SPATIO-TEMPORAL ANALYSIS OF HYDRO-METEOROLOGICAL DROUGHT IN THE MUDA RIVER BASIN, MALAYSIA

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by

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TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURES

Page

LIST OF SYMBOLS

x_i	Rainfall Mean
µ	Monthly rainfall recorded of the station
σ	Standard deviations
Z	Absolute value of more than $\pm$1.96 indicates significance trend at the 95 % confidence level
S	The $\pm$ of value S is indicate decreasing or increasing trend
N	Pairs of the data predicted
x_j	Values in j and k (j>k)
x_k	Values in j and k (k>j)
Q_i	Ranked from smallest to largest
D_D	Drought duration
D_I	Drought intensity
D_S	Drought severity
D_P	Drought peak
R_R	Response rate
n	The hydrological drought occurrences (SSI<0 when SPI<0)
m	Occurrences of meteorological droughts (SPI<0)
P	Spearman’s rho correlation
d_i	The difference between drought indices and atmospheric circulation indices
n	The number of the observations

LIST OF ABBREVIATIONS

ENSO	El Nino Southern Oscillation
IOD	Indian Ocean Dipole
MJO	Madden Julian Oscillation
MRB	Muda River Basin
SPI	Standardized Precipitation Index
SPEI	Standardized Precipitation Evapotranspiration
SSI	Standardized Streamflow Index
IDI	Integrated Drought Index

LIST OF APPENDICES

ANALISIS RUANG MASA KEMARAU HIDRO-METEOROLOGI DI LEMBANGAN SUNGAI MUDA, MALAYSIA

ABSTRAK

Kajian ini bertujuan untuk menganalisis perubahan ruang-masa kemarau di Lembangan Sungai Muda (MRB) dari tahun 1985 hingga 2019 dengan menggunakan *Standardized Precipitation Index (SPI)* dan *Standardized Streamflow Index (SSI)* pada skala masa yang berbeza (1-, 3-, 6-, & 12 bulan). Kaedah *Mann-Kendall* dan *Sens Slope* digunakan untuk menilai kecenderungan dan perubahan signifikan kemarau. Manakala, *Spearman's rho* digunakan untuk memahami hubungan antara kemarau dan peredaran atmosfera berskala besar seperti *El-Nino Southern Oscillation (ENSO)*, *Indian Ocean Dipole (IOD)*, dan *Madden-Julian Oscillation (MJO)*. Hasil kajian ini menunjukkan bahawa kemarau yang teruk di MRB kebanyakannya berlaku pada tahun 1991-1992, 1995, 1998, 2002-2003, 2005-2006, 2008, 2012-2013, dan 2016. Di samping itu, penurunan SPI dapat dilihat dari bulan Mei hingga Disember di kebanyakan stesen pada skala masa yang berbeza. Kira-kira 80% daripada stesen mengalami 10 peristiwa kemarau yang teruk, manakala hampir semua stesen mengalami sekurang-kurangnya 5 kejadian yang sangat kering, dengan kemarau yang lebih teruk dapay diperhatikan di bahagian atas Lembangan Sungai Muda. Kadar tindak balas SSI kepada SPI yang lebih tinggi didapati berlaku pada musim hujan rendah (80% hingga 90%) iaitu dari Januari hingga Mei berbanding musim hujan tinggi (70% hingga 80%) pada bulan Ogos hingga November. ENSO mempunyai kesan yang lebih besar terhadap pembentukan kemarau di MRB berbanding IOD dan MJO, terutamanya dari Januari hingga Mei. Akhir sekali, kebanyakan stesen telah mengalami kemarau yang lebih teruk dalam beberapa tahun kebelakangan ini, yang mungkin secara tidak langsung menjejaskan sumber air. Dapatan kajian ini boleh

digunakan dalam pengurusan sumber air dan penggubalan dasar dengan mengambil kira corak dan ciri kemarau yang telah berlaku.

SPATIO-TEMPORAL ANALYSIS OF HYDRO-METEOROLOGICAL DROUGHT IN THE MUDA RIVER BASIN, MALAYSIA

ABSTRACT

This study aims to analyse the spatiotemporal changes of historical droughts over the Muda River Basin (MRB) from 1985 to 2019 using the Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) at 1-, 3-, 6-, & 12-month time scales. The Mann-Kendall test and Sens' slope were used to evaluate the trends and magnitude changes of the droughts, respectively. While, Spearman's rho was applied to understand the relationships between droughts and large-scale atmospheric circulations such as the El-Nino Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Madden-Julian Oscillation (MJO). The results show that the intense droughts in the MRB mostly occurred in 1991-1992, 1995, 1998, 2002-2003, 2005-2006, 2008, 2012-2013, and 2016. In addition, a declining SPI trend was found from May to December at most of the stations on different time scales. About 80% of the stations experienced about 10 severely dry droughts, while almost all stations experienced at least 5 extremely dry events, with more intense droughts were observed in the in the upper part of the MRB. A higher response rate of SSI to SPI was found during low-rainfall months (80% to 90%) from January to May than high-rainfall months (70% to 80%) in August to November. The ENSO had a larger impact on the drought formations over the MRB compared to the IOD and MJO, especially from January to May. Lastly, most of the stations have experienced more intense droughts in recent years, which might indirectly affect the water resources. The findings of this study could be used in water resources management and policy formulation with the consideration of drought patterns and characteristics.

CHAPTER 1

INTRODUCTION

1.1 Introduction

In Malaysia, climate change is expected to have a significant impact. The number of heatwaves that occur each year is expected to increase dramatically as temperatures rise (Haliza , 2018). Variations in precipitation can produce droughts and floods in different parts of the country. The Intergovernmental Panel on Climate Change (IPCC) (2022) stated that observed increases in the frequency and intensity of climate and weather extremes, including hot extremes on land and in the ocean, heavy precipitation events, drought, and fire weather, have resulted in widespread, pervasive impacts to ecosystems, people, settlements, and infrastructure. The Sustainable Development Goal 13 prioritises combating climate change, which has prompted this research. Climate change adaptation and mitigation strategies are managed to reduce the risk of a climate disaster. It is critical to improve coordination between national meteorological and hydrological services, disaster management authorities, and development agencies.

Drought is a natural hazard defined the amount of precipitation is insufficient for meeting human activities and environmental demands when continued over a duration of a season or longer time (Wilhite et al., 1985). Drought is a regional phenomenon where characteristics vary according to the global climate system in which it occurs (Iglesias et al., 2009). Drought is frequently viewed as a creeping hazard due to its gradual onset and protracted endurance (Wilhite & Vanyarkho, 2000;Smith & Katz, 2013) Drought is not as physically destructive as other natural disasters, but it does affect broad areas and has a variety of economic, environmental, and social implications (Wilhite et al., 1985).

In general, drought can be categorised into four groups (Wilhite et al., 1985) which as follow;

1) Meteorological drought - a period of time when there is a lack of rainfall throughout a region. Commonly, the rainfall data used to analysis the meteorological (Pinkayan, 1966).

2) Hydrological drought - A time of insufficient surface and subsurface water resources for established water usage of a given water resources management system is referred to as a hydrological drought (Mishra & Singh, 2010; Van Loon, 2015). The hydrological drought analysis has been widely used with streamflow data (Clausen & Pearson, 1995).

3) Agricultural drought - Agriculture refers to a period of low soil moisture and resultant crop loss without reference to surface water. Several factors influence soil moisture loss, including climatic and hydrological droughts, and discrepancies between actual and prospective evapotranspiration. Plant water demand is influenced by weather, plant biology, stage of growth, and soil physical and biological features. Several drought indices have been developed based on precipitation, temperature, and soil moisture.

4) Socio-economic drought - Droughts are linked to the availability and demand of an economic benefit (water) (American Meteorological Society, 2004). The drought occurs when demand for an item exceeds supply due to weather related water shortages.

Drought is a global phenomenon, there has been a growing interest in studying how it effects play out regionally, including in Malaysia. Malaysia is divided into two parts: East Malaysia (Peninsular Malaysia) and West Malaysia (Borneo). Malaysia has an equatorial climate, which means that it is hot and humid all year. The Southwest and Northeast Monsoons have a strong influence on annual climatic variability. May to August is the Southwest Monsoon, whereas November to March is the Northeast Monsoon (Tan et al., 2021). In comparison to the Northeast Monsoon, which provides greater precipitation, the Southwest Monsoon has drier weather and less rainfall.

Malaysia had experienced numerous severe droughts and some of the drought event associated with the El-Nino, and one of the most significant events was the 1997/98 El-Nino, which impacted the environment and social activities throughout the country (Suhaila et al., 2010). In the northern states of Peninsular Malaysia, the Muda River Basin (MRB) is a very important basin that supplies freshwater to the northern states in Peninsular Malaysia. More than 80% Penang's, 96% of Kedah's and 50% of Perlis's raw water was extracted from the Muda River (Ramasamy, 2017). Severe drought events could seriously affect the agricultural, economic and societal aspects in this region, which is a home to the largest rice production in Malaysia (Hussin & Mat, 2013). For instance, My Metro (Noorazura, 2016) reported that 35 farmers in Pokok Sena Kedah lost almost 1 million Ringgit Malaysia (RM) in January 2020, when more than 72 hectares of the paddy field was affected by drought.

Suhaila et al. (2010) found that the total rainfall amount during the Northeast Monsoon (NEM) is the lowest rainfall amount receive in northern Peninsular Malaysia, which ranges between 300 mm and 900 mm. Low rainfall normally occurs in Perlis, Kedah, Penang and northern Perak during the final phase of the NEM from February to March. Furthermore, large-scale climate circulation plays an important role affecting the Malaysian weather (Kamil & Omar, 2017). The intense effect of the El-Nino Southern Oscillation (ENSO) on Malaysian rainfall is primarily due to the irregular anti-cyclonic circulation over the southern Philippines and northern Borneo (Tangang & Juneng, 2004). Moreover, the ENSO influences the inter-annual variability of Malaysian temperature for the past few decades (Tangang et al., 2007). During the Boreal winter, parts of the Maritime continent north of the equator likely to have larger precipitation anomalies due to ENSO (Juneng & Tangang, 2005). Besides that, the ENSO also affected the Johor River Basin, which supplies freshwater to Johor and Singapore, is experiencing a hydro-meteorological drought. (Tan et al., 2019).

The Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) are widely applied to analyse meteorological and hydrological droughts, respectively (Tan et al., 2019). The SPI is easy to apply as only required monthly rainfall data and it can be calculated at different time scales (Pathak & Dodamani, 2020, Guttman, 1999). The index has been used to identify and monitor drought events over Sarawak River basin, Malaysia (C. Bong & Richard, 2020). On the other hand, the SSI is frequently employed to understand the hydrological droughts (Shamshirband et al., 2020). SSI uses the same formulate as SPI, but with monthly streamflow data as input. Tan et al. (2019) have evaluated the response of SSI to SPI in the Johor River Basin to understand how meteorological drought affecting hydrological drought condition. They found that hydrological drought could also happened in this basin during the normal precipitation condition as the local authorities tended to store water for facing drought during the dry season. Therefore, it is essential to see the response of meteorological drought to hydrological drought in the MRB, which is important for irrigating the paddy fields. The drought characteristics evaluation could be useful for the policy makers on formulating better drought strategies especially in the Northern region of Peninsular Malaysia.

1.2 Problem Statement

Drought assessment is primary importance in water resource planning and management. From that point of view, the need to examine historically the causes and impacts of droughts in the area during their occurrences. One of the biggest threats to water resource management is the atmosphere of uncertainty. Drought is an important part of climate variability as environmental phenomena. The Muda River is a crucial river since it acts as the key source of water for southern Perlis, Kedah, and Pulau Pinang for potable water and irrigation. For example, in 2014, Bernama reported that a drought in Kedah had caused farmers to lose approximately RM 200,000. So, there is a need to assess the drought phenomena in the Muda River Basin.

Drought occurs in practically all climatic zones, including both high and low rainfall locations, and is defined as a drop in the amount of precipitation received over a long period of time. The hot and dry weather that followed the El Nino phenomenon in 2016 threatened the water levels in several major dams in Penang, resulting in water shortages, according to (MyMetro, 2016). The lack of information on the spatiotemporal analysis on the hydro-meteorological drought will cause the problem in water resources management and economic sector as the agricultural. Drought evaluation and monitoring by conventional method for the area are tedious and time-consuming depending on the availability of weather data.

Many studies have been conducted to determine the spatio-temporal changes of meteorological. The response of hydrological drought to meteorological drought changed over different periods, as well as the period of hydrological drought to meteorological drought is still under studied (Zhao et al., 2016). Therefore, it is essential to see the response of meteorological drought to hydrological drought in the MRB, which is important for irrigating the paddy fields. The drought characteristics evaluation could be useful for the policy makers on formulating better drought strategies especially in the Northern region of Peninsular Malaysia

According to Tomingas (2002), understanding the impact of large-scale climate circulation on local drought is critical to project future drought patterns. To the best of our knowledge, assessment of the impacts of the ENSO, Indian Ocean Dipole (IOD) and Madden Julian Oscillation (MJO) on hydro-meteorological droughts in the MRB is still limited. Therefore, studies on the relationship assessment between the large atmospheric circulation and local drought would help on enhance the understanding of drought formation in the MRB.

1.3 Study Objective

The aim of this study is to evaluate the spatiotemporal changes of drought in the MRB. The specific objectives of the current research are as follows;

a) To assess the spatiotemporal changes of meteorological and hydrological droughts over the MRB from 1985 to 2019.

b) To analyse the relationship between meteorological and hydrological droughts in the MRB.

c) To evaluate the impact of atmospheric circulations on the drought over the MRB.

1.4 Scope of the study

This study was carried out in the MRB, which cover the Kedah and Penang states in the northern region of peninsular Malaysia. The MRB is the most important river basin in northern Peninsular Malaysia, providing as a major source of water for agriculture and water supplies for the states of Kedah and Penang. The Muda River is

180 kilometres long and drainage channels 4210 km². The basin's top and middle sections are in the state of Kedah, while the 30-kilometer river downstream serves as an inter-state border between Kedah and Penang (Sim et al., 2018). In addition, there are four major dams within the MRB (Muda dam, Pedu dam, Ahning dam and Beris dam).

According to the IPCC report, warming is defined as a rise in the 30-year global average of combined air temperature over land and ocean surface water temperature. (Allen et al., 2018). The 30-year span takes into account natural variability, which can cause global temperatures to fluctuate from year to year. Moreover, this study focus on the historical drought assessment within 35 years of study period (1985 to 2019).

Drought indices are numerical representations of drought severity computed using climatic or hydro-meteorological inputs such as precipitation, temperature, streamflow, groundwater and reservoir levels, soil moisture, and snowpack. (Meteorological Organization & Global Water Partnership, 2016). The SPI and SSI were utilised in this study to assess the MRB's meteorological and hydrological drought. Furthermore, the drought assessment used the SPI and SSI to assess the drought in the MRB over different timescales, e.g. 1-, 3-, 6-, 12-month.

The large-scale flow of air that, together with ocean circulation, is utilised to redistribute thermal energy over the Earth's surface is known as atmospheric circulation. ENSO, IOD, and MJO are some of the circulation indices that have an impact on Malaysian rainfall. The ENSO, IOD, and MJO indicators were used to examine the impact of atmospheric circulations in the MRB on the drought.

1.5 Significance of the study

The inadequate of source regarding the drought information in MRB, this study try to provide and focus on the evaluation the historical drought using the drought indices, which could give the illustration of dryness and wetness of the Muda River Basin condition. The greater understanding on drought event that occurred in MRB provided by this study can be used as a foundation for other field of assessing drought hazards and laying the foundation for forecasting studies which is also important for better drought preparedness and increased resilience to drought. This study also could help on understanding the atmospheric circulations impact on the MRB, spatial patterns of drought occurrences and inform future policies on water resources management under changing drought patterns.

The theory applied in this study also could help on indicating the drought characteristic that occurred in the MRB, which help the analysis more detailed on the historical drought analysis in each of the selected station and for the whole condition of the MRB. In the point of view, this study contributed on the decision making for policy makers which is help on formulating better drought adaption strategies in the northern part of Peninsular Malaysia.

1.6 Thesis organization

This thesis is divided into five chapters, including the introduction to the research, literature review, research methodology and study area, result and discussion, last but not least the conclusion and recommendations. This organization has been designed in such a way that the objectives of the research can be fulfilled through the discussions that are presented chapter by chapter.

Chapter One presents the introduction to the thesis, an overview, and the objectives of the current study. The definition of drought, the need of historical drought monitoring and trend analysis also highlighted in this chapter. Drought issues as natural hazards also explained in problem statement. Besides, the drought monitoring using drought indices is also emphasized in this chapter. On top of that, the significance and the scope of the study are also defined.

Chapter Two discusses more about previous studies conducted by other researchers, which covers an overview of drought indices and the large scale of atmospheric circulation. The drought characterisation method used in this study is has explained in detail.

Chapter Three explain the study area background and the climate in northern part of peninsular Malaysia, which could give some view on the climate condition in MRB. Moreover, the data collection and research methodology has discussed in this chapter. Which the computation of each analysis has given, in order to achieve the spatiotemporal analysis of the hydro-meteorological drought in the MRB.

Chapter Four mainly focus on the findings obtained in this study. This chapter will reveal the meteorological and hydrological drought condition in the MRB. The relationship between the meteorological and hydrological drought also discussed in this chapter. Moreover, the relationship between the drought indices and the ENSO, IOD and MJO in MRB has been discussed in this study. This study also presents the discussion of the study, in which the drought trend, impact and mechanism of the drought has been discussed thoroughly.

Last but not least, **Chapter Five** is the main conclusion and recommendations for future works has mention. This chapter gives a summary of the results obtained and suggests improvement that can be made in future researchers

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Drought is known one of the threats to environmental widely. Drought assessment has attracted attention of environmentalist, ecologist, hydrologist, geologist and agricultural scientist. In terms of definitions, classifications, methods of analysis, and method procedures, there is a wealth of information on drought. In this chapter researchers have mentioned some previous studies to illustrate the climate change in order to further the analysis of spatiotemporal analysis of drought in the MRB.

Figure 2.1 showed the rainfall anomaly in Malaysia, which the rainfall has decreased in Peninsular Malaysia. The dry years observed from 1975 to 2005 in Peninsular Malaysia are more frequent and intense as compared to those of 1951 to 1975 (Figure 2.1). Most of the El-Niño events as of 1970 have resulted in severely dry years for Peninsular Malaysia. The three driest years for Peninsular Malaysia (1963, 1997 and 2002) have been recorded during El-Niño events. Nevertheless, the El-Niño phenomenon alone cannot be-responsible for dry spells over Peninsular Malaysia, as quite a number of equally relatively dry years have been recorded during the absence of the El-Niño. However, most La-Nina events have resulted in wet years for Peninsular Malaysia with the exception of 1998 and 1955.

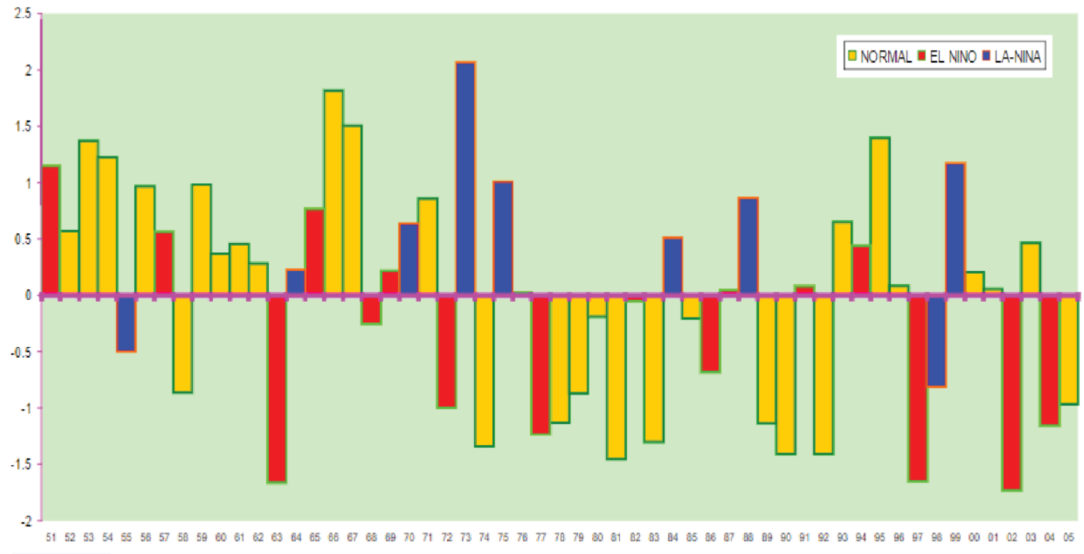

Figure 2.1 Standardized annual rainfall anomaly in Malaysia from 1951 to 2005.
Source: (Malaysian Meteorological Department, 2009)

Figure 2.1 has showed some deficit rainfall in certain year from 1951 to 2005. Table 2.1 shows that drought occurrences in the Northwest of Peninsular Malaysia, particularly around the Muda River, have been reported by researchers from various sources, as shown in Table 2.1. This can be guidance for researchers to ensure the analysis is aligned with the reported drought.

Table 2.1 Reported drought event within and surrounding the MRB

No	Reference	Findings	Date
1	Ahmad et al., (2012)	Six drought incidents were reported in the Muda area between 1977 and 1992	1977 -1992
2	Fadzilatulhusni et al., (2011)	In 2005, the rainfall distribution range recorded in Daerah Timur Laut, Penang was 0 mm to 500 mm which is considered low precipitation rate. In 2004, Penang has the lowest precipitation rates, ranging from 100 to 1600 mm/year.	2004 - 2005
3	MyMetro, (2016)	The continuous drought would affect the water resources in Penang. The Air Itam dam was at 59.9% of water level (expected to sustain for 59 days) which almost reaching the critical level and Teluk Bahang at dam 61.5% (expected can sustain for 187 days).	16 April 2016
4	Arudllas, (2016)	The government took steps to conduct more cloud seeding in catchments areas for Beris and Muda dam in Kedah to raise the level of the Muda River. If both of the dams dry up, Penang would be affected badly because Muda River	26 April 2016

		supplies more than 80% of the water demand in Penang	
5	The Straits Times, (2016)	Most of the farmers in Kedah and Perlis were affected by drought when they have to delay their paddy planting to March and April.	18 March 2016
6	Nasaruddin & Zaid, (2018)	At the end of June 2018, 13 meteorological stations recorded a deficit rainfall by more than 35% and 9 of the station is located at the northern region of Peninsular Malaysia	13 June 2018
7	Razak & Loh, (2019)	20,000 people in Kedah affected by drought and Kedah was the first state facing water supply cut due to the scorching heat and lack of rain.	13 March 2019
8	Jaseni Maidinsa, (2019)	The effective capacity of Air Itam dam decreased (31.8%) within two months (1 January 2019 to 6 March 2019). Muda River also showed decrease in water level: in 1 January 2019, the river level was 2.35mm, compared to 6 March 2019, when it was 1.55mm.	7 March 2019
9	Imran Hilmy, (2020)	The effective capacity of the dams at Ahning, Pedu, Muda, and Beris on January 15 was 62.48 percent, 47.60 percent, 17.88 percent, and 81.25 percent, respectively. Dams in Kedah were at an alarmingly low level.	18 January 2020
10	Predeep Nambiar, (2021)	Approximately 3,000 households in Kedah were without water as a result of the state's drought.	17 February 2021

2.2 Drought indices and drought detection

Indices are numerical representations of drought intensity based on climatic or hydro-meteorological variables that are widely calculated. Indices try to quantify the qualitative status of drought on the landscape over a certain time period (World Meteorological Organization & Global Water Partnership, 2016). Drought indices is a reliable quantitative measures for drought indicators and monitoring. Drought indices development is use for the drought characteristics identification, such as the duration, severity and drought intensity as well as its spatiotemporal pattern. In this study, the standardized precipitation index (SPI) and standardized streamflow index (SSI) primarily use to assess the drought that occurred in the MRB.

The World Meteorological Organization (WMO) recommends the use of the SPI for characterizing meteorological drought (Naz et al., 2020). The SPI was selected for drought analysis in this study because the rainfall transformed into a normalized value, so the wet and dry conditions were represented in a similar way (Mckee et al., 1993). Hence, The SSI enables simple yet effective quantification of the hydrological drought conditions of a river basin (Shamshirband et al., 2020).

2.2.1 Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) is a meteorological drought index established by Mckee et al. (1993) to evaluate precipitation deficiencies over a range of time scales. Short-term precipitation anomalies affect soil moisture, but longer-term precipitation anomalies affect ground water, streamflow, and reservoir storage (Hayes 1999). The computation of SPI in any location is based on the long-term precipitation observed data (at least 30 years) for the study period. Sanusi et al. (2014) assess the drought profiles in Peninsular Malaysia over a 38 years period (1970-2008) using a first order homogeneous Markov chain based on the Standardized Precipitation Index (SPI) and found the north-western of Peninsular Malaysia frequently occurred longest moderate drought.

The SPI can calculated in different time scales to assess the drought, Mckee et al. (1993) calculated the SPI for 3-, 6-, 12-, 24-, and 48- month time scales. By examining the effects of a precipitation shortfall on several water resource components (groundwater, reservoir storage, soil moisture, and streamflow), the effects of a precipitation deficit can be assessed. The index is a numeric value between 0 and 1 that indicates dry and wet conditions. Study that carried by Fung et al. (2020) which is assessing the drought condition in peninsular Malaysia applied the different time scale at 1, 3 and 6. Table 2.1 show the Standardized Precipitation Index (SPI) categories (Mckee et al., 1993).

Table 2.1 Standardized Precipitation Index (SPI)

SPI Values	Drought categories
>2.00	Extremely wet
1.50 to 1.99	Severely wet
1.00 to 1.49	Moderately wet
0.99 to 0.99	Near normal
−1.00 to −1.49	Moderately dry
−1.50 to −1.99	Severely dry
<−2.00	Extremely dry

The SPI can provide early warning of the severe drought because it can determine the drought conditions for each location. The longer period of time is good for using approximations to groundwater flow and water stress but it takes a long time to collect the data, and a wet period can be detected (Hayes et al., 1999). The WMO's Inter Regional Workshop on Indices and Early Warning Systems for Drought recommends the SPI for wider use in tracking meteorological drought (Hayes et al., 2011).

2.2.2 Standardized Streamflow Index (SSI)

The Standardized Streamflow Index (SSI) is used to quantify observed streamflow abnormalities (Svensson et al., 2016; Vicente-Serrano et al., 2012;. While the SSI is frequently estimated on a monthly basis, some studies employ longer accumulation periods, such as 3-12 months, to follow the cumulative water deficit across the hydrological year (Nalbantis & Tsakiris, 2008). The SSI is the sole drought index suggested in the current edition of the Handbook of Drought Indicators and

Indices for streamflow drought monitoring and early warning (Meteorological Organization & Global Water Partnership, 2016). Apart from being used to monitor streamflow droughts, the SSI has been utilized in numerous research to describe the characteristics of streamflow drought episodes (Barker et al., 2016; Malveira et al., 2012).

Tan et al. (2019) used the SPI and SSI in order to evaluate the hydro-meteorological drought in the Johor River Basin from 1975 to 2010. The SSI have been used to represent the hydrological drought. In addition, there are fewer studies used the SSI for drought monitoring in Malaysia.

2.3 Drought trend detection

Trend analysis is commonly used to examine long-term systematic changes in climate variables (Dinpashoh, 2006; Sonali & Nagesh Kumar, 2013; Rashid & Beecham, 2019; Gou et al., 2020; Liu et al., 2021). Many trend detection approaches (e.g., parametric, nonparametric, and Bayesian) have been developed to assess trends in hydro-climatic time series (Khaliq et al., 2009; Sonali & Nagesh Kumar, 2013; Dabanli, 2018), including the Mann-Kendall (MK) test and Sen's slope estimator. These techniques are frequently used to detect trends in meteorological drought indices (Partal & Kahya, 2006; Y. Zhang et al., 2015). The Mann-Kendall and Sen's Slope methods were used in this study to detect the drought trend in the MRB at different time scales.

2.3.1 Mann-Kendall test

Mann-Kendall analysis is a method that may be used to detect and evaluate the trend pattern of dry occurrences. The Mann-Kendall trend test (Mann, 1945; Hamed, 2008) is a frequently used non-parametric tool for detecting statistically significant trends in time series. The Mann-Kendall test is widely used on the trend detection of the hydro-meteorological time series (Wang et al., 2020). The Mann-Kendall test, as well as other non-parametric trend tests, is thus more suited to finding trends in the trend of hydrological time series. Mann Kendall Trend Test has been applied to examine the temporal variation trend of stream flow and water level from in the Pahang River Basin from 1972-2011 (Sulaiman et al., 2015).

2.3.2 Sen’s Slope

The non-parametric estimator approach of Sen, (1968)was used to forecast the magnitude (true slope) of hydro-meteorological time series data. Sen's slope estimator is a trend analysis technique that makes use of a linear model (Hussain et al., 2015). The Sen’s method has been widely used with the combination with Mann-Kendall test in analyzing the hydro-meteorological trend. Many of the studies has applied the Sen’s and Mann-Kendall method assessing the hydro-meteorological trend (Deni & Suhaila, 2010; Güner Bacanli, 2017; Tan et al., 2019; Basin et al., 2021). The evaluation of the hydro-meteorological trend is based on the indices employed in the research, such as the SPI and SSI, which were utilised to reflect the meteorological and hydrological drought trend in the current studies.

2.4 Drought characteristics

Drought occurrences are frequently defined by a number of variables (Ge et al., 2016), including duration, peak, intensity, frequency, and severity. Each of these traits may have a distinctly different effect on the surroundings. For example, severe droughts, even those of brief duration, would have a devastating effect on agriculture during the crop's growth stages (Rippey, 2015). By comparison, prolonged mild and moderate droughts would have a devastating effect on ecosystems and water supplies (AghaKouchak, 2015).

To identify each of the drought features, many researchers have employed the run theory introduced by (Yevjevich, 1967). Study conducted by Sharafati (2019) used the run theory to identify and extract the drought features at different time-scale of SPI. Fung et al. (2020) applied the run theory to investigate the stream flow seasonal hydrological drought indicator for the tropical region. Figure 2.1 show the illustration of the run theory, where the drought characteristics identify the duration, peak, severity, intensity and drought frequency.

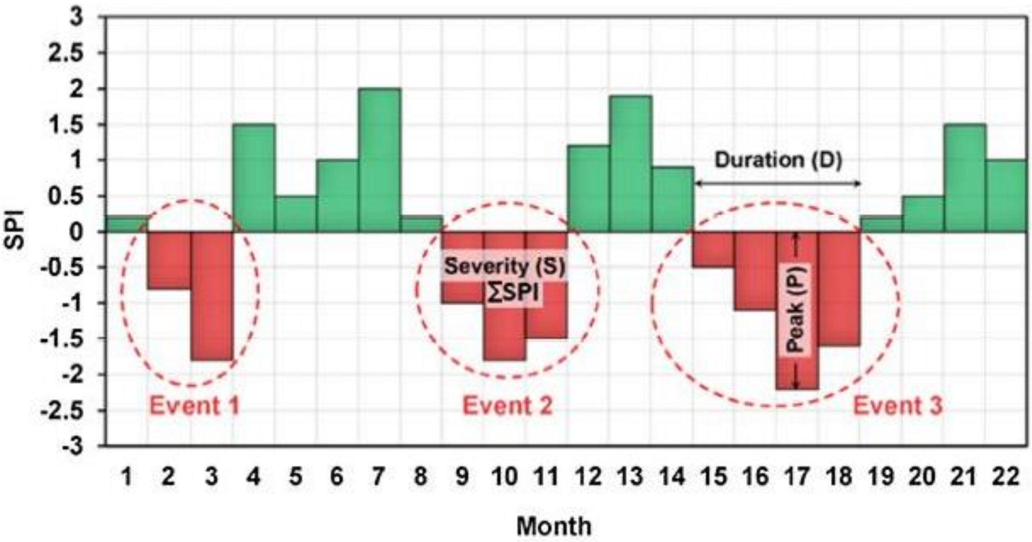

Figure 2.1 Illustrations of drought occurrences and characteristics based on the run theory (Yevjevich, 1967).

2.5 Correlation analysis

2.5.1 Response Rate

Response rate analysis is to evaluate the relationship between two variables. In present study, the relationship between the hydrological (SSI) and meteorological (SPI) drought evaluate with the response rate analysis to see how strong the relationship between these two variable in percentage. The response rate was expressed as the percentage of meteorological droughts that turned into hydrological droughts as a result of the hydrological cycle (Sattar & Kim, 2018). Meteorological drought occurred faster, as it only depends on the deficiency of the precipitation, due to the onset condition of the hydrological cycle. However, the hydrological drought lags behind meteorological drought. The lagging between hydrological and meteorological revealed that there is strong linkage between hydrological and meteorological droughts (Dracup et al., 1994; Wilhite & Vanyarkho, 2000).

Zhao et al. (2016) study the monthly SRI and SPEI at different timescales in 1976-2005 in order to understand how streamflow drought responded to meteorological drought in Xiangjiang river basin, a semi-humid basin of Central China. Sattar and Kim, (2018) used the response rate in their study in order to describe the percentage of meteorological drought propagated to hydrological drought. The study conducted in the Johor River Basin, Malaysia, also used the response rate analysis to analyse the monthly response between the SSI and SPI (Tan et al., 2019).

2.5.2 Spearman rho correlation analysis

The Pearson correlation coefficient's nonparametric counterpart is the Spearman rank correlation coefficient (Lund Research Ltd, 2018). Furthermore, because Spearman's assesses the strength of a monotonic association, the data must be associated in a monotonic way. This basically indicates that when one variable rises or decreases, the other variable also increases or decrease. To analyze the strength of a link between two sets of data, Spearman's Rank Correlation Coefficient is used. Present study, used Spearman rho analysis to evaluate the relationship between the atmospheric circulation and drought over the MRB from 1985 to 2019.

Tan et al. (2019) assessed the relationship between atmospheric circulations and drought over the Johor River Basin from 1975 to 2010 using the Spearman correlations and found there is El Niño-Southern Oscillation (ENSO) and Madden Julian Oscillation (MJO) impacts on drought events in the basin. The Spearman correlation test was used to investigate the links between meteorological and hydrological droughts in the Asku River Basin, Northwest China, using the SPI and Streamflow Drought Index (SDI) (Zhang et al., 2015).

2.6 Atmospheric circulation indices

The term atmospheric circulation refers to the Earth's general circulation and regional air movements around high and low pressure zones, this circulation corresponds to large-scale wind systems circling the Earth in east-west belts (Britannica, 2019). As air drops near 30° N and 30° S (the horse latitudes), trade winds sweep westward and equatorward.

The primary focus of attention in climatic responses to changes in atmospheric circulation is on the occurrence of severe events as the floods and droughts that cause significant environmental, social, and economic harm (Vicente-Serrano et al., 2011). Drought is the most damaging natural hydro-climatic hazard because it results in significant economic losses (Meehl et al., 2000; Knutson, 2008). The atmospheric circulation has seen as one of the factors influencing the climate change around the world.

The effect of ocean atmosphere events such as ENSO, IOD, and MJO over Southeast Asia in 2015 was explored by Islam et al. (2018), who discovered that ENSO, IOD, and MJO affected surface temperature and precipitation. Tangang et al. (2012) found that climate variability in Malaysia generally correspond with the ENSO, IOD and MJO. In this present study the El-Nino Southern Oscillation (ENSO), Indian Ocean

Dipole (IOD) and the Madden Julian Oscillation (MJO) atmospheric has been applied to assessed the drought indices correlation with the selected atmospheric indices.

2.6.1 El-Nino Southern Oscillation (ENSO)

The El Nino-Southern Oscillation (ENSO), shown in Figure 2.2, is composed of three phases: La Nina, El Nino, and Neutral. The trade winds blow east to west over the tropical Pacific Ocean's surface in a neutral condition (neither El Nino nor La Nina), bringing warm, moist air and warmer surface waters to the western Pacific while maintaining a relatively cool central Pacific Ocean. The thermocline is higher in the west than it is in the east. During an El Nino event, trade winds weaken or even reverse, allowing warmer-than-normal water to enter the central and eastern tropical Pacific Ocean. During a La Nina episode, the Walker Circulation becomes more powerful, with increased convection over the western Pacific and stronger trade winds.

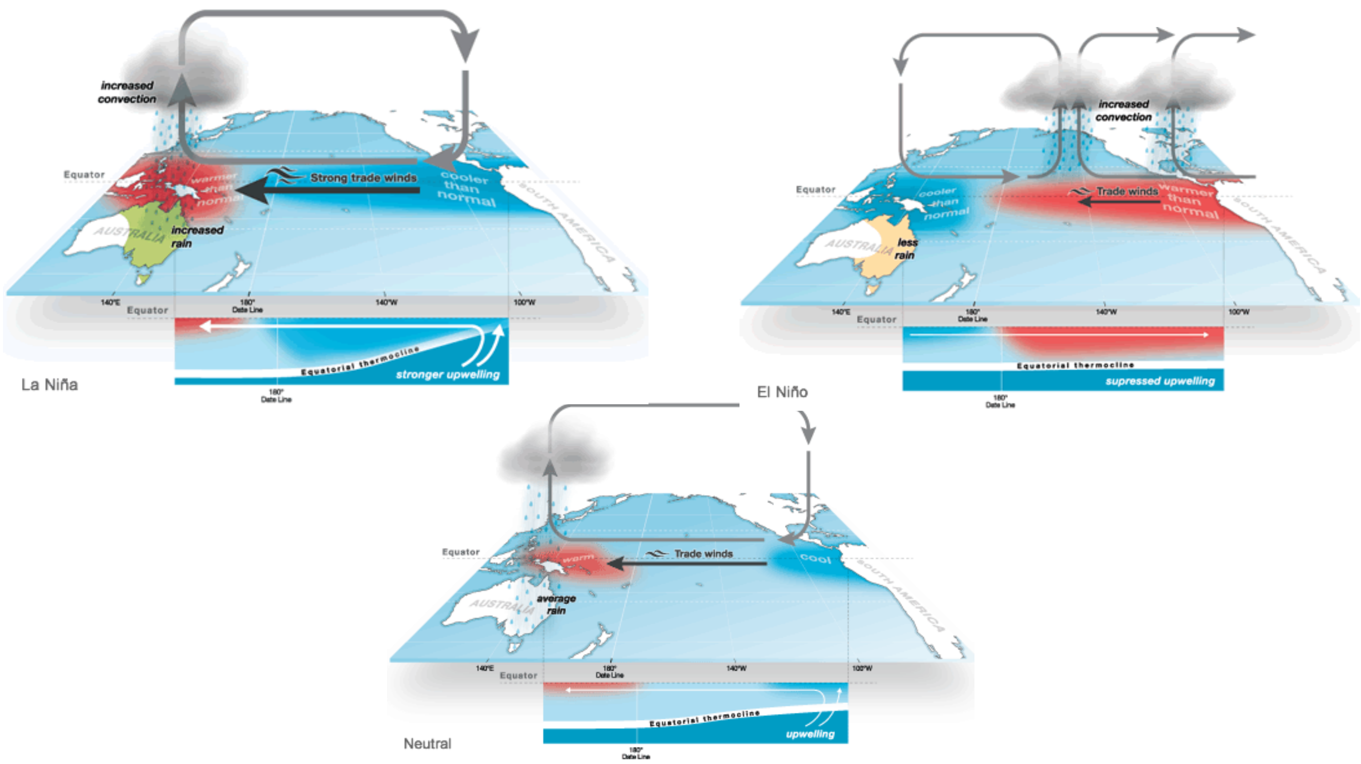

Figure 2.2 El Niño, La Niña and Neutral conditions of ENSO (Bureau of Meteorology, 2012).

The El Nino-Southern Oscillation (ENSO), which formed in the tropical Pacific Ocean as a result of atmospheric-occurrence interactions, is one of the most powerful inter-annual climatic variability patterns (Collins et al., 2010). Previous research in tropical and subtropical areas has shown a substantial link between ENSO and climatic variability (Kiladis & Diaz, 1989; Redmond & Koch, 1991). In the south Pacific Ocean, the El-Nino or La-Nina phases exhibit increased or reduced precipitation, whilst Australia, Southeast Asia, South Africa, and northern South America experience dry or rainy weather (Villar et al., 2009; Kothawale et al., 2010; Brown et al., 2020)

The ENSO has a significant effect on Malaysian climate variability on an inter-annual period (Tangang & Juneng, 2004; Tangang et al., 2017) . Many research have been conducted in Malaysia to assess the impact of ENSO and to associate it with the occurrence of drought. Furthermore, ENSO driven large-scale atmospheric teleconnections have the potential to cause significant damage to economies, agriculture, and ecosystems, as well as severe climatic disasters on a global scale (McPhaden et al., 2006; Deser et al., 2009).

2.6.2 Madden Julian Oscillation (MJO)

The Madden–Julian oscillation (MJO) is the most significant component of the tropical atmosphere's intra-seasonal (30–90-day) variability (Wilson et al., 2013). The American National Centre for Atmospheric Research's (NCAR) Roland Madden and Paul Julian found it in 1971.The Madden–Julian Oscillation (MJO), which is defined by an eastward-moving band of rain clouds, is the most dominating pattern of sub-seasonal variability in the tropics (Roxy et al., 2019). In general, it moves eastwards at about 4 to 8 ms^{-1}, crossing the tropics in 30 to 90 days as shown in Figure 2.3. Hence, intra-seasonal variability of monsoon rainfall is influenced by the MJO.

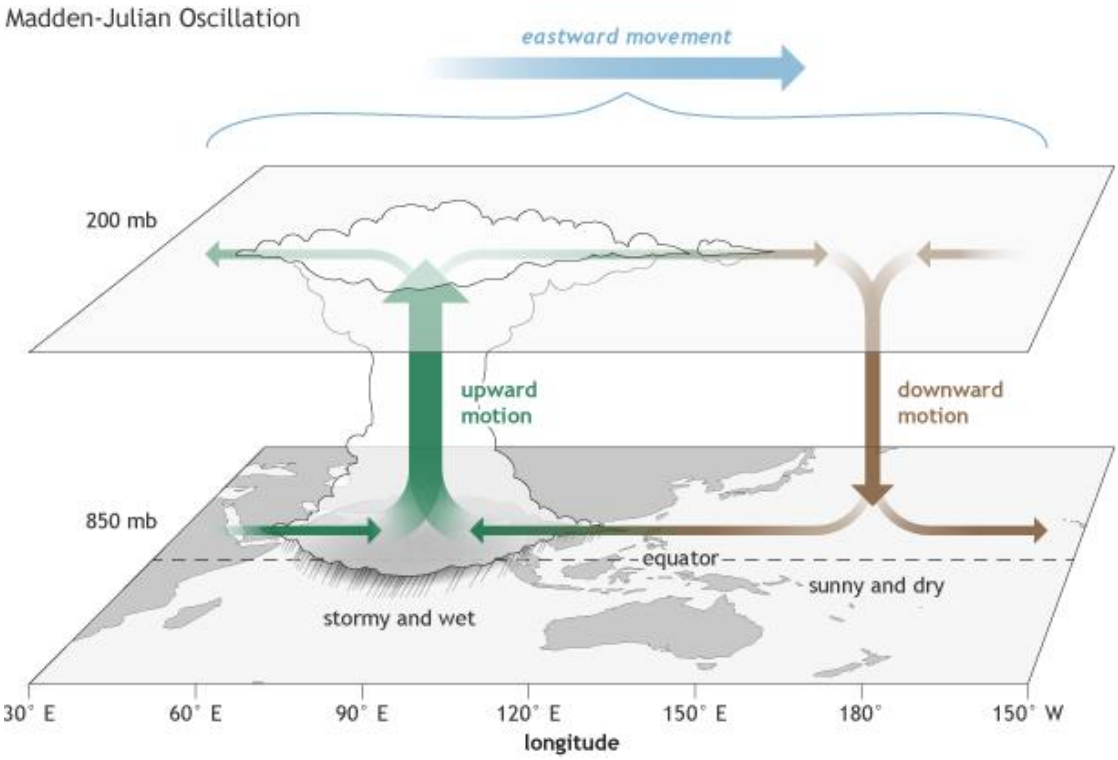

Figure 2.3 Madden Julian Oscillation (Gottschalck, 2014)

Salahuddin & Curtis (2011) indicate that the MJO has a distinct effect on the west coast of Peninsular Malaysia and Borneo Malaysia than it does on the east coast of Peninsular Malaysia. Numerous studies conducted throughout the world have established that the MJO causes fluctuations in rainfall, which is one of the primary variables influencing meteorological drought (Zaitchik, 2017). Additionally, the phase and amplitude activity of the MJO play a significant impact on rainfall variability (Hidayat, 2016). Most researchers have studied the MJO's influence on drought primarily by analysing the relationship between the rainfall. Tangang et al. (2008) demonstrated MJO's association with the Maritime Continent, which investigating the potential impact of atmospheric variables in causing extreme climate situations across the southern peninsular of Malaysia. Hidayat and Kizu, (2010) indicate that MJO phases influence Indonesian rainfall. When the MJO is in phase 1-4 or phase 5-8, the wet and dry patterns in Indonesia vary.

2.6.3 Indian Ocean Dipole (IOD)

Indian Ocean Dipole (IOD) is the Indian Ocean's counterpart to El Nino and La Nina in the Pacific. The term dipole refers to two "poles" or areas of distinction. The IOD quantifies the difference in Sea Surface Temperature (SST) between the western pole (Arabian Sea) and the eastern pole (Indian Ocean). Both poles are located between the equatorial of the Indian Ocean between 10ºN and 10ºS. IOD is an ocean-atmosphere linked phenomenon (Figure 2.4). Many regions around the Indian Ocean see varying rainfall and storm activity due to shifting warm or cool. The shift in temperature gradients across the Indian Ocean, similar to ENSO, affects where moisture and air rise and fall. To put it simply, the IOD is an ocean-atmosphere related phenomenon that occurs in the equatorial Indian Ocean, comparable to ENSO in nature. In concept, the IOD is linked to ENSO events via the westward extension of the Walker Circulation and the corresponding Indonesian through flow (the flow of warm tropical ocean water from the Pacific into the Indian Ocean).

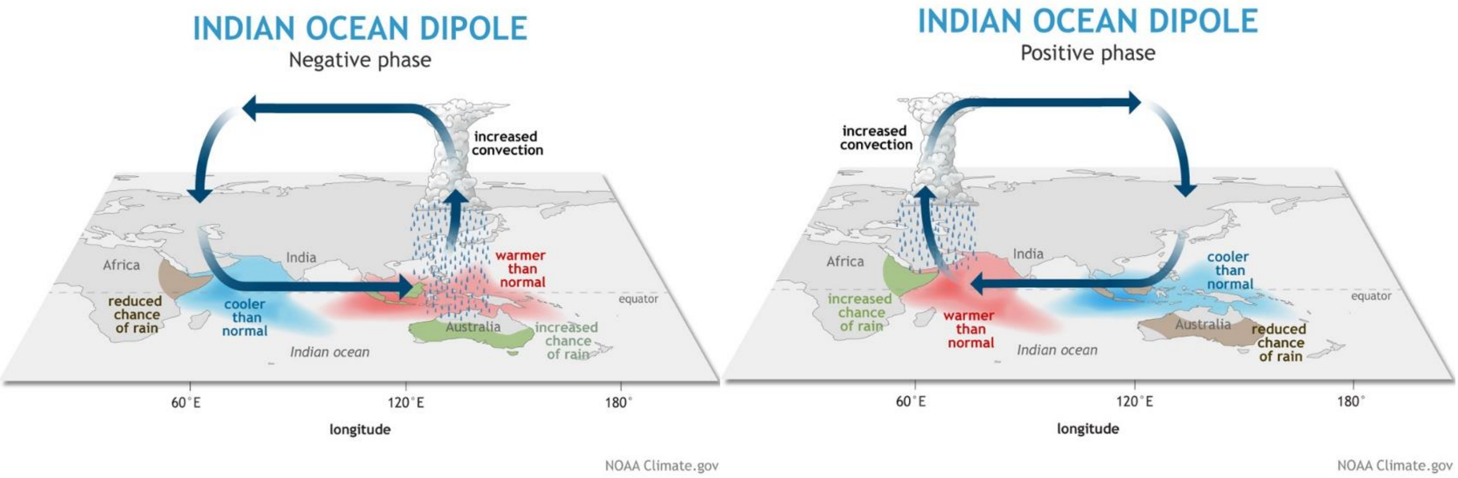

Figure 2.4 Indian Ocean Dipole (IOD) Negative and Positive phase (Johson, 2020)