ANALYSIS OF HISTORICAL MOISTURE CONDITIONS IN THE EAST COAST OF PENINSULAR MALAYSIA USING DROUGHT INDICES

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Civil Engineering

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DECLARATION

I hereby declare that this project report is on my original work except for citations and quotations duly acknowledged. I also declare that it has not been previously and or concurrently submitted for any other degree or award at UTAR or any other institution.

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APPROVAL FOR SUBMISSION

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ABSTRACT

It is undeniable that the East Coast of Peninsular Malaysia experiences a remarkable diverse climate of wet and dry seasons throughout the year, but the abnormally long periods of dry condition have recently become a highly concerned environmental issue, which is termed as drought. Drought is defined as a slow-onset random phenomenon with continuous deficiency of rainfall over an abnormally long duration. From 1978 to 2017, the East Coast of Peninsular Malaysia experienced numerous mild to extreme droughts and the impacts on the economy, social, environment as well as agriculture are significant. The development of a drought monitoring system with the best performing drought index is necessary in battling the disaster. Spatial and temporal analyses were conducted to study the variations of drought over space and time. The research was initiated by the raw data acquisition from Department of Irrigation and Drainage (DID) and the Malaysian Meteorological Department (MMD), including the 35-year data of precipitation, streamflow and temperature. Repairing of the missing rainfall and temperature data were performed using the four-quadrant method. All the data were then applied for the development of the Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI) and the Streamflow Drought Index (SDI) under various timescales. Temporal analysis was performed on a monthly basis, followed by computation of drought characteristics for spatial analysis using the Inverse Distance Weighting (IDW) method. The Average Moving Range (AMR) of drought indices were determined to understand the sensitivity of indices to the fluctuation of precipitation, streamflow and temperature data. The drought indices at the shortest timescale were shown to be the most sensitive timescale to variations of the data, with the recording of the highest AMR. The performance assessment of the drought indices in describing drought occurrence were conducted through the evaluation of the Probability of Detection (POD), the Mean Absolute Error (MAE), the Mean Bias Error (MBE) and the Mean Early or Delayed Prediction (MEDP). The findings showed that SPEI-1 has the best performance due to its high accuracy in detecting drought occurrence and duration, as well as the ability in recognizing high severity droughts. The analysis of relationship between drought indices and oceanic indices was also carried out. It showed that the SPEI-1 has better response to the high temperature condition brought by the El-Nino phenomenon. There is certain level of effects from the Indian Ocean Dipole (IOD) and the El Niño–

Southern Oscillation (ENSO) on the precipitation amounts falling over the East Coast of Peninsular Malaysia, but further research is required to formulate the linkage between IOD, ENSO, rainfall and temperature anomalies.

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LIST OF SYMBOLS / ABBREVIATIONS

a	recorded droughts detected by drought index
b	recorded droughts are not detected by drought index
c_0	coefficient for standard normal variable Z calculation
c_1	coefficient for standard normal variable Z calculation
c_2	coefficient for standard normal variable Z calculation
d_i	distance between x_0 and x_1
di	distance from station with data to station with missing data
d_1	coefficient for standard normal variable Z calculation
d_2	coefficient for standard normal variable Z calculation
d_3	coefficient for standard normal variable Z calculation
$f(x)$	probability density function
i	hydrological year
i	index value
i	range of observations in increasing sequence
j	month within the hydrological year
k	reference duration
m	coefficient that calculated based on I
n	number of sampled points used for the estimation
n	number of stations considered
p	power parameter
q	probability of zero
s	standard deviation of the rainfall
s_k	standard deviation of cumulative streamflow volume
t	t transform
w_s	PWMs of order s
w_1	PWMs of first order
w_2	PWMs of second order
y_i	detected drought duration
$y_{i,k}$	natural algorithms of cumulative streamflow volume

D_i	water surplus or deficit
F_i	estimator of frequency
G	group
$G(X)$	cumulative probability of an observed rainfall event
$H(x)$	cumulative probability of an observed rainfall event
I	heat index
K	correction coefficient
N	maximum possible sunshine hours
N	number of data
N	number of detected drought event
N	number of rainfall stations
NDM	number of days
P	probability of exceeding a determined D value
P_i	precipitation of station i
PET_i	potential evapotranspiration of station i
S	amount of available moisture in both layers of the soil at the beginning of the month
T	monthly-mean temperature, °C
U	statistics U
$V_{i,k}$	cumulative streamflow volume
W_i	weightage of station
Z	standard normal variable
$\overline{P}$	mean precipitation
$\overline{V}_k$	mean of cumulative streamflow volume
$\overline{X}$	mean of the rainfall
$\overline{X}_{\ln}$	log mean
$\hat{y}_i$	actual drought duration
α	scale parameter
β	shape parameter
γ	coefficient of runoff

γ	origin parameter
λ_i	an unknown weight for the measured value at the *i*th location
$\Gamma(\alpha)$	gamma function of α
$\Gamma(\beta)$	gamma function of β
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
AMR	average moving range
AWC	available water capacity
CAFEC	Climatically Appropriate for Existing Conditions
DEM	Digital Elevation Model
DID	Department of Irrigation and Drainage
DMI	Dipole Mode Index
ENSO	El Nino-Southern Oscillation
GDP	gross domestic product
GIS	geographic information system
HFO	habitat-forming organisms
IDW	Inverse Distance Weighted
IOD	Indian Ocean Dipole
KML	Keyhole Markup Language
KMZ	Keyhole Markup Language Zipped
KSWSI	Korean Surface Water Supply Index
MAE	mean average error
MBE	mean bias error
MEDP	mean early or delayed prediction
MEI	Multivariate ENSO Index
MJO	Madden/Julian Oscillation
MMD	Malaysian Meteorological Department
MPOB	Malaysian Palm Oil Board
MR	moving range
NASA	National Aeronautics and Space Administration
OK	Ordinary Kriging

ONI	Oceanic Nino Index
PDSI	Palmer Drought Severity Index
PET	potential evapotranspiration
PHDI	Palmer Hydrological Drought Index
PL	potential loss
POD	probability of detection
PPK	Pertubuhan Peladang Kawasan
PRO	potential runoff
QGIS	quantum geographic information system
RDI	Reconnaissance Drought Index
RMSE	root mean square error
SDI	Streamflow Drought Index
SPEI	Standardized Precipitation Evapotranspiration index
SPI	Standardized Precipitation Index
SOC	Soil Organic Carbon
SWSI	Surface Water Supply Index
USD	United States Dollar
USDA	United States Department of Agriculture

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

It is undeniable that water is an essential element for humans, animals and plants to survive on earth but this natural resource is unpredictable due to its random and varying nature of dry seasons and wet seasons. In the study by Horspool (2018), air without water means that there is no cloud to act as heat buffer and eventually temperature will rise. Loss of soil moisture content as well as drying of water reservoir and groundwater will occur, causing lifeless condition on the earth surface. In addition, water also acts as cushion to disasters like earthquakes in which the groundwater reduces the effect by slowing down the seismic waves. Furthermore, water bodies such as the ocean and lake serve as a home for aquatic animals and plants while we can treat water from natural water reservoir to obtain clean potable water for our daily routine; hence we have a great responsibility in preserving our water resources.

The main environmental problem that we will be most likely faced in the 21st century is water scarcity, or sometimes this water crisis problem is termed as a drought. Statistical and geographical data accumulated from the studies by scientists at NASA have shown that there has been substantial water depletion due to uncontrolled consumption in nineteen hotspots in the world; from China to the Caspian Sea. For instance, the Xinjiang province suffered decline in water resources due to uncontrolled extraction of groundwater for industry and irrigation despite receiving normal rainfall throughout the year (Harvey, 2018). Nevertheless, shrinking of the shoreline had happened in the Caspian Sea where the report by NASA has shown that the problem was mainly due to extraction of water from the river that feeds the seashore.

Drought as generally known is a slow-onset stochastic natural hazard with persistent precipitation deficit over an extended period. This extreme disaster spreads over a large region in which the adverse effects act on the physical environment and water resources in the regions, which may also suffer impacts from other phenomena. In this case, the random nature of drought caused difficulties to the experts and scientists in determining its onset, duration and end; unlike aridity, which is a permanent event. The impacts of drought on the economy, environment and agriculture are a national calamity. The development of accurate and reliable prediction of severity and duration of the droughts is difficult in view of the fact that the calamity always has large spatial coverage as compared to other disasters like earthquakes and floods. The intensity of drought is explained as the degree of the precipitation deficiency or severity of the impacts caused; and it is measured with an indicator and index (Wilhite, Sivakumar and Pulwarty, 2014).

Malaysia is the natural focus of the South-East Asia region where its climate is controlled by the Australian-Asian monsoon system. During the northeast monsoon, the East Coast of Peninsular Malaysia receives maximum values of rainfall amount as it is in a strong moisture convergence zone that is modulated by cold surges and the Borneo vortex circulations. During the southwest monsoon, Malaysia experiences drought as moisture brought by the southwest wind is blocked by the Barisan mountain range along Sumatra. The 1997-1998 El Nino event caused prolonged drought in Malaysia as most areas in Malaysia received less than one-fifth of the normal precipitation between late January and mid-April 1998. The El Nino-Southern Oscillation (ENSO) events are phenomena that cause the rise of surface temperature of the Pacific Ocean and resulting in dry spells in many countries across the globe (Low, 2016). In 1998, Malaysia suffered a national water crisis that lead to water rationing in the Klang Valley, some regions in Negeri Sembilan, Penang, Kedah and Perlis. It is without doubt that droughts affected people in the region besides causing economic impacts because the Selangor government had spent about RM 50 million in battling the disaster (The Star Online, 2014).

In March 2014, the Malaysia National Water Commission reported there were about 300 000 houses in Kuala Lumpur and Selangor affected with water rationing practice after the dam water depletion problems continued for two months. In the past, Malaysia experienced dry climate early in the year but the dry spell in this particular year unexpectedly severe following the warning from the Malaysian Meteorological Department (MMD) that the water scarcity phenomena could last for another month. From the aspect of health issue, the hot weather also boosted the reproduction of Aedes mosquitos carrying the dengue virus that can harm the people in the affected areas (ABC News, 2014). In 2015 until early 2016, the strongest El Nino since 1983 occurred in Southeast Asia. The dry and hot weather pattern brought by El Nino caused significant yield losses for crops in Malaysia due to rainfall deficit between June 2015 and March 2016. Statistical data by the Palm Oil Board (MPOB) has shown that there was about 8 % of drop in palm oil yield from 2014 to 2015. Furthermore, the strongest dry spell of the decades had reduced quality of the palm oil fruit. At this point, it is obvious that drought can trigger adverse negative impacts on agriculture (USDA, 2016).

In essence, drought is a global disaster that brings adverse effect to environment, economy and society. It remains challenging to determine the beginning of the water crisis hazard, duration and offset, and hence it is a potential central environmental issue in the 21st century. For Malaysia, drought is no longer a new topic since the 1998 damage to the water supply and agriculture. Droughts are also significant disasters besides floods ranked in the top deciles for most of the western regions in Malaysia. Thus, building a robust drought monitoring and prediction system with appropriate drought index and indicator is necessary as the system can effectively aid in formulating quick responds to its occurrence and ameliorate its impacts.

1.2 Importance of the Study

A study of moisture conditions in the East Coast of Peninsular Malaysia is essential to gain a better understanding about the water-related disasters, the impacts caused as well as the preventive measures and critical responses that can be adopted to overcome the calamities. In this case, drought indices are useful in the decision-making process as information are provided to decision makers such as government agencies to handle emergency drought relief response in the affected areas. Apart from this, the findings of the research can contribute to the planning of mandatory quick or short-term responses by the water supply companies in corporation with water authorities to apply proper water restriction and distribution policies throughout the drought period.

The study is also important for water engineers involved with the design and establishment and investments into the water resource facilities and their operation. In the agriculture industry, the research is important in monitoring and analysing long-term dry and wet spell conditions so that the water engineer can aid in the drought response actions whenever required. Furthermore, the results of the research help fire control managers in wildfire monitoring and prediction during the dry spells.

In short, the research aids in characterization of drought that is important in retrospective analysis and prospective analysis. Retrospective analysis focuses on past drought events and involves severity versus impacts analysis while prospective planning includes prediction and expectation of future event thus involves risk assessments. The study also emphasises on the need for precise drought early warning, thus aiding contingency planning and preparation.

1.3 Problem Statement

The impacts from the aspects of environment, society and economy caused by drought such as 1997-1998 and strong 2015-2016 El Nino phenomenon are significant. These impacts related to the water resources of Malaysia are important, as our national water needs are all dependent on the amounts of rainfall in a tropical zone. Agriculture is one of the main economic sectors in Malaysia in which it contributed 9.2 % to the Gross Domestic Product (GDP) in 2014 according to the statistical data from Department of Statistics Malaysia. Therefore, agricultural activities and production when greatly affected by drought events become serious national issues (Low, 2016). Drought also affects flowering, fruiting and grain producing plants during flowering stage besides reducing their growth and production of fruits. Plants in tropical zone have specific range of temperatures for growth. During drought with high temperature beyond maximum temperature for growth for a prolonged period, photorespiration of plants occurs, resulting low yield harvest.

According to the study by Bernama (2014), the northern and eastern parts of the Kelantan River Basin close to the coast, experienced an extended dry spell from February until March 2014. The drought event resulted in low precipitation and affected 8 000 paddy farmers in Kelantan with total losses of about USD 22 million. Furthermore, the dry climate hastened the breeding of the Aedes mosquito; in which the statistical data have shown that the dengue fever death cases were three times greater as compared to those in 2013. Droughts not only bring adverse effects to agriculture, but also harm our health. In Terengganu, El Nino hazard that happened in 2016 had destroyed about 200 ha of forest by fires, including forests in Pangkalan Jering in Dungun, Manir in Kuala Terengganu and Bukit Layat in Setiu. The extreme high temperatures during the dry season increase the occurrence probability of wildfires (David, 2016).

Drought indices and indicators are important for developing robust drought monitoring and prediction system besides planning for preventive measures. There are many drought indices proposed by researcher all around the world and each of them is unique in aspects of functionality, features and accuracy. Therefore, suitable indexes according to climate and result of retrospective analysis are required for improving the accuracy and efficiency in characterizing and understanding moisture conditions in the East Coast of Malaysia.

1.4 Aim and Objectives

The aim of the research is to conduct assessment on antecedent moisture conditions in the East Coast of Peninsular Malaysia using drought indices. The following are the specific objectives of the research to achieve the aim mentioned:

(i) To develop a suitable drought index for application in a drought monitoring system, and

(ii) To carry out spatial and temporal analysis of droughts in the study area.

1.5 Scope and Limitations of the Study

The research area is the East Coast of Peninsular Malaysia including Kelantan, Terengganu and Pahang, while the period of the research ranges from 1983 to 2017 with consideration of the 35-year period of meteorological and hydrological data. The data obtained from all the stations in the aforementioned study area are rainfall, streamflow and temperature data. The limitation of the study is that the development of the Palmer Drought Severity Index (PDSI) is not carried out due to the unavailability of the local available water content (AWC) data.

1.6 Contributions of the Study

Palm oil production and crops plantation in agriculture industry is a very vital part of the economy of Malaysia. Water resources are one of the main requirements for agriculture as water is essential for irrigation. Drought events that occur over a prolonged period will cause continuous water depletion and reduction in soil moisture content that can lead to crop yield losses. Better understanding and prediction of drought period is important in reducing economic impacts especially to the plantation industry. The reason is the analysis results can help water engineers develop operation and management plans to overcome the water scarcity problem before the onset of impending drought events.

Additionally, food crops plantation serves as an important element in maintaining the food security in Malaysia. A food crisis may trigger health issues and related problems in the society and thus sufficient and timely water supply for agriculture is definitely necessary to pre-empt predicaments, troubles, and losses.

Nonetheless, water scarcity ruins our daily routine since it is a dominant requirement to sustain lives. The study helps water authorities to manage water-rationing to preserve limited water resources during the dry spells. At this point, it is debatable that the research contributes in formulating quick responses to battle water crisis disaster.

1.7 Outline of the Report

The report consists of five chapters in total and the contents of each chapter are briefly described:

Firstly, Chapter 1 is the Introduction and this section presents the background of droughts in the world and in Malaysia. This chapter also covers the importance and contribution of the research, problem statement, aim, research objectives as well as the scope and limitation of the study.

Next is Chapter 2 with title "Literature Review" that reviews the previous findings of other researchers about drought such as characterization of drought and types of drought. In addition, the review tasks also involve detail description about different drought indices applicable in specific region or climate followed by spatial and temporal analysis method of drought.

Chapter 3 is about the Methodology and Work Plan for the research that involves the research plan, data collection, and repairing and analysis method. Formulas and software applied for calculation during data repairing and analysis are explained in detail.

Chapter 4 is entitled Results and Discussions. In this chapter, data and findings obtained are further discussed.

The last Chapter 5 covers the Conclusions and Recommendations where the conclusions of the research are stated while recommendations for better performance in future research are discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Chapter 2 discussed different ways in defining drought through classification of drought into different categories. Classification of drought can be performed from different perspectives and based on variables such as intensity, duration and spatial distribution related to shortage of precipitation following by the influence on other factors like runoff, soil moisture content, evapotranspiration rate and vegetation stress. Numerous drought indices along with indicators were discussed to explain variations in applications of drought indices in defining different types of drought. Moreover, temporal and spatial analysis of droughts are important in studying variation of drought and its distribution.

2.2 Types of Drought

Drought is a natural phenomenon that is stimulated by persistent precipitation deficiency. Drought events inevitably have significant effects on natural habitats, water resource systems, ecosystem as well as economy and social sectors. Among other natural disasters, drought has its unique characteristics as this hazard vary by features like intensity and duration. These features lead to widespread and subjective nature of its impacts, making it difficult to be precisely described (Agwata, 2014). In general terms, droughts are characterized in various dimensions such as severity, duration and spatial distribution. According to the research conducted by Pedro-Monzonis, et al. (2015), drought has been defined in two ways: conceptual and operational. Conceptual definition of drought describes the concept of drought in which this hazard is a result of exceptional shortage of precipitation which will then affect the water demand for either ecosystem or human activities (Wilhite, Sivakumar and Pulwarty, 2014). On the other hand, operational definition aims to point out starting, end as well as severity and magnitude of droughts. In this case, there is no specific definition can be used in all conditions to describe drought. Based on operational definition of drought, three major drought types are formed as shown in Figure 2.1: meteorological, agricultural and hydrological droughts. There is also another definition of drought, which is socioeconomic drought with its applications in water resources management.

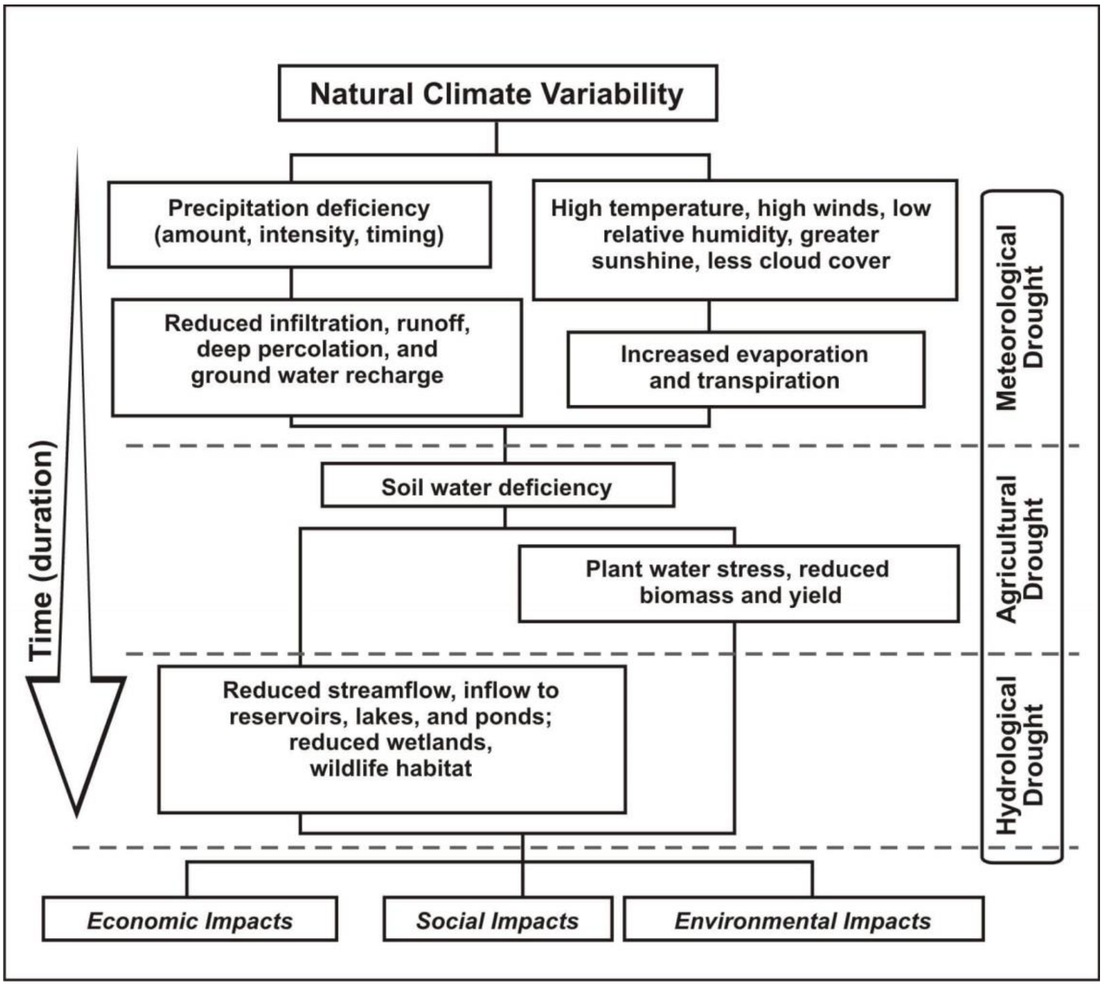

Figure 2.1: Factors and Order of Occurrence of Different Types of Main Drought Events (NDMC, 2018)

2.2.1 Meteorological Drought

Meteorological drought is described as continuous absence or decrement in precipitation, and the definition of this type of drought is remarkably depending on duration of precipitation deficiency as well as the amount and intensity. It can be characterized by indices such as SPI, SPEI and PDSI. The behavior of atmospheric conditions is important in defining meteorological drought due to the variation of atmosphere from region to region. In this case, the atmospheric conditions are governed by natural and human factors such as global warming, greenhouse effect and deforestation (Pedro-Monzonis, et al., 2015). Lower precipitation during drought period directly leads to reduction in runoff, infiltration and groundwater recharge. The land is exposed to high temperature and high winds with less cloud cover, and hence relative humidity becomes lower. Dry condition leads to more evaporation and transpiration of crops and eventually meteorological drought will lead to agricultural drought as plants grow aggressively (Zargar, et al., 2011).

Nevertheless, meteorological drought is also linked directly or indirectly to other categories of drought in which the related variables are precipitation, runoff, evaporation, groundwater storage and streamflow. All these variables are the components of hydrological cycle, and hence the effects of meteorological drought on hydrological drought is the key element for the developments of hydrological drought forecasting and early cautioning system (Zhao, et al., 2014). The time gap between occurrence of these two types of drought is the key of studying hydrological drought from the research on meteorological drought. The relationship between this type of drought and others is shown in Figure 2.2.

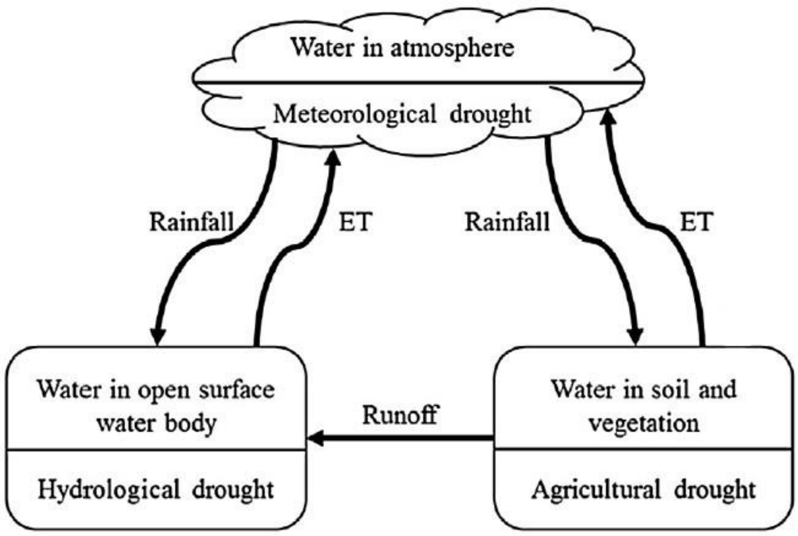

Figure 2.2: Relationship between Different Types of Drought (Zhou, et al., 2014)

2.2.2 Agricultural Drought

From the study conducted by Wang, et al. (2018), agricultural drought is recognized as duration of decline in flows of waterways and lakes as well as groundwater level below average. These phenomena generally refer to lowered humidity of the affected region below suitable humidity level, causing soil moisture deficiency for crop production. The worse scenario is the hot temperature, low relative humidity and dry winds, which usually add to the negative impact of the precipitation deficit. So, global temperature rise is one of the main environmental issues in this century and the current climate conditions, and the growing demand of economic development will cause the temperature continues to rise.

Agricultural drought poses damages to agriculture, food security and economies so this issue has gradually grabbed attention from the government and research academia (Zhou, et al., 2017). During agricultural drought, the plants lost water content, resulting in the condition such that the leaves are no longer in green. Depressed vegetation growth during agricultural drought will reduce crops and threaten the survival of animals including herbivores and omnivores that depends on vegetation for food supply. Many agricultural drought indices have been proposed to conduct observation on soil moisture and crop failure during dry season. In common, the indices consider soil moisture to illustrate drought and ignore vegetation water stress variable.

2.2.3 Hydrological drought

Similar to other types of drought, hydrological drought is defined based on referencing variables including frequency of occurrence, duration, severity, spatial and temporal distribution. The origin of the hydrological drought is the precipitation deficit that causes meteorological drought at initial and eventually transpose into deficit in runoff, which is the warning of potential hydrological drought (Lin, et al., 2017). This type of drought is greatly governed by climatology and human activities but in practice the hydrological model is used to create representation of drought without the consideration of human factor. The research carried out by Zhang, et al. (2018) showed that the frequency of occurrence of hydrological drought was dominant by precipitation, while the worse condition was governed by evapotranspiration. In this case, precipitation was the main factor followed by evapotranspiration rate and human activities. Nevertheless, changes in streamflow affected the pattern of the disaster in terms of occurrence, temporal variation and severity.

Hydrological drought is governed by occurrence of meteorological drought due to the process in hydrological cycle and thus its characteristics are controlled by the changes of process in hydrological cycle (Swetalina and Thomas, 2016). In this context, the occurrence of droughts in sequential order varies in a semi-arid climate and during cold season with accumulation of snow. The research carried out on hydrological drought is important for aquatic ecosystems and human activities in related to duration of drought in streamflow. The findings of the study contribute to adequate water resources management followed by good planning of water reticulation practice.

2.2.4 Socioeconomic drought

In the past, research about socioeconomic drought is uncommon. However, socioeconomic drought becomes a natural hazard to be concerned by policy makers because of rising water demand especially in the urban cities with growing population and industry (Huang, et al., 2016). Socioeconomic drought is the conditions in which water supply is not sufficient to fulfill water demand and leads to negative impacts on environment, economy and society. This type of drought has significant different with other droughts as it deals with supply and demand of water and hydropower. Furthermore, socioeconomic drought can also assimilate elements of meteorological drought, hydrological drought and ecological drought. The drought impacts will increase with frequent meteorological drought that is highly dependent on precipitation (Wilhite, Sivakumar and Pulwarty, 2014).

2.3 Drought Indices

Drought has afflicted economy, environment, society as well as causing socio-economic impacts in many countries around the world and it is known to be a recurrent hazard that affects large area. Droughts occur in many different ways, therefore there are different definitions depending on this nature. It has risen concern among government, policy makers and research community due to its recurrence nature. Researches on the drought are relatively important in management of water resources. The study of drought requires knowledge and understanding of historical drought events, which includes its impacts and methods applied to characterize its occurrence. Consequently, there is need for putting effort to study different definitions of drought so that monitoring, prediction and impacts mitigation strategies can be developed. In this case, the best way to characterize drought is by using drought indices to analyse different drought types in different sectors.

A drought index provides quantitative measures of drought severity, which aids in characterization of drought. In general, drought indices are able to characterize different drought events and conditions or in specific, reflect deviation of climate dryness as well as upcoming impacts in agricultural and hydrological sectors such as lowered relative soil humidity (Pedro-Monzonis, et al., 2015). Nowadays, drought index is even enhanced with high technology such as remote-sensing imagery in monitoring vegetation health. Multiple drought indices are introduced based on the concepts of drought's nature, characteristics and the impacts dealing with. In addition, the indices are further categorized into meteorological, agricultural and hydrological. As shown in Figure 2.3, the information is primarily collected by researchers and then indicators are used by managers. Basically, drought indices are used by decision-makers as well as policymakers, and hence the application of technology especially remote-sensor system is encouraged to customize indices with specific drought condition and region affected.

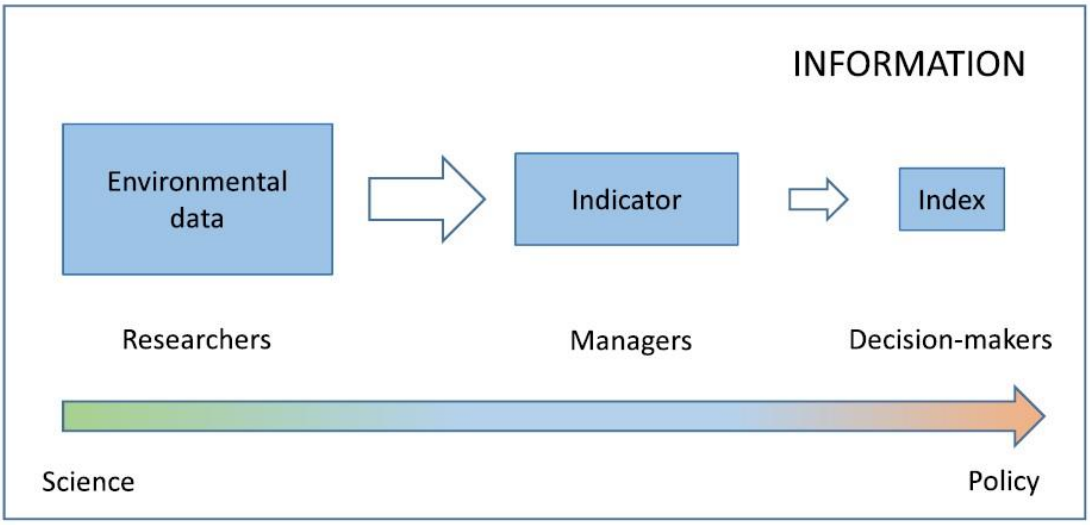

Figure 2.3: Sequence of Information Process in Water Resources Planning and Management (Petro-Monzonis, et al., 2015)

2.3.1 Standardized Precipitation Index (SPI)

Meteorological drought is the fundamental drought in the flow of occurrence and order of drought conditions. It is known that precipitation is solely the variable that affects the occurrence of meteorological drought. In this case, a suitable drought index that is the SPI was introduced in 1993 to characterize meteorological drought based on time basis. In general, the function of SPI is to perform estimation of dry or wet condition with only precipitation variable as input (Zin, Jemain and Ibrahim, 2012). Computation of the SPI is based on pre-set timescales according to research purpose and practice where the timescales normally used are 3, 6, 12, 24 and 48 months, which coincides with past similar timescales of observed precipitation data, respectively. Moreover, the analysis can further be interpreted using recurrence intervals or return periods.

From the perspective of mathematical function, SPI uses probability distribution function to convert long term rainfall data into a normal distribution with zero mean and one for value of standard deviation. The SPI values are then revealed in standard deviation in which positive values indicate more than median precipitation whereas values less than zero indicate smaller than median precipitation (Kumar, et al., 2009). In addition, a negative value of the SPI indicates there is drought event and the categories of drought based on the SPI are tabulated in Table 2.1.

Table 2.1: Categories of Drought Based on SPI (Kumar, et al., 2009)

SPI	Drought category
0 to −0.99	Mild drought
−1.00 to −1.49	Moderate drought
−1.5 to −1.99	Severe drought
−2.00 or less	Extreme drought

The advantage of this index is none other than its ability to adapt for determination of drought levels at variable timescales. The main feature of SPI is the severity or magnitude of drought can be used to express changes in water characteristics following gradually and occasionally varying effect to water resources, streamflow, runoff and groundwater due to precipitation deficiency over time (Zargar, et al., 2011). The effects associated with different timescales are shown in Table 2.2. Next, the SPI is also known of its simplicity and versatility. It is solely depending on precipitation data while it can also be applied in monitoring agricultural drought and hydrological drought that is indirectly affected by rainfall deficit. Furthermore, this index can be used to study and make comparison between various areas with different climatological characteristics. Another advantage is the index is different from other drought indices as it can monitor wet season although it is an index designed to characterize dry season.

Table 2.2: Conditions in Related to Different Timescales of the SPI and Their Applications (Zargar, et al., 2011)

SPI duration	Application
1 month SPI	Short-term soil moisture and crop stress (especially during the growing season)
3 month SPI	A seasonal estimation of precipitation
6 month SPI	Potential for effectively showing the precipitation over distinct seasons. e.g., for California, the 6 month SPI can effectively indicate of the amount of precipitation from Oct. to Mar.
9 month SPI	If $SPI_9 < -1.5$ then it is a good indication that substantial impacts can occur in agriculture (and possibly other sectors)
12 month SPI	Possibly tied to streamflows, reservoir levels, and also groundwater levels

For operational purpose, SPI has been progressively recognized as common and standard drought index to monitor, predict and characterize meteorological drought. One of the applications for SPI includes assessment of southern Amazon regions with homogeneous climate. Analysis conducted in terms of timescales produced results of decreased the SPI values between 1970 and 1999, indicating an increase in drought conditions (Kumar, et al., 2009). Besides that, Siti Nazahiyah Rahmat, Niranjali Jayasuriya and Muhammed Bhuiyan (2015) adopted the SPI in describing meteorological droughts in Victoria, Australia, by considering 55-year monthly rainfall data. The performance of the SPI was excellent in indicating starting and ending of two drought events, suggesting that it can be applied in other regions of east Australia. The SPI also demonstrated its better ability in measuring drought severity as compared to the deciles. Furthermore, the time length of droughts was longer when the computation of the SPI was based on longer timescale, due to the decrease in variation of index values.

Based on the research done by Tan, et al. (2018), the SPI was used to conduct analysis on meteorological droughts that occurred between 1975 and 2010 in Johor River Basin. The researches were highly concerned on the data gathering procedures in order to maintain high standard of the precipitation data for computation. The extreme data were excluded from the study and the missing data were repaired with data from surrounding stations. Moreover, the drought characteristics were developed using the index to detect drought events in different regions of the basin. As a result, the frequency of droughts in the upper region was higher than that in the lower basin, showing lesser precipitation amount over the Linggiu Dam.

Drought index that only depends on one variable may not have high accuracy of measurement because it ignored other parameters that may contribute to drought characterization. The index also does not posse ability to determine levels of drought in certain regions as study performed on these regions may require information of local climate conditions. In addition, the dependent on precipitation data limited the coverage of the monitoring tool as it does not consider changes in evapotranspiration. In this case, potential evapotranspiration is an additional indicator in which it is considered in alternative index such as SPEI.

2.3.2 Standardized Precipitation Evapotranspiration Index (SPEI)

Drought is recognized as a multi-scalar phenomenon that induced by extended period of precipitation deficit and eventually afflicted other elements in the hydrological cycle. In many semi-arid areas, potential evapotranspiration (PET) is dominant because it is higher than precipitation throughout the year. Thus, a drought index that merely dependent on precipitation variable might unsatisfactory for drought forecasting. Therefore, it is essential to involve other variables especially temperature in development of drought indices because the evapotranspiration rate is governed by temperature as well. In this case, the SPEI is a multi-scalar drought index which considers both precipitation and temperature (Tirivarombo, Osupile and Eliasson, 2018). The consideration of temperature as variable in the SPEI shows that this drought index recognizes evapotranspiration as the dominant way of water loss in the areas with extreme hotness conditions and dry climate.

The calculation of SPEI is very much the same to that of SPI but with modifications to consider PET. In any case, the calculation of the index only differs in the situation that PET varies from different conditions like global warming scenario. In this case, the Pearson Type III and log-logistic distribution adapted perfectly to regions with homogeneous climate and different characteristics (Vicente-Serrano, Begueria and Lopez-Moreno, 2010). Nonetheless, the self-determination of various timescales in measurement of rainfall deficit is suitable to model D (P - PET) values. At the end, the cumulative probabilities obtained are converted into a standardized variable.

According to the research done by Begueria, et al. (2014), SPEI considers the deviation between precipitation and evapotranspiration that is termed as climatic water balance to make comparison so that better measurement of drought severity can be performed. In recent years, efforts are put in improving formulation of the index to solve problems that have arisen during applications. These improved configurations involved methods applied to configure parameters of the log-logistic distribution and calculate PET, as well as the computing devices for calculation and analysis of the index. The SPEI associates precipitation with temperature as well as water balance and potential evapotranspiration. When there is absence of long-term trends of change in temperature, the SPEI can be considered quite similar to the SPI.

In the study of drought events that happened between 1982 and 2012, Li, et al. (2015) applied SPEI to perform regional, temporal and trend analysis of droughts. The computation of the monthly SPEI was based on different timescales, followed by calculation of mean value of the index over all the stations. Meanwhile, the interrelation of the drought index and two remotely detected drought indices were determined to evaluate the accuracy of the SPEI in identifying droughts. The results showed there was an increasing trend of drought, and this disaster became severe for about two years since 2010.

Chen, et al. (2018) also demonstrated the use of the SPEI in studying variation of droughts over space and time in Yangtze River Basin of China. The computation of the index was performed for four different timescales, in which the PET was determined based on Penman-Monteith method due to its consideration of more components. A total of 52-year data were considered and the outcomes of the research proved that the SPEI was suitable in analysis of drought conditions in the study region. In addition, the SPEI-1 functioned to describing short-term drought whereas SPEI at 3-month timescale displayed variations of the phenomenon over seasons.

On the other hand, Zhejiang district in China suffered from droughts due to the high temperature condition during the summer. The SPEI was adopted in the study of droughts' characteristics with the consideration of rainfall and temperature data from 1973 to 2013. At the meantime, assessment was also conducted on variations of droughts over region and time by using the index (Lou, et al., 2017). There was no remarkable variation for rainfall in July and August, while an increasing decadal trend of temperature was noticed for these two months. In short, the SPEI was proved to be excellent in detecting duration, as well as starting and ending of droughts.

2.3.3 Palmer Drought Severity Index (PDSI)

The Palmer Index was first published in 1965 by Wayne Palmer in which the method integrated variables including precipitation, demand and supply of soil moisture into a hydrological computing system. Based on the research done by Thornthwaite, the computation work of soil moisture for the Palmer Index considered a two-layered model following by assumptions made regarding field capacity and transfer of moisture between the layers (Dai, Trenberth and Qian, 2004). This model assumed moisture in the top layer of soil will only be transferred to the bottom layer or root zone when it is in saturated condition. Furthermore, runoff was assumed not to occur unless both soil layers are saturated. Palmer applied (CAFEC) to organize his methods so that spatial and temporal analysis can be performed. This method enabled the Palmer Index to identify abnormal wet (positive values) and dry (negative values) conditions with persistent normal precipitation and temperature as index of zero in any season or climate (Heim Jr, 2002).

The Palmer Index refers to three indices: PDSI, PHDI and Z Index, where PDSI is known as the most remarkable index used in the United States. The PDSI functions on the basis of water balance equation supply-and-demand or in other words and it has taken into consideration of abnormality in soil moisture deficit rather than precipitation deficiency. The index is a meteorological index corresponding to climate conditions and considers precipitation, temperature and local water content in the soil (soil moisture content) for computation of the water balance equation (Agwata, 2014). However, human activities such as irrigation and groundwater extraction are not taken into account. The variables in the water balance equation include: evapotranspiration, runoff, soil recharge and moisture. The classification of drought based on PDSI is shown in Table 2.3.

Table 2.3: Classification of Drought Based on PDSI (Agwata, 2014)

Value	Condition
≥ 4.0	extremely wet
3.0 – 3.99	very wet
2.0 – 2.49	moderately wet
1.0 - 1.99	slightly wet
0.5 – 0.99	insipient wet spell
0.49 - -4.9	near normal
-0.5 - -0.99	insipient dry spell
-1.0 - -1.99	mild drought
-2.0 - -2.99	moderate drought
-3.0 - -3.99	severe drought
≤ -4.0	extreme drought

The strengths of the index are none other than it is more extensive than precipitation-based index like the SPI, as the PDSI also incorporated evapotranspiration and soil moisture parameters. The index covers the impacts of global warming through the consideration of PET when using atmospheric temperature and physical water balance equation. In addition, the index is sensitive in identifying long-duration drought, especially in areas with low and middle altitudes. The index also takes precedent (monthly) conditions into account. According to the study conducted by Zargar, et al. (2011), there are noticeable limitations in application of the PDSI to be considered. First, the index is configured for U.S. Great Plains' conditions so its application for regions with mountainous terrain or locations with extreme climate and snow-pack. Second, it is not as good as the SPI for comparison across duration and regions. In this case, both mentioned limitations can be solved by using self-calibrated index. Sometimes, it is difficult to apply the index for drought associated with water management system because it does not consider water storage, snowfall and other supplies besides ignoring human activities.

2.3.4 Streamflow Drought Index (SDI)

Hydrological drought caused deficit in water resources in many ways, which are expressed in several hydrological variables like streamflow in conjunction with reservoir and groundwater level. Among the various hydrological variables mentioned, streamflow is the principal variable to be considered. The SDI is a simple and effective index introduced by Nalbantis and Tsakiris (2009) based on the comparison of volumes of streamflow in considered duration (i.e. monthly) to the long term average data. The origin of the index comes from Ben-Zvi work and it is analogous to the meteorological indices like SPI and RDI as intensity of hydrological drought are defined similarly to that of meteorological droughts. Hydrological drought is assigned to five states using the number starting from zero to four as illustrated in Table 2.4.

Table 2.4: Criteria of Hydrological Drought Based on SDI (Nalbantis and Tsakiris, 2009)

State	SDI Value	Criteria
0	SDI ≥ 0.0	Non-drought
1	−1 ≤ SDI ≤0	Mild drought
2	−1.5 ≤ SDI ≤−1.0	Moderate drought
3	−2.0 ≤ SDI ≤−1.5	Severe drought
4	SDI ≤−2.0	Extreme drought

The SDI under four different timescales was used to monitor hydrological drought in the north-west region of Iran between 1975 and 2009 by using streamflow data. There were different types of distributions considered in computing the SDI, in which at the end the log-normal distribution was proved to be the most suitable in fitting probability distribution for the streamflow data. The findings of the research also showed that the whole study region experienced droughts with exceptional high severity from 1975 to 2009 (Tabari, Nikbakht and Talaee, 2012). Furthermore, the analysis of droughts at the upper region of Yangtze River Basin was done by applying the SDI, in which the 11-year daily streamflow data were gathered from Yichang hydrological station. In this case, 12-month timescale was considered to compute SDI, followed by its application in recognizing drought events in the study region. As a result, the frequency and magnitude of the droughts was observed to be higher than in the past (Hong, et al., 2014).

2.3.5 Surface Water Supply Index (SWSI)

The SWSI takes into account the works done by Palmer and was developed to overcome the limitations PDSI. The index is designed by adding supplementary information including water supply data (snowpack, snowmelt and reservoir storage) as data inputs. Therefore, the SWSI considers precipitation, streamflow and water supply data in the efforts of characterizing hydrological droughts (Zargar, et al., 2011). The index assembles both hydrological and meteorological variables into a single index, where the index values are calculated at the basin level. One of the advantages of applying the index to analyse hydrological drought is its simplicity and it acts as a comprehensive indicator of the overall hydrological conditions for a particular basin (Agwata, 2014). In contrast, it is tough to develop a homogeneous series in as additional inputs are included. In this case, reconstruction of frequency distribution has to be performed due to consideration of extra inputs. Furthermore, extreme cases can also cause difficulty if the events are behind the time series considered. Similarly, recalculation of the index is required to include these extreme cases in developing frequency distributions.

From the research conducted by Kwon and Kim (2010), the SWSI was revised to assess the hydrological droughts that occurred in South Korea in semi-distributed mode. The amended SWSI replaced two original inputs, particularly snowpack and reservoir level data by dam inflow and groundwater level data. The revised SWSI was developed to consider both water content at above and beneath ground because of various types of water resource over the country. The nation was then split into multiple drainage basins for analysis. The results proved that more spatial details could be observed if there were more segregations of watershed.

Further in 2018, a new drought index named Korean Surface Water Supply Index (KSWSI) was introduced on the basis of SWSI to improve the revised SWSI. The first way was studying all the available hydrological and meteorological data in every sub-basin, where the suitable one was extracted for computation. Second, estimation and application of adequate probability distribution was done for every drought element (Jang, et al., 2018). These upgrades resulted in better performance of the KSWSI in describing drought condition than the modified SWSI. The applications of the revised SWSI and KSWSI in South Korea demonstrated the flexibility of the SWSI in adapting to local water variables.

2.4 Spatial and Temporal Analysis of Drought

Since droughts have been recognized as natural hazard that cause devastating effects on water resources and crops production, many researches have been done to analyse characteristics of various types of drought including severity, magnitude, duration and regional extent. According to the study done by Fniguire, et al. (2016), spatial and temporal variations of precipitation governed the behaviour of the dry spell conditions, and thus the disaster also known as a spatial-temporal dynamic phenomenon. Therefore, the study of the drought shall be carried out along with spatial and temporal analysis. The objective of the spatial and temporal analysis of the drought is none other than determining duration and spatial variation patterns of drought. The impacts of the changes in atmospheric condition are linked to the drought pattern and the variations are regional-based. The characteristics and patterns of drought vary geographically and significantly from one region to another. Furthermore, the disaster can also happen in areas with high or low precipitation and in any season. Hence, in consideration of the spatial nature of drought, analysis of regional conditions in terms of spatial-temporal variation is relatively important (Ndehedehe, et al., 2016).

2.4.1 Ordinary Kriging (OK)

Ordinary Kriging is a fundamental Kriging method that falls under geostatistical category among numerous spatial interpolation techniques. This method is univariate as it considers single element in prediction (Chabala, Mulolwa and Lungu, 2017). In statistics, there will be some data that are failed to be obtained from the un-sampled region. Therefore, these data are estimated with the application of OK method based on the mean weighted value of neighbouring sampling locations in a specific region. The OK is normally applied along with tools such as ArcGIS and QGIS to model the spatial distribution of data.

Chabala, Mulolwa and Lungu (2017) adopted OK to evaluate spatial variation of soil organic carbon (SOC) in Zumbia. The spatial distribution of SOC was generated with the exponential model of semivariogram, along with the fitting steps automatically. The results showed that the spatial relationship of data was strong within short distance, while the spatial maps generated can act as guidance for soil optimisation work. In the study by Agung Setianto and Tamia Triandini (2013), OK and IDW were applied to carry out lineament assessment based on data obtained from Digital Elevation Model (DEM). The analysis aimed to determine the best method for the generation of DEM, as lineament retrieved from DEM played an important role in characterization of geological features, which indirectly contributed to geological mapping of Kepil, Indonesia. The results showed that the simplicity of IDW had benefits for nominal data and the lineament generated by IDW was nicer than that produced by OK. Next, the accuracy of IDW was higher due to its ability to display small lineament and lesser maxima as compared to OK.

2.4.2 Inverse Distance Weighting (IDW)

The application of the Inverse Distance Weighting is based on the assumption that the interrelation between sampling stations that are at short distance to each other is strong. It is used to provide estimation of data at un-sampled stations using a linear integration of known values based on an inverse distance function (Agung Setianto and Tamia Triandini, 2013). The dominant element that governs the performance of this method is none other than the power parameter. The reason is the weightage reduced with the decrease of distance, leading to greater weightage at the surrounding points and greater effects on the estimation.

Zarco-Pellelo and Simoes (2017) applied the IDW and OK to estimate spatial distribution and abundance of habitat-forming organisms (HFO). Both methods applied the similar concept as mentioned, and the value was estimated by considering great weightage to the samples which were nearer to the un-sampled point. The findings of the research proved that IDW had high accuracy in spatial interpolating works, which displayed the regional distribution of every HFO. In agriculture, the difficulty of retrieving soil data is high due to the variation nature of soil characteristics over space. Thus, the estimation of soil composition at paddock was performed with the application of the IDW and OK. The analysis was conducted with multiple soil samples to produce the spatial maps of the soil characteristics, while the root mean square error (RMSE) was applied to assess the accuracy of the two spatial interpolators for pH and organic substances (Robinson and Metternicht, 2011). Finally, the IDW was verified to be better than OK in evaluating spatial variation of soil compositions.

2.5 Summary

The adverse impacts on agriculture, water resources system and society caused by drought or dry spell events have attracted the attention of government, policy makers, water management agency and research community. The research of drought becomes necessary to have better understanding of the phenomenon. The findings of the research play an important role in developing comprehensive drought monitoring system and mitigation planning. Drought is caused by unusual precipitation deficit and its unique characteristics make it varies across region as well as in terms of duration, magnitude and severity. In practice, droughts are categorized into meteorological, agricultural and hydrological, or sometimes the term socioeconomic drought is used in research. This natural disaster occurs in different ways, and thus there is no single definition can be used in general to describe droughts. Its recurrent nature and large areal extent make it difficult to determine its characteristics. Drought indices are introduced to provide quantitative measures of the drought. The indices differ in terms of data inputs, types of drought, impacts dealing with as well as the way the indices consider the variation of spatial and temporal drought distribution. Every drought index has its pros and cons, and hence appropriate drought index has to be selected depends on the objective of study. Spatial and temporal analysis is essential to be performed during the study on the drought to understand temporal and spatial extent of the drought events because the droughts' characteristics vary on regional basis.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Workflow

This chapter outlines all the methods and steps involved in conducting the research. The workflow, study area, raw meteorological and hydrological data collection, repairing and analysis procedures as well as software and formula used in the study are discussed. The methodology of the study is shown in Figure 3.1.

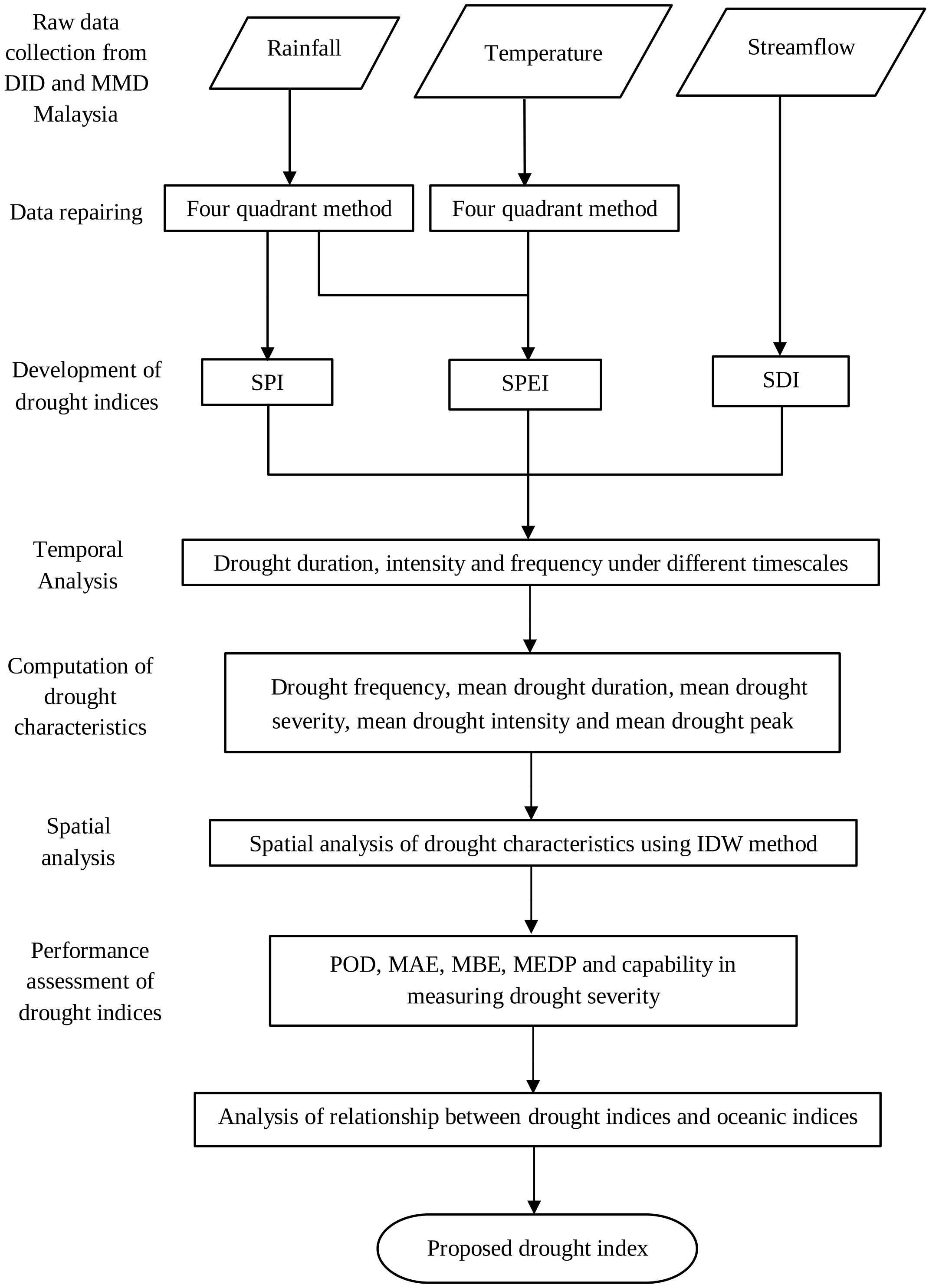

Figure 3.1: Workflow of Research

3.2 Mapping, Location of Study and Data Acquisition

The methodology of the study began with retrieving rainfall, streamflow and temperature data from DID and MMD Malaysia. Besides that, information of rainfall, streamflow and temperature stations including number, name, operation duration, coordinate and status were obtained from DID and MMD Malaysia. Then, the data were rearranged in an Excel table and this Excel sheet file was saved as a 'tab delimited' Text file. In Google Earth Pro, this Text file was imported to take latitude and longitude data of hydrological stations from within an Excel table and turn into Google Earth placemarks. These placemarks were saved as a KMZ file; then the file was converted into a KML file to be overlaid in the QGIS. Finally, the map of the study area was generated with the distribution of rainfall, streamflow and temperature stations using QGIS. The procedures of mapping of the study area are shown in Figure 3.2.

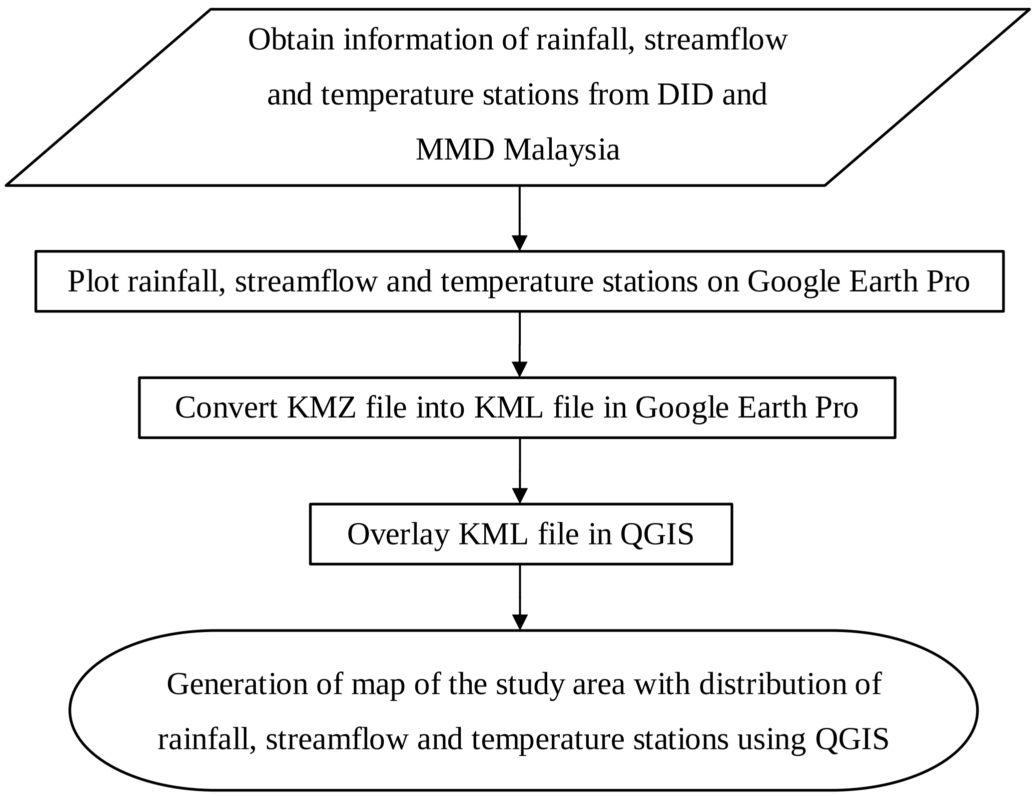

Figure 3.2: Mapping of the Study Area

The study area is the East Coast of Peninsular Malaysia which includes the three states: Terengganu, Kelantan and Pahang. The East Coast region has an exceptionally diverse climate with two clear seasons. The meteorological conditions of this region are directly affected by the northeast monsoon season from early November to February or Mid-March with strong winds and rain. In contrast, the weather is at its driest from April to October (Chew, 2013). The maps of study area with distributions of meteorological and hydrological stations are illustrated in Figure 3.3, while details of the stations are provided in Appendix A.

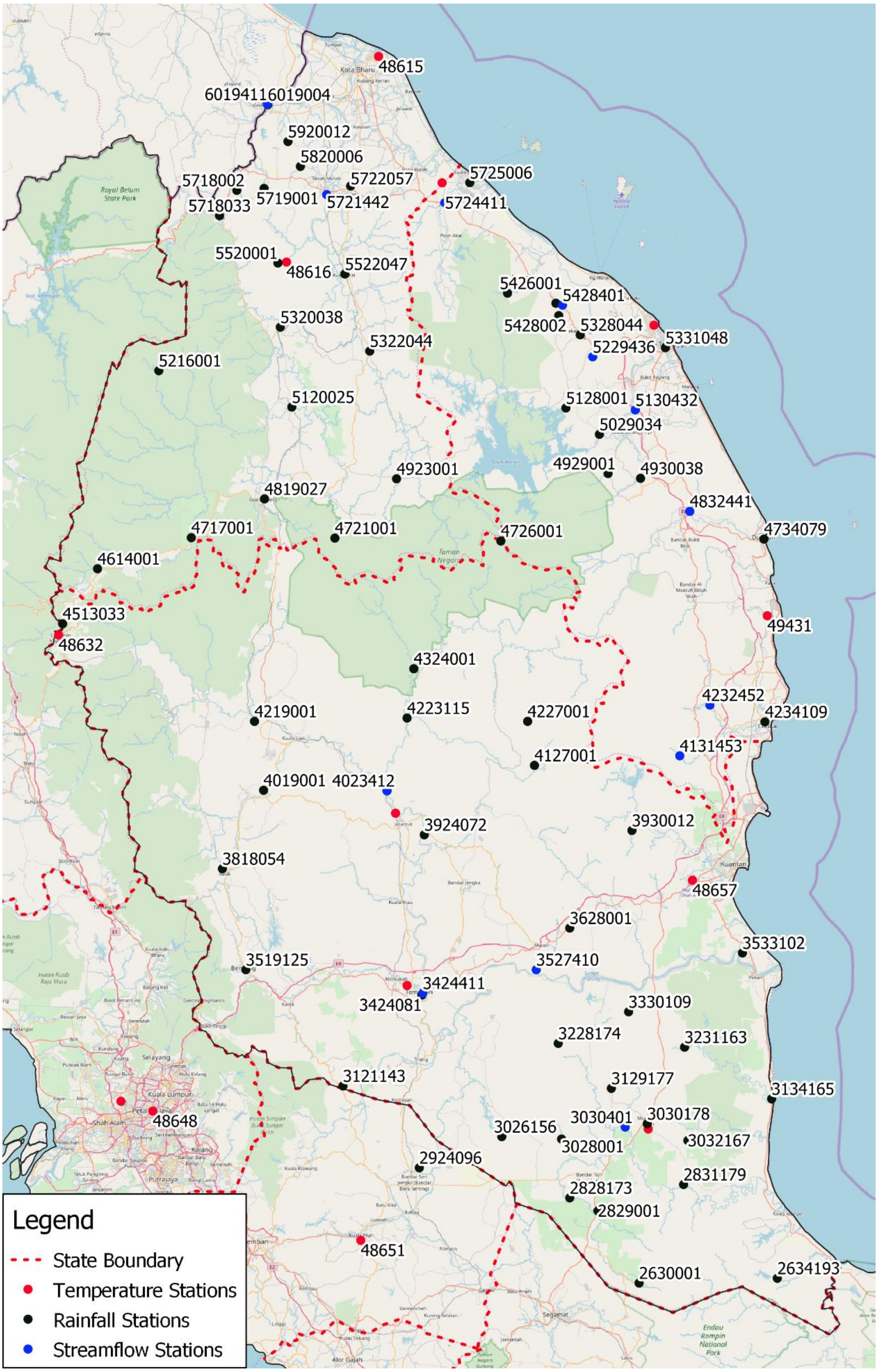

Figure 3.3: Distribution of Meteorological and Hydrological Stations in the Study Area

Kelantan is situated in the north-east region of the Peninsular Malaysia, with area of 15 101 km^2. The borderline of the state is formed by parts of southern Thailand, Perak, Pahang and Terengganu. The catchment area of the Kelantan Area Basin is about 13 000 km^2 or 85 % of the state. The area received an average annual rainfall of 2 460 mm in last 31 years with an average annual temperature of 27.5 °C. The rivers in the basin are the Kelantan River that divides into the Galas River and the Lebir River at Kuala Krai. Galas River is further dividing into the Balah River, Tarang River, Pergau River and Nenggiri River. There are other main rivers at the downstream including the Lemal River, Meranri River, Kemasin River, Peng Datu River and Pengkalan Chepa River (Mohd Talha Anees, et al., 2017). The economy of Kelantan is considered agrarian which is mainly dependent on rice, rubber and tobacco production while fishing activities along the coastline are also important economic activities. Latterly, tourism that is dominated by trips to an offshore island has become a significant economic activity. The climate of Kelantan is considered tropical. Extreme weather such as heavy rainfall resulting in floods and an extended period of dry spells in the region can affect these economic activities.

According to The Star Online (2017), the Sungai Golok, Sungai Kelantan and Sungai Galas can continue to rise following heavy rainfall for two consecutive days during the northeast monsoon season. Nonetheless, continuous heavy rain for a few days ago can cause floods to low-lying areas in Kelantan. Hence, the research is important to develop a drought index to analyse extreme weather conditions in the state. From the results of the study, mitigation strategies include such as deepening of rivers and construction of dam for multiple purposes: flood mitigation, water supply for agriculture and generation of electrical energy. Kelantan currently has the Pergau Dam in operation and there are proposals for construction of dams in the Nenggiri River and Lebir River (Bernama.com, 2017). Nonetheless, drought disaster harms crop production, as paddy fields require water supply for irrigation. Furthermore, low soil moisture content affects the growth of plants.

Terengganu is the state that faces the South China Sea, with an area of 13 035 km^2 and borders Kelantan state to the north and the Pahang state to the south. Terengganu is enriched with beaches and water ranging throughout its 225 km coastline that extends from Besut to Kemaman. The main economic activity of the state is fishing while the discovery of offshore oil and gas in the South China Sea has caused noticeable changes to its economy (Streetdirectory editorial team, 2018).

Although cities like Kuala Terengganu has transformed to modern city with the offshore oil installations, but farming and fishing still play important roles in economy of the state.

There are numerous islands located close to the coast of the state such as the Redang Island with snorkelling and diving opportunities for tourists. Drainage in the state mainly depends on two rivers: The Terengganu River and the Kemaman River while Kenyir Dam is a multipurpose dam for generating hydroelectric power (Sultan Mahmud Power Station) and flood mitigation works. The state receives heavy rainfall during the northeast monsoon, where some areas suffer flooding with average rainfall of 400 mm whereas the area experiences average rainfall of 190 mm during the dry season. According to Zarina Abdullah (2017), people in Kuala Terengganu always suffered from flood during northeast monsoon season thus the research is important to predict the extreme weather for the local government to prepare mitigation planning. Moreover, the extreme climate also poses a threat to tourism potential.

Another state in the study area is the state with largest area in Peninsular Malaysia: Pahang with area of 35 840 km^2. Kelantan, Perak, Selangor and Negeri Sembilan, Johor and the South China Sea form the borderline of the state. Pahang has eight rivers: The Pahang River, Endau River, Jelai River, Kuantan River, Lipis River, Rompin River, Tahan River and Tembeling River. During the northeast monsoon season, the Pahang River is the main channel for drainage from the Pahang River Basin into the South China Sea. Extreme rainfall due to the northeast monsoon resulted in higher streamflow and finally contributed to flood events at the Pahang River Basin (Pan, 2011).

From the aspect of the economy, logging and agriculture since the earlier days remain as activities of the state. In recent years, the income is no longer dependent on logging activities but from the palm oil industry (Roselan Ab Malek, 2018). Similar to other agricultural activities, water resources are important in palm oil production. Furthermore, drought events in the past had caused twenty-eight of the eighty water treatment plants in Pahang recording low levels. Hence, understanding the drought pattern is important in order for the local authorities to prepare for water restriction planning (The Star Online, 2014). The few dams in operation in the state include the Chematu Dam, Chereh Dam, Sultan Abu Bakar Dam, Chini Dam and Kelau Dam.

3.3 Data Repairing

The rainfall and temperature data collected has some missing data and these missing data can be filled using an estimation technique. There are several methods available for data repairing such as the normal ratio method, the inverse distance method and the four-quadrant method. In this research, due to its simplicity the four-quadrant method was applied to estimate the missing data. Equation 3.1 as follow denotes the four-quadrant method:

$$\overline{P} = \sum W_i P_i \tag{3.1}$$

where,

W_i = Weightage of station is given by Equation 3.2:

$$W_i = \frac{\left(\frac{1}{di^2}\right)}{\sum_{i=1}^{n}\left(\frac{1}{di^2}\right)} \tag{3.2}$$

$\overline{P}$ = Mean precipitation

P_i = Precipitation of stations

di = Distance from station with data to station with missing data

n = Number of station considered

Initially, a station with missing data was identified followed with identifying three neighbouring stations in each quadrant. There were a total of four quadrants in which the sequence is shown in Figure 3.4.

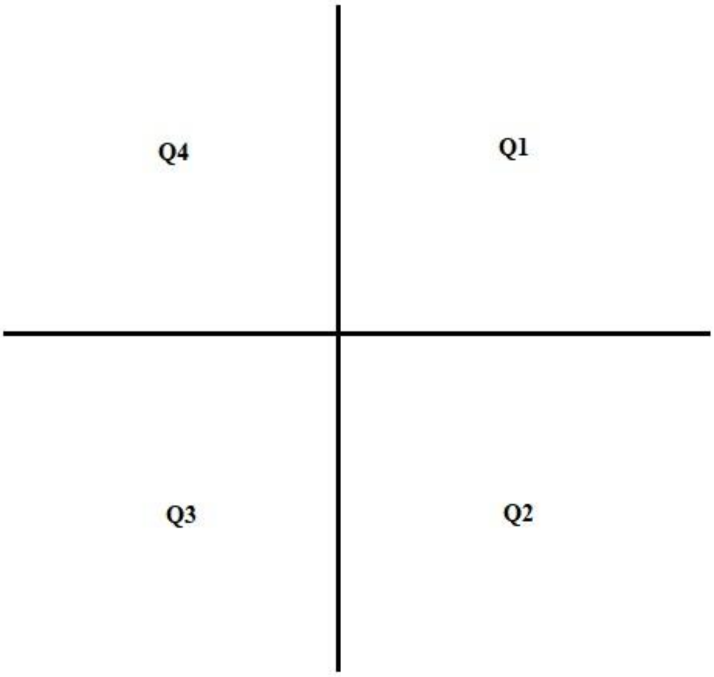

Figure 3.4: Sequence of Four Quadrants

Then, the distance from the considered station (station with missing data) to neighbouring stations were measured using “measure line” tool in QGIS. At last, only one station nearest to considered station in each quadrant was used for repairing purpose. In this case, there were probabilities of sixteen conditions as stated in Table 3.1 to be considered in the repairing calculation.

Table 3.1: Sixteen Conditions and Quadrant with Neighbouring Station in Consideration Respectively

Condition	Neighbouring station in consideration
0000	Neighbouring stations in all quadrants.
X000	Neighbouring stations in quadrant 2, 3 and 4.
0X00	Neighbouring stations in quadrant 1, 3 and 4.
00X0	Neighbouring stations in quadrant 1, 2 and 4.
000X	Neighbouring stations in quadrant 1, 2 and 3.
XX00	Neighbouring stations in quadrant 3 and 4.
X0X0	Neighbouring stations in quadrant 2 and 4.
00XX	Neighbouring stations in quadrant 1 and 2.

Table 3.1 (Continued)

0X0X	Neighbouring stations in quadrant 1 and 3.
0XX0	Neighbouring stations in quadrant 1 and 4.
X00X	Neighbouring stations in quadrant 2 and 3.
XXX0	Neighbouring stations in quadrant 4.
XX0X	Neighbouring stations in quadrant 3.
X0XX	Neighbouring stations in quadrant 2.
0XXX	Neighbouring stations in quadrant 1.
XXXX	No neighbouring station.

3.4 Development of Drought Indices

This section explains the formula and methods used in the development of drought indices. The drought index was developed to understand the characteristics and patterns of different types of droughts. Different drought indices have different variables considered in their development and computation. Thus, there are advantages and disadvantages for every drought index. Thus, the most suitable drought index selected is to define the droughts in the study area based on the results obtained.

3.4.1 Standardized Precipitation Index (SPI)

The SPI is the worldwide acceptable index that considers only precipitation data in development and it shows the actual precipitation as standardized deviation from probability distribution function. This feature make it became important in the recent years to function as drought indicator that is capable to perform temporal and spatial analysis. It was developed to analyse the drought conditions and characteristics from the probability distribution of long-duration precipitation with the gamma distribution function (Almedeij, 2014).

The computation of the SPI was conducted with time series data, including all of the 35-year rainfall data from 1983 to 2017, at 1-, 3-, 6- and 12-month timescales based on the gamma distribution function with two parameters. This process required long term rainfall data to develop the probability distribution function and then the function was transformed to log-normal values or normalized numerical values with zero mean and standard deviation value of one. The SPI values were expressed in standard deviations in which positive SPI values meant they are greater than the median precipitation while negative meant that the values are less than the median precipitation. These values used to determine the category of drought is illustrated in Table 3.2.

Table 3.2: Categories of Drought (Kumar, et al., 2009)

SPI	Drought category
0 to −0.99	Mild drought
−1.00 to −1.49	Moderate drought
−1.5 to −1.99	Severe drought
−2.00 or less	Extreme drought

Next, the parameters in gamma distribution function including *U* statistics, shape and scale parameters were calculated (Kumar, et al., 2009). These parameters were then used to determine the imperfect gamma cumulative probability of rainfall event, after which this incomplete gamma cumulative probability was transformed into gamma probabilities along with consideration of zero precipitation events occurrence. The last step was converting the gamma probabilities to standardized normal distribution using the equal-probability converting method. The purposes of converting the rainfall data into the SPI values are as follows:

(i) To transform the mean value of rainfall adjusted to zero.

(ii) To adjust the rainfall standard deviation to one.

(iii) To remodify existing data skewness to zero.

Having the above objectives achieved, the SPI can be interpreted as zero mean and standard deviation value of one. The mean of the rainfall is calculated as given by Equation 3.3:

$$Mean = \overline{X} = \frac{\sum X}{N} \qquad (3.3)$$

where *X* is the precipitation and *N* is the number of rainfall stations.

The standard deviation for the rainfall was computed as Equation 3.4:

$$s = \sqrt{\frac{\sum \left(X - \overline{X}\right)^2}{N}} \qquad (3.4)$$

The skewness of the given rainfall is given as Equation 3.5:

$$Skew = \frac{N}{(N-1)(N-2)} \sum \left(\frac{X - \overline{X}}{s} \right)^3 \qquad (3.5)$$

The rainfall data was transformed to log-normal values (normalized numerical values) and the parameters of gamma distribution function: statistics *U*, shape and scale parameters are computed as Equation 3.6, 3.7, 3.8 and 3.9:

$$\log mean = \overline{X}_{\ln} = \ln\left(\overline{X}\right) \qquad (3.6)$$

$$U = \overline{X}_{\ln} - \frac{\sum \ln(X)}{N} \qquad (3.7)$$

$$shape\ parameter = \beta = \frac{1 + \sqrt{1 + \frac{4U}{3}}}{4U} \qquad (3.8)$$

$$scale\ parameter = \alpha = \frac{\overline{X}}{\beta} \qquad (3.9)$$

After that, the parameters computed above were applied to determine the cumulative probability of an observed rainfall event. The formula of the cumulative probability is denoted as in Equation 3.10:

$$G(X) = \frac{\int_0^x x^{\alpha-1} e^{\frac{-x}{\beta}}\, dx}{\beta^{\alpha}\Gamma(\alpha)} \qquad (3.10)$$

As the gamma distribution function was undetermined for $x = 0$ and there is certain probability that rainfall distribution contained zeros, so the cumulative probability transformed to as given by Equation 3.11:

$$H(x) = q + (1-q)G(x) \qquad (3.11)$$

where q represents the probability of zero.

Further, the cumulative probability $H(x)$ was next converted to the standard normal random variable Z with zero mean and standard deviation of one, which was the SPI values by applying the approximate conversion as donated by Equation 3.12 or Equation 3.13:

$$Z = SPI = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad for\ 0 < H(x) \leq 0.5 \qquad (3.12)$$

$$Z = SPI = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad for\ 0.5 < H(x) \leq 1.0 \qquad (3.13)$$

where,

$$t = \sqrt{\ln\left(\frac{1}{H(x)^2}\right)} \quad for\ 0 < H(x) \leq 0.5 \qquad (3.14)$$

$$t = \sqrt{\ln\left(\frac{1}{\left(1.0 - H(x)\right)^2}\right)} \quad for\ 0.5 < H(x) \leq 1.0 \qquad (3.15)$$

where the coefficients in Equation 3.12 and 3.13 are given by:
$c_0 = 2.515517$, $c_1 = 0.802583$, $c_2 = 0.010328$;
$d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$.

3.4.2 Standardized Precipitation Evapotranspiration Index (SPEI)

In comparison to the SPI, the computation of the multi-scalar drought index, SPEI was dependent on the consideration of both the precipitation and the temperature data. The method of calculation of the SPEI is based on the SPI computation steps. The difference is that the SPI is computed using precipitation as input data whereas the computation of the SPEI applied the variation between precipitation and PET as input data. In this research, the Thornthwaite method was selected among other methods to calculate the PET due to its advantage of only having to consider monthly-mean temperature data to identify the PET. The calculations of the simple climatic water balance proposed by Thornthwaite, were conducted at different timescales to obtain the SPEI values (Vicente-Serrano, Begueria and Lopez-Moreno, 2010).

The computation of the PET (mm) using the Thornthwaite method follows that in Equation 3.16:

$$PET = 16K\left(\frac{10T}{I}\right)^{m} \tag{3.16}$$

where T represents the monthly-mean temperature with unit (°C); I is a heat index in which it was computed as the total of twelve monthly index values, i. The index values, i was computed using Equation 3.17 as follow:

$$i = \left(\frac{T}{5}\right)^{1.514} \tag{3.17}$$

while m is a coefficient that calculated depends on I using Equation 3.18:

$$m = 6.75\,x\,10^{-7} I^{3} - 7.71\,x\,10^{-5} I^{2} + 1.79\,x\,10^{-2} I + 0.492 \tag{3.18}$$

while K is a coefficient of correction calculated based on the latitude and month using Equation 3.19:

$$K = \left(\frac{N}{12}\right)\left(\frac{NDM}{30}\right) \tag{3.19}$$

where *NDM* means the number of days; *N* is the parameter that represents the maximum possible sunshine hours for various months and latitudes as illustrated in Table 3.3.

Table 3.3: Average Duration of Maximum Possible Sunshine Hours (N) per Day for Different Months and Latitudes (Doorenbos and Pruitt, 1977)

	Month											
Northern Lats (°)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Southern Lats (°)	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
50	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

As long as the PET value had been obtained, measurement of the water surplus or shortage of the considered month could be carried out by using Equation 3.20 as follow to calculate ($P - PET$) for the month *i*.

$$D_i = P_i - PET_i \tag{3.20}$$

where,

D_i = Water surplus or deficit

P_i = Precipitation of station i

PET_i = Potential evapotranspiration of station i

Accumulation of the D_i values obtained were at different timescales in similar fashion steps in the computation of the SPI. Several statistical distributions were proposed to model the D series including the Pearson III, log-normal, general extreme value and log-logistics as well as the selection of suitable distribution for modelling. This was challenging due to the similarity among all the distributions. In this case, the selection was based on the performance at the peak values. The result was the log-logistic distribution was the most suitable distribution to model the D series owing to its gentle reduction in the curve for low values and higher consistent probabilities for extreme low D values. Another reason was there were no values obtained below distribution origin parameter. Equation 3.21 denotes the probability density function of the log-logistic distributed variable with three parameters.

$$f(x)=\frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left[1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]^{-2} \quad (3.21)$$

where,

α = scale parameter

β = shape parameter

γ = origin parameter

All the above parameters for D values were in the range ($\gamma > D > \infty$). When L moments were determined, these log-logistic distribution parameters could be calculated as follow:

$$\beta=\frac{2w_1-w_0}{6w_1-w_0-6w_2} \quad (3.22)$$

$$\alpha=\frac{(w_0-2w_1)\beta}{\Gamma(1+1/\beta)\,\Gamma(1-1/\beta)} \quad (3.23)$$

$$\gamma = w_0 - \alpha\Gamma\left(1+\frac{1}{\beta}\right)\Gamma\left(1-\frac{1}{\beta}\right) \quad (3.24)$$

where $\Gamma(\beta)$ represents the gamma function of β.

When the log-logistic distribution parameters α, β and γ were determined, the probability-weighted moments (PWMs) method was applied with the plotting-position approach. The PWMs of order *s* are expressed as following:

$$w_s = \frac{1}{N}\sum_{i=1}^{N}(1-F_i)^s D_i \quad (3.25)$$

$$F_i = \frac{i-0.35}{N} \quad (3.26)$$

where,

F_i = Estimator for frequency

i = Range of observations in uprising sequence

N = Number of data

Next, the probability distribution function of *D* series depending on the log-logistic distribution is denoted as Equation 3.27:

$$F(x) = \left[1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1} \quad (3.27)$$

When the *F(x)* values were obtained, the SPEI could be easily determined as the standardized values of *F(x)* in which the computation of the SPEI is expressed as following:

$$SPEI = W - \frac{C_0 + C_1W + C_2W^2}{1 + d_1W + d_2W^2 + d_3W^3} \quad (3.28)$$

where,

$$W = \sqrt{-2\ln(P)} \quad for\ P \leq 0.5 \tag{3.29}$$

where the constants are given as below:
c_0 = 2.515517, c_1 = 0.802583, c_2 = 0.010328;
d_1 = 1.432788, d_2 = 0.189269, d_3 = 0.001308.

while *P* is the probability of going beyond a determined *D* value. It was computed by $P = 1 - F(x)$. If *P* is greater than 0.5, *P* is changed to $1 - P$ with the reversing of the sign of the SPEI. In reference to the log-logistic distribution, the mean value of the SPEI is zero and its standard deviation is one. Since the SPEI is a standardized variable, comparison with other SPEI values across time and space is expected. When the SPEI value is zero, the cumulative probability of *D* is expected to be 50%.

3.4.3 Streamflow Drought Index (SDI)

The SDI is a fundamental and effective index developed by Nalbantis and Tsakiris (2008) for characterizing hydrological droughts at different timescales. It was designed based on the SPI with the origin of idea in the Ben-Zvi work. Applications of the SDI at various timescales indicate the state of droughts at different periods. For instance, the drought index for duration of 3 months is used to reflect the water conditions that provide data for irrigation in agriculture, while the drought index for 12-month duration is applied to study the effects of climatic change on water resources in a region (Zeng, et al., 2015).

In this current research, the 1st of October was set as the starting of the hydrological year while the ending is the 30th of September every next year. This duration of a complete hydrological year is common for Malaysia. The analysis of drought was set regarding the timescales from the beginning of the hydrological year to last day of December, March, June and September. In addition, predictions of the future drought conditions were performed at the same dates. The aforementioned operational requirements tallied with the situations in which the water resource systems achieve substantial total storage volume by which inflows were integrated with time. In this case, the four overlapping timescales considered within every hydrological year are the October-December (3-month period), October-March, October-June as well as October-September. The reasons for the selection of 3-month intervals in drought analysis are given as follows:

(i) To study drought as detail as possible.

(ii) Reduce carry-over effects between consecutive time intervals, which are more remarkable for small timescales.

The assumption for computation of the SDI was that a single time series of streamflow volumes, $Q_{i,j}$ on monthly basis is available where i is the hydrological year while j donates the month within the hydrological year which is j = 1 for October and j = 12 for September. From the time series, Equation 3.59 was applied to obtain the cumulative streamflow volume, $V_{i,k}$ for the i-th hydrological year as well as the k-th reference duration, where k =1 for October-December and k = 2 for October-March. For October June timescale, k is donated by an integer of 3 while k =4 for October-September.

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,} \qquad i = 1, 2, \ldots \qquad j = 1, 2, \ldots, 12 \qquad k = 1, 2, 3, 4 \qquad (3.30)$$

From the cumulative streamflow volume, $V_{i,k}$, the SDI was computed for every reference duration k of the i-th hydrological year as Equation 3.60:

$$SDI_{i,k} = \frac{V_{i,k} - \overline{V}_k}{s_k} \qquad i = 1, 2, \ldots, \qquad k = 1, 2, 3, 4 \qquad (3.31)$$

where the cumulative streamflow volumes mean of reference duration is donated by $V_{i,k}$. $\overline{V}_k$ is the mean while the standard deviation is expressed as s_k. The estimation of these values was performed over a long duration. In this case, the truncation level was fixed to $\overline{V}_k$ even though other values could be considered. The SDI was considered equal to the standardized streamflow volume.

In this research, the two-parameter log-normal distribution was applied due to simplicity of normalization procedure. Natural logarithms of streamflow data were considered in computation of suffices of the two-parameter log-normal distribution. The further calculation of the SDI is denoted as Equation 3.61:

$$SDI_{i,k} = \frac{y_{i,k} - \bar{y}_k}{s_{y,k}} \quad i = 1, 2, \ldots, \quad k = 1, 2, 3, 4 \qquad (3.32)$$

where,

$$y_{i,k} = \ln\left(V_{i,k}\right) \quad i = 1, 2, \ldots, \quad k = 1, 2, 3, 4 \qquad (3.33)$$

are the natural algorithms of cumulative streamflow with mean $\bar{y}_k$ and standard deviation $s_{y,k}$. Positive values indicate wet conditions while negative values mean that there is a hydrological drought. The description of the states of the hydrological drought according to the SDI values was illustrated in Table 3.4.

Table 3.4: Description of States of Hydrological Drought According to SDI (Nalbantis and Tsakiris, 2009)

State	Description	Criterion	Probability (%)
0	Non-drought	$SDI \geq 0.0$	50.0
1	Mild drought	$-1.0 \leq SDI < 0.0$	34.1
2	Moderate drought	$-1.5 \leq SDI < -1.0$	9.2
3	Severe drought	$-2.0 \leq SDI < -1.5$	4.4
4	Extreme drought	$SDI < -2.0$	2.3

3.5 Computation of Average Moving Range (AMR)

A moving range (MR) provides the measurement of how fluctuation varies over time when the data are gathered as individual measurements (Azam Moraditadi and Soroush Avakhdarestani, 2016). In this research, the fluctuation of rainfall, streamflow and temperature data through MR was determined by two consecutive drought indices, in which the calculation is with Equation 3.34 as follow:

$$MR = \left| x_i - x_{i-1} \right| \qquad i = 1, 2, ... \qquad (3.34)$$

where,
x = SPI, SPEI or SDI

Then, AMR was computed to monitor average variation of data over time as donated by Equation 3.35:

$$AMR = \frac{\sum MR}{\sum Number\ of\ MR} \qquad (3.35)$$

3.6 Temporal Analysis

Temporal analysis is conducted along with drought indices to predict or determine the duration of drought. Characteristics of drought in terms of duration, intensity and frequency can vary monthly; hence, the trend analysis of drought is mandatory to understand the structure of drought with different severities in the study area. It is necessary to study the occurrence frequency and their seasonal fluctuation to identify regions having common temporal variability of droughts. The analysis can determine the relationships between duration, intensity and frequency.

3.6.1 Monthly Variations of Drought Duration, Intensity and Frequency under Different Timescales

The characteristics of drought can vary per month in a year and between a month in different years. In this case, temporal analysis on a monthly basis is considered as the most sensitive analysis as it can detect changes between short periods. Therefore, this method was applied to determine variation of drought duration, intensity and frequency based on SPI and SPEI under the 1-, 3-, 6- and 12-month timescales whereas that on SDI under the 3-, 6- and 12-month timescales. For example, the analysis was conducted to compare January of 2015 and January of 2016 followed by other months and different years.

3.7 Spatial Analysis

Topographic properties of the region have great contribution to the spatial pattern of the drought events. In this case, the variations are regional-based as the drought characteristics vary according to topographical features of the region and the changes are noticeable from one region to another. Hence, the spatial analysis was conducted to understand the regional variation of the drought characteristics, namely drought frequency, mean drought duration, mean drought severity, mean drought intensity and mean drought peak.

3.7.1 Data Spatial Structure Analysis

The objective of the data spatial structure analysis was to analyse the variation of the data across space. In simple terms, this analysis was conducted to check whether the data changes according to geographical locations. Presence of spatial structure indicates the dependent of variation of data on locations whereas a non-spatial structure signified the locational independent characteristic of the data. In this research, hydrological information was important as input data in modelling to predict extreme weather conditions such as droughts and floods. However, the network of the hydrological stations was scarce and the data provided were not sufficient to determine variation of the characteristics of the drought in terms of spatial distribution. Estimation of hydrological data could be conducted using spatial interpolation method in which each method had its pros and cons therefore the selection of methods was dependent on the characteristics of the data (Keblouti, Ouerdachi and Boutaghane, 2012).

Spatial interpolation used points with known data values to estimate unknown data at other points. This method when applied to a raster with estimation for all cells in a GIS application ended up with creating surface data from sample points. In this case, the points with known data values were termed as control points in which the amount and distribution of these points had a significant effect on the accuracy of the interpolation results (Wackernagel, 2013). There are several types of spatial interpolation: exact, inexact, global, local, deterministic and stochastic. The description of local and global spatial interpolation method is shown in Table 3.5. In this research, a local geo-statistical spatial interpolation method, the IDW was selected.

Table 3.5: Classification of Spatial Interpolation Methods (Wackernagel, 2013)

Global		Local	
Deterministic	**Stochastic**	**Deterministic**	**Stochastic**
Trend surface (inexact)*	Regression (inexact)	Thiessen (exact) Density estimation (inexact) Inverse distance weighted (exact) Splines (exact)	Kriging (exact)

3.7.2 Inverse Distance Weighting (IDW)

The IDW method functioned to estimate particular values at un-sampled locations using a linear composition of sampled point values. These values were weighted by inverse function of the distance from the considered point to the sampled point. This method assumed the values of the sampled points that had the smaller distance to the un-sampled point were more identical to it as compared to those that are further away. The weights can be expressed in Equation 3.64 as follow:

$$\lambda_i = \frac{1/d_i^{\,p}}{\sum_{i=1}^{n} 1/d_i^{\,p}} \qquad (3.36)$$

where,

d_i = Distance between x_0 and x_1

p = Power parameter

n = Sampled point number used for the estimation

Among above parameters, the value of the power parameter had significant effect on the accuracy of the IDW because the weights decreased when the distance increased with the rise of the power parameter. Thus, neighbouring samples had a greater weight and had greater effects on the estimation (Li and Heap, 2008).

3.7.3 Drought Frequency

The frequency of drought is known as the total number of drought occurrence. A drought event was shown with drought indices of less than zero, where its onset and offset were indicated by the initiation and ending of consecutive negative drought index values. The computation of drought frequency is given as Equation 3.37:

$$Drought\ frequency = \sum Number\ of\ drought\ event \tag{3.37}$$

3.7.4 Mean Drought Duration

According to a study by (Guo, et al., 2018), duration of drought is known as period between starting time and ending time of a drought phenomenon. Mean drought duration was determined by averaging summation of drought duration of all drought events throughout the study period over drought frequency, as donated by Equation 3.38:

$$Mean\ drought\ duration = \frac{\sum Drought\ duration}{Drought\ frequency} \tag{3.38}$$

3.7.5 Mean Drought Severity

Drought severity refers to the magnitude of the drought event as it represents the degree of rainfall deficiency or the effects caused by the disaster. From the research conducted by Guo, et al. (2018), severity of drought was measured by the drought index value itself and the formula for computation is given as Equation 3.39:

$$Mean\ drought\ severity = \frac{\sum Negative\ drought\ index}{\sum Drought\ duration} \tag{3.39}$$

3.7.6 Mean Drought Intensity

Based on the research by Zargar, et al. (2011), drought intensity is defined as the average value of drought magnitude within the drought duration, in which it was computed by dividing drought severity with drought duration as donated by Equation 3.40:

$$Drought\ intensity = \frac{\sum Negative\ drought\ index\ of\ a\ drought\ event}{Drought\ duration\ of\ a\ drought\ event} \quad (3.40)$$

Then, the mean drought intensity was calculated by averaging summation of drought intensity over drought frequency as given by Equation 3.41:

$$Mean\ drought\ intensity = \frac{\sum Drought\ intensity}{Drought\ frequency} \quad (3.41)$$

3.7.7 Mean Drought Peak

Drought peak is known as the lowest drought index value during a drought event and its mean value was determined as the ratio of total drought peak over drought frequency as given by Equation 3.42:

$$Mean\ drought\ peak = \frac{\sum Drought\ peak\ of\ a\ drought\ event}{Drought\ frequency} \quad (3.42)$$

3.8 Performance Assessment of Drought Indices

Research was conducted on recorded droughts that had previously occurred at the East Coast of Peninsular Malaysia from 1983 to 2017. The drought characteristics based on drought indices at different timescales were compared with that of the historical drought events to evaluate the accuracy of drought detection by different drought indices under various timescales. The performance evaluation was performed by determination of probability of detection (POD), mean absolute error (MAE), mean bias error (MBE), mean early or delayed prediction (MEDP) and capability in measuring drought severity.

3.8.1 Probability of Detection (POD)

The ability of drought indices that were computed based on different timescales were evaluated by POD (Zhu, et al, 2016). POD signifies the probability of actual drought detection and a high POD value definitely indicates excellent detection capability. The formula of POD is expressed as follow:

$$POD = \frac{a}{a+b} \quad (3.43)$$

Table 3.6: Contingency Table (Zhu, et al., 2016)

		Droughts detected by drought index	
		Yes	No
Recorded droughts	Yes	a	b

3.8.2 Mean Absolute Error (MAE)

The capability of the drought indices at different timescales in monitoring drought duration was evaluated by the assessment of MAE. The absolute errors were determined by calculating the absolute difference in month between detected and actual duration of droughts, while MAE is the average value of the absolute errors as given by Equation 3.44:

$$MAE = \sum_{i=1}^{N} \frac{|\hat{y}_i - y_i|}{N} \quad (3.44)$$

where,

y_i = Detected drought duration

$\hat{y}_i$ = Actual drought duration

N = Number of detected drought event

3.8.3 Mean Bias Error (MBE)

In similar to MAE, MBE was calculated to determine errors in detecting drought duration. A negative value of MBE indicates under-detection whereas positive MBE values mean over-detection. The formula of MBE is expressed as follow:

$$MBE = \sum_{i=1}^{N} \frac{\hat{y}_i - y_i}{N} \quad (3.45)$$

where,

y_i = Detected drought duration

$\hat{y}_i$ = Actual drought duration

N = Number of detected drought event

3.8.4 Mean Early or Delayed Prediction (MEDP)

The performance of drought indices under various timescales in describing droughts was further analysed with the checking of average early or delayed prediction of onset of droughts. The negative values mean that the drought is detected early whereas a positive value shows delay in prediction of drought. The MEDP is computed as given by Equation 3.46:

$$MEDP = \frac{\sum Early\ or\ delayed\ predicted\ duration}{\sum Number\ of\ detected\ drought\ event} \tag{3.46}$$

3.8.5 Capability in Measuring Drought Severity

The severity of drought is important to understand the level of impacts brought by the disaster. It is measured by the drought index value itself, thus the performance of drought indices in describing drought occurrence from the aspect of drought severity was checked by the ability in detecting severe and extreme drought (very low drought index value).

3.9 Summary

The overall procedures required to conduct the research were discussed and illustrated with flow charts. The rainfall, streamflow and water level data as well as information of hydrological stations were obtained from DID and MMD Malaysia. QGIS and Google Earth Pro software are used for mapping of the study area, with the information of meteorological and hydrological stations. The background of the study area including location, area, climate, rivers, dams and main economic activities were given. For rainfall data repairing task, the simple four-quadrant method was considered. The development of drought indices (SPI, SPEI and SDI) involved numerous equations, different input parameters and assumptions. The AMR was computed to understand fluctuation of rainfall, streamflow and temperature data over time. Temporal analysis of drought was performed by examination of monthly variations of drought duration, intensity and frequency under different timescales. The spatial analysis method was carried out by applying IDW method to observe spatial distribution pattern of drought characteristics. The accuracy checking was performed to evaluate the performance of drought indices at different timescales in detecting drought occurrence, through the assessment of POD, MAE, MBE, MEDP and ability in measuring drought severity.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

The research was founded upon the historical rainfall, streamflow and temperature data from 1983 to 2017 for the computation of drought indices. The 35-year rainfall and temperature data were used to calculate SPI and SPEI at 1-, 3-, 6- and 12-month timescales, whereas the 35-year streamflow data were used to compute the SDI at 3-, 6- and 12-month timescales. From the drought indices obtained, five drought characteristics, as well as their spatial distribution patterns were discovered. Apart from that, the average moving range of drought indices at different timescales were computed. Study of the historical droughts aimed to check the accuracy of various drought indices in detecting the occurrence of droughts. Monthly trend analysis was conducted to observe the temporal variation of the droughts. The results obtained are interpreted and discussed in the following sections.

4.2 Spatial Distribution of Drought Characteristics

Five drought characteristics: drought frequency, mean drought duration, mean drought severity, mean drought intensity and drought peak, were computed from drought indices at different timescales. The variation of these five drought characteristics across the study area was interpolated respectively using the IDW method.

4.2.1 Spatial Distribution of Drought Frequency

Figure 4.1 shows the spatial distribution of drought frequency for the SPI at timescales of 1-, 3-, 6- and 12-month, across the study area. Some of the areas in the southern region of the study area that have been coloured in red for all timescales, means the areas experienced droughts most frequently. In general, Pahang recorded high drought frequency for more than 75 based on SPI-1, except for some areas in the northern and southeast region of the state. The northern region of Kelantan and some areas in the southern region of the state had relatively low drought occurrence tendency, with station 5820006 in north Kelantan recorded the lowest frequency of 67 based on SPI-1. For SPI-3, low drought frequency distribution had extended over the whole Terengganu, in which the lowest drought frequency was observed at station 5128001.

The lowest frequency of drought based on SPI-6 was observed at both station 3628001 and station 2924096 in Pahang. Furthermore, spatial map of drought frequency based on SPI-12 shows that the occurrence of droughts in the study area was generally less than 24 excluding some areas in south and west Kelantan as well as some regions in south and west Pahang. Drought frequency decreased as the timescales lengthened from 1 month to 12 months, suggesting that there is a decreasing trend across the timescales.

Similarly, the highest drought frequency was observed at the southern region, which was coloured in dark red, based on SPEI-1, SPEI-3 and SPEI-6 (Figure 4.2). Nonetheless, northeast region recorded low frequency based on SPEI-1 and SPEI-3, while the drought frequency gradually increased from the north to the south Terengganu for both timescales. Another similarity for SPEI-1 and SPEI-3 is the lowest frequency was observed at station 5722057 and station 5522047 respectively in north Kelantan. From the spatial map based on SPEI-1, high drought frequency was observed focused at the southern region. In addition, there were also some areas in northwest Pahang and west Kelantan, as well as the areas near the central of Kelantan, which showed high rate of the occurrence of droughts based on SPEI-1. In general, relatively high drought frequency based on SPEI-3 was observed to be extended from south Kelantan to Pahang excluding a small area in southeast Pahang. Meanwhile, spatial map of drought frequency based on SPEI-6 shows that the whole study area recorded frequency of less than 38, except that high frequency was observed at station 3228174 near the central of Pahang. High frequency based on SPEI-12 was observed at the western and southern region, whereas the other regions of the study area recorded low frequency excluding some areas in north and east Terengganu.

In general, the whole Kelantan and Terengganu, as well as south Pahang, had low rate of drought occurrence based on SDI-3 (Figure 4.3). Furthermore, drought frequency was observed to have an increasing trend from the northwest to the central of Pahang, in which station 3527410 at the central of Pahang recorded the highest frequency based on SDI at 3-month timescale over the study area. In similarity to SDI-3, spatial map of drought frequency based on SDI-6 shows that the lowest frequency was observed at station 5130432 at south Terengganu. In contrast, the highest rate of drought occurrence based on SDI-6 was observed at station 5229436 in the southern region of the state. The spatial map of drought frequency based on SDI-12 shows that there is no significant trend for the northern region of the study area. This spatial distribution pattern, based on the SDI at 12-month timescale, extended to north Pahang, and ended with a high record of frequency at station 3424411 in west Pahang. The southern region experienced droughts with the lowest frequency based on SDI-12 recorded at station 3030401 over the whole study area.

There is similarity between spatial distribution pattern of drought frequency based on both the SPI and SPEI at 1-month timescale in which the light blue region was observed at the northern region, whereas moderate to high drought frequency region was observed at the other regions of the study area based on the spatial maps generated from SPI-1 and SPEI-1. In addition, spatial maps of drought frequency based on the SPI, SPEI and SDI at 3-month timescale show that relatively low drought frequency region was spotted at the northern and southernmost region. Another similarity across drought indices is that the central region in the spatial maps based on SPI-6 and SPEI-6 were both coloured in light blue. In brief, SPI, SPEI and SDI at 3-month timescale show similar spatial distribution of drought frequency although the inputs for each drought index are different.

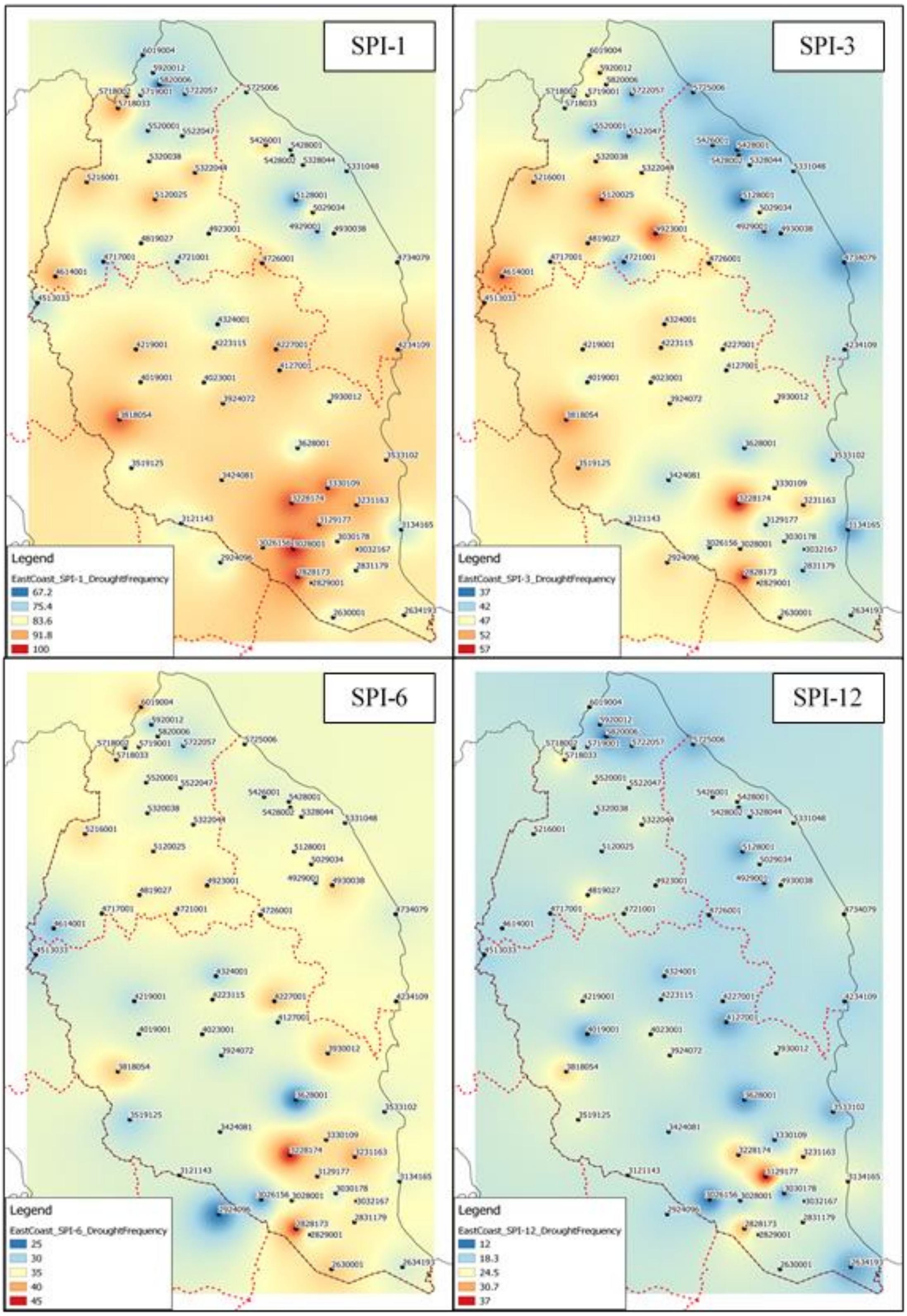

Figure 4.1: Spatial Maps of Drought Frequency Based on SPI at Different Timescales

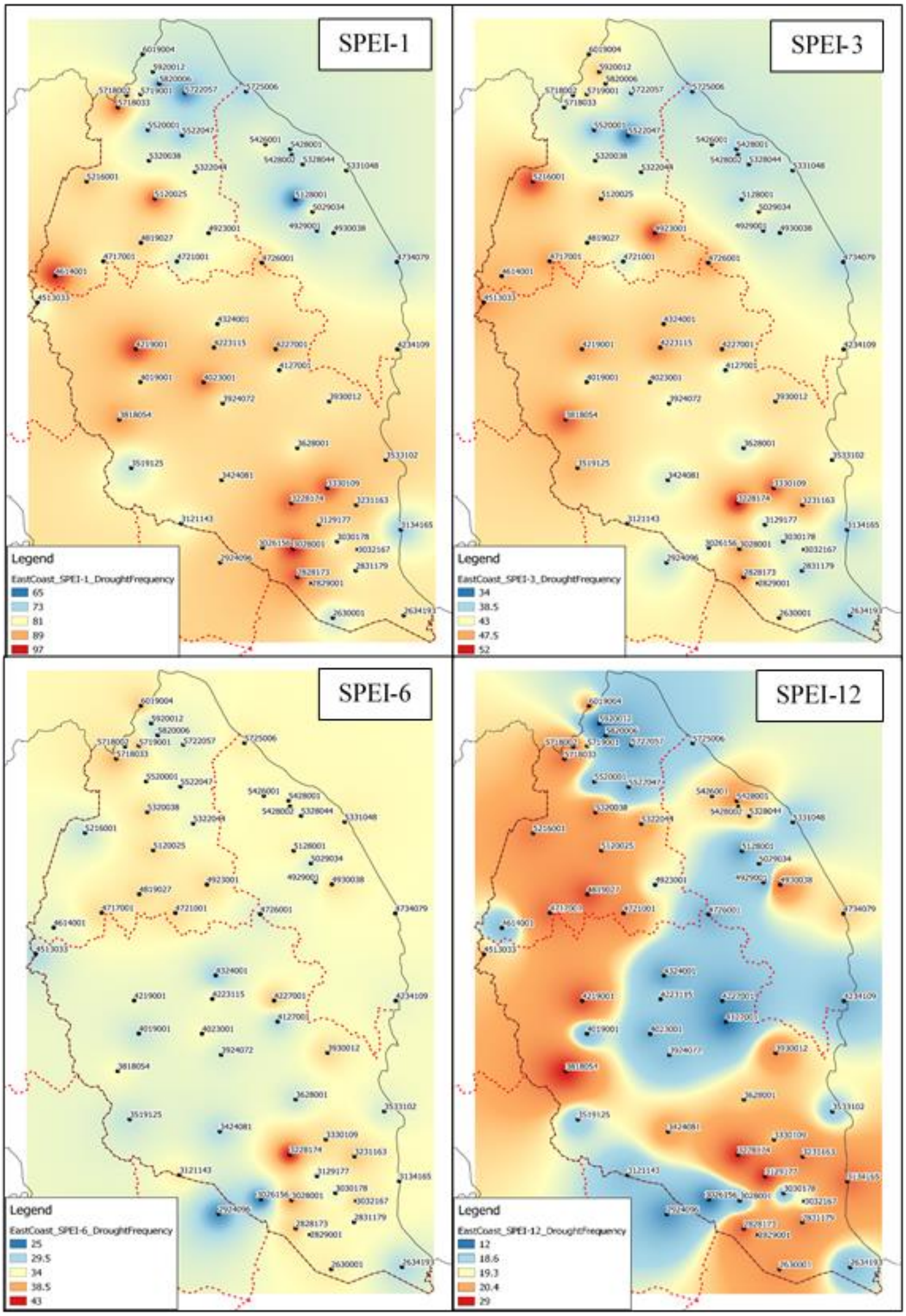

Figure 4.2: Spatial Maps of Drought Frequency Based on SPEI at Different Timescales

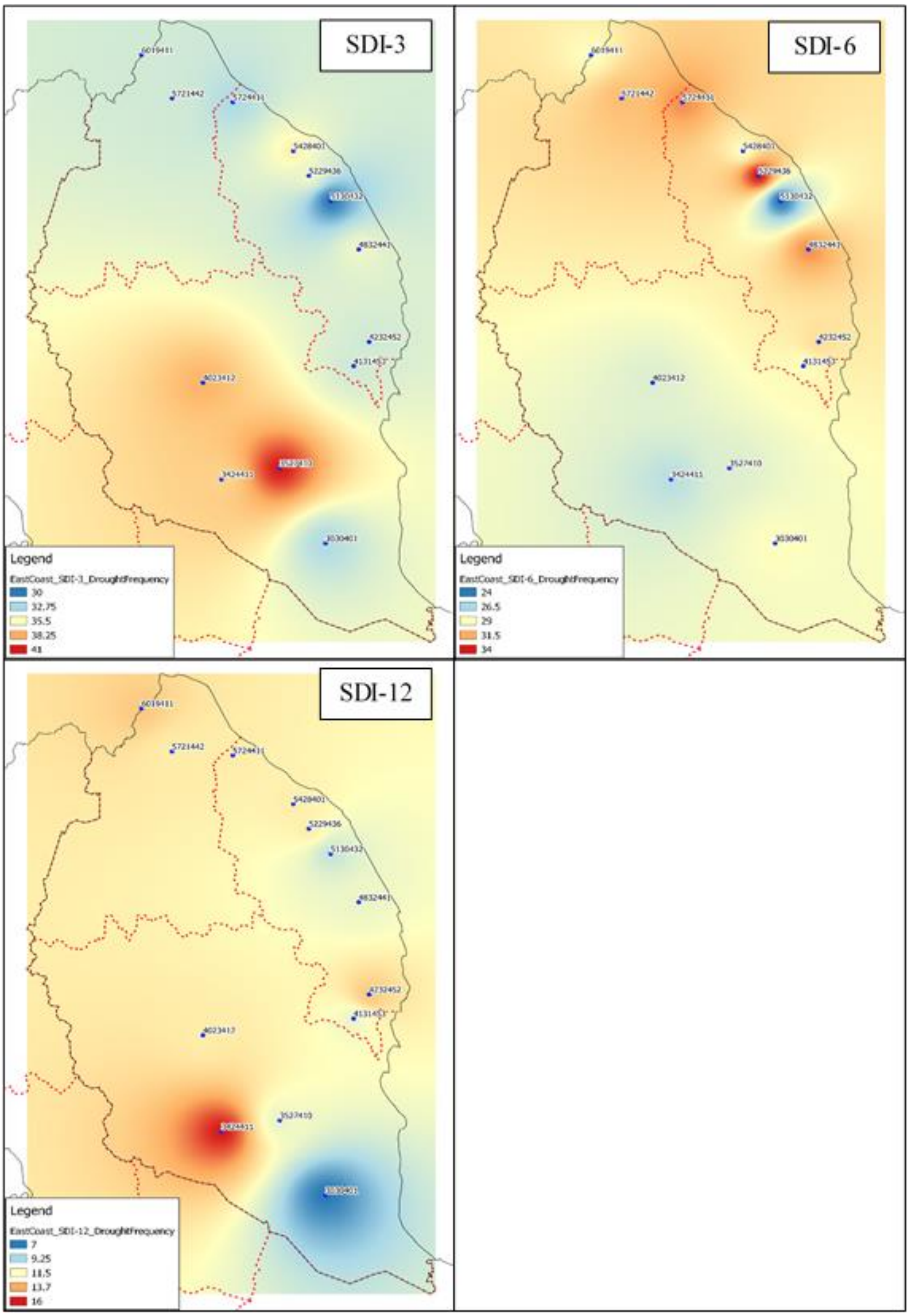

Figure 4.3: Spatial Maps of Drought Frequency Based on SDI at Different Timescales

4.2.2 Spatial Distribution of Mean Drought Duration

From a spatial distribution perspective, the shortest mean drought duration based on the SPI at both 1- and 3-month timescales were observed at west Kelantan (Figure 4.4). Spatial maps of mean drought duration based on SPI-1 and SPI-3 show that the region from north Terengganu to the central of the state, recorded high mean duration of drought. In general, the whole Kelantan and Pahang experienced droughts with mean duration shorter than 2.6 months, except for some areas at north Kelantan based on SPI-1. There is an increasing trend of mean drought duration based on SPI-3 from the western region to the eastern region, whereas there is no significant trend of spatial variation pattern for mean drought duration based on SPI-6 and SPI-12. However, the spatial maps based on SPI at 6- and 12-month timescales show an obvious similarity between them as it was observed that station 5920012 and station 5820006 in north Kelantan recorded the longest average duration based on respective timescale.

Short mean drought duration regions based on SPEI-1 and SPEI-3 are shown in blue at south Kelantan and almost the whole Pahang (Figure 4.5). From the spatial map based on SPEI at 1-month timescale, dark red region spotted close to the central of Terengganu, indicating station 5128001 in this region recorded the longest mean duration of drought over the study area. For mean drought duration generated from SPEI at 3-month timescale, its highest value was observed at station 5522047 in northern region, while light orange region that indicates mean duration of more than 4.66 covered north and central of Terengganu. The longest mean duration of drought based on SPEI-6 was observed at station 3026156 in south-west Pahang, whereas station 5820006 in north Kelantan recorded the greatest value of mean drought duration based on the SPEI-12.

From the spatial map of mean drought duration based on SDI-3, it is remarkable that the whole study area was coloured in orange or red in exception with some areas in north and central of Pahang, suggesting that the study area in overall recorded high mean duration of drought (Figure 4.6). The longest mean drought duration based on SDI-3 and SDI-12 was observed at station 3030401 in the southern region. Meanwhile, the spatial map based on SDI-6 shows an increasing trend of average duration of drought from north Kelantan to south Pahang excluding some areas in the eastern region of the map. In this case, an area at east Terengganu was marked in dark red with the longest mean drought duration based on SDI-6 recorded by station 5130432.

Nonetheless, the same spatial distribution of mean drought duration based on SPI-1 and SPEI-1 was observed, in which light orange region with the longest mean drought duration marked in dark red at station 5128001 was located at the eastern region whereas the other regions in the study area were coloured in blue. The similar condition applied to SPI and SPEI at 3-month timescale, excluding the difference in location of long mean duration of drought was spotted based on SPI-3 and SPEI-3. Besides that, there is notable similarity between spatial distribution pattern of mean drought duration based on SPI and SPEI at both 6- and 12-month timescales. From the spatial maps based on these two drought indices at -6- and 12-month timescales, the whole study area was noticed to be coloured in light blue except for a small region at the southernmost region that was marked in light orange. However, the above conditions show that there is no similarity for spatial variation pattern of mean drought duration between SPI, SPEI and SDI at all timescales.

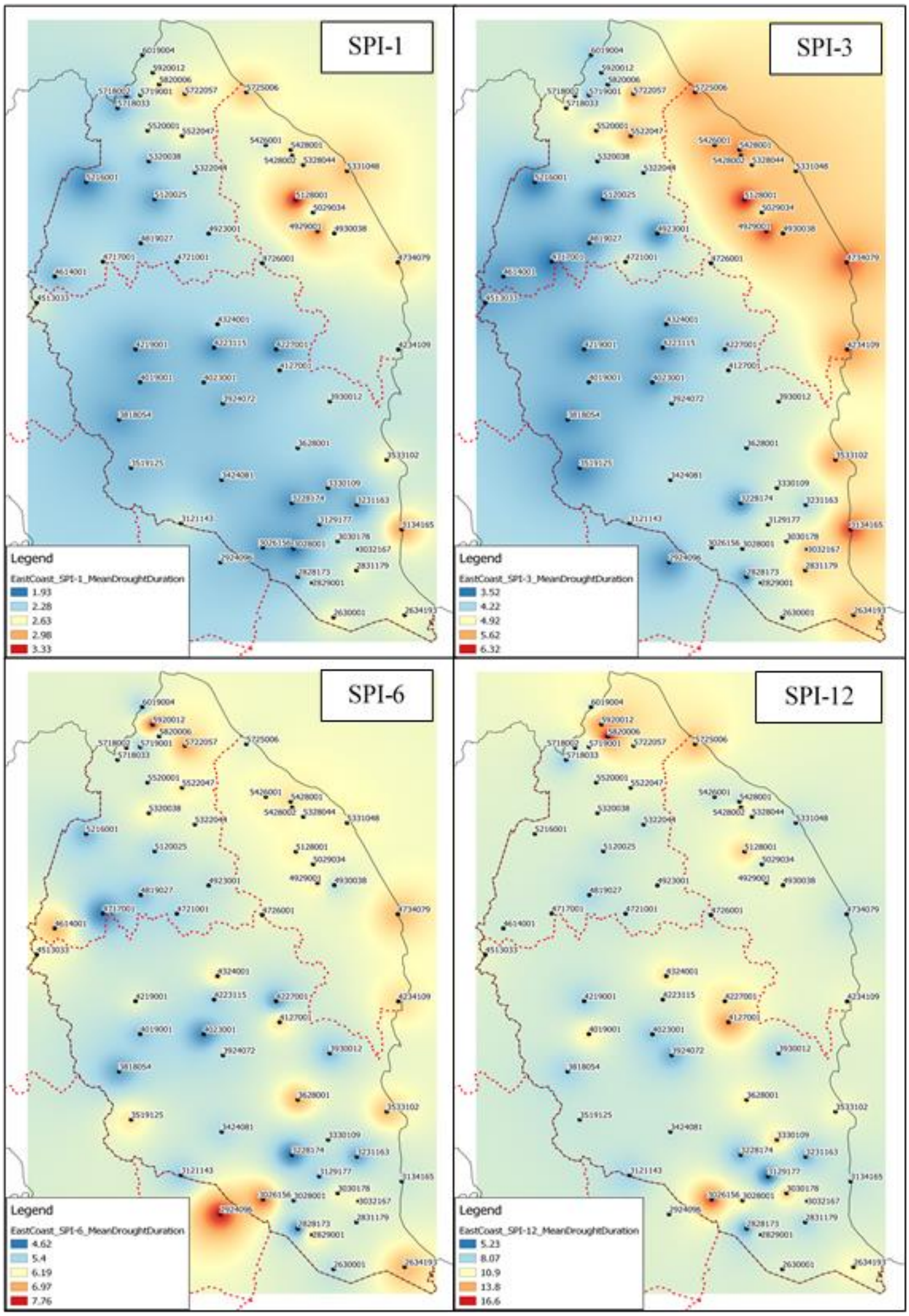

Figure 4.4: Spatial Maps of Mean Drought Duration Based on SPI at Different Timescales

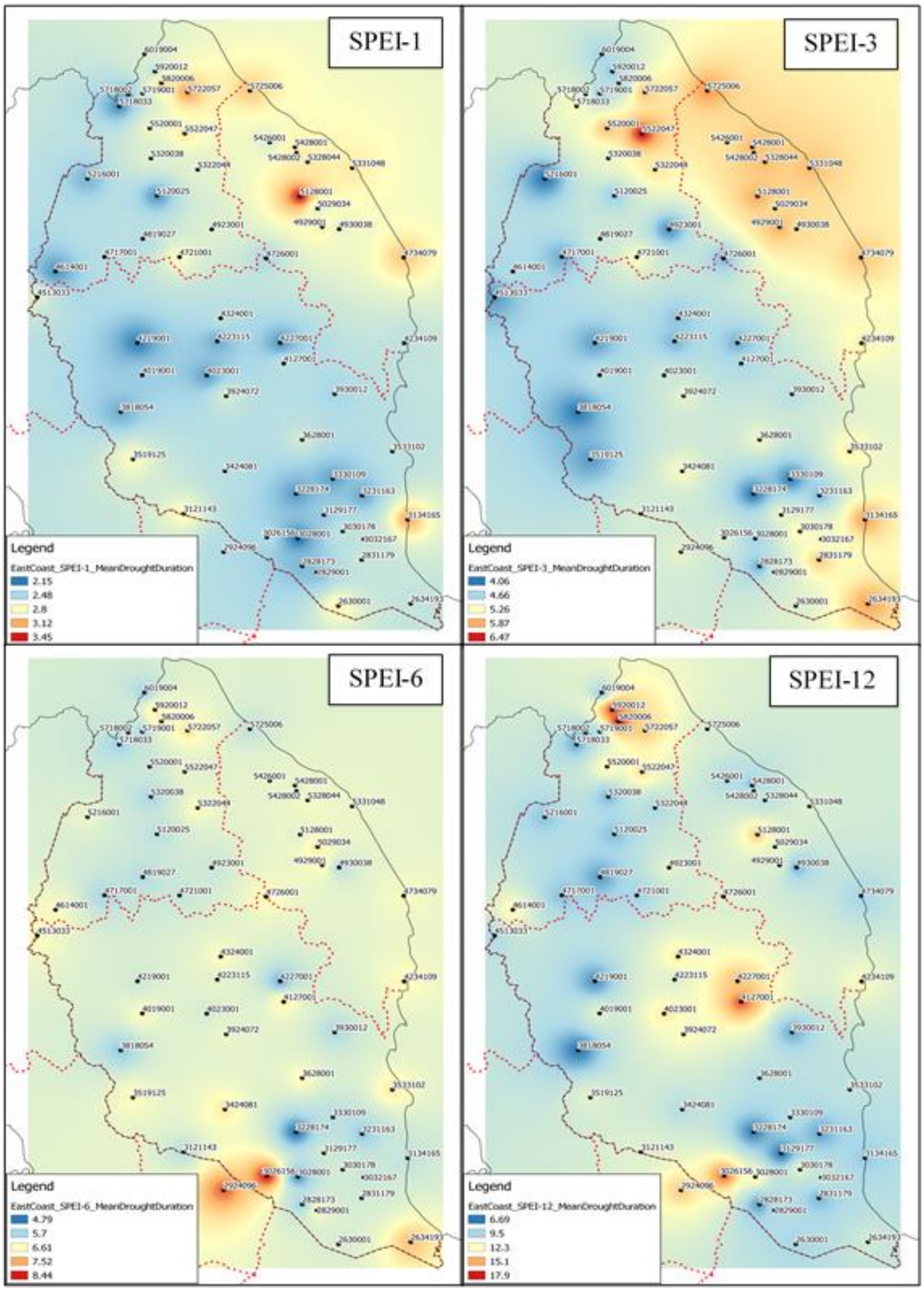

Figure 4.5: Spatial Maps of Mean Drought Duration Based on SPEI at Different Timescales

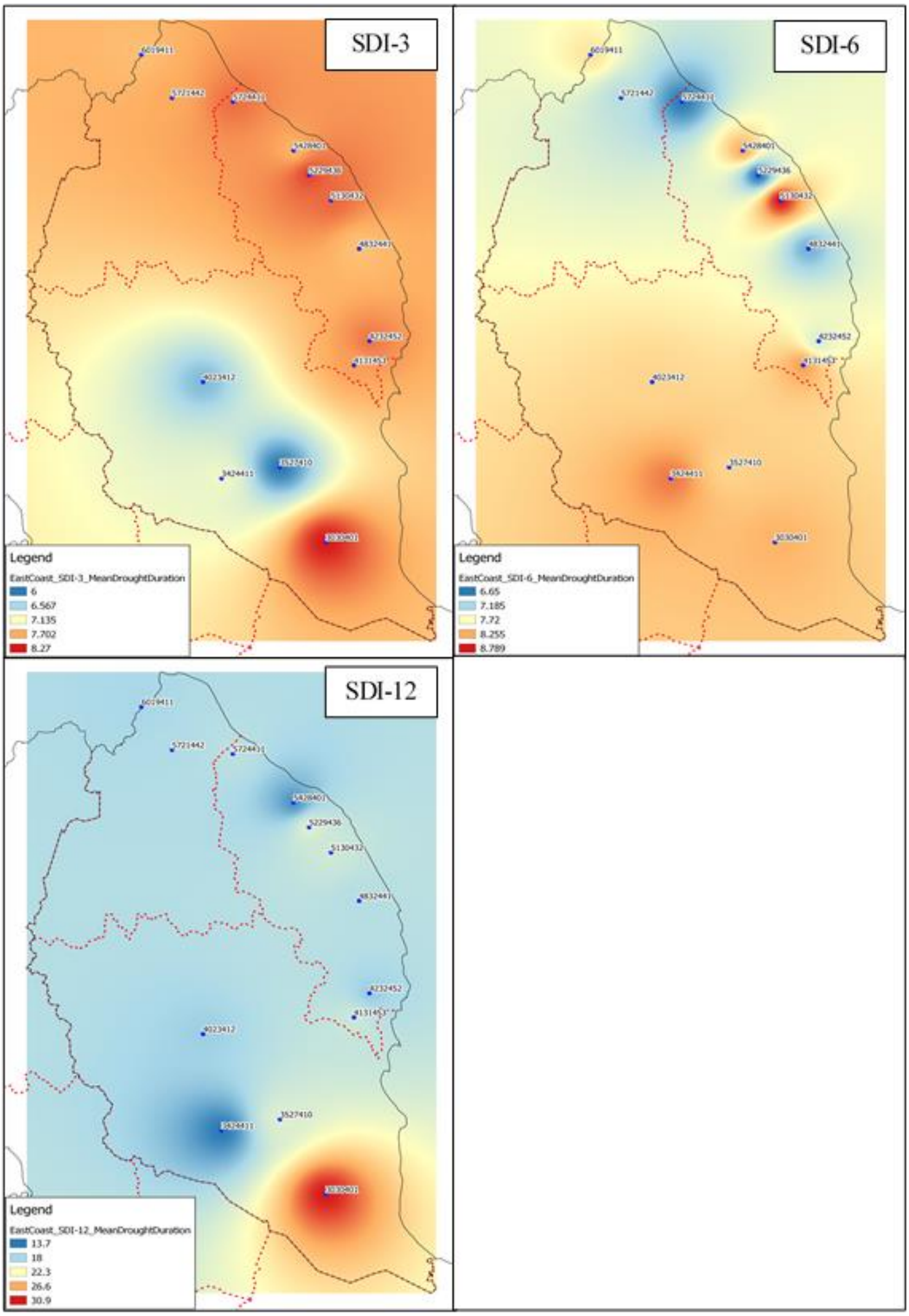

Figure 4.6: Spatial Maps of Mean Drought Duration Based on SDI at Different Timescales

4.2.3 Spatial Distribution of Mean Drought Severity

From spatial maps based on SPI at 1- and 3-month timescales, there is an increasing trend of mean drought severity from the eastern to the southern region (Figure 4.7). Some areas in south-west Kelantan, as well as north and west Pahang, experienced droughts with high mean severity according to the spatial map based on SPI-1, whereas dark red region that symbolises the highest mean drought severity was spotted recorded at station 4717001 in south-west Kelantan in the spatial map based on SPI-3. The whole study area generally experienced droughts with low severity throughout 35 years based on SPI-6 except for some areas in the western region and southern region. In this case, some areas in west and south-east Pahang, as well as south Kelantan, were marked by dark red, indicating that these regions recorded high mean drought severity based on SPI at 6-month timescale. Nevertheless, the highest mean drought severity based on SPI-12 timescale was spotted at station 2634193 in the southernmost region.

From the spatial map based on SPEI-1, the eastern and southern region were observed to be marked in light and dark blue, showing these regions experienced mild to moderate drought in terms of mean severity (Figure 4.8). In contrast, station 4717001 in north Kelantan recorded the highest mean drought severity as this region was coloured in dark red on the same spatial map. In similar to the spatial map of mean drought severity based on SPE-1, the eastern region also recorded relatively low mean drought severity based on SPEI at 3-month timescale. In general, light orange region that indicated moderate drought in terms of mean severity based on SPEI-3 extended from south Kelantan through north Pahang to areas near the central of Pahang, where the highest mean drought severity was observed at station 3519125 in west Pahang. There is no significant trend observed for spatial distribution pattern of average drought severity based on SPEI at 6-month timescale but the highest mean drought severity was marked in dark red at station 3134165 in south-east Pahang. Moreover, spatial map based on SPEI-12 shows that almost the whole study area was coloured in light orange (moderate drought in terms of mean severity), while the highest mean drought severity was spotted at station 4929001 in the central of Terengganu.

Figure 4.9 shows the spatial distribution of mean drought severity based on SDI at 3-, 6- and 12-month timescales. Overall, the whole study region experienced mild to moderate drought in terms of mean severity based on SDI-3 excluding some areas in north and central of Pahang. An area in north Pahang was marked in dark red, indicating station 4023412 in this area recorded the highest mean drought severity based on SDI-3. From the spatial map based on SDI at 6-month timescale, there is an overall increasing trend of average severity of droughts from the southern region to the northern region. In this case, the highest mean drought severity based on SDI-6 was discovered in dark red at station 5724411 in the northernmost region of Terengganu. The whole study region was generally recorded low to moderate droughts in reference to mean drought severity based on SDI-12 while the highest mean drought severity was observed at north-east Terengganu.

From the spatial maps of mean drought severity based on SPI and SPEI at 1-month timescale, whole Terengganu and south Pahang was observed to be recorded low mean drought severity while the western region experienced moderate to high mean drought severity. Nevertheless, light blue region was spotted at the eastern and southern region according to the spatial distribution pattern of mean drought severity based on all the three drought indices at 3-month timescale. In contrast, there is no common spatial variation pattern observed from the spatial maps based on SPI, SPEI and SDI at 6- and 12-month timescales. Hence, only the drought indices at 3-month timescale generated similar spatial distribution style of mean drought severity.

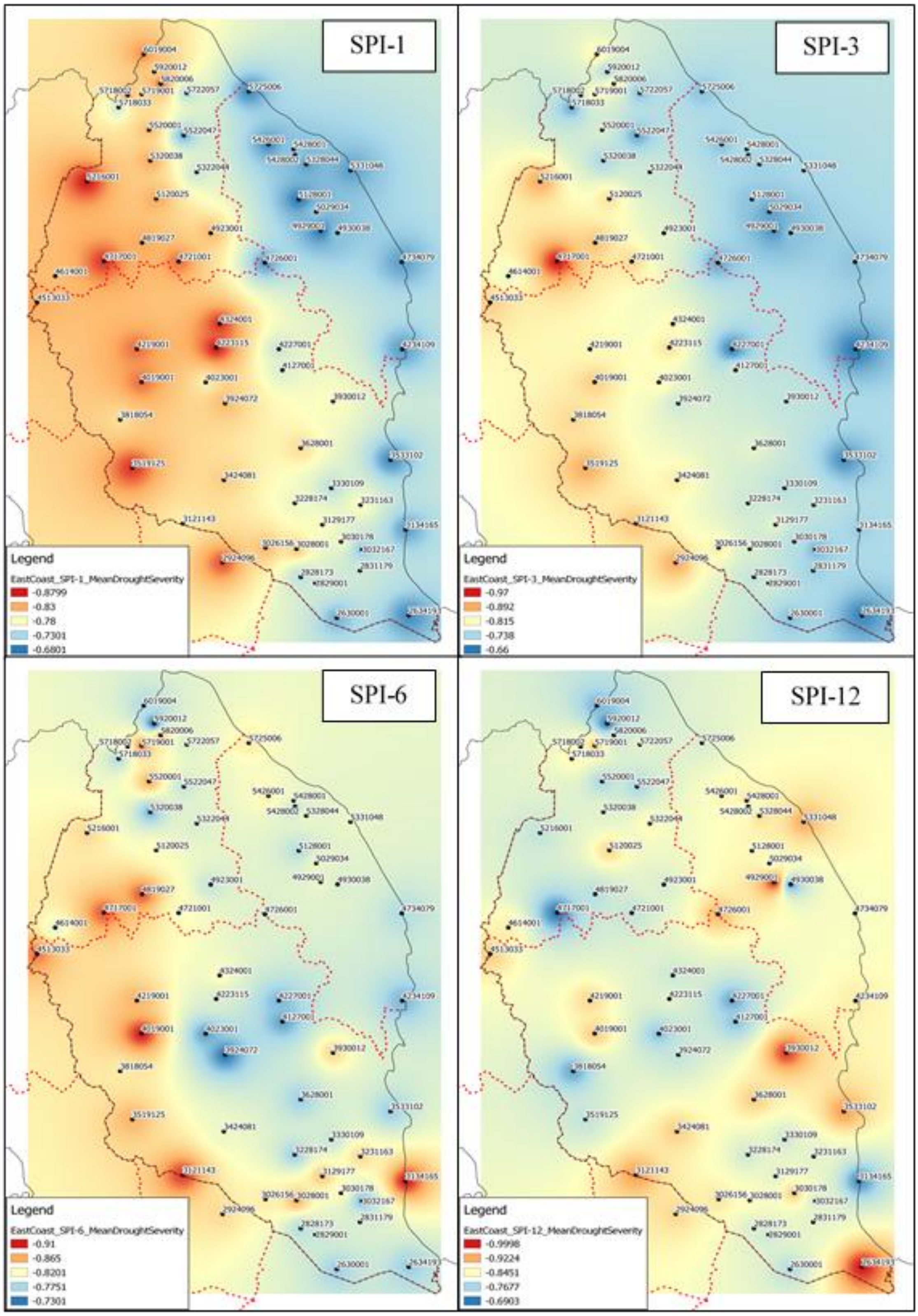

Figure 4.7: Spatial Maps of Mean Drought Severity Based on SPI at Different Timescales

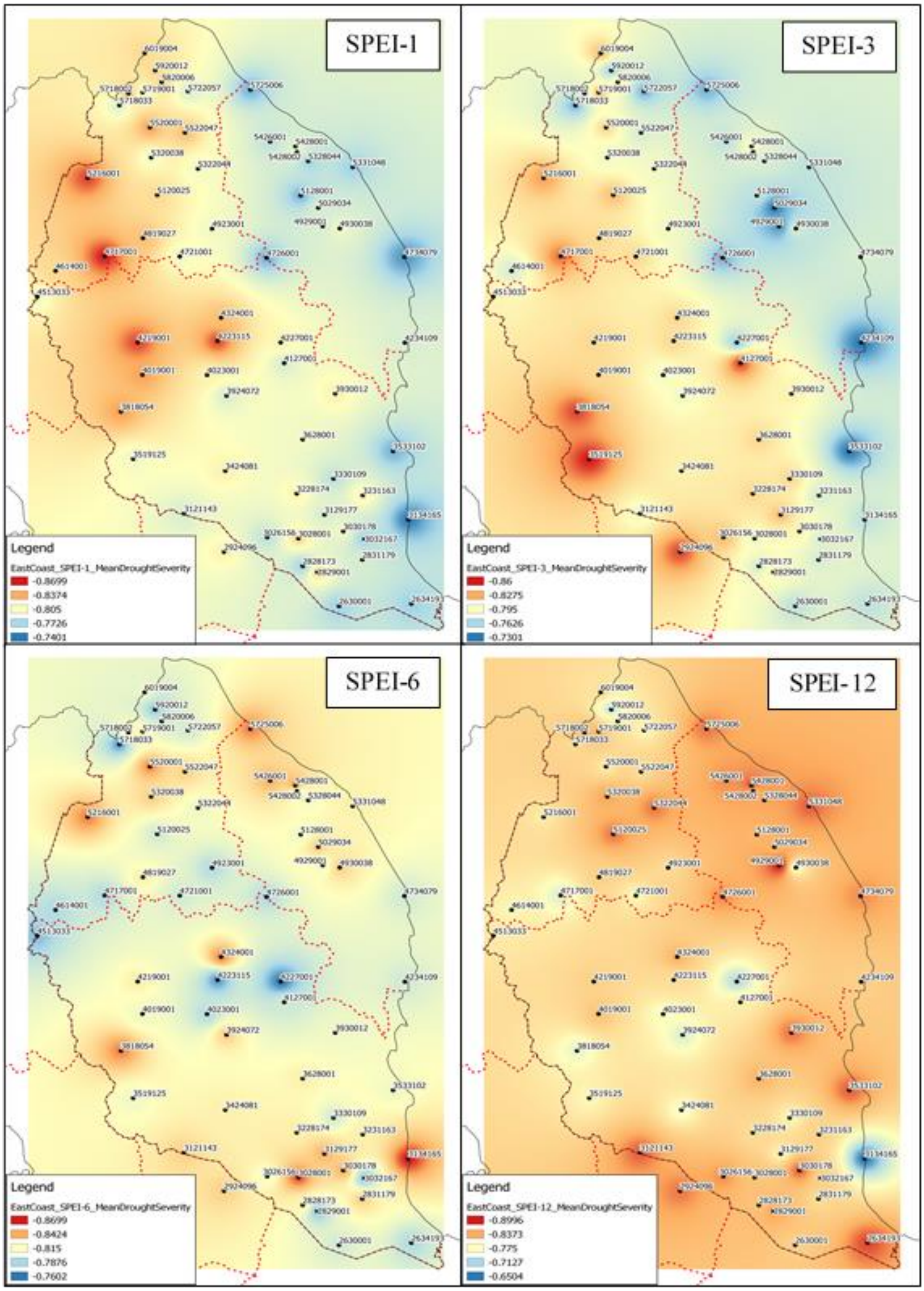

Figure 4.8: Spatial Maps of Mean Drought Severity Based on SPEI at Different Timescales

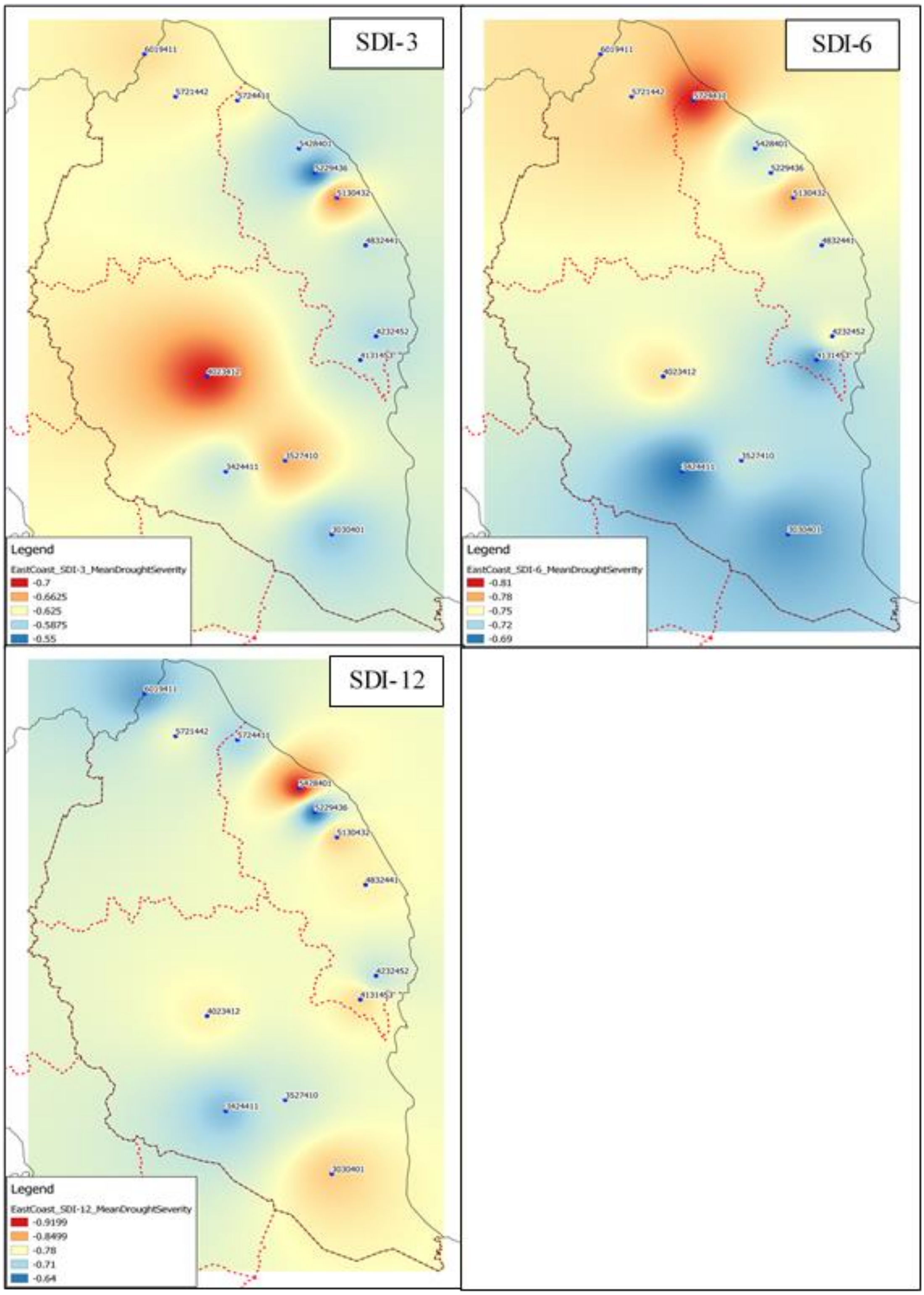

Figure 4.9: Spatial Maps of Mean Drought Severity Based on SDI at Different Timescales

4.2.4 Spatial Distribution of Mean Drought Intensity

From an overview on spatial map of mean drought intensity based on SPI-1 as illustrated in Figure 4.10, the eastern region in general recorded lower mean drought intensity than the southern region. In this case, great mean drought intensity based on SPI-1 was noticed at south and west Pahang, in which the greatest value was detected by dark red region at station 2829001 in west Pahang. Nonetheless, the whole Pahang was observed to be coloured in light and dark blue as well as orange, suggesting the state in general recorded low to moderate mean drought intensity based on SPI-3. However, there is an exception region, in which high mean drought intensity based on SPI at 3-month timescale was spotted in dark red at the western region of the state. In addition, similar dark red regions were also noticed at north-west region of the study area. Spatial map based on SPI at 6-month timescale shows that northern and northeast region recorded moderate average drought intensity except for the northernmost region of Terengganu, which was marked in dark red (highest mean drought intensity). In addition, the central region was observed to be marked in light blue, showing the region experienced mild drought in terms of mean drought intensity based on SPI-6. On the other hand, high mean drought intensity based on SPI-12 was noticed at Terengganu and south Pahang, where the highest value was labelled in dark red at station 3026156 in south-west Pahang.

There is no trend was seen on the spatial map based on SPEI-1 as illustrated in Figure 4.11. However, a dark red spot was seen near to the southern region of Pahang, which indicates that station 2829001 in this region recorded the highest mean drought intensity based on SPEI-1. Apart from that, the whole Kelantan was seen to be recorded relatively low mean drought intensity based on SPEI at 1-month timescale. From the spatial distribution of mean drought intensity based on SPEI-3, the northern region was generally recorded high mean intensity of droughts in which the highest value was detected at both station 5520001 and station 5522047 near the central of Kelantan. Moderate to high mean drought intensity based on SPEI at 6-month was observed in Terengganu, and the highest mean intensity was detected at station 5725006 in the northern region of the state. In this case, there are also two red regions that symbolised high average drought intensity discovered at station 4234109 in south Terengganu and station 3134165 in south-east Pahang, whereas relatively low average drought intensity region extended from north to the central of Pahang. According to the spatial map generated based on SPEI-12, the eastern region in similar to that based on SPEI-6 recorded high average drought intensity, and this spatial distribution pattern extended to east Kelantan and east Pahang.

From a spatial distribution perspective, a smooth increasing trend within Kelantan was observed in which mean drought intensity based on SDI-3 increased from the southern region to the northern region of the state (Figure 4.12). The highest value of mean drought intensity was noticed by dark red label at station 6019411 in the northern region, whereas the eastern and southern region experienced relatively low mean drought intensity. The spatial map based on SDI-6 shows that almost the whole study region recorded moderate to high mean drought intensity. In this case, the exception area was spotted in blue close to the central of Pahang, suggesting low mean drought intensity was detected at this region. Furthermore, the northern region recorded low average drought intensity based on SDI at 12-month timescale, whereas the highest value was detected at station 4131453 in the southernmost region of Terengganu.

Spatial maps of mean drought intensity show that the only similarity between the spatial distribution pattern of average drought intensity based on SPI and SPEI at 1-month timescale is light blue region that indicates low mean drought intensity was detected at the northernmost and eastern region. Moreover, exactly same spatial variation of mean drought intensity based on SPI-6 and SPEI-6 was displayed in which light orange region was observed at northern, eastern and southern region, whereas low average drought intensity region was detected at the other regions. Nonetheless, mean value of drought intensity had about the same spatial distribution style based on SPI and SPEI at 12-month timescale as moderate to high average value region was observed at Terengganu.

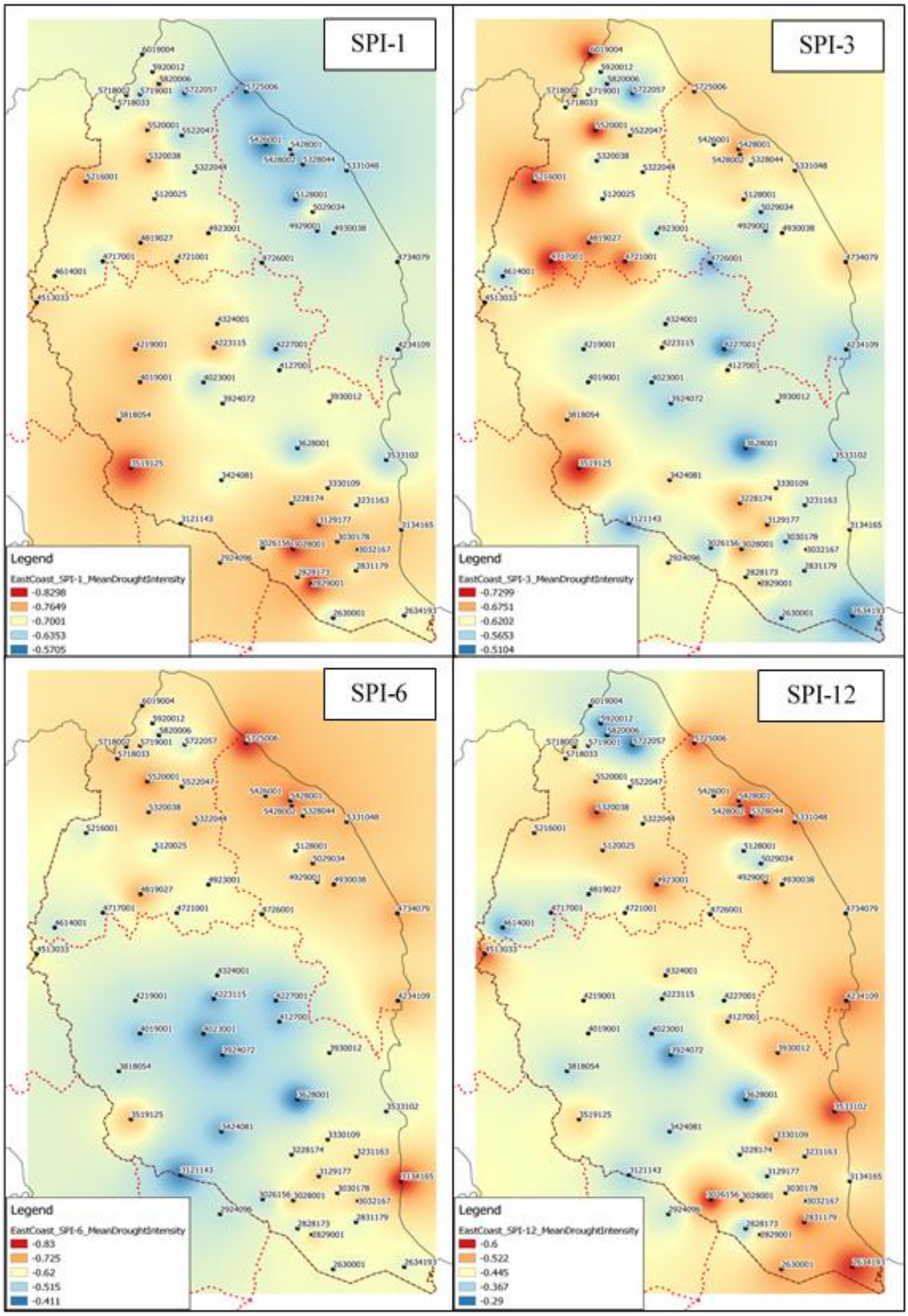

Figure 4.10: Spatial Maps of Mean Drought Intensity Based on SPI at Different Timescales

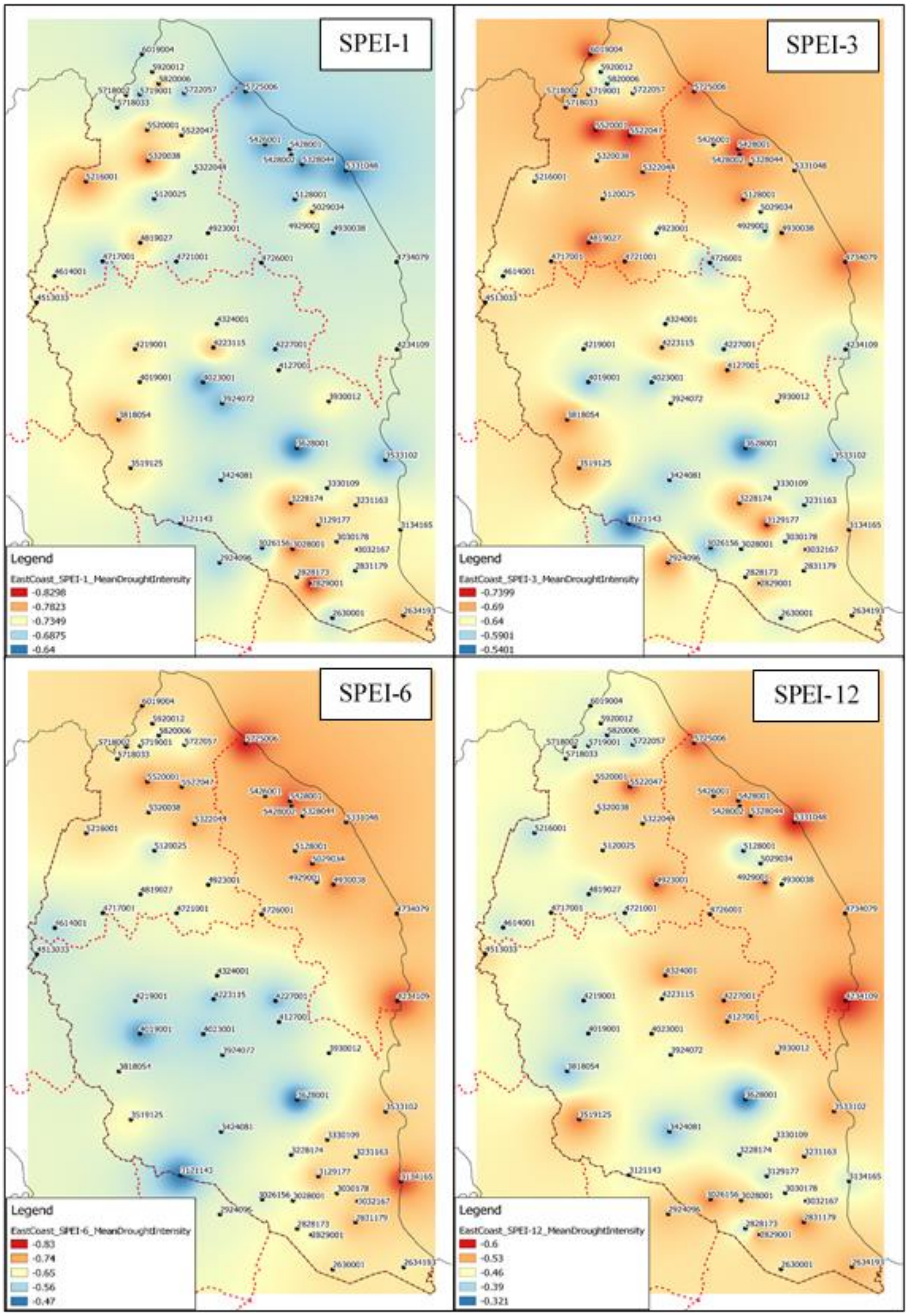

Figure 4.11: Spatial Maps of Mean Drought Intensity Based on SPEI at Different Timescales

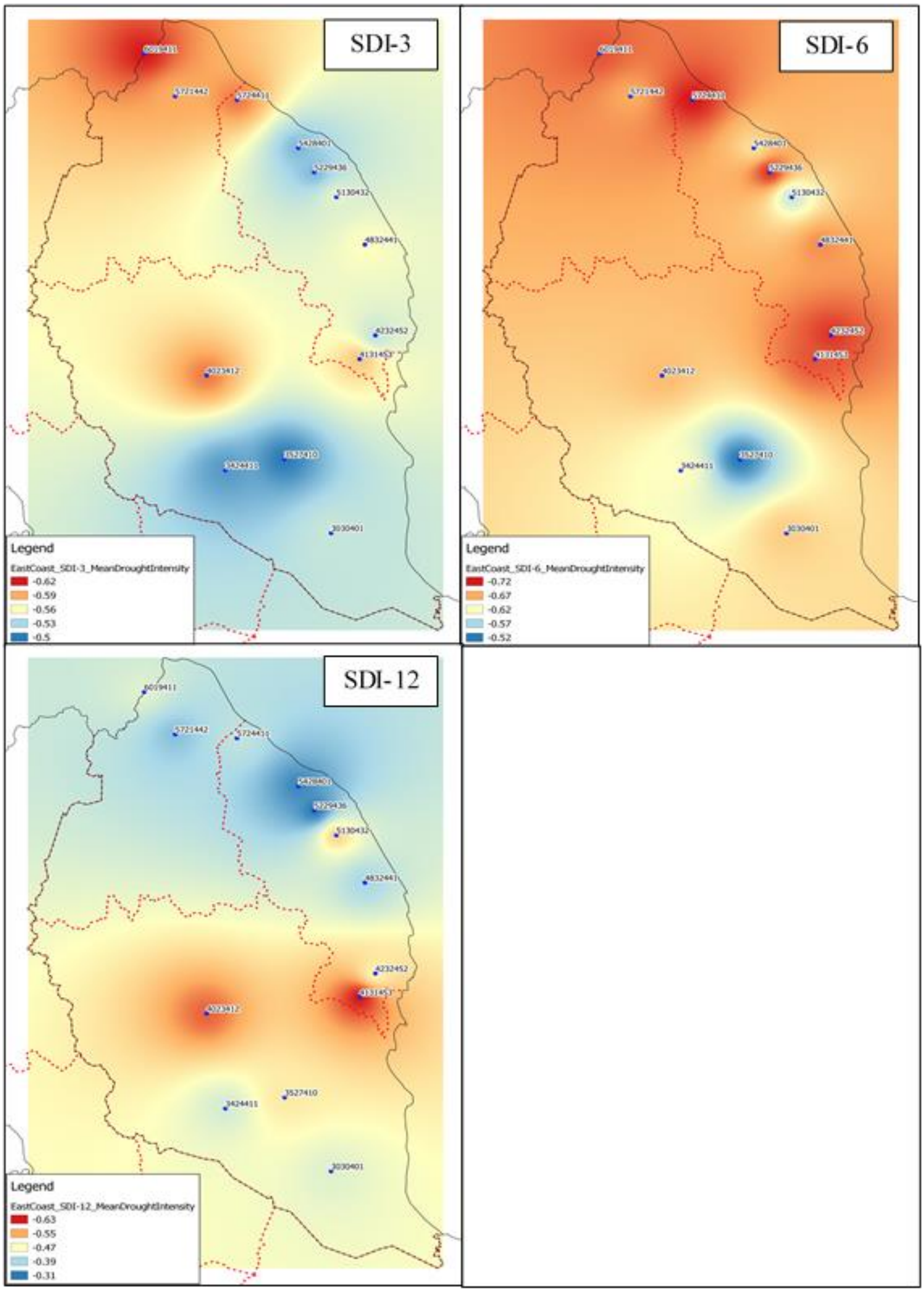

Figure 4.12: Spatial Maps of Mean Drought Intensity Based on SDI at Different Timescales

4.2.5 Spatial Distribution of Mean Drought Peak

Figure 4.13 displays the spatial distribution of mean drought peak based on SPI at different timescales. The spatial map based on SPI-1 shows that almost whole Terengganu and Pahang recorded low mean value of drought peak in general, whereas the highest average drought peak was spotted at station 5820006 in the northern region, besides a relatively high value detected at station 3519125 in west Pahang. From the spatial map based on SPI at 3-month timescale, the whole study area was observed to be having low to moderate mean drought peak except for a region coloured in dark red at around the central of Kelantan. Station 5520001 in this excluded region recorded the highest mean value of drought peak based on SPI-3 over the study area. Spatial map based on SPI-6, high average drought peak regions focused at the northern region whereas low mean drought peak regions that were marked in light blue were spotted at the central of Pahang. In this case, dark red regions that indicate high mean drought peak based on SPI-6 were observed at the northern region. The highest value of 1.37 based on SPI at 6-month timescale was recorded at station 5428001 in north Terengganu. Next, there is no notable trend for spatial distribution of mean drought peak based on SPI-12. Several high mean drought peak regions based on SPI-12 were detected with red spots at the southern region of the map, where the darkest red spot is noticed at both station 3533102 and station 3026156 in south Pahang.

The spatial map based on SPEI at 1-month timescale shows that the whole study area recorded moderate to high mean drought peak (light orange to dark red) excluding some areas near the central of Pahang (Figure 4.14). The highest average drought peak region labelled in dark red based on SPEI-1 was noticed at station 3134165 in south-east Pahang. In contrast, almost the whole study region in spatial map based on SPEI-3 was coloured in blue, suggesting that low mean value of drought peak was detected, whereas the highest mean drought peak was noticed at station 5522047 close to the central of Kelantan. From the spatial distribution generated on the basis of SPEI at 6-month timescale, the whole region was observed to be having moderate mean drought peak, except for some areas that recorded low values near the central of Pahang, as well as some dark red regions at the northern region that achieved high mean value of drought peak. Furthermore, there is no trend was spotted on the spatial map of mean drought peak based on SPEI at 12-month timescale. The highest average drought peak was observed to be coloured in dark red at station 4227001 in north-east Pahang.

It is notable that spatial distribution of mean drought peak based on SDI at 3- and 6-month timescales are literally similar as both spatial maps showed that the highest mean drought peak was recorded at the northernmost region (Figure 4.15). In contrast, the eastern and southern region was observed to be experiencing below intermediate average drought peak. In specific, the lowest average drought peak based on SDI-3 was detected at station 5229436 in north-east Terengganu, while that based on SDI-6 was noticed at station 3527410 in the central of Pahang. The spatial map based on SDI-3 shows that there is an area in south Terengganu recorded above intermediate mean value of drought peak, despite almost the whole state was coloured in light blue (below intermediate mean value). When the timescale became greater, the above intermediate mean drought peak areas based on SDI-3 at south Terengganu became greater as well in which the southern region of the state even joined with the high average drought peak region at north Pahang. Nonetheless, the northern region of the study area recorded below intermediate mean drought peak based on SDI-12, while the southern region was noticed to be having intermediate mean drought peak. In this case, high average drought peak was observed at the central region in which the highest mean value based on SDI at 12-month timescale was detected at station 4023412 near the central of Pahang. Meanwhile, dark blue region that symbolised the lowest mean drought peak area based on SDI-12 was noticed at station 5229436 in north-east Terengganu.

There is an obvious similarity between spatial variation style of mean drought peak based on SPI and SPEI at 3-month timescale as the dark red spot that indicated the highest average value of drought was noticed near the central of Kelantan. Besides that, the whole Pahang was observed to be coloured in light blue, suggesting this state recorded low mean drought peak based on both SPI-3 and SPEI-3. Spatial maps based on SPI and SPEI at 6-month timescale display the similar spatial distribution pattern in which the whole study region recorded moderate to high average drought peak except for some regions close to the central of Pahang.

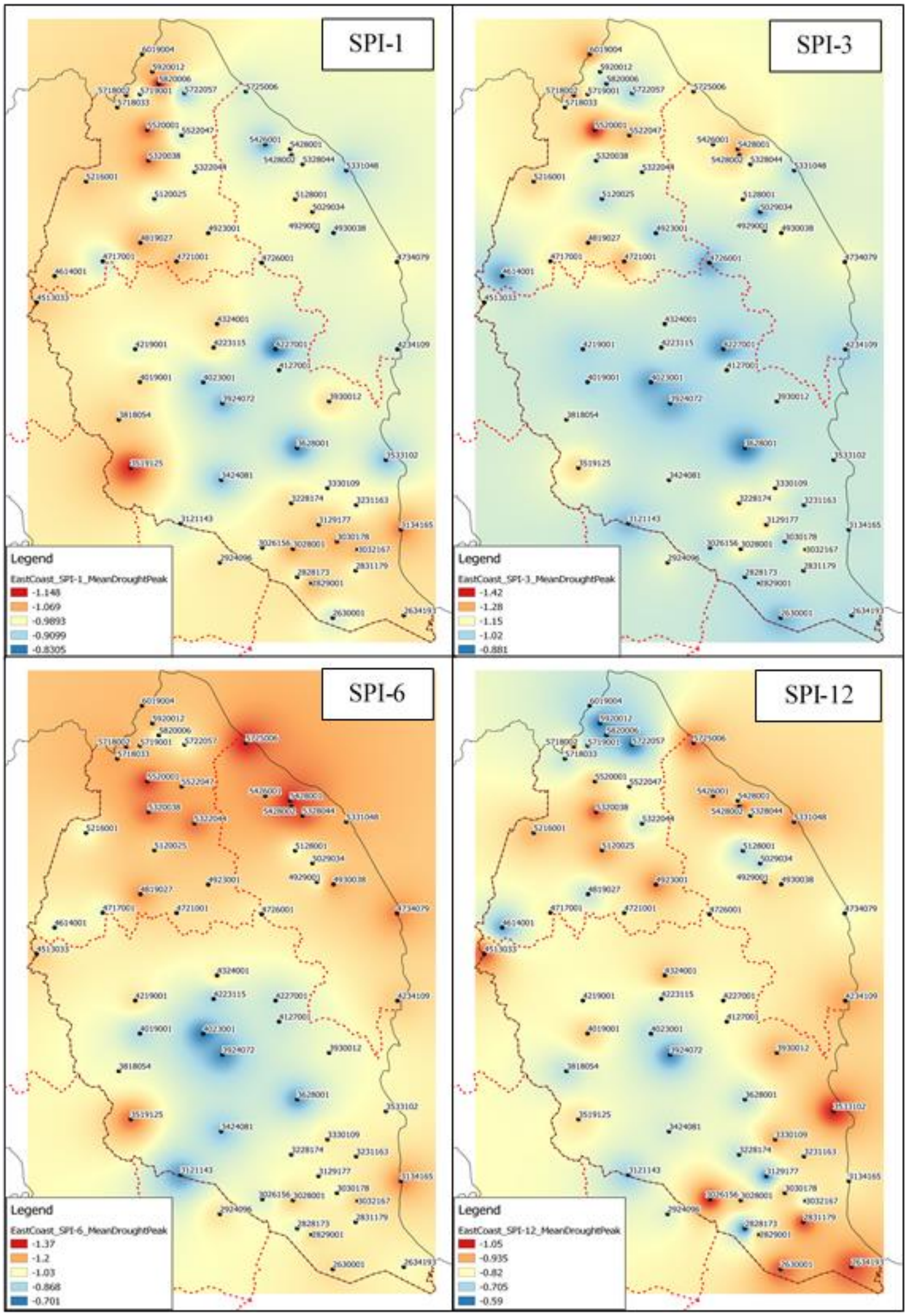

Figure 4.13: Spatial Maps of Mean Drought Peak Based on SPI at Different Timescales

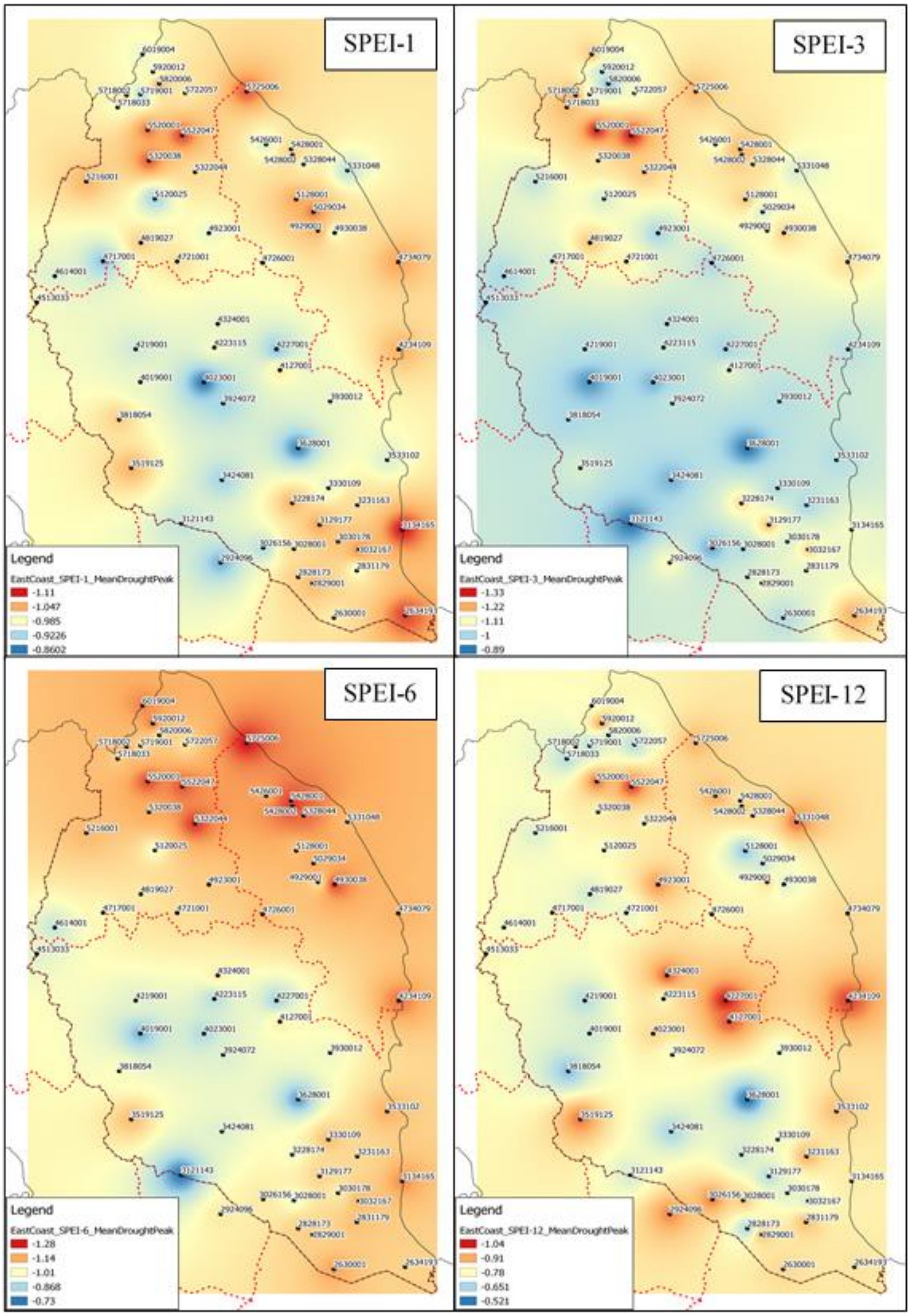

Figure 4.14: Spatial Maps of Mean Drought Peak Based on SPEI at Different Timescales

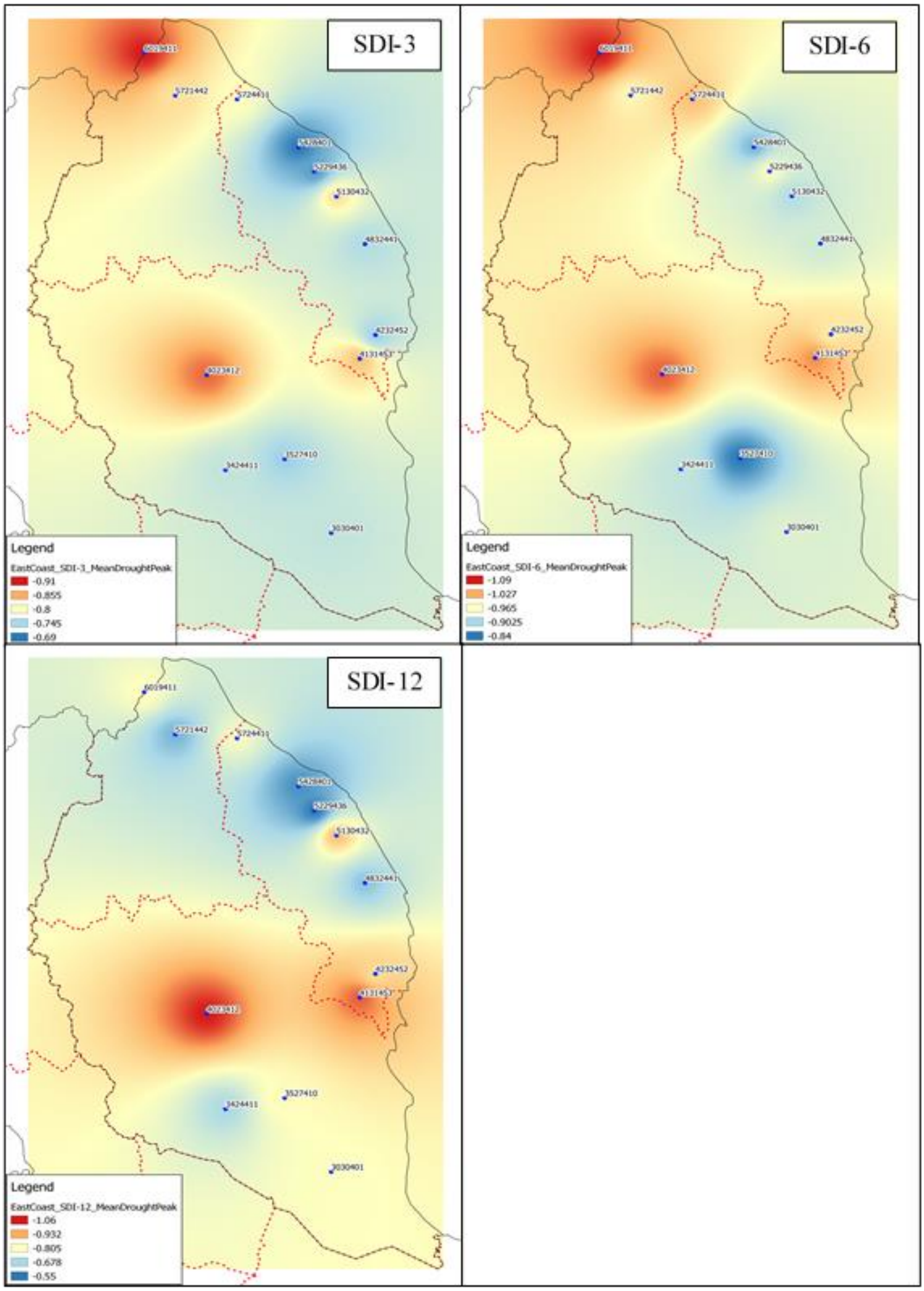

Figure 4.15: Spatial Maps of Mean Drought Peak Based on SDI at Different Timescales

4.3 Variation of Average Moving Range (AMR)

The average moving range (AMR) of SPI, SPEI and SDI at different timescales were computed to measure the variation of data over the time. The graphs of AMR against rainfall or streamflow stations based on different drought indices at various timescales were plotted as graphs. Figure 4.16, 4.17 and 4.18 show the AMR of SPI at different timescales for Kelantan, Terengganu and Pahang, respectively. There is a remarkable similarity between these figures, where the AMR of SPI at 1-month timescale is the greatest among other timescales, suggesting that SPI-1 is the most sensitive index in detecting variation of rainfall data over time. The fluctuation of rainfall data dropped with increasing timescale in which the lowest AMR of all rainfall stations based on SPI were detected at 12-month timescale.

AMR of SPI-1 for rainfall stations in Kelantan lies between the peak value of 0.98 at station 5120025 and the lowest value of 0.80 at station 5722057 (Figure 4.17). Figure 4.16 shows that the differences among AMR of SPI for rainfall stations in Terengganu were small at 3-, 6- and 12-month timescales, indicating that fluctuation of rainfall data for all the rainfall stations in Terengganu was about the same at these timescales. In contrast, the variation of rainfall data at different rainfall stations in Pahang had significant differences at 1-, 3-, 6- and 12-month timescales (Figure 4.18).

In similar to AMR of SPI, the highest AMR values of SPEI was noticed at 1-month timescale for rainfall stations in Kelantan, Terengganu and Pahang, as illustrated in Figure 4.19, 4.20 and 4.21, respectively. Moreover, AMR of SPEI decreased when the timescale became longer, suggesting sensitivity of SPEI in detecting fluctuation of rainfall and temperature data over time reduced with increasing timescale. Based on Figure 4.19, AMR value of SPEI-1 for Kelantan went up to its peak value of 0.99 at station 5120025 and can be as low as 0.79 at station 5722057, showing that there was significant difference between the highest and lowest AMR of SPEI-1 for rainfall stations in Kelantan. In contrast, line graph of AMR based on SPEI-6 shows that AMR of SPEI at 6-month timescale for all rainfall stations in Kelantan were relatively the same.

The line graph of AMR based on SPEI-3 is almost a straight line which means that the variation of rainfall and temperature data based on SPEI at 3-month timescale for rainfall stations in Terengganu are about the same (Figure 4.20). The similar condition applied to AMR of SPEI at 6- and 12-month timescale whereas significant difference for AMR of SPEI-1 was noticed among all rainfall stations in Terengganu

(Figure 4.21). On the other hand, Figure 4.22 shows the AMR of SDI for all streamflow stations in the study area in which the highest AMR value of SDI was recorded at 3-month timescale, suggesting that SDI at the shortest timescale is the most sensitive in detecting fluctuation of streamflow data over time. In similar to AMR of SPI and SPEI, AMR of SDI also decreased when the timescale was lengthened.

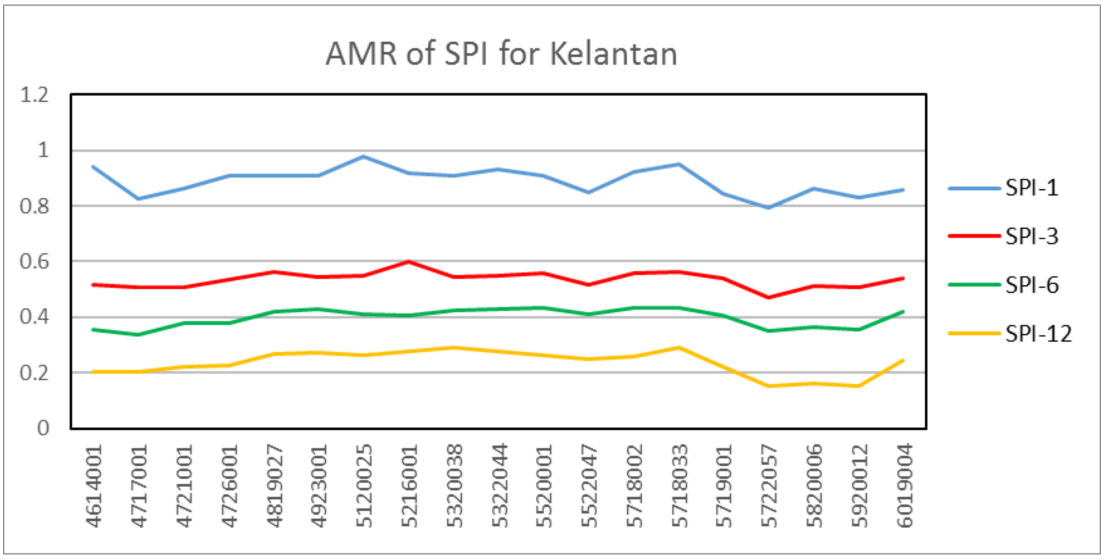

Figure 4.16: AMR of SPI at Different Timescales for Kelantan Rainfall Stations

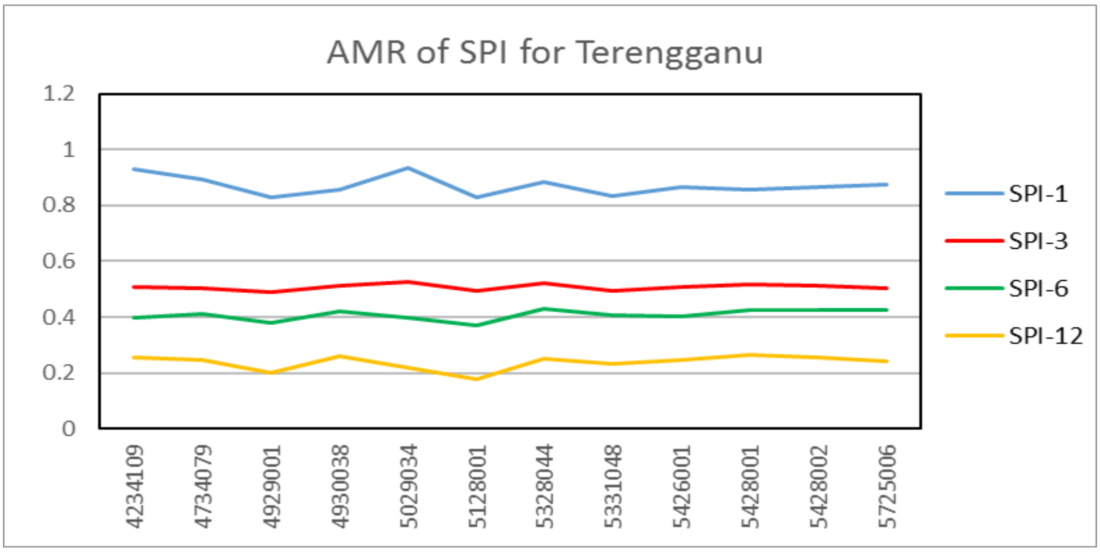

Figure 4.17: AMR of SPI at Different Timescales for Terengganu Rainfall Stations

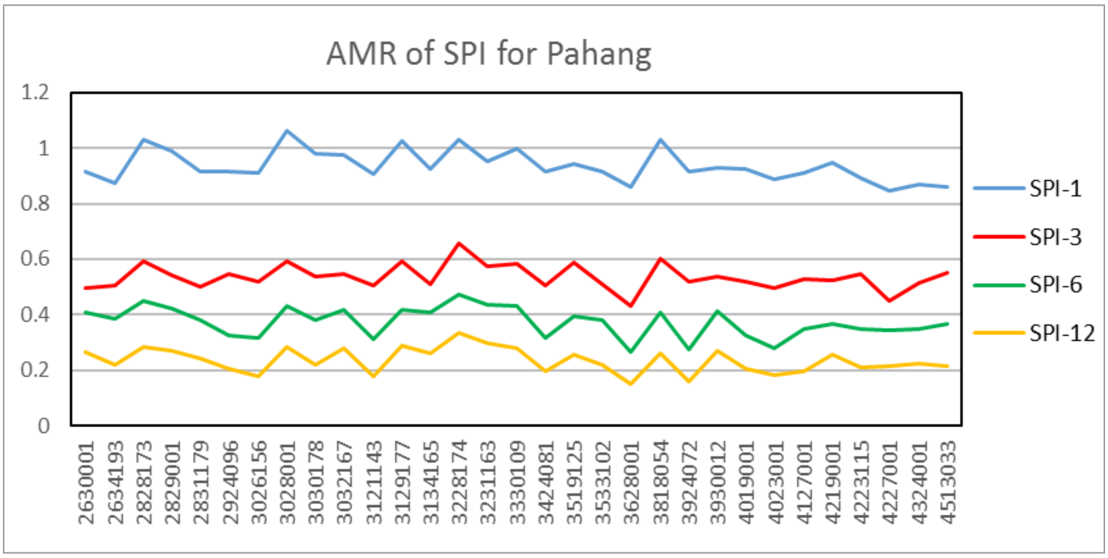

Figure 4.18: AMR of SPI at Different Timescales for Pahang Rainfall Stations

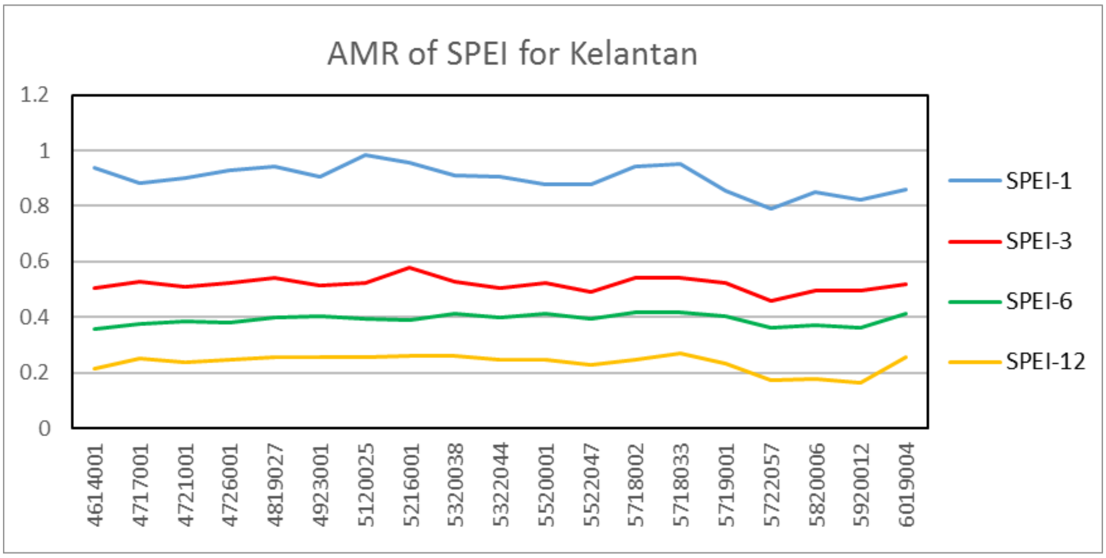

Figure 4.19: AMR of SPEI at Different Timescales for Kelantan Rainfall Stations

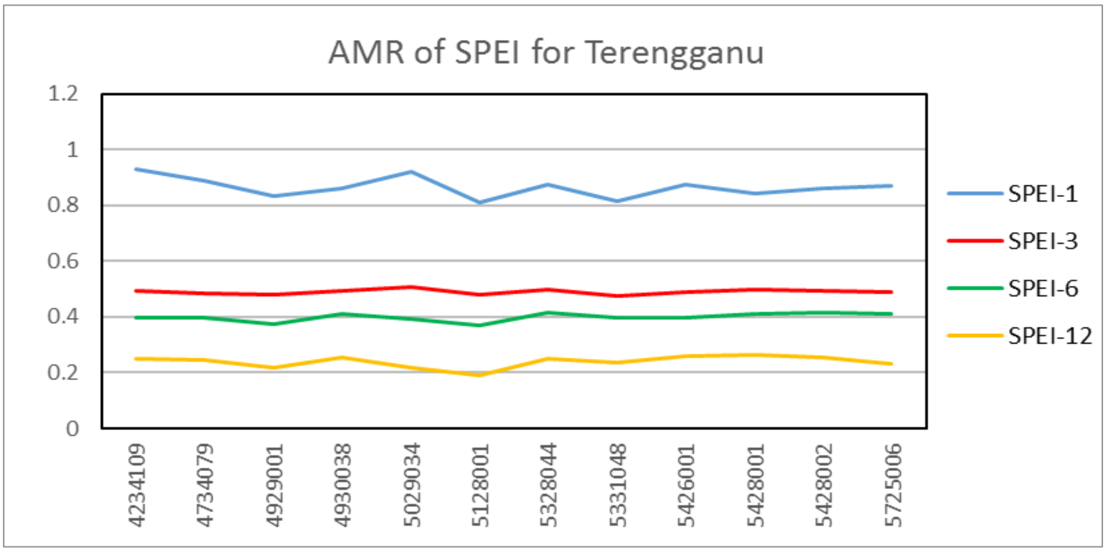

Figure 4.20: AMR of SPEI at Different Timescales for Terengganu Rainfall Stations

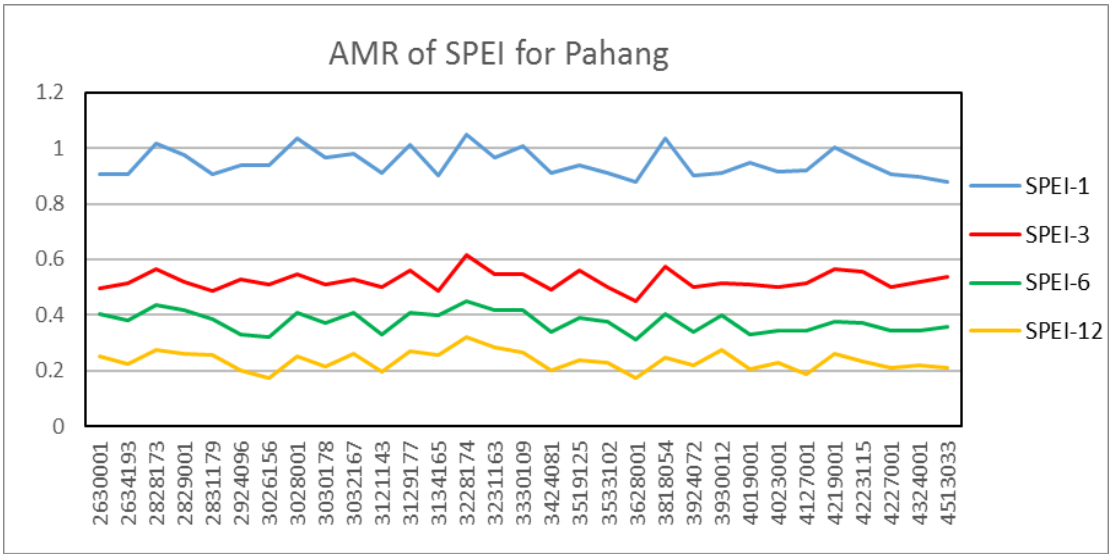

Figure 4.21: AMR of SPEI at Different Timescales for Pahang Rainfall Stations

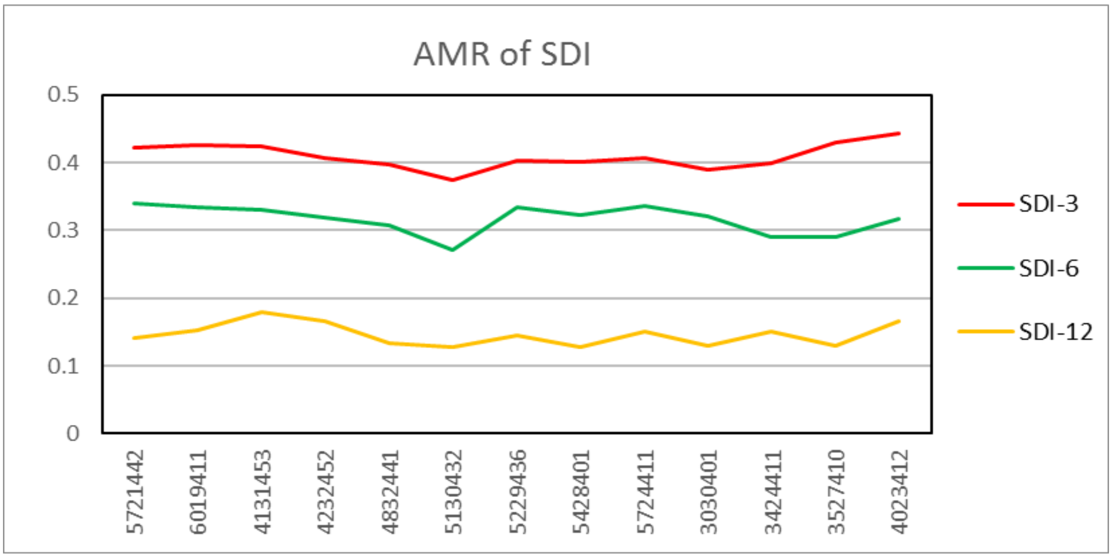

Figure 4.22: AMR of SDI at Different Timescales for the Whole Study Area

4.4 Performance of Drought Indices in Describing Drought Occurrence

The SPI, SPEI and SDI at various timescales were applied to discover the occurrence of droughts and define the drought characteristics. Drought events are represented by negative drought index values, where the beginning and ending of continuous negative drought indices are the onset and offset of a drought event. Based on the recorded droughts from 1983 to 2017, there are three sessions of historical droughts: 1997-1998 event (June 1997 to April 1998), 2014 event (January to March 2014) and 2016 event (January to April 2016) as illustrated in Figure 4.23, and these past drought events were further grouped according to different periods as shown in Table 4.1.

Table 4.1: Grouping of Historical Droughts According to Periods

Notation	Historical Drought Case	Onset	End
G1	Case 1	June 1997	April 1998
G2	Case 2	January 2014	March 2014
	Case 3	January 2014	March 2014
	Case 4	January 2014	March 2014
	Case 5	January 2014	March 2014
	Case 6	January 2014	March 2014
	Case 7	January 2014	March 2014
	Case 8	January 2014	March 2014
	Case 9	January 2014	March 2014
	Case 10	January 2014	March 2014
	Case 11	January 2014	March 2014
	Case 12	January 2014	March 2014
	Case 13	January 2014	March 2014
	Case 14	January 2014	March 2014
G3	Case 15	January 2016	April 2016
	Case 16	January 2016	April 2016
	Case 17	January 2016	April 2016
	Case 18	January 2016	April 2016
	Case 19	January 2016	April 2016

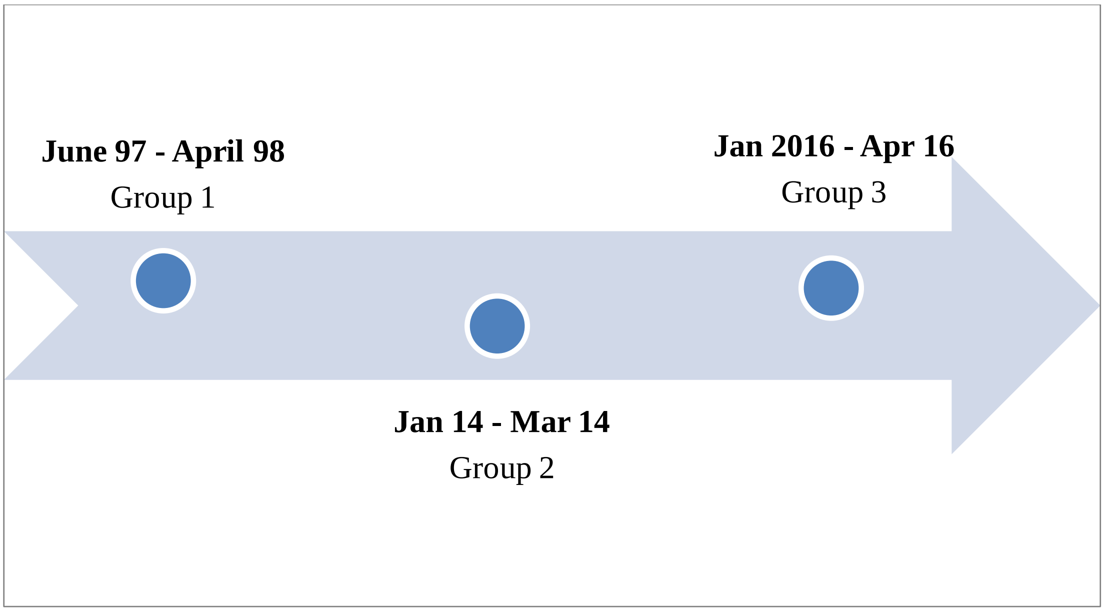

Figure 4.23: Timeline of Recorded Droughts from 1983 to 2017

The report on G1 indicates that severe 1997-1998 El Nino related drought occurred due to continuous deficiency of precipitation since the middle of 1997 and extending for 11 months (Shaaban and Low, 2013). The heatwave resulted in minimum flow for Kelantan River at Guillemard Bridge, and as a result, Pasir Mas Pump House was malfunctioned due to the river level was lower than that required for irrigation abstraction. On the other hand, G2 included historical droughts that had been reported in paddy farming areas in Kelantan, including Bachok, Pasir Mas, Pasir Puteh, PPK Tanjung Puri and Tumpat (Lembaga Kemajuan Pertanian Kemubu, 2018). The paddy farmers in these areas were affected as they were unable to perform farming due to irrigation problem. This situation was mainly caused by unusual prolonged dry spell from January 2014 to middle of March, causing drought phenomenon (Bernama, 2014; Leister, 2014).

In addition, reports on recorded droughts grouped under G2 indicate that some areas in Pahang also experienced drought problem as a result of long stretching period of well-below normal precipitation since early 2014 and continued through mid-March. The drought problem had caused low water level reading at 35 % of water treatment plants. However, the volume of water was still sufficient for supply to consumer of the area. Besides drought phenomenon, there is another reason that contributed to this issue, which is blocking of streamflow by sand at the water intake zone (Bernama, 2014; Leister, 2014).

During 2015 and early 2016, the strongest El Nino since 1983 suppressed precipitation over South-east Asia, causing extended period of drought stress in Malaysia. In specific, TodayOnline (2016) reported that this severe heatwave led to depleting water storage at dams nationwide from January to April 2016 where Bukit Kwong Dam in Kelantan was one of the seven dams that recorded water level of less than 50% (G3). Furthermore, reports on G3 told that droughts triggered by El Nino phenomenon have caused water supply problem at Chini, Air Jelai and Lubuk Kawah treatment plants. As a result, serious water shortage issues arised in Chini, Lancang, Lipis and Mentakab due to water supply problem at water treatment plants from the first month of 2014 and extending to March of the same year (TheSunDaily, 2016).

Further research had been performed on these recorded drought events thus the drought characteristics including duration, severity as well as the onset and end of detected droughts based on drought indices at different timescales were compared with that of the recorded droughts from 1983 to 2017 (Table 4.2 to Table 4.21). In this case, probability of detection of drought occurrence (POD), mean absolute error (MAE) and mean bias error (MBE) in detecting duration of droughts, early or delayed prediction (MEDP) of onset of droughts as well as ability in measuring drought severity, were determined to evaluate performance of SPI, SPEI and SDI at various timescales in describing drought occurrence.

Table 4.2: Comparison of Historical Drought at Guillemard Bridge with the Results Obtained from Various Drought Indices

Case 1	Location: Kelantan River (Guillemard Bridge), Onset: 06/1997, End: 04/1998 (Shaaban and Low, 2013)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	5722057				5722057				5721442		
Distance (km)	8.413				8.413				0.212		
Onset	02/1998	12/1996	03/1996	06/1996	02/1998	01/1997	01/1997	05/1996	03/1997	05/1997	08/1997
End	05/1998	10/1997	11/1997	11/1997	07/1998	10/1997	11/1997	12/1997	11/1997	11/1997	12/1997
Duration (Months)	4	11	21	17	4	10	11	20	9	7	5
Maximum Severity	-2.03	-1.48	-1.89	-1.34	-3.31	-1.10	-1.05	-1.38	-0.74	-0.94	-0.58
Mean Severity	-1.69	-0.43	-0.61	-0.84	-1.67	-0.46	-0.61	-0.88	-0.56	-0.72	-0.34

Table 4.3: Comparison of Historical Drought in Bachok with the Results Obtained from Various Drought Indices

Case 2	Location: Bachok, Onset: 01/2014, End: 03/2014 (Bernama, 2014; Leister, 2014)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	5725006				5725006				5724411		
Distance (km)	35.768				35.768				38.506		
Onset	02/2014	03/2014	-	02/2014	02/2014	03/2014	-	02/2014	03/2014	-	01/2014
End	06/2014	07/2014	-	08/2014	06/2014	08/2014	-	10/2014	11/2014	-	12/2017
Duration (Months)	5	5	-	7	5	6	-	9	9	-	48
Maximum Severity	-1.79	-2.04	-	-0.46	-2.44	-1.79	-	-0.62	-0.98	-	-2.34
Mean Severity	-0.98	-1.13	-	-0.27	-1.17	-1.06	-	-0.36	-0.88	-	-1.13

Table 4.4: Comparison of Historical Drought in Pasir Mas with the Results Obtained from Various Drought Indices

Case 3	Location: Pasir Mas, Onset: 01/2014, End: 03/2014 (Bernama, 2014; Leister, 2014)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	6019004				6019004				6019411		
Distance (km)	18.110				18.110				18.261		
Onset	02/2014	03/2014	-	02/2014	02/2014	03/2014	-	02/2014	03/2014	-	11/2012
End	05/2014	07/2014	-	11/2014	05/2014	09/2014	-	11/2014	10/2014	-	03/2017
Duration (Months)	4	5	-	10	4	7	-	10	8	-	53
Maximum Severity	-2.35	-2.58	-	-0.73	-1.99	-1.85	-	-0.75	-1.27	-	-1.29
Mean Severity	-1.44	-1.08	-	-0.44	-1.32	-0.82	-	-0.43	-0.90	-	-0.64

Table 4.5: Comparison of Historical Drought in Pasir Puteh with the Results Obtained from Various Drought Indices

Case 4	Location: Pasir Puteh, Onset: 01/2014, End: 03/2014 (Bernama, 2014; Leister, 2014)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	5725006				5725006				5724411		
Distance (km)	18.785				18.785				14.792		
Onset	02/2014	03/2014	-	02/2014	02/2014	03/2014	-	02/2014	03/2014	-	01/2014
End	06/2014	07/2014	-	08/2014	06/2014	08/2014	-	10/2014	11/2014	-	12/2017
Duration (Months)	5	5	-	7	5	6	-	9	9	-	48
Maximum Severity	-1.79	-2.04	-	-0.46	-2.44	-1.79	-	-0.62	-0.98	-	-2.34
Mean Severity	-0.98	-1.13	-	-0.27	-1.17	-1.06	-	-0.36	-0.88	-	-1.13

Table 4.6: Comparison of Historical Drought in PPK Tanjung Puri with the Results Obtained from Various Drought Indices

Case 5	Location: PPK Tanjung Puri, Onset: 01/2014, End: 03/2014 (Bernama, 2014; Leister, 2014)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	5920012				5920012				6019411		
Distance (km)	23.066				23.066				26.232		
Onset	02/2014	-	-	-	02/2014	-	-	-	03/2014	-	11/2012
End	04/2014	-	-	-	04/2014	-	-	-	10/2014	-	03/2017
Duration (Months)	3	-	-	-	3	-	-	-	8	-	53
Maximum Severity	-3.31	-	-	-	-1.52	-	-	-	-1.27	-	-1.29
Mean Severity	-1.54	-	-	-	-1.07	-	-	-	-0.90	-	-0.64

Table 4.7: Comparison of Historical Drought in Tumpat with the Results Obtained from Various Drought Indices

Case 6	Location: Tumpat, Onset: 01/2014, End: 03/2014 (Bernama, 2014; Leister, 2014)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	6019004				6019004				6019411		
Distance (km)	28.681				28.681				28.723		
Onset	02/2014	03/2014	-	02/2014	02/2014	03/2014	-	02/2014	03/2014	-	11/2012
End	05/2014	07/2014	-	11/2014	05/2014	09/2014	-	11/2014	10/2014	-	03/2017
Duration (Months)	4	5	-	10	4	7	-	10	8	-	53
Maximum Severity	-2.35	-2.58	-	-0.73	-1.99	-1.85	-	-0.75	-1.27	-	-1.29
Mean Severity	-1.44	-1.08	-	-0.44	-1.32	-0.82	-	-0.43	-0.90	-	-0.64

Table 4.8: Comparison of Historical Drought in Bentong with the Results Obtained from Various Drought Indices

Case 7	Location: Bentong, Onset: 01/2014, End: 03/2014 (Bernama, 2014; Leister, 2014)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	3519125				3519125				3615412		
Distance (km)	1.211				1.211				46.686		
Onset	01/2014	02/2014	01/2014	02/2014	01/2014	02/2014	08/2013	02/2014	02/2010	02/2010	03/2010
End	02/2014	03/2014	03/2014	03/2014	03/2014	03/2014	03/2014	03/2014	12/2017	12/2017	12/2017
Duration (Months)	2	2	3	2	3	2	8	2	95	95	94
Maximum Severity	-3.09	-1.44	-0.81	-0.42	-1.68	-1.23	-0.60	-0.56	-1.69	-1.78	-1.73
Mean Severity	-1.91	-1.35	-0.49	-0.40	-0.84	-1.09	-0.25	-0.53	-1.01	-1.11	-1.18

Table 4.9: Comparison of Historical Drought in Bera with the Results Obtained from Various Drought Indices

Case 8	Location: Bera, Onset: 01/2014, End: 03/2014 (Bernama, 2014)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	3424081				3424081				3424411		
Distance (km)	14.351				14.351				14.658		
Onset	01/2014	03/2014	-	-	01/2014	03/2014	-	-	03/2014	-	-
End	03/2014	04/2014	-	-	03/2014	08/2014	-	-	11/2014	-	-
Duration (Months)	3	2	-	-	3	6	-	-	9	-	-
Maximum Severity	-1.78	-1.56	-	-	-1.29	-1.87	-	-	-1.27	-	-
Mean Severity	-0.96	-0.82	-	-	-0.85	-0.91	-	-	-0.92	-	-

Table 4.10: Comparison of Historical Drought in Jerantut with the Results Obtained from Various Drought Indices

Case 9	Location: Jerantut, Onset: 01/2014, End: 03/2014 (Bernama, 2014)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	3924072				3924072				4023412		
Distance (km)	8.637				8.637				11.494		
Onset	02/2014	03/2014	02/2014	02/2014	02/2014	03/2014	02/2014	03/2013	-	-	-
End	03/2014	04/2014	03/2014	03/2014	03/2014	04/2014	03/2014	11/2014	-	-	-
Duration (Months)	2	2	2	2	2	2	2	21	-	-	-
Maximum Severity	-1.69	-1.00	-0.10	-0.09	-1.38	-0.78	-0.04	-0.77	-	-	-
Mean Severity	-0.92	-0.70	-0.07	-0.06	-0.92	-0.68	-0.03	-0.36	-	-	-

Table 4.11: Comparison of Historical Drought in Lipis with the Results Obtained from Various Drought Indices

Case 10	Location: Lipis, Onset: 01/2014, End: 03/2014 (Bernama, 2014)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	4219001				4219001				4023412		
Distance (km)	14.011				14.011				34.360		
Onset	02/2014	02/2014	-	-	02/2014	02/2014	-	-	-	-	-
End	03/2014	04/2014	-	-	03/2014	09/2014	-	-	-	-	-
Duration (Months)	2	3	-	-	2	8	-	-	-	-	-
Maximum Severity	-1.38	-0.79	-	-	-1.21	-1.54	-	-	-	-	-
Mean Severity	-0.91	-0.49	-	-	-0.98	-0.82	-	-	-	-	-

Table 4.12: Comparison of Historical Drought in Maran with the Results Obtained from Various Drought Indices

Case 11	Location: Maran, Onset: 01/2014, End: 03/2014 (Bernama, 2014)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	3628001				3628001				3527410		
Distance (km)	11.371				11.371				7.955		
Onset	02/2014	03/2014	-	-	02/2014	03/2014	-	-	03/2014	-	-
End	03/2014	04/2014	-	-	03/2014	04/2014	-	-	11/2014	-	-
Duration (Months)	2	2	-	-	2	2	-	-	9	-	-
Maximum Severity	-1.05	-0.89	-	-	-0.93	-0.81	-	-	-0.98	-	-
Mean Severity	-0.84	-0.46	-	-	-0.89	-0.54	-	-	-0.62	-	-

Table 4.13: Comparison of Historical Drought in Pekan with the Results Obtained from Various Drought Indices

Case 12	Location: Pekan, Onset: 01/2014, End: 03/2014 (Bernama, 2014)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	3533102				3533102				3030401		
Distance (km)	9.898				9.898				63.950		
Onset	02/2014	03/2014	-	-	02/2014	03/2014	-	-	-	07/2013	03/2012
End	04/2014	09/2014	-	-	04/2014	09/2014	-	-	-	01/2014	11/2017
Duration (Months)	3	7	-	-	3	7	-	-	-	7	69
Maximum Severity	-1.58	-2.14	-	-	-2.00	-1.91	-	-	-	-1.06	-1.54
Mean Severity	-1.38	-0.63	-	-	-1.46	-0.74	-	-	-	-0.70	-0.74

Table 4.14: Comparison of Historical Drought in Rompin with the Results Obtained from Various Drought Indices

Case 13	Location: Rompin, Onset: 01/2014, End: 03/2014 (Bernama, 2014)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	2634193				2634193				2533474		
Distance (km)	22.485				22.485				33.897		
Onset	01/2014	03/2014	-	02/2014	01/2014	03/2014	-	02/2014	03/2014	02/2014	02/2014
End	04/2014	11/2014	-	03/2017	07/2014	11/2014	-	04/2017	12/2017	12/2017	12/2017
Duration (Months)	4	9	-	38	7	9	-	39	46	47	47
Maximum Severity	-2.26	-1.89	-	-1.96	-1.79	-2.06	-	-1.77	-1.03	-1.25	-1.49
Mean Severity	-1.11	-0.81	-	-1.02	-0.78	-0.99	-	-1.18	-0.79	-0.95	-1.17

Table 4.15: Comparison of Historical Drought in Temerloh with the Results Obtained from Various Drought Indices

Case 14	Location: Temerloh, Onset: 01/2014, End: 03/2014 (Bernama, 2014)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	3121143				3121143				3424411		
Distance (km)	12.124				12.124				27.823		
Onset	01/2014	03/2014	-	-	01/2014	03/2014	-	-	03/2014	-	-
End	02/2014	10/2014	-	-	09/2014	10/2014	-	-	11/2014	-	-
Duration (Months)	2	8	-	-	9	8	-	-	9	-	-
Maximum Severity	-1.88	-1.09	-	-	-1.38	-1.39	-	-	-1.27	-	-
Mean Severity	-1.29	-0.57	-	-	-0.64	-0.88	-	-	-0.92	-	-

Table 4.16: Comparison of Historical Drought in Bukit Kwong Dam with the Results Obtained from Various Drought Indices

Case 15	Location: Bukit Kwong Dam, Onset: 01/2016, End: 04/2016 (TodayOnline, 2016; USDA, 2016)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	5920012				5920012				6019411		
Distance (km)	8.855				8.855				9.077		
Onset	02/2016	03/2016	-	-	02/2016	03/2016	-	-	03/2016	03/2016	11/2012
End	05/2016	06/2016	-	-	05/2016	06/2016	-	-	11/2016	12/2016	03/2017
Duration (Months)	4	4	-	-	4	4	-	-	9	10	53
Maximum Severity	-1.96	-1.59	-	-	-2.33	-2.04	-	-	-1.11	-1.08	-1.29
Mean Severity	-0.91	-0.86	-	-	-1.21	-1.15	-	-	-0.63	-0.64	-0.64

Table 4.17: Comparison of Historical Drought in Chini with the Results Obtained from Various Drought Indices

Case 16	Location: Chini, Onset: 01/2016, End: 04/2016 (TheSunDaily, 2016; USDA, 2016)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	3330109				3330109				3527410		
Distance (km)	13.114				13.114				19.708		
Onset	03/2016	03/2016	06/2015	09/2015	03/2016	03/2016	06/2015	07/2015	04/2015	06/2015	11/2015
End	05/2016	12/2016	12/2016	03/2017	05/2016	12/2016	12/2016	03/2017	12/2016	01/2017	04/2017
Duration (Months)	3	10	19	19	3	10	19	21	21	20	18
Maximum Severity	-1.72	-2.43	-2.35	-2.57	-2.24	-2.67	-2.08	-2.30	-1.15	-1.47	-1.46
Mean Severity	-1.34	-0.75	-1.23	-1.52	-2.00	-0.99	-1.37	-1.49	-0.74	-0.91	-1.06

Table 4.18: Comparison of Historical Drought in Lancang with the Results Obtained from Various Drought Indices

Case 17	Location: Lancang, Onset: 01/2016, End: 04/2016 (TheSunDaily, 2016; USDA, 2016)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	3533102				3533102				3030401		
Distance (km)	19.868				19.868				60.181		
Onset	01/2016	03/2016	04/2016	12/2015	03/2016	03/2016	04/2016	12/2015	03/2015	07/2014	03/2012
End	04/2016	09/2016	09/2016	12/2016	04/2016	09/2016	11/2016	02/2017	01/2017	02/2017	11/2017
Duration (Months)	4	7	6	13	2	7	8	15	23	32	69
Maximum Severity	-1.89	-1.25	-1.07	-1.18	-3.22	-1.55	-1.42	-1.51	-0.82	-1.10	-1.54
Mean Severity	-0.89	-0.58	-0.65	-0.67	-2.50	-0.88	-0.76	-0.96	-0.63	-0.77	-0.74

Table 4.19: Comparison of Historical Drought in Lipis with the Results Obtained from Various Drought Indices

Case 18	Location: Lipis, Onset: 01/2016, End: 04/2016 (TheSunDaily, 2016; USDA, 2016)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	4219001				4219001				4023412		
Distance (km)	14.011				14.011				34.360		
Onset	01/2016	02/2016	03/2016	07/2014	01/2016	02/2016	03/2016	07/2014	04/2016	-	-
End	04/2016	11/2016	12/2016	03/2017	04/2016	11/2016	12/2016	03/2017	10/2016	-	-
Duration (Months)	4	10	10	33	4	10	10	33	7	-	-
Maximum Severity	-1.97	-1.85	-1.32	-1.24	-1.94	-1.89	-1.64	-1.55	-0.49	-	-
Mean Severity	-1.12	-0.69	-0.81	-0.43	-1.28	-1.05	-1.15	-0.74	-0.31	-	-

Table 4.20: Comparison of Historical Drought in Mentakab with the Results Obtained from Various Drought Indices

Case 19	Location: Mentakab, Onset: 01/2016, End: 04/2016 (TheSunDaily, 2016; USDA, 2016)										
Drought Index	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
Nearest Station	3424081				3424081				3424411		
Distance (km)	9.834				9.834				9.827		
Onset	12/2015	02/2016	03/2016	12/2015	12/2015	02/2016	03/2016	11/2014	04/2016	-	-
End	08/2016	10/2016	12/2016	02/2017	08/2016	10/2016	12/2016	04/2017	12/2016	-	-
Duration (Months)	9	9	10	15	9	9	10	30	9	-	-
Maximum Severity	-1.78	-1.78	-1.70	-1.27	-2.18	-2.00	-1.97	-1.66	-1.39	-	-
Mean Severity	-0.65	-1.06	-0.93	-0.56	-1.06	-1.37	-1.31	-0.68	-0.86	-	-

4.4.1 Probability of Detection (POD) of Drought Occurrence

The POD of drought occurrence were calculated to determine the ability of SPI, SPEI and SDI at various timescales in detecting the occurrence of total nineteen recorded droughts from 1983 to 2017. A detected drought event was coloured in light green with a tick symbol, whereas a dash symbol signified failure in detection of droughts.

Table 4.21: Total Number of Detected Droughts for SPI, SPEI and SDI at Various Timescales

Case	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	✓	✓	-	✓	✓	✓	-	✓	✓	-	✓
3	✓	✓	-	✓	✓	✓	-	✓	✓	-	✓
4	✓	✓	-	✓	✓	✓	-	✓	✓	-	✓
5	✓	-	-	-	✓	-	-	-	✓	-	✓
6	✓	✓	-	✓	✓	✓	-	✓	✓	-	✓
7	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
8	✓	✓	-	-	✓	✓	-	-	✓	-	-
9	✓	✓	✓	✓	✓	✓	✓	✓	-	-	-
10	✓	✓	-	-	✓	✓	-	-	-	-	-
11	✓	✓	-	-	✓	✓	-	-	✓	-	-
12	✓	✓	-	-	✓	✓	-	-	-	✓	✓
13	✓	✓	-	✓	✓	✓	-	✓	✓	✓	✓
14	✓	✓	-	-	✓	✓	-	-	✓	-	-
15	✓	✓	-	-	✓	✓	-	-	✓	✓	✓
16	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
17	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
18	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	-
19	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	-
Σ Detected droughts	19	18	7	12	19	18	7	12	16	7	12

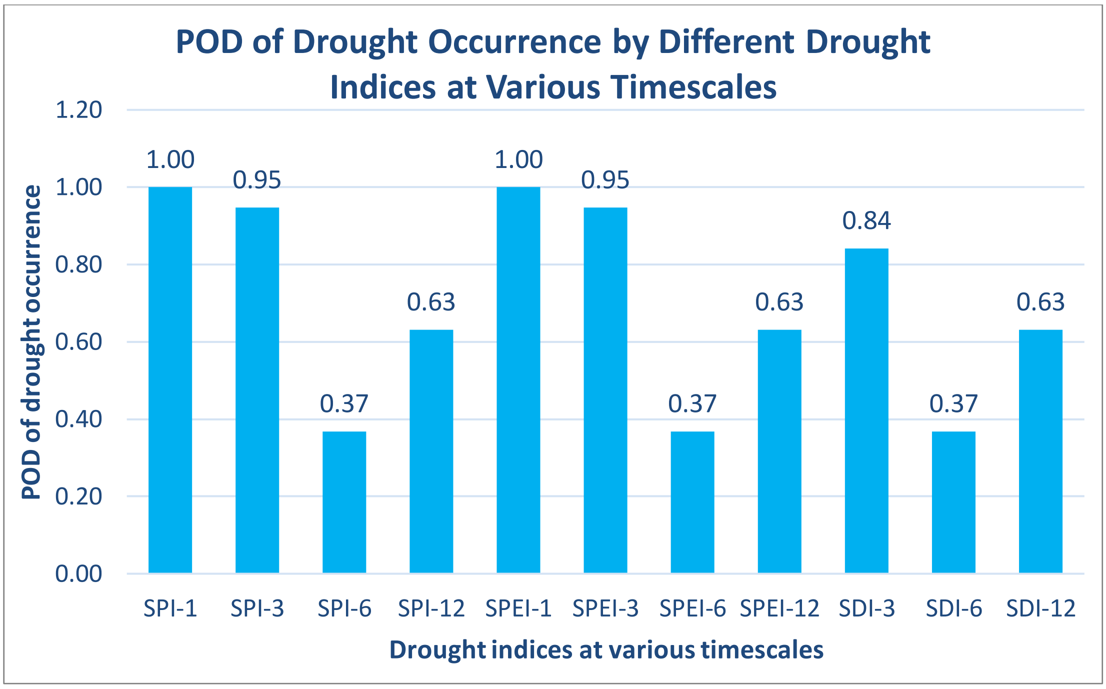

Figure 4.24: Graph of POD of Drought Occurrence by Different Drought Indices at Various Timescales

Figure 4.24 shows that SPI-6, SPEI-6 and SDI-6 recorded the lowest POD of drought occurrence with the value of 0.37. The reason is when the time period of data in consideration for computation of drought indices had been lengthened to six months, the drought indices are less sensitive to variation in rainfall, streamflow and temperature data. The periods of negative and positive values of drought indices decrease in number but the duration become longer. Therefore, the POD drops due to lesser periods of negative drought index values at 6-month timescale, leading to difficulty in detecting short-term droughts such as recorded droughts grouped under G2 (Case 2 to Case 14). Further, when the drought indices were computed based on 12-month timescale, the periods of negative values that indicated drought events become even lesser in number whereas the duration become even longer. So, SPI-12, SPEI-12 and SDI-12 had higher probability in recognizing droughts as compared to drought indices at 6-month timescale because the range of input data in consideration for computation is greater, which is more likely to detect droughts. However, POD for drought indices at 12-month timescale is still lower than that at small timescales.

The performance of SPI, SPEI and SDI in identifying the occurrence of droughts was observed to be the best at the smallest timescale especially SPI-1 and SPEI-1, which were capable to detect all the nineteen recorded droughts. This observation was linked to rapid climate change of the study area affected by diverse wet and dry seasons, causing high fluctuation in precipitation, streamflow and temperature. In this case, the highest AMR values of drought indices at 1-month timescale show that SPI-1, SPEI-1 and SDI-1 are the most sensitive in recognizing fluctuation of input data. As a result, high fluctuation of drought indices given that the computation were based on small timescale define the ability in detecting droughts. This theory best explained the peak performance of SPI-1, SPEI-1 and SDI-3 as compared to greater timescales in detecting drought occurrence. Moreover, SPI and SPEI at 3-month timescale recorded probability of just slightly lower than that at 1-month timescale, further supporting the aforementioned theory that the drought indices at small timescale have the highest sensitivity in detecting variation of rainfall, temperature and streamflow data, as 3-month timescale was also considered as small timescale.

On the other hand, SDI-3 was observed to be having worse performance as compared to SPI and SPEI in detecting drought occurrence at similar timescale. The reason is none other than the difference input in consideration for computation of the index in which SDI considered streamflow data in consideration whereas computation of both SPI and SPEI included precipitation data. As the recorded droughts showed that drought events occurred in the study area were induced by persistent continuous absence of rainfall, both SPI and SPEI that relied on precipitation are more suitable in detecting drought occurrence. Another reason is delayed detection of drought by SDI which leads to failure in detecting short term droughts. This scenario is related to computation of SDI that based on streamflow data as certain duration of time required for the effect of persistent deficiency of rainfall to be taken by streamflow. Therefore, SDI is expected to have delay in drought detection and this condition leads to misunderstanding of incapability of SDI-3 in detecting short-term droughts. In brief, SDI is not suitable to be applied for drought detection and this makes SPI-1 and SPEI-1 the best in describing drought occurrence with the POD of 1.

4.4.2 Mean Absolute Error (MAE) in Detecting Drought Duration

Table 4.22: Absolute Errors in Detecting Drought Duration for Different Drought Indices at Various Timescales

Case	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
1	7	0	10	6	7	1	0	9	2	4	6
2	2	2	-	4	2	3	-	6	6	-	45
3	1	2	-	7	1	4	-	7	5	-	50
4	2	2	-	4	2	3	-	6	6	-	45
5	0	-	-	-	0	-	-	-	5	-	50
6	1	2	-	7	1	4	-	7	5	-	50
7	1	1	0	1	0	1	5	1	92	92	91
8	0	1	-	-	0	3	-	-	6	-	-
9	1	1	1	1	1	1	1	18	-	-	-
10	1	0	-	-	1	5	-	-	-	-	-
11	1	1	-	-	1	1	-	-	6	-	-
12	0	4	-	-	0	4	-	-	-	4	66
13	1	6	-	35	4	6	-	36	43	44	44
14	1	5	-	-	6	5	-	-	6	-	-
15	0	0	-	-	0	0	-	-	5	6	49
16	1	6	15	15	1	6	15	17	17	16	14
17	0	3	2	9	2	3	4	11	19	28	65
18	0	6	6	29	0	6	6	29	3	-	-
19	5	5	6	11	5	5	6	26	5	-	-
MAE	1.32	2.61	5.71	10.75	1.79	3.39	5.29	14.42	14.44	27.71	47.92

The MAE in detecting drought duration were calculated to determine the accuracy of SPI, SPEI and SDI at various timescales in monitoring drought duration by comparing the recorded duration with the detected duration of droughts. From Table 4.22, it is remarkable that SPI, SPEI and SDI recorded the smallest MAE at the smallest timescale due to the high fluctuation in the drought index values. On the other hand, drought indices were less sensitive in responding to variation in rainfall, streamflow and temperature data when the time period of input data for computation increased, causing the detected drought duration becomes longer with increasing timescale. This concept can be proved by drought indices that always detected the longest drought duration at 12-month timescale for most of the historical droughts, leading to the greatest error in detecting the duration of drought.

Furthermore, SDI was observed to be recording the greatest MAE as compared to other drought indices at every timescale. This observation was due to streamflow required certain period of time to rise from low to normal water level when dry and hot condition during drought ended as compared to precipitation amount that back to normal immediately after the drought phenomenon. Therefore, SDI tends to detect longer duration of drought, indicating lower accuracy in recognizing drought duration as compared to other drought indices. Overall, both SPI-1 and SPEI-1 showed high accuracy in monitoring duration of drought with MAE of less than two months. In specific, SPI-1 recorded the smallest MAE of 1.32, while SPEI showed relatively low MAE of 1.79 months. However, the smallest MAE did not suggest that SPI is more capable in monitoring drought duration than SPEI at 1-month timescale since the difference between SPI-1 and SPEI-1 was not significant.

4.4.3 Mean Bias Error (MBE) in Detecting Drought Duration

Table 4.23: Bias Errors in Detecting Drought Duration for Different Drought Indices at Various Timescales

Case	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
1	-7	0	10	6	-7	-1	0	9	-2	-4	-6
2	2	2	-	4	2	3	-	6	6	-	45
3	1	2	-	7	1	4	-	7	5	-	50
4	2	2	-	4	2	3	-	6	6	-	45
5	0	-	-	-	0	-	-	-	5	-	50
6	1	2	-	7	1	4	-	7	5	-	50
7	-1	-1	0	-1	0	-1	5	-1	92	92	91
8	0	-1	-	-	0	3	-	-	6	-	-
9	-1	-1	-1	-1	-1	-1	-1	18	-	-	-
10	-1	0	-	-	-1	5	-	-	-	-	-
11	-1	-1	-	-	-1	-1	-	-	6	-	-
12	0	4	-	-	0	4	-	-	-	4	66
13	1	6	-	35	4	6	-	36	43	44	44
14	-1	5	-	-	6	5	-	-	6	-	-
15	0	0	-	-	0	0	-	-	5	6	49
16	-1	6	15	15	-1	6	15	17	17	16	14
17	0	3	2	9	-2	3	4	11	19	28	65
18	0	6	6	29	0	6	6	29	3	-	-
19	5	5	6	11	5	5	6	26	5	-	-
MBE	-0.05	2.17	5.43	10.42	0.42	2.94	5.00	14.25	14.19	26.57	46.92

The bias error check aimed to examine under-detection or over-detection of drought duration in which under-detection represented by negative values whereas over-detection indicated by positive values. Table 4.23 shows that MBE increased with the increasing timescale for every drought index, proving that the duration of detection became longer and getting much more longer than the actual duration as the fluctuation of drought indices decreased. Nonetheless, SDI was observed to be recording the greatest MBE as compared to SPI and SPEI at every timescale. This observation tallied with the concept as mentioned in previous section in which SDI detected longer duration than the actual due to its computation method. In this case, SDI recorded very bad performance in describing drought occurrence in the study area in accordance with the high MAE and MBE.

In overall, all drought indices at various timescales recorded positive value of MBE, which signified over-detection of drought duration expect SPI-1. From the aspect of weather forecasting, the over-detection of drought duration brings more benefits than harm although the period of dry spell is over-estimated. As the accuracy of drought indices in drought duration prediction is not always 100% for any drought event, it is better to coordinate preventive measures and critical responses for longer period of time than the predicted drought duration. This method is effective in reducing or preventing losses in case that the duration of drought is longer than the expected. Thus, SPEI-1 with the lowest MBE could be good in monitoring drought duration although over-detection may indirectly increase the cost spent in battling the drought problems. On the other hand, negative MBE value for SPI-1 indicated the under-detection of drought duration, however, the value of -0.05 month could be negligible. In brief, it was still debatable that either SPI-1 or SPEI-1 had the best performance in describing drought occurrence.

4.4.4 Mean Early or Delayed Prediction (MEDP) of Drought

Table 4.24: Early or Delayed Drought Prediction for Different Drought Indices at Various Timescales

Case	SPI-1	SPI-3	SPI-6	SPI-12	SPEI-1	SPEI-3	SPEI-6	SPEI-12	SDI-3	SDI-6	SDI-12
1	9	-6	-15	-12	8	-5	-5	-11	-3	-1	2
2	1	2	-	1	1	2	-	1	2	-	0
3	1	2	-	1	1	2	-	1	2	-	-14
4	1	2	-	1	1	2	-	1	2	-	0
5	1	-	-	-	1	-	-	-	2	-	-14
6	1	2	-	1	1	2	-	1	2	-	-14
7	0	1	0	1	0	1	-5	1	-49	-49	-48
8	0	2	-	-	0	2	-	-	2	-	-
9	1	2	1	1	1	2	1	-10	-	-	-
10	1	1	-	-	1	1	-	-	-	-	-
11	1	2	-	-	1	2	-	-	2	-	-
12	1	2	-	-	1	2	-	-	-	-6	-22
13	0	2	-	1	0	2	-	1	2	1	1
14	0	2	-	-	0	2	-	-	2	-	-
15	1	2	-	-	1	2	-	-	2	2	-38
16	2	2	-7	-4	2	2	-7	-6	-9	-7	-2
17	0	2	3	-1	2	2	3	-1	-10	-18	-46
18	0	1	2	-18	0	1	2	-18	3	-	-
19	-1	1	2	-1	-1	1	2	-14	3	-	-
MEDP	1.05	1.33	-2.00	-2.42	1.11	1.39	-1.29	-4.50	-2.81	-11.14	-16.25

The checking of early or delayed drought prediction is to examine the ability of SPI, SPEI and SDI at different timescales in detecting drought occurrence. Table 4.24 shows that all drought indices at different timescales were early in prediction of onset of drought, excluding SPI and SPEI at 1- and 3-month timescale. Early drought prediction is beneficial for water engineers in water resource management as water supply restriction policy can be applied earlier to ensure sufficient water supply before the drought phenomenon begins. However, these drought indices that recorded early drought prediction could be applied to describe drought occurrence in the study area due to bad performance from the aspects of POD, MAE and MBE. In this case, the focus in terms of early or delayed prediction is switched to SPI-1 and SPEI-1 that recorded good performance as mentioned in the previous sections in spite of around one-month delay in detecting onset of drought.

4.4.5 Capability in Measuring Drought Severity

The assessment of POD of drought occurrence for all drought indices shows that SPI-1 and SPEI-1 had the best performance in identifying occurrence of drought, due to the highest sensitivity in responding to fluctuation of rainfall and temperature data. Meanwhile, SPI and SPEI at 1-month timescale recorded the smallest MAE in detecting drought duration as compared to other timescale. In specific, SPI-1 recorded smaller MAE than SPEI, but this condition did not suggest that SPI is better in monitoring drought duration as the difference between SPI-1 and SPEI-1 was not significant. From the aspect of MBE in detecting duration of drought, SPEI-1 recorded the lowest positive MBE, which was good in monitoring drought duration although over-detection could increase the cost spent in battling the disaster. In contrast, negative MBE for SPI-1 meant under-detection of drought duration, but this small error could be negligible. Besides that, SPI-1 and SPEI-1 were considered having good performance in detecting drought duration in spite of around one-month delay in recognizing starting of drought. Hence, it was still questionable that either SPI-1 or SPEI-1 had the best performance in describing drought occurrence.

The severity of drought is an important drought characteristic that must not be ignored when developing an efficient drought monitoring system. In this case, the drought index value itself is a measure of drought severity hence the mean severity based on SPI, SPEI and SDI at various timescales were determined to compare with the severity of recorded droughts. For drought case 1, severe 1997-1998 El Nino related drought occurred from the middle of 1997 to April 1998 due to precipitation deficit over an extended duration and this condition resulted in minimum flow for Kelantan River at Guillemard Bridge. In this case, high mean severity was detected at both SPI-1 and SPEI-1 that rely on precipitation as input, showing that the performance of SPI and SPEI at 1-month timescale were the best in detecting severe drought as SDI or SPI as well as SPEI at other timescales were only able to detect mild drought. Moreover, the performance of SPI and SPEI at 1-month timescale in detecting high severity drought had proved the high sensitivity of SP1-1 and SPEI-1 in discovering fluctuation of rainfall data based on the AMR values at 1-month timescale.

According to the reports on drought events grouped under G3, the drought events occurred between January and April 2016 were induced by the strongest 2015-2016 El Nino phenomenon after the 1997-1998 El Nino throughout the history. This 2015-2016 El Nino related drought was more severe than that occurred from 1997 to 1998, causing serious water depletion problems in Kelantan and Pahang. At this point, SPEI-1 is better than SPI-1in recognizing high severity drought as SPEI-1 recorded higher mean severity than SPI-1 for case 15, 16, 17 and 19. In specific, SPEI at 1-month timescale recorded extreme droughts for case 16 and 17 as compared to SPI-1 that was only capable to detect mild and moderate droughts. The main reason was the difference between the input data for computation in which SPEI also considered temperature data other than rainfall data. Hence, SPEI was better than SPI in identifying extreme El Nino related drought in the study area due to its ability to detect high temperature condition brought by the El Nino phenomenon.

4.5 Relationship between Drought Indices and Oceanic Indices

The effects of the Indian Ocean to the west of Peninsular Malaysia and the South China Sea to the east, on amount of precipitation in the study area were studied by comparing 35-year monthly trend of SPEI to that of DMI and ONI. A positive value of ONI indicates the presence of El Nino phenomenon (warmer condition), whereas negative value of DMI represents negative phase of IOD, which caused warmer than normal condition in the study area. Since the negative values of SPI-1 and SPEI-1 indicate the occurrence of drought, the sign of ONI was reversed so that all negative values of SPI-1, SPEI-1, ONI and DMI represented warmer condition. Table 4.25 shows the 35-year monthly trend of DMI and ONI in which a positive sign in red indicated increasing trend (warmer condition), whereas a negative sign in green indicated a decreasing trend (cooler condition). In similar, the 35-year monthly trend of SPI-1 and SPEI-1 recorded by a total of 62 rainfall stations are shown in Table 4.26. The matching percentage of 35-year monthly trend of SPI-1 and SPEI-1 to that of DMI and ONI for 62 rainfall stations were determined and shown in Figure 4.25 and Figure 4.26.

Table 4.25: 35-year Monthly Trend of DMI and ONI

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
35-year monthly trend of DMI	+	+	+	+	-	+	-	-	-	-	-	-
35-year monthly trend of ONI	+	+	+	+	+	+	+	+	+	-	-	-

Table 4.26: 35-year Monthly Trend of SPI-1

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2630001	-	+	-	+	-	+	+	+	+	+	-	-
2634193	-	+	-	+	+	+	+	+	+	-	-	-
2828173	-	+	+	+	-	+	+	+	-	-	-	-
2829001	-	+	-	+	+	+	+	+	+	-	-	-
2831179	-	+	-	+	+	+	+	+	+	-	-	-
2924096	+	+	-	-	-	+	+	+	-	-	-	-
3026156	+	+	-	-	+	+	-	+	-	-	-	-
3028001	+	+	-	-	+	+	+	+	-	-	-	-
3030178	-	+	-	+	+	+	+	+	-	-	-	-
3032167	-	+	+	+	+	+	+	+	+	-	-	-
3121143	+	+	+	+	+	+	+	-	-	-	-	-
3129177	-	+	+	+	-	+	+	+	-	-	-	-
3134165	-	+	+	+	+	+	+	+	+	-	-	-
3228174	+	+	+	+	-	+	+	+	-	-	-	-
3231163	-	+	-	+	+	+	+	+	-	-	-	-
3330109	-	+	+	+	+	+	+	+	-	-	-	-
3424081	+	+	-	-	-	+	+	+	-	-	-	-
3519125	+	+	-	+	+	+	+	+	-	-	-	-
3533102	+	+	+	+	+	+	+	+	-	+	-	-
3628001	-	+	+	+	-	+	+	-	-	-	-	-
3818054	+	+	-	-	-	+	+	+	-	-	-	-
3924072	+	+	+	+	-	+	+	-	+	-	-	-
3930012	-	+	+	+	+	+	+	+	-	-	-	-
4019001	+	+	-	-	-	+	-	+	-	-	-	-
4023001	+	+	+	-	+	+	+	+	-	-	-	-
4127001	+	+	-	-	-	+	+	+	-	-	-	-
4219001	+	+	+	+	-	+	+	+	-	+	-	+
4223115	+	+	+	-	-	-	-	-	-	-	-	-
4227001	+	+	-	-	-	-	+	+	-	-	-	-
4234109	+	+	+	+	+	+	+	+	-	+	-	-
4324001	+	+	+	-	-	-	-	+	-	-	-	-
4513033	+	+	+	-	-	+	+	+	-	-	-	-
4614001	+	+	+	-	-	-	+	-	-	+	-	-

Table 4.26 (Continued)

4717001	+	+	+	-	-	+	-	-	-	-	-	-
4721001	+	+	+	+	+	-	-	+	-	-	-	-
4726001	+	+	-	+	+	+	+	+	-	-	-	-
4734079	+	+	+	+	+	+	+	+	-	-	-	-
4819027	+	+	+	+	-	-	-	-	-	-	-	-
4923001	+	+	+	+	+	+	-	-	-	-	-	-
4929001	-	+	+	+	+	+	+	+	+	+	-	-
4930038	+	+	+	+	+	+	+	+	-	-	-	-
5029034	+	+	+	+	+	+	+	+	+	-	-	-
5120025	+	+	+	+	-	+	-	-	-	-	-	-
5128001	+	+	+	+	+	+	+	+	+	-	-	-
5216001	+	+	+	+	-	+	-	+	-	-	-	-
5320038	+	+	+	+	-	+	-	-	-	-	-	-
5322044	+	+	+	+	-	+	-	+	-	-	-	-
5328044	+	+	+	+	+	+	+	-	-	-	-	-
5331048	+	+	+	+	+	+	+	+	-	+	-	-
5426001	+	+	+	+	+	+	+	+	-	-	-	-
5428001	+	+	+	+	+	+	+	-	-	-	-	-
5428002	+	+	+	+	+	+	+	-	-	-	-	-
5520001	+	+	+	+	+	+	-	+	-	-	-	-
5522047	+	+	+	+	+	+	+	+	-	-	-	-
5718002	+	+	+	+	-	-	-	+	-	-	-	-
5718033	+	+	+	+	-	+	+	+	-	-	-	-
5719001	+	+	+	+	+	+	-	+	-	-	-	-
5722057	+	+	+	+	+	+	+	+	-	-	-	-
5725006	+	+	+	+	+	+	+	+	-	-	-	-
5820006	+	+	+	+	+	+	+	-	-	-	-	-
5920012	+	+	+	+	+	+	+	+	+	-	-	-
6019004	+	+	+	+	+	+	+	-	-	-	-	-

Table 4.27: 35-year Monthly Trend of SPEI-1

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2630001	-	+	-	+	-	+	+	+	-	-	-	-
2634193	-	+	-	+	+	+	+	-	+	-	-	-
2828173	-	+	+	+	+	+	+	+	-	-	-	-
2829001	-	+	-	+	+	+	+	+	+	-	-	-
2831179	-	+	-	+	+	+	+	+	+	-	-	-
2924096	+	+	-	+	+	+	+	+	-	-	-	-
3026156	-	+	-	+	+	+	+	+	-	-	-	-
3028001	-	+	-	+	+	+	+	+	-	-	-	-
3030178	-	+	-	+	+	+	+	+	-	-	-	-
3032167	-	+	-	+	+	+	+	-	+	-	-	-
3121143	-	+	+	+	+	+	+	-	-	-	-	-
3129177	-	+	-	+	+	+	+	+	-	-	-	-
3134165	-	+	+	+	+	+	+	+	-	-	-	-
3228174	-	+	+	+	-	+	+	+	-	-	-	-
3231163	-	+	-	+	+	+	+	+	-	-	-	-
3330109	-	+	+	+	+	+	+	+	-	-	-	-
3424081	-	+	-	-	+	+	+	+	-	-	-	-
3519125	+	+	-	+	+	+	+	+	-	-	-	-
3533102	-	+	-	+	+	+	+	+	-	-	-	-
3628001	-	+	+	+	-	+	+	-	-	-	-	-
3818054	+	+	-	-	+	+	+	+	-	-	-	-
3924072	+	+	+	+	+	+	+	+	-	-	-	-
3930012	-	+	+	+	+	+	+	+	-	-	-	-
4019001	+	+	+	+	-	+	-	+	-	-	-	-
4023001	+	+	+	+	+	+	+	+	-	-	-	-
4127001	+	+	-	-	+	+	+	+	-	-	-	-
4219001	+	+	+	+	-	+	+	+	-	+	-	-
4223115	+	+	+	+	+	-	-	-	-	-	-	-
4227001	-	+	-	+	-	-	+	+	-	-	-	-
4234109	-	+	+	+	+	+	+	+	-	-	-	-
4324001	+	+	+	-	+	-	-	+	-	-	-	-
4513033	+	+	+	+	-	+	+	+	-	-	-	-
4614001	+	+	+	+	+	+	+	-	+	-	-	-

Table 4.27 (Continued)

4717001	+	+	+	+	-	+	-	-	-	-	-	-
4721001	+	+	+	+	+	-	-	+	-	-	-	-
4726001	-	+	-	+	+	+	+	+	-	-	-	-
4734079	+	+	+	+	+	+	+	+	-	-	-	-
4819027	+	+	+	+	-	-	-	+	-	-	-	-
4923001	+	+	+	+	+	+	+	-	-	-	-	-
4929001	-	+	+	+	+	+	+	+	-	+	-	-
4930038	-	+	+	+	+	+	+	+	-	-	-	-
5029034	-	+	+	+	+	+	+	+	+	-	-	-
5120025	+	+	+	+	-	+	-	-	-	-	-	-
5128001	+	+	+	+	+	+	+	+	-	-	-	-
5216001	+	+	+	+	-	+	-	+	-	-	-	-
5320038	+	+	+	+	-	+	-	-	-	-	-	-
5322044	+	+	+	+	-	+	-	+	-	-	-	-
5328044	+	+	+	+	+	+	+	-	-	-	-	-
5331048	+	+	+	+	+	+	+	+	-	+	-	-
5426001	+	+	+	+	+	+	+	+	-	-	-	-
5428001	+	+	+	+	+	+	+	-	-	-	-	-
5428002	+	+	+	+	+	+	+	-	-	-	-	-
5520001	+	+	+	+	+	+	-	+	-	-	-	-
5522047	+	+	+	+	+	+	+	-	-	-	-	-
5718002	+	+	+	+	+	+	+	+	-	-	-	-
5718033	+	+	+	+	-	+	+	+	-	-	-	-
5719001	+	+	+	+	+	+	+	+	-	-	-	-
5722057	+	+	+	+	+	+	+	+	-	-	-	-
5725006	+	+	+	+	+	+	-	-	-	-	-	-
5820006	+	+	+	+	+	+	+	-	-	-	-	-
5920012	+	+	+	+	+	+	+	+	-	-	-	-
6019004	+	+	+	+	+	+	+	-	-	-	-	-

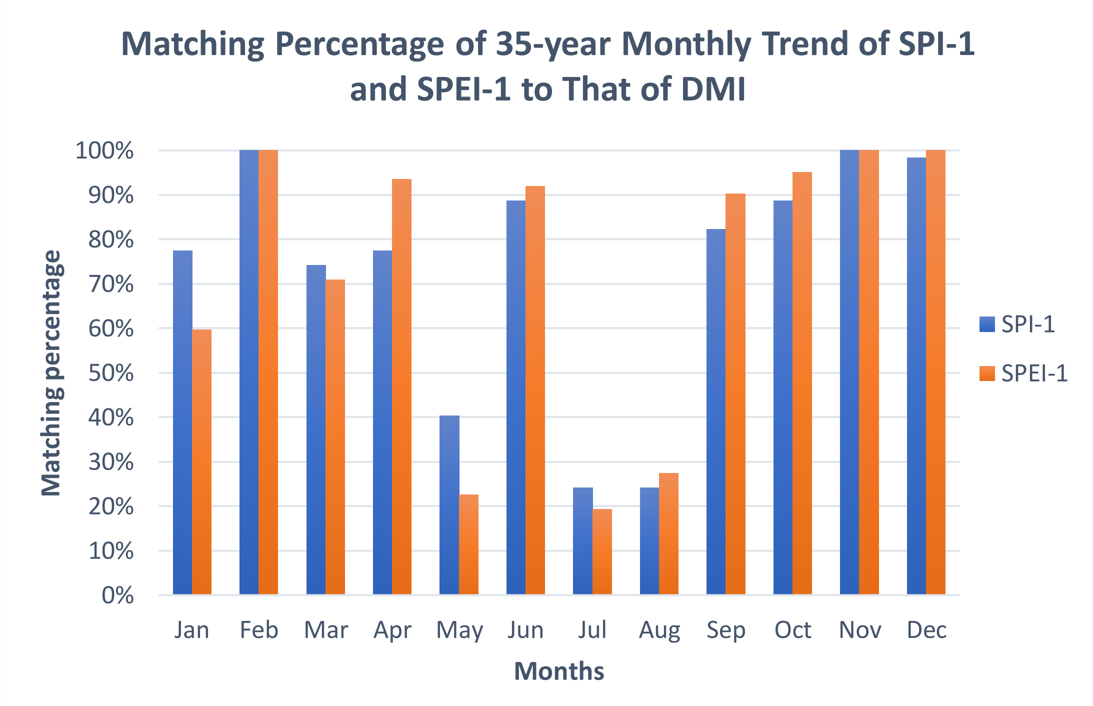

Figure 4.25: Matching Percentage of 35-year Monthly Trend of SPI-1 and SPEI-1 to That of DMI for 62 Rainfall Stations

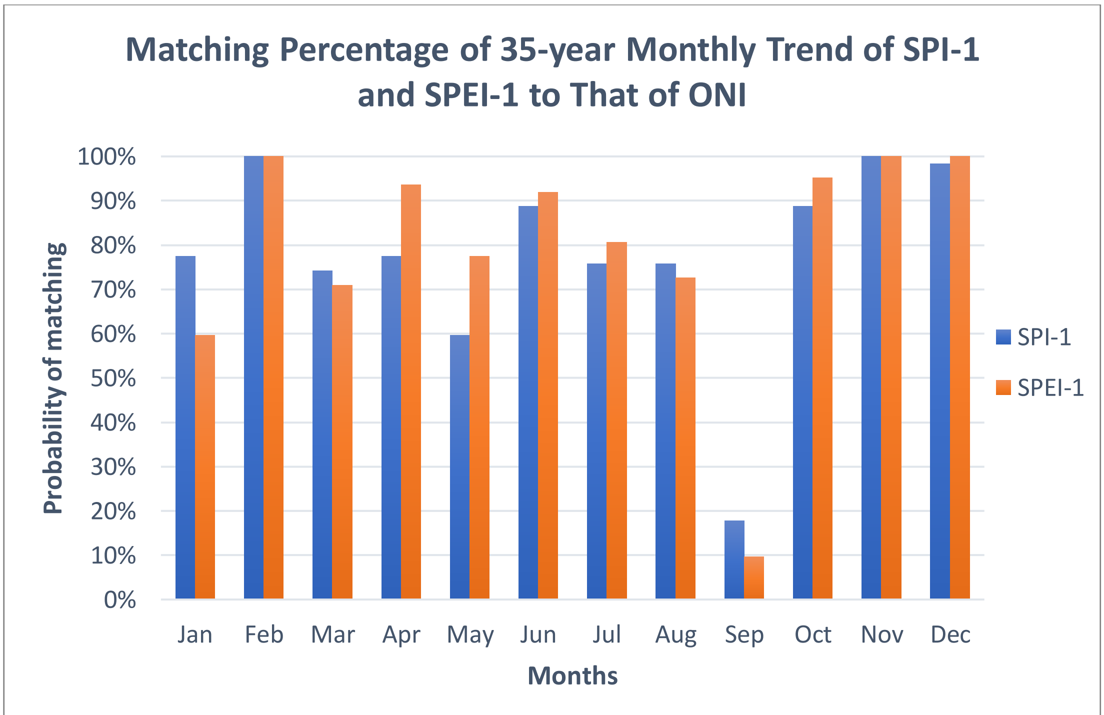

Figure 4.26: Matching Percentage of 35-year Monthly Trend of SPI-1 and SPEI-1 to That of ONI for 62 Rainfall Stations

In general, it was noticeable that there were certain levels of effects of IOD and ONI on precipitation amount in the study area, as shown by the monthly matching percentage of 35-year monthly trend between SPI-1, SPEI-1, DMI and ONI. Besides that, higher matching percentage of SPI and SPEI at 1-month timescale to ONI than that to DMI suggested that ONI might have greater effect as compared to IOD on El Nino disaster in the East Coast of Peninsular Malaysia. In specific, Figure 4.26 shows that SPEI-1 recorded higher matching percentage of 35-year monthly trend to ONI than SPI-1 for six months, indicating that SPEI-1 responded better to abnormal dry and hot weather caused by El Nino events. However, there is still no full understanding about the extent to which the precipitation pattern of the study area is affected by the IOD and ONI. Further research is required to study the linkage among IOD, ONI, precipitation and temperature anomalies.

4.6 Summary

In essence, the spatial distribution patterns of drought characteristics based on SPI, SPEI and SDI at different timescales were shown on the spatial maps. Assessment was conducted on AMR of drought indices at various timescales to study the fluctuation of data over time. The beginning of droughts was indicated by negative drought index values, whereas the drought phenomenon is considered ended when the drought index value changes to positive. Research had been done on nineteen historical droughts recorded in the East Coast of Peninsular Malaysia from 1983 to 2017, drought characteristics based on drought indices were compared to that of recorded droughts. The reports on historical droughts showed that the severe to extreme droughts occurred in the study area were induced by hot and dry weather brought by El Nino phenomenon. Further assessments were carried out on the recorded drought events by comparing the drought characteristics of detected droughts to that of recorded droughts. The performance of SPI, SPEI and SDI at various timescales in describing drought disaster were evaluated through the assessments of POD, MAE, MBE, MEDP, as well as the ability in measuring drought severity. The relationship between drought indices and oceanic indices was studied by comparing 35-year monthly trend of SPI-1 and SPEI-1 to that of DMI as well as ONI.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

An assessment was conducted on the historical moisture conditions of the East Coast of Peninsular Malaysia using several drought indices, which are the SPI, SPEI and SDI that were computed based on different inputs and timescales. The AMR of drought indices at various timescales were also determined to measure temporal fluctuation of rainfall, temperature and streamflow data. The findings show that the AMR values of the SPI, SPEI and SDI at 1-month timescale are the greatest among other timescales, indicating that the drought indices at the shortest timescale are the most sensitive to fluctuation of data time. Furthermore, the sensitivity of the SPI, SPEI and SDI in detecting variation of data on a time basis decreases with increasing timescale. The drought indices at different timescales were applied to detect drought occurrence and to define drought characteristics, in which the drought events are those represented with drought index reading of less than zero. The onset and offset of a drought event are indicated by the starting and ending of continuous drought indices.

From the study on recorded droughts from 1983 to 2017, droughts that occurred in the East Coast of Peninsular Malaysia were induced by abnormal precipitation deficit over an extended period. Severe to extreme droughts are reportedly caused by the strong El Nino phenomenon in 1997-1998 and 2015-2016, showing that the consideration of temperature in developing drought index is important. The duration, severity as well as onset and end of actual droughts were compared to that of detected droughts. The computation of POD of drought occurrence, MAE and MBE in detecting duration of droughts, as well as early or delay prediction of onset of droughts aimed to evaluate performance of SPI, SPEI and SDI at various timescales in describing drought occurrence. The results show that both the SPI and the SPEI at 1-month timescale are excellent from the aspects of POD, MAE, MBE and MEDP. However, the SPEI-1 is better than SPI-1 in recognizing high severity droughts due to its computation that included temperature data as input. The consideration of temperature for computation makes the SPEI-1 the most suitable drought index to be applied in drought monitoring system at the East Coast of Peninsular Malaysia, as it is able to detect rainfall deficiency as well as high temperature condition brought by El-Nino phenomenon.

Spatial analysis was carried out on five drought characteristics: drought frequency, mean drought duration, mean drought severity, mean drought intensity and mean drought peak, using QGIS software. Spatial maps were generated to display the spatial distribution of each drought characteristic over the East Coast of Peninsular Malaysia. There are similarities in spatial distribution pattern between drought indices at certain timescale. In addition, temporal analysis of drought index was conducted on monthly basis and the 35-year monthly trend of SPEI-1 was computed to compare with that of DMI and ONI, since the SPEI-1 is the best drought index for drought monitoring. DMI is abnormal SST gradient that represents IOD, in which negative value of DMI indicates negative phase of IOD, causing exceptionally warmer weather at the East Coast region. On the other hand, a positive value of ONI shows the warmer condition brought by El Nino phenomenon. The comparison of the 35-year monthly trend of the SPEI-1 with that of DMI and ONI showed that there are effects of IOD and ONI on precipitation amount of the study area to certain extent. The SPEI recorded higher matching percentage to ONI as compared to DMI, proving that it had better response to abnormal hot weather brought by El Nino disaster. Finally, it remains that the gap in the science of climate change in the East Coast of Peninsular Malaysia remains open ended.

5.2 Recommendations for Further Studies

The following are some of the recommendations for future studies:

(i) It is recommended to examine a composite index that considers precipitation, streamflow, reservoir level and groundwater data for computation, such as SWSI.

(ii) The SPI, SPEI and SDI can be computed based including other timescales such as 2-, 4- and 5-month timescale for better understanding of drought conditions.

(iii) A study of relationship between oceanic indices and drought indices may turn out more information about droughts. It is also recommended to evaluate correlation between atmospheric circulation indices such as

Multivariate ENSO Index (MEI), Madden/Julian Oscillation (MJO) Index and drought indices.

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APPENDICES

APPENDIX A: Tables

Table A-1: Rainfall Stations in the Study Area

Station No	State	Latitude (°S)	Longitude (°E)
4614001	Kelantan	4.68	101.48
4717001	Kelantan	4.77	101.76
4721001	Kelantan	4.77	102.17
4726001	Kelantan	4.76	102.66
4819027	Kelantan	4.88	101.97
4923001	Kelantan	4.94	102.35
5120025	Kelantan	5.15	102.05
5216001	Kelantan	5.25	101.66
5320038	Kelantan	5.38	102.02
5322044	Kelantan	5.31	102.28
5520001	Kelantan	5.56	102.01
5522047	Kelantan	5.53	102.20
5718002	Kelantan	5.78	101.89
5718033	Kelantan	5.70	101.84
5719001	Kelantan	5.78	101.97
5722057	Kelantan	5.79	102.22
5820006	Kelantan	5.84	102.07
5920012	Kelantan	5.92	102.04
6019004	Kelantan	6.02	101.98
4234109	Terengganu	4.23	103.42
4734079	Terengganu	4.76	103.42
4929001	Terengganu	4.95	102.97
4930038	Terengganu	4.94	103.06
5029034	Terengganu	5.07	102.94
5128001	Terengganu	5.14	102.84
5328044	Terengganu	5.36	102.89
5331048	Terengganu	5.32	103.13
5426001	Terengganu	5.48	102.68
5428001	Terengganu	5.45	102.82
5428002	Terengganu	5.41	102.82

Table A-1 (Continued)

5725006	Terengganu	5.80	102.57
6019004	Kelantan	6.02	101.98
2630001	Pahang	2.60	103.06
2634193	Pahang	2.62	103.46
2828173	Pahang	2.85	102.86
2829001	Pahang	2.81	102.94
2831179	Pahang	2.89	103.19
2924096	Pahang	2.94	102.42
3026156	Pahang	3.03	102.66
3028001	Pahang	3.02	102.83
3030178	Pahang	3.07	103.08
3032167	Pahang	3.02	103.20
3121143	Pahang	3.18	102.20
3129177	Pahang	3.17	102.98
3134165	Pahang	3.14	103.44
3228174	Pahang	3.30	102.82
3231163	Pahang	3.29	103.19
3330109	Pahang	3.39	103.03
3424081	Pahang	3.44	102.43
3519125	Pahang	3.51	101.92
3533102	Pahang	3.56	103.36
3628001	Pahang	3.63	102.86
3818054	Pahang	3.81	101.85
3924072	Pahang	3.90	102.43
3930012	Pahang	3.92	103.04
4019001	Pahang	4.03	101.97
4023001	Pahang	4.03	102.33
4127001	Pahang	4.11	102.75
4219001	Pahang	4.23	101.94
4223115	Pahang	4.24	102.38
4227001	Pahang	4.23	102.73
4324001	Pahang	4.39	102.40
4513033	Pahang	4.52	101.38

Table A-2: Streamflow Stations in the Study Area

Station No	State	Latitude (°S)	Longitude (°E)
5721442	Kelantan	5.76	102.15
6019411	Kelantan	6.03	101.98
4131453	Terengganu	4.13	103.18
4232452	Terengganu	4.28	103.26
4832441	Terengganu	4.84	103.20
5130432	Terengganu	5.14	103.05
5229436	Terengganu	5.29	102.92
5428401	Terengganu	5.44	102.83
5724411	Terengganu	5.74	102.49
3030401	Pahang	3.06	103.02
3424411	Pahang	3.44	102.43
3527410	Pahang	3.51	102.76
4023412	Pahang	4.03	102.33

Table A-3: Temperature Stations in the Study Area

Station No	State	Latitude (°S)	Longitude (°E)
48615	Kelantan	6.16	102.30
48616	Kelantan	5.57	102.03
48617	Kelantan	5.80	102.49
48618	Terengganu	5.38	103.10
49431	Terengganu	4.54	103.43
48632	Pahang	4.48	101.37
48642	Pahang	3.97	102.35
48649	Pahang	3.05	103.08
48653	Pahang	3.47	102.38
48657	Pahang	3.77	103.21