Journal of
Water & Climate Change

 Journal of Water and Climate Change Vol 14 No 11, 4183 doi: 10.2166/wcc.2023.546

Comparative assessment of drought indices for evaluating drought patterns in Peninsular Malaysia

Jing Lin Ng[a,*], Yuk Feng Huang[b], Aik Hang Chong[c], Jin Chai Lee[c], Muyideen Abdulkareem[c], Nur Ilya Farhana Md Noh[a], Majid Mirzaei[d] and Ali Najah Ahmed[e]

[a] School of Civil Engineering, College of Engineering, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Selangor, Malaysia
[b] Department of Civil Engineering, Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, Jalan Sg. Long, Bandar Sg. Long, 43000, Kajang, Selangor, Malaysia
[c] Department of Civil Engineering, Faculty of Engineering, Technology and Built Environment, UCSI University, Kuala Lumpur, 56000, Malaysia
[d] Department of Environmental Science and Technology, University of Maryland, College Park, MD 20742, USA
[e] Department of Civil Engineering, College of Engineering, Universiti Tenaga Nasional (UNITEN), Selangor 43000, Malaysia
*Corresponding author. E-mail: jinglin.ng@uitm.edu.my

JLN, 0000-0002-7400-1538

ABSTRACT

Drought has been the main environmental issue in Peninsular Malaysia. Hence, this study undertook a thorough evaluation of drought assessment methodologies and focused on the temporal analysis of multiple drought indices, namely, the standardised precipitation index (SPI), deciles index (DI), percent of normal precipitation index (PNPI), rainfall anomaly index (RAI) and *Z*-score index (ZSI) – across timescales of one-, six- and 12-month durations. This assessment incorporates the average moving range (AMR), Mann–Kendall (MK) test and Sen's slope estimator in temporal analysis and the results showed that shorter timescales lead to higher fluctuation in AMR values, indicating short-term droughts are best assessed using drought indices of shorter timescale. It was found that most drought indices exhibited a similar trend and trend magnitude in all timescales. SPI is utilised as the standard model for the accuracy evaluation of drought indices using root mean square error (RMSE), mean absolute error (MAE) and mean absolute percentage error (MAPE). The results showed that ZSI has the highest accuracy of all indices. The novelty of this study lies in evaluating the accuracy and temporal characteristics of precipitation-based drought indices in tropical areas, particularly in Peninsular Malaysia.

Key words: drought, drought index, precipitation, temporal analysis

HIGHLIGHTS

- Drought indices have higher fluctuations on shorter timescales.
- Northwest, northeast and southwest regions of Peninsular Malaysia experienced an increasing trend in drought indices.
- Temporal analysis suggested that significant trends could be detected in drought indices computed on larger timescales.
- Most drought indices showcased a similar trend in assessing drought.
- SPI and ZSI performed similarly in drought monitoring.

INTRODUCTION

Drought is a phenomenon where a region does not receive the normal amount of rainfall for a prolonged period. Factors, such as lack of rainfall, overuse of water, overpopulation and human activities, may lead to drought. According to Gil *et al.* (2013), drought events have brought direct and indirect impacts to the human population, society and the agricultural sectors. The direct impacts include reduced clean water sources, increase in wildfire frequency, destruction of aquatic habitat and reduced crop yield, whereas the indirect impacts comprise reduced income for the agricultural sector, increment in food prices and increased unemployment rate. These impacts are interconnected, thus drought needs to be monitored. With millions of people relying on the agricultural sector as their main source of income, drought may impact agricultural production, posing a big challenge in preventing poverty and hunger in affected regions. In addition, an insufficient supply of crops also leads to price inflation. The Food Price Index by the United Nations Food and

Agriculture Organization showed that food prices have been hiked up since 2011 due to insufficient supply of grains, vegetables, oils and butter as farmers around the world face an array of difficulties, which include drought (Coulibaly 2013). Moreover, drought may cause water shortage that leads to health issues, namely malnutrition, increased risk of infectious diseases, mental health issues and disruption of local health services, which are all interconnected and caused by limited availability of food, water supplies and sanitation (Palmer 1968). These issues reflect the importance of drought monitoring, which can help decision-makers or authorities in drought assessment and agricultural planning to improve resilience against drought.

Peninsular Malaysia is a humid tropical country that has two monsoonal seasons, namely, the southwest monsoon (SWM) and the northeast monsoon (NEM). These two monsoonal seasons occur from November to March (NEM) and from June to September (SWM), causing certain areas to experience high rainfall at certain periods and experience drier climate during other periods. Thus, Peninsular Malaysia is vulnerable to drought. Other than that, El Nino events have also been among the culprits of drought occurrence, namely the drought events in Klang Valley in 1997 and 2016 (Shaadan *et al.* 2015). Apart from the difficulties faced by the population due to water shortages, Peninsular Malaysia's economy took a big hit during those drought events due to the downturn in agricultural sectors (Sanusi *et al.* 2015). Hence, drought monitoring is essential in Peninsular Malaysia.

To assess drought conditions, drought indices are utilised as numerical representations of drought severity. Drought indices can be classified into a few categories based on their input data: (1) precipitation and potential evapotranspiration (PET)-based indices, such as standardised precipitation evaporation index (SPEI) Vicente-Serrano et al. (2010). and Palmer drought severity index (PDSI) (Palmer 1965); (2) streamflow-based indices such as streamflow drought index (SDI) (Nalbantis & Tsakiris 2008); and (3) precipitation-based indices such as the deciles index (DI) (Gibbs & Maher 1967), reconnaissance drought index (RDI) (Tsakiris & Vangelis 2005) and standard precipitation index (SPI) (Edwards & McKee 1997).

Drought may occur at various temporal scales ranging from one to 24 months (Kam *et al.* 2014). The effect of different timescales on the performance of the drought indices differs under different geographical conditions (Prajapati *et al.* 2021). Hence, it is important to consider the timescales of drought indices while assessing the drought of a particular region to reduce operational error from time intervals between droughts .

With various drought indices developed in the past, the comparison between drought indices for specific study areas has been the main subject of recent studies. Liu *et al.* (2018) compared three drought indices that used the data of different natures (precipitation-based and evapotranspiration-based and precipitation-based respectively), namely the PDSI, SPI and SPEI based on their correlation with each other. Both SPI and SPEI performed similarly in terms of identifying agricultural drought trends and showed higher correlation coefficients compared with the PDSI. The study mentioned above successfully compared multiple drought indices in terms of comparison between indices on multiple timescales but lacked an accurate analysis of the indices based on historical drought events. Salimi *et al.* (2021) carried out a study by comparing three different types of drought indices, namely, precipitation-based, evapotranspiration-based and streamflow-based indices. Standard streamflow index (SSI) is used as a model index for correlation analysis with the performance of SPI and SPEI in drought assessment. Although this study examined the accuracy of various types of drought indices, it did not consider the impact of temporal variability in evaluating drought.

Of all drought indices, SPI has been used extensively on many occasions due to its ease of calculation which requires only precipitation data (Javed *et al.* 2021; Yaseen *et al.* 2021). Nonetheless, it is still important to evaluate the accuracy and temporal characteristics of various drought indices in Peninsular Malaysia as different indices' performance may vary in different geographical conditions. Far too little attention has been paid to comparing precipitation-based drought indices in terms of accuracy and temporal characteristics in tropical regions, especially in Peninsular Malaysia. Thus, this study aimed to assess five precipitation-based drought indices consisting of the SPI, DI, percent of normal precipitation (PNPI), rainfall anomaly index (RAI) and *Z*-score index (ZSI) at various timescales (one-, six- and 12-month) throughout Peninsular Malaysia from 1984 to 2018. The temporal characteristics of each index were compared by conducting a temporal trend analysis. Additionally, accuracy evaluation was carried out using SPI as the model index by analysing DI, PNPI, RAI and ZSI using a statistical analysis. The finding of the study will provide a better understanding of how each drought index performs on different timescales and determine an alternative precipitation-based drought index other than SPI for drought assessment in Peninsular Malaysia.

Study area and data collection

Peninsular Malaysia is located between longitude 100° E and 119°E and latitude 1°N and 7°N. It is surrounded by sea and located near the equator. Its climate is categorised as equatorial, as it experiences a warm and humid climate throughout the year. In addition, Peninsular Malaysia also experiences monsoon seasons which lead to drought or flood, namely the NEM, SWM, the first inter-monsoonal cycle and the second inter-monsoonal cycle.

Daily rainfall data from January to December 1984–2018 were obtained from the Malaysia Meteorological Department (MMD) and they were aggregated into monthly values. The details of the 11 meteorological stations are summarised in Table 1 and Figure 1. Other than that, it is also necessary to mention that missing data might exist in some stations due to factors such as station maintenance, instrumental failures and the absence of an observer. Thus, data-repairing was performed by using the normal ratio method (Singh 1994) and its equation can be expressed as follows:

$$P_x = \frac{1}{m}\sum_{i=1}^{m}\left[\frac{N_x}{N_i}\right]P_i \quad (1)$$

where P_x is the missing rainfall value for the target station, P_i is the rainfall value of rain gauges used for estimation, N_x is the normal annual rainfall of x station, N_i is the annual rainfall at nearby stations on an average basis and m is the number of nearby stations.

METHODOLOGY

Drought indices

All five indices were computed using precipitation data of one-month (short-term), six-month (mid-term) and 12-month (long-term) timescales to analyse the trend and accuracy of the indices.

Standardised precipitation index

Due to its ease of use in determining drought incidence, the SPI has become one of the most extensively used indices around the world. The SPI calculation procedure only needs rainfall data. The cumulative probability of rainfall was calculated by using the gamma distribution, as expressed below:

$$G(x) = \int_0^x g(x)dx = \frac{1}{\beta^\alpha \Gamma(\alpha)}\int_0^x x^{\alpha-1} e^{-\frac{x}{\beta}}\, dx, \ \text{for } x > 0 \quad (2)$$

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

Table 1 | Geographical locations of each meteorological station in Peninsular Malaysia

Station code	Station name	State	Record period	Duration (years)	Latitude	Longitude
48670	Batu Pahat	Johor	1992–2019	28	01° 52′N	102° 59′E
48679	Senai	Johor	1984–2019	36	01° 38′N	103° 40′E
48615	Kota Bharu	Kelantan	1950–2019	70	06° 17′N	102° 28′E
48616	Kuala Krai	Kelantan	1985–2019	35	05° 53′N	102° 20′E
40546	P. Ter. Haiwan Tanah Merah	Kelantan	1977–2019	43	05° 50′N	102° 09′E
40432	RPS Kuala Betis	Kelantan	1974–2019	46	04° 42′N	101° 45′E
40431	Pos Blau	Kelantan	1974–2019	46	04° 46′N	101° 45′E
40516	Pos Gob	Kelantan	1976–2019	44	05° 16′N	101° 39′ E
48601	Bayan Lepas	Penang	1984–2019	36	05° 30′N	100° 40′E
48625	Ipoh	Perak	1984–2019	36	04° 57′N	101° 10′E
48647	Subang	Selangor	1984–2019	36	03° 12′N	101° 55′E

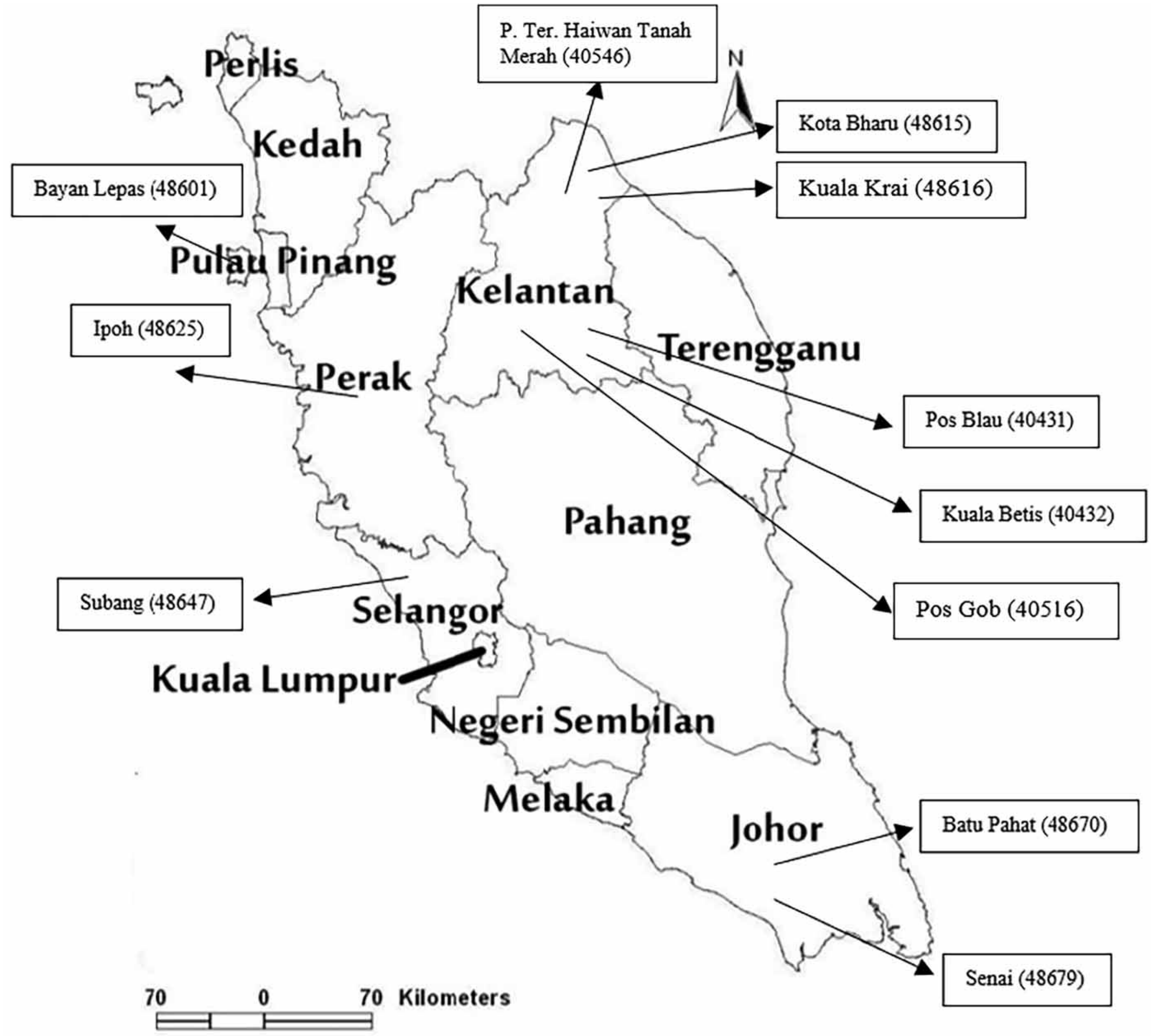

Figure 1 | The location of the meteorological stations in Peninsular Malaysia.

$$\beta = \frac{\bar{x}}{\alpha} \tag{4}$$

$$A = \ln(\bar{x}) - \frac{\Sigma \ln(x)}{n} \tag{5}$$

where β represents the scale parameter, α denotes the shape parameter and x indicates the rainfall amount; $g(x)$ is integrated with respect to x by estimating the coefficients β and α using the equations above, thus developing an interpretation for the cumulative probability $G(x)$ by observing a definite amount of rain during a given month and for a certain time frame. However, the gamma function cannot be interpreted for $x = 0$. Therefore, when there is no rainfall, the cumulative probability develops into:

$$H(x) = q + (1 - q)G(x) \tag{6}$$

where q indicates the likelihood of no rainfall. $H(x)$ is computed into a standard variable Z with an average value of 0 and a standard deviation of 1. Thus, the SPI is then shown as:

$$Z = \text{SPI} = \left\{ -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right), \quad \text{for } 0 < H(x) \leq 0.5 \right. \tag{7}$$

$$Z = \text{SPI} = \left\{ +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right), \quad \text{for } 0.5 < H(x) < 1 \right. \tag{8}$$

where

$$t = \left\{ \sqrt{\ln\left[\frac{1}{(H(x))^2}\right]}, \quad \text{for } 0 < H(x) \leq 0.5 \right. \tag{9}$$

$$t = \left\{ \sqrt{\ln\left[\frac{1}{(1 - H(x))^2}\right]}, \quad \text{for } 0.5 < H(x) < 1 \right. \tag{10}$$

where x is the rainfall, $H(x)$ is the cumulative probability of rainfall value and $c_0, c_1, c_2, d_1, d_2, d_3$ are constants with the values listed below:

$$c_0 = 2.515517, \quad c_1 = 0.802853, \quad c_2 = 0.010328$$
$$d_1 = 1.432788, \quad d_2 = 0.189269, \quad d_3 = 0.001308$$

Rainfall anomaly index

The RAI uses precipitation data to identify the frequency and intensity of humid and dry years. It considers the rank of precipitation values to determine the positive or negative precipitation anomalies. The RAI is calculated as follows (van Rooy 1965):

$$\text{RAI} = \frac{R - \bar{R}}{\bar{R}} \tag{11}$$

where R is the obtained rainfall value, and $\bar{R}$ represents the average rainfall value over a specific period.

Deciles index

For the computation of DI, monthly precipitation values were ranked from the highest to the lowest to form a cumulative frequency distribution. The cumulative frequency is split into ten parts of deciles which are then grouped into five classes with two deciles per class. Deciles 1 and 2 are classified as much below normal if rainfall values fall into the lowest 20%. Deciles 3 and 4 are classified as below normal with between 20% and 40% rainfall values while deciles 5 and 6 indicate near-normal rainfall of between 40% and 60%. Deciles 7 and 8 are between 60% and 80% above normal and deciles 9 and 10 are the wettest 20%.

Z-score Index

The ZSI measures moisture or dryness abnormality and reflects the departure of moisture conditions of a particular month from normal moisture conditions. Similar to SPI, ZSI is simple to calculate as it is computed by subtracting the mean precipitation value from the target rainfall value and then dividing the difference by the standard deviation. However, ZSI does not require adjusting data to be fitted into frequency distributions. This index is calculated as follows (Javed *et al.* 2021):

$$\text{ZSI} = \frac{x_i - \bar{x}}{\sigma} \tag{12}$$

where x_i is the obtained rainfall value, $\bar{x}$ represents the average value over a specific period and σ represents the standard deviation of the records.

Percent of normal precipitation index

PNPI is used to assess precipitation levels in relation to normal conditions and can be computed on multiple timescales, and is thus appropriate for drought assessment (Willeke *et al.* 1994). PNPI is typically expressed in percentages. It can be obtained from the equation below:

$$\text{PNPI} = \frac{P_i}{P} \times 100 \tag{13}$$

where PNPI is the percent of normal precipitation index, P represents the long-term average of rainfall and P_i is the rainfall of the computed year.

Temporal analysis

Temporal fluctuation in indices

The average moving range (AMR) is used to estimate the sensitivity of drought indices. Moving range (MR) is first calculated and it measures how the variation of a data series changes over time. The AMR can estimate the variations in the series using the following equations:

$$\text{MR} = \frac{1}{n-1}\sum_{i=2}^{n}|X_i - X_{i-1}| \tag{14}$$

$$\text{AMR} = \frac{\sum \text{MR}}{\text{Total number of MR}} \tag{15}$$

where X represents the values of drought indices and n represents the data size.

The Mann–Kendall test

The Mann–Kendall (MK) test (Mann 1945; Kendall 1975) was first introduced as a statistical test used to analyse data collected over a period to detect increasing and decreasing trends in values. It is a non-parametric test, meaning that the data used in distributions do not have to meet the assumption of normality. However, data should not have a serial correlation. The MK test is computed as follows:

$$S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \text{sgn}(x_j - x_k) \tag{16}$$

where x_j is the data value in years j, x_k is the data value in year k with $j > k$ and n denotes the length of the dataset's records while sgn is the sign function. The sign function can be expressed as given in the following equation:

$$\text{sgn}(x_j - x_k) = \begin{cases} +1 \; \textit{if} \; x_j - x_k > 0 \\ 0 \; \textit{if} \; x_j - x_k = 0 \\ -1 \; \textit{if} \; x_j - x_k < 0 \end{cases} \tag{17}$$

A positive S indicates that the trend is increasing, whereas a negative S indicates that the trend is falling. The var(S)and Z are expressed as:

$$\text{var}(S) = \left(\frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18} \right) \tag{18}$$

$$z = \begin{cases} (s-1)/\sqrt{\text{var}(s)} & \textit{if } S > 0 \\ 0 & \textit{if } S = 0 \\ (s+1)\sqrt{\text{var}(s)} & \textit{if } S < 0 \end{cases} \tag{19}$$

where m represents the number of tied groups of values and t_i represents the number of ties with i tied values.

Sen's slope estimator

Linear regression is usually used to compute the least square estimates to estimate the slope for a linear trend. According to Viessman *et al.* (1989), hydrological variables showed a pronounced right skewness and do not usually adapt to a normal distribution due to the influence of natural phenomena. Hence, Sen's slope estimator (Sen 1968) is recommended by the World Meteorological Organisation as a trend detection test in hydrometeorological data. The slope estimate can be calculated as follows:

$$Q = \frac{Y_{i'} - Y_i}{i' - i} \tag{20}$$

where Q is a slope estimate, and $Y_{i'}$ are Y_i the values at times i' and i, where i' is greater than i.

Evaluation of the accuracy of drought indices

SPI is a drought index widely used in humid and sub-humid regions to characterise drought events due to its accuracy and simplicity (Mondol *et al.* 2017). In this study, SPI was used as the standard model to evaluate the performances of the other drought indices and indicate which drought index is most suitable to be applied as an alternative index to SPI (Khanmohammadi *et al.* 2022). Three statistical tests, such as mean absolute percentage error (MAPE), root mean square error (RMSE) and mean absolute error (MAE), were applied in this study to evaluate the accuracy of drought indices.

Mean absolute percentage error

The MAPE is a simple average value of absolute errors in percentage. The accuracy of the drought index was evaluated by the MAPE as it can determine the error between the actual and forecast length of drought occurrences. The formula for MAPE is expressed as follows:

$$\text{MAPE} = \frac{\sum \frac{|A - F|}{A}}{N} \times 100\% \tag{21}$$

where A is the actual duration of drought events, F indicates the forecast duration of drought events and N is the number of detected events.

Root mean square error

The RMSE is used to compare the error difference between two drought indices. Lower values of RMSE show a better accuracy of a drought index. By applying RMSE, a drought index with a lower degree of accuracy will be eliminated from the list of the best indices for predicting droughts in Peninsular Malaysia. The RMSE is expressed as follows:

$$\text{RMSE} = \sqrt{\sum_{i=1}^{N} \frac{(x_i - y_i)^2}{N}} \tag{22}$$

where x_i, y_i and N are the obtained values, predicted values and number of events, respectively.

Mean absolute error

The MAE is a measure of the magnitude of error in forecasts of drought indices. Lower values of MAE show better accuracy of a drought index. The MAE is defined as follows:

$$\text{MAE} = \sum_{i=1}^{N} \left(\frac{x_i - y_i}{N} \right) \tag{23}$$

where x_i, y_i and N are the obtained values, predicted values and number of events, respectively.

RESULTS AND DISCUSSION

This section is divided into two subsections which include temporal analysis and performance evaluation of drought indices. Temporal analysis is divided into two sub-subsections: average moving range (MAE), and MK and Sen's slope estimator.

Temporal analysis

Average moving range

The temporal evaluation of all five drought indices was done to help us understand the temporal variation of drought events in Peninsular Malaysia. For this case, AMR was used to quantify the degree of fluctuations at the different prescribed timescales, which are one-, six- and 12-month. The AMR values represented the mean values between two moving averages of monthly drought index values in a series. Higher values of AMR indicated a higher sensitivity of drought indices. Table 2 shows the AMR of the SPI, PNPI, DI, RAI and ZSI on one-, six- and 12-month timescales, respectively.

Table 2 | AMR of SPI, ZSI, PNPI, DI and RAI

	Kota Bahru	Kuala Krai	P. Ter. Haiwan Tanah Merah	Bayan Lepas	Ipoh	Pos Blau
SPI1	1.13	1.18	1.10	1.10	1.06	1.04
SPI6	0.46	0.48	0.46	0.37	0.35	0.35
SPI12	0.25	0.25	0.27	0.25	0.22	0.21
ZSI1	0.00	1.15	1.08	1.08	1.06	1.03
ZSI6	0.47	0.46	0.46	0.37	0.34	0.36
ZSI12	1.12	1.08	1.07	1.06	1.03	0.99
PNPI1	65.16	65.12	60.12	54.98	45.76	71.90
PNPI6	12.72	11.19	10.22	8.62	7.37	11.97
PNPI12	63.99	59.93	54.30	45.62	71.21	60.98
DI1	3.11	3.31	3.12	3.15	2.99	2.93
DI6	1.29	1.25	1.33	1.15	0.97	1.03
DI12	3.26	3.11	3.11	2.97	2.91	3.03
RAI1	3.52	3.73	3.54	3.38	3.30	3.29
RAI6	1.43	1.40	1.40	1.16	1.04	1.07
RAI12	3.66	3.54	3.35	3.29	3.27	3.36
	Kuala Betis	**Pos Gob**	**Subang**	**Batu Pahat**	**Senai**	
SPI1	1.04	1.07	1.18	1.08	1.13	
SPI6	0.34	0.40	0.50	0.44	0.42	
SPI12	0.23	0.27	0.35	0.29	0.26	
ZSI1	1.01	1.08	1.19	1.07	1.13	
ZSI6	0.32	0.40	0.49	0.43	0.42	
ZSI12	1.06	1.18	1.06	1.12	1.08	
PNPI1	61.74	54.99	49.30	47.83	52.54	
PNPI6	9.75	9.57	7.86	8.76	8.07	
PNPI12	54.15	49.05	47.09	51.54	59.06	
DI1	3.07	3.06	3.46	3.03	3.20	
DI6	1.10	1.17	1.39	1.27	1.28	
DI12	3.02	3.44	3.00	3.16	3.20	
RAI1	3.40	3.44	3.74	3.35	3.62	
RAI6	1.13	1.29	1.57	1.42	1.33	
RAI12	3.40	3.72	3.32	3.58	3.56	

Based on Table 2, a comparison of each drought index on different timescales revealed that all drought indices experienced the highest sensitivity on a one-month timescale, with SPI-1 ranging from 1.04 to 1.18, PNPI-1 ranging from 45.79 to 71.90, DI-1 ranging from 2.93 to 3.46, RAI-1 ranging from 3.29 to 3.74 and ZSI-1 ranging from 0.00 to 1.19. From this it was concluded that short-term precipitation data (one-month) are more responsive to the fluctuation of dry and wet conditions in short-term periods. Similarly, all drought indices showcased lower fluctuation when timescales increased as all indices have the lowest AMR value when deploying 12-month rainfall values, clearly showcasing long-term drought features. The findings are consistent with Fung *et al.* (2020), who revealed drought indices on one-month timescales had the highest fluctuation, indicating that a series on smaller timescales has lower stability.

Figure 2 shows the visualisation of AMR values for all the drought indices on different timescales and the results obtained are shown in Table 2, showing that the drought indices (SPI, PNPI, DI, RAI and *Z*-score) on a one-month timescale had a higher sensitivity compared with the other timescales (six- and 12-month). Due to the reactivity of the one-month timescale to the fluctuation of drought indices, it can be concluded that shorter timescales correspond better to short-term drought and vice versa. This finding agreed with Wu *et al.* (2021), where it was found that longer timescales of hydrological drought corresponded to larger propagation thresholds from meteorological drought to hydrological drought and vice versa.

MK and Sen's slope estimator

Trends of dry spell events over the 25 years (1984–2018) were analysed in this study. The MK test and Sen's slope estimator were conducted to assess temporal analysis for five different drought indices at 11 rainfall stations over the study period. *Z*-value indicates the presence of an upward (positive) or downward (negative) trend. The significance level is set to be

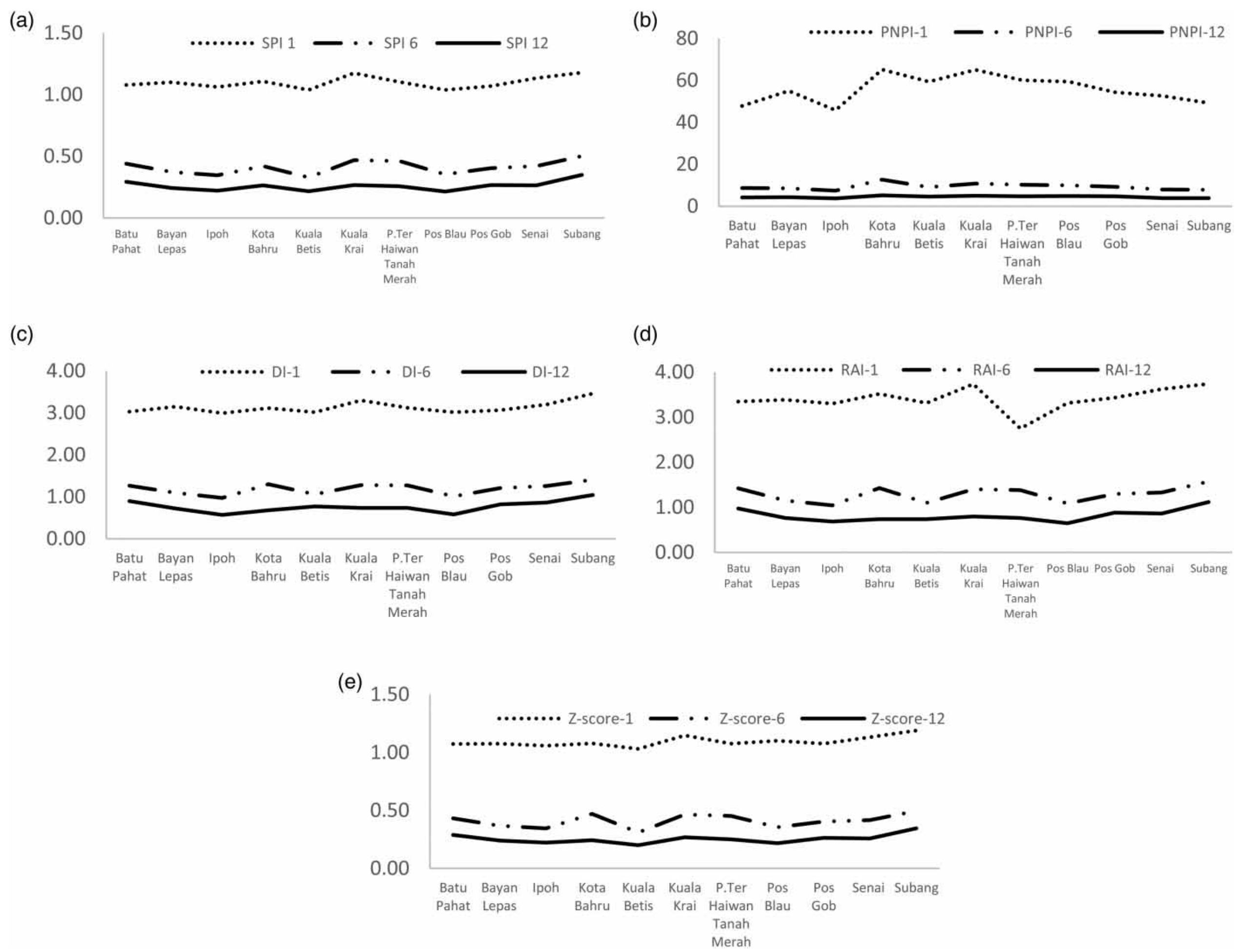

Figure 2 | AMR (1984–2018) of (a) SPI, (b) PNPI, (c) DI, (d) RAI, (e) ZSI.

95%, and if the P-value is lower than 0.05, the trend is then statistically present in the time-series data. Sen's slope estimator indicates the magnitude of the increasing or decreasing trend of every drought index on each timescale. The trend analysis results are presented in Table 3.

As shown in Table 3, most stations (Ipoh, Bayan Lepas, Kuala Krai, P.Ter Haiwan Tanah Merah, Pos Blau and Subang) showed an increasing trend for SPI on one-, six- and 12-month timescales. A significant increasing trend can be observed in both SPI-6 and SPI-12 in Bayan Lepas, Ipoh and Subang stations. P.Ter Haiwan Tanah Merah and Pos Blau exhibited a significant increasing trend for SPI on all timescales except for SPI-1. Of all meteorological stations, SPI-12 at Subang station exhibited the highest trend magnitude with a Sen's slope of 0.0047. Kuala Betis station was the only station that exhibited negative trends in both SPI-6 and SPI-12. No significant trend was found in any drought indices for stations Senai, Kota Bahru and Batu Pahat.

Based on the results obtained from temporal analysis, all drought indices had similar outcomes and indicated that six out of 11 stations (Bayan Lepas, Ipoh, Kuala Krai, P.Ter Haiwan Tanah Merah, Pos Blau and Subang) exhibit increasing trends on one-, six- and 12-month timescales. This indicated an increasing trend of wet conditions in those regions. Other than that, drought indices in Kuala Betis exhibited both increasing and decreasing trends on different timescales. When drought indices were computed on a one-month timescale, SPI, ZSI, RAI and DI exhibited an increasing trend while all five indices exhibited a decreasing trend when computed on six- and 12-month timescales for Kuala Betis station. This suggested that drought indices on a one-month scale are more sensitive to short-term variations in rainfall. When these indices are calculated on longer scales such as six- and 12-month, the short-term variation may be averaged out, revealing a more accurate representation of the longer-term patterns. Other than that, Pos Gob is the only rainfall station to exhibit a decreasing trend, with a Z-value and Sen's of -0.0767 and -0.0013, respectively, for ZSI-6. Although only ZSI-6 exhibited a significant decreasing trend, other indices especially on six- and 12-month scales also showed marginally significant trends. While these indices did not meet the 0.05 threshold, it is possible that with more data or a larger sample size, these trends could become statistically significant. This suggested that the Pos Gob region is more likely to experience drought, which is supported by the occurrence of multiple severe droughts in the past in that region (Tan *et al.* 2017).

Performance evaluation of drought indices

RMSE, MAE and MAPE were applied to determine the highest accuracy drought index by comparing them with SPI. The drought index that obtained the lowest-measure values among the other drought indices would be chosen as the most accurate drought index.

Table 4 shows the performances of PNPI, DI, RAI and ZSI on one-, six- and 12-month timescales. Statistical tests used in this study evaluate drought indices based on error, for example, if a drought index obtains a lower score on any of the statistical tests (RMSE, MAE and MAPE), it indicates that the index has higher accuracy and vice versa. Although all drought indices use precipitation data as their only parameter, ZSI obtained the lowest RMSE, MAE and MAPE values for all stations on every timescale, which indicated that it acquired the highest accuracy among the other drought indices. Like SPI, ZSI indicates the desertion of moisture conditions by computing a standard deviation above or below the mean precipitation value of a data series. However, the indices should not be confused with each other as precipitation data do not require to be fitted into a probability distribution in the computation of ZSI. With the similarity in the performance of ZSI and SPI and the addition of ease in calculation, ZSI is regarded as the best alternative drought index (Dogan *et al.* 2012). In comparison, PNPI showcased weaker accuracy than SPI, obtaining the highest RMSE, MAE and MAPE values. This revealed that PNPI was not suitable to identify droughts. The DI obtained the second lowest RMSE, MAE and MAPE values followed by the RAI. This finding has been supported by Myronidis *et al.* (2018) and Shahabfar & Eitzinger (2013), who revealed that the Z-score is a better tool for monitoring droughts.

CONCLUSION

This study focuses on drought assessment by developing five drought indices (SPI, PNPI, DI, RAI and ZSI) on timescales of one-, six- and 12-month from 1994 to 2018 throughout Peninsular Malaysia. Comparisons between all drought indices were made based on their behaviour via temporal analysis. AMR shows that all drought indices fluctuate more by short-term rainfall (one-month). In comparison, the sensitivity of drought index fluctuation decreases when long-term rainfall is used, as the smallest AMR values are detected for drought indices on a 12-month timescale. Other than that, the MK test and Sen's slope estimator were used to investigate the trend magnitude of drought indices. The results of MK showed that most drought indices performed similarly in terms of trends on different timescales. Stations such as Senai, Kota Bahru and Batu Pahat did not exhibit any significant trend for all drought indices.

Table 3 | Temporal analysis of SPI and PNPI on one-, six-, 12-month timescales

		SPI			PNPI			RAI			ZSI			DI		
	Stations	**1**	**6**	**12**	**1**	**6**	**12**	**1**	**6**	**12**	**1**	**6**	**12**	**1**	**6**	**12**
Z	Batu Pahat	−0.0079	0.0256	0.0614	−0.0063	0.0256	0.0586	−0.0032	0.0259	0.0616	−0.0042	0.0266	0.0606	−0.008	0.0244	0.0455
P-value		0.8384	0.5089	0.1132	0.8719	0.5096	0.1304	0.9348	0.5037	0.1115	0.9133	0.4928	0.1179	0.8439	0.5488	0.2628
Sen's slope		−0.0002	0.0004	0.001	−0.0049	0.0087	0.0138	−0.0002	0.0015	0.0033	−0.0001	0.0005	0.001	0	0	0
Z	Bayan Lepas	0.0369	0.0898	0.129	0.0221	0.0888	0.1269	0.0372	0.0879	0.1284	0.0381	0.0878	0.1285	0.0359	0.1003	0.141
P-value		0.3408	**0.0205**	**0.0009**	0.569	**0.0219**	**0.0011**	0.337	**0.0232**	**0.0009**	0.325	**0.0234**	**0.0009**	0.377	**0.0135**	**0.0005**
Sen's slope		0.0007	0.0016	0.0023	0.0181	0.0356	0.0389	0.002	0.0048	0.007	0.0006	0.0015	0.0022	0	0	0.0056
Z	Ipoh	0.0549	0.1154	0.1381	0.0555	0.1177	0.1385	0.0546	0.1155	0.1395	0.0579	0.1162	0.1377	0.048	0.1347	0.1468
P-value		0.1569	**0.0029**	**0.0004**	0.1521	**0.0024**	**0.0004**	0.1589	**0.0029**	**0.0003**	0.1352	**0.0027**	**0.0004**	0.2377	**0.0009**	**0.0003**
Sen's slope		0.001	0.0021	0.0025	0.0424	0.0456	0.0415	0.003	0.0064	0.0077	0.001	0.0021	0.0025	0	0.0052	0.0056
Z	Kota Bahru	0.0416	0.0458	0.0526	0.0596	0.006	−0.033	0.0493	0.0049	−0.0342	0.0541	0.0033	−0.0333	0.0504	0.0011	−0.0307
P-value		0.2833	0.2373	0.1748	0.1241	0.8773	0.395	0.2029	0.8996	0.3779	0.1622	0.9316	0.3905	0.2144	0.9783	0.4504
Sen's slope		0.0008	0.0008	0.0009	0.0544	0.0033	−0.0126	0.0024	0.0003	−0.0019	0.0008	0.0001	−0.0006	0	0	0
Z	Kuala Betis	0.1054	−0.1337	−0.1868	0.1081	−0.1278	−0.1826	0.1085	−0.1321	−0.1848	0.11	−0.1338	−0.1868	0.1164	−0.1233	−0.1927
P-value		**0.007**	**0.0006**	**1.46×10^{-6}**	0.0053	**0.001**	**0.0001**	**0.0051**	**0.0006**	**0.0001**	**0.0045**	**0.0006**	**0**	**0.0041**	**0.0024**	**0.0001**
Sen's slope		0.0019	−0.0021	−0.0028	0.0962	−0.0513	−0.0541	0.0057	−0.0068	−0.0091	0.0017	−0.0019	−0.0024	0.0043	−0.0049	−0.0084
Z	Kuala Krai	0.0369	0.1127	0.2044	0.0404	0.1137	0.2029	0.0413	0.1155	0.2029	0.0331	0.1139	0.2043	0.0418	0.1249	0.2144
P-value		0.3408	**0.0037**	**1.37×10^{-7}**	0.2972	**0.0033**	**0.0001**	0.2862	**0.0029**	0	0.3934	**0.0033**	**0**	0.3036	**0.0021**	**0.0001**
Sen's slope		0.0007	0.0022	0.0038	0.0366	0.0496	0.0662	0.0022	0.0065	0.0113	0.0006	0.0022	0.0039	0	0.0047	0.0097
Z	P.Ter Haiwan Tanah Merah	0.042	0.1681	0.2661	0.0646	0.1781	0.2735	0.2728	0.1707	0.2728	0.042	0.1707	0.2732	0.0468	0.1827	0.2855
P-value		0.2787	**<0.0001**	**<0.0001**	0.0952	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	0.2787	**<0.0001**	**<0.0001**	0.2492	**<0.0001**	**<0.0001**
Sen's slope		0.0008	0.0029	0.0043	0.0556	0.0785	0.0891	0.0146	0.0093	0.0146	0.0007	0.003	0.0047	0	0.008	0.0128
Z	Pos Blau	0.1054	0.1879	0.1976	0.1081	0.1881	0.1961	0.1085	0.1887	0.1962	0.1085	0.1888	0.1967	0.1164	0.1988	0.2102
P-value		**0.007**	**<0.0001**	**<0.0001**	**0.005**	**<0.0001**	**<0.0001**	**0.005**	**<0.0001**	**<0.0001**	**0.005**	**<0.0001**	**<0.0001**	**0.004**	**<0.0001**	**<0.0001**
Sen's slope		0.0019	0.0034	0.004	0.0962	0.088	0.0869	0.0057	0.0099	0.0117	0.0057	0.0032	0.0039	0.0043	0.0089	0.0096
Z	Pos Gob	−0.0372	−0.0756	−0.0721	−0.0552	−0.075	−0.071	−0.039	−0.073	−0.0745	−0.0374	−0.0767	−0.0719	−0.0519	−0.0635	−0.0838
P-value		0.337	0.0512	0.0629	0.1539	0.0545	0.0653	0.3144	0.0608	0.0543	0.3341	**0.048**	0.0634	0.2011	0.1179	0.039
Sen's slope		−0.0007	−0.0013	−0.0012	−0.0491	−0.03	−0.021	−0.0021	−0.004	−0.0042	−0.0007	−0.0013	−0.0012	0	0	0
Z	Senai	0.0191	0.0458	0.0526	0.0145	0.044	0.055	0.0233	0.0451	0.0514	0.0217	0.046	0.0514	0.0278	0.0409	0.0562
P-value		0.6224	0.2373	0.1748	0.709	0.2561	0.1562	0.5477	0.244	0.1845	0.5752	0.2348	0.1842	0.4939	0.3137	0.1662
Sen's slope		0.0003	0.0008	0.0009	0.01	0.0145	0.013	0.0013	0.0025	0.0028	0.0004	0.0008	0.0009	<0.0001	<0.0001	<0.0001
Z	Subang	0.0632	0.2015	0.2783	0.0644	0.1996	0.2754	0.0642	0.2012	0.2779	0.0642	0.2013	0.2781	0.06	0.2159	0.2957
P-value		0.1031	**<0.0001**	**<0.0001**	0.0964	**<0.0001**	**<0.0001**	0.0972	**<0.0001**	**<0.0001**	0.0975	**<0.0001**	**<0.0001**	0.1395	**<0.0001**	**<0.0001**
Sen's slope		0.0011	0.0035	0.0047	0.0479	0.0535	0.0508	0.0036	0.0109	0.0148	0.0012	0.0035	0.0047	0	0.0094	0.0134

Note: Bold values indicates significant trend for the drought index.

Table 4 | Results of performance measures for drought indices

Drought Indices			Batu Pahat	Bayan Lepas	Ipoh	Kota Bahru	Kuala Betis	Kuala Krai
PNPI	1-month	RMSE	109.34	113.03	108.97	121.81	115.32	119
		MAE	99.99	100	100	100.01	99.99	100
		MAPE	227.26	454.55	185.19	59.53	43.67	434.79
DI		RMSE	5.78	5.78	5.78	5.79	5.78	5.78
		MAE	5.48	5.48	5.47	5.49	5.47	5.48
		MAPE	12.44	24.91	10.14	3.27	2.39	23.81
RAI		RMSE	2.15	2.18	2.137	2.36	2.25	2.34
		MAE	0.05	0.12	0.06	0.13	0.14	0.09
		MAPE	0.12	0.56	0.11	0.08	0.06	0.41
MZSI		RMSE	0.2	0.2	0.19	0.35	0.23	0.27
		MAE	**0.0015**	**0.0007**	**0.0018**	**0.0056**	**0.0076**	**0.0008**
		MAPE	**0.0033**	**0.0033**	**0.0033**	**0.0033**	**0.0033**	**0.0033**
PNPI	6-month	RMSE	**101.77**	**102.39**	**101.98**	**104.14**	**103.75**	**102.61**
		MAE	100	100	100	100	100	100
		MAPE	2,001.39	3,333.38	5,000.047	1,111.13	294.12	1,666.64
DI		RMSE	5.79	5.78	5.78	6.23	5.81	5.78
		MAE	5.48	5.48	5.48	5.48	5.48	5.48
		MAPE	256.44	182.56	274	60.89	16.12	91.34
RAI		RMSE	2.25	2.11	2.02	3.21	2.59	2.03
		MAE	0.08	0.09	0.011	0.02	0.11	0.05
		MAPE	1.56	2.85	0.55	0.27	0.33	0.85
ZSI		RMSE	0.093	0.092	0.0766	1.43	0.14	0.088
		MAE	**0.004**	**0.0001**	**0.0002**	**0.0003**	**0.0011**	**0.0002**
		MAPE	**0.0033**	**0.0033**	**0.0033**	**0.0033**	**0.0033**	**0.0033**
PNPI	12-month	RMSE	**100.89**	**101.4**	**101.2**	**102.29**	**102.28**	**101.3**
		MAE	99.99	99.99	100	100	100	100
		MAPE	1,667	1,249.99	1,111.1	1,666.67	312.51	833.33
DI		RMSE	5.8	5.78	5.78	6.26	5.82	5.78
		MAE	5.48	5.48	5.48	5.48	5.48	5.48
		MAPE	91.34	68.5	60.89	91.34	17.13	45.66
RAI		RMSE	2.33	2.13	2.03	3.25	2.65	1.95
		MAE	0.03	0.12	0.042	0.018	0.08	0.03
		MAPE	0.54	1.44	0.46	0.3	0.26	0.28
ZSI		RMSE	**0.076**	**0.075**	**0.06**	**1.48**	**0.12**	**0.062**
		MAE	**0.0002**	**0.0002**	**0.0003**	**0.0002**	**0.001**	**0.0004**
		MAPE	**0.0033**	**0.0033**	**0.0033**	**0.003**	**0.003**	**0.0033**

Drought Indices			P.Ter Haiwan Tanah Merah	Pos Blau	Pos Gob	Senai	Subang
PNPI	1-month	RMSE	117.51	115.32	112.79	110.73	107.93
		MAE	100	99.99	99.99	100	100
		MAPE	322.59	43.67	54.34	555.57	125
DI		RMSE	5.78	5.78	5.79	5.79	5.79
		MAE	5.48	5.47	5.47	5.48	5.48
		MAPE	17.68	2.39	2.97	30.44	6.85
RAI		RMSE	3.03	2.25	2.24	2.24	2.17
		MAE	0.06	0.14	0.07	0.11	0.04
		MAPE	0.21	0.06	0.04	0.6	0.06
ZSI		RMSE	0.25	0.23	0.28	0.21	0.21
		MAE	**0.001**	**0.0076**	**0.0061**	**0.0006**	**0.0027**
		MAPE	**0.0033**	**0.0033**	**0.0033**	**0.0033**	**0.0033**

(*Continued.*)

Table 4 | Continued

Drought Indices			P.Ter Haiwan Tanah Merah	Pos Blau	Pos Gob	Senai	Subang
PNPI	6-month	RMSE	**102.81**	**103.4**	**102.44**	**101.78**	**101.08**
		MAE	100	100	100	100	100
		MAPE	103.09	1,249.96	1,250.66	1,111.14	2,000.02
DI		RMSE	5.8	5.78	5.79	5.79	5.78
		MAE	5.48	5.48	5.48	5.48	5.48
		MAPE	5.65	68.5	548	60.89	109.6
RAI		RMSE	2.12	2.07	2.22	2.25	2.15
		MAE	0.06	0.04	0.02	0.04	0.03
		MAPE	0.06	0.51	2.36	0.43	0.68
ZSI		RMSE	0.15	0.11	0.099	0.092	0.0674
		MAE	**0.0032**	**0.0003**	**0.0003**	**0.0003**	**0.0002**
		MAPE	**0.0033**	**0.0033**	**0.0033**	**0.0033**	**0.0033**
PNPI	12-month	RMSE	**101.69**	**102.26**	**101.45**	**100.95**	**100.49**
		MAE	100	100	100	100	100
		MAPE	119.04	5,000.03	625	1,666.66	1,675.66
DI		RMSE	5.81	5.77	5.8	5.79	5.78
		MAE	5.47	5.48	5.48	5.48	5.48
		MAPE	6.52	17.52	34.25	91.28	43.55
RAI		RMSE	2.16	1.98	2.43	2.34	2.15
		MAE	0.06	0.0008	0.053	0.04	2.19
		MAPE	0.07	0.039	0.33	0.74	0.35
ZSI		RMSE	**0.14**	**0.085**	**0.096**	**0.068**	**0.046**
		MAE	**0.0028**	**0.0001**	**0.0005**	**0.0002**	**0.0002**
		MAPE	**0.0033**	**0.0033**	**0.0033**	**0.0033**	**0.0033**

Note: Bold values indicate highest accuracy.

Moreover, the results from the accuracy evaluation showed that ZSI is the best alternative drought index due to its similar performance to SPI. The results from MAE, MAPE and RMSE indicated that ZSI has the highest accuracy on all timescales (one-, six- and 12-month). Other than that, the calculation of ZSI is less complex than the other indices and is even more suitable to be applied in regions with limited access to precipitation data (Jain *et al.* 2015). Combined with the results obtained from temporal analysis, SPI and ZSI can be applied interchangeably for drought assessment in Peninsular Malaysia.

In addition, it is recommended to compare drought indices that take into account PET's impact, such as the standardised precipitation evapotranspiration index (SPEI) in future studies since the drought indices evaluated in this study only use precipitation data. To top that off, a drought index such as the SDI is recommended to be compared for a better understanding of drought characteristics in Peninsular Malaysia. Since several stations in this study are located in Kelantan State, it is recommended to include more stations in other locations throughout Peninsular Malaysia for drought assessment.

ACKNOWLEDGEMENT

The authors would like to thank the Malaysian Meteorological Department (MMD) for the provision of the meteorological data.

AUTHOR CONTRIBUTIONS

All authors equally contributed to the preparation of this manuscript. All authors read and approved the final manuscript.

FUNDING

The study was funded by the Malaysian Ministry of Higher Education through the Fundamental Research Grant Scheme (FRGS/1/2021/TK0/UCSI/03/3).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Coulibaly, A. L. 2013 *The Food Price Increase of 2010-2011: Causes and Impacts*. Publication No. 2013-02-E, Library of Parliament (Bibliothèque du Parlement), Ottawa, ON, Canada.

Dogan, S., Berktay, A. & Singh, V. P. 2012 Comparison of multi-monthly rainfall-based drought severity indices, with application to semi-arid Konya closed basin, Turkey. *Journal of Hydrology* **470–471**, 255–268. doi:10.1016/j.jhydrol. 2012.09.003.

Edwards, D. C. & McKee, T. B. 1997 *Characteristics of 20th Century Drought in the United States at Multiple Time Scales*. Atmospheric Science Paper 634, Department of Atmospheric Science, Colorado State University, Fort Collins, CO, USA, pp. 1–30.

Fung, K. F., Huang, Y. F. & Koo, C. H. 2020 Assessing drought conditions through temporal pattern, spatial characteristic and operational accuracy indicated by SPI and SPEI: case analysis for Peninsular Malaysia. *Natural Hazards* **103**, 2071–2101. https://doi.org/10.1007/s11069-020-04072-y.

Gibbs, W. J. & Maher, J. V. 1967 *Rainfall Deciles as Drought Indicators*. Bureau of Meteorology Bulletin No. 48, Melbourne, Australia.

Gil-Quintana, E., Larrainzar, E., Seminario, A., Díaz-Leal, J. L., Alamillo, J. M., Pineda, M., Arrese-Igor, C., Wienkoop, S. & González, E. M. 2013 Local inhibition of nitrogen fixation and nodule metabolism in drought-stressed soybean. *Journal of Experimental Botany* **64** (8), 2171–2182.

Javed, T., Li, Y., Rashid, S., Li, F., Hu, Q., Feng, H., Chen, X., Ahmad, S., Liu, F. & Pulatov, B. 2021 Performance and relationship of four different agricultural drought indices for drought monitoring in China's mainland using remote sensing data. *Science of the Total Environment* **759**, 143530. https://doi.org/10.1016/j.scitotenv.2020.143530.

Jain, V. K., Pandey, R. P., Jain, M. K. & Byun, H.-R. 2015 Comparison of drought indices for appraisal of drought characteristics in the Ken River Basin. *Weather and Climate Extremes* **8**, 1–11.

Kam, J., Sheffield, J. & Wood, E. F. 2014 Changes in drought risk over the contiguous United States (1901–2012): the influence of the Pacific and Atlantic Oceans. *Geophysical Research Letters* **41** (16), 5897–5903.

Kendall, M. 1975 *Rank Correlation Methods*. Charles Griffin, London, UK.

Khanmohammadi, N., Rezaie, H. & Behmanesh, J. 2022 Investigation of drought trend on the basis of the best obtained drought index. *Water Resources Management* **36** (4), 1355–1375.

Liu, X., Zhu, X., Pan, Y., Bai, J. & Li, S. 2018 Performance of different drought indices for agriculture drought in the North China Plain. *Journal of Arid Land* **10**, 507–516.

Mann, H. B. 1945 Nonparametric tests against trend. *Econometrica: Journal of the Econometric Society* **13** (3), 245–259. doi:10.2307/1907187.

Mondol, M. A. H., Ara, I. & Das, S. C. 2017 Meteorological drought index mapping in Bangladesh using standardized precipitation index during 1981–2010. *Advances in Meteorology* **2017**, 4642060.

Myronidis, D., Fotakis, D., Ioannou, K. & Sgouropoulou, K. 2018 Comparison of ten notable meteorological drought indices on tracking the effect of drought on streamflow. *Hydrological Sciences Journal* **63** (15–16), 2005–2019. doi:10.1080/02626667.2018.1554285.

Nalbantis, I. & Tsakiris, G. 2008 Assessment of hydrological drought revisited. *Water Resources Management* **23** (5), 881–897.

Palmer, W. C. 1965 *Meteorological Drought*. Research Paper No. 45, Department of Commerce, Washington, DC, USA.

Palmer, W. C. 1968 Keeping track of crop moisture conditions, nationwide: the New Crop Moisture Index. *Weatherwise* **21**, 156–161.

Prajapati, V. K., Khanna, M., Singh, M., Kaur, R., Sahoo, R. N. & Singh, D. K. 2021 Evaluation of time scale of meteorological, hydrological and agricultural drought indices. *Natural Hazards* **109**, 89–109. https://doi.org/10.1007/s11069-021-04827-1.

Salimi, H., Asadi, E. & Darbandi, S. 2021 Meteorological and hydrological drought monitoring using several drought indices. *Applied Water Science* **11**, 11.

Sanusi, W., Jemain, A. A., Zin, W. Z. W. & Zahari, M. 2015 The drought characteristics using the first-order homogeneous Markov chain of monthly rainfall data in Peninsular Malaysia. *Water Resources Management* **29** (5), 1523–1539.

Sen, P. K. 1968 Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association* **63**, 1379–1389. https://doi.org/10.1080/01621459.1968.10480934.

Shaadan, N., Jemain, A. A., Latif, M. T. & Deni, S. M. 2015 Anomaly detection and assessment of PM_{10} functional data at several locations in the Klang Valley, Malaysia. *Atmospheric Pollution Research* **6** (2), 365–375.

Shahabfar, A. & Eitzinger, J. 2013 Spatio-temporal analysis of droughts in semi-arid regions by using meteorological drought indices. *Atmosphere* **4**, 94–112. doi:10.3390/atmos4020094.

Singh, V. P. 1994 *Elementary Hydrology*. Prentice Hall of India, New Delhi, India.

Tan, M. L., Tan, K. C., Chua, V. P. & Chan, N. W. 2017 Evaluation of TRMM product for monitoring drought in the Kelantan River Basin, Malaysia. *Water* **9** (1), 57. https://doi.org/10.3390/w9010057.

Tsakiris, G. & Vangelis, H. 2005 Establishing a drought index incorporating evapotranspiration. *European Water* **9/10**, 3–11.

Van Rooy, M. P. 1965 A rainfall anomaly index (RAI) independent of time and space. *Notos* **14**, 43–48.

Vicente-Serrano, S. M., Begueria, S. & López-Moreno, J. I. 2010 A multi-scalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *Journal of Climate* **23**, 1696–1718.

Viessman, W., Lewis, G. L. & Knapp, J. W. 1989 *Introduction to Hydrology*, 3rd edn. Harper & Row Publishers lnc., New York, USA.

Willeke, G., Hosking, J. R. M., Wallis, J. R. & Guttman, N. B. 1994 *The National Drought Atlas*. Institute for Water Resources Report 94-NDS-4, US. Army Corps of Engineers, Alexandria, VA, USA, pp. 582–587.

Wu, J., Chen, X., Yao, H. & Zhang, D. 2021 Multi-timescale assessment of propagation thresholds from meteorological to hydrological drought. *Science of the Total Environment* **765**, 144232.

Yaseen, Z. M., Ali, M., Sharafati, A., Al-Ansari, N. & Shahid, S. 2021 Forecasting standardized precipitation index using data intelligence models: regional investigation of Bangladesh. *Scientific Reports* **11**, 3435. https://doi.org/10.1038/s41598-021-82977-9.

First received 20 June 2023; accepted in revised form 12 September 2023. Available online 25 September 2023