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CASE STUDY

Spatiotemporal analysis of rainfall variability using satellite precipitation in watersheds

M.D. Syaifullah[1], A. Purwandani[2], M. Kudsy[3,*], Tukiyat[3], S. Tikno[3], A.E. Sakya[4], F.H. Widodo[3], S. Bahri[3], Muktiyono[3]

[1] *Research Center for Climate and Atmosphere, National Research and Innovation Agency, Serpong 15314, Indonesia*

[2] *Research Center for Conservation of Marine and Inland Water Resources, National Research and Innovation Agency, Cibinong 16911, Indonesia*

[3] *Research Center for Limnology and Water Resources, National Research and Innovation Agency, Serpong 15314, Indonesia*

[4] *Research Center for Geological Disaster, National Research and Innovation Agency, Serpong 15314, Indonesia*

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ABSTRACT

BACKGROUND AND OBJECTIVES: Comprehending spatial and temporal rainfall variability is essential for effective water resource management in Indonesia, where diverse landscapes and dynamic tropical climates lead to irregular precipitation patterns that can trigger localized floods or droughts. This study seeks to explore the impact of geomorphological and topographical differences across the Toba-Asahan, Brantas, and Larona-Malili watersheds in Indonesia influence rainfall distribution and trends, with the goal of enhancing adaptive and sustainable watershed management.

METHODS: This study analyzes rainfall variability in three distinct Indonesian watersheds, Toba-Asahan, Brantas, and Larona-Malili, using climate hazards group infrared precipitation with Station version 2 satellite precipitation data. The patterns of rainfall, both spatial and temporal, are analyzed in connection with the distinct geomorphological and topographical features of each watershed. Basic statistical analysis and mapping techniques are used to identify trends and visualize distribution patterns, with the goal of offering insights into the impact of natural landscape features on rainfall patterns and water availability within the watershed context.

FINDINGS: The results reveal a significant long-term increase in rainfall in the Larona-Malili watershed, while no statistically significant trends are observed in the Brantas and Toba-Asahan watersheds. The dominant rainfall patterns illustrate the distinct climatic features of each watershed region. Spectral analysis highlights the influence of El Niño Southern Oscillation and Indian Ocean Dipole, showing semi-annual rainfall patterns in Toba-Asahan and Larona-Malili, and an annual cycle in Brantas. The sensitivity to climate varies among the three watersheds, as indicated by the differing impacts of the Webster-Yang Monsoon Index, El Niño Southern Oscillation, and Indian Ocean Dipole.

CONCLUSION: This study comprehensively analyzes rainfall variability in three significant watersheds in Indonesia; the Brantas, the Toba-Asahan, and the Larona-Malili watersheds. The findings of this study further suggest that the Asian Monsoon plays a crucial role in shaping the seasonal rainfall patterns of the Brantas watershed. Conversely, the Toba-Asahan and Larona-Malili watersheds are influenced by both local and regional factors, where alterations in land use contribute to variations in rainfall and affect water resources. Annual patterns vary among the watershed, with Toba-Asahan experiencing year-round rainfall peaking from August to December, Brantas dominated by afternoon convection-driven rain from January to April and November to December, and Larona-Malili showing morning-to-noon rainfall from May to July due to local circulation and topographic effects. Another observation from this study indicates that the Asian Monsoon has a significant impact on the seasonal rainfall patterns within the Brantas watershed. Ultimately, the outcomes of this study could inform water resource management strategies in the three watersheds, particularly in response to anticipated climate change and extreme weather fluctuations

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*Corresponding Author:
Email: *maha001@brin.go.id*
Phone: +62811945991
ORCID: 0000-0001-8185-2958

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INTRODUCTION

Effective water resource management in tropical regions like Indonesia requires a comprehensive understanding of the spatial and temporal variability of rainfall at the watershed scale. Unpredictable rainfall patterns frequently result in hydrological extremes like floods and droughts, which can happen concurrently within the same region (Alemu and Bawoke, 2020). Climate change amplifies these challenges by increasing monsoonal variability and the frequency of extreme weather occurrences (Li *et al.,* 2023). Although satellite-based precipitation datasets such as Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) and Global Satellite Mapping of Precipitation Near-Real-Time (GSMaP-GNRT) have enhanced rainfall monitoring, the relationship between rainfall variability, watershed geomorphology, and atmospheric circulation remains insufficiently explored (Saharia *et al.,* 2021). The diverse hydroclimatic conditions and complex geography of Indonesia create a perfect backdrop for studying the interplay between rainfall patterns, watershed attributes, and overarching climatic factors. The Brantas, Toba-Asahan, and Larona-Malili watersheds are strategically important for hydropower, irrigation, and tourism, yet are increasingly vulnerable to both climatic and anthropogenic pressures. Each basin represents distinct geomorphological and climatic conditions, ranging from the volcanic highlands of Lake Toba, the densely populated and intensively cultivated Brantas basin, to the mountainous terrain of the Larona-Malili region. The variability of rainfall throughout the archipelago is influenced by its physical geography, dominant wind patterns, and terrain, leading to distinct equatorial, monsoonal, and localized rainfall patterns (Kurniadi *et al.,* 2023). Previous studies have emphasized the importance of seasonal rainfall variability in water resource planning (Aksu, 2023; Narulita *et al.,* 2021) and the utility of satellite-derived products like CHIRPS for hydrological assessments (Wiwoho *et al.,* 2021). Furthermore, numerous research initiatives have investigated the hydrological and environmental dynamics in Indonesian watersheds, concentrating on flood susceptibility, alterations in land use, and the deterioration of water quality. For instance, Dede *et al.,* (2023) investigated the link between land use patterns and river ecosystem services using spatial correlation methods. The study conducted by Setiawan *et al*. (2024) employed the analytical hierarchy process (AHP) alongside a geographic information system (GIS) framework to identify suitable micro-hydropower dam sites in Banyumas, highlighting the importance of slope, land cover, and river proximity. Narendra *et al.,* (2024) used principal component analysis (PCA) and GIS to map flood vulnerability on Lombok Island, while Rosyidy and Frimawaty (2024) documented spatiotemporal patterns of oil palm expansion in Jambi Province. Furthermore, Marisi *et al.,* (2025) indicated that alterations in land use and land cover (LULC) within the Upper Bekasi watershed were associated with rising levels of pollutant concentrations. While these studies offer valuable insights, most emphasize spatial analyses and direct land use impacts, relying heavily on GIS-based methods and remote sensing, without fully integrating long-term temporal variability or the influence of large-scale climate oscillations. This study aims to fill this gap by performing an extensive spatiotemporal analysis of rainfall variability in the three primary Indonesian watersheds discussed earlier, covering the period from 2000 to 2023. By integrating high-resolution satellite precipitation datasets (CHIRPS and GSMaP-GNRT), applying Mann-Kendall trend tests, and employing fast fourier transform (FFT) analyses, this research captures both temporal trends and frequency-domain characteristics of rainfall. Moreover, it uniquely incorporates correlations with large-scale climate phenomena such as the El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Western Pacific Monsoon Index (WPMI), providing a more holistic understanding of how global climatic variability influences regional hydrological processes. The results indicate that only the Larona-Malili watershed exhibits a significant increasing trend in rainfall, implying varying climate sensitivities among the basins. This study provides insights that support the creation of more adaptable and region-specific strategies for water management. The insights generated aim to inform flood and drought mitigation planning, support climate adaptation policies, and enhance the long-term sustainability of water resources in Indonesia. This study's innovation is its comparative examination of rainfall variability through satellite data across various watersheds in Indonesia, highlighting specific results for each

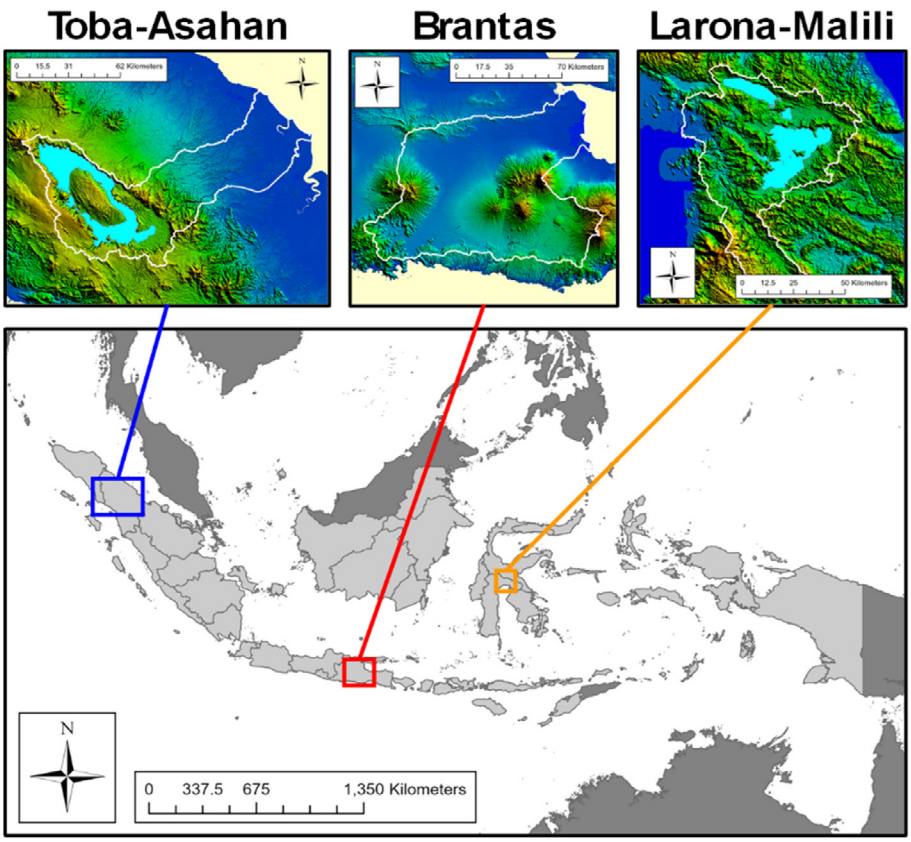

Fig. 1: Geographical location of the study area in the Toba-Asahan, Brantas, and Larona-Malili watershed regions, in Indonesia

basin. Notably, the Larona-Malili watershed shows a significant increasing rainfall trend that is not present in the other two watersheds; it also reveals distinct rainfall patterns that correspond to the unique climatic traits of each region, as well as varying climate sensitivities among the three watersheds. This study provides a foundation for more effective and sustainable water resource management strategies and supports the growing urgency for climate adaptation policies in Indonesia. This study has been condacted in Asahan Toba, Brantas, and Larona Malili watersheds, Indonesia in 2023-2024.

MATERIALS AND METHODS

The study area

The Larona-Malili watershed, in Sulawesi, is influenced by tropical rainforest ecosystems and hydroelectric power activities. These watersheds were selected due to their diverse hydrological and climatological conditions, illustrating a range of watershed traits across Indonesia. Fig. 1 shows the study area for the three watersheds.

Materials

GSMaP-GNRT data, part of the GPM dataset, was utilized to provide global rainfall information with high spatial and temporal resolution GPM uses radar instruments and microwave measurements on multiple satellites to collect rainfall data. The GSMaP-GNRT (version 6) Real-time Gauge-adjusted Precipitation product from Japan Aerospace Exploration Agency (JAXA) is processed 4 hours after observation and distributed with a spatial resolution of 0.1 degree (°) × 0.1° and a temporal resolution of 1 hour. This dataset has been available since April 2000. Generally, the accuracy of gauge-adjusted products is higher than that of uncorrected products (Kubota *et al.*, 2020; Li *et al.*, 2024). The dataset is

publicly accessible through the JAXA Global Rainfall Watch System (Kubota *et al.*, 2020). The GSMap_NRT data has been validated using rainfall data from three watersheds in Indonesia, which include the Brantas and Larona-Malili watersheds. Syaifullah (2014) found that the GSMap_NRT value has a pattern that follows the observed (actual) rainfall, although the value tends to be below the estimate. This variation could stem from the use of rain gauges that are not sufficiently representative of the watershed, causing the average rainfall in the region to be an unreliable indicator of the watershed's conditions. The CHIRPS exploited in this study is a satellite-based rainfall dataset designed to analyze rainfall in global land regions. This dataset is frequently utilized to investigate rainfall trends, climate variability, and the effects of extreme weather, particularly in tropical areas. Spatial resolution: 0.05° x 0.05° (~5 km), temporal resolution: daily, decadal (10 days), and monthly. The CHIRPS dataset (Funk *et al.*, 2015) covers the global region between 50° North (N) and 50° South (S), with a focus on tropical and subtropical areas. The dataset used includes monthly data from 1981 to 2024. The geomorphological analysis of the three catchments was carried out using the 2019 land use map published by the Ministry of Environment and Forestry (KLHK), the watershed boundary map, and the high-resolution topographic map (DEMNAS) obtained from the Geospatial Information Agency (BIG). The dipole mode index (DMI) is an essential indicator in climate studies. It is capable of assessing the fluctuations in sea surface temperature between two significant areas in the Indian Ocean. It is often used to monitor and analyze the phenomenon known as the Dipole Mode or Indian Ocean Dipole (IOD). Sea surface temperature (SST) in the Niño 3.4 region is a crucial indicator in climate studies used to monitor and analyze El Niño and La Niña phenomena. Data sources for DMI and Niño 3.4 SST anomalies are available from the Physical Sciences Laboratory (PSL) of the National Oceanic and Atmospheric Administration (NOAA) in the United States, and can be downloaded.

Methods

The study begins with the identification of the three watersheds, including their geomorphological and topographical characteristics, through a thematic watershed analysis that considers land use and cover. Land-use changes in Java's Brantas watershed from 1995 to 2015 were driven by economic, social, technological, and biophysical factors, leading to significant transitions from forests and agriculture to urban areas (Wiwoho *et al.*, 2023). The study of temporal analysis focuses on historical precipitation trends across daily and monthly intervals. Land-use changes, sedimentation, coastal erosion, and rainfall variability highlight the need for sustainable planning and adaptive strategies in Java (Nofirman *et al.*, 2023). The three selected watersheds—Toba-Asahan, Brantas, and Larona-Malili—exhibit varied hydrological and climatological conditions, representing different characteristics of Indonesian watersheds. The study initiates by identifying these watersheds, emphasizing their geomorphological and topographical characteristics through a thematic analysis that takes into account land use and cover. A temporal analysis investigates historical rainfall patterns on both monthly and daily scales. This study underlines the importance of managing water resources, which encompasses irrigation strategies and drought prevention measures. Rainfall distribution is analyzed by calculating the average CHIRPS rainfall during periods of significant climate phenomena, and descriptive statistics are used to assess regional average differences between phases with negative and positive standard deviations. An annual examination of daily variations in watersheds deepens insight into daily meteorological and hydrological behaviors, highlighting diurnal cycle trends and essential rainfall phases that can fluctuate across various watersheds. (Kamal *et al.*, 2019) Employed the non-parametric Mann-Kendall test to identify climate variable behavior using database records. Conducted a trend analysis of annual average temperature, rainfall, and river discharge in Afghanistan from 1980 to 2022 using the Mann-Kendall (MK) test and Sen's Slope estimator (SS) with ECMWF reanalysis v5 (ERA5) data (Akhundzadah, 2024). The Mann-Kendall and Sen's Slope tests identified a decreasing rainfall trend in Mempawah, an increasing trend in Kubu Raya, and significant drying in Sungai Kunyit as -33.20 milligrams per year (mm/y), highlighting the impact of climate change on water availability in West Kalimantan from 2000 to 2019 (Aditya *et al.*, 2021). Diurnal Hovmöller analysis for the three watersheds illustrates the temporal and spatial rainfall patterns specific to region. This strategy

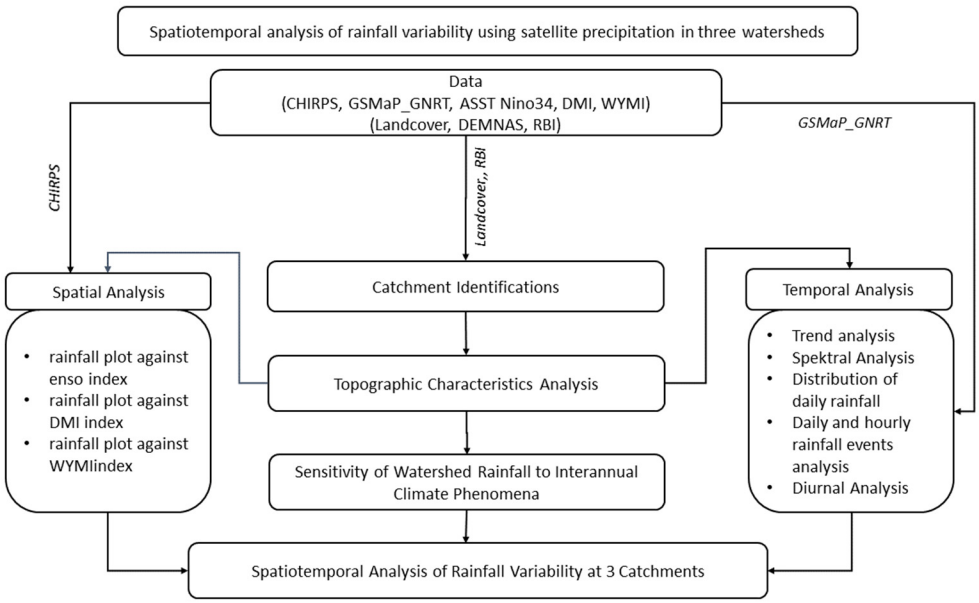

Fig. 2: Research flowchart

facilitates the visualization of daily fluctuations throughout the year, offering essential insights for watershed management, disaster prevention, and hydrological analysis. For instance, it can determine whether rainfall frequently occurs in the afternoon to evening due to topographical influences, valley-mountain wind cycles, or orographic effects. Rainfall patterns in the Ili region fluctuate according to the terrain, exhibiting afternoon peaks in mountainous areas and evening peaks in the valleys, largely driven by vertical velocity and the mixing ratio of water vapor (Li, *et al*., 2023). Organized convection drives most seasonal rainfall in South America, moving westward across the Amazon Basin, influenced by wind patterns, Convective Available Potential Energy (CAPE), and transient disturbances (Filho *et al*., 2015). The impact of climate phenomena on rainfall in the three watersheds is influenced by factors such as the monsoon, represented by the Webster and Yang Monsoon Index (Webster *et al*., 1992), IOD indicated by the Dipole Mode Index, and the El Niño Southern Oscillation (ENSO) measured using the Nino3.4 index (Trenberth *et al*., 1997). Conducting a sensitivity analysis of watershed rainfall to these interannual climate phenomena, including the El Niño-Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Madden-Julian Oscillation (MJO), is essential for understanding their long-term effects. Utilizing spectral analysis allows for the identification of key frequencies or oscillation periods in time series data (Wilks, 2011), with a focus on detecting cyclical trends in rainfall data recorded on a daily or monthly basis. This method has been applied in various studies in Indonesia, such as analyzing zonal wind components in the Pontianak region to determine monsoon intensity and employing spectral analysis to investigate variations in sea level and wind fluctuations through cross-correlation spectrum analysis (Oktavia *et al*., 2011). Furthermore, spectral Fast Fourier Transform (FFT) analysis was applied to assess fluctuations in sea level and wind wind fluctuations using cross-correlation spectrum analysis, components such as cross-energy density spectrum, squared coherence, and phase difference. The Webster-Yang Monsoon Index (WYMI) is determined by the difference in zonal wind speed between the upper level as 200 hectoPascal (hPa) and the lower level (850 hPa) within the Asian monsoon core region (40° East (E)–110°E, 0°–20° North (N)), calculated as WYMI = U850 − U200. Here, U850 represents the zonal wind at 850 hPa and U200 at 200 hPa. Strong monsoon intensity is indicated by positive WYMI values, which are associated with a strong southwest monsoon flow, while negative values represent weak monsoon

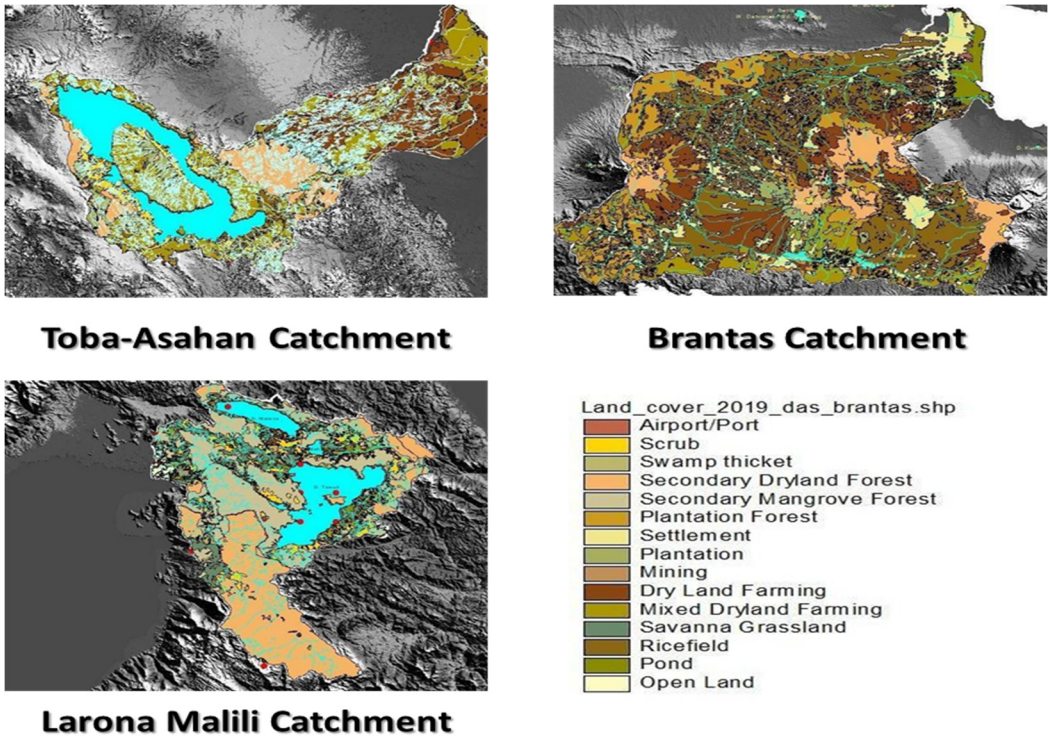

Fig. 3: Land cover map of the Toba-Asahan, Brantas and Larona-Malili watersheds.

conditions. Elevated WYMI values are generally linked to vigorous monsoon activity, potentially leading to severe rainfall occurrences in specific watersheds. Sensitivity analysis is performed utilizing correlation and regression models. The correlation model determines the relationship between rainfall and SST_Nino34, WYMI, and DMI. In contrast, the regression model measures the combined contribution or influence of SST_Nino34, WYMI, and DMI on rainfall in each watershed. Data processing is conducted using R studio. Fig. 2 shows the flowchart of the current study.

RESULTS AND DISCUSSION

Fig. 3 depicts the land cover maps of the Toba-Asahan, Brantas, and Larona-Malili watersheds issued by the Ministry of Environment and Forestry (KLHK) in 2019.

Topographic characteristics of the Toba-Asahan watershed

The Toba-Asahan watershed comprises Toba Lake and the Asahan River in North Sumatra, Indonesia. Covering an area of approximately 7,415 square kilometers (km²), it is part of the Toba-Asahan River Region, designated as a national strategic river region by Presidential Decree No. 12 of 2012 of the Republic of Indonesia. Toba Lake, recognized as the largest volcanic lake globally, spans about 100 kilometers in length and 30 kilometers in width, with depths reaching as much as 508 meters. Water from Toba Lake flows through the Asahan River, a main river that stretches 153.82 km with an average width of 50 m, from the outlet of Toba Lake in Porsea District to the coast at the Malacca Strait (Tanjung Balai City). The geomorphology of the Toba-Asahan watershed in North Sumatra is notably complex, a result of ancient volcanic eruptions. This substantial eruption resulted in a large caldera that now contains Toba Lake, with the Asahan River being its primary drainage. The topography of the Toba-Asahan watershed ranges from the lake's surface level (approximately 905 meters above sea level) to the surrounding mountains, which reach heights of over 2,000 meters. The region surrounding the caldera is characterized by steep slopes and mountains.

Industrial activities such as the Asahan Hydroelectric Power Plant (PLTA Asahan) are significant elements in this watershed, utilizing the Asahan River's flow as an energy source. The geographical features of the Toba-Asahan watershed have a major impact on the area's precipitation trends. According to the 2019 land use map analysis by KLHK, the Toba-Asahan watershed is predominantly composed of dryland agriculture as 38.7 percent (%), plantations (25%), secondary dryland forest (14%), shrubs (6.2%), plantation forests (5.4%), and paddy fields (4%). Residential areas account for only about 1.3% of the total watershed area. Modifications to land cover in watershed zones greatly impact the nature of water flows and rainfall (Syarifuddin, 2022). This circumstance has a profound effect on the administration of water resources in the region. The land cover of the Toba-Asahan watershed (Fig. 3) significantly influence rainfall patterns. The mountains in the vicinity function as barriers to moist air masses, forcing them to rise, cool adiabatically, and undergo condensation. Due to the southwest monsoon, higher rainfall occurs on windward slopes, primarily in the west and southwest. In contrast, the rain shadow effect causes leeward slopes (those facing east and northeast) to be drier. Lake Toba increases local precipitation by releasing moisture through evaporation, especially during the afternoon when elevated temperatures initiate daily rain patterns in the vicinity of the lake. Dryland agriculture (38.7%) has lower infiltration rates than forests, resulting in increased runoff and a greater reliance on rainfall and irrigation. Plantations (25%) have high water demands, and poor conservation can accelerate runoff. Residential areas (1.3%) have relatively low water needs. The balance of agricultural activities, plantations, and forests is crucial for the watershed's water resources. Its dominance by dryland agriculture and plantations increases drought vulnerability. For sustainability, it is vital to implement effective land conservation, manage irrigation properly, and protect watersheds.

Topographic characteristics of the Brantas watershed

The Brantas watershed, one of Indonesia's largest, is in East Java Province. The Brantas River, the main river, is approximately 320 km long and is the second-longest river on Java Island after Bengawan Solo. The Brantas watershed spans an area of roughly 12,069 km², equivalent to around 25% of East Java Province's total area. Over thousands of years, volcanic activity and sediment deposition have sculpted the Brantas watershed. Topographically, the Brantas watershed encompasses a range of hilly to lowland areas. The upstream section is characterized by hilly and mountainous topography, particularly around Mount Arjuno and Welirang, with steep slopes. Downstream, the topography becomes gentler and tends to be flat. In the vicinity of the Sutami Reservoir, certain watersheds capture water from the Brantas River prior to its downstream flow. Elevation in the watershed ranges from over 3,000 meters in the upstream mountainous areas of Mount Arjuno to around 200 meters in the lowland areas near the reservoir. The Brantas watershed encompasses vast agricultural regions, mainly featuring irrigated rice fields in the low-lying areas and dryland farming in the hilly terrain. The main land use surrounding the reservoir is agriculture, which includes a variety of food crops, including rice, maize, and vegetables. These forests are crucial for maintaining soil stability and water flow to the reservoir. The Brantas watershed encompasses both residential and urban regions, particularly in the vicinity of Malang City. According to the 2019 land use map analysis by KLHK, the Brantas watershed is dominated by paddy fields (35.5%), residential areas (16.2%), plantation forests (15.5%), dryland agriculture (11.4%), mixed dryland agriculture (8.8%), secondary dryland forest (7.3%), fish ponds (2%), and plantations (1.3%). Urban and rural residential areas significantly dominate the total watershed area. The Brantas watershed features a varied landscape, shifting from steep mountainous terrains in the upstream regions surrounding Mount Arjuno and Welirang (exceeding 3,000 m) to more gradual lowlands close to the Sutami Reservoir (about 200 m). The upstream region features steep slopes and forested areas, whereas the middle and lower reaches become flatter, supporting extensive agricultural activities. The Sutami Reservoir and its adjacent watersheds are essential for managing water flow prior to its arrival in downstream regions. Agriculture dominates the watershed, particularly irrigated paddy fields (35.5%) and dryland farming, with crops such as rice, maize, and vegetables. Protected forests (15.5% plantation, 7.3% secondary) act as erosion buffers and help regulate river flow, although their limited coverage affects overall hydrological stability. Urban expansion of urban

environments, particularly in Malang City, leads to more infrastructure development and rising water demand, thereby affecting sedimentation and the quality of water. The watershed is facing significant pressure from urbanization and agricultural activities, resulting in increased erosion and potential sedimentation in rivers and reservoirs. The significant proportion of paddy fields, residential zones (16.2%), and dryland farming necessitates efficient land and water management approaches. If not correctly managed, sedimentation can reduce reservoir storage capacity, affecting water supplies for irrigation and domestic use. Achieving a balance between agricultural productivity, urban expansion, and hydrological sustainability remains a critical challenge for watershed management.

Topographic characteristics of the Larona-Malili watershed

The Larona-Malili watershed is in East Luwu Regency, South Sulawesi, Indonesia. This watershed comprises three large lakes that form a cascade: Lake Matano, Lake Mahalona, and Lake Towuti. Water from these lakes is channeled into the Larona River, which is utilized for the Larona Hydroelectric Power Plant (PLTA Larona). The Larona-Malili watershed covers a rainfall catchment area of approximately 4,943 km². The Larona-Malili watershed exhibits a varied topography, with elevation levels that transition from lowlands adjacent to valleys and lakes to the encircling mountain ranges. According to land use map analysis, the Larona-Malili watershed is predominantly covered by primary forests, consisting of primary dryland forests (36.3%) and secondary dryland forests (35.4%), followed by shrubs (10.4%), mixed dryland agriculture (8.8%), dryland agriculture (2.7%), open land (1.8%), and paddy fields and fish ponds, each comprising 1%. Approximately 0.4% of the entire watershed area is comprised of residential neighborhoods, predominantly found in the downstream region. Characterized by tropical forests, the Larona-Malili watershed functions as a conservation area and a hub for biodiversity. Besides forests, residential areas, small-scale agriculture, mining, and fishing activities surround the lakes. The extensive primary and secondary forests (71.7%) that dominate this area indicate that the watershed's condition is still relatively good. Maintaining the hydrological cycle heavily relies on primary and secondary dryland forests. The dense plant life within these forests promotes the infiltration of rainwater into the soil, curtails surface runoff, and sustains groundwater availability all year long, contributing to stable river discharge. It reduces drought risk during the dry season. Open land areas (1.8%) have a high risk of erosion due to the lack of vegetation protecting the soil from rain erosion. When found in upstream locations, this can result in heightened sedimentation within rivers and reservoirs, potentially reducing water storage capacity. The presence of reservoirs and the dominance of primary forests can help reduce sedimentation and maintain a stable water supply for existing hydroelectric power plants (PLTA). The limited residential zone (0.4%) located in the lower section of the watershed indicates that the demand for domestic water may remain relatively low in relation to the total water availability. However, if there is rapid residential growth, effective management of clean water and sanitation is necessary to prevent contamination of water sources. The central water bodies include the Larona River and Malili Reservoir, which play essential roles in irrigation and power generation. Certain regions show clear signs of environmental degradation, primarily due to deforestation linked to the expansion of plantations and mining operations. Overall, the Larona-Malili watershed has good water resource potential due to the dominance of primary forests, which contribute to water conservation and hydrological regulation. Nonetheless, challenges must be taken into account, including the possible degradation of open land regions and alterations in land use that may impact future water resources

Spatial distribution of rainfall in watersheds

The spatial rainfall assessment of the three watersheds utilizes precipitation data from CHIRPS, recognized for its relatively high resolution. Monthly rainfall maps were created using CHIRPS data from 2001 to 2024 for the three watersheds, linked to three climate phenomena: ENSO, represented by the Niño3.4 Index; Dipole Mode, represented by the DMI; and the monsoon, represented by the Webster-Yang Monsoon Index (WYMI). Each index was analyzed under two conditions: below the negative standard deviation of the index value (SD-) and above the positive standard deviation of the index value (SD+). The results are presented in Fig. 4. As illustrated in

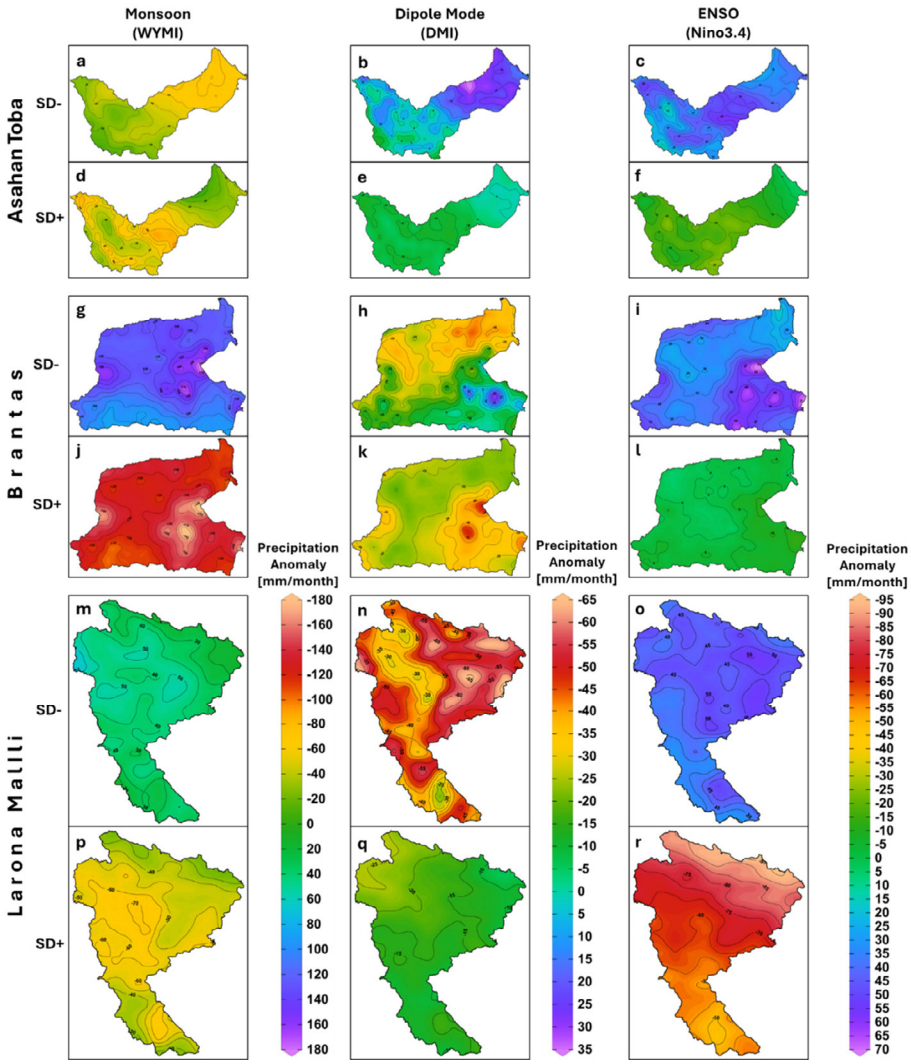

Fig. 4: Rainfall distribution patterns in the Asahan Toba, Branstas, and Larona Malili watersheds (from top to bottom) are influenced by WYMI, DMI, and Niño3.4 (from left to right) in the positive phase (SD+, above the positive standard deviation) and negative phase (SD-, below the negative standard deviation). The values in the rainfall legend for each climate phenomenon are different.

Fig. 4, the analysis of the distance from the watershed (DAS) to the source and the traits of each climate phenomenon indicates that the Brantas watershed is governed by a monsoon system, significantly influenced by the fluctuations in monsoon activity. Meanwhile, the Asahan Toba watershed, closest to the origin of the IOD, exhibits the most potent influence among the three climate phenomena. The Larona Malili watershed is notably impacted by the ENSO, given that its source is in close proximity to Larona Malili. When ranked by watershed, the Asahan Toba watershed demonstrates the most prominent climate phenomena in sequence: IOD, ENSO, and Monsoon. In contrast, the Brantas watershed is influenced by Monsoon, IOD, and ENSO, while the Larona Malili watershed is affected by ENSO, Monsoon, and IOD. Table 1 supports the findings illustrated in Fig. 4, highlighting the key climate phenomena that quantitatively impact each watershed. Conversely, it also reveals the ranking of watersheds based on the

Table 1: Minimum and maximum values and the difference between the average rainfall anomalies of each watershed area for each climate phenomenon between SD- and SD+

Climate phenomena	Phase	Asahan Toba			Brantas			Larona Malili		
		Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
Monsoon (WYMI)	SD-	-75	-11	-45	84	184	123	15	64	38
	SD+	-89	-6	-47	-187	-104	-132	-79	-22	-50
Difference				2			255			88
Dipole Mode (DMI)	SD-	-12	38	11	-44	29	-21	-67	-18	-47
	SD+	-13	1	-7	-49	-20	-29	-26	-6	-16
Difference				18			7			-31
ENSO (Nino3.4)	SD-	14	57	38	18	73	40	29	56	44
	SD+	-27	5	-15	-14	5	-3	-95	-47	-71
Difference				52			43			115

(Green indicates the most significant difference, and red means the smallest)

strength of influence of each climate phenomenon. The more significant the difference between the SD- and SD+ mean rainfall areas, the stronger the impact of the respective climate phenomenon (highlighted in green). Furthermore, these values demonstrate the cumulative impacts of climatic factors across watersheds and different climate events. The maximum difference of 225 mm/month occurs in the Brantas watershed under the influence of the monsoon. The second highest difference is ENSO, with 115 mm/month, followed by another significant difference in the Brantas watershed, with a 43 mm/month value. This trend continues in subsequent different rankings. The rainy season has significantly affects rainfall variability in the Brantas watershed compared to Larona-Malili or Toba-Asahan. Of the three, Larona-Malili experiences the greatest impact from the rainy season, whereas Toba-Asahan is the least impacted. The rainy season has a considerable effect on Brantas due to its position in Region A, which is marked by a monsoonal climate featuring distinct wet and one dry season. The dipole mode event (DME) has a significant impact on Toba-Asahan, primarily because of its close geographical location to the DME activity center. This is supported by previous studies, including Khaldun *et al.* (2017) and Hendon (2003), which provide detailed analyses of the DME's influence on rainfall fluctuations in the Toba-Asahan region. Meanwhile, ENSO plays a dominant role in Larona-Malili, establishing it as a key ENSO-sensitive watershed. In terms of ENSO-related variability, Larona-Malili's rainfall ranks second, just behind Brantas, and is predominantly influenced by seasonal monsoon rains. Studies by Lestari *et al*. (2023) and Arsyad *et al.* (2023) have further explored the impact of ENSO on rainfall patterns in and around the Larona-Malili watershed.

Temporal trend of rainfall

The study employs the Mann-Kendall method to analyze temporal rainfall trends in the Toba-Asahan, Brantas, and Larona-Malili watersheds using monthly GSMaP_GNRT data from 2001 to 2024. The analysis provides the slope, Z-score, and P-value, where a positive slope represents a rising trend, a negative slope represents a falling trend, and a slope that is nearly zero implies no significant variation. The Z-score determines statistical significance, at $|Z|>1.96$ at $\alpha=0.05$ demonstrates a meaningful trend. Table 2 presents the results of the Mann-Kendall analysis. The findings of the Mann-Kendall test for the three watersheds, as presented in Table 2, can be interpreted in the following manner: For the Toba-Asahan watershed, the Z-score value of 1.178532946 is smaller than the critical value of 1.96 (for $\alpha=0.05$), indicating that there is no significant trend. The P-value of 0.2385842 is greater than 0.05; therefore, the null hypothesis is not rejected, meaning there is no significant trend. The Z-score of

Table 2: Mann-Kendall test results for the three watersheds with a data length of 288 months (2001 ~ 2024)

Parameters	Watershed		
	Toba-Asahan	Brantas	Larona-Malili
Trend	no-trend	no-trend	increasing
Z-Score	1.17853294649	1.19200323480	2.5052247900
P-Value	0.238584205709	0.23325997688	0.01223735914
Sen's slope estimated	0.092604347826	0.0437962962	0.257294323979

the Brantas watershed is 1.1920032, which is below the critical threshold of 1.96 (for α=0.05), suggesting that there is no observable trend. The P-value of 0.233260 is more significant than 0.05. Thus, the null hypothesis is accepted, meaning there is no trend. For the Larona-Malili watershed, the Z-score value of 2.50522479 is greater than the critical value of 1.96 (for α = 0.05), indicating that the trend is statistically significant and increasing. The P-value of 0.012237359 is smaller than 0.05; therefore, the null hypothesis is rejected, meaning there is a significant trend of an increased rainfall of 0.2573 mm/month. The findings indicate that the Larona-Malili watershed exhibits a notable upward trend, observed both statistically and in practical applications. Few publications discuss the rainfall trends and their relationship to the increase in water levels in the lakes within the Larona-Malili watershed, including Lake Matano, Lake Mahalona, and Lake Towuti. The growing levels of rainfall have a favorable effect on the Larona-Malili watershed, as it supports a hydroelectric power station that necessitates an adequate water for nickel manufacturing. Additionally, the adequate water resources in these three lakes benefit the surrounding communities. As for the Brantas watershed, there is no significant statistical trend. Thus, no definitive conclusion can be drawn about long-term changes in rainfall. The result of Toba-Asahan watershed suggests that observed variations in rainfall are more likely due to interannual fluctuations rather than a consistent long-term trend. Previous study by Irwandi et al. (2021) indicated that the water level of Lake Toba is affected by rainfall and runoff; however, the present analysis does not reveal any clear patterns of rainfall variation over time.

Spectral rainfall analysis in the watersheds

To perform spectral analysis of daily GSMaP data for the three watersheds, the fast fourier transform (FFT) technique is employed to transform the data from the time domain to the frequency domain, thereby identifying the spectral peaks. In Fig. 5, part a) presents the time series of daily rainfall data, while part b) displays the power spectrum for the Toba-Asahan, Brantas, and Larona-Malili watersheds. The outcomes of the spectral analysis regarding daily rainfall across the three watersheds can be articulated as follows. The FFT rainfall analysis in the Toba-Asahan watershed shows two spectral peaks at frequencies of 0.00272 (367 days or 12 months) and 0.00546 (182 days or 6 months). The FFT analysis of precipitation in the Brantas watershed reveals a single spectral peak at a frequency of 0.00271, corresponding to 369 days or one year. In the Larona-Malili watershed, the FFT analysis of precipitation identifies four prominent spectral peaks at frequencies of 0.00272 (367 days or one year), 0.00546 (183 days or 6 months), 0.0082 (122 days or 4 months), and 0.0109 (92 days or 3 months). Fig. 5 shows that for the Toba-Asahan watershed, the dominant period of 367 days/12 months shows an annual cycle reflecting the seasonal rainfall cycle, which is likely related to monsoon changes affecting the Toba-Asahan watershed following the tropical yearly cycle. The period of 182 days/6 months indicates a semi-annual cycle associated with the influence of two prominent rainy season peaks in a year. This occurrence is frequently seen in tropical regions that experience transitional seasons. The dominant period of the Brantas watershed is 369 days/12 months, which reflects a strong and regular monsoon cycle similar to that of the Toba-Asahan watershed. The absence of additional frequencies or periods suggests that a straightforward annual cycle predominates in the Brantas watershed, with minimal influence from semi-annual or shorter cycles. The Larona-Malili watershed's dominant period of 367 days, equivalent to 12 months, is also observed, indicating an annual pattern that reflects a significant monsoon influence in this watershed, similar to the Toba-Asahan and Brantas watersheds.

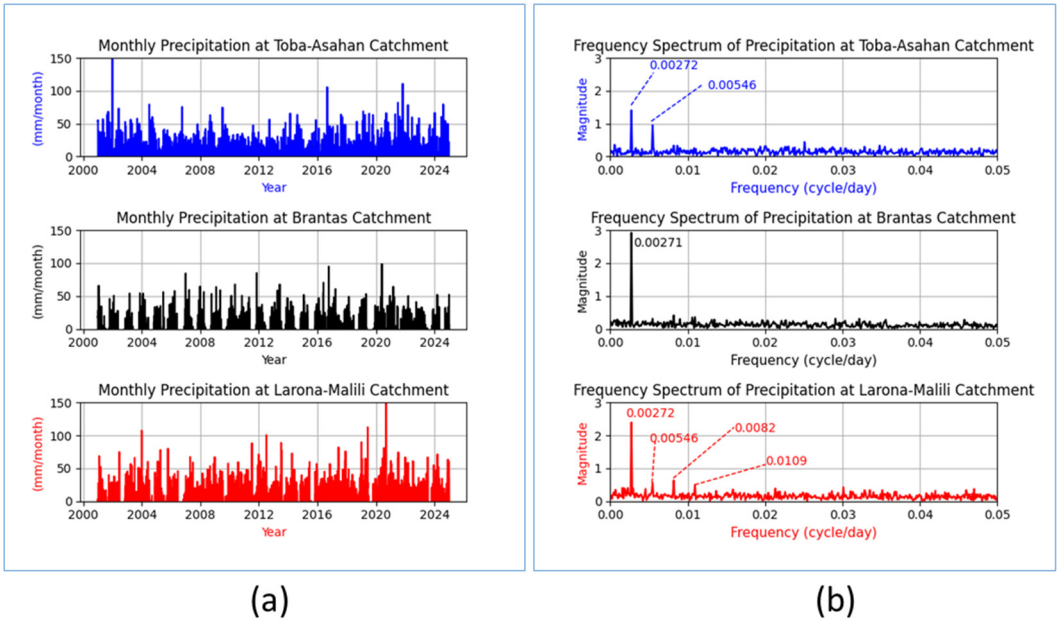

Fig. 5: Time series of monthly/daily rainfall (a) and its power spectrum (b)

There are also semi-annual, quarterly, and intra-seasonal patterns that correspond to durations of 6 months, 4 months, and ~2.5 months, respectively. The semi-annual pattern indicates the presence of two main rainy seasons within a year, similar to the Toba-Asahan watershed. The quarterly trend is probably connected to regional variations or the impact of sub-seasonal phenomena such as the MJO. Variability in local or regional weather systems, such as tropical cyclones, atmospheric waves, or micro-monsoon influences, can lead to a shorter intra-seasonal pattern. The dominant annual pattern observed in all three watersheds, lasting 12 months, highlights the significant impact of the annual monsoon cycle on rainfall. In contrast, the Toba-Asahan and the Larona-Malili watersheds have a semi-annual pattern (6 months), indicating two main rainy seasons within a year. The Brantas watershed exhibits a more straightforward spectral pattern, characterized by a single dominant frequency (~12 months), indicating that rainfall in this watershed tends to be relatively stable, with minimal sub-seasonal fluctuations. Factors that impact spectral variability in climatic occurrences imply that the both annual and semi-annual cycles are usually related to monsoon phenomena. Simultaneously, the quarterly and intra-seasonal trends may be associated with the MJO, Kelvin waves, or Rossby waves.

Distribution of daily rainfall in the watersheds

The examination of the daily rainfall distribution map facilitates the identification of both spatial and temporal rainfall trends and irregularities in the watershed regions under review. The daily rainfall distribution for the three watersheds is presented in Fig. 6, featuring the vertical axis indicating the dates from January 1 to December 31 and the horizontal axis representing the years 2001 to 2024. As depicted in Fig. 6, precipitation occurrences in the Toba-Asahan watershed are nearly constant throughout the month, with increased intensity observed from July to December. El Niño years (2002-2003, 2004-2005, 2006-2007, 2009-2010, 2014-2016, 2018-2019, and 2023-2024) do not significantly alter rainfall patterns in this watershed. This trend reveals that local conditions, particularly orographic effects and regional atmospheric circulation, are crucial in regulating rainfall pattern. In the Brantas watershed, rainfall is most frequent from January to May and November to December. During El Niño years, the

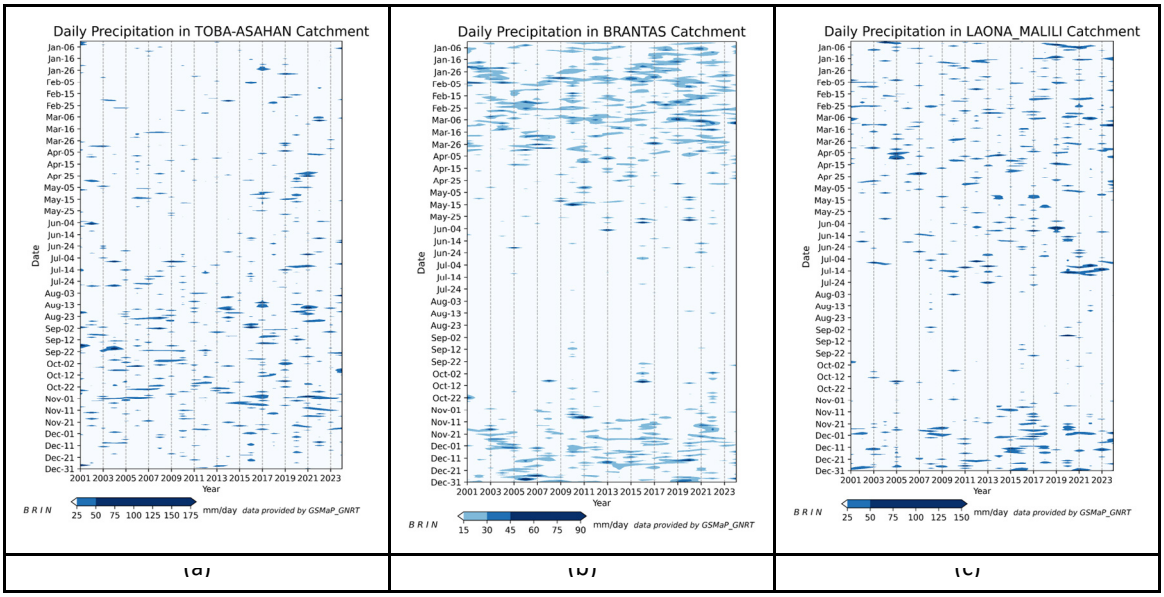

Fig. 6: Distribution of Daily Rainfall in the three watersheds Toba-Asahan (a), Brantas (b) and Larona-Malili (c) respectively from 2001 to 2023

dry season is prolonged due to a notable decrease in rainfall, as reflected in extended dry periods. Rainfall in the Larona-Malili watershed is particularly intense from January through July and from November to December. Unlike Brantas, El Niño years do not cause a substantial reduction in rainfall, as sporadic rainfall events persist even during typically dry months. These findings align with the classification of three distinct climatic regions in Indonesia, where ENSO has a strong influence on rainfall variability in Regions A and C. Conversely, Region B reveals a less pronounced ENSO signal, demonstrating notable correlations between SST and rainfall fluctuations, especially from June to November (Aldrian and Susanto, 2003).

Distribution of daily and hourly rainfall events

The data on rainfall can be segmented into predetermined intervals to evaluate the distribution of rainfall events within the three watersheds. For daily rainfall events, the intervals are: 15mm-20mm, 20mm-25mm, 25mm-30mm, 30mm-40mm, 40mm-50mm, 50mm-60mm, 60mm-80mm, 80mm-100mm, and >100mm. For hourly rainfall events, the intervals are 8mm-10mm, 10mm-12mm, 12mm-14mm, 14mm-16mm, 16mm-18mm, 18mm-20mm, and >20mm. The results are presented in Fig. 7.

The profile of daily rainfall distribution shows a gradual decrease, except for the 30-40 millimeters per day (mm/d) interval. According to the Meteorology, Climatology, and Geophysics Agency (BMKG), extreme rainfall is defined as rainfall with an intensity of more than 50 mm/day or 20 millimeters per hour (mm/h). In line with these criteria, the Toba-Asahan watershed encountered four significant hourly events, the Larona-Malili watershed experienced one, and the Brantas watershed did not experience any events that fulfilled these criteria. For daily rainfall events, the Toba-Asahan watershed experienced 180 extreme events, the Larona-Malili watershed experienced 232 events, and the Brantas watershed experienced 92 events. It is essential to recognize that rainfall measurements, whether conducted daily or hourly, rely on the average watershed area. Fig. 7 shows that the Toba-Asahan watershed (180 events) and the Larona-Malili watershed (232 events) experience a higher frequency of extreme daily rainfall compared to the Brantas watershed (92 events). The distinct characteristics are largely driven by the topographic and atmospheric conditions associated with each watershed. The Toba-Asahan watershed features

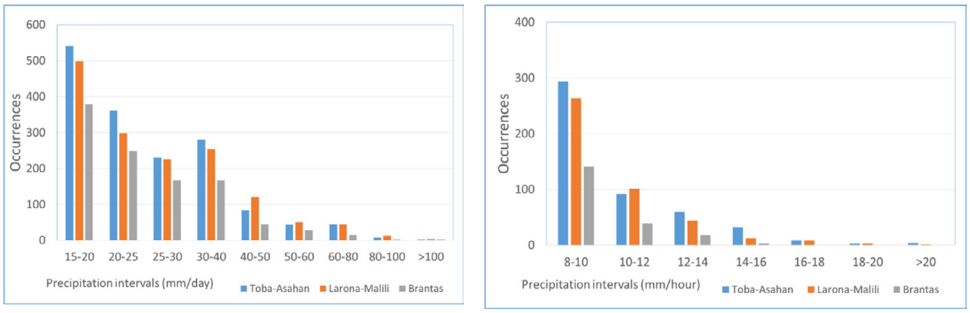

Fig. 7: Distribution of the number of daily rainfall events (a) and hourly rainfall events (b) in the three watersheds from 2001 to 2024

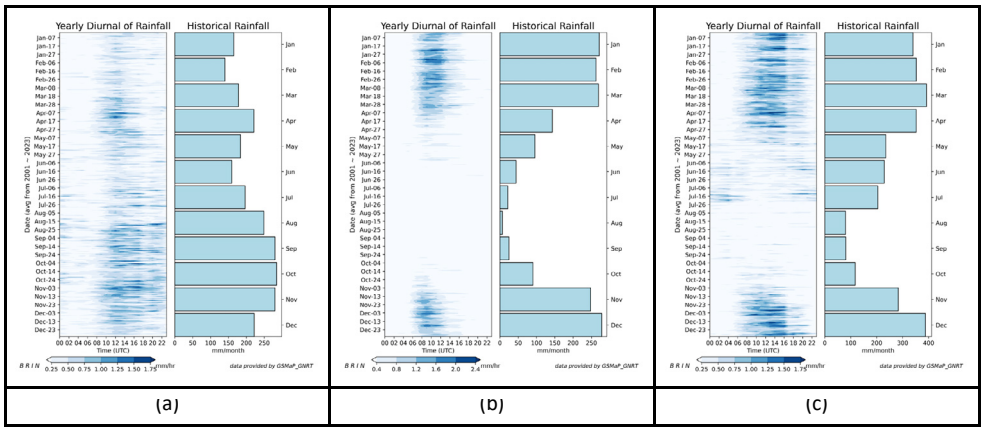

Fig. 8: Diurnal-daily analysis for each watershed Toba-Asahan (a), Brantas (b) and Larona-Malili (c), respectively from 2001 to 2024

significant mountainous terrain, particularly in the upstream region, which enhances orographic lifting and convective activity, leading to frequent heavy rainfall events. Likewise, the Larona-Malili watershed in South Sulawesi is shaped by monsoonal winds and its diverse mountainous topography, which results in significant rainfall intensity. In contrast, despite receiving high annual rainfall, the Brantas watershed exhibits a more uniform spatial distribution of rainfall with lower daily intensities. The middle and lower watershed regions experience reduced orographic effects, which likely contribute to a lower frequency of extreme rainfall events. The rate of extreme hourly rainfall occurrences is low in every watershed, implying that high-intensity rainfall over short timeframes is less prevalent than daily rainfall. The results, which show stark differences in extreme rainfall events among the three watersheds, are likely due to climatological, topographic, and atmospheric factors. Greater emphasis is necessary on flood management and disaster mitigation for the Toba-Asahan and Larona-Malili watersheds concerning severe rainfall occurrences. Further research can be conducted to understand the meteorological factors, atmospheric dynamics, and local rainfall patterns of each watershed, thereby supporting disaster risk mitigation and adaptation planning.

Diurnal-daily analysis in the watersheds

The diurnal-daily analysis observes the diurnal distribution of rainfall, determining whether rainfall predominantly occurs in the morning, afternoon, evening, or even at night. This technique is essential for analyzing the daily cycle patterns that are impacted by local conditions (such as topography and land use) and larger phenomena (including the monsoon and MJO). Besides identifying peak rainfall times (morning, afternoon, evening, and night), this

analysis provides valuable information for flood risk mitigation or water resource management. The following is the diurnal-daily analysis for the Toba-Asahan, Brantas, and Larona-Malili watersheds. The vertical axis (Y-axis) represents the average date from January 1 to December 31 for 2001 to 2024, while the horizontal axis (X-axis) represents the hours from 00 to 23 in Universal Time Coordinated (UTC). The annual distribution of rainfall on a daily basis is depicted in Fig. 8. The left profile shows the diurnal rainfall distribution, while the right profile shows the monthly average rainfall. According to Fig. 8, the Toba-Asahan watershed experiences rainfall nearly throughout the year, with peak intensity observed from August to December. Diurnally, it is not explicitly shown, but rainfall events occur from 08:00 UTC (15:00 Local Time (LT)) to nighttime, even into early morning, from August to December. The onset of morning rain occurs at 00:00 UTC (07:00 LT), implying that the lake plays a role in morning rainfall patterns or is related to nocturnal radiative cooling. The Brantas watershed exhibits different rainfall characteristics compared to the Toba-Asahan watershed; rainfall typically begins around 06:00 UTC (13:00 LT) and lasts until 14:00-16:00 UTC (21:00-23:00 LT), with no significant rainfall events occurring at dawn. Historically, rainfall is predominantly concentrated in the periods of January to April and November to December. The rainfall characteristics in the Brantas watershed indicate more frequent afternoon rainfall due to local convection from surface heating during the day and orographic factors. In mountainous regions, including the Brantas watershed, afternoon rainfall is common due to orographic lifting. The Larona-Malili watershed has rainfall characteristics that differ from those of the Brantas and Toba-Asahan watersheds. Rainfall events dominate from January to April and November to December, generally starting around 06:00 UTC (13:00 LT) and decreasing in intensity until early morning. Analysis of the rainfall characteristics in the Larona-Malili watershed shows that afternoon precipitation is often frequent, driven by local convection caused by daytime surface heating and the influence of orographic factors. Mountainous regions, such as the Larona-Malili watershed, tend to experience afternoon rainfall due to orographic lifting. Interestingly, rainfall events are observed from morning to noon and evening to early morning, with lower intensity from May to July. Rainfall occurring from morning to noon is frequently linked to the cooling of air at night, which leads to local convergence. This cooling enhances cloud formation through land breeze circulation or local convective processes triggered by morning solar heating. The topography in the Larona-Malili watershed, with hills or mountains, can amplify this pattern due to airlifting triggered by slope heating (orographic lifting). Wind patterns and rainfall in the Larona watershed are influenced by the El Niño-Southern Oscillation (ENSO), with El Niño reducing rainfall by up to 22% and La Niña increasing it by 50%, thereby affecting water availability for hydroelectric power generation. The most significant rainfall in the Larona watershed occurs in the regions surrounding Mahalona, southeastern Matano, and northwestern Towuti. The dry season occurs in August and September, while the watershed is considered a moderate water reservoir with a runoff coefficient of 0.6 (Syaifullah, 2013).

Sensitivity of rainfall conditions over the watershed to interannual climate phenomena

A correlation analysis examined the rainfall sensitivity in the three watersheds to ENSO, DMI, and Monsoon WYMI. This technique facilitates the assessment of the relationship strength between rainfall and the three parameters using the Pearson Correlation test, along with a 2-tailed significance test. The test criteria are that if the 2-tailed significance value is less than the significance level (alpha level), the test result is significant. Alternatively, a test result is regarded as insignificant when the two-tailed significance value exceeds the predetermined significance level. The analysis results are presented in Table 3. The statistical analysis components were essential in explaining the patterns and factors influencing rainfall variability in the studied watersheds. Specifically, correlation analysis was used to assess the relationships between rainfall and various spatiotemporal factors, revealing significant dependencies and highlighting the complexity of precipitation dynamics (Adler *et al.,* 2018).

The correlation coefficients have been obtained in this study, such as -0.122 and -0.141, indicate weak correlations. This suggests that the relationships among the analyzed variables are neither strong nor consistent. Rainfall data obtained from satellites are recognized to have significant uncertainty and bias, potentially impacting correlation outcomes.

Table 3: Correlation between the three watersheds with ESNO, DMI, and WYMI

Catchment area	Parameter	ASST-Nino34	WYMI	DMI
Toba-Asahan	Pearson correlation	-0.122*	0.205**	-0.033
	Sig. (2 tailed)	0.039	< 0.001	0.582
Brantas	Pearson correlation	-0.141*	0.732**	-0.138*
	Sig. (2 tailed)	0.016	< 0.001	0.019
Larona-Malili	Pearson correlation	-0.112	-0.591**	-0.043
	Sig. (2 tailed)	0.057	< 0.001	0.472

** Correlation is significant at the 0.001 level (2-tailed);
* Correlation is significant at the 0.05 level (2-tailed)

The variability of rainfall in Indonesia, influenced by climatic phenomena such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), may also contribute to these weak correlations, as noted by Aldrian and Susanto (2003). Additionally, alterations in land use and human activities can modify rainfall patterns, resulting in weak correlations. From a statistical perspective, Beck *et al.,* (2017) pointed out that correlations between global precipitation datasets can vary widely, indicating that weak correlations do not necessarily imply a lack of relationship, but rather reflect relationships that are not strong or consistent. Conducting a spatiotemporal analysis of rainfall variability is crucial for establishing climate-resilient watershed management strategies. It helps in recognizing changes in precipitation patterns, evaluating drought risks, and detecting extreme rainfall events, which in turn supports the formulation of adaptive measures such as optimized reservoir management, flood mitigation systems, and drought preparedness initiatives (Mishra and Singh, 2010; Ward *et al.,* 2020). This approach improves water allocation efficiency, supports early warning systems, and guides ecosystem-based adaptation strategies such as reforestation and wetland conservation, all of which improve natural water retention and reduce erosion (IPCC, 2022; Pahl-Wostl, 2019). Furthermore, such analysis feeds climate-smart agricultural practices and adaptive governance frameworks, ensuring long-term water resource management in the face of increased climate unpredictability. Utilizing spatiotemporal rainfall data enhances the resilience of watersheds, mitigates climate-related risks, and fosters enduring socio-ecological stability in at-risk areas (UNEP, 2023).

CONCLUSION

This study offers an in-depth spatiotemporal analysis of rainfall fluctuations in three major watersheds in Indonesia: Brantas, Toba-Asahan, and Larona-Malili. Key findings highlight a significant increasing rainfall trend in the Larona-Malili watershed, while no statistically significant trends were found in the Brantas and Toba-Asahan basins. Unique patterns of rainfall were noted across different seasons and times of day, influenced by regional climate systems, local air movements, and geographical features. Brantas is primarily influenced by the Asian Monsoon, while the Toba-Asahan and Larona-Malili watersheds are more sensitive to local and regional factors, including land-use changes. Spectral analysis further reveals that ENSO and IOD drive interannual rainfall variability, with semi-annual and annual rainfall cycles observed across the basins. The differing responses to climatic indices such as ENSO, IOD, and WPMI reflect the varied climate sensitivities among the watersheds. This comprehensive method connects local hydrological fluctuations with broader climate patterns, offering a fresh perspective on rainfall dynamics in Indonesian catchments. The findings contribute to improving adaptive water resource planning and climate risk mitigation strategies. However, this study is not without limitations. The analysis relies primarily on satellite-based rainfall datasets without extensive validation using ground-based observations, due to the limited availability of in-situ data across the study area. Furthermore, while the study spans a period of twenty years (2000–2023), extending the data records could enhance the identification of trends and the evaluation of variability. The study also does not incorporate hydrological modeling to assess runoff or water availability impacts. Future research should include ground-truthing with rain gauge data, integration of hydrological models to simulate water balance and streamflow response, and application of higher spatial-resolution datasets. Moreover, including more watersheds that exhibit a range of geomorphological conditions and land-use intensities

would strengthen the study's generalizability. Investigating the compound effects of anthropogenic changes and climate variability at finer temporal scales (e.g., sub-seasonal or diurnal) could further support the development of resilient and region-specific water management strategies under future climate change scenarios.

AUTHOR CONTRIBUTIONS

M.D. Syaifullah performed design, writing, review and editing, visualization, temporal and spectral analysis, research flowchart, writing original draft, methodology, and software. A. Purwandani has done the spatial distribution of rainfall in watersheds analysis, writing, visualization, editing, and software. Tukiyat performed the statistical analysis, sensitivity analysis, editing, reviewing of the manuscript. S. Tikno did the geomorphology and topography analysis. A.E. Sakya reviewed the geomorphology and topography, editing and reviewing the manuscript. M. Kudsy performed the corresponding author, reviewed meteorology and climatology, and edited the manuscript. F.H. Widodo performed the geomorphology and hydrology analysis, S. Bahri did the meteorology and climatology analysis. Muktiyono performed the writing, review, editing and visualization.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the authors have fully addressed the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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The author(s) declare that no AI tools or services were used or applied during the preparation of this work.

ABBREVIATIONS

°	Degree
²	Square
%	Percent
AHP	Analytical hierarchy process
BIG	Badan informasi geospasial (Geospatial information agency)
CAPE	Convective available potential energy
CHIRPS	Climate hazards group infrared precipitation with station
DEM	Digital elevation model
DEMNAS	DEM nasional
DMI	Dipole mode index
E	East
ECMWF	European Center for medium-range weather forecasts
ENSO	El niño southern oscillation
ERA5	ECMWF reanalysis v5
FFT	Fast fourier transform
GIS	Geographic information system
GPM	Global precipitation measurement
GSMaP-GNRT	Global satellite mapping of precipitation near-real-time
hPa	Hectopascal
IOD	Indian ocean dipole
Km	Kilometers
Km²	Square kilometers
KLHK	Kementerian lingkungan hidup dan kehutanan (Ministry of environment and forestry)
LT	Local time
LULC	Land use and land cover
mm/d	Milimeter per day
mm/h	Milimeter per hour
MJO	Madden-julian oscillation
MK	Mann-Kendall
N	North
NetCDF	Network common data format
NOAA	National oceanic and atmospheric administration
PCA	Principal component analysis
PLTA	Pembangkit listrik tenaga air (hydroelectric power plant)
PSL	Physical sciences laboratory
S	South
SS	Sen's slope estimator
SST	Sea surface temperature
U850	Zonal wind component at 850 hPa
U200	Zonal wind component at 200 hPa
UTC	Universal time coordinated
WYMI	Webster-yang monsoon index

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AUTHOR (S) BIOSKETCHES

Syaifullah, M.D., M.Sc., Research Center for Climate and Atmosphere, National Research and Innovation Agency (BRIN), Serpong 15314, Indonesia.
- Email: *muha042@brin.go.id*
- ORCID: 0009-0005-8265-2620
- Web of Science ResearcherID: NA
- Scopus Author ID: 57211929385
- Homepage: http://brin.go.id/

Purwandani, A., M.Sc., Research Center for Conservation of Marine and Inland Water Resources, National Research and Innovation Agency (BRIN), Cibinong 16911, Indonesia.
- Email: *andri.purwandani@brin.go.id*
- ORCID: 0000-0002-7675-5069
- Web of Science ResearcherID: MXL-9334-2025
- Scopus Author ID: 8335951000
- Homepage: http://brin.go.id/

AUTHOR (S) BIOSKETCHES

Tukiyat, Ph.D., Principal Research Engineer, Research Center for Limnology and Water Resources, National Research and Innovation Agency (BRIN), Serpong 15314, Indonesia.
▪ Email: *tuki001@brin.go.id*
▪ ORCID: 0000-0001-7568-6237
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: NA
▪ Homepage: http://brin.go.id/

Tikno, S., M.Sc., Research Center for Limnology and Water Resources, National Research and Innovation Agency (BRIN), Serpong 15314, Indonesia.
▪ Email: *sunu001@brin.go.id*
▪ ORCID: 0009-0000-7675-8238
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: NA
▪ Homepage: http://brin.go.id/

Sakya, A.E., Ph.D., Principal Research Engineer, Research Center for Geological Disaster, National Research and Innovation Agency (BRIN), Serpong 15314, Indonesia.
▪ Email: *andi.eka.sakya@brin.go.id*
▪ ORCID: 0000-0002-5490-1846
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 57201667644
▪ Homepage: http://brin.go.id/

Kudsy, M., Ph.D., Principal Research Engineer, Research Center for Limnology And Water Resources, National Research and Innovation Agency (BRIN), Serpong 15314, Indonesia.
▪ Email: *maha001@brin.go.id*
▪ ORCID: 0000-0001-8185-2958
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: 6602489366
▪ Homepage: http://brin.go.id/

Widodo, F.H., M.Sc., Research Center for Limnology and Water Resources, National Research and Innovation Agency (BRIN), Serpong 15314, Indonesia.
▪ Email: *flor003@brin.go.id*
▪ ORCID: 0009-0000-4984-6945
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: NA
▪ Homepage: http://brin.go.id/

Bahri, S., M.Sc., Research Center for Limnology and Water Resources, National Research and Innovation Agency (BRIN), Serpong 15314, Indonesia.
▪ Email: *sams001@brin.go.id*
▪ ORCID: 0009-0004-5954-6312
▪ Web of Science ResearcherID: NA
▪ Scopus Author ID: NA
▪ Homepage: http://brin.go.id/

Muktiyono, M.Sc., Research Center for Limnology and Water Resources, National Research and Innovation Agency (BRIN), Serpong 15314, Indonesia.
Email: *muktiyono@brin.go.id*
ORCID: 0009-0001-2639-9406
Web of Science ResearcherID: NA
Scopus Author ID: NA
▪ Homepage: http://brin.go.id/

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