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APPLICATION OF RAINFALL DATA IN DROUGHT HAZARD PREDICTION IN THE BENGAWAN SOLO RIVER BASIN USING THE RAINFALL ANOMALY INDEX (RAI) AND STANDARDIZED PRECIPITATION INDEX (SPI)

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Abstract

This study investigates the impact of the Southern Oscillation Index (SOI) on meteorological droughts in the Bengawan Solo River Basin, Indonesia, from 2004 to 2023. Indonesia's climate is influenced by the El Niño Southern Oscillation (ENSO), with negative SOI values (El Niño conditions) linked to drought events and positive values associated with the rainy season. This study analyzed the values of multiple stations' Rainfall Anomaly Index (RAI) and Standardized Precipitation Index (SPI). This study evaluates the compatibility of drought indices obtained from the Rainfall Anomaly Index (RAI) and the Standardized Precipitation Index (SPI) with the Southern Oscillation Index (SOI). The study's results indicate that the drought index using the Standardized Precipitation Index (SPI) method yields a higher percentage of compatibility with the Southern Oscillation Index (SOI), averaging 60.78%. The compatibility of the SPI method can also be observed in the number of meteorological dry months during 2010, the year of the most severe La Niña, and in 2015, during the most severe El Niño. Through the SPI method, it can also be demonstrated that rainfall data can accurately reflect drought events and rainy seasons, consistent with climate change occurrences.

***Keywords**: Meteorological Drought, Rainfall Anomaly Index, Standardized Precipitation Index, Southern Oscillation Index*

1. INTRODUCTION

Drought, a compound and multi-dimensional phenomenon, significantly harms agriculture, natural ecosystems, and societal structures (Dobler-Morales and Bocco, 2021; UNDRR, 2021; Wahab et al., 2022). Climate change has triggered significant changes in precipitation patterns, increasing extreme weather events (Munaweera et al., 2022; Effiong et al., 2024). A series or combination of drought events can profoundly affect human and environmental health (Kchouk et al., 2022; Munaweera et al., 2022). Drought can be classified into five types Meteorological, Hydrological, Agricultural, Socio-economic, and Groundwater drought (Bayer Altin and Altin, 2021; Zhang et al., 2021). Meteorological drought occurs due to a significant decrease in precipitation over a prolonged period, typically spanning a season or longer (Meresa et al., 2023; Hisdal et al., 2024). Meteorological drought, resulting from inadequate rainfall, normally emerges quickly as the initial phase. Over time, sustained low precipitation levels lead to insufficient runoff and groundwater recharge (Zhu et al., 2023; Tanarhte et al., 2024; Tao, Meng

& Huang, 2024). The World Meteorological Organization (WMO) has endorsed the Standardized Precipitation Index (SPI) for widespread adoption by national Meteorological and Hydrological Services to identify Meteorological drought and enhance existing local drought indices (Han and Singh, 2023; Calim Costa et al., 2024). The Southern Oscillation Index (SOI) quantifies the broad fluctuations in atmospheric pressure at sea level between the La Niña and El Niño phenomena (Maruyama, 2023; Jaroszewicz et al., 2024). The Southern Oscillation Index (SOI) monitors substantial changes in sea-level pressure differences between La Niña and El Niño conditions. During El Niño years, sea surface temperatures (SST) are significantly elevated, spanning from the west coast of South America to the mid-equatorial Pacific. In contrast, La Niña years are defined by considerably colder sea waters in that area (Mallick et al., 2022; McGowan & Theobald, 2023).

In Indonesia, most years experiencing drought are correlated with El Niño episodes, with fewer droughts occurring during non-El Niño periods (Chapman et al., 2020). Drought is one of the disasters caused by climate change that frequently occurs in Indonesia, with varying frequencies and risk levels in each region. One of the impacts of drought disasters is on the agricultural and food sectors of Indonesia, an agrarian country where the majority of the population's livelihood is farming (Boer and Suharnoto, 2012; Pratiwi, Ramadhani, 2020; Rozaki et al., 2021). Indonesia also has a population of 261 million, all requiring food sources (Arifin et al., 2019). Therefore, when a drought disrupts the food sector, it significantly affects the economy and the sustainability of the Indonesian state (Syaukat, 2011; Yeny et al., 2022).

The Bengawan Solo River, the longest river on the island of Java (Lusiana *et al.*, 2022; Hasan *et al.*, 2023), flows through regions that are notably prone to drought occurrences (Affandy et al., 2022). The incorporation of Geographic Information Systems (GIS) into drought analysis plays a pivotal role in addressing these challenges (Patel & Patel, 2024). GIS facilitates sophisticated spatial and temporal interpolation of climatic data collected from various meteorological stations. Interpolation, a method for estimating values in areas that were not directly sampled or measured, is crucial for creating detailed maps and distributions of values across the river basin. This approach enables the detailed mapping and analysis of drought patterns by employing interpolation methods such as Trend, Spline, Inverse Distance Weighted (IDW), and Kriging (Asadi Oskouei et al., 2022). These insights are essential for developing effective drought management strategies.

2. METHODOLOGY

2.1. Study Area

The Bengawan Solo River (BSR), the largest river basin on Java Island, Indonesia, spans 548 kilometers and covers a catchment area of approximately 16,389 square kilometers. Positioned between latitudes 6°48′ S and 8°60′ S, and longitudes 110°25′ E to 112°40′ E, it traverses 17 districts and three cities across the provinces of Central Java and East Java. Fig. 1 shows the map of the study area. The river is crucial to the local economies of these regions. Nonetheless, communities residing along the BSR are often afflicted by water-related disasters, including frequent droughts (Marhaento, Booij & Ahmed, 2021).

Fig. 1. Study Area

The study's meteorological stations are strategically dispersed across six Bengawan Solo River (BSR) system basins. Fig. 1 provides a visual representation of the precise locations and spatial attributes of these stations within the BSR, and Table 1 details the exact coordinates and basin categorizations.

Table 1. Coordinate and basin

No	Watershed (DAS)	Station	Easting	Southing
1	Downstream Solo River Basin	Bojonegoro	599152.371 E	9207217.438 S
2	Upstream Solo River Basin	Klaten	456378.2621 E	9145788.5750 S
3	Downstream Solo River Basin	Waduk Gondang	640425.5497 E	9203826.58 S
4	Madiun River Basin	Ngawi	550380.37 E	9181066.49 S
5	Downstream Solo River Basin	Nglirip	587519.115 E	9229770.486 S
6	Grindulu-Lorog River Basin	Pacitan	511421.4539 E	9093731.5808 S
7	Upstream Solo River Basin	Tawangmangu	513428.988 E	9152588.129 S
8	Madiun River Basin	Telaga Ngebel	569337.6662 E	9138848.1368 S

2.2. Methodology

2.2.1 Rainfall Anomaly Index (RAI)

The Rainfall Anomaly Index (RAI) method provides a way to analyze rainfall patterns by factoring in the average rainfall at a given station, along with the averages of the 10 highest and 10 lowest recorded rainfall values. The formula for calculating the RAI index, as explained by Muarifah, Harisuseno (2021), involves a two-part equation depending on whether the actual rainfall is above or below the long-term average. If the actual rainfall (R) exceeds the average rainfall ($\bar{R}$), the formula is:

$$RAI = 3 (R - \bar{R}) / (M - \bar{R}) \quad (1)$$

But if the actual rainfall is below the average, the formula changes slightly:

$$RAI = -3 (R - \bar{R}) / (X - \bar{R}) \quad (2)$$

In these equations:

R = the actual recorded rainfall (measured in millimeters)
$\bar{R}$ = the long-term average rainfall (also in millimeters)
M = the average of the 10 highest rainfall measurements
X = the average of the 10 lowest rainfall measurements

By applying this method, as outlined by Aprilansi and Harisuseno, (2018) in Table 2, the RAI can help classify meteorological drought conditions, offering a clearer understanding of how rainfall patterns deviate from normal in a specific region. This classification can be vital in managing water resources and planning for potential drought scenarios.

Table 2. Classification of RAI values

RAI Index Value	Drought Classification
> 3	Extremely Wet
2.1 – 3	Very Wet
1.2 – 2.1	Wet
0.3 – 1.2	Slightly Wet
-0.3 – 0.3	Normal
-1.2 – -0.3	Slightly Dry
-2.1 – -1.2	Dry
-3 – -2.1	Very Dry
< -3	Extremely Dry

2.2.2 Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) has become a popular and straightforward measure of drought. The equation used for SPI calculation is as follows:

$$Zij = (x\_ij - x\_i)/\sigma \quad (3)$$

In these equations:

Z_{ij} = Standard precipitation index (SPI)
X_{ij} = Average rainfall for month j in year range i
X_i = Average rainfall in year range i
σ = Standard deviation

The results of this SPI calculation are then classified into 7 drought level classifications based on Table 3 below:

Table 3. Classification of SPI values as per McKee et al. (1993)

SPI Index Value	Drought Classification
>2.0	Extremely Wet
1.5 to 1.99	Very Wet
1.0 to 1.49	Moderately Wet
-0.99 to 0.99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry

3. RESULT AND DISCUSSION

3.1 Rainfall Data Consistency Analysis

The Bengawan Solo River Basin has 107 rain gauge stations distributed throughout the watershed. The selection of 8 stations in this study was based on several criteria:

1) Data completeness and continuity for the 2001-2020 period
2) Spatial representation covering various parts of the watershed (upstream, midstream, and downstream)
3) Consistent recording quality

Fig. 2. Rain Stations Location Map

The eight selected stations (Fig. 2) effectively represent rainfall characteristics across different parts of the Bengawan Solo River Basin, with distribution covering from upstream to downstream areas. This selection considers representation from various sub-watersheds to comprehensively understand drought conditions in the study area.

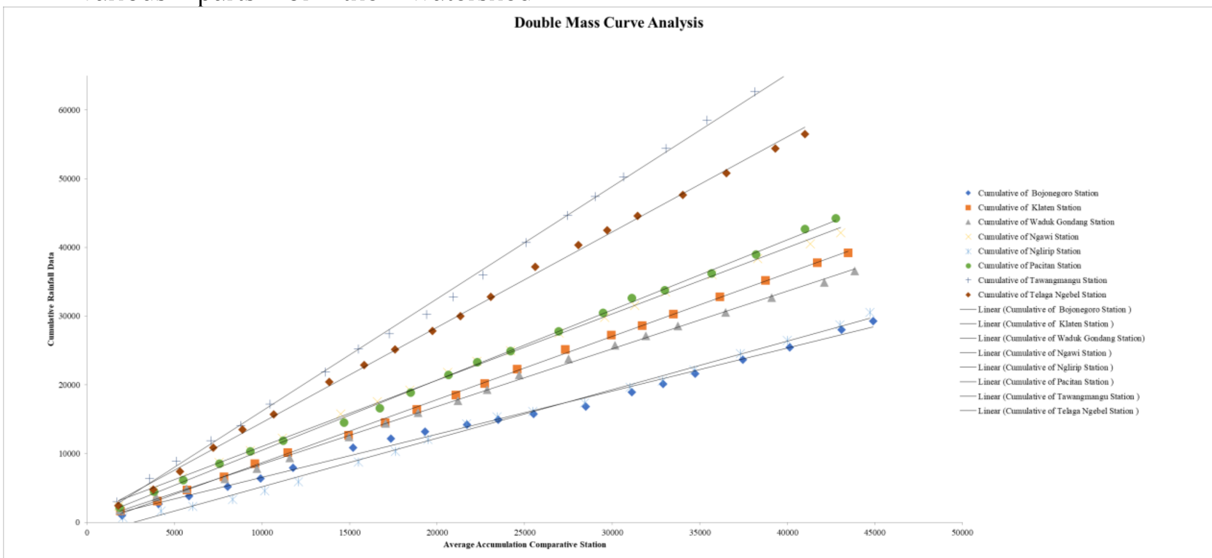

Fig. 3. Double Mass Curve Analysis

The Fig. 3 above illustrates the rainfall data consistency analysis results conducted at eight rainfall stations. The consistency evaluation was performed using the cumulative data of an individual station compared to the average cumulative data of other stations. The analysis indicates that all rainfall stations exhibit consistent data, as evidenced by the absence of any trend changes.

3.2 Drought Analysis

Table 4. below displays the maximum index values for each rainfall station from 2004 to 2023, using the RAI and SPI methods. The more negative the

meteorological drought index value, the stronger the heat event experienced (Tongkukut, 2011). According to the RAI method, the most severe meteorological drought occurred in Nglirip, with a value of -3.19. In contrast, the SPI method indicated the most extreme drought in Waduk Gondang, with a value of -2.53.

Table 4. The maximum index values using both the RAI and SPI methods

Name of Station	RAI	SPI
Bojonegoro	-3.14	-1.97
Klaten	-3.14	-2.37
Waduk Gondang	-3.13	-2.53
Ngawi	-3.10	-2.03
Nglirip	-3.19	-1.58
Pacitan	-3.08	-1.75
Tawangmangu	-3.07	-2.31
Telaga Ngebel	-3.09	-1.72

Table 5. Meteorological Drought Events (Month)

Station	Method	Meteorological Drought Events (Month)	
		2010	2015
Sta. Bojonegoro	RAI	5	7
	SPI	0	11
Sta. Klaten	RAI	3	6
	SPI	5	7
Sta. Waduk Gondang	RAI	3	7
	SPI	2	7
Sta. Ngawi	RAI	3	7
	SPI	2	10
Sta. Nglirip	RAI	2	9
	SPI	2	12
Sta. Pacitan	RAI	4	7
	SPI	5	10
Sta. Tawamangu	RAI	4	6
	SPI	2	8
Sta. Telaga Ngebel	RAI	4	7
	SPI	2	8

Table 5 shows the meteorological drought events in 2010 and 2015. From Table 4, using the RAI and SPI methods show minimal differences. The wettest year was 2010, when SPI and RAI methods predominantly indicated wet conditions. In 2010, the SPI at Bojonegoro station did not show any meteorological drought, but the RAI method recorded five months of drought. Historically, the SPI method is more appropriate for La Niña events, as La Niña in 2010 caused more rainfall during the dry season (Agustiarini et al., 2022). In contrast, in 2015, SPI identified an 11-month drought at Bojonegoro station, attributed to a stronger and longer El Niño than in 1997 (Yuniasih, et al., 2022).

In contrast to Nglirip Station, according to the SPI method, where a full 12 months or 1 year of drought occurred during the peak of El Niño in 2015, the RAI method only recorded 9 months of drought, a difference of 4 months. However, during the most severe La Niña event in 2010, the SPI and RAI methods recorded the same number of dry months, which was 2 months.

At Pacitan Station, during the wet drought 2010, the RAI method recorded 4 months of drought, whereas the SPI method indicated 5 months. This demonstrates that at Pacitan Station, the RAI method yielded fewer dry months than the SPI method. In contrast, during the prolonged drought of 2015, the SPI method proved to be more accurate, as it recorded a greater number of dry months compared to the RAI method—10 months versus 7 months, respectively.

Based on the sample from three rain stations for drought calculations in 2010 during the most severe La Niña and in 2015 during the most severe El Niño mentioned above, it can be concluded that the SPI method is more accurate than the RAI method for drought calculations. A comparison of the meteorological drought index using the SPI and RAI methods from 2004 to 2023 is presented in Fig. 4 below.

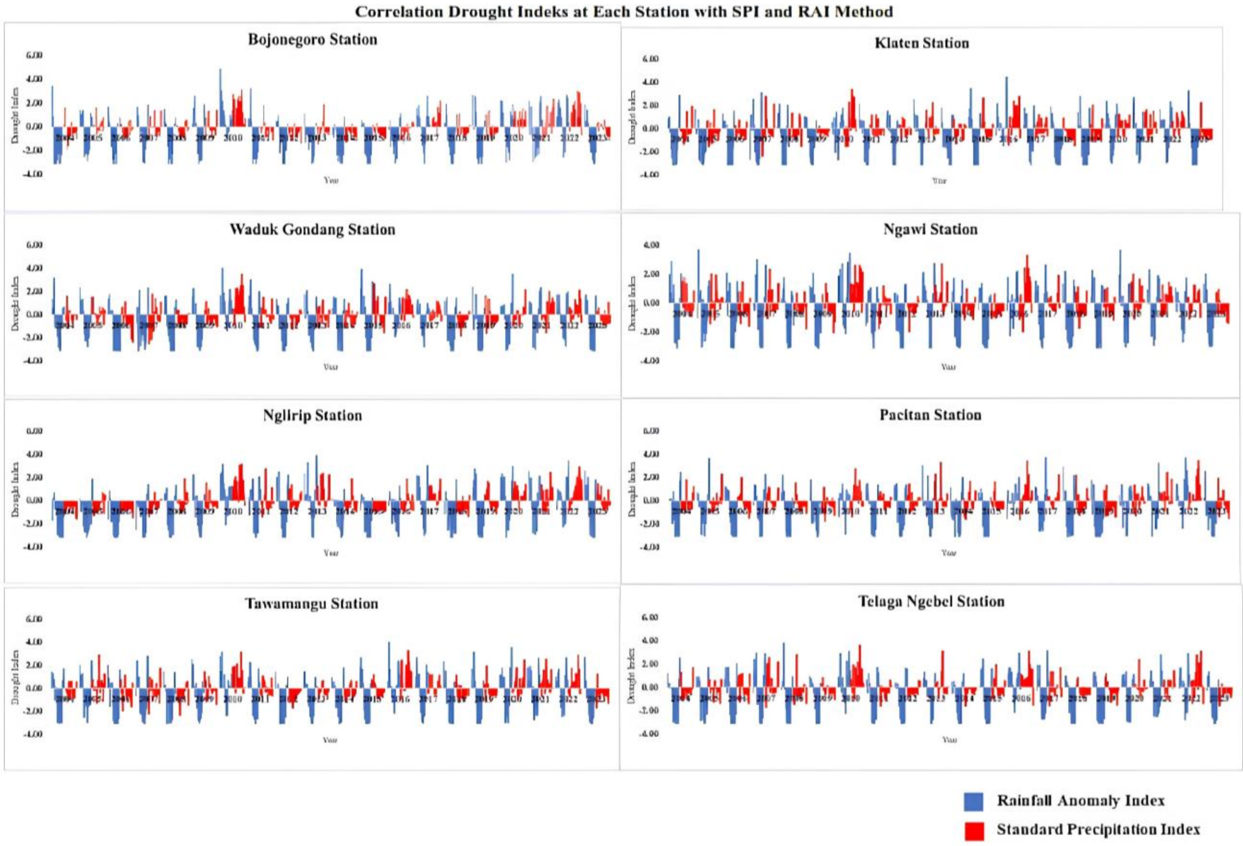

Fig. 4. Results of the Meteorological Drought Index of 8 Rain Stations

The Southern Oscillation Index (SOI) data as shown in Fig. 5 reveals discrepancies between meteorological drought estimates using the SPI and RAI methods and SOI data from ENSO. For instance, in early 2004, both SPI and RAI indicated positive values signaling a wet year, while SOI data suggested drought. Similarly 2010, despite SPI and RAI indicating a wet year, SOI showed negative values pointing to meteorological drought. On the contrary, in 2016, SPI and RAI pointed to drought, while SOI data indicated a wet year. Bojonegoro station experienced fewer droughts, with only 108 months of drought according to the SPI method, 144 months according to SOI, and 140 months using the RAI method.

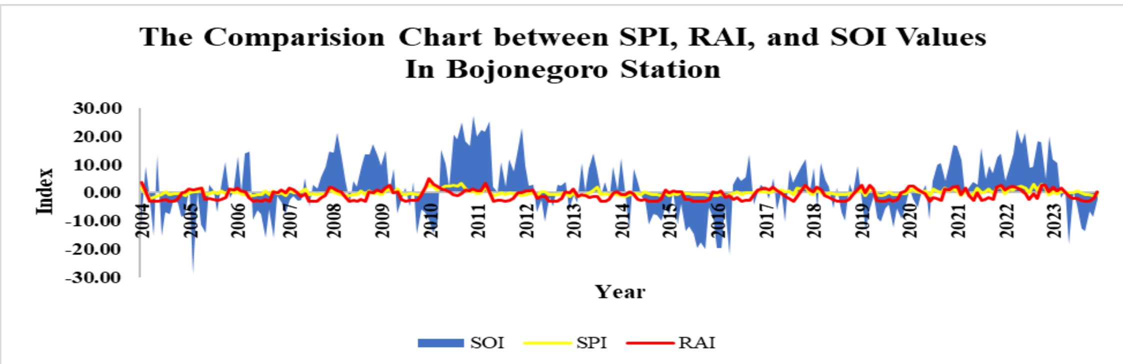

Fig. 5. Correlation between SOI, RAI, and SPI (SOI from http://www.bom.gov.au/climate/enso/soi/)

Table 6 shows the correlation between wet and dry months from 2004 to 2023 across eight stations compared to SOI data. Pacitan station had the highest data match using SPI at 65.00%, while Bojonegoro and

Tawangmangu stations showed the lowest correlation at 53.33%. SPI showed a higher overall match with SOI data at 60.78%, 3.91% higher than RAI.

Table 6. Correlation of Drought Index with the Southern Oscillation Index (SOI)

Name of Station	Correlation of Drought Index with the Southern Oscillation Index (SOI)	
	RAI	SPI
Bojonegoro	53.33%	58.33%
Klaten	56.67%	57.08%
Waduk Gondang	59.58%	63.75%
Ngawi	57.08%	60.83%
Nglirip	60.83%	62.92%
Pacitan	60.42%	65.00%
Tawangmangu	53.33%	60.42%
Telaga Ngebel	53.75%	57.92%
Average	56.88%	60.78%

4. CONCLUSION

Based on the results of the research conducted, it can be concluded as follows:

1. The calculation of meteorological drought indices using the RAI and SPI methods closely matched SOI, with SPI showing a higher correlation of 60.78%.
2. SPI is also relevant when evaluated against historical El Niño and La Niña events, particularly in 2010, when La Niña resulted in wet conditions during the dry season, with SPI indicating zero drought events. This highlights that using rainfall data for meteorological drought indices is adequate when considering historical El Niño and La Niña data.
3. The SPI method further demonstrates that utilizing rainfall data effectively captures drought events and rainy seasons, aligning well with the impacts of climate change.

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