Spatiotemporal variation of drought characteristics based on Standardized Precipitation Index in Central Java over 1990-2010

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Abstract. Drought is a natural hazard that results from a deficiency of precipitation, leading to low soil moisture and river flows, reduced storage in reservoirs, and less groundwater recharge. This study investigates the spatial variations of drought characteristics (drought event frequency, duration, severity, and intensity). This study using the Standardized Precipitation Index (SPI) to analyse the drought characteristics in Central Java during 1990-2010. The rain gauge station data and CHIRPS rainfall data over Central Java is used to calculate the SPI index. The SPI was calculated at multiple timescales (1-, 3-, 6-, 12-, 24- and 48-month), the run theory was used for identification and characterization of drought events. Analysis of drought characteristics by SPI from 1990 to 2010 shows the longest drought event is four months, the maximum drought severity is 6.06, and the maximum drought intensity is 2.02. El Nino year probability drought occurrence reached 100% in August for moderate drought, severe drought, and extreme drought category, whereas the probability drought occurrences in the Normal and La Nina year range 0-70% for moderate drought, 0-50% for severe drought category and 0-40% for extreme drought category. The results of this study may help inform researchers and local policymakers to develop strategies for managing drought.

Keyword: drought index, SPI, drought characteristic

1. Introduction
Drought is one of the most common natural disasters that frequently occurs in Indonesia, with significant negative consequences for agricultural production, water resources, socioeconomic and ecosystem [1,2]. Drought affects to decrease in the harvest area of rice in Central Java as 9,735 ha in 1997 and 117,817 ha in 2003 compared to previous years. The production of rice also declines to 30,349 tons in 1997 and 279,684 tons in 2003[3].

Several methods have been developed to quantify drought characteristics. The indices are commonly used to quantify and to understand drought characteristics as duration, severity, intensity, and spatial extent [4]. To characterize and monitor meteorological, agricultural drought, and hydrological droughts, various drought indices have been developed. Some of these are the standardized precipitation evapotranspiration index (SPEI) [5], the Palmer drought severity index (PDSI) [6], and
Standardized Precipitation Index (SPI) [7]. SPI is one of the most widely used for drought evaluation and monitoring drought. WMO also has recommended the meteorological agency used SPI in analysing drought severity [8]. SPI was developed as a simple index, which required simple parameters, only considered rainfall in the calculation of SPI but provide a reliable representation of wetness and dryness [9].

Drought has been a frequent occurrence in many parts of the world in recent years, resulting in increased water demand and severe socioeconomic consequences [10,11]. As the risk of drought increases, a good understanding of the spatiotemporal characteristics of droughts is critical for water resource planning and management. Drought indices describe a comprehensive characteristic drought condition required for decision-making. A drought index must be able to capture the onset and termination of drought [12].

The goal of this study was to investigate drought characteristics; duration, severity, and intensity for 1990–2010 in Central Java. The results are expected to provide decision-makers and a wide range of stakeholders interested in the occurrence and consequences of drought events with useful information on drought risk.

2. Materials and Methods

2.1. Study area and data

Central Java is located in Java island, extending over 5°40′–8°30′ S and 108°30′ – 111°30′ E, covering an area of about 32,801 km² (25.04 % of Java Island area) and has second largest rice field in Indonesia (10,496 Ha). Central Java has a monsoonal rainfall pattern with the peak of rainfall season from December to March [13], with annual mean rainfall is 1500-3500 mm [14].

Historical rainfall data are covering the period of 1990-2010 for 161 rain gauge stations obtained from Agro-climate and Hydrology Research Institute (Figure 1). This study also uses rainfall data acquired from Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) to fill incomplete rain gauge station data during the study period. CHIRPS has considered a good correlation to observation station rainfall data [15,16]. CHIRPS data is obtained from http://chg.geog.ucsb.edu/data/chirps/ [17].

![Figure 1. Location of rain gauge used in this study](image-url)
2.2. Methods

2.2.1. Calculation of Standardized Precipitation Index

The SPI is an index that is calculated based on the probability distribution of long-term rainfall data time series [7]. The climatological precipitation time series is fitted well to gamma distribution [18]. To determine the SPI, the time series of rainfall data were fitted to incomplete gamma probability density function (PDF) as:

\[ g(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \]  \hspace{1cm} (1)

Where, \( \alpha > 0 \) is a shape factor, \( \beta > 0 \) is a scale factor, \( x \) is the precipitation amount \( (x > 0) \) and \( \Gamma(\alpha) \) is gamma function, define as:

\[ \Gamma(\alpha) = \int_0^\infty y^{\alpha-1} e^y dy \]  \hspace{1cm} (2)

Shape parameter and scale parameters can be estimated as:

\[ \alpha = \frac{1}{4A} \left(1 + \frac{4A}{3} \right) \]  \hspace{1cm} (3)

\[ \beta = \frac{\bar{x}}{\alpha} \]  \hspace{1cm} (4)

\[ A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \]  \hspace{1cm} (5)

Where, \( n \) = number of rainfall observations

Integrating PDF to obtain the cumulative probability distribution function \( G(x) \) given by:

\[ G(x) = \int_0^x g(x)dx = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{-x/\beta} dx \]  \hspace{1cm} (6)

Letting \( t = x/\beta \) to the incomplete gamma function, then \( G(x) \) found as:

\[ G(x) = \frac{1}{\Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{-t} dt \]  \hspace{1cm} (7)

The gamma function is undefined for \( x=0 \), and a rainfall distribution may contain zeros, the cumulative probability becomes:

\[ H(x) = q + (1 - q)G(x) \]  \hspace{1cm} (8)

Where \( q \) is the probability of zero \( P \). The cumulative probability \( H(x) \) is transformed into the standard normal SPI variable with mean zero and variance one [19]. SPI can be expressed as:

\[ SPI = \begin{cases} 
- \left( t - \frac{C_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right), & t = \sqrt{\ln \left( \frac{1}{(H(x))^2} \right)}, \quad 0 < H(x) \leq 0.5 \\
- \left( t - \frac{C_0 + c_1 t}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right), & t = \sqrt{\ln \left( \frac{1}{1 - H(x)} \right)}, \quad 0.5 < H(x) \leq 1 
\end{cases} \]  \hspace{1cm} (9)
with $c_0 = 2.515517$, $c_1 = 0.802853$, $c_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, and $d_3 = 0.001308$. Positive SPI values indicate wet condition, and negative values indicate dry condition (Table 1).

**Table 1. Classifications of SPI**

| SPI values | Class          |
|------------|----------------|
| $\geq 2.00$ | Extreme wet    |
| 1.50 ~ 1.99 | Severe wet     |
| 1.00 ~ 1.49 | Moderate wet   |
| -0.99 ~ 0.99 | Normal        |
| -1.49 ~ -1.00 | Moderate drought |
| -1.99 ~ -1.50 | Severe drought |
| $\leq -2.00$ | Extreme drought |

### 2.2.2. Drought identification using run theory

The run theory has been used frequently to identify drought parameters [20], investigate statistical properties of drought, and characterize drought events [10,21]. As shown in Fig 2, a drought event is characterized by drought duration ($D_d$), drought severity ($S_d$), and drought intensity ($I_d$). Drought initiation time ($T_i$) is the onset time of a drought event. Drought termination time ($T_t$) is the month when the water shortage becomes sufficiently small so that drought conditions no longer persist. Drought duration ($D_d$) is drought period time between the initiation and termination of a drought. Drought severity ($S_d$) is defining as a cumulative deficiency of a drought parameter below the critical level. Drought intensity ($I_d$) is obtained by the ratio of drought severity to the drought duration.

$$D_d = t_e - t_i \quad (10)$$

$$D_s = \sum_{i=1}^{d_d} SPI_i \quad (11)$$

$$I_d = \frac{S_d}{D_d} \quad (12)$$

**Figure 2.** The characteristics scheme identification using run theory, $X_i$=drought index value; $X_0$=threshold value; $T_i$=drought initiation time; $T_t$=drought termination time; $D$=duration; $S$=severity [20,22]
3. Result and Discussion

3.1.1. Temporal and spatial distribution of drought in Central Java

Multiple timescales of SPI were plotted in Figure 3 to obtain a deep view into drought characteristics. Drought events occurred with lower frequency and severity but longer duration as the timescale increased. For example, at the 12-, 24- and 48-month timescales, the drought duration is much longer compared to the short timescales 1-, 3-, and 6-month timescales. This could indicate the availability of various usable water sources under drought conditions, allowing for the monitoring of various drought types.

Figure 3. Temporal SPI for 1-, 3-, 6-, 12-, 24-, and 48-month timescales

Figure 4 shows some examples of the spatial distribution of the drought index according to SPI in Central Java. This example is shown based on El Nino, Normal, and La Nina years. The selection of El Nino, Normal, and La Nina years is based on the Oceanic Nino Index (ONI) issued by NOAA (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php), where 1997 was the strongest El Nino, 2010 was the strongest La Nina, and 2005 was chosen as the representative of the normal year. The distribution of drought in 1997 showed that the deficit was in a somewhat dry category (-1.49 ~ -1.0) began to occur around the Sragen area, in June the deficit conditions began to
expand into a somewhat dry and dry category (-1.50 ~ -2.0), in July the deficit condition increased to a dry category for most of the Central Java region, while the extreme deficit condition with an index value of less than -2 began to occur in August and the most extreme condition with an index reaching -3 occurred in September.

**Figure 4.** The sample of the spatial distribution of SPI in 1997 (El Nino), 2005 (Normal), and 2010 (La Nina)
3.1.2. Drought identification and characterization

The spatial characteristics of drought obtained from SPI calculations for 1990-2010 for the number of events, duration, severity, and intensity are shown in Figures 5, 6, 7, and 8. The number of drought events occurred at most 19 times, and the lowest was 13 times. Most incidents occurred in the southern region of Central Java, and the lowest incidence occurred in the northern region of Central Java.

![Figure 5](image5.png)

**Figure 5.** The drought event period 1990-2010 in Central Java

![Figure 6](image6.png)

**Figure 6.** The drought duration period 1990-2010 in Central Java

Figure 6 shows the average drought duration in Central Java, which is obtained from the ratio between the total number of drought duration and the total number of drought occurrences over 21 years (1990-2010). The duration of drought that occurs in Central Java ranges from 2 months to 4 months. The longest duration of drought occurs in the northeast, central and southern parts of Central Java, while the shortest duration of drought occurs in the eastern and western parts of Central Java.

Figure 7 shows the spatial pattern of the average severity of drought in Central Java, which is obtained from the total of drought severity divided to the total of drought events during the 1990-2010 period. The highest drought severity is shown in red, and the lowest is shown in blue. The drought severity ranges from 4.02 to 6.06. The highest level of drought severity occurred in the northeast and southwest of the Central Java region, while low severity occurred almost evenly in most parts of Central Java.
3.1.3. Probability of Drought events
The SPI index has three drought categories, namely moderate drought, severe drought, and extreme drought. The probability of each of these categories is illustrated respectively in Figures 9, 10, and 11. The probability of drought occurring each month is also calculated based on the years of El Nino, Normal, and La Nina events in the period 1990-2010, where El Nino years occurred in 1991, 1994, 1997, 2002, 2004, 2006, and 2009. Normal years occurred in 1990, 1992, 1993, 1996, 2001, 2003, 2005, and 2008 and the La Nina Years occurred in 1995, 1998, 1999, 2000, 2007, and 2010.

Figure 9 shows the probability of the occurrence of the moderate drought of SPI. The probability of drought occurring 3 in El Nino years is high from July to September, with the highest probability reaching 70-100% in August in almost all areas of Central Java. In January-April and December, the chance of drought is only up to 20%. In May, October, and November, the chance of drought is around 20-70%. The probability of drought occurring in normal years is lower than El Nino years, where the
probability of drought occurring tends to be high in June-September but only in a small part of Central Java, while in other months, the probability of drought occurring is below 20%. The probability of drought occurring in La Niña is lower than the probability of drought occurring in El Nino and Normal years.

Figure 9. The probability of moderate drought of SPI (-1.49 ~ 1.00)
Figure 10 illustrates the probability of severe drought of SPI. The probability of severe drought occurring in El Nino years is higher than in Normal and La Nina years, with the highest chance of drought occurring in August followed by September, which reaches 100%, while the probability of drought in other months ranges from 0-60%. In normal and La Nina years, the probability of drought occurring ranges from 0 to 60% in the dry months and below 20% in the wet months.

**Figure 10.** The probability of severe drought of SPI (-1.99 ~ 1.50)
Figure 11. The probability of extreme drought of SPI (≤ -2.00)

Figure 11 shows the probability of extreme drought events of SPI. The probability of extreme drought in El Nino reaches 100% in August in the western region of Central Java and ranges from 0-70% in September, while the probability of drought in other months ranges from 0-50%. The probability of drought in normal and La Nina years reaches 0-40% in August and September, while in other months, the probability of drought is between 0-10%.
4. Conclusion
The result of this study shows that the most extreme drought occurs in El Nino year (1997) from July to September. Drought characteristic in Central Java for the period 1990-2010 show that the maximum drought event is 19 times with the maximum drought duration is 4 months, the maximum drought severity is 6.06, and the maximum drought intensity is 2.02.

Drought probability in El Nino year (1997) reaches 100% in August and September for moderate drought, severe drought, and extreme drought. In normal year (2005), drought probability is varied from 0-70% for moderate drought, 0-50% for severe drought, and 0-40% for extreme drought. Spatiotemporal characteristics of drought are expected to provide useful information on drought risk for decision-maker to establish drought management strategies.

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