



Spatiotemporal analysis of hydro-meteorological drought in the Johor River Basin, Malaysia

Mou Leong Tan^{1,2} · Vivien P. Chua² · Cheng Li³ · K. Brindha⁴

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Abstract

Assessment of historical hydro-meteorological drought is important to develop a robust drought monitoring and prediction system. This study aims to assess the historical hydro-meteorological drought of the Johor River Basin (JRB) from 1975 to 2010, an important basin for the population of southern Peninsular Malaysia and Singapore. The Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) were selected to represent the meteorological and hydrological droughts, respectively. Four absolute homogeneity tests were used to assess the rainfall data from 20 stations, and two stations were flagged by these tests. Results indicate the SPI duration to be comparatively low (3 months), and drier conditions occur over the upper JRB. The annual SSI had a strong decreasing trend at 95% significance level, showing that human activities such as reservoir construction and agriculture (oil palm) have a major influence on streamflow in the middle and lower basin. In addition, moderate response rate of SSI to SPI was found, indicating that hydrological drought could also have occurred in normal climate condition. Generally, the El Niño-Southern Oscillation and Madden Julian Oscillation have greater impacts on drought events in the basin. Findings of this study could be beneficial for future drought projection and water resources management.

1 Introduction

Drought is a protracted period of deficit precipitation relative to the local normal condition over land (Dai 2011). Wilhite and Glantz (1985) categorized drought into four main groups: (1) meteorological drought—rainfall shortage; (2) hydrological drought—inadequate streamflow, low water supply; (3) agriculture drought—crops affected due to abnormal dry conditions; and (4) socioeconomic drought—impact of meteorological, hydrological, and agricultural droughts on social and economic conditions. Drought is one of the most destructive

natural disasters, resulting in loss of lives and affecting the economy. Globally, drought events from 1900 to 2015 have caused about 131 billion USD in damages and deaths of more than 11 million people (<http://www.emdat.be/>, accessed on 4 March 2017). Drought happens almost in all parts of the world, but its impacts are site-specific (Tan et al. 2017b). Therefore, assessment of drought impacts for a specific region is critical for developing drought adaptation strategies and policies.

Various drought indices such as Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) have been developed for analyzing long-term (> 30 years) meteorological and hydrological droughts. SPI is widely applied by researchers around the world (Di Lena et al. 2014; He et al. 2015; Spinoni et al. 2015; Li and Wang 2016; Wang et al. 2016) as it is recommended by the World Meteorological Organization (WMO) (Hayes et al. 2011). Likewise, SSI has widespread use as a hydrological drought index (Telesca et al. 2012; Huang et al. 2016). Both indices require monthly precipitation or streamflow data for calculation, and they can identify abnormal dryness and wetness at difference time-scales (e.g. 1, 3, 6, 12, and 24 months). However, the relationship between meteorological and hydrological droughts is still not well studied in Asia (Zhao et al. 2016), particularly in Southeast Asia.

✉ Mou Leong Tan
mouleong@gmail.com; mouleong@usm.my

¹ Geography Section, School of Humanities, Universiti Sains Malaysia, 11800 Penang, Malaysia
² Department of Civil and Environmental Engineering, National University of Singapore, No. 1 Engineering Drive 2, Singapore 117576, Singapore
³ Department of Ecology, School of Horticulture and Plant Protection, Yangzhou University, Yangzhou 225009, China
⁴ Hydrogeology Group, Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany

Good quality long-term historical ground-based observations are essential for reliable drought assessment. However, actual hydro-climatic trends and patterns could be hidden by inhomogeneous data, which may lead to false conclusions and decisions (Hosseinzadeh et al. 2014). Inhomogeneity of ground-based data is often caused by station relocations, changes in environment, measurement practices, and instruments. Therefore, reliability and homogeneity of ground-based observations should be checked prior to using them in any hydro-climatic studies. Wijngaard et al. (2003) proposed a two-step approach: (1) use of four homogeneity tests including Pettit test, standard normal homogeneity test (SNRT), Buishand range test (BRT), and von Neumann Ratio test (VNRT) to analyze the rainfall data; and (2) categorizing results into three groups namely, “useful,” “doubtful,” and “suspect.” This method has been proven useful and is widely applied to evaluate homogeneity of rainfall data in various regions (de Lima et al. 2013; Santos and Frago 2013; Che Ros et al. 2016; Ribeiro et al. 2016).

As a specific case, the sharing of water resources between Malaysia and Singapore only involves the Johor River Basin (JRB) in southern Peninsular Malaysia. The basin is a source of freshwater for about 7 million people. Even with high annual rainfall (about 2300 mm/year), Singapore is still regarded as a “water-stressed” country due to high human and industrial population density. The country is highly dependent on freshwater supply from the Johor River to meet about 40% of the total water requirement for domestic and industrial use (Kog 2015). However, water shortage in JRB during dry season is becoming progressively apparent in the recent years even though JRB experiences a typical tropical rainforest climate as Singapore, with abundant rainfall throughout the year. For example, water level at the Linggiu Reservoir located in the northern of the JRB has hit its historical low of 31% in April 2016 due to dry spell compared to the water level at 80% in the beginning of the year. Hence, more drought-related studies should be conducted in the JRB to provide valuable input for effective water resources management.

Climate of JRB is influenced by El Niño-Southern Oscillation (ENSO), Madden Julian Oscillation (MJO), and Indian Ocean Dipole (IOD) (Tangang et al. 2012; Tan et al. 2017a). Thereby, relationship among these large-scale atmospheric circulations on drought conditions in the basin poses a good research question. The aim of this study is to assess and analyze historical hydro-meteorological drought (1975–2010) of the JRB. Specific objectives are (1) to evaluate the homogeneity of annual and monthly rainfall over the JRB, (2) to assess the trend of spatio-temporal dryness/wetness conditions, (3) to analyze the response rate of hydrological drought to meteorological drought, and (4) to determine the impacts of large-scale atmospheric circulation on droughts. This study will be the first attempt to evaluate

meteorological-hydrological droughts relationship and the influence of large-scale atmospheric circulation in the JRB. The findings from comprehensive historical drought assessment of 36 years will act as a baseline for future drought assessment.

2 Material and methods

2.1 Study area

The JRB lies between the latitudes 1°30' N and 2°30' N, and the longitudes 103° E and 104° E (Fig. 1). The basin drains a total area of about 1652 km², and the elevation ranges between 3 and 977 m above mean sea level (Tan et al. 2015b). Length of the Johor River is about 122 km and flows roughly from north to south direction towards the Strait of Johor. The basin has a tropical rainforest climate, with heavy rainfall mainly brought by the northeast monsoon (NEM) from November to early March (Tan and Santo 2018). On the other hand, the basin experiences drier condition with lesser rainfall during the southwest monsoon (SWM) from June to September. There are the inter-monsoon periods with intense convective rain between the NEM and SWM.

Flooding is the main hydro-meteorological hazard in Johor, and it occurs frequently during the NEM. One of the most destructive floods occurred during the period of December 2006 to January 2007. It caused 18 deaths, around 0.5 billion USD losses and affected more than 100,000 people (Kia et al. 2012). On the other hand, JRB's drought events are generally categorized as meteorological drought, as the drought duration is between 1 and 3 months. Due to increasing population, economic growth, and climate change, the meteorological drought events have caused water shortage problem in JRB, impacting both Johor and Singapore's growth. For instance, during the 2015–2016 drought, the Johor Water regulating body requested additional water supply from the Public Utilities Board (PUB), Singapore, to address the water shortage in Johor.

Major land-uses are irrigated areas, forest, and water bodies. Oil palm and rubber are the primary crops cultivated. As one of the major oil palm producing countries, the water system of JRB is highly equipped for large-scale irrigation networks. In the 1970s, huge forest areas were cleared by the Federal Land Development Authority (FELDA) and the South East Johore Development Authority (KEJORA) for oil palm plantation, which occupies more than 60% of the total basin area (Tan et al. 2015b). Carr (2011) reported the large impact of water shortage on oil palm yield, wherein even 100 mm deficit in soil water could lead to 10% reduction in fresh fruit yield. Therefore, effective irrigation system capable of coping with drought is essential to optimize the oil palm productivity.

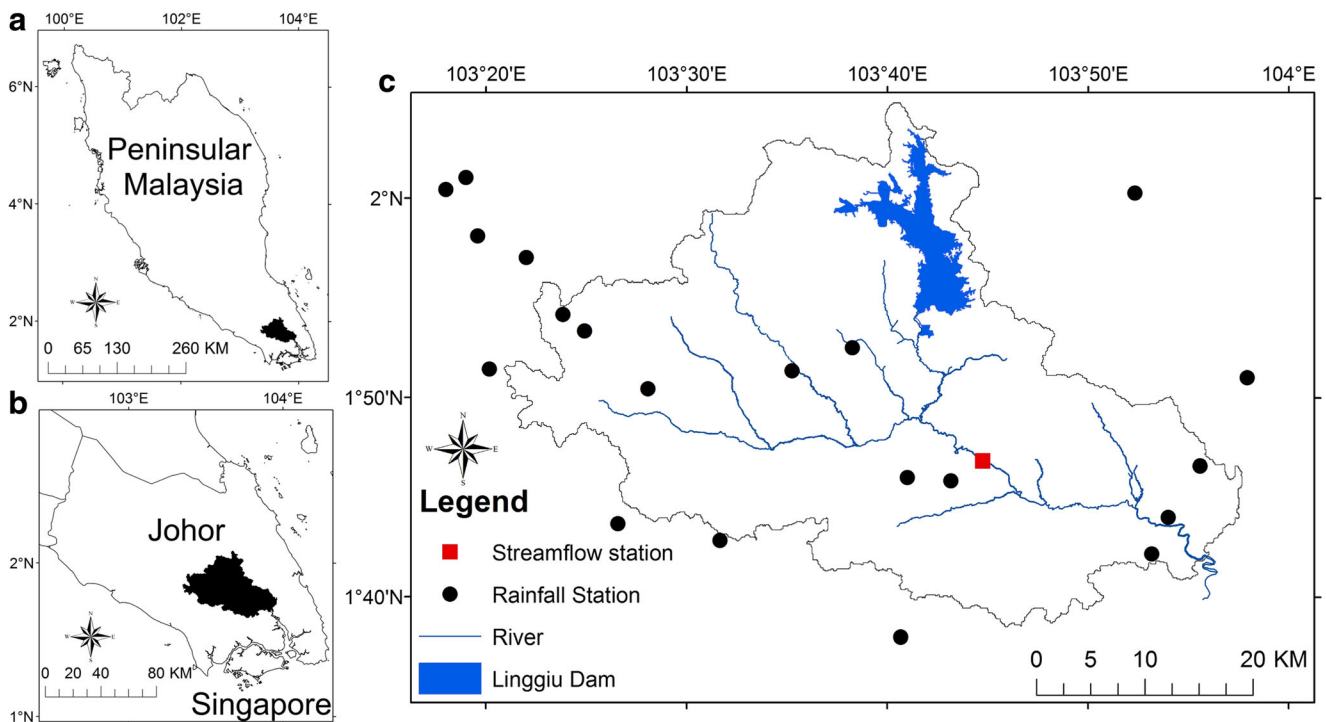


Fig. 1 a Peninsular Malaysia, b Johor state and c Johor River Basin

On 24 November 1990, a Linggiu water agreement was signed between the Johor state government, Malaysia, and the PUB, Singapore, which allowed Singapore to build and maintain a reservoir across the Linggiu River, a tributary of the Johor River for storing and facilitating freshwater until the year 2061. The Linggiu Reservoir started its operation in 1995 and allows Singapore to draw water up to 1136 million liters per day (Mld) (Ewing and Domondon 2016). It has a total storage capacity of 760 million m^3 . Raw water is purified at three water treatment plants before public supply.

2.2 Data availability

Daily rainfall data from 20 rain gauge stations within JRB and its surrounding were collected from the Malaysian Meteorological Department (MMD) and the Department of Irrigation and Drainage, Malaysia (DID) from 1975 to 2010 (Fig. 1 and Table 1). These stations were selected based on data quality, i.e., stations with < 10% missing data were selected, as missing values > 20% could seriously influence rainfall extremes and trends estimation (Zolina et al. 2005). Most rainfall data were recorded using an automatic tipping rain gauge with a sensitivity of 0.5 mm/tip (Suhaila et al. 2008). Daily rainfall was the collection of 24-h rainfall amount at 8.00 a.m. local time, which is equivalent to 00:00 UTC time.

Data quality control is important to remove erroneous in rainfall measurements. This includes two steps: (1) Unreasonable rainfall (e.g. extremely high and negative

values) was removed by comparing with nearby stations, and (2) the homogeneity of each rainfall series was performed using the two-step method suggested by Wijngaard et al. (2003). Then, the missing data of selected station was filled with rainfall from nearby station. Monthly rainfall of each station was obtained by summing the daily rainfall data, and similarly, annual rainfall data was a sum of monthly rainfall.

Daily streamflow data between 1975 and 2010 measured at the Rantau Panjang station (ID 1737451) in the middle of the JRB was used (Fig. 1). This is the only station with good quality long-term streamflow data, which is operated and maintained by the DID. Similarly, the streamflow data was accumulated into monthly and annual time series. More detailed information about streamflow measurement in Malaysia can be found in DID (1995). The year 1995 was used to separate unregulated and regulated flow regime, as the Linggiu Reservoir began its operation in early 1995. The study period thus spans into the unregulated natural flow period from 1975 to 1994 and the regulated flow regime from 1995 to 2010.

2.3 Homogeneity test

In this study, four absolute homogeneity tests, namely the Pettitt (Pettitt 1979), SNHT (Alexandersson 1986), BRT (Buishand 1982), and VNRT (von Neumann 1941), were used. Based on Wijngaard et al. (2003), the first three tests could be used to detect the break year, while the last test only evaluates whether any breaks had occurred within a time

Table 1 Rainfall stations in the Johor River Basin

| ID | Name | Latitude | Longitude |
|---------|---------------------------------------|----------|-----------|
| 47120 | Hospital Kota Tinggi | 1.73 | 103.90 |
| 47134 | GRC Layang-Layang | 1.84 | 103.47 |
| 47146 | Felda Bukit Permai | 1.77 | 103.68 |
| 47158 | Felda Mardi Kluang | 1.95 | 103.37 |
| 48672 | Kluang | 2.02 | 103.32 |
| 48679 | Senai | 1.63 | 103.68 |
| 1734001 | Loji Pembersih Bkt. Batu | 1.73 | 103.44 |
| 1735125 | Ldg. Sedenak di Sedenak | 1.71 | 103.53 |
| 1737001 | Sek. Men. Bkt. Besar di Kota Tinggi | 1.76 | 103.72 |
| 1738131 | Ldg. Getah Malaya di Kota Tinggi | 1.70 | 103.89 |
| 1739003 | Ldg. Permatang di Kota Tinggi | 1.78 | 103.93 |
| 1833092 | Ldg. Simpang Rengam di Simpang Rengam | 1.86 | 103.34 |
| 1834122 | Ldg. Rengam di Rengam | 1.89 | 103.42 |
| 1835001 | Ldg. Pekan Layang-Layang | 1.86 | 103.59 |
| 1836001 | Rancangan Ulu Sebol | 1.88 | 103.64 |
| 1839196 | Simpang Mawai-Kuala Sedili | 1.85 | 103.97 |
| 1933121 | Ldg. Getah See Sun di Rengam | 1.90 | 103.40 |
| 1933151 | Ldg. Lambak di Kluang | 1.97 | 103.33 |
| 2033152 | Ldg. Mengkibol di Kluang | 2.01 | 103.30 |
| 2038001 | Rancangan Belia Sg. Ara | 2.00 | 103.87 |

series. Both Pettitt test and BRT assess breaks in the middle of the time series, while the SNRT detects break in the beginning and end of the time series. These homogeneity tests were conducted using the XLSTAT tool, a user-friendly Microsoft Excel add-in. Homogeneity of data series was identified using 95% significance level. Final classification of the rainfall series was based on three classes: (1) useful—none or only one of the tests reject the null hypothesis at 95% significance level, indicating that the time series is homogeneous and can be used for further study; (2) doubtful—two of the tests reject the null hypothesis at 95% significance level, showing that there are indications of in-homogeneity in the time series and should be carefully considered prior application; and (3) suspect—three or all tests reject the null hypothesis at 95% significance level, where the time series is inhomogeneous and should be removed from the study. Finally, the doubtful and suspect data were compared with nearby useful data to double check the inhomogeneous trend, as some break years could be due to natural climate variability. Decision on the data for further study was also based on local knowledge on the climate system and the metadata from the stations. For instance, relocation information available from the metadata of stations was a guide to remove any inhomogeneous stations.

2.4 Drought indices

Drought indices are quantitative measures of drought level by assimilating single or multiple variables (e.g. rainfall and

temperature) into a single numerical value, which is more usable than the original variables (Zargar et al. 2011). Generally, droughts could be analyzed in terms of severity, duration, intensity, and spatial distribution components (Huang et al. 2016). In this study, the SPI and SSI were used for assessing severity, duration, and intensity of drought condition in the basin. Drought duration is defined as the number of months less than a specific threshold of SPI or SSI. This normally involves a period of more than 3 months, whereas the drought severity is the total deficits of SPI or SSI values that is continuously lower than a specific threshold. Ratio of drought severity to drought duration is considered as drought intensity. In this study, -1 is selected as the moderate drought threshold due to its frequent use in various studies (Zin et al. 2013; Zhou and Liu 2016).

SPI developed by McKee et al. (1993) has the main advantage to analyze drought at difference temporal scales for different types of drought. For regional drought assessment, regional rainfall is at first obtained by averaging the rainfall of all the stations, and then SPI is calculated from the average rainfall (Dash et al. 2012; Zhou and Liu 2016). The SSI uses the monthly streamflow series (Modarres 2007; Telesca et al. 2012). It can be applied to observed, modeled, and forecasted data for analyzing historical and future hydrological drought impacts. Based on the SPI and SSI values, the climate conditions are further divided into seven classes: (1) extremely wet (> 2), (2) very wet (1.5 to 2), (3) moderately wet (1 to 1.5), (4) near-normal (1 to -1), (5) moderately dry (-1 to

– 1.5), (6) very dry (– 1.5 to – 2), and (7) extremely dry (< – 2) conditions.

Calculation of both indices is based on various pre-defined time-scales to fit the objectives and scope of the research. According to Tangang and Juneng (2004), seasonal climatic studies in Malaysia could be divided into December to February (DJF), March to May (MAM), June to August (JJA), and September to November (SON). As drought in Johor normally begins from March, the corresponding time intervals for this study are March to May (3 months) and March to February (12 months).

The basin is further divided into the upper and lower basin, as the drought condition in the upper basin largely influences the water level of the Linggiu Reservoir. Rainfall stations categorized as the lower basin include stations 47120, 47146, 48679, 1735125, 1737001, 1839196, and 2038001 (Table 1), while the remaining stations were considered as the upper basin. In addition, the increasing or decreasing trends of drought indices were measured using the Mann-Kendall test, a non-parametric statistical method that is commonly used in hydro-meteorological time series studies (Vicente-Serrano et al. 2015; Liu et al. 2016; Huang et al. 2017a). Drought indices' trends are considered as significant at 95% significance level, if the Mann-Kendall's absolute value is > 1.96, with positive value indicating an increasing trend and negative value, a decreasing trend (Huang et al. 2017b). Spatial distribution of historical drought was produced using the ArcMap 10.2 software.

2.5 Atmospheric circulation indices

ENSO is one of the most important coupled ocean-atmosphere phenomena, affecting the climate variability of tropical and subtropical regions on an inter-annual timescale. The Multivariate ENSO Index (MEI) was developed to monitor ENSO (Wolter and Timlin 1998), which is calculated by the first un-rotated principal component using a combination of sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky. This index is freely available at <http://www.esrl.noaa.gov/psd/enso/mei/table.html> hosted by the National Oceanic and Atmosphere Administration (NOAA). Meanwhile, the MJO indices can be accessed at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_mjo_index/proj_norm_order.ascii. These indices are calculated for different longitude locations using the raw 200-hPa velocity potential anomalies. The MJO index 2 measured along 100° E was used in this study.

Known as the Indian Niño, the IOD is defined as the difference of sea surface temperature between the Arabian Sea and the eastern Indian Ocean. Like ENSO, the negative IOD events are related to La Niña, while the positive IOD with El

Niño. Generally, the Dipole Mode Index (DMI) is used to represent the IOD and can be downloaded at the Japan Agency for Marine-Earth Science and Technology's website (<http://www.jamstec.go.jp/frcgc/research/d1/iod/HTML/Dipole%20Mode%20Index.html>). In this study, the Spearman's rho correlation method was applied to evaluate the correlation between atmospheric circulation indices (MEI, DMI, and MJO) and the drought indices (SPI and SSI) for the study period.

3 Results

3.1 Homogeneity tests

Historical information of these inhomogeneous stations was first checked with the reports provided by related agencies, and no relocations of these stations were reported. Table 2 presents the inhomogeneous rainfall stations that were classified as suspect and doubtful, and their break years. Results indicate inhomogeneity during 1981, 1983, 1989–1991, 1995–1996, 2002, and 2008–2009. Based on the Wijngaard et al. (2003) homogeneity performance classification, 17 and 9 rainfall stations were found to be homogeneous at the annual and monthly scale, respectively. For the annual scale, most of the tests clearly detected an inhomogeneity at 95% significance level for the stations 1738131, 1739003, and 1835001, which mainly occurred during 1990–1991 and 1995–1996. This is contradictory with the results reported by Kang and Yusof (2012), which concluded 1738131 and 1835001 stations as homogeneous. Reason could be because their study period only considered 10 years of rainfall (1996–2005), whereas the evaluated period of the present study is longer (1975–2010). Changes in these stations can be attributed to deforestation, agricultural activities, urbanization, and dam development in JRB (Tan et al. 2015b). Several decades ago, most of the rainfall stations were surrounded by forests. However, these huge forest areas were cleared and replaced by oil palm and rubber plantations since 1970s. In addition, the two nearby stations (1739003 and 1738131) are located in southern JRB, one of the most developed areas in the basin, known as the Kota Tinggi District. These large-scale environmental changes could lead to inhomogeneity in the rainfall information.

Homogeneity tests for the monthly rainfall series showed 9 out of the 20 stations as homogeneous for all months at 95% significance level. The remaining rainfall stations showed an inhomogeneous pattern in only 1 month (Table 2), except for the station 1739003 which was considered as suspect in May and September, and as doubtful in December. No inhomogeneity was detected between February and April, while the greatest number of inhomogeneity was found in September. The inhomogeneous monthly rainfall data was further

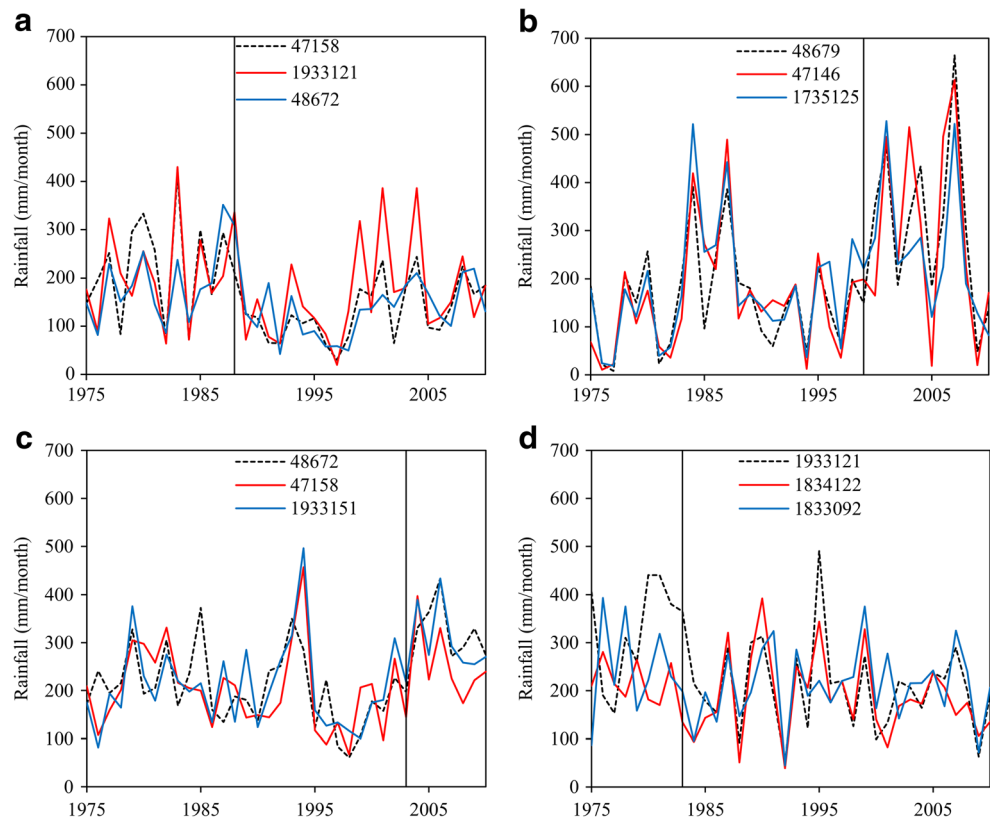
Table 2 Inhomogeneous rainfall stations and their break periods (in bracket)

| Station | Status | Month | Pettitt's test | SNHT test | Buishand's test | von Neumann's test |
|---------|----------|-------|----------------|--------------|-----------------|--------------------|
| Annual | | | | | | |
| 1738131 | Doubtful | | 148 (1990) | 11.39 (2009) | 4.62 (2002) | 1.14 |
| 1739003 | Suspect | | 243 (1995) | 16.10 (1996) | 11.90 (1996) | 1.13 |
| 1835001 | Suspect | | 213 (1989) | 7.40 (1989) | 8.16 (1989) | 0.83 |
| Monthly | | | | | | |
| 47158 | Suspect | Sep | 166 (1988) | 8.62 (1988) | 8.71 (1988) | 1.95 |
| 48672 | Suspect | Nov | 165 (2003) | 11.48 (2003) | 8.16 (2003) | 1.10 |
| 48679 | Doubtful | Jan | 145 (1999) | 8.97 (1999) | 8.39 (1999) | 1.40 |
| 1737001 | Suspect | May | 193 (1995) | 7.76 (1995) | 8.35 (1995) | 1.66 |
| 1738131 | Doubtful | Jan | 147 (1994) | 7.19 (2000) | 7.56 (1997) | 1.25 |
| 1739003 | Suspect | May | 216 (1996) | 8.53 (1996) | 8.79 (1994) | 1.81 |
| | Suspect | Sep | 249 (1993) | 16.18 (1993) | 12.22 (1993) | 1.45 |
| | Doubtful | Dec | 151 (1995) | 6.39 (1992) | 7.69 (1992) | 1.42 |
| 1835001 | Doubtful | Jul | 184 (1994) | 7.84 (1994) | 8.46 (1994) | 1.78 |
| 1839196 | Doubtful | Aug | 180 (1992) | 7.40 (1992) | 8.28 (1992) | 1.62 |
| 1933121 | Doubtful | Oct | 143 (1983) | 8.67 (1983) | 7.76 (1983) | 1.65 |
| 1933151 | Suspect | Sep | 180 (1988) | 8.68 (1988) | 8.74 (1988) | 1.74 |
| 2038001 | Doubtful | Jun | 143 (1993) | 12.70 (2006) | 7.39 (1993) | 1.12 |

compared with nearby homogeneous stations for visualization and final checking. Figure 2 shows similar monthly rainfall pattern between inhomogeneous and homogeneous stations. For example, low rainfall in September after the 1988 break

year at the 47158 station is similar as the 48672 and 1933121 stations (homogeneous). This shows that some stations cannot be considered as inhomogeneous because some detected break years occurred due to naturally high rainfall variation

Fig. 2 Monthly rainfall of inhomogeneous stations **a** 47158 (September), **b** 48672 (November), **c** 48679 (January), and **d** 1933121 (October) with nearby homogeneous stations (vertical lines represent break years)



(Che Ros et al. 2016). After rigorous analyses, the 1738131 and 1739003 stations that have inhomogeneous rainfall pattern were excluded from this study.

3.2 Meteorological drought

For identification of meteorological drought event in this study, the drought duration, severity, and intensity were measured using the SPI monthly data from 1975 to 2010. From Table 3, the occurrences of drought events for the entire basin, upper basin, and lower basin were three, four, and two times, respectively. As a tropical basin, the meteorological drought duration was relatively low, lasting only for 3 months. Sanusi et al. (2015) mentioned that any drought condition in Malaysia would generally recover to non-drought condition in 2 to 3 months. More meteorological drought events were observed in the upper basin compared to the lower basin, showing a drier condition over the Linggiu Reservoir.

It is evident that annual meteorological drought occurred in 1976, 1978, 1991, 1998, and 2010, which was similar to that reported by MMD (2009). The seasonal SPI for the entire upper and lower parts of the basin is depicted in Fig. 3. There are four to five drought events recorded during 1975–2010, with greatest drought condition occurring during MAM season in 1977. It was one of the worst droughts in Malaysian history, which had caused substantial loss in the oil palm industry (Bonell et al. 1993).

The Mann-Kendall analysis of monthly SPI-3 at various rainfall stations from 1975 to 2010 is listed in Table 4. Most of the stations had decreasing trends in February, April, May,

and September. All stations exhibited an increasing trend in January, with 95% significance level observed at stations 47146, 1835001, and 1836001. Figure 4 shows the spatial pattern of the Mann-Kendall analysis at the seasonal scale. More than 65% of the station showed increasing trends in DJF, MAM, and JJA, which were dominant in eastern, middle, and southern regions. By contrast, about 78% of the stations had decreasing trends during SON and were mostly well-distributed over the basin.

3.3 Hydrological drought

As listed in Table 3, eight hydrological drought events occurred between 1975 and 2010, with the most severe event extending up to 8 months, i.e., from February to September 2005. Similarly, the main hydrological drought episode of MAM and JJA seasons occurred in 2005 (Fig. 3). Another major hydrological drought event was found from March to September 2003. These major hydrological drought events occurred due to the deficit of precipitation, mainly caused by the El Niño event.

Surprisingly, no hydrological drought event was found during JJA and SON prior to the Linggiu Reservoir operation, while various severe droughts occurred between 2001 and 2005 (Fig. 3b, c). Damming activities in the upper basin have changed the flow characteristics of the Johor River. Additionally, the annual temperature of JRB had increased by 0.44–0.47 °C between 1980s and 2000s (Tan et al. 2015b). Larger amount of water vapor would transfer to atmosphere due to increasing evaporation rates, causing changes in the

Table 3 Severity, duration, and intensity of droughts in Johor River Basin (threshold = -1) (*SPI* Standardized Precipitation Index, *SSI* Standardized Streamflow Index)

| | Duration | Severity | Intensity | Period |
|-------------------|----------|----------|-----------|----------------------|
| SPI | 3 | 5.16 | 1.72 | Feb to Apr 1983 |
| | 3 | 4.67 | 1.56 | Aug to Oct 1992 |
| | 3 | 4.13 | 1.38 | Apr to June 2004 |
| SPI (upper basin) | 3 | 4.42 | 1.47 | Feb to Apr 1983 |
| | 3 | 5.97 | 1.99 | Aug to Oct 1992 |
| | 3 | 3.72 | 1.24 | Jun to Aug 2001 |
| | 3 | 3.97 | 1.32 | May to July 2009 |
| SPI (lower basin) | 3 | 6.21 | 2.07 | Feb to Apr 1983 |
| | 3 | 4.12 | 1.37 | Dec 2009 to Feb 2010 |
| SSI | 3 | 3.25 | 1.08 | Jan to Mar 1981 |
| | 3 | 3.41 | 1.14 | Dec 1988 to Feb 1989 |
| | 3 | 3.31 | 1.10 | Jan to March 1991 |
| | 5 | 6.73 | 1.35 | July to Nov 2001 |
| | 6 | 8.38 | 1.40 | July to Dec 2002 |
| | 7 | 10.16 | 1.45 | March to Sep 2003 |
| | 8 | 21.11 | 2.64 | Feb to Sep 2005 |
| | 3 | 3.6 | 1.20 | Oct to Dec 2008 |

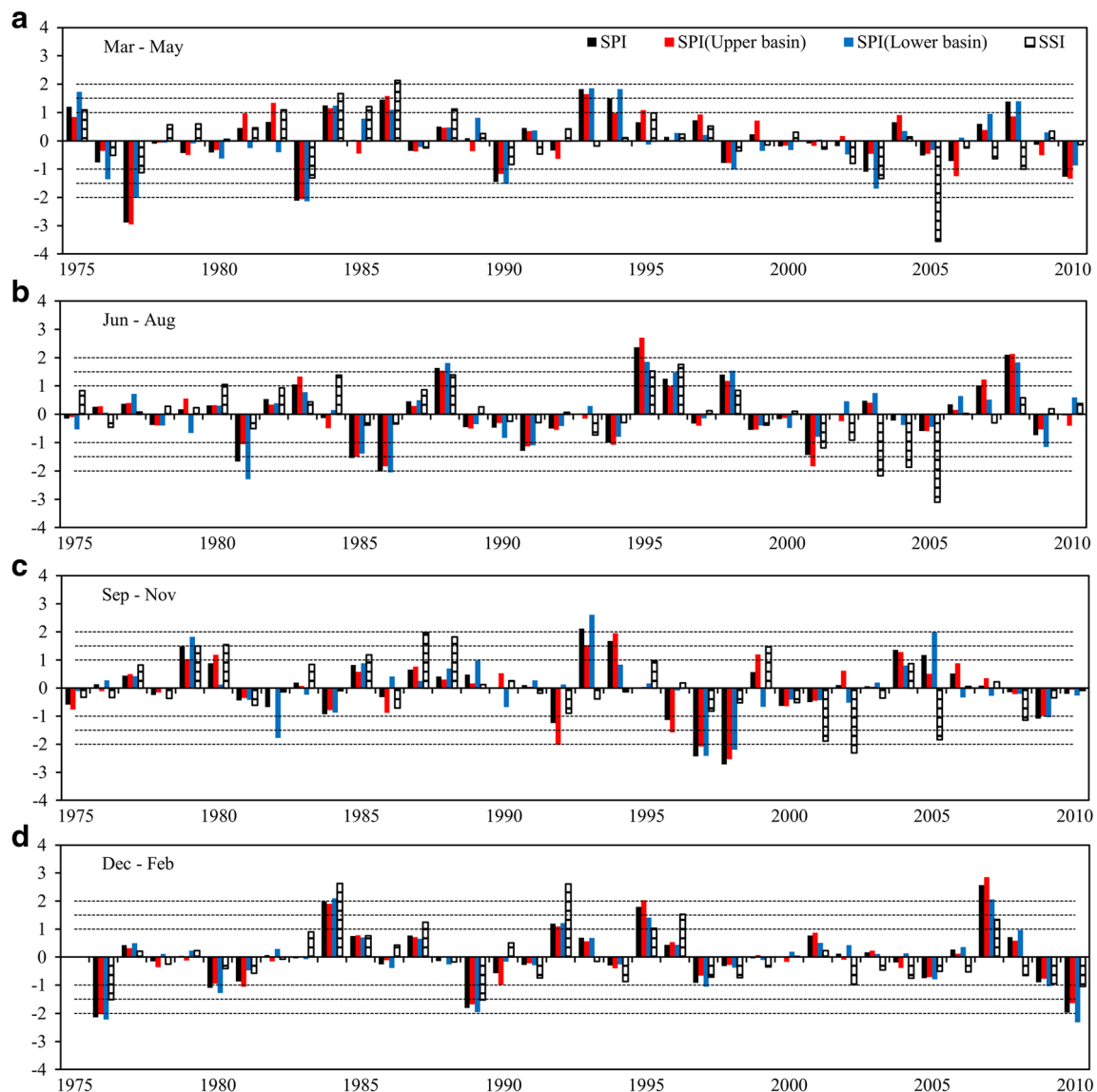


Fig. 3 SPI and SSI values from **a** March to May, **b** June to August, **c** September to November, and **d** December to February (1975 to 2010)

local hydrological cycle (Trenberth 1999). This phenomenon will be more severe in future as the surface temperature of JRB is expected to increase by 0.6 to 3.21 °C by the end of the twenty-first century (Tan et al. 2014).

To evaluate the impact of this human activity, the trend analysis of SSI was divided into entire (1975–2010), unregulated (1975–1994), and regulated (1995–2010) periods (Table 5). As listed in Table 5, the annual SSI had a strong decreasing trend at 95% significance level for the entire period. Trend analysis also showed an increase in the annual SSI during unregulated period and a decrease in the regulated period, which were not statistically significant. Seasonal SSI of MAM, JJA, and SON showed a decreasing trend for all three evaluated periods. At the monthly scale, a decreasing trend of SSI during regulated period was observed for every month, indicating that drier conditions can be expected in the

future. This reduction could be due to deforestation, urbanization, agricultural land expansion, and local hydro-climatic changes.

4 Discussions

4.1 Relationship between meteorological and hydrological droughts

Overall, the hydrological drought poses uncertainty in the JRB. So, assessment of the linkages between SPI and SSI is critical to understand their role in affecting regional hydro-meteorological conditions. Response rate of the hydrological drought to the meteorological drought was measured by dividing the occurrence times of meteorological drought (SPI <

Table 4 SPI-3 trend analysis at various rainfall stations from 1975 to 2010 (bold indicates 95% significance level)

| Station | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---------|-------------|--------------|-------|--------------|--------------|-------------|-------|-------|-------|--------------|-------|-------|
| 47120 | 0.45 | -0.48 | 1.12 | 0.27 | 0.15 | 0.76 | 0.22 | -0.12 | -1.78 | -1.62 | 0.41 | -0.68 |
| 47134 | 1.51 | -0.48 | 0.72 | -0.05 | -0.49 | 0.97 | 0.00 | -0.44 | 0.52 | 0.00 | -0.56 | -0.25 |
| 47146 | 2.26 | -0.95 | 1.14 | 0.05 | 1.04 | 0.91 | 1.01 | 0.42 | 0.97 | 0.69 | -1.46 | -0.01 |
| 47158 | 0.99 | -0.93 | 0.40 | -0.90 | -0.38 | -0.16 | -0.57 | 0.53 | -1.23 | 1.88 | 0.27 | -0.29 |
| 48672 | 1.59 | -1.93 | 0.97 | -0.29 | 0.59 | -1.13 | 0.34 | 0.37 | -0.35 | 0.69 | 1.08 | 0.40 |
| 48679 | 1.77 | -1.40 | 0.86 | 0.03 | -0.37 | 0.79 | 0.72 | 1.04 | 0.74 | -0.11 | -0.54 | -0.68 |
| 1734001 | 1.38 | -1.78 | 0.31 | -0.31 | -1.68 | 0.01 | -0.64 | 0.14 | -0.27 | 0.42 | -0.30 | 0.56 |
| 1735125 | 1.80 | -1.58 | 0.89 | -0.78 | -0.84 | 0.80 | -0.41 | -0.25 | -0.45 | -1.73 | -1.25 | -0.69 |
| 1737001 | 1.42 | -0.91 | -0.48 | -1.27 | -2.14 | -0.52 | -0.10 | -0.91 | 1.20 | 0.00 | -1.81 | -0.67 |
| 1833092 | 1.51 | -1.36 | -0.29 | -2.14 | -0.80 | -0.01 | 0.26 | -0.22 | -0.33 | -0.23 | 0.07 | 0.84 |
| 1834122 | 1.10 | -1.35 | 0.71 | -0.74 | -1.21 | 0.35 | -0.07 | -0.57 | -0.67 | -1.53 | 0.53 | -0.52 |
| 1835001 | 2.00 | -1.06 | 0.90 | 0.12 | 1.55 | 1.47 | 1.31 | 1.27 | 1.06 | 1.25 | -0.10 | 0.29 |
| 1836001 | 1.99 | -1.29 | 0.54 | -0.41 | -0.86 | 0.59 | 1.23 | 1.53 | -0.35 | 0.97 | -0.34 | -0.29 |
| 1839196 | 0.63 | -0.35 | 0.60 | 0.42 | -0.29 | -0.54 | -0.84 | 1.93 | -1.48 | 1.27 | 1.05 | -0.68 |
| 1933121 | 1.54 | -2.00 | 0.22 | -1.25 | -0.56 | 0.26 | -0.95 | 0.69 | -0.29 | -1.96 | -0.37 | -0.89 |
| 1933151 | 1.39 | -1.66 | 1.77 | -1.27 | -1.12 | 0.08 | -0.54 | 0.35 | -1.80 | -0.01 | 1.53 | 0.19 |
| 2033152 | 1.66 | -1.40 | 0.80 | -0.61 | -0.37 | -1.12 | -0.49 | -0.80 | -1.50 | 0.33 | 0.49 | 0.54 |
| 2038001 | 1.02 | -0.54 | 0.00 | -0.15 | -0.01 | 2.55 | 1.25 | -0.08 | -0.90 | 0.41 | -0.91 | -0.80 |

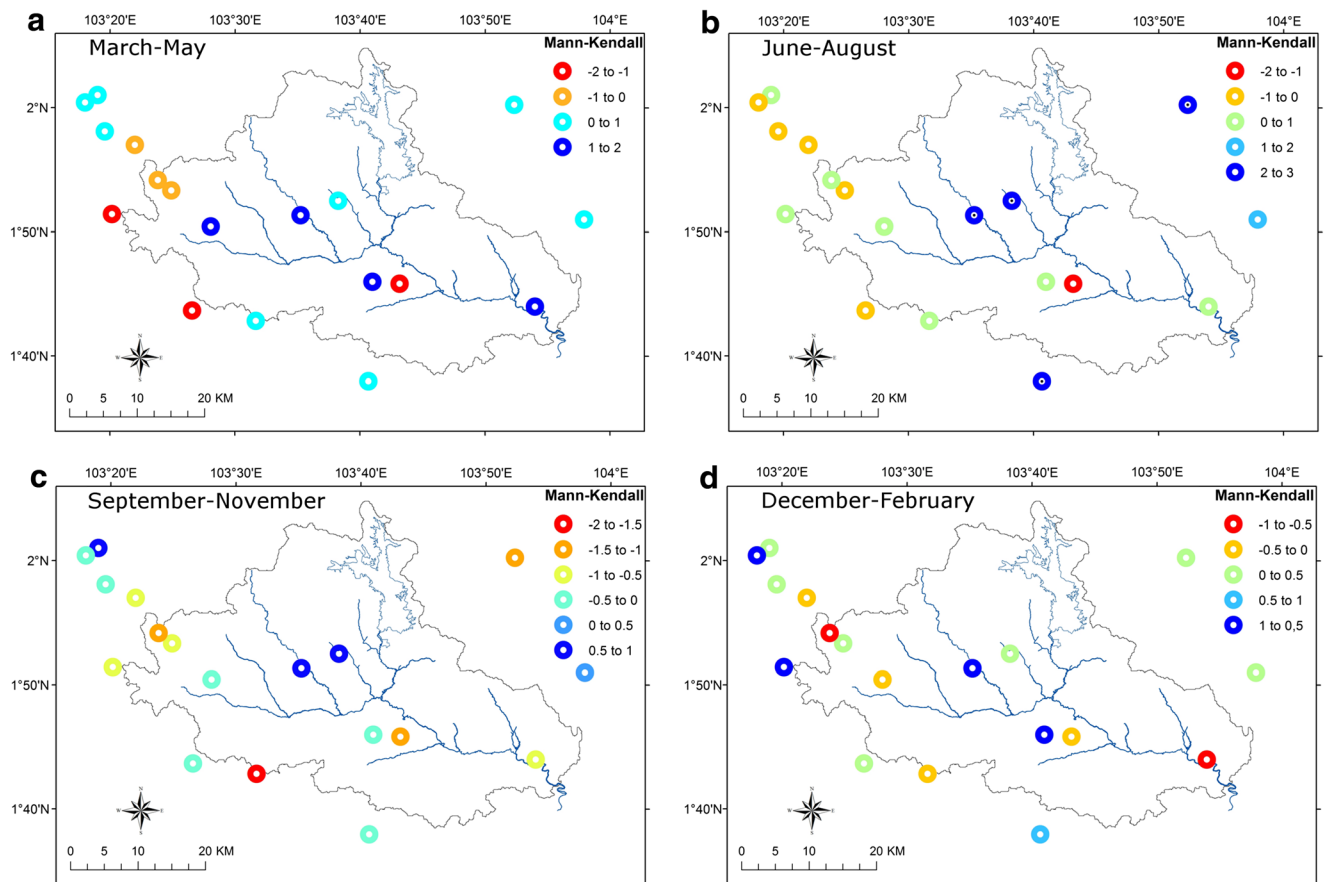


Fig. 4 Spatial pattern of Mann-Kendall analysis of SPI-3 for **a** March to May, **b** June to August, **c** September to November, and **d** December to February (1975 to 2010) (dotted = significant trends; positive = increase trend; negative = decrease trend)

Table 5 SSI trend analysis for the three periods at Rantau Panjang stations (bold indicates 95% significance level)

| Period | 1975–2010 | 1975–1994 | 1995–2010 |
|---------|-----------|-----------|-----------|
| Annual | –2.63 | 0.32 | –1.89 |
| Mar–May | –2.17 | –0.19 | –1.58 |
| Jun–Aug | –1.51 | –0.78 | –1.04 |
| Sep–Nov | –1.61 | –0.32 | –0.23 |
| Dec–Feb | –1.58 | 0.28 | –1.94 |
| Jan | 0.12 | 0.03 | –0.32 |
| Feb | 0.64 | 1.04 | –1.76 |
| Mar | –0.46 | –0.16 | –1.58 |
| Apr | –2.27 | –0.68 | –1.22 |
| May | –3.68 | –0.55 | –2.21 |
| Jun | –1.98 | –0.45 | –0.9 |
| Jul | –1.93 | –2.08 | –0.77 |
| Aug | –0.93 | –1.1 | –1.22 |
| Sep | –0.95 | –0.88 | –0.23 |
| Oct | –0.74 | –0.49 | –0.86 |
| Nov | –2.37 | –0.23 | –0.14 |
| Dec | –2.83 | 0.62 | –1.13 |

0) with the occurrence times of hydrological drought ($SSI < 0$) under meteorological drought ($SPI < 0$), and then the value was converted into percentage (Zhao et al. 2016).

Figure 5 shows the response rate of hydrological drought to meteorological drought at annual, seasonal, and monthly scales for the entire (1975–2010), unregulated (1975–1994), and regulated (1995–2010) periods. Moderate response rate was found at the annual scale for the entire (57.9%) and unregulated (45.45%) periods, while high response rate was observed for the regulated (75%) period. The findings show that the response rate of hydrological drought to the meteorological drought is higher after the Linggiu reservoir was

constructed. Heavy rainfall brought by the SWM is largely reduced by the Sumatra mainland before reaching the JRB (Tan et al. 2015a). To store sufficient water to face the drought season, the related agencies control the flow from the Linggiu Reservoir and maintain the water capacity. Hence, hydrological drought at the Rantau Panjang station could also occur under normal climatic or heavy rainfall conditions.

The SON and DJF seasons showed stronger response in their relationship between hydrological and meteorological droughts compared to MAM and JJA (Fig. 5). Similar robust relationship was also found between October and February at the monthly scale, indicating higher response rate normally during the NEM (wet season). The possible reason is that the streamflow could be affected by direct rainfall into the river, as the NEM has more frequent and intense rainfall compared to the SWM (dry season). Therefore, human activities have less impact on hydrological drought during the wet season than the dry season.

4.2 Relationship between atmospheric circulations and droughts

Large-scale atmospheric circulations are influencing the world climate system either intra-seasonally or inter-annually. For SPI, the MEI correlated strongly during the dry season, while the MJO had better correlation in the wet season (Table 6). Similarly, Tangang et al. (2008) found that the MJO had a greater impact on the heavy rainfall events during December 2006 to January 2007. In fact, most of the dry years in Malaysia have been recorded during the El Niño events, where the dry spells have become more frequent and intense after 1975 (MMD 2009). Tangang and Juneng (2004) indicated that the strong influence of ENSO in Malaysian rainfall is mainly due to the anomalous anti-cyclonic circulation over the southern Philippines and the northern Borneo. The findings

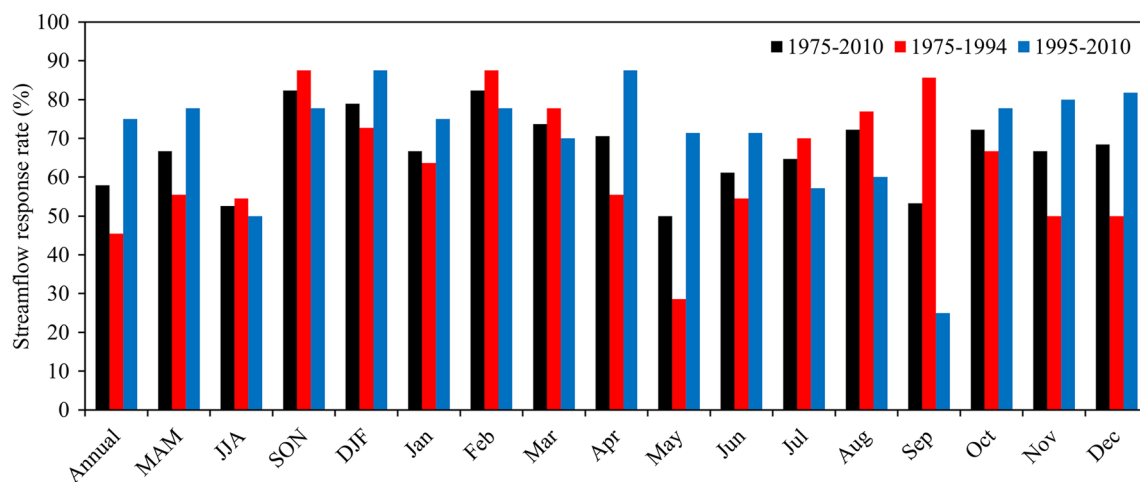


Fig. 5 Response rate of the hydrological drought to meteorological drought under different temporal scales for the entire (1975–2010), unregulated (1975–1994), and regulated (1975–2010) periods

Table 6 Spearman's rho correlation between large-scale atmospheric circulation indices and drought indices from 1975 to 2010 (bold indicates 95% significance level)

| | SPI | | | SSI | | |
|---------|--------------|-------|--------------|-------|--------------|--------------|
| | MEI | DMI | MJO | MEI | DMI | MJO |
| Mar–May | −0.30 | 0.14 | −0.17 | −0.25 | −0.20 | −0.41 |
| Jun–Aug | −0.01 | 0.24 | −0.15 | −0.12 | −0.02 | −0.14 |
| Sep–Nov | 0.17 | 0.25 | 0.03 | −0.13 | 0.00 | −0.12 |
| Dec–Feb | 0.06 | −0.16 | −0.32 | 0.14 | −0.34 | −0.20 |
| Jan | 0.16 | −0.12 | −0.32 | 0.29 | −0.27 | −0.13 |
| Feb | −0.28 | −0.24 | −0.58 | 0.17 | −0.01 | −0.51 |
| Mar | −0.50 | 0.16 | −0.44 | −0.29 | 0.02 | −0.31 |
| Apr | −0.12 | 0.18 | −0.09 | −0.27 | 0.12 | −0.44 |
| May | 0.09 | 0.09 | 0.17 | −0.18 | −0.10 | −0.11 |
| Jun | −0.07 | 0.24 | −0.16 | 0.02 | −0.07 | −0.01 |
| Jul | −0.17 | −0.03 | −0.02 | −0.32 | −0.14 | −0.11 |
| Aug | 0.01 | 0.31 | −0.29 | −0.21 | 0.03 | −0.29 |
| Sep | −0.06 | −0.14 | −0.24 | −0.32 | −0.18 | −0.37 |
| Oct | 0.08 | 0.14 | −0.07 | −0.20 | −0.11 | −0.23 |
| Nov | 0.22 | 0.24 | −0.18 | 0.22 | 0.19 | 0.00 |
| Dec | 0.19 | −0.03 | −0.05 | 0.23 | −0.10 | 0.07 |

MEI Multivariate ENSO index, MJO Madden-Julian Oscillation, DMI Dipole Mode Index, SPI Standardized Precipitation Index, SSI Standardized Streamflow Index (SSI)

show that ENSO and MJO play a key role in affecting the dryness/wetness conditions in the JRB.

The MJO had stronger correlation with SSI in the dry season (MMA and JJA) compared to the MEI and IOD, indicating that MJO has a greater impact on hydrological drought in the basin. More negative phase of MJO conditions can be observed after the late 1990s, which results in lesser rainfall in the basin. Chang et al. (2015) stated that the increase in global temperature might lead to more frequent and stronger MJO phenomena. Therefore, more intense hydrological droughts are expected to occur in the future.

4.3 Malaysia-Singapore droughts

Southern Peninsular Malaysia, Singapore, and part of Indonesia experience similar drought conditions due to their proximity. For instance, Malaysia and Singapore are separated only by the Johor Strait with an approximate width of 2 km. The warmest year in the history of Singapore is 2016, where the amount of precipitation in the first half of 2016 was lower than 26% of the normal conditions (MSS 2016). Tan et al. (2018) studied the 2015–2016 drought of southern Peninsular Malaysia and Singapore using Tropical Rainfall Measurement Mission (TRMM) data and found that severe drought conditions happened in January, March, and April 2016. The longest recorded

dry spell in Singapore was 62 days (13 January and 15 March 2014), followed by 42 days (January to February 2008) and 40 days (January to February 2005) (McBride et al. 2015).

Reduction of freshwater supply is the main negative impact of severe droughts over the southern Peninsular Malaysia-Singapore region. Water shortage problem could lead to water usage limitation, reduction of agricultural productivity, and economic losses in this region. Besides that, the nearby regions (i.e. Borneo and Sumatra Indonesia) are subject to extreme forest fire events once in a few years, particularly during the El Niño-induced drought periods (Sloan et al. 2017). The 1997–1998, 1982–1983, and 2015–2016 El Niño events caused unprecedented forest fires in Indonesia, thus leading to severe transboundary haze in Southeast Asia. Therefore, more robust drought adaptation strategies are required such as the development of more number of desalination plants and increased use of recycled wastewater, and reduction of “slash and burn” agricultural activities in the future.

5 Conclusions

This study analyzes the historical hydro-meteorological drought (1975–2010) of the JRB, Malaysia. Due to insufficient freshwater resources, Singapore has been importing freshwater from the JRB for the past few decades. Therefore, water scarcity in this basin will directly affect the economic growth and population of both countries. The relationship between droughts and large-scale atmospheric circulations was also evaluated. The main conclusions are summarized as follows:

1. Four absolute homogeneity tests were used to assess the reliability of rainfall data collected from 20 climate stations (<10% missing data). Most rainfall data were homogeneous at annual scale, while 11 stations were found to be suspect or doubtful at the monthly scale. After a rigorous analysis, two inhomogeneous stations were excluded from further analysis.
2. Meteorological drought duration was relatively low in this basin, lasting only for 3 months. More droughts occurred in the upper part of the basin than the lower part, showing drier conditions over the Linggiu Reservoir. The monthly SPI values had a decreasing trend in February, April, May, and September, and a remarkably increasing trend in January.
3. Eight hydrological drought events were identified at the Rantau Panjang station, implying that hydrological droughts occurred moderately in the basin. Annual SSI had a dramatically decreasing trend at 95% significance level. In addition, no drought event occurred prior to the operation of the Linggiu Reservoir during JJA and SON seasons.

4. Moderate relationship occurred between meteorological and hydrological drought at the annual scale, as the response rate of hydrological drought was lower during the dry season. Human activities including reservoir development and oil palm irrigation have influenced the river flow in JRB. Thus, hydrological drought could have occurred as a stand-alone without the meteorological drought.
5. For meteorological drought, ENSO had a stronger correlation during the dry season, while the MJO showed better correlation during the wet season. Contrastingly, the MJO had a greater impact on hydrological drought during the dry season.

In general, this study reveals robust knowledge to improve drought adaptation strategies for reducing water shortage problems in Malaysia and Singapore. Upcoming study will focus on the assessment of future drought impacts on water resources in the basin with hydrological and general circulation models. In addition, reliability of satellite data in drought indices estimation which is still not understood will also be a focal area. Assessment of drought impacts on the productivity of major crops (oil palm, paddy, and rubber) in Malaysia will also be conducted in the future.

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