this study is to investigate the seasonal hydrological drought in the Northern Region from 2003 to 2017 using streamflow as the indicator, with the following objectives:

(i) To define the seasonal water deficits in the Northern Region of Peninsular Malaysia under a tropical climate using the SDI with the timescale of 3 months (SDI-3).
(ii) To identify and characterize droughts using the 'run theory'.
(iii) To evaluate the accuracy of the SDI-3 in drought identification, in terms of occurrence, duration and onset.
(iv) To carry out spatial analysis on drought characteristics across the Northern Region of Peninsular Malaysia.

MATERIALS AND METHODS

Study area and data acquisition

The study area includes four states, i.e. Perlis, Kedah, Penang and Perak, collectively referred to as the Northern Region of Peninsular Malaysia. In the study area, there are seven streamflow stations that are able to provide us with 15 years of continuous historical streamflow data; five of them are located in Perak and one each in Kedah and Perlis, as shown in Figure 1.

The Northern Region covers an area of 32,331 km^2 (Perlis: 821 km^2, Kedah: 9,427 km^2, Penang: 1,048 km^2 and Perak: 21,035 km^2). Geographically and historically, the relatively flat topography at the northwest zone makes it a suitable place for agricultural expansion, especially

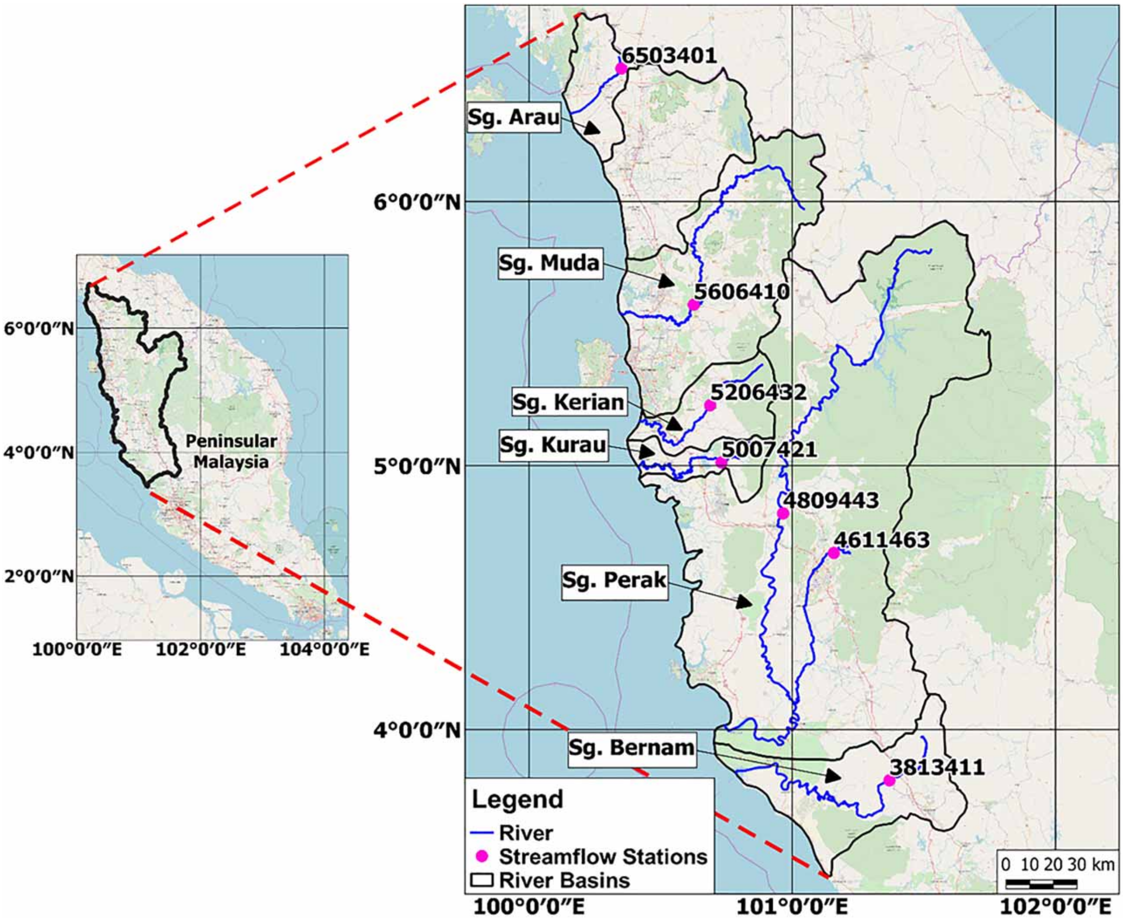


Figure 1 | River basins with streamflow stations in the Northern Region of Peninsular Malaysia. 'Sg.' is short for 'Sungai', meaning 'river'.

with rice plantations. However, the presence of the Titiwangsa Range, which separates the Northern Region from the eastern part of Peninsular Malaysia, obstructs this area from receiving rainfall during the NEM rainy season (December to March) (NWRS 2011).

For the study, the monthly streamflow data of these stations were collected from the Department of Irrigation and Drainage (DID), Malaysia, from 2003 to 2017. As previously mentioned, there are seven well-functioning streamflow stations recording historical streamflow data for the Northern Region of Peninsular Malaysia, as shown in Table 1.

Streamflow Drought Index (SDI)

The SDI is a rather simpler drought index computed based on the monthly streamflow volumes. It is utilized to identify hydrological drought. Based on the cumulative streamflow volume ($V_{i,k}$), the SDI was calculated in a manner similar to the normal standardization procedure, which is given as

$$SDI_{i,k} = \frac{V_{i,k} - \overline{V}_k}{s_k} \tag{1}$$

where $\bar{V}_k$ and s_k are, respectively, the mean and the standard deviation of cumulative streamflow volumes of reference period k (3 months). The classification of hydrological drought based on the SDI value is given in Table 2. Four major drought categories were classified according to the different values of SDI.

For the watercourses with complete streamflow data throughout the hydrological year, the formula can be applied directly. It is also applicable for watercourses with temporary flow that do not dry out completely over a

Table 1 | Details of the streamflow stations

Basin name	Basin area (km^2)	State	Station no.	Station name	Station latitude	Station longitude	Average monthly streamflow (m^3/s)
Sg. Bernam	3,201.6	Perak	3813411	Sg. Bernam @ Jam. Skc	03° 48′ 27″N	101° 21′ 70″E	1,521.8
Sg. Perak	17,556.3	Perak	4611463	Sg. Kinta @ Tg. Rambutan	04° 40′ 10″N	101° 09′ 30″E	144.2
Sg. Perak	17,556.3	Perak	4809443	Sg. Perak @ Jambatan Iskandar	04° 49′ 10″N	100° 57′ 55″E	5,762.8
Sg. Kurau	873.4	Perak	5007421	Sg. Kurau @ Pondok Tanjung	05° 00′ 45″N	100° 43′ 55″E	658.4
Sg. Kerian	1,509.6	Perak	5206432	Sg. Kerian @ Selama	05° 13′ 45″N	100° 41′ 20″E	732.7
Sg. Muda	5,593.0	Kedah	5606410	Sg. Muda @ Jam Syed Omar	05° 36′ 35″N	100° 37′ 35″E	2,326.8
Sg. Arau	1,124.3	Perlis	6503401	Sg. Arau @ Ldg. Tebu Felda	06° 30′ 10″N	100° 21′ 05″E	29.9

Table 2 | Classification of hydrological drought based on the SDI value

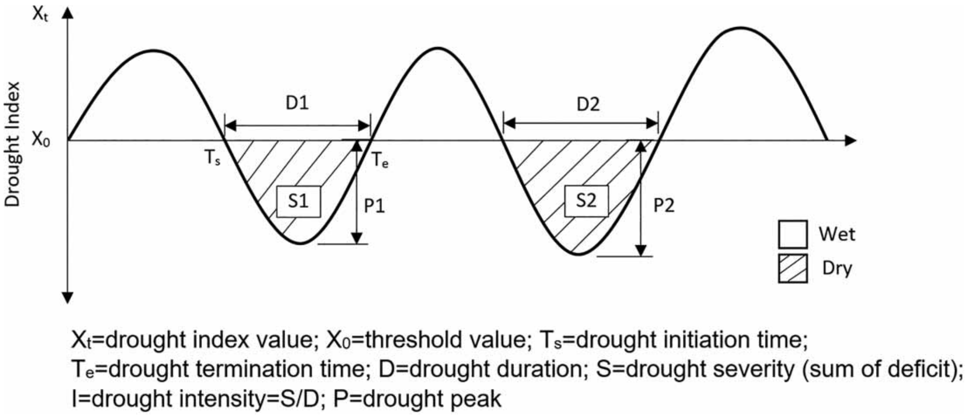
Criterion	Description
$\mathrm{SDI} \geq 0.0$	Non-drought
$-1.0 \leq \mathrm{SDI} < 0.0$	Mild drought
$-1.5 \leq \mathrm{SDI} < -1.0$	Moderate drought
$-2.0 \leq \mathrm{SDI} < -1.5$	Severe drought
$\mathrm{SDI} \leq -2.0$	Extreme drought

whole hydrological year, as the cumulative streamflow will still give positive values for computation. However, the watercourses with no flow at all in a hydrological year will be directly classified as being in extreme drought without computation (Zhao *et al.* 2016).

Since the Northern Region is located in the tropical zone with humid climatic conditions, the watercourses have complete streamflow data throughout the hydrological year and the formula was applied to define the seasonal hydrological droughts using the SDI with a 3-month timescale.

Drought identification using the 'run theory'

This study applies the 'run theory', which was originally proposed by Yevjevich in 1967 (Li *et al.* 2017) for drought characterization. It is illustrated in Figure 2. It has been frequently used in time series of irregular hydrologic events to identify drought components and investigate their statistical properties (Nam *et al.* 2015). A run is defined as a portion of the time series of the variable that is less than the chosen threshold (Lee *et al.* 2017). Following Nalbantis & Tsakiris (2009), the drought event in this study is defined as a consecutive sequence of months with SDI values (X_t) less than the threshold value (X_0) of zero. The drought initiation time (T_s) is the onset a drought event, which is the month when the SDI values fall to zero or less. After continuous months of drought (i.e. drought duration (DD)), the water deficit becomes sufficiently small and drought ends at termination time (T_e). Drought severity (DS) is the cumulative negative values of the drought index below the



X_t=drought index value; X_0=threshold value; T_s=drought initiation time;
T_e=drought termination time; D=drought duration; S=drought severity (sum of deficit);
I=drought intensity=S/D; P=drought peak

Figure 2 | Drought characteristics identification using the 'run theory' for a continuous time series.

truncation level; drought intensity (DI) is the ratio of DS over DD; and drought peak (DP) is the most negative SDI value during the drought event.

Drought characteristics

In order to investigate the spatial variation of drought characteristics, a series of event indices were estimated based on drought events identified by the 'run theory' in each station. First of all, drought frequency (DF) was estimated to represent the total number of droughts that had occurred during 2003–2017. The mean drought duration (MDD), mean drought severity (MDS), mean drought intensity (MDI) and the mean drought peak (MDP) were also estimated using the simple arithmetic mean of the corresponding characteristics of a single drought event, as shown in the equations below:

$$MDD = \frac{\sum_{i=1}^{N} DD_i}{N} \tag{2}$$

$$MDS = \frac{\sum_{j=1}^{N} DS_j}{N},\ DS = \sum_{i=1}^{DD} SDI_i,\ DS < 0 \tag{3}$$

$$MDI = \frac{\sum_{j=1}^{N} DI_j}{N},\ DI_j = \frac{\sum\limits_{i=1}^{DD} DS_i}{DD} \tag{4}$$

$$MDP = \frac{\sum_{j=1}^{N} DP_j}{N},\ DP = {}^{\min}_{1\le i\le DD} SDI_i \tag{5}$$

where i represents the SDI or DS value in month i; j represents the DS, DI or DP of the jth drought event.

Thereafter, the Inverse Distance Weighting (IDW) method was used to interpolate and analyse the spatial variations of drought characteristic across the Northern Region, as shown in the following equation:

$$\hat{Z} = \frac{\sum_{i=1}^{n} \frac{Z_i}{d_i^k}}{\sum_{i=1}^{n} \frac{1}{d_i^k}} \tag{6}$$

where $\hat{Z}$ is the estimated value at an unsampled point, n is the number of control points used for estimation, k is the power by which the distance is raised, d is the distance from each control point to an un-sampled point.

RESULTS AND DISCUSSION

Evaluation of accuracy of index

As mentioned above, the 'run theory' was used to identify droughts detected by the SDI-3 in this study. Events with continuous SDI-3 values lower than zero were identified as drought events and compared with reported historical droughts to evaluate the performance of the SDI-3 in defining droughts, as shown in Table 3.

The differences in drought onset and duration between the reported and SDI-3 identified events were used to

Table 3 | Comparison between actual and identified droughts

Areas	**Nearest streamflow station**	**Actual onset**	**Actual end**	**Identified onset**	**Identified end**	**Onset difference (month)^a**	**Actual duration (month)**	**Identified duration (month)**	**Duration difference (month)^a**
Sungai Kerian at Selama (DID 2005a, 2005b)	5206432	Apr-05	Jul-05	Jan-05	Oct-05	−3	4	10	+6
Beris Dam, Air Itam Dam, Teluk Bahang Dam, Seberang Prai, Muda River (USDA 2016; The Star Online 2016; Astro Awani 2016)	5606410	Jan-16	Apr-16	Feb-16	Oct-16	+1	4	9	+5
Muda Dam (Astro Awani 2017; Majid 2017)	5606410	Jan-17	Mar-17	Feb-17	Mar-17	+1	3	2	s1

[a] Positive and negative signs in 'Onset difference' indicate late and early identified onsets, respectively; positive and negative signs in 'Duration difference' indicate longer and shorter identified duration, respectively.

evaluate the drought identification accuracy of the SDI-3. As shown in Table 3, there were three major historical drought events reported in the Northern Region during the period 2003–2017, and these were in 2005, 2016 and 2017. According to the DID (2005a, 2005b), the whole of Peninsular Malaysia experienced drought in 2005 and this caused a substantial drop in streamflow. The drought event started in April and lasted until the end of June, when most of the rivers regained their normal streamflow amount, except for the Sungai Kerian (Kerian River) at Selama. Unlike other rivers monitored on-line, the streamflow of this river only started to rise in July even though most of the nearby areas received substantial amounts of rainfall during the second and third weeks of June.

As for the onset and duration of this 2005 drought event identified by the SDI-3, the results show that the drought identified from the nearest station 5206432 started in January and ended in October. Compared to the reported onset (April) and duration (4 months), the identified drought had a 3-month earlier onset (January) and longer duration (9 months). An explanation for the early identification of onset is that it could have arisen due to the El Niño event that had started in July 2004 (Climate Prediction Centre 2018). The long period of increased temperatures caused by the El Niño event resulted in higher atmospheric water demand. Hence, even if there had been rainfall, the streamflow could also have been reduced as a consequence of high evaporation and evapotranspiration, especially given the large tropical forest area upstream of the Sg. Kerian. In view of these reasons, the SDI-3 identified the drought earlier than expected as it defines droughts based on the water deficit observed from streamflow amount. For the longer duration identified, the long El Niño event could have influenced it. As previously mentioned, the El Niño started in July 2004 and lasted for 9 months before the arrival of the no-rain drought event. This would have reduced the water reserve in the forest and underground due to the high consumption from evaporation and evapotranspiration. Thus, when rainfall returned to normal in July 2005, the streamflow did not return to its normal amount immediately due to the 'loss' for groundwater replenishment and overland surface storage. However, it was observed that the streamflow had slowly increased since July 2005, as shown in Figure 3. This agrees with the previous discussion that normal rainfall had returned and started to replenish the streamflow but a period of time was needed for the streamflow to return to normal.

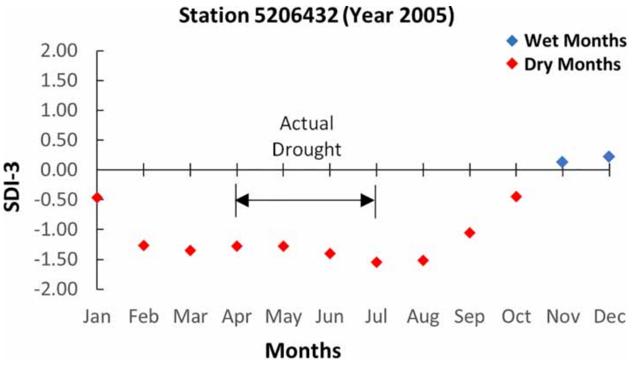


Figure 3 | SDI-3 values from station 5206432 during the drought in 2005.

The drought in 2016 was known as a 'super drought' in reports and deemed to be caused by the 2015/16 El Niño event, which had suppressed rainfall over a wider area of South East Asia (USDA 2016). This severe drought affected nearly the whole of Peninsular Malaysia and caused severe water deficit. For example, Seberang Prai in Penang suffered 31 continuous low rain days during this event (Astro Awani 2016). The Teluk Bahang dam and the Air Itam dam only received 91 mm and 59 mm of rainfall in April 2016, respectively (The Star Online 2016), compared to 955 mm and 200 mm, respectively, in April 2015. So there was a severe drought during that period. Similarly, the Beris dam and the Muda River, which are the main water sources for Kedah state, also experienced low rainfall during this 'super drought' (The Star Online 2016). These low amounts of rainfall caused drastic drops in the water levels of the Beris dam and the Sg. Muda river. Water reserves in the Muda dam normally used for irrigation purposes had to be released to sustain the Beris dam in regulating the Sg. Muda (The Star Online 2016). In view of these, the irrigation for paddy fields in the Northern Region needed to stop temporarily until the rains returned. The planting season was delayed, with compensation given to the farmers. There were subsequent losses for both the government and the rice farmers.

In this event, the SDI-3 identified that the hydrological drought started in February 2016 and ended in October 2016. These results showed differences of 1-month delayed onset identification and 5-month extended duration compared to the reported onset and duration. Compared to the early identification by the SDI-3 in the previous case, this delayed onset identification may have been due to the existence of two streamflow regulating dams for the Sg. Muda. As mentioned by The Star Online (2016), the Sg. Muda is regulated by the Beris dam and even the Muda dam in critical situations. This shows that even if there is a drastic drop in rainfall amounts that cause low water levels in the main servicing dam (the Beris dam), the streamflow will not be affected immediately due to the additional replenishment from Muda dam. Furthermore, the Sg. Muda is a river with a larger capacity than the Sg. Kerian, as shown by the average monthly streamflow (Table 1). This may result in higher sensitivity at the Sg. Kerian to the atmospheric changes compared to the Sg. Muda. In view of these factors, the streamflow of the Sg. Muda has a slower drought response time compared to the Sg. Kerian. Hence the onset identified by the SDI-3 being delayed by 1 month compared to the reported date.

According to the USDA (2016), the drought experienced by all of Peninsular Malaysia in 2016 was induced by the increase in temperature due to 2015/16 El Niño event, including the Northern Region. The 2015/16 El Niño, being one of the three strongest El Niño events since 1950 (Cook *et al.* 2016), resulted in the region experiencing severe water deficits during the period. As in the previous case, the streamflow may not have returned to its original condition even after near-normal rainfall once El Niño weakened. In Figure 4, it can be observed that the values of the SDI-3 started to increase in April 2015 (reported at the end of the month); this showed that the rainfall had started to replenish the river. However, 5 months (May to September) were needed for the streamflow to return to its normal level, possibly due to the loss for groundwater replenishment and/or the controlled water release to restore the exhausted water dam. Hence, although there is a delayed onset identification and prolonged duration, the SDI-3 is deemed to be suitable for hydrological drought monitoring in Northern Region.

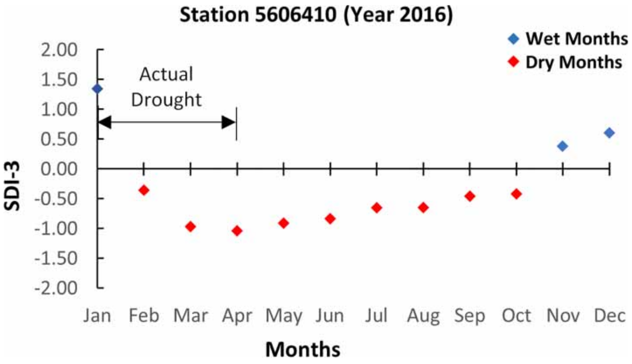


Figure 4 | SDI-3 values from station 5606410 during the drought in 2016.

Lastly, a drought with a relatively lower impact was also reported in 2017. According to Astro Awani (2016), the deficit of water began in January and lasted until March. With experience from the 'super drought' in 2016, the Muda Agricultural Development Authority (MADA) had urged rice farmers in the Muda area to employ the dry direct seeding method in the early drought period to optimize the use of water (Majid 2017). The Muda dam had a record low water level but was not at a critical stage during the event. In view of the dry direct seeding during the early drought, less water was consumed during the event and the streamflow was able to achieve an immediate return to normal conditions when rainfall returned, as shown in the exact end month of the SDI-3 identified drought with the reported end month, which were both in July (Figure 5). However, due to the longer response time of the Sg. Muda to water deficit, there was still a delay of 1 month in the onset identification. With only 1 month's difference in both onset and duration, this case again concluded that the SDI-3 is suitable for drought identification in the Northern Region.

Other than the justifications given to each individual case above, the insufficient distribution of streamflow stations may also have contributed to the difference in the

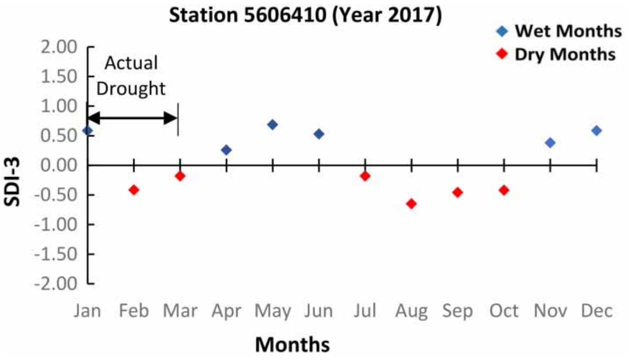


Figure 5 | SDI-3 values from station 5606410 during the drought in 2017.

onset and duration between the reported and identified drought events. For example, if the streamflow station used is located downstream of the basin, there may be a delay in the identified onset as replenishment from the water stored in the forest and underground may be interrupted in the early drought period and delay the drought downstream even if drought has already occurred upstream. It is similar for the prolonged drought duration identified, where rainfall may have returned the upstream streamflow to its normal conditions but not downstream due to the loss midstream for forest or groundwater replenishment. Hence, it is recommended to have more stations, at least one station up-, mid- and downstream of a river. Thereafter, the identification of droughts can be done by relating the water deficiency of these stations for more accurate hydrological drought identification and monitoring.

Drought characteristics

With the applicability of the SDI-3 confirmed, the drought characteristics of the Northern Region were spatially interpolated to visualize the spatial variation of the moisture conditions identified by the SDI-3. The IDW interpolation method was cross-validated with the standard statistical tests (Najafzadeh & Zahiri 2015; Zahiri & Najafzadeh 2017), namely the root mean squared error (RMSE) and the coefficient of correlation (R) to ensure the accuracy and correlation of the interpolated values with the original recorded data in the region (Table 4).

Based on Table 4, the IDW method shows an average RMSE and R of 0.630 and 0.586, respectively. The R values of IDW interpolation carried out in other earlier studies, with a higher number of stations, are 0.568–0.619 for IDW interpolation from 20 rainfall stations in West Peninsular Malaysia (Jamaludin *et al.* 2008), and 0.55 for IDW interpolation from 104 rainfall stations in all of Peninsular Malaysia (Kamaruzaman *et al.* 2017). The R values in this study, in the range of 0.504–0.745 and with an average of 0.586, showed an acceptable interpolation accuracy for the Northern Region. Hence, the drought characteristics estimated from the SDI-3, namely the DF, MDD, MDS, MDI and MDP were transformed into raster surface spatial maps for visual interpretation across the region using the cross-validated IDW method (Figure 6).

Based on Figure 6(a), it can be observed that the drought events identified by the SDI-3 occurred 12–19 times across the Northern Region. Among the seven stations investigated, relatively high DF values were identified from stations 3813411, 5606410 and 6503401, which were 18, 18 and 19, respectively. In contrast, the MDD estimated from these stations were relatively low compared to other areas in the region (Figure 6(b)), with durations of 4.67, 6.39 and 5.32 months, respectively. These show that the probability of the Northern Region having short-term drought is higher compared to long-term drought. In view of the humid tropical climate pattern of the Northern Region, the frequent short-term droughts identified by the SDI are deemed to be water deficits due to the rapidly varying climate in the region, except for droughts triggered by global climatic anomalies e.g. El Niño events. In other words, the Northern Region is more likely to have short-term dry spells instead of severe droughts due to long-term water deficiency.

In terms of drought severity, the spatial interpolation of the MDS, MDI and MDP were plotted as Figure 6(c)–6(e) to investigate the variation across the Northern Region. For the MDS, it can be observed that the SDI-3 ranged from −0.51 to −0.86. With these values, the hydrological droughts experienced in the Northern Region are classified as mild drought events (Table 2). This suggests that the drought impacts on the Northern Region should be relatively low compared to those in arid or semi-arid

Table 4 | Statistical test results for the accuracy of IDW interpolation

	Stations							
Statistical tests	**3813411**	**4611463**	**4809443**	**5007421**	**5206432**	**5606410**	**6503401**	**Average**
RMSE	0.655	0.638	0.685	0.669	0.524	0.572	0.667	0.630
R	0.569	0.504	0.522	0.547	0.745	0.709	0.510	0.586

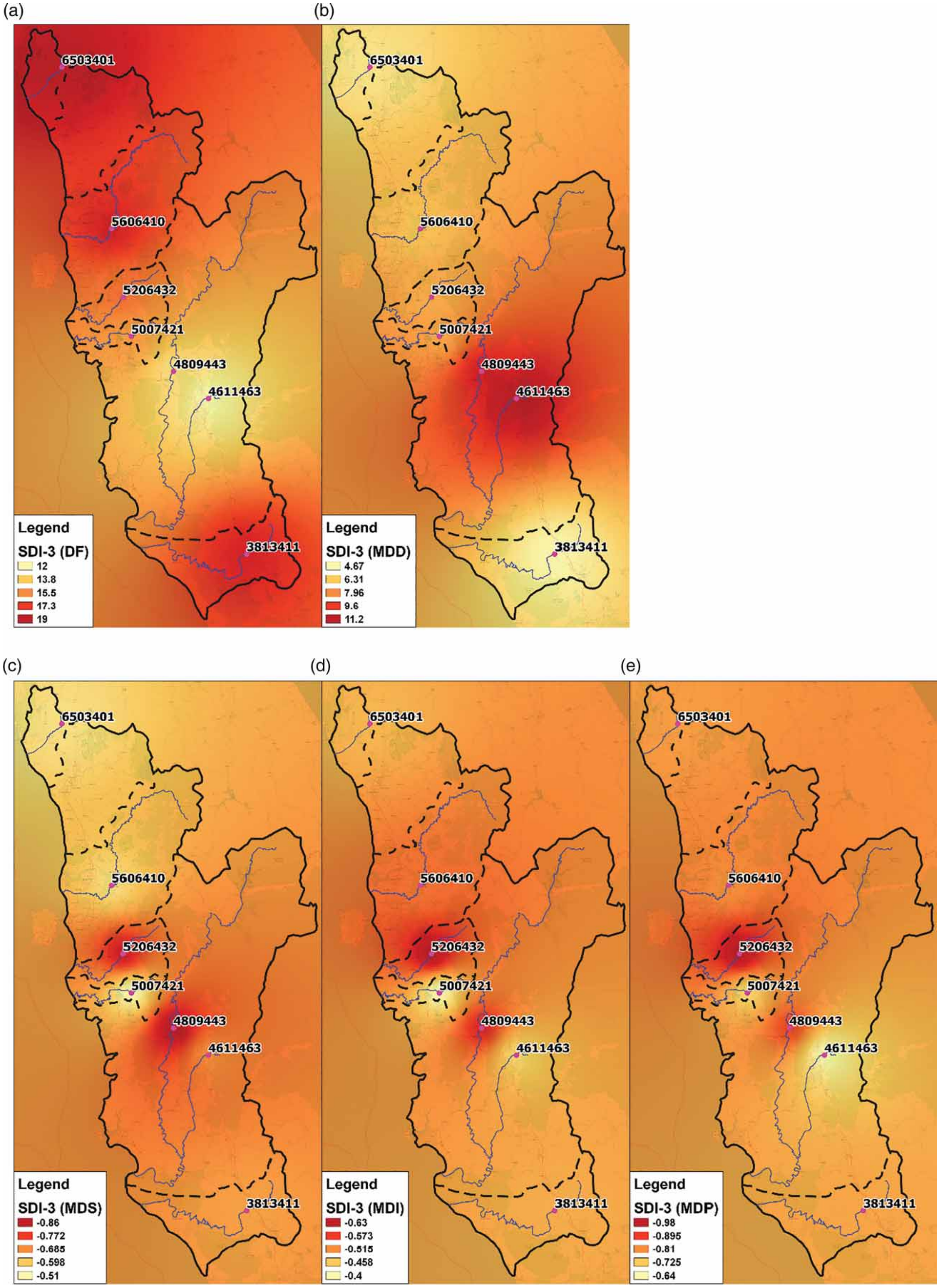


Figure 6 | Heat maps for (a) drought frequency (DF), (b) mean drought duration (MDD), (c) mean drought severity (MDS), (d) mean drought intensity (MDI) and (e) mean drought peak (MDP).

areas, as those may have severe or even extreme categories of drought.

As for the spatial distribution of drought severity, it was observed that although all stations are in the same category of mild drought, there are still differences in drought severity. For example, the areas nearby stations 5206432 and 4809443 were identified as having droughts with relatively higher severity compared to other areas in Northern Region. Similar spatial patterns were also observed for the MDI and the MDP and this suggests that other than severity, areas around stations 5206432 and 4809443 were also identified as having droughts with relatively high intensity and peak values in the region. By relating these findings to the DF and MDD, it was found that the central part of the Northern Region was more prone to droughts with relatively higher severity but with a lower probability of occurrence than in the other areas. In other words, most of the areas in the Northern Region are more prone to short-term droughts with mean severity up to mild category except the central part, which was identified as having more severe droughts, although less likely to occur.

It could be observed that station 5007421 differs significantly in terms of the MDS, MDI and MDP from stations 4809443 and 5206432, as shown in Figure 6(a)–6(c), respectively. This suggests that there is high spatial variation for drought severity in the region. In view of this, it is recommended to increase the number of streamflow stations as suggested in the previous section. This would provide a more evenly distributed observation of drought conditions in the region and more detailed spatial representation of the drought characteristics across the region.

CONCLUSION

This study investigated the hydrological droughts in the Northern Region of Peninsular Malaysia using streamflow data as the indicator. The streamflow base drought index SDI with a 3-month timescale was used to define the seasonal droughts that had occurred from 2003 to 2017. Drought events were identified from the SDI-3 through the ‘run theory’ and were compared with the three main observed historical events to evaluate its drought identification accuracy.

The evaluation results showed that all three events were sufficiently identified by the SDI-3, albeit with the differences of a 3-month earlier onset with a 6-month longer duration; a 1-month delayed onset with a 5-month longer duration; a 1-month delayed onset with a 1-month shorter duration, respectively, compared to the actual onsets and durations. However, reasonable justifications were provided in each case to explain the phenomena, such as the increase in evaporation and evapotranspiration due to increases in temperature, losses for groundwater replenishment and human factors. The SDI-3 was concluded to be suitable for hydrological drought monitoring in the Northern Region. It is recommended that for better drought monitoring using the streamflow values, the number of streamflow stations be increased as this would allow for better accounting for the flow changes over a shorter distance.

The heat maps for DF, MDD, MDS, and MDP were generated using the IDW interpolation technique. This technique was cross-validated with an average RMSE and R equal to 0.630 and 0.586 respectively, for its applicability for investigating the spatial variations of drought characteristics across the region. Based on the heat maps generated, it was found that most of the areas in the Northern Region are more prone to short-term droughts with mean severity up to mild, except for the central part, which was identified as having more severe droughts although they were less likely to occur. Similarly, the results of the spatial analysis of drought characteristics also supported an increase in the number of streamflow stations in the region for more detailed observations, as high spatial variation was observed in this study. In conclusion, the SDI-3 is applicable for drought identification and monitoring in the Northern Region.

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