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Meteorological Drought and its Relationship with Southern Oscillation Index (SOI)

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Abstract

Drought monitoring, including its severity, spatial, and duration is essential to enhance resilience towards drought, particularly for overcoming drought risk management and mitigation plan. The present study has an objective to examine the suitability of the Standardized Precipitation Index (SPI) and Percent of Normal Index (PN) on assessing drought event by analyzing their relationship with the Southern Oscillation Index (SOI). The monthly rainfall data over twenty years of the observation period were used as a basis for data input in the drought index calculation. The statistical association analyses, included the Pearson Correlation (r), Kendal tau (τ), and Spearman rho (r_s) used to assess the relationship between the monthly drought indexes and SOI. The present study confirmed that the SPI showed a more consistent and regular pattern relationship with SOI basis which was indicated by a moderately high determination coefficient (R^2) of 0.74 and the magnitude of r, τ, and rs that were of 0.861, 0.736, and 0.896, respectively. Accordingly, the SPI showed better compatibility than the PN for estimating drought characteristics. The study also revealed that the SOI data could be used as a variable to determine the reliability of drought index results.

Keywords: Drought Index; Meteorological Drought; Percent of Normal Index; Southern Oscillation Index; Standardized Precipitation Index.

1. Introduction

In the recent decade, climate change phenomena have been a main issue in the worldwide since its impact on many sectors of economic and social, including water resources sector as the foundation of civilization – agriculture [1]. Information on drought phenomena along with its duration, severity, and areal extent must be well available to be used as a guide for water resource managers to support good planning and management in the water resource field, particularly in mitigation and adaptation planning [2, 3]. Quantitative analysis of drought monitoring commonly deals with an estimation of a drought index, which is normally derived from a comparison between magnitudes of rainfall with mean rainfall in a certain period. Some previous researches had been carried out to obtain drought overview temporally and spatially. Homdee et al. [4] applied the Standardized Precipitation Index (SPI) and the Standardized Evapotranspiration Index (SPEI) methods and confirmed that the SPEI method is more accurate. Harisuseno [5] demonstrated that the SPI showed good reliability in assessing drought characteristics when compared with the RAI, while [6] utilized TRMM satellite data and SPI for monitoring and developing the spatiotemporal map of meteorological drought. Zhang and Li [7] examined the implications of different probability functions and parameter estimation on the SPI index, including drought intensity, duration, and frequency. The Standardized Precipitation Index (SPI) is more frequently applied to drought analysis regarding owing effortless calculation since the method is recommended by the World Meteorological Organization [8, 9]. The application of the Percent of Normal Index (PN)

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was conducted by Adnan et al. (2017) [10] and Wable et al. (2018) [11] found that the method was more sensitive to drought conditions in terms of intensity and strongly correlated in similar time scales and poorly correlated for dissimilar time scales as well.

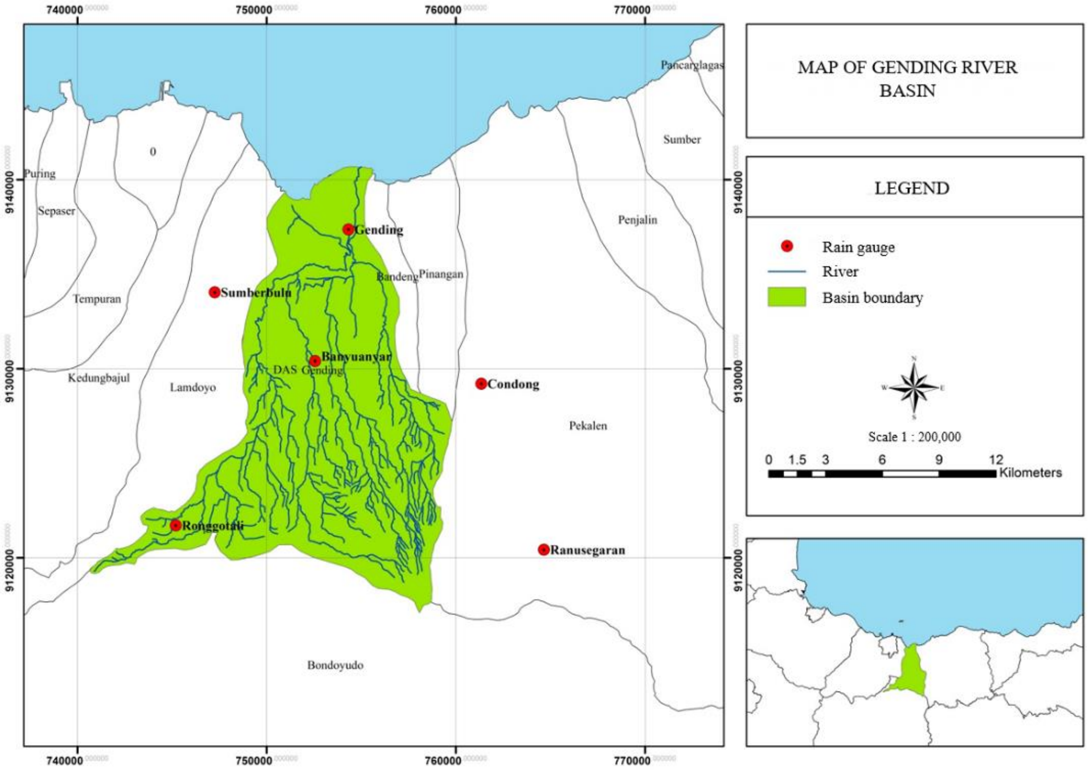


Figure 1. Map of the study area along with rain gauge

Esfahanian et al. [12] introduced a comprehensive drought index (MASH) that incorporates meteorological, agricultural, stream health, and hydrological aspects to predict a drought occurrence. Ali et al. [13] developed a novel method – Standardized Precipitation Temperature Index (SPTI) that incorporate regional temperature variable for drought estimating and SPTI showed good reliability in drought monitoring in varying time scales. Some researches attempted to discuss the drought occurrence associated with phenomena of ENSO (El Nino Southern Oscillation) as reported by Kousari et al. [14]. However, the previous researches did not specifically explain the ENSO as a consideration tool to examine the suitability of the drought index method. The previous studies mentioned above exposed that despite many researchers on comparison drought indices have been conducted worldwide, however, only a small number of studies have been reported from Indonesia until recent situations. Moreover, the study concerning the comparison between the Standardized Precipitation Index (SPI) and Percent of Normal Index (PN), particularly in an agrarian, semi-arid, and drought susceptible regions is still rarely carried out. Additionally, there are still a few studies concerning the use of the Southern Oscillation Index (SOI) characteristic to examine the suitability of the method of drought index. The selection of an appropriate drought index that can be used for assessing drought characteristics within the Gending River basin is important for preparing mitigation, adaptation, and contingency plan of drought. Therefore, the present study has an aim to examine the application of two meteorological drought index, i.e the Standardized Precipitation Index (SPI) and Percent of Normal Index (PN), and subsequently determine their suitability by assessing their relationship with the Southern Oscillation Index (SOI) in the Gending River basin. To achieve the aims, this study is carried out systematically based on the materials and methods which is outlined in Section 2. The results of the analysis accompanied by some discussions concerning the meteorological drought index and its comparison with the Southern Oscillation Index (SOI) are provided in Section 3. The paper is ended with the conclusions describing which drought method reliable to assess drought characteristics in the study area (Section 4).

2. Materials and Methods

2.1. Study Area

The location of the study area was situated in the Gending River basin, Probolinggo regency, East Java Province, Indonesia. The Gending River basin encompasses an area of 193.414 km^2 and lies between latitude 7° 47' to 7° 58' S and longitude 113° 18' to 113° 23' E. The length of rainfall data used in the present study collected in the monthly period during 1999 to 2018 from six rain gauges i.e Gending, Banyu Anyar, Condong, Ranusegaran, Ronggotali, and

Sumber Bulu rain gauge stations. Figure 1 presents the location of the basin study area along with the rain gauges. The normality data were assessed by using The Shapiro-Wilk test was used to perform the normality test, while the homogeneity test was conducted through the Levene's test [15, 16]. The meteorological drought analysis was performed at monthly based for twenty years from 2000 to 2019. The resulting drought indexes of SPI and PN were evaluated and compared with Southern Oscillation Index (SOI) through statistical analyses, including Pearson Correlation (r), Kendal tau (τ), and Spearman rho (r_s) and their suitability for assessment of drought attribute were examined. The drought method that shows the best performance in the statistical performance criteria is considered as the method of drought index chosen for assessing the regional drought characteristic in the study area. Figure 2 presents the flow diagram of the study.

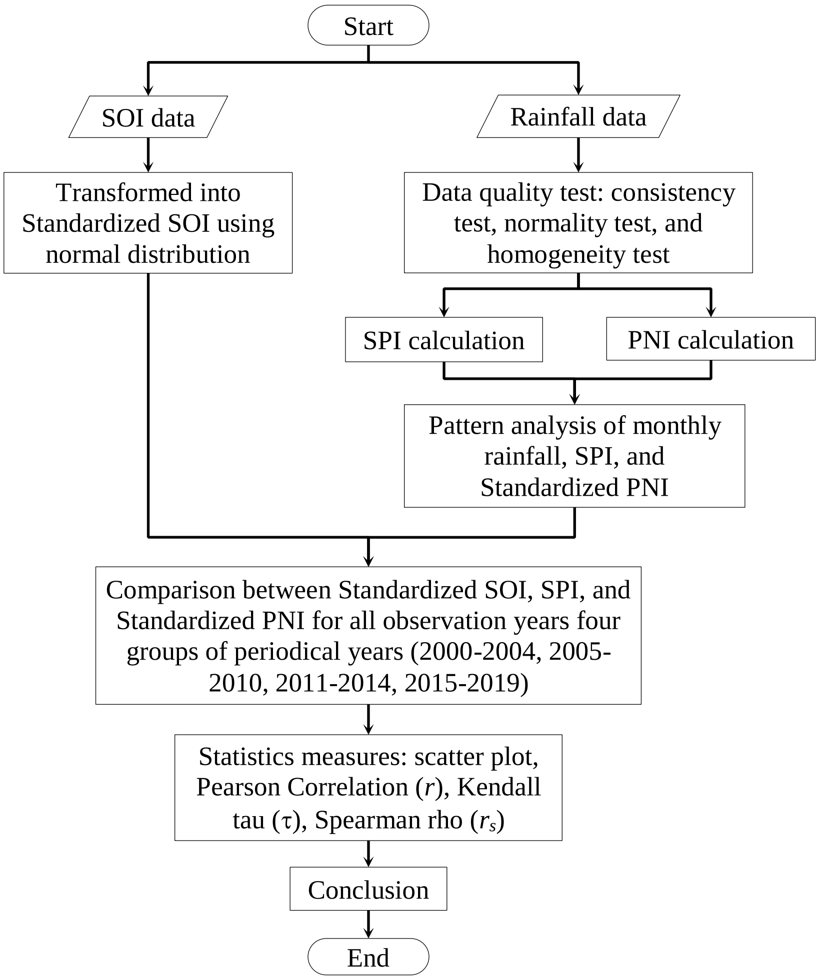


Figure 2. Flow diagram of the study

2.2. Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) was proposed by McKee et al. (1993) [17] and known as the simple method to estimate drought index considering only rainfall as a single input. The method can assess drought for different time scales of rainfall period, including 3 months, 6 months, 9 months, 12 months, or 24 months of cumulative precipitation [9, 18]. The basic concept of the SPI involves an assumption that the rainfall series fit a particular probability density function [17]. In many cases, the gamma distribution is known as the appropriate distribution for describing the rainfall pattern. The gamma distribution function could be explained as follows [19] for monthly rainfall (P) > 0:

$$G(P) = \frac{1}{\beta^{\alpha}\,\Gamma(\alpha)}\, P^{\alpha-1} e^{-P/\beta} \tag{1}$$

Where α and β values denote the shape and scale parameters, P is the monthly rainfall, and Γ (α) is the gamma function. For zero value monthly rainfall (P = 0), hence the cumulative probability change into:

$$H(P) = q + (1-q).G(P) \tag{2}$$

Where q denotes the probability of a zero value of rainfall event and G(P) is the cumulative probability of the incomplete gamma function. Transformation of the cumulative probability, H(P) to the standard normal distribution Z addresses the SPI value. The form of transformation equation depends on the value of *H(P)* where for: *0<H(P)≤0.5*, the Equation 3 is used whereas Equation 3 is employed for *0.5<H(P)≤ 1.0*.

$$Z = SPI = -\left(t - \frac{c_0 + c_1 + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad (3)$$

$$Z = SPI = \left(t - \frac{c_0 + c_1 + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad (4)$$

$$t = \sqrt{\ln\left(\frac{1}{(H(P))^2}\right)} \quad (5)$$

$$t = \sqrt{\ln\left(\frac{1}{(1.0 - H(P))^2}\right)} \quad (6)$$

The Equation 4 is applied to calculate t value for range 0*<H(P)≤0.5* while for *0<H(P)≤1.0*, the t value is calculated with Equation 5 and 6 where c_0, c_1, c_2 are 2.516, 0.803, and 0,010 while d_1, d_2, d_3 are 1.433, 0.189, and 0.001 respectively. The drought level of the SPI range is categorized into near normal condition (0.99<SPI<-0.99), moderately dry (-1.0 < SPI < -1.49), severely dry (-1.5 <SPI<-1.99) and extremely dry (SPI < -2.0) [11].

2.3. Percent of Normal Index (PN)

The Percent of Normal (PN) was defined as a percent of the rainfall to the normal rainfall where the normal rainfall was commonly determined from a long term mean or median rainfall [20]. The calculation for PN could be calculated as [21]:

$$PN = \frac{P_i}{P} \times 100 \quad (7)$$

Where PN is the percent of normal rainfall (%), Pi is the rainfall in i period (mm), and is the average of rainfall of period (mm). The resulted indexes of PN then must be transformed into the standard normal distribution to make similar to the numerical format of SPI. The drought level of PN Index is grouped into normal conditions (>80%), slightly drought (70%-80%), moderately drought (55%-70%), severely drought (40% - 55%), and extremely drought (< 40%) [21].

2.4. Southern Oscillation Index (SOI)

Yan et al. [22] defined the Southern Oscillation Index (SOI) as the difference between the sea level pressure of antiphase oscillatory behavior at Tahiti, in the Eastern Pacific, and Darwin, in the Western Pacific. It is an atmospheric condition that commonly indicates the development and intensity of El Nino and La Nina events that cover the Pacific Ocean and influences the weather in Indo-Australian areas [23]. The impact of El Nino Southern Oscillation (ENSO) has been recognized as the main factor controlling the climate of Southeast Asian countries, included Indonesia [24]. For that reason, the investigation of the degree of suitability of the SPI and PN was done through comparison analysis between the drought index resulted from both methods with the Southern Oscillation Index (SOI). The monthly SOI data were collected over the period 2000–2019 from the website of the Australian Government, Bureau of Meteorology. To determine the relationship between the Southern Oscillation Index (SOI) and the drought index of SPI and PN, the monthly SOI data were transformed to a normal distribution to obtain standardized SOI data.

3. Results and Discussions

3.1. Annual Rainfall Characteristics

Summary of annual characteristics for six rain gauges over the period 2000 to 2019 was demonstrated in Table 1. The magnitude of the coefficient of variation (CV) as shown in Table 1 showed values of 0.22 – 0.42 that indicated relatively homogeneity characteristic of the annual rainfall data. The description of mean monthly rainfall characteristics during the entire observation year was exhibited in Figure 3. As shown in Figure 3, the dry months occurred during the entire observation year from May to October that indicated a dry season.

Table 1. Summary of annual rainfall characteristics in the study area

Sta. No	Rain gauge	Elev.	Latitude	Longitude	Mean annual (mm)	Coeff. of variation (*CV*)
1	Gending	010	7º 48’ 29” S	113º 18’ 22” E	1336	0.34
2	Ranusegaran	350	7º 57’ 41” S	113º 23’ 11” E	2671	0.42
3	Ronggotali	265	7º 53’ 51” S	113º 07’ 50” E	2290	0.34
4	Sumber Bulu	035	7º 49’ 41” S	113º 14’ 31” E	1517	0.29
5	Banyu Anyar	089	7º 52’ 21” S	113º 12’ 24” E	1690	0.22
6	Condong	095	7º 58’ 13” S	113º 22’ 14” E	1905	0.27

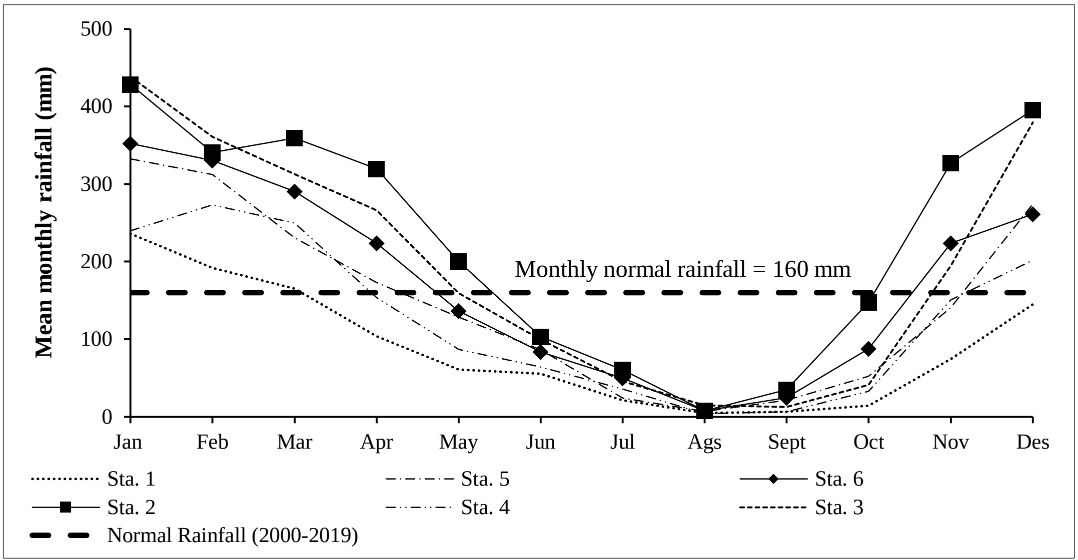


Figure 3. Mean monthly rainfall during 1999-2018

Hence, drought occurrence potentially took place from May to October annually in the study area. The summary of statistical testing for maintaining rainfall data quality was demonstrated in Table 2. In this study, the statistical testing for data quality comprised with homogeneity test using the Levene’s test and the Shapiro-Wilk test for examining the normality of rainfall data. The statistical program packages Minitab ver. 17 was employed to conduct statistical tests. The decision to accept or reject the null hypothesis was decided by assessing the *p*-value and the *sig*. level, where *p*-value > 0.05 indicates acceptance of the null hypothesis. As displayed in Table 2, the Levene’s test and Shapiro-Wilk test showed *p*-values >0.05 for all rain gauges, thus it could be concluded that rainfall data fulfilled the assumption of homogeneity and normality data.

Table 2. Statistical testing of rainfall data for each rain gauge

Sta. No	Levene’s test[a)]		Shapiro-Wilk test[b)]	
1	*p*-values	0.10	*p*-values	0.10
2		0.25		0.10
3		0.87		0.10
4		0.50		0.10
5		0.57		0.07
6		0.04		0.09

Table 3. Mean monthly areal rainfall, drought index, and drought status period 2000-2019

Month	Mean monthly areal rainfall (mm)	SPI value	Drought status	Standardized PN value	Drought status
Jan	280	1.25	Moderately wet	1.50	Normal
Feb	272	1.21	Moderately wet	1.42	Normal
Mar	215	0.91	Near normal	0.86	Normal
Apr	164	0.6	Near normal	0.37	Normal
May	83	-1.07	Moderately dry	-0.43	Moderate dry
Jun	58	-1.28	Moderately dry	-0.67	Severe dry
Jul	28	-1.42	Moderately dry	-0.96	Extreme dry
Aug	5	-1.86	Severly dry	-1.19	Extreme dry
Sep	12	-1.41	Severly dry	-1.12	Extreme dry
Oct	40	-1.16	Moderately dry	-0.85	Extreme dry
Nov	137	0.41	Near normal	0.10	Normal
Dec	224	0.96	Near normal	0.95	Normal

3.2. Meteorological Drought Index

The present study adopted the arithmetic mean method to compute the monthly mean areal rainfall, which subsequently used as an input for the SPI and Percent of Normal Index (PN) [25]. Table 3 presents the magnitude of mean monthly areal rainfall computed from 2000 – 2019, the drought index of SPI, and PN, along with the drought status. Based on Table 3, it could be seen that the drought index resulted from the SPI and PN showed similarity concerning the pattern of the value of drought index and drought status. Further, from Table 3, it could be revealed that the drought status of moderately dry to extremely dry averagely took place from May to October. This result was confirmed with the magnitude of mean monthly areal rainfall that tends to decrease from May to October (which is included in dry months or dry season) [26]. As shown in Table 3, the result of the drought index of the method of SPI and PN displayed that the most severe dry status occurred in August which indicated with the smallest magnitude of rainfall. Figure 4 exhibits the mean monthly pattern of areal rainfall along with the drought index from the method of SPI and PN. As shown in Figure 4, it could be seen that the value of drought index having a similar pattern between the method of SPI and PN. Furthermore, Figure 4 reveals that the positive magnitudes of drought index tend to last from November to April, whereas the negative magnitudes took place from May to October. This result was concurrent with the rainfall event pattern where the relatively high rainfall tends to occur from November to April, while May to October experienced the relatively small rainfall. The result of the statistical Pearson correlation (r) that describes the relationship between the mean monthly areal rainfall and the drought index from the two methods showed the magnitude of 0.915 and 0.885 for SPI and PN, respectively

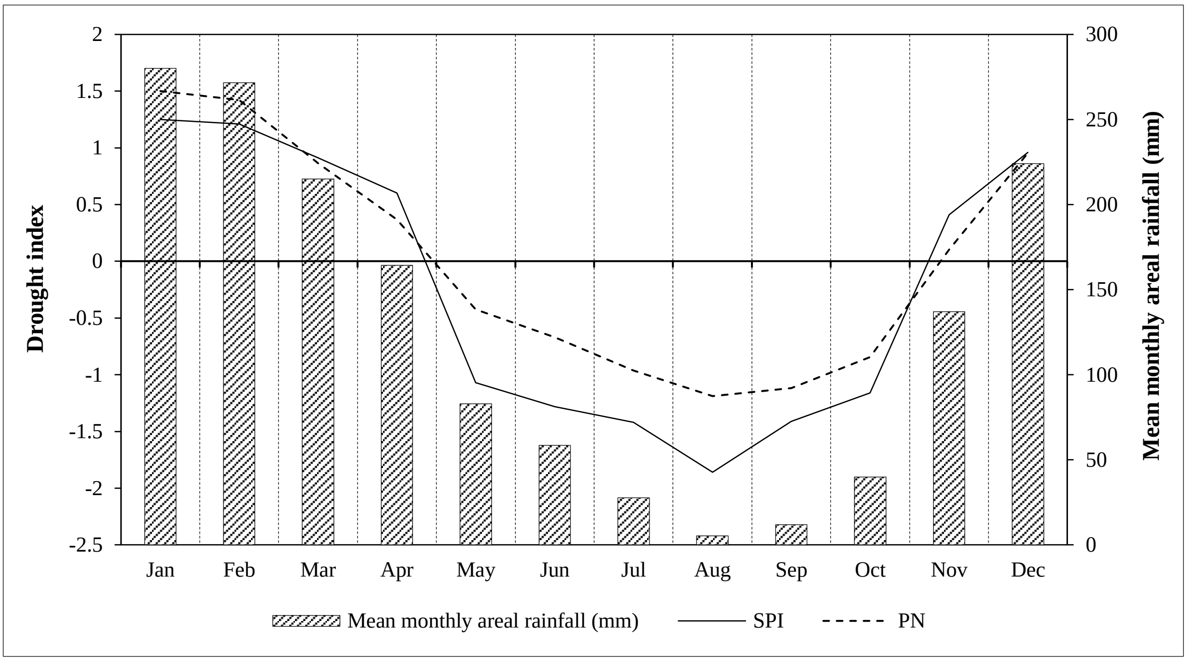


Figure 4. Mean monthly areal rainfall and drought index

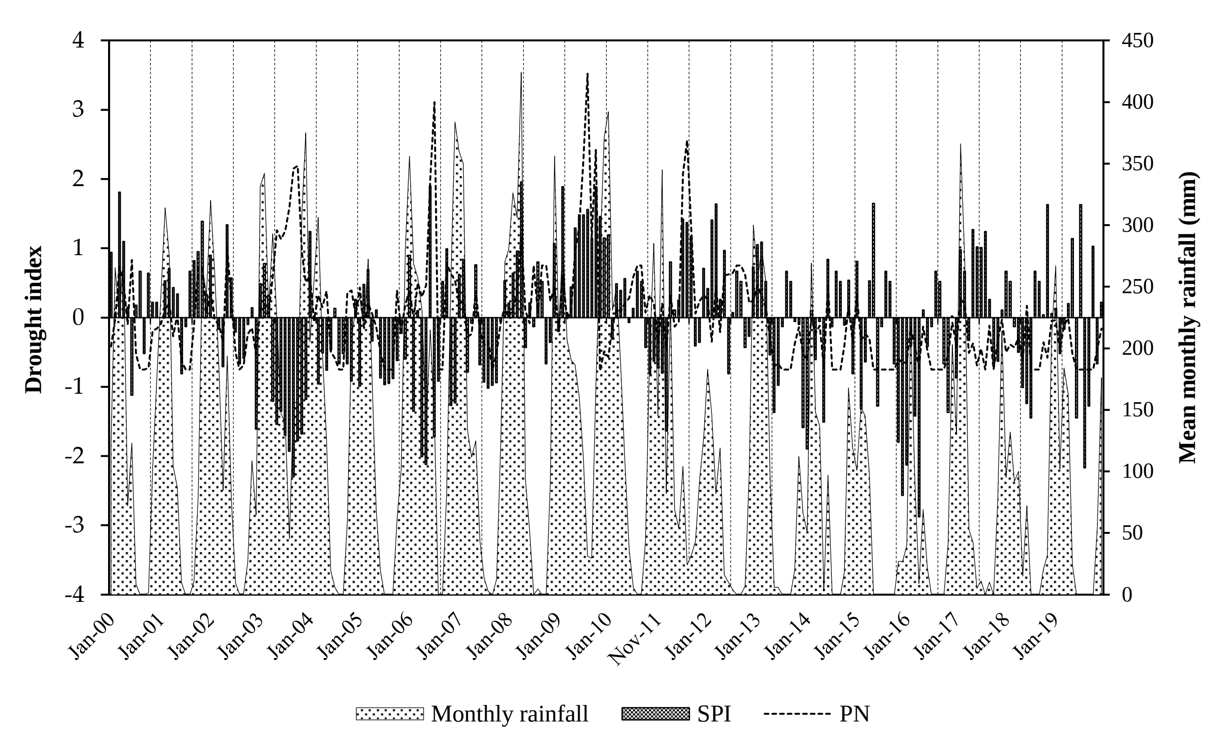


Figure 5. Monthly rainfall along with drought index of SPI and PN

The relatively high of the Pearson correlation confirms the pattern similarity between the drought index from the SPI and PN and the mean monthly areal rainfall in the study area. Figure 5 presents the plotting of the monthly rainfall along with the drought index of SPI and PN for the entire observation years (2000 – 2019). As displayed in Figure 5, there was a similarity in the pattern of mean monthly rainfall with the drought index of the two methods despite the level of the similarity was not as good as if compared with what was displayed in Figure 4.

3.3. Comparison Analyses between Meteorological Drought Index and SOI

To know further regarding the suitability level of the practicability of the two drought index methods for assessing drought event in the study area, the drought index resulted from the SPI and PN was compared with the Southern Oscillation Index (SOI) over the period 2000 – 2019 obtained from the website of the Australian Government, Bureau of Meteorology. Figure 6a and Figure 6b demonstrate the relationship pattern among the monthly standardized SOI, SPI, and PN computed from 240 monthly rainfall data over the period 2000 – 2019. From Figure 6a, it could be known that generally, there is a good similarity pattern between the standardized SOI and SPI compared with PN (Figure 6b). The result was concurrent with what was found by [18] who compared the pattern of SPI with the SOI data. The comparison result showed that there is a rather good similarity pattern among the standardized SOI, SPI, and PN where the determination coefficient (R^2) shows a value of 0.74 for SOI *vs* SPI and 0.51 for SOI *vs* PN.

This result indicates that there is a good agreement among the standardized SOI and SPI which means that the SPI shows better performance than PN. The result was consistent with [27] who found that between the SPI and PN showed a small difference in estimating drought occurrence where nearly all methods showed the same years as a dry year. The statistical association analyses, included the Pearson Correlation (r), Kendal tau (τ), and Spearman rho (r_s) for describing the quality degree of relationship between the SOI and SPI was showed by the value of 0.861, 0.736, and 0.896, respectively, while 0.706, 0.568, and 0.761 for the SOI and PN. It was known that the value of the Pearson correlation (r), Kendall tau (τ), and Spearman rho (r_s) showed a high value for the relationship between the SOI and SPI if compared with what was displayed by the SOI and PN. These results indicate that the drought method of SPI is more suitable compared with the PN method. A similar result was shown by [28] who found that the SPI was a little more robust than PN in modeling historical drought in the Yarra River basin. Furthermore, [10] decided to choose the SPI as a prime index considering its reliability for assessing drought compared with other indices. The result was concurrent with [29] who revealed that SPI had a strong correlation with El Nino Southern Oscillation Index during the dry season in Malaysia region which has similar climate characteristics with Indonesia. Furthermore, [30] identified spatio-temporal patterns of SPI had correlations with the SOI index on different time scales in Poyang lake basin of China, while [31] noticed that the SOI is positively correlated to the SPI-3 in Sahel region.

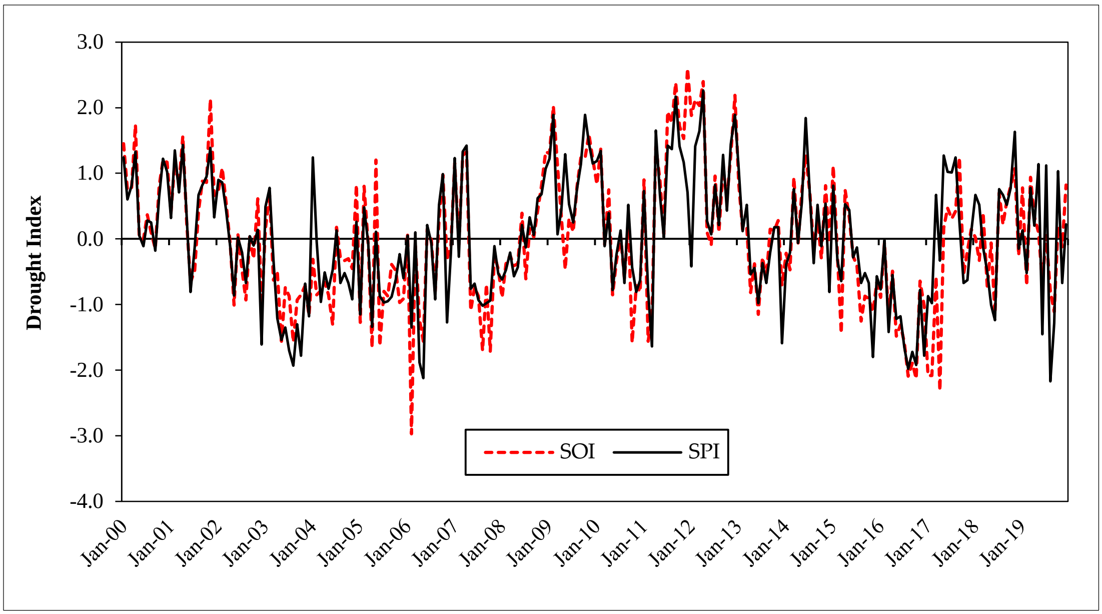


Figure 6a. The relationship pattern on monthly basis for SOI *vs* SPI during 2000 - 2019

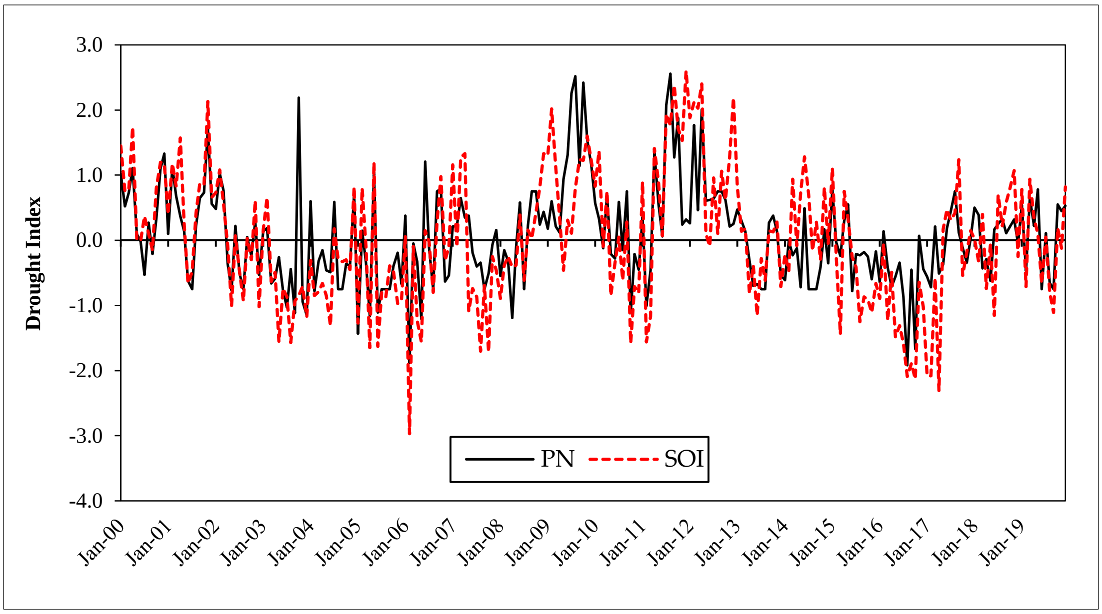
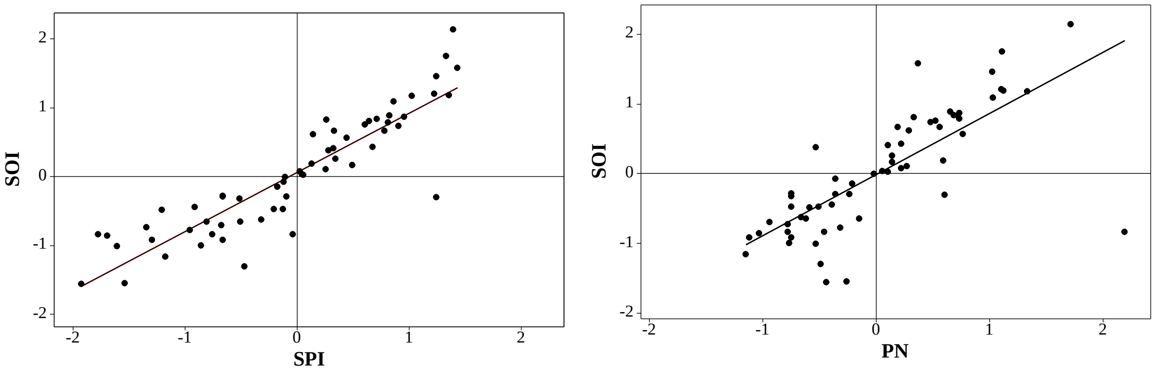


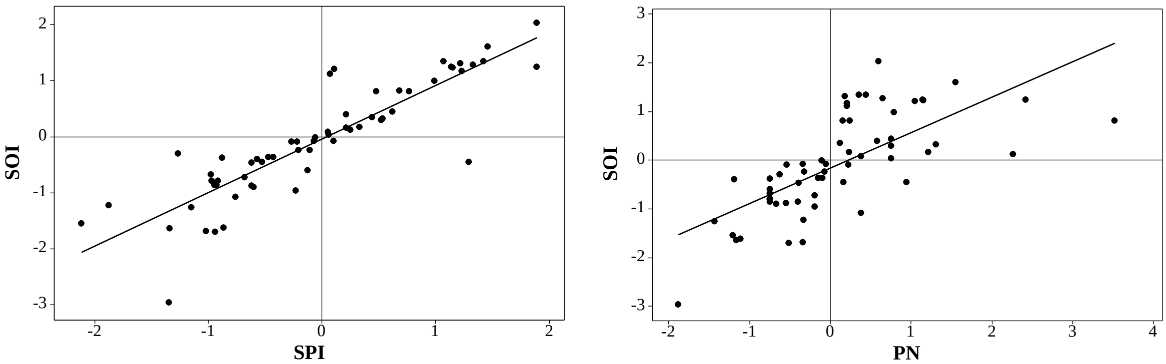
Figure 6b. The relationship pattern on monthly basis for SOI *vs.* PN during 2000 - 2019

It seems that the relationship between the meteorological drought index and the SOI index demonstrates a good quality in semi-arid and tropical regions. However, [32] found that there was an insignificant correlation between SOI and drought characteristics in Cyprus. The different climate region probably leads to why the result showed a weak association considering that the study was conducted in the European region. Accordingly, the method of SPI is considered as an appropriate method to assess the drought event characteristics in the study area.

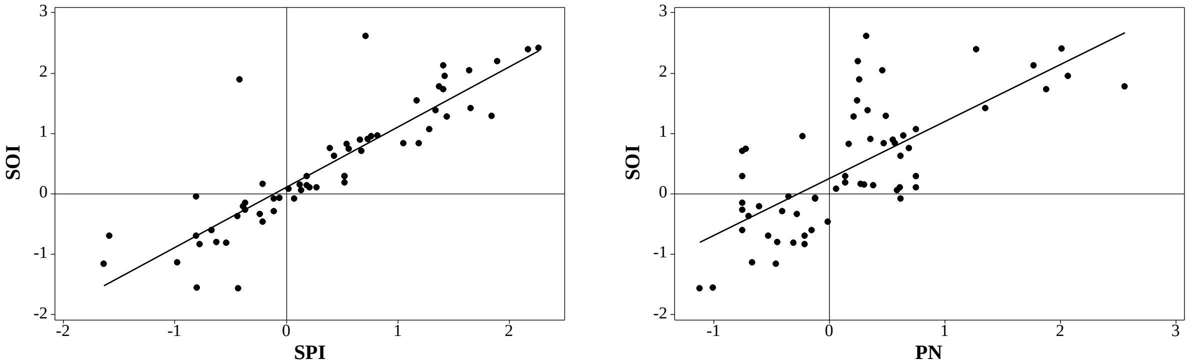
In order to know more concerning the pattern between the SOI and the two drought methods, the observation years were divided into four groups of the periodical years namely 2000 – 2004, 2005 – 2010, 2011–2014, and 2015 – 2019. Quantitative analysis using the Pearson correlation (r), Kendall tau (τ), and Spearman rho (r_s) were carried out for each group of the periodical years. Figure 7a to7d displays the scatter plot diagram to depict relationships among the SOI, SPI, and PN for each of the groups of the periodical year. Overall, the consistency and regular pattern were shown by the relationship between the SOI and SPI, while the relationship between the SOI and PN showed in contrast. As shown in those figures, the relationship pattern among the standardized SOI, SPI, and PN demonstrate a pattern that tends to slightly irregular in the group of the periodical year of 2010 – 2014 and 2015 – 2019 which was quantitatively shown by declining of the magnitude of Pearson correlation (r), Kendall tau (τ), and Spearman rho (r_s) as shown in Table 4. This condition is most likely due to the inconsistency of rainfall data caused by the climate change phenomenon and alteration of basin environment, thus it is essential to investigate the possibility of an alteration of rainfall data due to an alteration of basin environment and climatological characteristics.



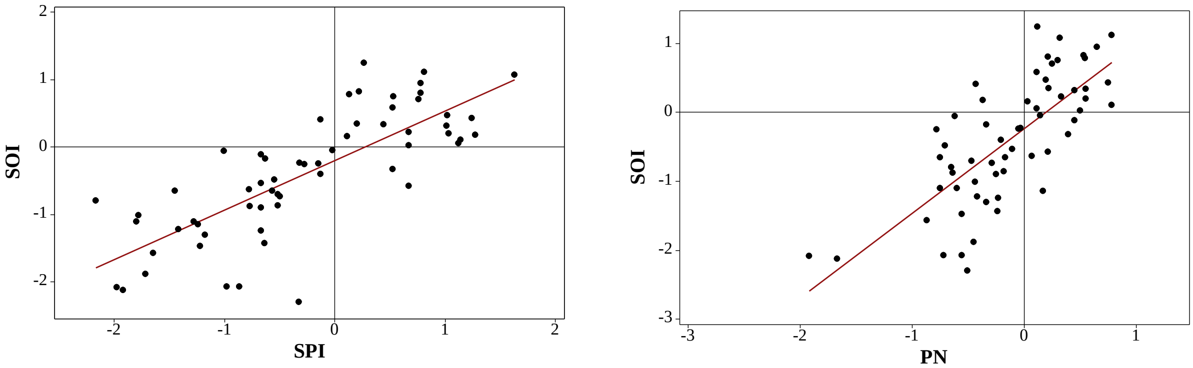
(a) 2000 – 2004



(b) 2005 - 2009



(c) 2010 - 2014



(d) 2015 - 2019

Figure 7. Scatter plot SOI versus SPI and PN for period: (a) 2000 - 2004; (b) 2005 - 2009; (c) 2010 - 2014; (d) 2015 - 2019

Table 4. Summary the statistical correlation of SOI vs. SPI and PN for each periodical year

Period (year)	Standardized Southern Oscillation Index (SOI) *vs.* Standardized Precipitation Index (SPI)			Standardized Southern Oscillation Index (SOI) *vs.* Percent of Normal Index (PN)		
	r	τ	r_s	r	τ	r_s
2000– 2004	0.81	0.78	0.92	0.57	0.66	0.81
2005 – 2009	0.77	0.79	0.91	0.55	0.57	0.68
2010 – 2014	0.75	0.77	0.91	0.52	0.55	0.57
2015 - 2019	0.61	0.59	0.81	0.48	0.51	0.52

Additionally, a more reasonable explanation concerning the declining tendency of the coefficients of correlation most probably associates with the possibility of climate change impact and alteration of basin environment that give an influence on the pattern of rainfall characteristic in the study area. Therefore, it is important to develop advanced research to examine to what extent the climate change impact and alteration of the basin environment significantly influence rainfall and climatological characteristics in the study area. Based on Table 4, it could be known that the SPI method showed a moderately high correlation for all coefficient of correlation compared with the PN method where the coefficient of correlation encompassed a value of 0.61 – 0.81 (Pearson correlation, r), 0.59 – 0.78 (Kendall tau, τ), and 0.81 – 0.92 (Spearman rho, r_s). From overall of the comparative analyses that have been performed on the drought index of SPI and PN methods, it could be taken a conclusion that the method of SPI has better performance and compatibility than the method of PN. The result was concurrent with Quiring (2009) [33] who stated that the SPI was the most suitable for monitoring meteorological drought compared with the PN and other indexes. Thereby, the results of the present study have confirmed that the method of SPI is feasible and well applied as a tool for assessing drought events and characteristics in the study area.

4. Conclusion

The present study used meteorological drought concept to assess drought characteristics in the study area. The Standardized Precipitation Index (SPI) and Percent of Normal Index (PN) were chosen as the method of drought index considering their simplicity and practicability since they only need a rainfall data as an input in their calculation. The monthly rainfall data were used for data input in the drought index calculation in the two drought methods to obtain a monthly drought index. The results of monthly drought index of the method of SPI and PN were compared with the standardized Southern Oscillation Index (SOI) data where the Pearson correlation (r), Kendall tau (τ), and Spearman rho (r_s) were employed to assess the degree of relationship among standardized SOI, SPI, and PN. The present study revealed that the SPI method showed a moderately high correlation for all coefficient of correlation compared with the PN method which confirmed that the SPI method more suitable and reliable to assess drought characteristics. Moreover, the consistency and regular pattern were shown by the relationship between the standardized SOI and SPI. Based on the overall comparison analyses that had been performed, the Standardized Precipitation Index (SPI) shows better compatibility than the Percent of Normal Index (PN) for estimating drought characteristics. Accordingly, the Standardized Precipitation Index (SPI) was proposed as a reliable drought method for analyzing drought characteristics in the study area. The study also confirmed the importance of developing advanced research concerning how the climate change impact and alteration of basin environment on drought characteristics. Further, the results revealed that the SOI data could be used as a variable to determine the reliability of drought index results.

5. Acknowledgement

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6. Conflicts of Interest

The authors declare no conflict of interest.

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