



Analysis of Meteorological–Hydrological Drought Propagation for the Development of a Drought Early Warning System in the Special Region of Yogyakarta (DIY): A Case Study of the 2023 El Niño Event

Yana Arifin¹, Yohana Noradika Maharani², Tedy Agung Cahyadi³

¹Master's Program in Disaster Management, UPN "Veteran" Yogyakarta, Indonesia

²Master's Program in Disaster Management, UPN "Veteran" Yogyakarta, Indonesia

³Department of Geological Engineering, UPN "Veteran" Yogyakarta, Indonesia

ABSTRACT: The drought that affected the Special Region of Yogyakarta (DIY) as a consequence of the 2023 El Niño event was characterized by prolonged dry conditions resulting from exceptionally low rainfall, depletion of water resources, and significant impacts on agriculture, dams, reservoirs, as well as the socio-economic conditions of local communities. This study aims to examine, in a spatiotemporal framework, the influence of El Niño on drought conditions across the DIY Province and to analyze the stages and propagation of meteorological, agricultural, and hydrological drought. The analysis uses rainfall observations from 122 rain gauges and three BMKG stations. Drought assessment begins with rainfall deficit analysis, followed by meteorological drought identification using the Standardized Precipitation Index (SPI), agricultural drought assessment using the groundwater availability index (KAT), and hydrological drought assessment using the Hydrological Drought Index (HDI/IKH). The results show that meteorological drought was first detected in April 2023 in Bantul, Gunungkidul, and Kulon Progo Regencies, then expanded toward the central and northern parts of DIY in May 2023. Agricultural drought emerged in June 2023 in the same three regencies, indicated by KAT values falling below 40% of field capacity. The drought reached its peak in October 2023 as hydrological drought, when reservoir volume availability at Q80 dropped below 50%. Meteorological drought appeared 1–2 months after the onset of rainfall deficit (dry season), progressed into agricultural drought with a lag of 2–3 months, and culminated in hydrological drought with a lag of 5–6 months. The development of a regional Integrated Drought Early Warning System should incorporate monitoring and forecasting outputs, enabling drought alerts to be issued 3–6 months before critical conditions arise.

KEYWORDS: 2023 El Niño, agricultural drought, hydrological drought, meteorological drought, early warning system, drought propagation.

INTRODUCTION

In 2023, the Special Region of Yogyakarta (DIY) experienced an extreme drought triggered by the El Niño phenomenon. The Regional Disaster Management Agency (BPBD) of DIY reported that the event affected 100 hamlets, damaged 378 hectares of agricultural land, and left 8,316 residents with limited access to clean water (BPBD, 2023). The BMKG Dry Day Count (HTH) map indicated that parts of Java, including DIY, experienced more than 90 consecutive dry days in October 2023—classified as an extreme HTH category (BMKG, 2023). These conditions spurred a multidimensional crisis, including water scarcity, desiccated agricultural land, declining crop yields due to crop failure, and increased potential for social conflict driven by competition over water resources (Aprianto, 2023; Nugroho & Wahyuni, 2023). Field observations in DIY showed cracked soils, dried-up wells, and widespread reliance on water-tank distribution.

According to the World Meteorological Organization (WMO, 2012), drought is categorized into four interrelated types: (1) meteorological drought (rainfall deficit), (2) agricultural/agronomic drought (insufficient soil moisture and groundwater availability for crops), (3) hydrological drought (reduced river discharge, reservoir storage, and groundwater levels), and (4) socio-economic drought. These types typically occur sequentially, beginning with meteorological drought as the initial trigger, followed by impacts on agriculture, then hydrological stress, and ultimately socio-economic crises (Mishra & Singh, 2010; Wilhite, 2010).

Drought in DIY is not an isolated event but reflects structural vulnerability exacerbated by climate change. The region's heterogeneous topography—from Mount Merapi in the north to the karst hills of southern DIY—relies heavily on seasonal rainfall



patterns that have become increasingly erratic (BPS, 2024). El Niño, characterized by anomalous warming of sea surface temperatures in the central and eastern Pacific Ocean, disrupts atmospheric circulation and leads to substantial reductions in rainfall across Indonesia (Qian *et al.*, 2023; Aldrian & Susanto, 2023). In 2023, El Niño was intensified by a positive Indian Ocean Dipole (IOD), further amplifying dry conditions in southern Indonesia, including DIY (Kurniadi *et al.*, 2023; BMKG, 2023). BPBD DIY recorded 2,256 drought-related incidents throughout 2023 (Kompas, 2023), with impacts on 100 hamlets, 378 hectares of damaged farmland, and an increase in affected residents from 4,150 to 8,316 people. Reports indicate that prolonged drought in several villages across DIY led to severe water shortages (BPBD, 2023). Consequently, the provincial government allocated IDR 80,000,000 to address the clean-water crisis.

At present, sectoral drought monitoring systems are routinely implemented by various agencies: the Meteorology, Climatology, and Geophysics Agency (BMKG) monitors rainfall anomalies and meteorological drought; the Ministry of Agriculture focuses on agronomic planting calendars; the Ministry of Public Works and Housing (PUPR) monitors hydrological conditions; and the National Disaster Management Agency (BNPB) addresses water-related crises (BMKG, 2023). BMKG provides early warnings for extreme climate conditions, the Ministry of Agriculture operates a drought and flood monitoring system for agricultural impacts, and the Ministry of Public Works maintains reservoir and dam monitoring systems targeting hydrological drought.

However, these systems operate independently and remain unintegrated within a unified early warning platform, causing early warning information to be delayed or insufficiently aligned with local needs (BNPB, 2015). Addressing this gap, the present study proposes the development of an Integrated Drought Early Warning System using an interdisciplinary approach that combines climatological, hydrological, and agricultural analyses. Methodologically, the study applies the Standardized Precipitation Index (SPI) (McKee *et al.*, 1993), the Soil Water Availability Index (KAT/ATi), and the Hydrological Drought Index (HDI/IKH) based on reservoir discharge. Spatial integration is conducted using Geographic Information Systems (GIS), while drought propagation is examined through cross-correlation and lag-time analysis. This approach aligns with recommendations from UNDRR (2022) and the IPCC AR6 (2022), which highlight the need for multi-indicator early warning systems.

METHOD

This study employs a quantitative approach to analyze the onset and progression of meteorological, agricultural, and hydrological drought during the 2023 El Niño event in the Special Region of Yogyakarta (DIY). Secondary data were obtained from reliable sources, including monthly rainfall records for 2023 from 122 rain gauges and three BMKG stations, soil water availability data (KAT/ATi) as an indicator of agricultural drought, and discharge and storage data from the Sermo Reservoir for hydrological drought assessment. Meteorological drought was analyzed using the monthly Standardized Precipitation Index (SPI-1) (McKee *et al.*, 1993), standardized by WMO (2016). Agricultural drought was assessed through a land-water balance approach using the Soil Water Availability Index (KAT), while hydrological drought was evaluated using the Hydrological Drought Index (HDI/IKH) with a Q80 threshold following Avicenna (2015).

Spatial interpolation was conducted using the Inverse Distance Weighting (IDW) method, allowing visualization of drought propagation across the DIY region. Drought propagation time was examined by comparing time series of SPI, KAT, and IKH. The overall workflow—from data collection, drought index computation, and spatial analysis to the development of the early warning system.

FINDINGS AND DISCUSSION

El Niño in 2023

The El Niño phenomenon is monitored through the ENSO index, which reflects positive (warm) or negative (cool) phases of sea surface temperature conditions in the equatorial Pacific. At the beginning of 2023, the ENSO index was in a Neutral phase (ENSO ± 0.5), following NOAA standards. It gradually shifted toward an El Niño phase starting in May 2023, as illustrated in Figure 1.



Figure 1. Monthly ENSO Index for 2023

El Niño continued to intensify, indicated by a steady increase in the monthly ENSO index from June to October 2023. The event reached its peak in November 2023 and gradually weakened from December onward, returning to Neutral conditions by April of the following year. At the same time, the Indian Ocean Dipole (IOD) was also active, beginning in July 2023 and peaking in November and December 2023. The evolution of the IOD index is shown in Figure 2 below.

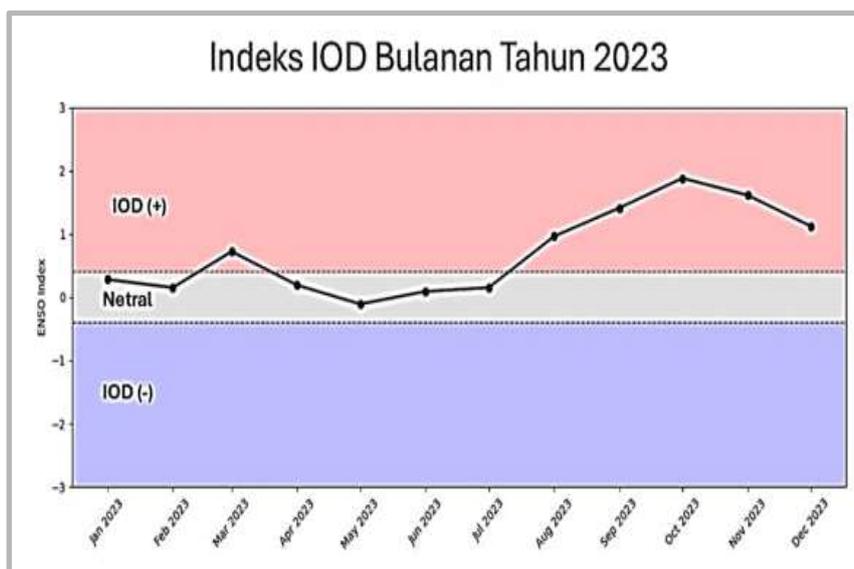


Figure 2. Monthly IOD Index for 2023

Impacts of the 2023 El Niño on the Climate of DIY

The El Niño phenomenon generally affects Indonesia, including the Special Region of Yogyakarta (DIY), by reducing rainfall and increasing air temperature. El Niño can also delay the onset of the rainy season in DIY, resulting in lower rainfall totals and heightened drought risk. The spatial distribution of low rainfall throughout 2023 is shown in Figure 3.

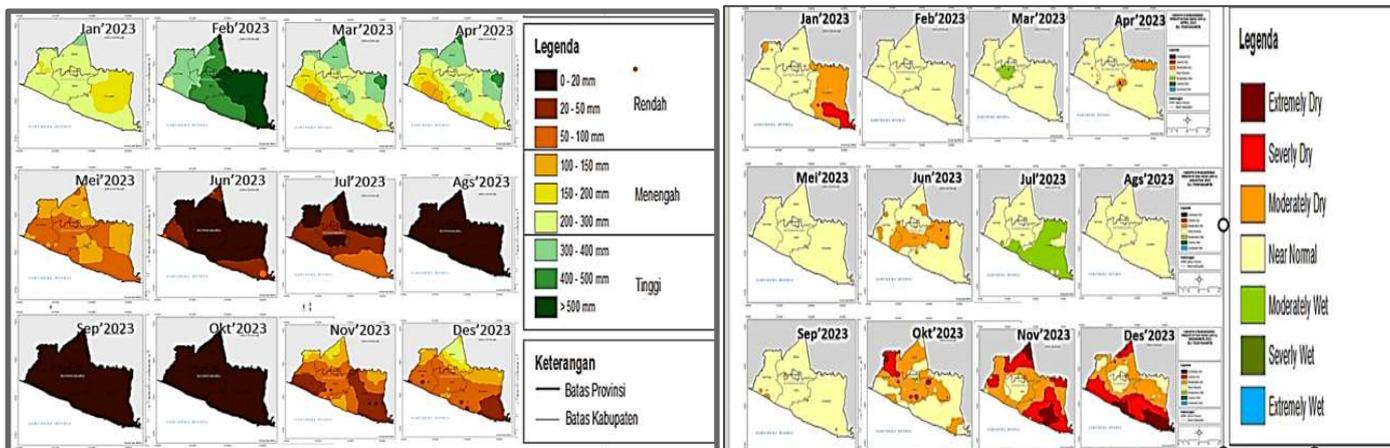


Figure 3. Monthly Rainfall Map of DIY in 2023

Low rainfall was first observed in Kulon Progo and Bantul starting in April 2023. By May, areas with low rainfall (brown shading) expanded and became more widespread. Spatial patterns show that rainfall deficits initially emerged in the eastern and southern parts of the region. In June and July, the reduction in rainfall intensified, spreading from southern DIY toward central, northern, and western areas. The most severe rainfall deficits occurred during August, September, and October, when monthly rainfall generally fell below 20 mm. Even in November and December 2023, rainfall across DIY remained low, ranging from only 20–50 mm per month.

Meteorological Drought

A significant reduction in monthly rainfall can trigger meteorological drought as measured using the Standardized Precipitation Index (SPI), consistent with findings by McKee *et al.* (1993), McKee (1997), Purnamasari (2017), Andika (2014), and Muliawan (2012). During the 2023 El Niño event, the prolonged dry season (Supari *et al.*, 2018) also contributed to sectoral drought, beginning with meteorological drought (Surmaini, 2015; Van Loon, 2015). The analysis of the SPI throughout 2023 reveals spatial and temporal fluctuations in drought patterns across the study area. Figure 5 presents SPI-1 (monthly scale) used to identify monthly meteorological drought conditions.

Monthly meteorological drought analysis for DIY is presented temporally in Figure 5. The results indicate that meteorological drought began to develop in April 2023, although initially only in Gunungkidul Regency. By June 2023, drought conditions intensified and expanded, reaching moderate levels (brown shading). The drought further escalated to dry (orange) and very dry (red) conditions during September–October, and persisted in the “very dry” category throughout November and December 2023 across nearly all regencies in DIY, as shown in Figure 4.

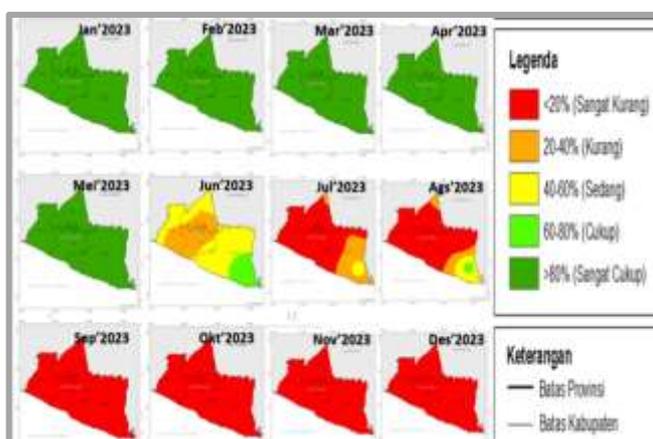


Figure 4. Monthly Meteorological Drought (SPI) Map for DIY in 2023

Agricultural Drought

The 2023 El Niño not only triggered meteorological drought but, when prolonged, also led to agricultural drought, affecting crops—particularly rice—consistent with Surmaini *et al.* (2015) and Irawan *et al.* (2025). Agricultural drought was first observed in August 2023, indicated by soil water availability (KAT) dropping below 40% of field capacity (Figure 4). The analysis of agricultural drought based on KAT indicates that in June 2023, soil water availability fell into the “Moderate” category in only two regencies—Kulon Progo and Gunungkidul—while the other regencies had already reached the “Low” category. By July 2023, nearly all regencies in DIY were classified as “Low” to “Very Low,” as shown in Figure 4.

Agricultural drought typically emerges after the onset of meteorological drought (Boken, 2005; Irawan *et al.*, 2023), supporting the use of meteorological indicators as early warnings for agricultural drought (Surmaini *et al.*, 2015). Spatial and temporal analysis of the KAT index shows that water availability for vegetation in DIY had already declined to moderate-to-low levels by June 2023. This aligns with the regional climate, as August–October marks the peak dry season when rainfall is extremely low, with more than 90 consecutive dry days recorded. Rainfall remained very low during November and December, contributing to the expansion and intensification of agricultural drought. Initially observed in western and northern DIY, the drought gradually spread toward central, southern, and eastern areas, becoming most pronounced in the southern and eastern regions by December 2023.

Hydrological Drought

Hydrological drought is detected through declines in reservoir water levels, river discharge, or lake volume. Monitoring data from the Sermo Reservoir throughout 2023, at both 10-day and monthly scales, indicate a significant decline beginning in late September. This marks the onset of hydrological drought. By October 2023, reservoir volume had fallen below the Q80 threshold (reliable discharge), and continued decreasing to below Q50, indicating the start of hydrological drought warning conditions, as shown in Figure 5.

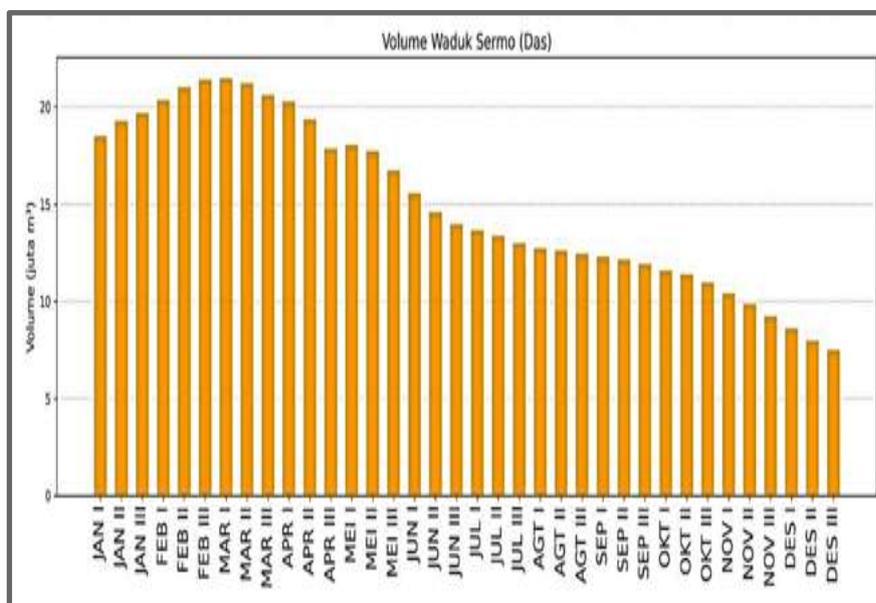


Figure 5. Sermo Reservoir Volume (million m³)

Hydrological drought in this study was assessed using the Hydrological Drought Index (HDI/IKH), as shown in Table 2. According to Avicenna (2015) and Affandy *et al.* (2024), the “Dry” category (IKH 0.000–0.0155) began to appear in June 2023. The “Very Dry” category (–0.0006 to 0.000) emerged in late September. In October 2023, IKH values reached –0.033 to –0.56, significantly below the threshold for “Very Dry” conditions. These negative values persisted until the end of 2023 (Table 1).

Table 1. Reservoir Discharge and IKH Values

Dasarian	TMADas	Debit	Selisih (Deb-Q80)	IKH
JAN I	134,71	18.506.737,63	1.327.962,64	0,08
JAN II	135,25	19.285.445,38	2.106.670,40	0,12
JAN III	135,54	19.687.736,35	2.508.961,36	0,15
FEB I	135,99	20.356.876,71	3.178.101,72	0,19
FEB II	136,43	21.010.935,22	3.832.160,23	0,22
FEB III	136,69	21.400.449,89	4.221.674,91	0,25
MAR I	136,74	21.473.468,73	4.294.693,75	0,25
MAR II	136,57	21.223.489,89	4.044.714,91	0,24
MAR III	136,16	20.612.897,94	3.434.122,95	0,20
APR I	135,94	20.277.138,41	3.098.363,42	0,18
APR II	135,34	19.362.726,84	2.183.951,86	0,13
APR III	134,25	17.866.154,46	687.379,47	0,04
MEI I	134,38	18.045.189,68	866.414,70	0,05
MEI II	134,15	17.731.348,24	552.573,25	0,03
MEI III	133,42	16.742.813,84	- 435.961,14	- 0,03
JUN I	132,53	15.573.605,86	- 1.605.169,13	- 0,09
JUN II	131,75	14.586.804,41	- 2.591.970,58	- 0,15
JUN III	131,25	13.967.742,40	- 3.211.032,59	- 0,19
JUL I	130,99	13.647.418,97	- 3.531.356,02	- 0,21
JUL II	130,77	13.381.841,64	- 3.796.933,34	- 0,22
JUL III	130,42	12.978.438,55	- 4.200.336,43	- 0,24
AGT I	130,21	12.728.054,07	- 4.450.720,91	- 0,26
AGT II	130,11	12.607.244,35	- 4.571.530,63	- 0,27
AGT III	129,98	12.443.786,58	- 4.734.988,40	- 0,28
SEP I	129,85	12.293.156,15	- 4.885.618,83	- 0,28
SEP II	129,73	12.159.000,21	- 5.019.774,78	- 0,29
SEP III	129,51	11.921.732,67	- 5.257.042,32	- 0,31
OKT I	129,21	11.583.570,99	- 5.595.204,00	- 0,33
OKT II	129,04	11.398.729,58	- 5.780.045,40	- 0,34
OKT III	128,66	10.976.235,35	- 6.202.539,64	- 0,36
NOV I	128,12	10.396.455,61	- 6.782.319,37	- 0,39
NOV II	127,61	9.861.742,77	- 7.317.032,21	- 0,43
NOV III	126,98	9.229.644,29	- 7.949.130,70	- 0,46
DES I	126,37	8.614.900,57	- 8.563.874,42	- 0,50
DES II	125,67	7.988.021,95	- 9.190.753,03	- 0,54
DES III	125,10	7.493.432,97	- 9.685.342,02	- 0,56
Q80		17.178.774,98		

Overall, the analysis shows that hydrological drought progressively intensified over time. Hydrological drought was first detected in June 2023 with an IKH of -0.09 , then further declined to -0.03 and beyond, indicating severe reservoir deficits from late September through December 2023.

Drought Propagation: Empirical Evidence of a Tiered Transmission

The progression of drought is quantified by correlating monthly indicators of meteorological drought (SPI), agricultural drought (KAT), and hydrological drought (IKH). This chain of propagation unfolds through a sequence that starts with rainfall deficits, followed by meteorological drought, reduced soil moisture for crops, and ultimately a decline in river discharge or reservoir/lake volume. This pattern aligns with previous studies (Budianto *et al.*, 2020; Sutanto *et al.*, 2024). Although such conditions can escalate into socio-economic drought, that aspect is not covered in this research.

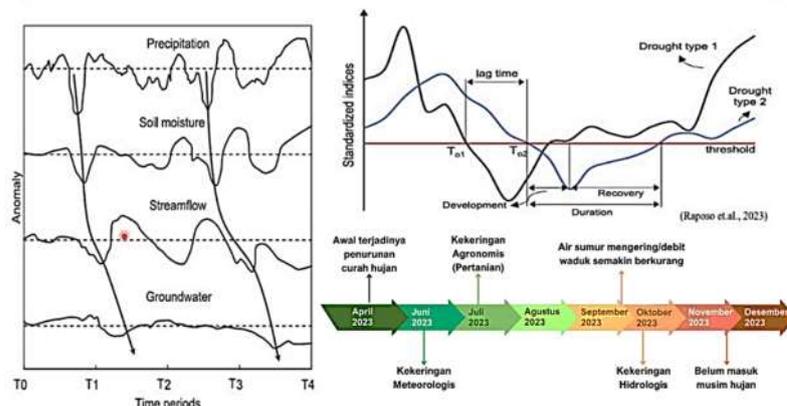
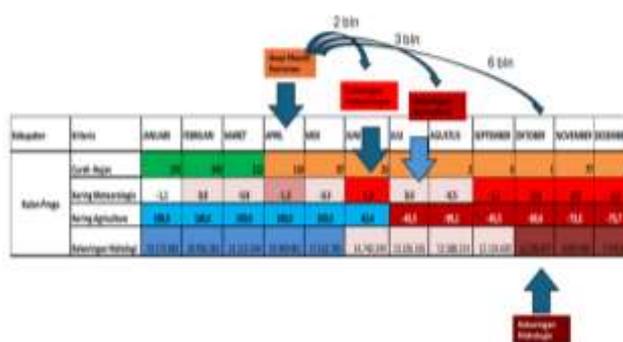


Figure 6. Drought Propagation in the Special Region of Yogyakarta (DIY)

Temporal propagation is assessed by comparing monthly drought indices in tabular form, while spatial propagation is identified through comparisons of monthly drought maps throughout 2023, as shown in Figure 8. The findings reveal that drought phenomena interact across stages—beginning with atmospheric anomalies (Zhou *et al.*, 2025), followed by rainfall anomalies, leading to meteorological drought (Surmaini *et al.*, 2015; Avicenna *et al.*, 2015), and further advancing into hydrological drought as the cycle continues (Budianto *et al.*, 2020; Irawan *et al.*, 2023).

The sequence of drought development, as summarized in Table 2, begins with the onset of the dry season in the Special Region of Yogyakarta (DIY).

Table 2. Lag Time of Drought Propagation



Low rainfall was first observed in April 2023. This early deficit set off the initial stage of drought progression. The reduced rainfall in April was followed by the emergence of meteorological drought (SPI) in May 2023, classified as Normal to Dry in two regencies. By June 2023—around two months after the onset of the dry season—meteorological drought intensified, with the Very Dry category spreading across all regencies in the region.

The prolonged rainfall deficit gradually reduced soil moisture, reflected in declining soil water availability (KAT) recorded in July 2023. This marks the onset of agricultural drought, which appeared three months after the beginning of the dry season and about two months after meteorological drought began to intensify.

Hydrological drought was assessed using the water volume of Sermo Reservoir in Kulon Progo as a representative indicator of regional hydrological conditions. The reservoir volume, initially around 19,173,383 m³ between January and April 2023, dropped to approximately 11,298,257 m³ by October 2023. This level is far below the Q80 threshold of 17,718,774 m³, consistent with the calculated Hydrological Drought Index (IKH) for October 2023. These findings demonstrate a clear onward propagation of drought—temporally showing a 2–3 month delay between stages and extending to 5–6 months from the first rainfall deficit in April.

This pattern aligns with earlier research (Sutanto *et al.*, 2024; Budianto *et al.*, 2020), indicating that each phase of drought requires a lag time before influencing the next. When the deficits persist for an extended period, they culminate in a prolonged drought disaster.

A comparative analysis of SPI, KAT, and IKH illustrates a systematic drought progression during the 2023 El Niño event in the Special Region of Yogyakarta. As shown in Figure 7, the sequence unfolded as follows:

- April 2023: Start of the dry season marked by low rainfall
- June 2023: SPI-1 ≤ -1.5, indicating meteorological drought
- August 2023: KAT ≤ 40%, signaling the onset of agricultural drought
- October 2023: IKH ≤ -0.006 and reservoir volume < 50% of normal, marking hydrological drought

The empirical lag time between each drought stage is 2–3 months from meteorological to agricultural drought, and another 2–3 months before hydrological drought emerges—totaling roughly 5–6 months from the onset of the dry season. These findings parallel the conclusions of Sutanto *et al.* (2024) and Zhou *et al.* (2025).

Integrated Early Warning System Based on Drought Propagation

Building on the drought analysis conducted in the Special Region of Yogyakarta, particularly during the El Niño year, drought disasters can essentially be anticipated 3 to 6 months before they peak. By combining historical drought records with climate forecasts for the next several months, an integrated Drought Early Warning System (DEWS) can be developed. The foundation of such a system

lies not only in real-time monitoring but also in establishing reliable meteorological drought prediction capabilities. Near real-time data, along with medium- to long-range forecasts (3–7 months ahead), is crucial for generating timely warnings.

This study formulates an integrated drought early warning system designed to produce proactive, tiered, and time-based responses, illustrated in Figure 7.

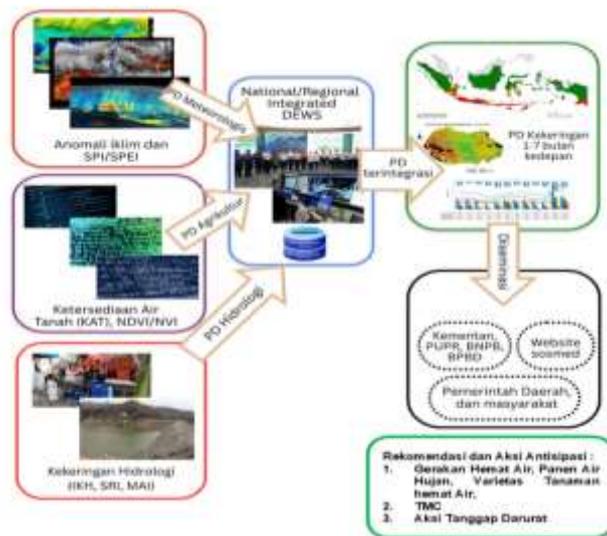


Figure 7. Integrated Regional/National Drought Early Warning System

The proposed system is structured to take advantage of a 6-month predictive lead time to build three interconnected warning levels, each with its own triggers, target stakeholders, and mitigation actions tailored to the regional context of Yogyakarta. The findings establish a scientific basis showing that an Integrated Early Warning System can fully utilize lag time to deliver proactive, coordinated, and sequential response strategies aligned with the drought stages.

Constructing the Integrated Drought Early Warning System (DEWS)

Developing a National–Regional DEWS requires strong intersectoral collaboration at the national scale. The formation of DEWS involves coordinated work across several national and regional priorities, including sectoral engagement, stakeholder participation, public–private partnerships, and collaboration between central and local governments.

Observation and prediction stages play an essential role in planning and responding to drought events. With nationwide observation networks, sector-specific drought indicators can be monitored and predicted. Combining real-time observations with forecasts makes it possible to generate timely drought warnings. Dissemination of the warnings is carried out through official channels to relevant sectors such as Agriculture, Public Works and Water Resources, and Disaster Management agencies (BNPB/BPBD). Each sector can then implement its own early mitigation actions, from institutional coordination to community-based response and public information through websites or social media.

Because there is a clear lag time between meteorological, agricultural, and hydrological drought, this progression forms a dynamic structure that can serve as a scientific backbone for a time-based DEWS. The system consists of three warning levels, each tied to specific triggers and mitigation actions. Rather than simply mapping risk, it offers a proactive, time-sensitive risk management framework that provides up to 6 months of strategic lead time before hydrological crisis emerges.

The system demonstrates that drought impacts can be anticipated early, allowing mitigation measures to be carried out more effectively while the region is still in the “alert” stage. The mechanism also incorporates continuous monitoring and evaluation, ensuring the system remains adaptive, dynamic, and responsive to real-time data rather than static alerts.

The algorithm developed in this research defines three interconnected warning levels:

⚠ Warning Level 1 — Meteorological Drought

Trigger: $SPI-1 \leq -1.5$ sustained for 1–2 months

Timing: Detected 1–2 months after the dry season begins

Purpose: Early alert phase

Recommended actions: Outreach to farmers regarding early drought risk, Preparation of irrigation water reserves, Adjustment of planting schedules. These actions are preventive, aimed at reducing potential impacts.

⚠️ ⚠️ Warning Level 2 — Agricultural Drought

Trigger: Soil Water Availability (KAT) < 40% of field capacity

Timing: Detected around 2–3 months after the dry season starts

Purpose: Critical phase for agriculture

Recommended actions: Promotion of drought-tolerant crop varieties, Use of high-yield seeds, Implementation of water-saving practices (mulching, drip irrigation). These actions are corrective, meant to minimize yield loss and maintain land productivity.

⚠️ ⚠️ ⚠️ Warning Level 3 — Hydrological Drought

Trigger: $IKH \leq -0.0006$ and river/ reservoir discharge < 50% of Q80

Example: October 2023 in Yogyakarta

Purpose: Crisis-phase action

Recommended actions: Emergency water distribution to affected villages, Restrictions on non-essential water use. These actions are responsive, aimed at protecting lives and ensuring basic needs.

The system is designed to streamline coordination among agencies such as BMKG, the Agriculture Office, PUPR, BNPB, and BPBD. Through a unified national platform, each institution can collaborate efficiently under an Integrated Drought Early Warning System, ensuring that early warnings translate into timely, actionable mitigation at every level—from national policymakers to local communities.



Figure 8. Flowchart of the Drought Early Warning System



To illustrate the structure of the drought early warning system developed from empirical findings during the 2023 El Niño event in the Special Region of Yogyakarta, Table 1 summarizes the three calibrated response levels derived from field data:

- a. Alert Level (Meteorological Drought)
- b. Standby Level (Agricultural Drought)
- c. Critical Level (Hydrological Drought)

Table 3. Summary of the Drought Early Warning System Framework

LEVEL PERINGATAN	INDIKATOR TRIGGER	WAKTU DETEKSI (setelah Awal Musim Kemarau)
Level 1: Peringatan Waspada (metrologis)	SPI -3 ≤ 1.5 (kering)	Bulan ke 2 (Juni 2023)
Level 2: Peringatan Siaga (Pertanian)	KAT ≤ 40 % (ketersedian air tanah kritis)	Bulan ke 4 (Agustus 2023)
Level 3: Peringatan Awas (hidrologi)	SSI ≤ 1.5 & Debit sungai < 50% Normal	Bulan ke 6 (Oktober 2023)

Drought Disaster Mitigation Recommendations

Based on the integrated drought early warning system, mitigation measures are designed to be proactive and tiered according to the three warning levels. At Level 1 (Alert–Meteorological Drought, June 2023), actions focus on prevention and preparedness, including public dissemination of drought risk through local media and farmer groups, routine inspections of irrigation infrastructure and bore wells in vulnerable regions such as Gunungkidul and Kulon Progo, and the enhancement of real-time rainfall monitoring supported by automated SPI updates on digital platforms. At Level 2 (Standby–Agricultural Drought, August 2023), the recommended actions are more tactical, involving official adjustments to planting schedules, promotion of drought-tolerant crop varieties, distribution of superior seeds, organic fertilizers, and mulching materials, capacity building on water-conservation techniques such as biopores and drip irrigation, and the development of micro-irrigation systems through collaboration between the Agriculture Office and the Public Works and Water Resources Agency. At Level 3 (Critical–Hydrological Drought, October 2023), responses shift to emergency measures through coordinated actions, including clean-water distribution to affected villages—particularly in Gunungkidul and southern Kulon Progo—restrictions on non-essential water use, provision of food aid, and activation of the Contingency Team to ensure effective inter-sectoral communication and timely response. These recommendations leverage a lead time of up to six months, enabling a transition from reactive to proactive disaster management in line with the Sendai Framework and long-term climate resilience principles.

Long-Term Strategic Recommendations

Beyond the tiered response guided by drought propagation dynamics, this study proposes three long-term strategic actions to strengthen climate resilience in the Special Region of Yogyakarta. First, the development of an integrated digital Early Warning System that consolidates real-time SPI data from BMKG, ATi from the Agriculture Office, and SSI from the Public Works and Water Utility Agency into a unified monitoring platform. Second, the establishment of the Drought Early Warning Coordination Team (TKPDK-DIY) as an inter-sectoral forum responsible for routine risk assessments and coordinated mitigation during the dry season. Third, the allocation of an annual budget within the regional government budget (APBD) to support system maintenance, field-officer training, community-based outreach, and continued research and development of drought-adaptation technologies. Collectively, these measures aim to build sustainable institutional capacity, reduce dependence on emergency responses, and promote data-driven, collaborative disaster-risk governance aligned with the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015).

CONCLUSION

This study aims to analyze the characteristics and propagation of meteorological, agricultural, and hydrological droughts in the Special Region of Yogyakarta during the 2023 El Niño event, while also developing a regional drought early warning system workflow. The findings indicate that meteorological drought emerges 1–2 months after a rainfall deficit during the dry season, progresses into agricultural drought with a 2–3-month lag, and reaches its peak as hydrological drought about 5–6 months after the



onset of the dry season. Spatially, drought propagation begins in the southern and eastern parts of the region, moves toward the central and northern areas, and eventually extends westward with an approximate one-month delay at similar drought severity levels. These observations suggest that an integrated drought early warning system can be designed based on monitoring and forecasting of drought indices, providing a lead time of 3 to 6 months before impacts occur. In line with these insights, the study proposes three strategic actions: first, the official adoption of a three-level early warning protocol (Alert, Standby, Critical) as a provincial operational standard; second, the development of an integrated digital DIY Drought EWS platform that consolidates real-time data from BMKG, the Agriculture Office, the Public Works and Water Resources Office, and BPBD with spatial mapping and automated field notifications; and third, the prioritization of anticipatory mitigation through annual budgeting for preventive measures such as weather modification, distribution of drought-tolerant seeds, water-conservation initiatives, and public water-saving campaigns in preparation for extreme dry years.

REFERENCES

1. Affandy, N.A., Iranata, D., Anwar, N., Maulana, M.A., Prastyo, D.D., Jaelani, L.M., & Suyadi, F.X. 2023. Modelling Causality between Agricultural and Meteorological Drought Indices in the Corong River Basin, East Java Indonesia. *Journal of Water and Land Development*, 58: 178–188. doi:10.24425/jwld.2023.146610.
2. Affandy, N.A., Iranata, D., Anwar, N., Maulana, M.A., Wardoyo, W., Prastyo, D.D., & Sukojo, B.M. 2024. The Relationship between Hydro-Agricultural Drought in the Corong River Basin: A Causal Time Series Regression Model. *Civil Engineering Dimension*, 26(2): 173–190. <https://doi.org/10.9744/ced.26.2.173-190>
3. Aldrian, E. & Susanto, D. 2003. Identification of Three Dominant Rainfall Regions Within Indonesia and Their Relationship to Sea Surface Temperature. *International Journal of Climatology*, 23: 1435–1452.
4. Van Loon, A.F. 2015. Hydrological drought explained. *WIREs Water*, 2: 359–392. doi:10.1002/wat2.1085.
5. Aprianto, Y. 2023. Impact of El Niño 2023 on Agricultural Productivity in Java, Indonesia. *Journal of Climate Change and Agricultural Sustainability*, 15(3): 245–260.
6. Apriyana, Y. & Kailaku, T.E. 2015. Variabilitas iklim dan dinamika waktu tanam padi di wilayah pola hujan muson dan equatorial. *Prosiding Seminar Nasional Masyarakat Biodiversitas Indonesia*, 1(2): 366–372.
7. Arsyad, S. 2005. Hidrogeologi untuk Irigasi dan Air Tanah. Gadjah Mada University Press.
8. Australian Government, Department of Agriculture and Water Resources. 2019. *Managing Water in Australia: National Water Initiative*.
9. Awchi, T.A. & Kalyana, M.M. 2017. Meteorological drought analysis in Northern Iraq using SPI and GIS. *Sustainable Water Resources Management*, 3(4): 451–463.
10. Avicenna, A.K., Hadiani, R., & Solichin. 2015. Indeks Kekeringan Hidrologi di DAS Keduang berdasarkan Metode Flow Duration Curve (FDC). *Matriks Teknik Sipil*, 3(3): 824–829.
11. BMKG. 2018. *Sistem Peringatan Dini Kekeringan di Indonesia (Ina-DEWS)*. Jakarta: BMKG.
12. BMKG. 2023. *Analisis Dampak El Niño 2023 terhadap Curah Hujan di Indonesia*. Laporan Teknis BMKG, Jakarta.
13. BNPB. 2012. *Pedoman Umum Pengkajian Risiko Bencana*. Jakarta: BNPB.
14. BNPB. 2007. UU No. 24 Tahun 2007 tentang Penanggulangan Bencana. <https://bnpb.go.id/sistem-penanggulangan-bencana>
15. BNPB. 2025. *Indeks Risiko Bencana Indonesia (IRBI) 2025*. https://www.bnpb.go.id/storage/app/media/Buku%20BNPB/BUKU%20IRBI%202024_BNPB_lowres.pdf
16. BPS. 2023. *Statistik Kekeringan di Provinsi Daerah Istimewa Yogyakarta (DIY)*.
17. Budianto, M.B., Putra, I.G., & Saidah, H. 2020. Indeks Kekeringan Hidrologi Berdasarkan Debit (Studi Kasus DAS Sidutan). *Spektrum Sipil*, 7: 115–125.
18. Cai, W. *et al.* 2018. Increased variability of eastern Pacific El Niño under greenhouse warming. *Nature Climate Change*, 8(12): 1139–1145. <https://doi.org/10.1038/s41558-018-0335-1>
19. Creswell, J.W. 2014. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. Sage Publications.
20. De Medeiros, G.C., Maia, A.G., & de Medeiros, J.D. 2019. Assessment of Two Different Methods in Predicting Hydrological Drought from the Perspective of Water Demand. *Water Resources Management*, 33(5): 1851–1865.
21. Gebrechorkos, S.H. *et al.* 2023. Global high-resolution drought indices for 1981–2022. *Earth System Science Data*, 15: 5449–5466.



22. Esri. 2023. ArcGIS Pro: The next generation of GIS.
23. Harijono, S.W.B. 2008. Analisis Dinamika Atmosfer di Bagian Utara Ekuator Sumatera saat El Niño dan Dipole Mode Positif. *Jurnal Sains Dirgantara*, 5(2): 130–148.
24. Hayes, M. *et al.* 2011. The Lincoln Declaration on drought index recommended. *Bulletin of the American Meteorological Society*, 92(4).
25. IPCC. 2007. *Climate Change 2007: Synthesis Report*. WMO, Geneva.
26. IPCC. 2018. *Special Report: Global Warming of 1.5°C*.
27. IPCC. 2022. *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Cambridge University Press.
28. Irawan, A.N.R., Komori, D., & Hendrawan, V.S.A. 2023. Correlation analysis of agricultural drought risk on wet farming crop and meteorological drought index in the tropical-humid region. *Theoretical and Applied Climatology*, 153: 227–240.
29. Kogan, F.N. 1995. Application of Vegetation Index and Brightness Temperature for Drought Detection. *Advances in Space Research*, 13(5): 111–120.
30. Kostopoulou, E. *et al.* Temporal and spatial trends of SPI in Greece.
31. Kurniadi, A. *et al.* 2021. Independent ENSO and IOD impacts on rainfall extremes over Indonesia. *International Journal of Climatology*, 41(6): 3640–3656.
32. Lesk, C., Rowhani, P., & Ramankutty, N. 2016. Influence of extreme weather disasters on global crop production. *Nature*, 529: 84–87.
33. Li, J. & Heap, A.D. 2014. Spatial interpolation methods applied in the environmental sciences: A review. *Environmental Modelling & Software*, 53: 173–189.
34. Liang, X. *et al.* 1994. A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes. *Journal of Geophysical Research*, 99(D7): 14415–14428.
35. Liu, L.H. *et al.* 2012. Hydro-climatological drought analyses and projections in Oklahoma. *Water Resources Management*, 26(10): 2761–2777.
36. Liu, Y. *et al.* 2021. Evaluation of drought indices in tropical monsoon regions. *Journal of Hydrology*, 599: 126321.
37. Ma'rifah, U., Hidayat, R., & Prasasti, I. 2017. Analysis of meteorological & agricultural drought using SPI and VHI. *IOP Conference Series: Earth and Environmental Science*, 54(1): 012008.
38. Svoboda, M. *et al.* 2002. The Drought Monitor. *Bulletin of the American Meteorological Society*: 1181–1190.
39. Marta, L. 2017. Analisa Indeks Kekeringan dengan SPI dan PNI di Pulau Lombok. *Skripsi, Universitas Mataram*.
40. Martono & Wardoyo, T. 2017. Impacts of El Niño 2015 and IOD 2016 on Rainfall. *Forum Geografi*, 31(2): 184–195.
41. Mathbout, S. *et al.* 2018. Drought variability in Syria. *Atmospheric Research*, 200: 153–168.
42. McKee, T.B., Doesken, N.J., & Kleist, J. 1993. The relationship of drought frequency and duration to time scales. *Proc. 8th Conf. Applied Climatology*: 179–184.
43. McKee, T.B., Doesken, N.J., & Kleist, J. 1995. Drought monitoring with multiple time scales. *Proc. 9th Conf. Applied Climatology*: 233–236.
44. Mishra, A.K. & Singh, V.P. 2022. *Drought and Water Crises: Science, Technology, and Management Issues*. CRC Press.
45. Narasimhan, B. & Srinivasan, R. 2005. Development of Soil Moisture Deficit Index. *Journal of Hydrology*, 303: 311–322.
46. National Drought Mitigation Center. 2024. What is Drought? <http://www.drought.unl.edu>
47. Widodo, N. 2013. Analisis Indeks Kekeringan Meteorologi Menggunakan TRMM di Sumatera. *Skripsi, IPB*.
48. Widiyantoro, N. 2022. Analisis Daerah Rawan Kekeringan Berbasis GIS di DIY.
49. Nugroho, S.P. & Wahyuni, E.T. 2023. Drought Resilience Strategies in DIY. *Disaster Prevention and Management*, 32(4): 378–395.
50. Nugroho, S.P. 2001. Prediksi Kekeringan Pengaruh El Niño 2001–2002. *Jurnal STM Cuaca*, 2(1): 75–80.
51. Pemprov DIY. 2025. Detil Geografis Provinsi DIY. <https://provinsi>
52. DIYkab.go.id.
53. Pulwarty, R.S. & Verdin, J. 2013. Developing Early Warning Systems for drought. *WMO Bulletin*, 62(1): 4–12.
54. Purboningtyas, T.R. *et al.* 2018. Dampak variabilitas iklim terhadap nafkah petani. *Jurnal Sosiologi Pedesaan*, 6(3): 189–197.
55. Saha, S. *et al.* 2014. The NCEP Climate Forecast System Version 2. *Journal of Climate*, 27: 2185–2208.



56. Vicente-Serrano, S.M. *et al.* 2022. Global drought trends and projections. *Philosophical Transactions of the Royal Society A*, 14(1): 1–11.
57. Sugiyono. 2018. *Metode Penelitian Kuantitatif, Kualitatif, dan R&D*. Alfabeta.
58. Sultana, M.S. *et al.* 2021. Agricultural drought assessment using geospatial techniques. *Environmental Challenges*, 4: 100120.
59. Supari *et al.* 2018. ENSO modulation of rainfall in Indonesia. *Climate Dynamics*, 51: 2559–2580.
60. Supari, S. *et al.* 2018. Changes in extreme temperature and precipitation in Indonesia. *International Journal of Climatology*, 38(4): 1979–1997.
61. Surendran, U.P. *et al.* 2019. Drought analysis using DrinC model. *Water Resources Management*, 33(1).
62. Surmaini, E. *et al.* 2015. Early detection of drought impact on rice paddies. *Theoretical and Applied Climatology*, 121: 669–684.
63. Surmaini, E. 2016. *Sistem komunikasi dan Diseminasi Prediksi Iklim*. Balai Penelitian Agroklimat.
64. Sutikno, D. *et al.* 2021. Impact of El Niño on Drought Characteristics in Yogyakarta.
65. Sutanto, S.J. *et al.* 2024. Hydrological drought forecasts. *Communications Earth & Environment*, 5: 118.
66. Sutanto, S.J. & Adidarma, W.K. 2015. Analisis kekeringan menggunakan model iklim. *Jurnal SDA*, 11(1): 1–6.
67. Svoboda, M. *et al.* 2022. The evolving role of drought monitoring. *Bulletin of the American Meteorological Society*, 103(3): E705–E722.
68. Svoboda, M., Hayes, M., & Wood, D. 2012. *Standardized Precipitation Index User Guide*. WMO.
69. Tareke, K.A. & Awoke, A.G. 2022. Hydrological drought using SDI in Ethiopia. *Advances in Meteorology*, 2022: 7067951.
70. UNISDR. 2009. *Terminology on Disaster Risk Reduction*. Geneva.
71. Tian, Y. *et al.* 2020. Machine learning for drought prediction using satellite data. *Remote Sensing*, 12(7): 1102.
72. Trenberth, K.E. *et al.* 2014. Attribution of climate extreme events. *Earth's Future*, 2: 311–313.
73. Turner, S. *et al.* 2021. The 2018/2019 drought in the UK. *Weather*, 76: 248–253.
74. UNISDR. 2009. *Community-based Disaster Risk Management*.
75. UNDRR. 2017. *The Sendai Framework Terminology on Disaster Risk Reduction*.
76. UNDRR. 2022. *Global Assessment Report on Disaster Risk Reduction 2022*.
77. Van Loon, A.F. 2015. Hydrological drought explained. *WIREs Water*, 2: 359–392.
78. Vicente-Serrano, S.M. *et al.* 2023. Global characterization of hydrological and agricultural droughts. *Nature Communications*, 14: 1–11.
79. Vicente-Serrano, S.M., Beguería, S., & López-Moreno, J.I. 2010. SPEI: A multiscalar drought index. *Journal of Climate*, 23: 1696–1718.
80. Wahyuni, D. & Suparno. 2020. Penentuan Ketersediaan Air Tanah untuk Irigasi Pertanian.
81. Wenju Cai *et al.* 2021. Changing ENSO in a warming climate. *Nature Reviews Earth & Environment*, 2(9): 1139–1145.
82. Wilhite, D.A. 2010. Drought as a Natural Hazard: Concepts and Definitions.
83. Wilhite, D.A., Svoboda, M.D., & Hayes, M.J. 2007. Understanding the complex impacts of drought. *Water Resources Management*, 21: 763–774.
84. WHO. 2019. *Health Emergency and Disaster Risk Management Framework*. WHO.
85. WMO. 2012. *Guidelines on Analysis of Extreme Events*.
86. WMO. 2016. *Standardized Precipitation Index User Guide (WMO-No. 1090)*. Geneva.
87. WMO & GWP. 2016. *Handbook of Drought Indicators and Indices*. IDMP.
88. WMO. 2023. *State of the Global Climate 23*. WMO-No. 1289.
89. Zahroh, N.F. & Syafira, S.A. 2015. Identifikasi Kekeringan Hidrologi di DAS Citarum Hulu. *Jurnal STM Cuaca*, 16: 21–47.
90. Zhou, Y. *et al.* 2025. The Evolution of Drought and Propagation Patterns in the Pearl River Basin. *Water*, 17(8): 1116.

Cite this Article: Arifin, Y., Maharani, Y.N., Cahyadi, T.A. (2025). Analysis of Meteorological–Hydrological Drought Propagation for the Development of a Drought Early Warning System in the Special Region of Yogyakarta (DIY): A Case Study of the 2023 El Niño Event. International Journal of Current Science Research and Review, 8(12), pp. 6414-6426. DOI: <https://doi.org/10.47191/ijcsrr/V8-i12-52>