

Analysis of Meteorological Drought Propagation to Hydrological Drought in the Tarei Watershed, Sumbawa River Basin

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Abstract: Drought is a type of natural disaster that progresses slowly and persists over an extended period until the rainy season arrives. Deficit in precipitation is referred to as meteorological drought, deficiency in soil moisture is defined as agricultural drought, and shortages in groundwater, river streamflow, and lake storage are known as hydrological drought. Monitoring and predicting drought are crucial activities to anticipate and mitigate its impacts. This study aims to determine the drought indices and the propagation of meteorological drought into hydrological drought in the Tarei Watershed using the Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) methods. The SPI and SSI methods can identify potential droughts, as precipitation and discharge are the primary indicators of meteorological and hydrological droughts, respectively. The propagation of meteorological drought to hydrological drought was then analyzed using Pearson Correlation. The drought analysis using the SPI method in the Tarei Watershed revealed that the "exceptionally dry" category occurred in December 2001, February 2004, March 2012, and January 2023, with drought indices of -2.445, -2.633, -2.332, and -2.177, respectively. Meanwhile, using the SSI method, hydrological drought in the Tarei Watershed under the "exceptionally dry" category occurred in March 2022, October 2023, March 2024, and March 2025, with drought indices of -3.515, -2.773, -3.048, and -2.425, respectively. Drought propagation was evaluated by correlating SPI values against SSI using 1-month, 2-month, and 3-month time steps. The highest 1-month correlation occurred at a 0-month lag with a value of 0.683, while the 2-month and 3-month methods yielded the highest correlation values of 0.955 and 0.950, respectively. These results indicate a strong correlation between hydrological and meteorological drought in the Tarei Watershed, which can serve as a guideline for anticipating hydrological drought

Keywords: Drought; Hydrological drought; Meteorological drought; Tarei

Introduction

Indonesia is a tropical country characterized by two distinct seasons: the dry season and the rainy season. A specific feature of the Indonesian region is high rainfall during the rainy season and low rainfall during the dry season. Meteorological conditions cause these two seasons to alternate. Consequently, managing excess water during the rainy season is challenging, whereas meeting water demand during a prolonged dry season

becomes difficult. Rainfall is one of the primary factors determining surface conditions from a water resources perspective.

Rain serves as an input processed by the land surface to generate an output (Vicente-Serrano et al., 2005). Regions with low rainfall levels experience a progressive decline in both groundwater and surface water resources, significantly impacting socio-economic activities and the community (Mishra et al., 2011).

Drought is a type of natural disaster that develops slowly and lasts for a long period until the rainy season

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arrives (Wilhite et al., 1985). Drought differs from other natural disasters such as earthquakes, floods, and landslides due to its distinct behavior and the absence of a universally accepted definition (Mishra et al., 2010; Wilhite et al., 1985). Generally, the impacts of drought accumulate gradually over a prolonged and extended period, sometimes lasting for years, making its onset and termination difficult to determine (Mishra et al., 2011). A deficit in precipitation is termed meteorological drought, a deficiency in soil moisture is classified as agricultural drought, and shortages in groundwater, stream flow, and lake storage are recognized as hydrological drought (Tallaksen et al., 2004; Van Loon, 2015).

The impacts of drought are widespread and do not damage physical structures in the manner of landslides, floods, or earthquakes (Wilhite et al., 1985). Drought leads to reduced water supply availability, lowered food production, and increased risks of forest or land fires (Mishra & Singh, 2010). Therefore, drought monitoring and prediction are vital tasks to anticipate and minimize these impacts (Barker et al., 2016; Van Loon et al., 2012).

Dompu Regency features a tropical monsoon climate (Aw according to the Köppen classification) characterized by a rainy season from November to March and a dry season from April to October. Rainfall here is highly influenced by the Australian and Asian monsoons and by the El Niño-Southern Oscillation (ENSO), resulting in a relatively longer dry season compared to western parts of Indonesia (D'Arrigo et al., 2008). Dompu Regency is classified as an area with moderate to low rainfall by Indonesian standards. Based on climatological data from Dompu Regency, the average monthly rainfall is approximately 72 mm (BBWS NT I Mataram, 2025).

The 2025 dry season peaked between August and September. During this period, several areas in Dompu Regency experienced extended consecutive dry days, escalating the risk of depletion in surface and groundwater availability. The Bureau of Meteorology, Climatology, and Geophysics (BMKG) designated several districts in Dompu Regency under drought alert (siaga) to warning (awas) categories for meteorological drought. The 2025 drought affected the majority of areas in Dompu. According to data from the Regional Disaster Management Agency (BPBD) of Dompu Regency as of September 2025, the number of affected residents reached 8,899 households (approx. 26,697 individuals) experiencing clean water crises. The drought expanded to 7 out of 8 districts within Dompu Regency, with Kempo District being the only area reported as relatively safe from severe impacts. Woja District was identified as the most severely affected region. This severity is attributed to the concentration of residential areas situated on hilly terrains with rocky, impermeable soil

structures, making groundwater sources highly inaccessible during the dry season. This condition highlights the urgency for sustainable water resource management through the construction and optimization of water retention infrastructures, such as dams, retention basins (embung), and irrigation networks. Such efforts are required to enhance water resilience in Dompu Regency against recurring drought events during the dry season.

The Tarei Watershed is a utility watershed located within the Sumbawa River Basin. Geographically, the Tarei Watershed lies between 118°23'47.82" E and 8°32'0.54" S, encompassing an area of 241.46 km². Administratively, the Tarei Watershed is situated in Woja District, Dompu Regency, which is the most severely affected drought area.

Given the routine occurrence of drought events in West Nusa Tenggara Province, an analysis is required to determine the severity and duration of droughts; this is crucial to serve as an early warning system for further drought escalation. One of the methods utilized to analyze drought is the Standardized Precipitation Index (SPI) (Guttman, 1999; McKee et al., 1993). The SPI method serves as a meteorological drought index that utilizes monthly rainfall data. On the other hand, hydrological drought analysis utilizes the Standardized Streamflow Index (SSI), which operates on the principle of accumulating river discharge data over specified time scales as its analysis parameter (Shukla et al., 2008; Vicente-Serrano et al., 2012). Drought propagation can be analyzed by examining the correlation and identifying the propagation patterns from meteorological drought to hydrological drought (Barker et al., 2016; Lorenzo-Lacruz et al., 2013).

The author intends to analyze this propagation within the Tarei Watershed, a drought-prone area in Dompu Regency, to provide essential early information for anticipating upcoming drought periods in this region and its surroundings, considering that drought can cause extensive impacts across sectors, including water deficits, food shortages, and forest fires.

Method

This study was conducted in the Tarei Watershed, Sumbawa River Basin. Geographically, the Tarei Watershed is situated between 118°23'47.82" E and 8°32'0.54" S, covering a total area of 241.46 km².

Secondary data were utilized in this study, consisting of historical rainfall records from the Dompu rainfall station and river discharge data from the Matua stream gauging station spanning 27 years, obtained from the Balai Besar Wilayah Sungai Nusa Tenggara I Mataram. The research stages carried out in this study

include drought analysis using the SPI method, drought analysis using the SSI method, and the analysis of meteorological drought propagation into hydrological drought. This study aims to determine the relationship and connectivity between meteorological and hydrological drought. The practical benefit of this research is to provide early warning information to better anticipate upcoming drought periods in the region, minimizing cross-sectoral impacts such as water scarcity, food deficits, and land fires.

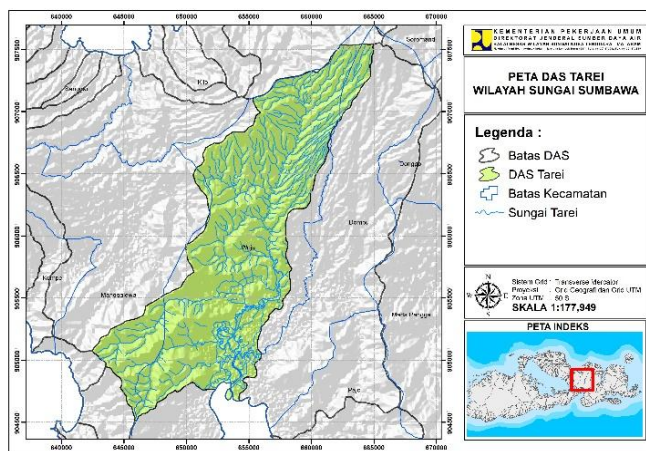


Figure 1. Tarei watershed

Drought Classification

Drought originates from a deficit in precipitation below normal levels for a season, a phenomenon defined as meteorological drought, which marks the early onset of a drought event (Wilhite et al., 1985). The subsequent stage involves the depletion of soil moisture causing crop stress (known as agricultural drought). The final stage manifests as a deficit in surface and groundwater supplies, marked by declining water levels in rivers, reservoirs, or lakes (known as hydrological drought) (Van Loon, 2015; Van Loon et al., 2012).

Drought is classified into three main types: (a) Meteorological Drought: Defined as a deficit in precipitation from normal or expected levels over a specific period (Heim, 2002). Computing meteorological drought severity provides the first indication of impending drought conditions (Black, 2024). (b) Agricultural Drought: Occurs following meteorological drought symptoms (Mishra et al., 2010). It relates to the depletion of soil moisture content, rendering the soil incapable of meeting crop water requirements during a given period (Amalo et al., 2018). It is characterized by a soil moisture deficit. (c) Hydrological Drought: Defined as a deficiency in surface and groundwater supplies, including lake/reservoir storage, river streamflow, and groundwater tables (Tallaksen et al., 2004). Hydrological drought is measured based on water level elevations in

rivers, reservoirs, lakes, and groundwater monitoring wells (Nalbantis, 2008).

Standardized Precipitation Index (SPI) Method

The SPI for a specific location is computed based on a long-term precipitation record for a desired time scale (Guttman, 1999; Svoboda et al., 1987). McKee et al. (1993) established a classification system to identify drought intensity and event criteria for specific time scales. A drought event occurs when the SPI is continuously negative and reaches an intensity of -1.0 or less, and the event terminates when the SPI value becomes positive (Barker et al., 2016).

Calculating the Average

$$\bar{x} = \frac{\sum x}{n} \quad (1)$$

Where:

$\bar{x}$ = average rainfall event value (mm)
 $\sum x$ = total sum of rainfall events (mm)
 n = number of data

Calculating the Standard Deviation

$$Sd = \sqrt{\frac{\sum (x - \bar{x})^2}{n}} \quad (2)$$

Where: S = standard deviation. Calculated in Microsoft Excel using the function =STDEV

Calculating Alpha

$$\alpha = \frac{\bar{x}^2}{Sd^2} \quad (3)$$

where: $\bar{x}$ = average rainfall event value (mm); Sd = standard deviation

Calculating Beta

$$\beta = \frac{\bar{x}}{\alpha} \quad (4)$$

where: $\bar{x}$ = average rainfall event value (mm); α = shape parameter/alpha

Calculating the Gamma Distribution

$$G(x) = \int_0^x g(x)dx = \frac{1}{\beta^a \Gamma(a)} \int_0^x t^{a-1} e^{-\frac{x}{\beta}} dx \quad (5)$$

Calculating the Transformed Gamma Distribution

For $0 < H(x) \leq 0.5$

$$t = \sqrt{\ln \left[\frac{1}{H(x)^2} \right]} \quad (6)$$

For $0.5 < H(x) < 1.0$

$$t = \sqrt{\ln \left[\frac{1}{(1 - H(x))^2} \right]} \quad (7)$$

where:

$$H(x) = q + (1 - q)G(x) \quad (8)$$

$q = m/n$ where m is the number of 0 mm rainfall events in the rainfall data series.

Calculating the SPI value

For $0 < H(x) \leq 0.5$

$$Z = SPI = -(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}) \quad (9)$$

For $0.5 < H(x) \leq 1.0$

$$Z = SPI = +(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}) \quad (10)$$

Where: $c_0 = 2.515517$; $c_1 = 0.802853$; $c_2 = 0.010328$; $d_1 = 1.432788$; $d_2 = 0.189269$; $d_3 = 0.001308$.

Standardized Streamflow Index (SSI) Method

Hydrological drought is identified using the Standardized Streamflow Index (SSI) method (Shukla et al., 2008). The SSI calculation follows the same principle as the SPI, which begins by accumulating discharge data over a specific period of time (Vicente-Serrano et al., 2012). There is no single probability distribution function universally used to calculate the SSI (Nalbantis, 2008).

Discharge data from the Matua station were used for drought analysis with the SSI method. The SSI calculation was performed by first accumulating discharge data over 1, 3, 6, and 12-month periods. The 3, 6, and 12-month accumulated rainfall/discharge data were obtained by creating a 3-month, 6-month, and 12-month moving average of the monthly discharge data. The SSI calculations from the 1-month, 3-month, 6-month, and 12-month accumulated discharge data are subsequently denoted as SSI 1, SSI 3, SSI 6, and SSI 12.

Next, the index values are calculated, and the characteristics of the hydrological drought are analyzed. The SSI calculation procedure is identical to the SPI calculation procedure.

Drought Propagation

Drought propagation is quantified by correlating hydrological drought indicators with meteorological drought indicators to identify the time scale at which precipitation deficits propagate through the hydrological cycle and cause deficits in the watershed system (Barker et al., 2016; Bhardwaj et al., 2020). One of the objectives of conducting this correlation is to determine whether a relationship exists between two or more variables of a phenomenon or event (Lorenzo-Lacruz et al., 2013). Efforts to measure this relationship are known as measuring association.

Simple correlation analysis is defined as a data analysis method aimed at observing the relationship between two variables. The objectives of correlation analysis include: (1) to find evidence of whether a relationship (correlation) exists between variables, (2) if a relationship already exists, to see the strength or magnitude of the relationship between variables, and (3) to obtain clarity and certainty on whether the relationship is significant (convincing) or not significant (unconvincing). If the correlation index number has a plus sign (+), the correlation is positive and moves in the same direction, whereas if the correlation index number has a minus sign (-), the correlation is negative and moves in opposite directions, and if the correlation index equals 0, it indicates that there is no correlation.

Furthermore, to determine the level of closeness of the relationship between the studied variables, the obtained correlation coefficient is compared with the following correlation table (Abdurrahman, 2011).

Table 1. Correlation Coefficient

R Value	Interpretation
0.00 - < 0.20	Very Weak
≥ 0.20 - < 0.40	Low
≥ 0.40 - < 0.70	Moderate
≥ 0.70 - < 0.90	High
≥ 0.90 - < 1.00	Very Strong

Result and Discussion

Drought Analysis Using the SPI Method

Based on the analysis results and the graph above, the most severe drought falling under the "exceptionally dry" category occurred in December 2001, February 2004, March 2012, and January 2023 with drought indices of -2.445, -2.633, -2.332, and -2.177, respectively (Guttman, 1999; McKee et al., 1993).

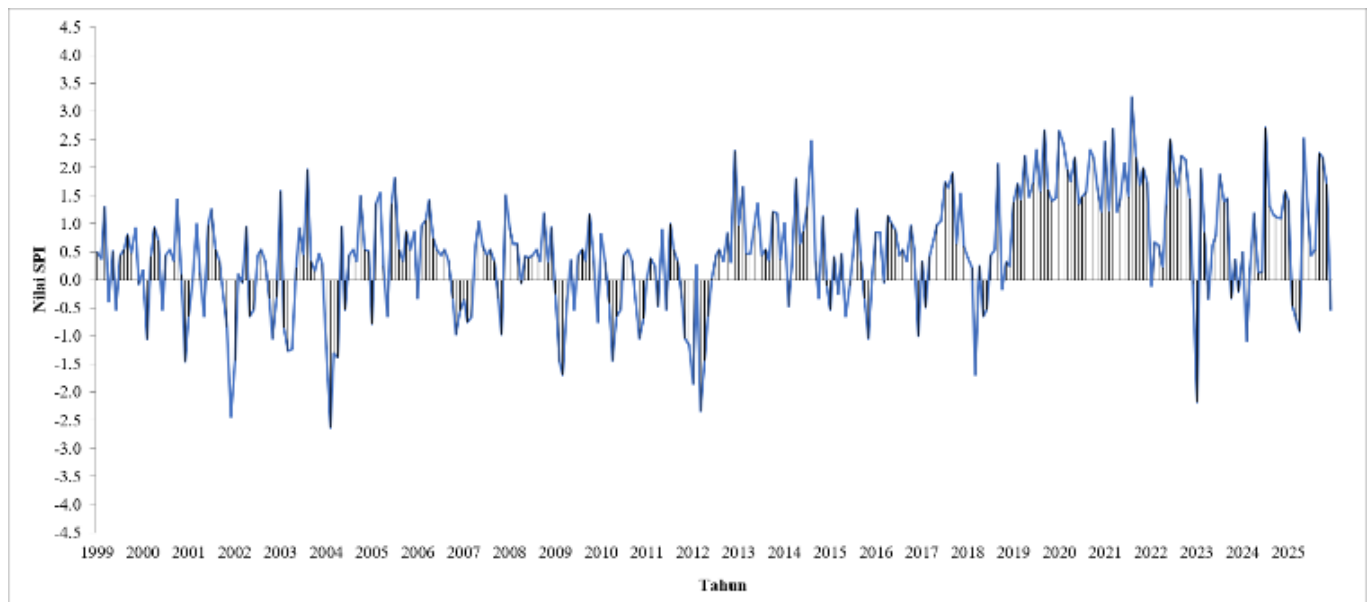


Figure 2. SPI graph of the Tarei watershed

Drought Analysis Using the SSI Method

Based on the analysis results and the graph above, the most severe drought falling under the "exceptionally dry" category occurred in March 2022, October 2023,

March 2024, and March 2025 with drought indices of -3.515, -2.773, -3.048, and -2.425, respectively (Nalbantis, 2008; Shukla et al., 2008).

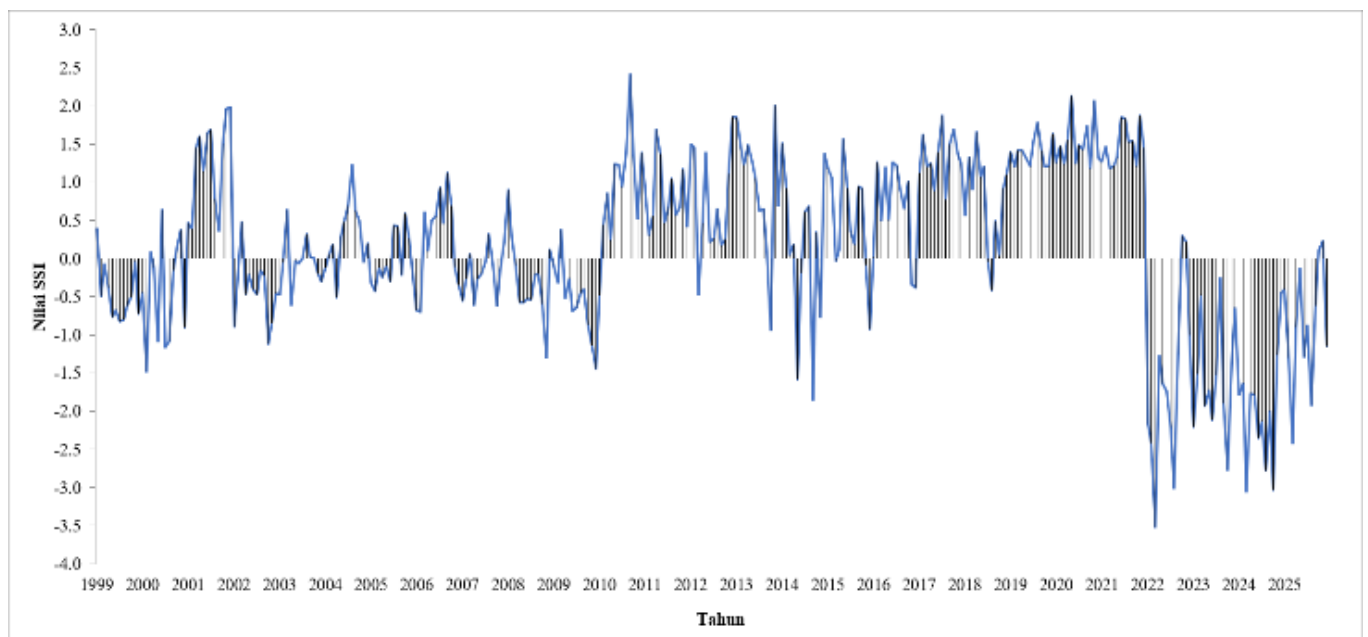


Figure 3. SSI graph of the Tarei watershed

Meteorological Drought Propagation to Hydrological Drought

Drought propagation in this study is intended to describe the transformation of meteorological drought signals into hydrological drought through the hydrological cycle (Van Loon, 2015). Drought propagation is quantified by correlating hydrological drought indicators (Lorenzo-Lacruz et al., 2013).

The 1-month SSI was correlated with 1-12 month meteorological drought SPI indicators to identify the time scale at which precipitation deficits propagate through the hydrological cycle and cause deficits in the watershed system (Barker et al., 2016). To analyze the existence of a time lag between meteorological and hydrological drought events, correlations were carried out between the 1-month SSI and 1-12 month SPI using

a time lag of 0–3 months (Bhardwaj et al., 2020; Lorenzo-Lacruz et al., 2013).

The 1-12 month SPI accumulation periods and the 1-month SSI were cross-correlated using the Pearson correlation coefficient to determine the most appropriate SPI accumulation period to characterize SSI 1 (Lorenzo-Lacruz et al., 2013; Barker et al., 2016). The SPI accumulation period that has the strongest correlation with SSI 1 is used as an indicator to analyze drought propagation by observing whether it is accompanied by values indicating a drought classification or not

(Bhardwaj et al., 2020). A drought event occurs when the value remains negative for a minimum period of 1 month in accordance with the pre-determined thresholds, namely: -1 (moderately dry), -1.5 (severely dry), and -2 (exceptionally dry) (Lloyd-Hughes et al., 2002).

In this study, correlations were conducted using 1-month, 2-month, and 3-month methods to examine and compare the best and most accurate correlation results for measuring the propagation of meteorological drought toward hydrological drought.

Table 2. Highest Correlation Values for a 1-Month Time Step

Year	Highest Correlation	Lag Time	Year	Highest Correlation	Lag Time
1999	1	10	2013	0.464	9
2000	0.254	1	2014	0.423	9
2001	0.618	4	2015	0.436	1
2002	0.623	11	2016	0.566	0
2003	0.554	2	2017	0.381	3
2004	0.52	1	2018	0.605	5
2005	0.427	8	2019	0.614	8
2006	0.683	1	2020	0.459	10
2007	0.515	8	2021	0.193	3
2008	0.475	0	2022	0.609	4
2009	0.688	10	2023	0.466	5
2010	0.478	8	2024	0.637	5
2011	0.387	9	2025	1	10
2012	0.668	6			

From Table 2, the correlations between SPI and SSI per single month in 1999 and 2025 yielded the highest correlation values of 1.000, but with a lag time of 10 months. This is less acceptable due to the excessively long time gap, as an unrealistically long lag does not reflect a physically meaningful propagation process (Barker et al., 2016). On the other hand, the highest correlation with the shortest lag time occurred in 2006 with a correlation value of 0.683 at a 1-month lag.

Table 3. Highest Correlation Values for a 2-Month Time Step

Year	Correlation	Year	Correlation
1999	0.283	2013	0.208
2000	0.509	2014	-0.089
2001	-0.39	2015	0.091
2002	-0.043	2016	0.955
2003	0.909	2017	-0.568
2004	0.658	2018	-0.733
2005	0.505	2019	-0.039
2006	0.272	2020	0.062
2007	0.425	2021	-0.15
2008	0.52	2022	0.23
2009	-0.272	2023	0.33
2010	0.067	2024	-0.164
2011	0.213	2025	0.415
2012	0.333		

For the calculation of SPI to SSI correlation values using the 2-month method, higher correlation values were obtained, with the highest correlations occurring in 2003 and 2016, yielding values of 0.909 and 0.955.

Table 4. Highest Correlation Values for a 3-Month Time Step

Year	Correlation	Year	Correlation
1999	0.581	2013	0.95
2000	0.347	2014	-0.848
2001	-0.819	2015	0.749
2002	-0.217	2016	0.933
2003	-0.441	2017	0.887
2004	0.351	2018	-0.831
2005	0.531	2019	-0.404
2006	0.771	2020	-0.322
2007	-0.65	2021	-0.602
2008	0.948	2022	0.824
2009	-0.743	2023	-0.622
2010	0.407	2024	0.662
2011	0.925	2025	0.937
2012	0.869		

For the calculation of SPI to SSI correlation values using the 3-month method, the highest correlations occurred in 2008, 2011, 2013, 2016, and 2025, with correlation values of 0.948, 0.925, 0.950, 0.933, and 0.937, respectively. This indicates that drought in the Tarei

Watershed is strongly influenced by the precipitation deficits of the concurrent month up to three months prior.

Conclusion

Based on the research findings, the SPI method has the potential to serve as an early warning tool for hydrological drought in the Tarei Watershed, given the high and significant correlation values obtained when meteorological and hydrological droughts occur simultaneously, where the correlation for a 1-month time step is 0.683, a 2-month time step is 0.955, and a 3-month time step is 0.950. This study reinforces the evidence that there is an interconnected relationship between hydrological drought and meteorological drought. The nearly simultaneous occurrence of hydrological and meteorological drought events opens up the possibility of utilizing meteorological drought indicators as an early detection tool for hydrological drought within the Tarei Watershed.

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Author Contributions

Conceptualization, M.Q.N. and I.W.Y.; methodology, M.Q.N. and I.W.Y.; software, M.Q.N.; validation, M.Q.N., I.W.Y. and H.S.; formal analysis, M.Q.N.; investigation, M.Q.N.; resources, M.Q.N.; data curation, M.Q.N.; writing – original draft preparation, M.Q.N.; writing – review and editing, I.W.Y. and H.S.; visualization, M.Q.N.; supervision, I.W.Y. and H.S.; project administration, M.Q.N. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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