JURNAL EMACS
[Engineering, MAthematics and Computer Science] Vol.8 No.2 May 2026: 193-204
e-ISSN: 2686-2573
DOI: 10.21512/emacsjournal.v8i2.16557

Development of an Extreme Rainfall-Based Hazard Index for the Air Bengkulu Watershed, Indonesia

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Abstract *– Extreme rainfall is one of the main hydrometeorological factors that drive flood-related hazards in tropical watersheds. However, individual rainfall indicators may not sufficiently capture the combined spatial characteristics of extreme precipitation. The objective of this research is to develop a Rainfall Hazard Index (RHI) for the Air Bengkulu Watershed, Indonesia, based on multiple indices of extreme rainfall. Daily rainfall data of four stations for the period 2007-2025 are analyzed to compute Maximum 1-Day Rainfall (Rx1day), Maximum Consecutive 5-Day Rainfall (Rx5day), Very Wet Days precipitation (R95p) and Rainfall Trend (RT). Rainfall trends were assessed by Mann–Kendall test and Sen's slope estimator. Inverse Distance Weighted (IDW) interpolation was applied to generate spatial distributions. The indicators were combined with Analytical Hierarchy Process (AHP) weighting to construct the RHI. The RHI was classified into five hazard categories by Jenks Natural Breaks. The AHP results gave the highest weight to Rx5day (0.471) followed by R95p (0.284), Rx1day (0.172) and RT (0.073) with a Consistency Ratio of 0.0185. The hazard class of extremely high rainfall covered 60.73% of the watershed, mainly in the upstream areas. A preliminary comparison with historical flood records from the Regional Disaster Management Agency (BPBD) and direct field observations revealed a match at 11 of 15 locations (73.3%). These findings show RHI as a first stage spatial screening tool for rainfall-related hazards that can be used in watershed management and spatial prioritization rather than full flood prediction.*

Keywords: *Analytical Hierarchy Process; Extreme Rainfall; Rainfall Hazard Index; Watershed*

I. INTRODUCTION

Flooding is one of the most common hydrometeorological disasters in the tropics and is affected by a number of factors including extreme rainfall, watershed characteristics, land-use changes and drainage capacity. Intense rainfall events can lead to increased surface runoff, soil moisture and river discharge and potentially increase impacts related to flooding especially in watersheds with complex topography and high variability in precipitation (Aminoto et al., 2026); (Mulyanti et al., 2020); (Audu et al., 2021). Therefore, the knowledge of the spatial and temporal characteristics of extreme rainfall is important for the assessment of rainfall related hazards and water resources management and disaster mitigation planning.

Extreme precipitation has been extensively investigated in previous studies using rainfall indices developed by the Expert Team on Climate Change Detection and Indices (ETCCDI), statistical trend analysis and spatial interpolation methods (Abdila & Nugroho, 2021); (Kumar et al., 2020); (Imran et al., 2023); (Shafiq et al., 2024); (Tung et al., 2022). These methods provide valuable information on the variability of precipitation, magnitude of extreme rainfall, and long-term trends. However, the individual evaluation of rainfall indicators does not directly provide a composite spatial representation of different characteristics of extreme rainfall. Thus, there is a need for an integrated framework to synthesize complementary rainfall indicators into a spatial index to distinguish relative levels of rainfall hazard within a watershed.

The choice of extreme rainfall indicators is significant because each parameter is linked to different hydrometeorological characteristics. The maximum 1-day rainfall (Rx1day) is the magnitude of the most intense daily precipitation event, which can result in rapid production of runoff. Maximum Consecutive 5-Day Rainfall (Rx5day) is the total precipitation accumulated over 5 consecutive days

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that gives information on antecedent wetness and potential soil saturation. Very Wet Days precipitation (R95p) measures the amount of precipitation on days with precipitation above the 95th-percentile threshold, thus describing the contribution of very wet days. Meanwhile, Rainfall Trend (RT), estimated using Mann–Kendall test and Sen's slope , provides information about the direction and magnitude of temporal precipitation changes (Kumar et al., 2020); (Imran et al., 2023); (Shafiq et al., 2024); (Zhoua et al., 2023). This combination of indicators allows different aspects of extreme rainfall to be considered together, rather than individually.

Previous studies of rainfall in Indonesia have concentrated on rainfall trends, extreme rainfall indices, and spatial rainfall distribution with statistical and geospatial approaches (Aditya et al., 2021); (Darmawan et al., 2023); (Rachmadini Chandrarien et al., 2024); (Marthadyanti et al., 2024). Although these studies have important methodological foundations, the combined application of Rx1day, Rx5day, R95p, and rainfall trends in the form of a weighted spatial rainfall hazard index has not been proven in the studies reviewed for the Air Bengkulu Watershed. This is a specific research gap because individual rainfall maps and trend assessments do not directly quantify the relative contribution of these complementary indicators within a combined watershed scale assessment. The combined use of these indicators with AHP (Analytical Hierarchy Process) provides a systematic way to determine the relative importance and the IDW (Inverse Distance Weighted) technique provides the spatial representation of the rainfall features based on station observations.

The Air Bengkulu Watershed, located in Bengkulu Province, Indonesia, is characterized by mountainous terrain in its upstream area, undulating topography in its middle reaches, and lowland areas extending toward the Indian Ocean. These contrasting physiographic conditions, together with high rainfall and recurring flood events, make the watershed relevant for investigating spatial variations in extreme rainfall characteristics. However, a rainfall-based spatial index is required to characterize the relative distribution of extreme rainfall hazard across the watershed without conflating meteorological conditions with other factors controlling flood occurrence, such as land use, topography, river capacity, and drainage systems.

Therefore, this study aims to formulate a Rainfall Hazard Index (RHI) for the Air Bengkulu Watershed by combining Rx1day, Rx5day, R95p and RT using daily rainfall data from 4 stations for the period 2007-2025. Rainfall trends were analyzed applying the Mann–Kendall test and Sen's slope; spatial distributions of indicators were obtained with IDW interpolation; and a composite rainfall hazard index was created with AHP weighting. The resulting RHI is classified into five levels of rainfall hazard and a preliminary comparison with field observations is performed. The key contribution of this work is a transparent, spatially explicit framework that combines the magnitude, accumulation, and occurrence of very wet precipitation and temporal trends of rainfall into a single watershed-scale index. The proposed RHI is not a flood prediction or risk assessment model, but rather a preliminary rainfall hazard screening tool to assist spatial prioritization, water resources planning and further flood hazard investigations.

II. METHODS

2.1. Study Area

This study was conducted in the Air Bengkulu Watershed, Bengkulu Province, Indonesia, geographically located between approximately 102°14′–102°35′ E and 3°37′–3°50′ S. The watershed covers approximately 510.21 km^2, based on the spatial boundary used in the Rainfall Hazard Index (RHI) classification. The river system drains toward the Indian Ocean.

The watershed exhibits diverse physiographic characteristics, ranging from mountainous terrain in the upstream region to undulating landforms in the middle watershed and relatively flat alluvial plains downstream. These topographic, provide an appropriate setting for investigating extreme rainfall patterns.

Four rainfall stations were used in this study: Batu Raja, Bajak Tanjung Jaya, And Taba Mutung. Although the batu raja station outside the watershed boundary, it was included due to its proximity to the study area and potential contribution to the spatial representation of rainfall. The watershed boundary and station distribution are presented in Figure 1, while the station coordinates and observation periods are provided in Table 1.

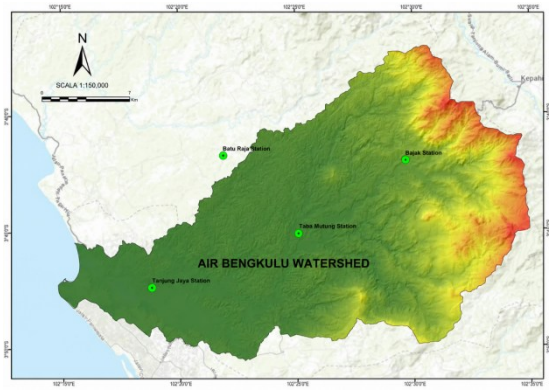

Figure 1. Location of the Air Bengkulu Watershed and rainfall station distribution

2.2. Research Data

The main data set consisted of daily rainfall data for the period 2007-2025 from four rainfall stations acquired from Balai Wilayah Sungai Sumatera VII (BWS VII). The data set was used to compute the indices of extreme rainfall and to infer the temporal rainfall trends.

Supporting spatial data were the air Bengkulu watershed boundary, the Indonesian National Digital Elevation Model (DEMNAS) with approximately 8m spatial resolution and the flood-related observation information. Watershed boundary data was obtained from the relevant government spatial data source. DEMNAS was provided by Geospatial Information Agency (BIG). The resultant RHI map was initially compared spatially with flood incident information and field observations. The geographical coordinates and observation periods of the rainfall stations are summarized in Table 1. The sources and characteristics of the supporting datasets are summarized in Table 2.

Table 1. Rainfall stations used in the study

No	Rain Station	Longitude (X)	Latitude (Y)	Period
1	Batu Raja	102,3654	-3,6959	2007-2025
2	Bajak	102,4952	-3,7000	2007-2025
3	Tanjung Jaya	102,3139	-3,7901	2007-2025
4	Taba Mutung	102,4185	-3,7521	2007-2025

Table 2. Data used in the study

No	Data	Source	Period/Resolution
1	Daily rainfall	BWSS VII	2007–2025
2	DEMNAS	BIG	8 m
3	Boundaries of the Bengkulu River Basin	KLHK	Spatial
4	Flood locations	BPBD	Scene of the incident
5	Non-flooding areas	Survey/control site	Control points

2.3. Research Methods

This research was conducted through six main stages. First, daily rainfall records for 2007-2025 were collected and subjected to quality control. Second, three extreme rainfall indices, namely Maximum 1-day rainfall (Rx1day), maximum consecutive 5-day rainfall (Rx5day), and very wet days precipitation (R95p), were calculated from the rainfall records using definitions based on the Expert Team on Climate Change Detection and Indices (ETCCDI).

Third, rainfall trends were analyzed using the Mann-Kendall test and Sen's Slope estimator. Fourth, the spatial distributions of Rx1day, Rx5day, R95p, and Rainfall Tren (RT) were generated using the Inverse Distance Weighted (IDW) interpolation method.

Fifth, the indicator values were normalized and integrated using weight derived from the Analytical Hierarchy Proses (AHP) to develop the composite RHI. The resulting index was classified into five rainfall hazard categories using the Jenks Natural Breaks Method.

Finally, a preliminary field-based comparison was conducted at 15 observation locations to examine the correspondence between the spatial RHI classification and recorded or observed flood conditions. This comparison was intended to provide supporting spatial evidence rather than an independent assessment of flood prediction accuracy.

2.4. Rainfall Data Quality Control

Rainfall data quality control was considered an essential step before calculating the extreme precipitation indicators. Daily rainfall records from the four observation stations were assessed with regard to temporal coverage, data completeness, and consistency over the 2007-2025 study period.

Data completeness was defined as the proportion of available daily rainfall observations relative to the total number of expected observations within the assessment period, expressed as:

$$DC = \frac{N_{valid}}{N_{expected}} x100\% \quad (1)$$

Explanation of the Formula:
DC = Rainfall data completeness rate (%).
N_{valid} = number of valid daily rainfall observations.
$N_{expected}$ = the number of daily observations that should be available during the evaluation period.

2.5. Extreme Rainfall Indicators

Maximum 1-Day Rainfall (Rx1day), Maximum Consecutive 5-Day Rainfall (Rx5day) and Very Wet Days (R95p) are indicators developed by the Expert Team on Climate Change Detection and Indices (ETCCDI) and used to analyze the characteristics of extreme rainfall (Kumar et al., 2020); (Imran et al., 2023); (Shafiq et al., 2024).

Rx1day is the maximum rainfall recorded in a single day, which is calculated as follows:

$$Rx1day = \max(P_i) \quad (2)$$

Explanation of the Formula:
Rx1day = maximum daily rainfall (mm) in a year
max = maximum value or largest value.
P_i = daily rainfall on day i (mm).

The maximum accumulated rainfall for five consecutive days is Rx5day, which is defined as:

$$Rx5day = \max (P_i+P_{i+1}+P_{i+2}+P_{i+3}+P_{i+4} \quad (3)$$

Explanation of the Formula:
Rx5day = maximum consecutive five-day total rainfall (mm).
max = the maximum value of the total five-day accumulated rainfall during the observation period.
P_i = Daily rainfall on the 1st (mm).
P_{i+1} = Daily rainfall on the second day (mm).

Meanwhile, R95p is calculated as the amount of rainfall on days with rainfall greater than the 95th percentile, as:

$$R95p = \sum P_i, P_i > P_{95} \quad (4)$$

Explanation of the Formula:
R95p = the total annual rainfall from very wet days (mm)
P95 = The long-term baseline period 95th percentile of daily precipitation on rainy days (precipitation >1 mm). This value is taken as a threshold.

Where Pi represents the daily rainfall and P95 denotes the 95th-percentile threshold.

2.6. Extreme Rainfall Trend Analysis

Temporal rainfall trends were assessed using the non-parametric Mann–Kendall test and Sen's slope estimator (Aditya et al., 2021); (Zhou et al., 2023). The direction and magnitude of trends were evaluated separately, using a two-sided significance threshold of $p < 0.05$. Positive and negative Sen's slopes indicate increasing and decreasing rainfall, respectively.

The Mann-Kendall test statistics are defined by the following equation:

$$s = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}\,(x_j - x_i) \quad (5)$$

Explanation of the Formula:
s = Mann-Kendall test statistic value
x_i = observation value at time-i
x_j = observation value at time-j
n = number of observations in a time series
sgn = a function whose sign indicates the direction of the difference between two observed values

The magnitude of the rainfall trend was determined using Sen's Slope as follows:

$$Q = \text{Median}\left[(X_j - X_i)/(j-i)\right] \quad (6)$$

Explanation of the Formula:
Q = Shows the direction and magnitude of the change in the data.
Xi = The observation value at the initial time point.
Xj = The value of the dependent variable at the final observation point or time.

The Sen's Slope value was used as the Rainfall Trend (RT) parameter in the development of the Rainfall Hazard Index (RHI).

2.7. Spatial Interpolation

The Inverse Distance Weighted (IDW) method of interpolation was used to produce the spatial distributions of Rx1day, Rx5day, R95p and Rainfall Trend (RT). IDW was selected as a deterministic spatial interpolation method that estimates the values of unsampled locations based on observations that are weighted by distance from the nearest surrounding rainfall stations. Previous studies have shown its application to rainfall mapping, and emphasized the necessity of accounting for rainfall variability and the distribution of stations to choose interpolation methods (Workneh et al., 2024):(Susanto et al., 2024): (Marthadyanti et al., 2024). In this study, IDW interpolation was applied separately to the four rainfall indicators using observations from four rainfall stations, and the resulting surfaces were clipped to the Air Bengkulu Watershed boundary. Given the limited station network, the interpolated rainfall surfaces were interpreted as approximate spatial representations rather than independently validated estimates of local precipitation.

2.8. Parameter Normalization and Weighting

All extreme rainfall parameters were normalized using the Min–Max Normalization method (Arabameri et al., 2020):

$$X_n = (X - X_{min})/(X_{max} - X_{min}) \quad (7)$$

The researchers developed the AHP pairwise comparison judgments based on a literature-informed assessment of the four rainfall indicators. The evaluation took into account the complementary nature of daily rainfall extremes (Rx1day), five consecutive day rainfall accumulation (Rx5day), precipitation from very wet days (R95p) and temporal rainfall trends (RT). Literature based AHP comparisons have been used in previous studies for flood related spatial assessments (Afify et al., 2025) and the relevance of ETCCDI indicators for characterizing different dimensions of extreme precipitation (Gimeno et al., 2022).

Table 3. S1. Literature-informed rationale for pairwise comparisons of rainfall hazard indicators

Pairwise comparison	Judgment value (a_{ij})	Scientific rationale
Rx1day / Rx5day	0,450	Rx5day was prioritized because cumulative rainfall over consecutive days characterizes prolonged wet conditions and potential antecedent soil saturation, whereas Rx1day represents a single-day maximum.
Rx1day / R95p	0,606	R95p represents precipitation accumulated on very wet days and was assigned greater relative importance than a single-day maximum for characterizing repeated extreme rainfall contributions.

Rx1day / RT	1,887	Rx1day directly quantifies the magnitude of daily rainfall extremes, whereas RT represents longer-term changes in rainfall conditions.
Rx5day / R95p	2,073	Rx5day emphasizes rainfall accumulated within a consecutive five-day period, while R95p summarizes precipitation exceeding a percentile threshold, without requiring consecutive occurrence.
Rx5day / RT	6,630	Rx5day was assigned substantially greater importance because it directly represents multi-day rainfall accumulation, while RT provides supplementary information on temporal changes.
R95p / RT	4,920	R95p quantifies accumulated precipitation from very wet days, whereas RT describes the rate and direction of long-term changes rather than rainfall magnitude itself.

Note: The pairwise judgment values were assigned by the researchers based on a literature-informed assessment. The scientific rationales explain the selected priority directions but do not independently establish the numerical magnitudes of the comparisons. The reciprocal values were used to complete the AHP matrix.

The relative importance of the four indicators was assessed using the Analytical Hierarchy Process (AHP) based on pairwise judgments using Saaty's 1–9 scale. The comparison criteria addressed daily rainfall extremes (Rx1day), five-day accumulation (Rx5day), very wet day precipitation (R95p), and rainfall trend (RT).

The pairwise comparison matrix was formulated as:

Table 4.Pairwise comparison matrix

Indicator	Rx1day	Rx5day	R95p	RT
Rx1day	1	a_{12}	a_{13}	a_{14}
Rx5day	$1/a_{12}$	1	a_{23}	a_{24}
R95p	$1/a_{13}$	$1/a_{23}$	1	a_{34}
RT	$1/a_{14}$	$1/a_{24}$	$1/a_{34}$	1

Normalization and weight equations that can be entered:

$$n_{ij}=\frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \quad (8)$$

$$w_i=\frac{1}{n}\sum_{j=1}^{n} N_{ij} \quad (9)$$

The priority weights were obtained from the principal eigenvector of the comparison matrix

$$Aw=(\lambda_{max}w) \quad (10)$$

The principal-eigenvector priority weights were evaluated for consistency using the Consistency Index (CI) and Consistency Ratio (CR). For four indicators, the Random Index (RI) is 0.90, and CR < 0.10 was adopted as the acceptability criterion.

$$CI=(\lambda_{max}-n)/(n-1) \quad (11)$$

where λmax is the maximum eigenvalue and n is the number of parameters.

$$CR= CI/RI \quad (12)$$

2.9. Rainfall Hazard Index Development

The Rainfall Hazard Index (RHI) was developed by integrating the Rx1day, Rx5day, R95p, and Rainfall Trend (RT) parameters based on the weights obtained from the AHP analysis. The RHI equation is expressed as:

$$RHI= W_1Rx1day_n+W_2Rx5day_n+W_3R95p_n +W_4RT_n \quad (13)$$

The RHI values were then classified into five hazard classes using the Jenks Natural Breaks method: very low, low, moderate, high, and very high.

III. RESULTS AND DISCUSSION

3.1. Quality Control

Table 5.Rainfall Data Completeness and Quality Control (2007-2025)

Rain Station	Observation period	Excpected record (days)	Valid record (days)	Data completeness (%)
Batu Raja	2007-2025	6,940	6,938	99,97
Bajak	2007-2025	6,940	6,908	99,54
Tanjung Jaya	2007-2025	6,940	6,936	99,94
Taba Mutung	2007-2025	6,940	6,939	99,99

3.2. Extreme Rainfall Characteristics

The characteristics of extreme rainfall in the Air Bengkulu Watershed were analyzed using the Rx1day, Rx5day, and R95p indices based on daily rainfall data for the period 2007–2025.

Table 6. Descriptive statistics of extreme rainfall indicators for 2007–2025

Parameters	Minimum	Maksimum	Average	Standard Deviation
Total rainfall (mm)	2236,43	4216,03	3176,61	1388,70
A rainy day (day)	142,16	175,84	155,95	26,12
Rx1day (mm)	100,09	143,98	131,04	48,90
Rx5day (mm)	534,02	903,39	751,44	273,40
R95p (mm)	177,65	307,77	249,24	107,28

The descriptive statistical analysis shows that the characteristics of extreme rainfall in the Air Bengkulu Watershed exhibit considerable variability across the ETCCDI indices. Rx1day values range from 100,09 to 143,98 mm (mean 131,04 mm) and Rx5day ranges from 534,02 to 903,39 mm (mean 751,44 mm). In addition, the R95p values vary from 177,65 to 307,77 mm with an average of 249,24 mm, which indicates that a significant portion of the total annual rainfall is contributed by a small number of very high-intensity rainfall events. The variation shows that extreme rainfall in the Air Bengkulu Watershed is not only characterized by extreme daily rainfall events, but also by rainfall accumulation in several consecutive days.

High values of Rx1day, from the hydrological point of view, suggest that some regions of the watershed might be exposed to daily rainfall intensities exceeding the soil infiltration capacity, thus favoring rapid generation of surface runoff. At the same line, high values of Rx5day indicate that the buildup of prepetition over multiple days could saturate the soil and reduce its capacity for further water uptake. When the ground is like this more of the next rainfall will flow over surface. This means the risk of flooding can be higher.

These result are in agreement with (Kumar et al., 2020), who found that the Rx1day is a major indicator to characterize extreme rainfall event on daily basis while the Rx5day is more representative of the role of accumulated rainfall on flood generation. Similar results were also reported by (Imran et al., 2023) and (Shafiq et al., 2024), demonstrating that the combination of multiple ETCCDI indices can provide a more comprehensive representation of extreme rainfall characteristics than the use of a single rainfall parameter.

3.3. Spatial Distribution of Rx1day, Rx5day, R95p, and RT

The spatial distribution of extreme rainfall indicators was analyzed using the Inverse Distance Weighted (IDW) method to illustrate variations in rainfall characteristics across the Air Bengkulu Watershed. The parameters included Maximum 1-Day Rainfall (Rx1day), Maximum Consecutive 5-Day Rainfall (Rx5day), Very Wet Days (R95p), and Rainfall Trend (RT). These four parameters constitute the main components of the Rainfall Hazard Index (RHI); therefore, their spatial distributions were analyzed to understand the variations in extreme rainfall characteristics prior to the normalization and weighting processes using the Analytical Hierarchy Process (AHP).

The result section shows objectively the presentation of the research key results without any interpretation using text, tables and figures. The result section begins with text, presenting the key finding, and referring to the tables and figures. The table must not print screen, specific numerical values, compare and contrast values, and minimum of 2 row and column. The figures must be clear (provide original file as supplementary file in article submission), highlight trends, pattern, and relationship. The result section must present how the author ensures the data validity and reliability.

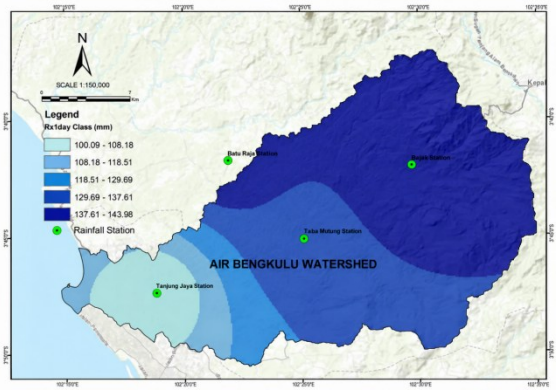

Figure 2. Spatial distribution of Rx1day in the Air Bengkulu Watershed

The Rx1day map shows that maximum daily rainfall tends to increase from the middle to the upstream areas of the Air Bengkulu Watershed. However, the downstream regions have relatively low values. Such pattern indicates that the potential of high intensity rainfall is not uniform but is determined by the physiographic features of the region.

Climatologically, this condition can be explained by the influence of the topography of the Air Bengkulu Watershed which is dominated by hilly to mountainous topography in the upstream area. Moist air masses from the Indian ocean are forced upwards orographically over higher terrain, enhancing convective cloud formation and leading to more intense rainfall.

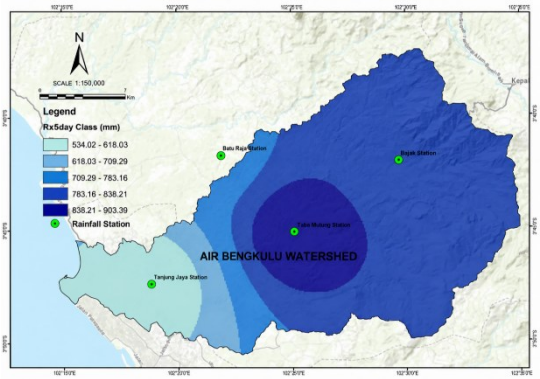

Figure 3. Spatial distribution of Rx5day in Air Bengkulu Watershed

The Rx5day map shows a pattern similar to that of Rx1day, but with a broader extent of areas exhibiting high values. This indicates that the central

part of the watershed not only experiences high-intensity daily rainfall but also receives substantial rainfall accumulation over several consecutive days. Such conditions increase the likelihood of soil saturation, thereby reducing infiltration capacity and increasing surface runoff.

The high Rx5day values indicate that flood generation in the Air Bengkulu Watershed is more strongly influenced by accumulated rainfall than by short-duration rainfall events. This finding also supports the AHP weighting results, which placed Rx5day as the parameter with the highest weight in the development of the Rainfall Hazard Index.

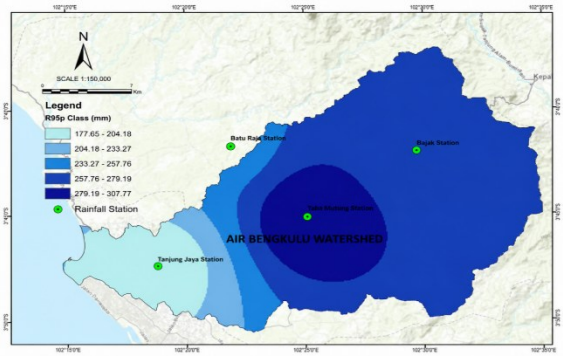

Figure 4. Spatial distribution of R95p in the Air Bengkulu Watershed

The R95p map shows that areas with a high contribution of very wet rainfall are concentrated in the central part of the Air Bengkulu Watershed. This indicates that a substantial proportion of the total annual rainfall is contributed by very high-intensity rainfall events. The dominance of very wet rainfall increases hydrometeorological pressure, making these areas more susceptible to increased surface runoff and river discharge.

These results demonstrate that the use of the R95p index provides additional information that cannot be obtained solely from the analysis of maximum daily rainfall. Therefore, the integration of Rx1day, Rx5day, and R95p provides a more comprehensive representation of extreme rainfall characteristics.

In addition to these three indices, this study also uses Rainfall Trend (RT) as a parameter representing the tendency of changes in extreme rainfall over the observation period. Unlike Rx1day, Rx5day, and R95p, which characterize rainfall based on its magnitude, RT provides information on the direction of gradual changes in extreme rainfall over time. Thus, RT completes the other three indices and offers a more complete representation of the rainfall hazard by considering not only the rainfall intensity and accumulation but also the dynamics of local climate change.

Table 7. Result of trend analysis of extreme rainfall

Rain Station	Z Mann Kendall	p-value	Sen's Slope (mm/year)	Trends Category
Batu Raja	0,39	0,70	2,35	An insignificant increase
Bajak	2,10	0,04	13,06	A significant increase
Tanjung Jaya	-0,07	0,94	-0,12	A non-significant decrease
Taba Mutung	-1,68	0,09	-3,35	A non-significant decrease

The trend of extreme rainfall in the Air Bengkulu Watershed was deferent in the rainfall stations based on the mann-kendall test and sen's slope. Of four stations analyzed, only Bajak station shows a statistically significant increasing trend of extreme rainfall with Z value 2,10, p-value 0,04 and Sens's Slope value 13,06 mm/year. Batu raja station also showed an increasing tendency in extreme rainfall but was not statistically significant. Conversely, the Tanjung Jaya and Taba Mutung stations showed decreasing tendencies in extreme rainfall, but changes were not statistically significant.

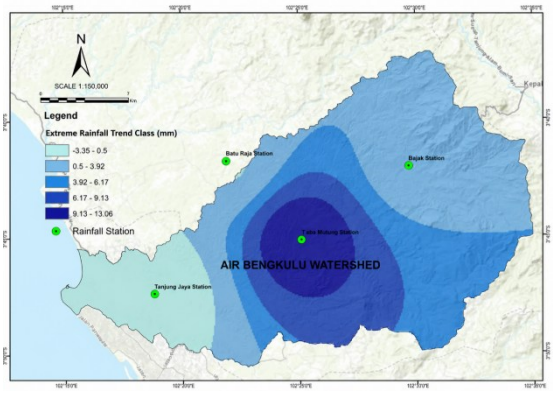

Figure 5. Spatial pattern of Rainfall Trend (IDW Interpolation)

The spatial distribution map of Rainfall Trend shows that the area affected by the Bajak Station has a stronger tendency toward increasing extreme rainfall than with other areas. Conversely, the areas influenced by the Tanjung Jaya and Taba Mutung Stations show a decreasing rainfall tendency, although the magnitude of change is relatively small. This spatial distribution indicates that hydrometeorological pressure in the Air Bengkulu Watershed is not uniformly distributed, so mitigation methods need to consider the variation of rainfall characteristics in different parts of the watershed.

The four extreme rainfall indices are characterized by different characteristics and units of measurement, and thus these do not allow for direct comparison. Therefore, before being incorporated into the rainfall hazard index, all parameters were weighted by Analytical Hierarchy Proses (AHP) based on their contribution to the formation of rainfall hazard.

3.4. Normalization and AHP Weighting

The weight of each parameter based on its relative importance in the formation of extreme rainfall hazard was determined using the Analytical Hierarchy Process (AHP) method.

Table 8. AHP pairwise comparison matrix of rainfall hazard indicators

Indicator	Rx1day	Rx5day	R95p	RT
Rx1day	1	0,450	0,606	1,887
Rx5day	2,222	1	2,073	6,630
R95p	1,651	0,482	1	4,920
RT	0,530	0,151	0,203	1
Total	5,403	2,083	3,882	14,437

Table 9. Normalized Pairwise

Indicator	Rx1day	Rx5day	R95p	RT
Rx1day	0,185	0,216	0,156	0,131
Rx5day	0,411	0,480	0,534	0,459
R95p	0,306	0,232	0,258	0,341
RT	0,098	0,072	0,052	0,069

Indicator	Average	weight	LAMDA (λ)	CI
Rx1day	0,172	17,195	4,034	0,017
Rx5day	0,471	47,113	4,088	
R95p	0,284	28,389	4,066	
RT	0,073	7,302	4,011	

RI (n =4)	CR	
0,9	0,0185	CR<0,1

Table 10. Weight of RHI parameters

Parameter	symbol	weight AHP
Maximum 1-Day Rainfall	Rx1day	0,172
Maximum Consecutive 5-Day Rainfall	Rx5day	0,471
R95p	R95p	0,284
Rainfall Trend	RT	0,073
Consistency Ratio	CR	0,0185

The result of the analytical hierarchy process (ahp) revealed that maximum weight was assigned to Rx5day (0,471), followed by R95p (0,284), Rx1day (0,172), and Rainfall Tren (RT) (0,073) with a consistency Ratio (CR) of 0,0185 indicating the pairwise comparisons are consistent. Rx5day is given more weight because the hydrological significance of rainfall accumulated over five consecutive days can increase antecedent soil moisture, promote soil saturation, and enhance surface runoff generation during subsequent rainfall events. Rx5day, which characterizes the total rainfall conditions over a longer period as compared to Rx1day representing maximum daily precipitation. Therefore, Rx5day was assigned the highest relative importance in the AHP weighting framework.

The dominant weight of Rx5day also influences the spatial distribution of the resulting Rainfall Hazard Index (RHI). In the weighted integration, areas with relatively high normalized Rx5day values receive a greater contribution to the composite index than areas with comparable normalized values of lower-weighted indicators. Consequently, the high and very high RHI classes tend to reflect the spatial pattern of five-day rainfall accumulation, particularly in the central and upstream regions of the Air Bengkulu Watershed. Nevertheless, the final RHI distribution also depends on the contributions of Rx1day, R95p, and RT. Therefore, the dominance of Rx5day is a manifestation of its relative importance assigned within the AHP framework rather than a demonstration of a stronger causal effect on flood occurrence.

3.5. Rainfall Hazard Index Map

The Rainfall Hazard Index (RHI) was deployed by combining the parameters of Rx1day, Rx5day, R95p, and Rainfall Trend (RT) using the weight obtained from the Analytical Hierarchy Process (AHP). The integration of these parameters produces a spatial index of the level of extreme rainfall hazard in Air Bengkulu Watershed.

Table 11. Rainfall Hazard Index classes are

RHI Value	RHI Class	Area (ha)	Percentage (%)
1,00-2,17	Very Low	2162,35	4,24
2,17-3,00	Low	8575,86	16,81
3,00-3,55	Moderate	6797,48	13,32
3,55-4,28	High	2497,60	4,90
4,28-4,92	Very High	30987,44	60,73
Total		51020,73	100 %

The Rainfall Hazard Index (RHI) was developed by integrating Rx1day, Rx5day, R95p and Rainfall Trend (RT) with their AHP weights. The resulting RHIs were classified into five rainfall hazard classes using the Jenks Natural Breaks method (Table 10 and Figure 6). The very low hazard class (RHI values 1.00–2.17) occupied 2,162.35 ha (4.24%) of the study area followed by the low class (2.17–3.00) which covered 8,575.86 ha (16.81%). The moderate class (3.00–3.55) was

6797.48 ha (13.32%) and the high class (3.55–4.28) was 2497.60 ha (4.90%). The very high class (4.28 – 4.92) dominated the 30,987.44-ha watershed (60.73%). Total classified area was 51,020.73 ha and total of five class percentages was 100.00% after rounding to two decimal places.

The spatial analysis showed that the very high rainfall hazard class dominated the upstream region of the Air Bengkulu Watershed, and the moderate to high classes were mostly found in the middle watershed. The low and very low classes of hazard of rainfall mostly characterized the downstream region. This distribution is generally in agreement with the spatial patterns of the extreme rainfall indicators, particularly Rx5day that got the highest AHP weight. The relatively larger share of Rx5day in the weighted index can inflate RHI values in regions with high five-day rainfall totals. However, the resulting spatial pattern is the combined effect of all four rainfall indicators and not the contribution of Rx5day alone.

The dominance of the very high RHI class indicates that a substantial share of the watershed exhibits high values of the integrated extreme rainfall indicators. However, these categories are relative hazard conditions based on rainfall and cannot be directly interpreted as flood inundation probability or full flood risk. Additional hydrological, topographical and exposure information is needed to provide a more complete understanding of flood hazards and related risks.

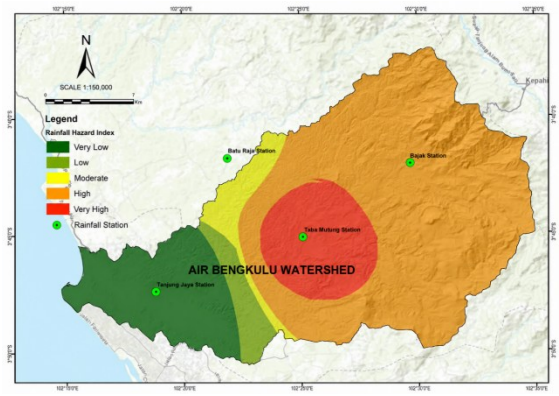

Figure 6. Rainfall Hazard Index map of the Air Bengkulu Watershed

The Rainfall Hazard Index map shows that zones with high to very high hazard levels are mainly concentrated in the central and upstream regions of the Air Bengkulu Watershed. This spatial pattern is consistent with the distribution of the Rx1day, Rx5day, and R95p indices analyzed previously. Therefore, the integration of multiple extreme rainfall indices using the AHP method is able to produce a spatial distribution of rainfall hazard that is consistent with the meteorological characteristics of the study area.

The findings of this study are consistent with previous research on hydrometeorological hazard indices, which indicates that the simultaneous use of multiple extreme rainfall indices can provide a better representation of hazard conditions than the use of a single rainfall parameter. (Audu et al., 2021) demonstrated that integrating multiple extreme rainfall indices provides better capability for representing the spatial distribution of rainfall hazard. Similar findings were reported by (Yu et al., 2020), who showed that combining multiple ETCCDI indices is more effective in identifying areas experiencing high hydrometeorological pressure than using maximum daily rainfall alone.

3.6. RHI Validation

Table 12. Validation of the Rainfall Hazard Index

No	Latitude	Longitude	RHI Class	Survey Results	Agreement
1	-3,7912	102,3252	Very Low	Non-Flood	✓
2	-3,7797	102,3014	Very Low	Non-Flood	✓
3	-3,7814	102,3036	Very Low	Flood	△
4	-3,7816	102,3115	Very Low	Non-Flood	✓
5	-3,7800	102,3134	Very Low	Non-Flood	✓
6	-3,7825	102,3038	Very Low	Non-Flood	✓
7	-3,7581	102,4114	sangat tinggi	Non-Flood	△
8	-3,7932	102,3134	Very Low	Non-Flood	✓
9	-3,8152	102,3231	Very Low	Non-Flood	✓
10	-3,8101	102,3056	Very Low	Non-Flood	✓
11	-3,7930	102,3118	Very Low	Non-Flood	✓
12	-3,7874	102,3240	Very Low	Flood	△
13	-3,7932	102,3246	Very Low	Non-Flood	✓
14	-3,7898	102,3006	Very Low	Flood	△
15	-3,7858	102,3224	Very Low	Non-Flood	✓

Noted:
✓ = Consistent,
△ = Requires Further Assessment.

The Rainfall Hazard Index (RHI) was initially evaluated in the field using historical flood incident data from the Regional Disaster Management Agency (BPBD) and supported by direct field observations. In total 15 observation locations were

analyzed by comparing the recorded flood occurrence and field condition with the respective rainfall hazard classes derived from the RHI map. The comparison was not aimed at testing the accuracy of the flood prediction but to evaluate the initial spatial agreement between the rainfall-related hazard levels and the observed flood conditions.

Comparison results are shown in Table 11. Agreement between the RHI classification and available flood information was found at 11 of the 15 (73.3%) observation locations, while discrepancies were found at 4 locations (26.7%) that warrants further assessment. Agreement was defined as low rainfall hazard classes corresponding to locations with no documented or observed flooding, or high rainfall hazard classes corresponding to locations with evidence of flooding. Sites with different conditions were identified as needing further evaluation.

The differences may be due to physical and hydrological factors that are not captured by the rainfall-based index, such as local topography, land-use characteristics, soil properties, river conditions and drainage capacity.

3.7. Implications for Flood Risk Management

The Rainfall Hazard Index (RHI) that is developed in this study can provide initial information on spatial rainfall hazard in the Air Bengkulu Watershed. The RHI combines various extreme rainfall indicators to identify areas of relatively high rainfall intensity, accumulation and temporal changes. This information can be used to initially identify priority areas for rainfall monitoring, watershed management and further hydrological investigation.

Sites estimated to have a high and very high rainfall hazard may require more detailed assessments of flood generating processes such as surface runoff, river discharge, drainage capacity and local topographic conditions. However, RHI should not be interpreted directly as an indicator of the probability of flood occurrence, extent of inundation or flood risk as it does not account for all relevant hydrological, hydraulic, exposure and vulnerability factors.

Thus, RHI is most appropriate as an initial rainfall-based hazard screening tool to complement rather than replace comprehensive flood hazard and risk assessments. The RHI can be integrated with hydrological and hydraulic modeling, land-use data, topographic information and exposure data in future applications to support more comprehensive watershed-scale flood management and disaster risk reduction strategies.

IV. CONCLUSION

The study developed the Rainfall Hazard Index (RHI) in the Air Bengkulu Watershed by integrating four rainfall indicators, namely Maximum 1-Day Rainfall (Rx1day), Maximum Consecutive 5-Day Rainfall (Rx5day), Very Wet Days precipitation (R95p), and Rainfall Trend (RT) using rainfall observation data from 2007 to 2025. The Analytical Hierarchy Process (AHP) gave the highest weight to Rx5day (0.471), followed by R95p (0.284), Rx1day (0.172) and RT (0.073) with a Consistency Ratio (CR) of 0.0185 which is acceptable by the consistency criterion. These weights result from the higher relative importance of the five-day rainfall accumulation in the proposed index.

The RHI map produced classified the watershed in five classes of the rainfall hazard, the very high class with 60.73% of the study area (mainly in the upstream) is predominant. Moderate to high hazard classes were mostly found in the middle watershed and low to very low classes were mostly downstream. Preliminary comparison with flood records from the Regional Disaster Management Agency (BPBD) and direct field observations showed agreement at 11 of 15 locations (73.3%). However, this agreement is a limited descriptive assessment and should not be taken to indicate definitive validation, or flood prediction accuracy.

The main limitations of this study are the selection of only four rainfall stations, and spatial distribution of field observation points Also, the RHI does not consider physical and hydrological conditions such as topography, land use, soil properties, river conditions, and drainage capacity. Additional rainfall observations, independent validation with spatially more representative flood and non-flood data and sensitivity analyzes should be included in future research to assess the influence of AHP weights and hazard class thresholds on RHI classification. Thus, the proposed RHI should be viewed as a preliminary rainfall-based hazard screening tool for watershed management and spatial prioritization and not a full-fledged flood hazard, flood risk or flood prediction model.

AUTHOR'S CONTRIBUTION

Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing: Bima Kurniawan, Gusta Gunawan, Rena Misliniyati, Besperi, and Khairul Amri.

AVAILABILITY DATA AND MATERIALS

The data on rainfall and other supporting materials for this study were collected from the concerned government agencies and field survey activities. Data availability is subject to the permissions and data sharing policies of the respective data providers.

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