ANALYSIS OF METEOROLOGICAL DROUGHT PROPAGATION TOWARDS HYDROLOGICAL DROUGHT IN THE UPPER BRANTAS WATERSHED, EAST JAVA

Analisis Perambatan Kekeringan Meteorologi Menuju Kekeringan Hidrologi Di DAS Brantas Hulu, Jawa Timur

Samba Wirahma[1)], I Putu Santikayasa[2)*], Muh Taufik[2)], Findy Renggono[3)]

[1)]Pascasarjana Klimatologi Terapan, Institut Pertanian Bogor, Kampus IPB Darmaga Bogor 16680
[2)]Departemen Geofisika dan Meteorologi, Fakultas Matematika dan Ilmu Pengetahuan Alam, Institut Pertanian Bogor, Kampus IPB Darmaga Bogor 16680
[3)]Pusat Riset Iklim dan Atmosfer, Badan Riset dan Inovasi Nasional, Puspiptek Serpong, Tangerang 15314
[*]E-mail: ipsantika@apps.ipb.ac.id

Intisari

Kekeringan didefinisikan sebagai kondisi defisit air dari kondisi normal dalam sistem hidrologi. Kekeringan hidrologis merupakan proses yang kompleks yang didahului oleh defisit curah hujan. Tidak seperti banyak bencana alam yang lain, kekeringan berkembang perlahan, sehingga sangat sulit untuk menentukan awal dan akhir dari suatu peristiwa kekeringan. Riset yang berfokus mempelajari perambatan dari kekeringan meteorologis ke kekeringan hidrologis sangat penting untuk mengungkapkan proses serta mekanisme perambatan kekeringan. Perambatan kekeringan menggambarkan perubahan sinyal kekeringan meteorologi menjadi kekeringan hidrologi melalui siklus hidrologi. Penelitian ini bertujuan untuk menganalisis karakteristik kekeringan dan mengevaluasi perambatan kekeringan di DAS Brantas Hulu Jawa Timur. Penelitian ini menggunakan metode Standardized Precipitation Index (SPI) dan Standardised Streamflow Index (SSI) dengan akumulasi waktu 1, 3, 6 dan 12 bulan untuk menganalisis karakteristik kekeringan meteorologi dan hidrologi, sementara perambatan kekeringannya dianalisis menggunakan korelasi Pearson. Hasil penelitian menunjukan durasi dan keparahan kekeringan bertambah seiring peningkatan periode akumulasi SPI dan SSI, sedangkan jumlah kejadian kekeringan berbanding terbalik dengan periode akumulasi SPI dan SSI. Tingkat keparahan kekeringan hidrologi lebih tinggi dari keparahan meteorologi. Kekeringan hidrologi terparah (SSI1 = -22,9) dengan durasi 12 bulan terjadi pada periode tahun 1997-1998. Korelasi yang tinggi pada kondisi tidak ada selang waktu antara SSI dan SPI menunjukan bahwa indikator kekeringan meteorologi dengan SPI berpotensi untuk dijadikan sebagai alat deteksi dini kekeringan hidrologi pada DAS Brantas Hulu. Penelitian ini mampu menjadi langkah awal untuk membangun teknik deteksi dini kekeringan hidrologi yang sangat bermanfaat dalam manajemen sumberdaya air dalam DAS untuk operasional PLTA.

Kata Kunci: Perambatan kekeringan, Kekeringan hidrologi, Kekeringan meteorologi, SPI, SSI

Abstract

Drought is defined as a water deficit condition from normal conditions in the hydrological system. Hydrological drought is a complex process that is preceded by a rainfall deficit. Unlike many other natural disasters, droughts develop slowly, making it difficult to pinpoint the beginning and the end of a drought event. Research that focuses on studying the propagation of meteorological drought to hydrological drought is fundamental to revealing the processes and mechanisms of drought propagation. Drought propagation describes the change of meteorological drought signal into hydrological drought through the hydrological cycle. This study aims to analyze the characteristics of drought and evaluate the propagation of drought in the Upper Brantas watershed of East Java. This study uses the Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) methods with an accumulated time of 1, 3, 6, and 12 months to analyze meteorological and hydrological drought characteristics, while the drought propagation was analyzed using Pearson correlation. The results showed that the duration and severity of drought increased with the increase in the period of accumulation of SPI and SSI, while the number of drought events was inversely proportional to the period of accumulation of SPI and SSI. The severity of hydrological drought is higher than the severity of meteorological. The worst hydrological drought (SSI1 = -22.9) with a duration of 12 months occurred in 1997-1998. The high correlation in the condition that there is no time lapse between SSI and SPI shows that the meteorological drought indicator with SPI has the *potential to be used as an early detection tool for hydrological drought in the Upper Brantas watershed. This research can be the first step to developing a hydrological drought early detection technique that is very useful in water resource management in watersheds for hydropower operations.*

Keywords: Drought propagation, Hydrological drought, Meteorological drought, SPI, SSI

1. INTRODUCTION

Drought is a complex phenomenon that occurs at various spatial and temporal scales (Wilhite, 2000). Drought can lead to forest fires (Taufik et al., 2017), desertification (Liu and Diamond, 2005), reduced water supplies (DeGaetano, 1999; Sun et al., 2018; Van Loon et al., 2016), and reduced yields. harvest (Lesk et al., 2016; Wang et al., 2014). Unlike many other natural disasters, droughts develop slowly, making it difficult to pinpoint the beginning and end of a drought event.

Droughts are generally grouped into three categories: meteorological droughts (below average rainfall), agricultural droughts (below normal groundwater levels), and hydrological droughts (below-expected river flows) (Tallaksen and Van Lanen, 2004); Van Loon et al., 2016). Meteorological and hydrological droughts are the most researched categories for scientists (Ye et al., 2016). Research that focuses on studying the propagation of meteorological drought to hydrological drought is fundamental to revealing the processes and mechanisms of drought propagation. It can help build a drought early warning system (Vicente-Serrano and López-Moreno, 2005; Van Loon and Laaha, 2015; Barker et al., 2016).

Early hydrological drought detection is a fundamental requirement in water resource management in watersheds. Several early detection methods are formed from understanding hydrological drought propagation patterns (Hannaford et al., 2011; Wong et al., 2013). The occurrence of drought can be explained through drought properties, which can also be called drought characteristics. Identification of drought characteristics is needed to understand the process and impact of drought (Van Loon and Laaha, 2015). The need to identify and quantitatively analyze drought duration, severity, onset, and end of drought has led to the development of drought indicators. Drought indicators are developing rapidly to identify drought characteristics in the form of time of occurrence, drought duration, the volume of drought deficit, and drought intensity (Fleig 2004; Tallaksen and Van Lanen 2004). Lloyd-Hughes (2014) states that there are more than 100 drought indicators. One of the uses of drought indicators is monitoring and early warning systems, which is an essential part of drought preparedness (Bachmair et al., 2016).

Meteorological drought indices such as PDSI (Palmer Drought Severity Index) (Palmer, 1965), SPEI (Standardized Precipitation Evapotranspiration Index) (Vicente-Serrano et al., 2010), and SPI (Standardized Precipitation Index) (Mckee et al., 1993) are indexes often used to monitor meteorological droughts around the world. Compared to PDSI and SPEI, SPI is more widely accepted because the calculation is simple, can be calculated for various timescales, and has fewer input requirements (only requires rainfall data) (Mo, 2008; Andreadis et al., 2005; Wang et al., 2011; AghaKouchak and Nakhjiri, 2012; Stagge et al., 2015; Balbo et al., 2019). SPI has been widely adopted to investigate drought in various regions. SPI calculations with different time scales can impact the assessment of drought conditions in multiple areas. A fundamental advantage is that it can be calculated for various timescales, which allows the SPI to monitor short-term and long-term droughts such as agricultural droughts and hydrological droughts, respectively (Mishra and Singh, 2010).

Tom McKee, Nolan Doesken, and John Kleist (1993) of the Colorado Climate Center first developed the SPI method to define and monitor drought. The advantage of the SPI method is that the index value can be compared spatially and temporally. In addition, the SPI also provides an indicator of the severity and probability of drought events. The addition of a negative value indicates an increasingly severe drought (Lloyd-Hughes and Saunders, 2002). One of the shortcomings of the SPI is that the selection of the right opportunity distribution is still in the literature review (Stagge et al., 2015), and fitting the probability distribution function with data that has a lot of zero values is often problematic (Wu et al., 2017). SPI is indispensable for measuring variations in hydrological response to meteorological drought because of its ability to investigate drought severity at different time scales (Vicente-Serrano & Lopez-Moreno, 2005). Its simple calculation, comparability, and flexibility make SPI one of the indicators of choice for monitoring meteorological drought by the World Meteorological Organization (Hayes et al., 2011).

Svensson et al. (2015) and Barker et al. (2016) developed a standardized hydrological drought indicator called the Standardized Streamflow Index (SSI). SSI uses the same principle as SPI, which combines river flow data over a predetermined period of accumulation of time (Vicente-Serrano et al., 2011; Lorenzo-Lacruz et al., 2013). Unlike the calculation of rainfall and SPI, there is no probability distribution function attached to the river flow data for SSI analysis. Likewise, in developing a hydrological drought early warning system, it is necessary to understand the propagation of the meteorological deficit to the formation of hydrological drought. Streamflow, and so the SSI, integrates catchment-scale hydrogeological processes. A comparison with the SPI indicates the time taken for precipitation deficits to propagate through the hydrological cycle to streamflow deficits. Folland et al. (2015) and Barker et al. (2016) used standardized indicators to assess the propagation of meteorological drought to hydrological drought.

One of the sectors affected by drought is the energy sector (Van Loon, 2015). The Upper Brantas Watershed in East Java Province was chosen as the study area because the watershed is an area that has strategic value. River water in the Upper Brantas watershed is used for various purposes, including power generation (PLTA), irrigation, raw water for Regional Drinking Water Companies (PDAM) and industry, fisheries, and tourism.

Hydropower in the Brantas watershed requires water resources that remain above the operational threshold, but in reality, the rainfall has changed from its normal condition and can trigger hydrological drought. The application of weather modification technology has often been carried out to overcome shortages in the Upper Brantas watershed. Still, accurate information on the time and duration of drought is needed to support the application of weather modification technology.

This research was conducted to identify the characteristics of meteorological drought and hydrological drought using the SPI and SSI methods in the Upper Brantas watershed, evaluate the relationship between meteorological drought and hydrological drought and identify propagation patterns from meteorological drought to hydrological drought. This study is the first step to developing a hydrological drought early detection technique in the Upper Brantas watershed, which is very useful in managing water resources for hydropower operations.

2. RESEARCH METHOD

2.1. Location

The research location is devoted to the Upper Brantas watershed, East Java, with an area of ±2,200 km² (Figure 1). The topography is bounded by the Bromo-Tengger-Semeru Mountains in the east, while in the west, it is bordered by the Arjuno-Welirang and Mount Kawi mountains. The main river flow confounds several tributaries on the western and eastern slopes. Karangkates Lake (Sutami Reservoir) is in the south as a flowing reservoir in the Upper Brantas watershed.

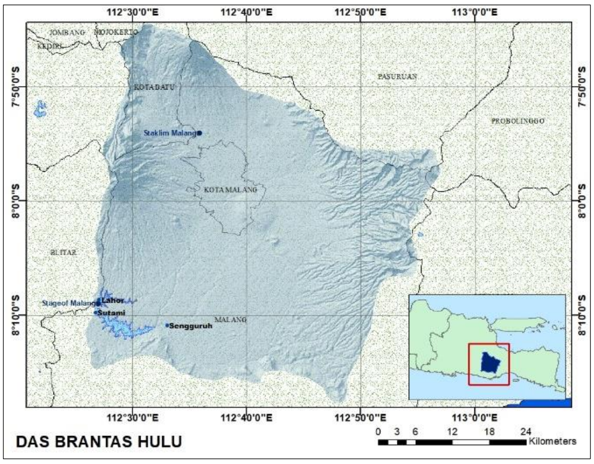


Figure 1. Map of rain station and hydropower in the Upper Brantas watershed

2.2. Materials and Tools

The data used in this study is in the form of daily rainfall data and monthly inflow of the Upper Brantas watershed area. Rainfall data were obtained based on the results of measurements from 2 (two) locations with different data durations, namely the Malang climatology station (location in the northern part of the watershed) from 1991-2020 (30 years) and the Malang geophysics station (location in the southern part of the watershed) from 2010-2020 (11 years), while monthly inflow data of Sutami Reservoir for 1991-2020 were obtained from AWLR of Sutami Reservoir. In addition, an administrative map of the Upper Brantas watershed is needed. The tools used include a set of computers equipped with R software, Minitab 19, ArcGIS 10.1, and Microsoft Office.

2.3. Data Analysis

This research is divided into three stages: 1) Analysis of regional rainfall and inflow data from the Sutami Reservoir; 2) Identification of meteorological drought characteristics using the SPI method and hydrological drought using the SSI method; 3) Analysis of meteorological drought propagation to hydrological drought.

2.3.1. Data Analysis of Rainfall and Inflow of Sutami Reservoir

The calculation of the value of regional rainfall using the arithmetic method (equation 1). Regional rainfall from Malang climatology station and Malang geophysics station 1991-2020 (according to data availability) was used for SPI calculations.

$$P_w = \frac{i}{n}\sum_{i=1}^{n} P_i \quad [1]$$

where P_w is the regional rainfall, and P_i is the rainfall at the i-th station. Daily rainfall data is made monthly by adding up the daily rainfall in one month.

The daily inflow data is converted into monthly data by averaging the daily inflow every month for all time series observed data (years 1991-2020). Using the SSI method, this data is used as input for hydrological drought analysis. In addition, monthly inflow data is also used to describe seasonal inflow conditions (January-December) by calculating the average inflow for 30 years.

2.3.2. Identification of Meteorological and Hydrological Drought Characteristics

Meteorological drought was identified using the SPI method. The SPI value is calculated by first accumulating rainfall data within a specified period (1, 3, 6, 9, 12, or 24 months) and fitting the rainfall accumulation value with the probability distribution function. Furthermore, the probability distribution value transforms into a standardized normal distribution with an average of 0 and a standard deviation of 1. The SPI calculation describes the number of standard deviations of the accumulated rainfall value from its long-term average (McKee et al., 1993; Lloyd-Hughes and Saunders, 2002; Stagge et al., 2015; Barker et al., 2016). The results of research by McKee et al. (1993), Guttman (1999), and Stagge et al. (2015) show that the Gamma distribution is mainly following the distribution of rainfall so that each rainfall accumulation data for 30 years is then converted into the form of a Gamma distribution.

Hydrological drought was identified using the SSI method. The SSI calculation procedure is the same as the SPI by first accumulating debit data for a specific time (Vincente-Serrano, 2011). Vincente-Serrano (2011) uses several probability distribution functions in calculating SSI.

The SPEI package in R (Begueria and Vincen-Serrano, 2015) is used to calculate the SPI and SSI for the accumulation period of 1, 3, 6, and 12 months. The accumulation period is expressed as SPIx and SSIx. SPI3 and SSI1 show SPI with a 3-month rainfall accumulation period and SSI with a 1-month inflow accumulation period.

McKee et al. (1993) used the SPI classification to determine drought intensity (Table 1) based on the proportion of occurrences in 100 years, with 24% mild dry, 9.2% moderately dry, 4.4% dry, and 2.3% very dry.

Table 1. SPI classification (McKee et al., 1993)

SPI	Category
≥ 2.00	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.00 to -1.49	Moderately dry
-1.50 to -1.99	Severely dry
≤ -2.00	Extremely dry

Drought occurrence is defined as a period when the index value is continuously negative for one month (McKee et al., 1993; Vidal et al., 2010; Barker et al., 2016). Thresholds to define drought are divided into three classes, namely <-1 (slightly dry), <-1.5 (dry), and <-2 (very dry) (Lloyd-Hughes and Saunders, 2002). The drought characteristics identified were the duration of each drought event in monthly resolution and the drought severity (sum of the SPI or SSI index values) in each drought event (Vidal et al., 2010; Barker et al., 2016).

2.3.3. Drought Propagation

A comparison of SPI with SSI indicates the time it takes for a rainfall deficit to pass through the hydrological cycle until a deficiency in the watershed occurs. The SPI accumulation period of 1-12 months and SSI1 were cross-correlated using the Pearson correlation coefficient to analyze the SPI accumulation period that most accurately characterizes SSI1. Monthly minimum flows are well-described at the 1-month SSI, reflecting the 30-day flow average commonly used in annual minimum flow studies (Gustard et al., 1992; Barker et al., 2016). The SPI accumulation period, which has the strongest correlation with SSI1, is used as an indicator for analyzing drought propagation (Barker et al., 2016). Furthermore, correlations between SPI 1-12 months and SSI1 were also carried out with an interval of 0-3 months after the SPI time series to illustrate the existence of a lag between meteorological and hydrological drought events.

3. RESULTS AND DISCUSSION

3.1. Watershed Hydrological Conditions

The Upper Brantas watershed area has a rainfall pattern with one peak in the rainy season and one peak in the dry season in the one-year. The pattern indicates that rain in the Upper Brantas watershed is influenced by monsoon winds (Aldrian and Susanto, 2003). The observations for 30 years from 1991 to 2020 from the Malang Climatology station and Malang Geophysics station show that the wet period of the Upper Brantas watershed (rainfall is more than 200 mm/month) occurs from November to March (Figure 2). The peak of the rainy season occurs in December-January-February, with the average rainfall in January reaching 322,9 mm. The dry period of the Upper Brantas watershed lasts from May to October. The driest month is August, with only 17,2 mm of rainfall. The annual rainfall of the Upper Brantas watershed reaches 1902,9 mm/year, with an average monthly rainfall of 158,6 mm.

An increase follows the pattern of increasing rainfall in the Upper Brantas watershed in the inflow pattern of the Sutami Reservoir in the next 1-2 months (Figure 2). The maximum inflow period occurs in February-March-April, with the peak inflow in March of 118,4 m^3/s or equivalent to 0,3 x 10^9 m^3/month. The minimum period occurs in August-September-October, with the lowest inflow in September, 42,9 m^3/s. During this month, the inflow of the Sutami Reservoir was only 0,1 x 10^9 m^3/month or decreased by 70% from the maximum inflow in March. Overall, the average monthly inflow of the Sutami Reservoir is 78,3 m^3/s (0,2 x 10^9 m^3/month) with an annual inflow volume of 2,4 x 10^9 m^3.

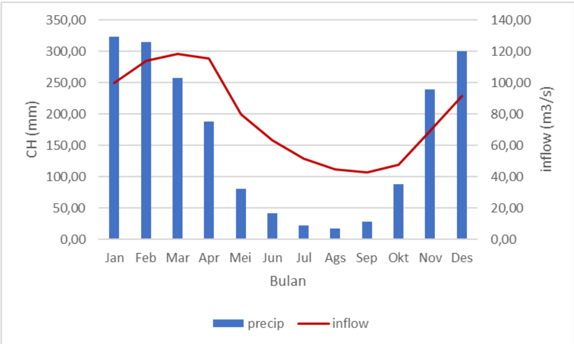
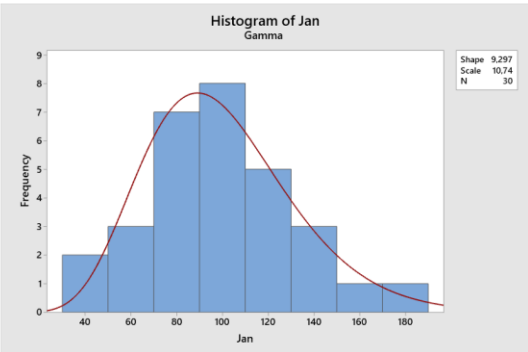
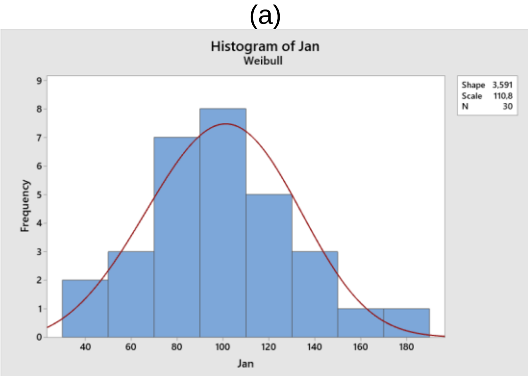


Figure 2. Average monthly rainfall and inflow of the Upper Brantas Watershed based on historical data analysis 1991-2020.

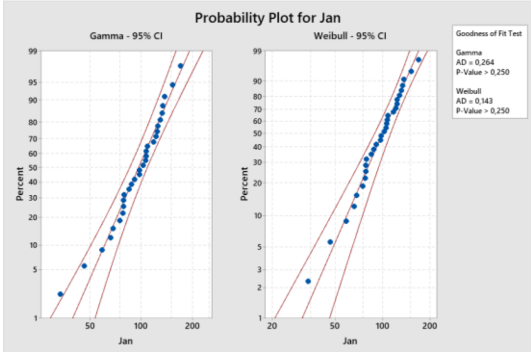
Monthly inflow data in the Sutami Reservoir was chosen for drought analysis using the SSI method because it describes the flow rate that enters the Upper Brantas watershed system. The monthly inflow data testing results using the Gamma and Weibull distributions show that the inflow data mostly follow the Gamma and Weibull distributions, as evidenced by the smaller Anderson Darling value (Figure 3).



(a)



(b)



(c)

Figure 3. (a) Histogram and Gamma distribution of the January inflow of the Sutami Reservoir. (b) Histogram and Weibull distribution of the January inflow of the Sutami Reservoir., and (c) Probability plot for Gamma and Weibull of the January inflow of the Sutami Reservoir.

3.2. *Drought Characteristics*

Drought characteristics that show the nature of drought in the Upper Brantas watershed are expressed in terms of the number of drought events, the beginning and end of the drought, duration of drought, and drought severity. Drought events are stated when the SPI and SSI index values show a value of less than -1. The red lines in Figures 4 and 5 indicate the threshold for drought events. The index value of -1,0 to -1,49 is expressed as a slightly dry condition. Dry conditions when the index is worth -1,5 to -1,99 and very dry when the index is -2 (Lloyd-Hughes and Saunders, 2002).

3.2.1. *Meteorological Drought*

The time series of meteorological drought index values for the Upper Brantas watershed 1991-2020 with an SPI accumulation period of 1 month to 12 months is presented in Figure 4. Figure 4 shows that according to SPI1, a drought occurred almost every year until 2019, with a dry month period of 48 months (13%). Drought occurred until 2019, according to SPI3, for 49 months (14%). According to SPI6, there was a drought with 50 dry months (14%). The Upper Brantas watershed did not experience any meteorological drought events after 2018, according to an analysis with SPI12. The dry period in SPI12 was 49 months (14%).

Most of the droughts in the Upper Brantas watershed are in the moderately dry category, with the number of dry months according to SPI 1, 3, 6, and 12 months, 8%, 7%, 9%, and 9%. The dry category ranged from 1-4%, while the arid months only comprised 2-3% of the total study months (360 months).

The results of the SPI index plot in Figure 4 show that the duration and severity of meteorological drought increase with increasing SPI accumulation period. This can be seen from the dry and wet periods, which are getting clearer, and the fluctuations in the index value are decreasing. A recapitulation of drought characteristics in the form of duration and severity of drought is presented in Table 2. There are 41 meteorological drought events in the Upper Brantas watershed, according to SPI1. The number of droughts was reduced to 28 according to SPI3, 23 events based on SPI6, and only 13 events found on SPI12. Meteorological drought in the Upper Brantas watershed has a different duration in each SPI accumulation period. In SPI1, 83% of drought events lasted one month with a maximum of 2 months. In SPI3, 61% of drought events have a duration of 1 month with a maximum period of 5-6 months (May – October 1997 and November 2006 – March 2007), and in SPI6, 57% of drought events have a duration of 1 month with a maximum duration of 8-9 months (July 1997 - March 1998 and November 2006 – July 2007). At the same time, the maximum duration of SPI12 results is 8-12 months. The duration of drought events is getting longer with increasing SPI accumulation period. The average duration according to SPI 1-12 is 1,1, 1,8, 2,2, and 3,8 months, respectively. The maximum drought duration occurred in the 1997-1998 and 2006-2007 droughts.

The severity of the drought resulted from the sum of the drought index of less than -1 during a period of drought events. Drought severity increased with increasing drought duration. Based on the SPI1 analysis, the maximum drought severity value was -3,5 – (-3,7) from December 1997 – to January 98 and March – April 2009. Identification with SPI3 resulted in a severity value of up to -12,8 with an average of -2,8. Two drought events with the highest severity were in May - October 1997 and November 2006 - March 2007, with -9,8 and -12,8. November 2006 – March 2007 was a very dry period (index value -2,3 to -3,2 while in 1997, the average was identified as slightly dry). The maximum severity of SPI6 and SPI12 was –23 and -32,6 occurred between 2006-2007, with the average severity of SPI6 and SPI12 being -3,5 and -6,3.

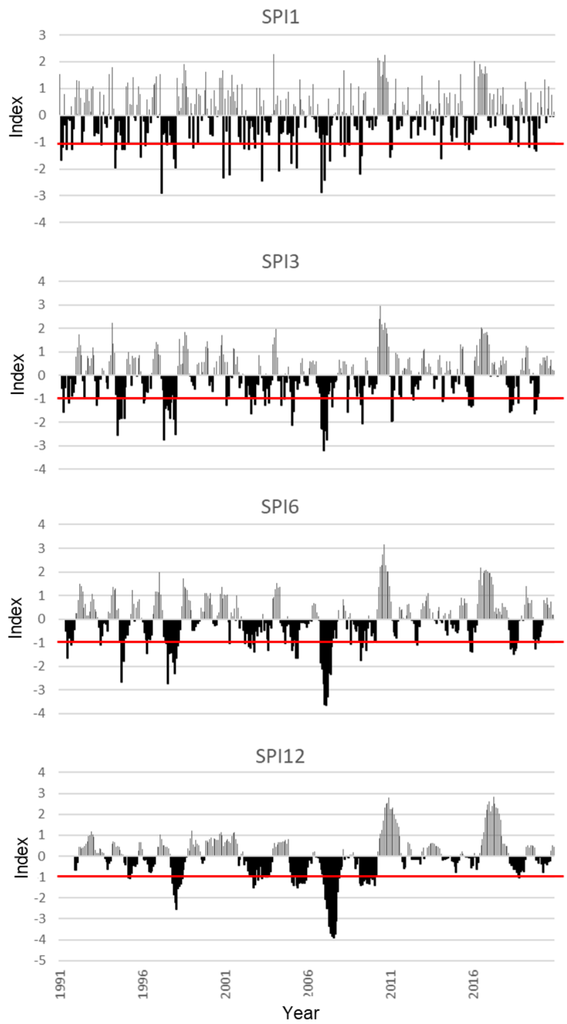


Figure 4. Meteorological drought time series in the Upper Brantas watershed 1991-2020 according to SPI 1-12 months. (The red line shows the threshold for meteorological drought.

Table 2. Drought characteristics of the Upper Brantas watershed 1991-2020.

	Number of events	Duration (Month)		Severity(-)	
		Average	Max	Average	Max
SPI1	41	1,1	2	-1,8	-3,7
SPI3	28	1,8	6	-2,8	-12,8
SPI6	23	2,2	9	-3,5	-23,0
SPI12	13	3,8	12	-6,3	-32,6
SSI1	16	2,8	12	-4,2	-22,9
SSI3	13	3,8	13	-6,0	-26,4
SSI6	8	5,9	15	-9,4	-30,2
SSI12	8	6,8	18	-10	-33,7

3.2.2. Hydrological Drought

The time series of hydrological drought index values in the Upper Brantas watershed 1991-2020 with an SSI accumulation period of 1 month to 12 months is presented in Figure 5. Based on Figure 5, it can be seen that according to SSI1, SSI3, and SSI6, the hydrological drought in the Upper Brantas watershed lasted until 2020, with The number of dry months for SSI 1-6 months in a row being 44 months (12%), 50 months (14%) and 47 months (13%). Drought only occurred until 2007, according to SSI12, with a total of 54 dry months (15%). Most of the droughts in the Upper Brantas watershed are in the moderately dry category with the number of dry months according to SSI 1, 3, 6, and 12 months in a row, namely 7%, 8%, 5%, and 9%. The dry category ranges from 3-5%, while the very dry month is only 2-3% of the total study month (360 months).

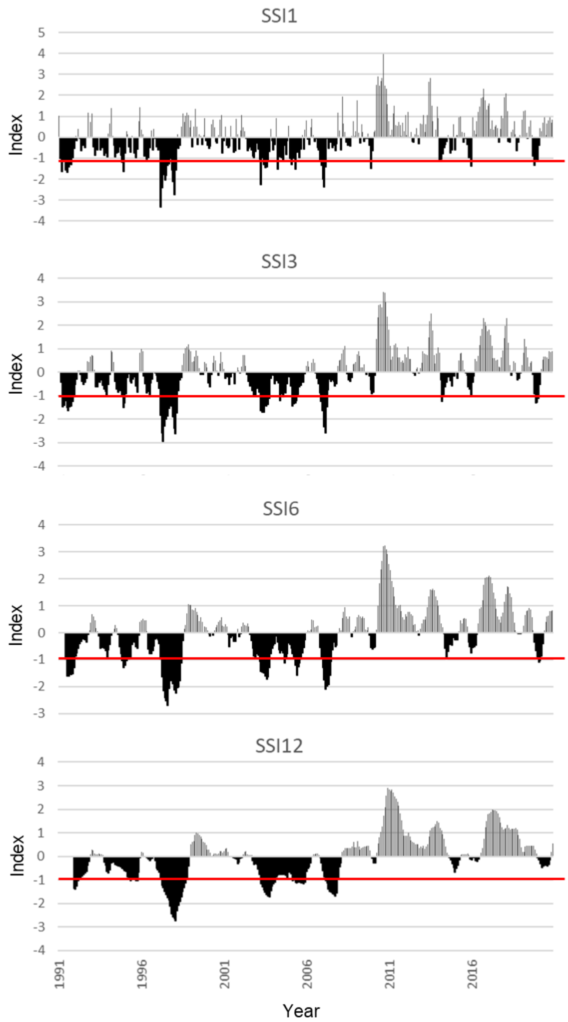


Figure 5. Hydrological drought time series of the Upper Brantas watershed 1991-2020 according to SSI 1-12 months. (The red line shows the threshold for meteorological drought)

The incidence of hydrological drought in the Upper Brantas watershed from SSI for 1-12 months was 16, 13, 8, and 8 events (Table 2). The incidence of this drought is less than that of meteorological drought for all periods of SSI accumulation. The hydrological drought in SSI 1-3 mostly (45-50%) lasted one month with an average of 2,8 – 3,8 months and a maximum of 12 and 13 months. Although SSI6 and SSI12 have the same number of hydrological events (8 events), the maximum hydrological drought duration based on SSI6 is 15 months with an average duration of 5,9 months, while for SSI12, the maximum hydrological drought duration is 18 months with an average duration of 6,8 months. The maximum drought duration of 18 months occurred from April 1997 – to September 1998. The average hydrological drought duration was longer than the average meteorological drought duration.

The severity of the drought increased with increasing periods of SSI accumulation. Based on Figure 5, it can be seen that the highest drought severity occurred in the dry periods 1997-1998, 2006-2007, and 2003-2004, with a range of severity values (SSI 1-12) successively -22,9 to -33,7, -8,2 to -12,9 and -5,2 to -15,4. In this period, there were very dry hydrological conditions (index value per month -2), namely in the period March 1997 - January 1998, April 2003 and February 2007 (SSI1), April 1997 - February 1998, and February-March 2007 (SSI3). May 1997 – April 1998 and March 2007 (SSI6) and October 1997 – April 1998 according to SPI12. This drought is known to cause the water level of the Sutami Reservoir to drop below 260 m. The mean and maximum severity of the hydrological drought yielded by SSI 1-12 months is greater than the meteorological severity. Barker et al. (2016) found that hydrological drought has a higher severity and longer duration than meteorological drought. A study of 121 watersheds in the UK showed that the number of occurrences of meteorological drought was greater than that of hydrological drought.

3.3. *Drought Propagation*

Drought propagation describes changes in meteorological drought signals into hydrological droughts through the hydrological cycle. Drought propagation is quantified by correlating the 1-month SSI indicator with the 1-12-month SPI indicator to see the timescale when the rainfall deficit propagates through the hydrological cycle, causing a deficit in the watershed system. The correlation was carried out between 1-month SSI and 1-12 month SPI using 0-3 months to see the lag between meteorological droughts and hydrological droughts.

Figure 6 shows the time series of the drought index with a cross-correlation coefficient between the 1-month SSI and the 1-12-month SPI. The correlation between SSI 1 month and SPI 1-12 months in the Upper Brantas watershed in 1991-2020 is presented in Table 3. The correlation results show that SSI 1 is strongly correlated (r ≥ 0.50) with SPI 1, 3, and 6 months. The strongest correlation occurred with the 3-month SPI with a correlation value of 0.60. This shows that the hydrological drought in the Upper Brantas watershed is strongly influenced by the rainfall deficit in the same month up to the previous three months. This is similar to the research results by

Barker et al. (2016) and Vicente-Serrano and Lopez-Moreno (2005), which stated that most of the watershed hydrological droughts were strongly correlated with SPI 1-3 months. Based on these results, it can be concluded that SPI 1-3 months can be used as an early indicator of hydrological drought events in the Upper Brantas watershed.

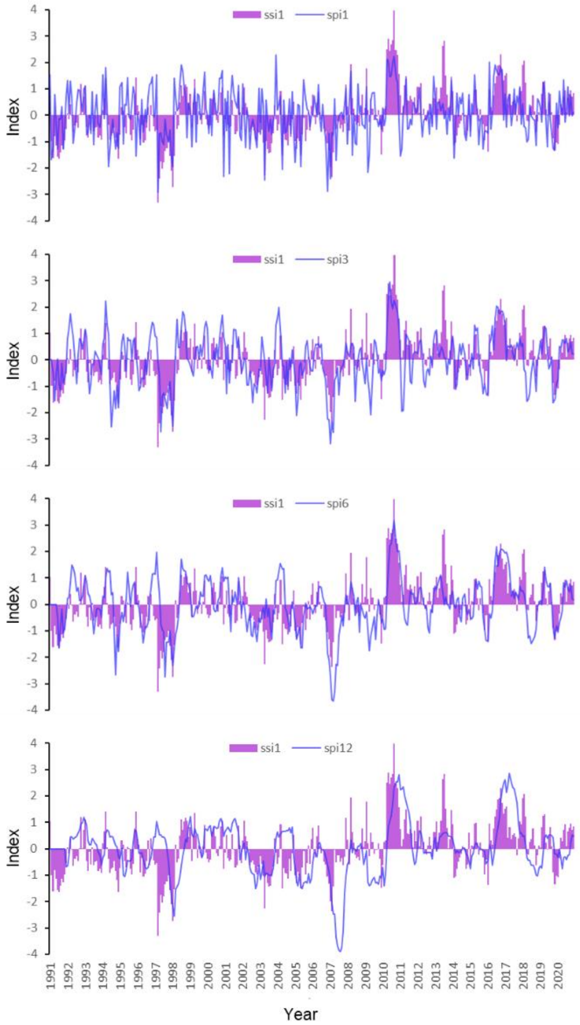


Figure 6. Drought index time series with cross-correlation coefficient between 1 month SSI and 1, 3, 6, and 12-month SPI.

Table 3. Correlation of SPI 1-12 months with SSI 1 month at 95% confidence interval (α=0.05).

No	SPI	SSI1
1	1	0,55
2	3	0,60
3	6	0,58
4	12	0,44

The results of the correlation of SSI1 and SPI 1-12 with an interval of 0-3 months are presented in Figure 7. Based on this figure, it can be seen that the strongest correlation with the inflow of the Sutami Reservoir was obtained when there was no time lapse with SPI. This means that most hydrological drought events coincide with meteorological droughts. For example, the hydrological drought in 2006, which lasted from November according to SSI1, was preceded by a meteorological drought that lasted from November according to SPI1 and September according to SPI3. Very dry hydrological conditions in November 2006 occurred when meteorological conditions were dry in the same month.

The correlation value decreases with increasing SPI accumulation time. These results indicate a significant effect between the rainfall deficit of the previous 1-12 months on the occurrence of monthly hydrological drought in the Upper Brantas watershed. However, the rainfall deficit from that month up to the last three months has a more significant influence than other accumulation periods.

Vicente-Serrano and Lopez-Moreno (2005) found that the SPI accumulation period of 1-3 months was significantly (α=0.05) correlated with standardized river discharge in small-story watersheds in Spain. Lorenzo-Lacruz et al. (2013) found that in geological conditions with low permeability, 1-month SSI significantly (α=0.05) was strongly correlated with a short SPI accumulation period, while in areas dominated by limestone SSI 1 was strongly correlated with SPI 12.

The high correlation with SPI without time-lapse indicates that meteorological drought has the potential to be used as an early detection tool for hydrological drought in the Upper Brantas watershed. This pattern of relationships has been used to estimate seasonal discharge (high, medium, or low) in the UK (Svensson, 2015). The correlation gets weaker with the increasing time interval between the SSI index and the SPI for all periods of SPI accumulation.

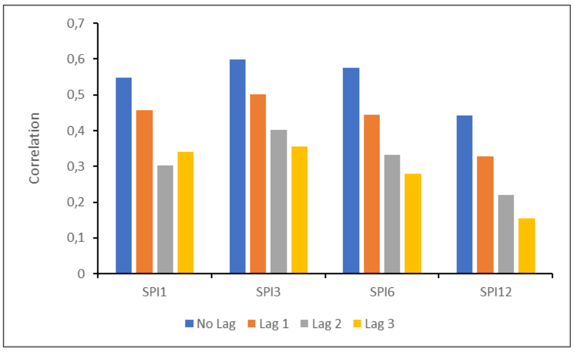


Figure 7. Correlation of 1 month SSI with an interval of 0-3 months from SPI 1-12 months. (No lag, lag 1, lag 2, and lag 3 represent the difference between meteorological and hydrological drought at lag 0 – 3 months)

4. CONCLUSION

SPI and SSI methods were used to analyze meteorological and hydrological drought characteristics. Drought characteristics that show the nature of drought in the Upper Brantas watershed are expressed in terms of the number of drought events, the beginning and end of the drought, duration of drought, and drought severity. The duration and severity of drought increased with the increase in the period of accumulation of SPI and SSI, while the number of drought events was inversely proportional to the period of accumulation of SPI and SSI. The incidence of hydrological drought in the Upper Brantas watershed is less than that of meteorological drought. The average duration of hydrological drought in the watershed is longer than that of meteorological drought. The severity of hydrological drought is higher than the severity of meteorological. The worst hydrological drought (SSI1 = -22,9) with a duration of 12 months occurred in 1997-1998.

The hydrological drought in the Upper Brantas watershed is strongly influenced by the rainfall deficit in the same month up to the previous three months. This is indicated by the Pearson correlation value ≥ 0.50. The 1-3 month SPI method can indicate hydrological drought events in the Upper Brantas watershed. The correlation value decreases with increasing SPI accumulation time. The high correlation in the condition that there is no time lapse between SSI and SPI shows that the meteorological drought indicator with SPI has the potential to be used as an early detection tool for hydrological drought in the Upper Brantas watershed, which is very useful in managing water resources in the watershed for hydropower operations.

5. REFERENCE

AghaKouchak A, Nakhjiri N. 2012. A near real-time satellite-based global drought climate data record. *Environ Res Lett.* 7(4): 1812–1818. doi:10. 1088/1748-9326/7/4/044037.

Aldrian E, Susanto RD. 2003. identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature. *Int. J. Climatol*. 23:1435–1452. doi: 10.1002/joc.950.

Andreadis KM, Clark EA, Wood AW, Hamlet AF, Lettenmaier DP. 2005. Twentieth-century drought in the conterminous United States. *J Hydrometeorol.* 6(6): 985–1001. doi: 10.1175/JHM450.1.

Bachmair S, Stahl K, Collins K, Hannaford J, Acreman M, Svoboda M, Knutson C, Smith KH, Wall N, Fuchs B, Crossman ND, Overton IC. 2016. Drought indicators revisited: the need for a wider consideration of environment and society. *WIREs Water*. doi:10.1002/wat2.1154.

Balbo F, Wulandari RA, Nugraha MRR, Dwiandani A, Syahputra MR, Suwarman R. 2019. The evaluation of drought indices: Standard Precipitation Index, Standard Precipitation Evapotranspiration Index, and Palmer Drought Severity Index in Cilacap-Central Java. *IOP Conf. Ser.: Earth Environ. Sci.* 303 012012. doi:10.1088/1755-1315/303/1/012012.

Barker LJ, Hannaford J, Chiverton A, Svensson C. 2016. From meteorological to hydrological drought using standardized indicators. *Hydrology and Earth System Sciences.* 20(6): 2483–2505. doi:10.5194/hess-20-2483-2016.

DeGaetano AT. 1999. A temporal comparison of drought impacts and responses in the New York City metropolitan area. *Climatic Change.* 42(3): 539–560. doi:10.1023/A:1005413410160.

Fleig A., 2004. Hydrological drought –A comparative study using daily discharge series from around the world [disertasi]. Univesitas Albert-Ludwigs., Freiburg.

Folland, C. K., J. Hannaford, J. P. Bloomfield, M. Kendon, C. Svensson, B. P. Marchant, J. Prior, E. Wallace. 2015. Multiannual droughts in the English Lowlands: a review of their characteristics and climate drivers in the winter half-year. Hydrol. Earth Syst. Sci. 19(5), pp. 2353–2375. doi: 10.5194/hess-19-2353-2015

Gustard A, Bullock A, Dixon JM. 1992. Low flow estimation in the United Kingdom, Institute of Hydrology, Wallingford, UK, IH Report No. 108, 88 pp.

Guttman, N. B., 1999. Accepting the standardized precipitation index: a calculation algorithm. J. Am. Water Resour. As., 35 (2), pp. 311–322. doi: 10.1111/j.1752-1688.1999.tb03592.x.

Hannaford J, Lloyd-Hughes B, Keef C, Parry S, Prudhomme C. 2011. Examining the large-scale spatial coherence of European drought using regional indicators of precipitation and streamflow deficit. *Hydrol Process.* 7:1146–1162. doi:10.1002/hyp.7725.

Hayes M, Svoboda M, Wall N, Widhalm M. 2011. The Lincoln declaration on drought indices: universal meteorological drought index recommended. *B Am Meteorol Soc.* 92:485–488. doi: 10.1175/2010BAMS3103.1.

Lesk C, Rowhani P, Ramankutty N. 2016. Influence of extreme weather disasters on global crop production. *Nature.* 529:84–87. doi:10.1038/nature16467

Liu JG, Diamond J. 2005. China's environment in a globalizing world. *Nature.* 435(7046):1179–1186. doi:10.1038/4351179a.

Lloyd-Hughes B. 2014. The impracticality of a universal drought definition. *Theor Appl Climatol*. 117: 607–611. doi: 10.1007/s00704-013-1025-7.

Lloyd-Hughes B, Saunders MA. 2002. A drought climatology for Europe. *Int. J. Climatol*. 22: 1571–1592. doi: 10.1002/joc.846.

Lorenzo-Lacruz J, Morán-Tejeda E, Vicente-Serrano, SM, López-Moreno JI. 2013. Streamflow droughts in the Iberian Peninsula between 1945 and 2005: spatial and temporal patterns. *Hydrol Earth Syst Sci.* 17:119–134. doi:10.5194/hess-17-119-2013.

McKee TB, Doesen NJ, Kleist J. 1993. The relationship of drought frequency and duration to time scales. *Proceedings of the 8th Conference on Applied Climatology. Boston: American Meteorological Society.* 17(22):179–183.

Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. *J. Hydrol*. 391(1–2), 204–216. http://dx.doi.org/10.1016/j.jhydrol.2010.07.012.

Mo K. 2008. Model-based drought indices over the United States. *J Hydrometeorol.* 9:1212–1230. doi:10.1175/2008JHM1002.1.

Palmer WC. 1965. Meteorological Drought. Department of Commerce Weather Bureau, Washington, DC.

Stagge JH, Tallaksen LM, Gudmundsson L et al. 2015. Candidate distributions for climatological drought indices (SPI and SPEI). *Int J Climatol.* 35(13):4027–4040. doi:10.1002/joc.4267.

Sun QH, Miao CY, Duan QY, Ashouri H, Sorooshian S, Hsu KL. 2018. A review of global precipitation datasets: Data sources, estimation, and intercomparisons. *Reviews of Geophysics.* 56:79–107. doi:10.1002/2017RG000574.

Svensson, C., A. Brookshaw, A. Scaife, V. Bell, J. Mackay, C. Jackson, J. Hannaford, H. Davies, A. Arribas, S. Stanley. 2015. Long-range forecasts of UK winter hydrology, Environ. Res. Lett. 10(6), 064006, pp. 1-6

Tallaksen LM, Van Lanen HAJ. 2004. Hydrological drought: processes and estimation methods for streamflow and groundwater. Elsevier.

Taufik M, Torfs, PJJF, Uijlenhoet R, Jones PD, Murdiyarso D, Van Lanen HAJ. 2017. Amplification of wildfire area burnt by hydrological drought in the humid tropics. *Nature Climate Change.* 7(6):428–431. doi:10.1038/nclimate3280.

Van Loon AF, Laaha G. 2015. Hydrological drought severity explained by climate and catchment characteristics. *Journal of Hydrology.* 526:3-14. doi: 10.1016/j.jhydrol.2014.10.059.

Van Loon AF, Gleeson T, Clark J, Dijk AIJM, Stahl K, Hannaford J et al. 2016. Drought in the Anthropocene. *Nature Geoscience.* 9(2):89–91. doi:10.1038/ngeo2646.

Vicente-Serrano SM, Lopez-Moreno JI. 2005. Hydrological response to different time scales of climatological drought: An evaluation of the Standardized Precipitation Index in a mountainous Mediterranean basin. *Hydrology and Earth System Sciences.* 9(5):523–533. doi:10.5194/hess-9-523-2005.

Vicente-Serrano SM, Begueria S, Lopez-Moreno JI. 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *J Clim.* 23(7):1696–1718. doi:10.1175/2009JCLI2909.1.

Vicente-Serrano SM, Lopez-Moreno JI, Begueria S et al. 2011. Accurate computation of a streamflow drought index. *J Hydrol Eng.* 17(2):318–332. doi:10.1061/(ASCE)HE.1943-5584.0000433.

Wang D, Hejazi M, Cai X et al. 2011. Climate change impact on meteorological, agricultural, and hydrological drought in central Illinois. Water Resour Res. 47(9):1995–2021. doi:10.1029/2010WR009845.

Wang QF, Wu JJ, Lei TJ, He B, Wu ZT, Liu M et al. 2014. Temporal-spatial characteristics of severe drought events and their impact on agriculture on a global scale. *Quaternary International.* 349:10–21. doi:10.1016/j.quaint.2014.06.021.

Wilhite DA. 2000. Drought as a natural hazard concepts and definitions. *Drought: A Global Assessment Vol. I,* chap. 1:3–18

Wong G, Van Lanen HAJ, Torfs PJJF. 2013. Probabilistic analysis of hydrological drought characteristics using meteorological drought. *Hydrological Sciences Journal.* 58(2):253-270. doi: 10.1080/02626667.2012.753147.

Ye XC, Li XH, Xu CY, Zhang Q. 2016. Similarity, difference, and correlation of meteorological and hydrological drought indices in a humid climate region - the Poyang Lake catchment in China. *Hydrology Research.* 47(6):1211–1223. doi:10.2166/ nh.2016.214.