

The Enhanced Hazard Assessment of Rainfall-Induced Slope Failures in Tropical Regions through 45-Year Trend Analysis and Hydro-Geotechnical Modeling

Putu tantri Kumala Sari

tantri@ce.its.ac.id

Sepuluh Nopember Institute of Technology

Yudhi Lastiasih

Sepuluh Nopember Institute of Technology

Hisham Mohamad

Universiti Teknologi Petronas

Ahmad Dzikrullah Akbar

Sepuluh Nopember Institute of Technology

indrasurya B. Mochtar

Sepuluh Nopember Institute of Technology

Noor Endah

Sepuluh Nopember Institute of Technology

Herman Wahyudi

Sepuluh Nopember Institute of Technology

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The Enhanced Hazard Assessment of Rainfall-Induced Slope Failures in Tropical Regions through 45-Year Trend Analysis and Hydro-Geotechnical Modeling

Abstract

Global climate change is altering rainfall patterns in tropical regions and increasing the risk of rainfall-induced landslides. Therefore, this study aims to investigate the impact of the changing patterns on slope stability in East Java, Indonesia by integrating hydrological, statistical, and geotechnical analyses. A 45-year dataset from 29 rainfall stations was analyzed using Gumbel and Generalized Extreme Value (GEV) distributions to identify trend and predict extreme rainfall intensities for 5 to 100-year return periods. The results showed the existence of a localized increase in rainfall intensity with Pacitan exhibiting the most significant rise by reaching a predicted 50-year maximum of 416 mm. Subsequent numerical modeling was applied using the Limit Equilibrium and Finite Element Methods to evaluate slope safety factors (SF) under different rainfall scenarios and soil drainage conditions. The results showed that soil drainage capacity was the most important factor controlling slope stability. This was because poor drainage conditions characterized by low hydraulic conductivity at 10^{-6} m/s led to a drastic reduction in the SF and triggered instability ($SF < 1.0$) during extreme short-duration or prolonged rainfall events. Meanwhile, slopes with good drainage maintain a stable SF of 1.5–1.8. This study concluded that inadequate drainage significantly amplified slope vulnerability to provide a critical basis for targeted landslide mitigation strategies in tropical regions under a changing climate.

Keyword : Climate change; Rainfall landslide; Hydro-Geotechnical Modeling; Natural hazard

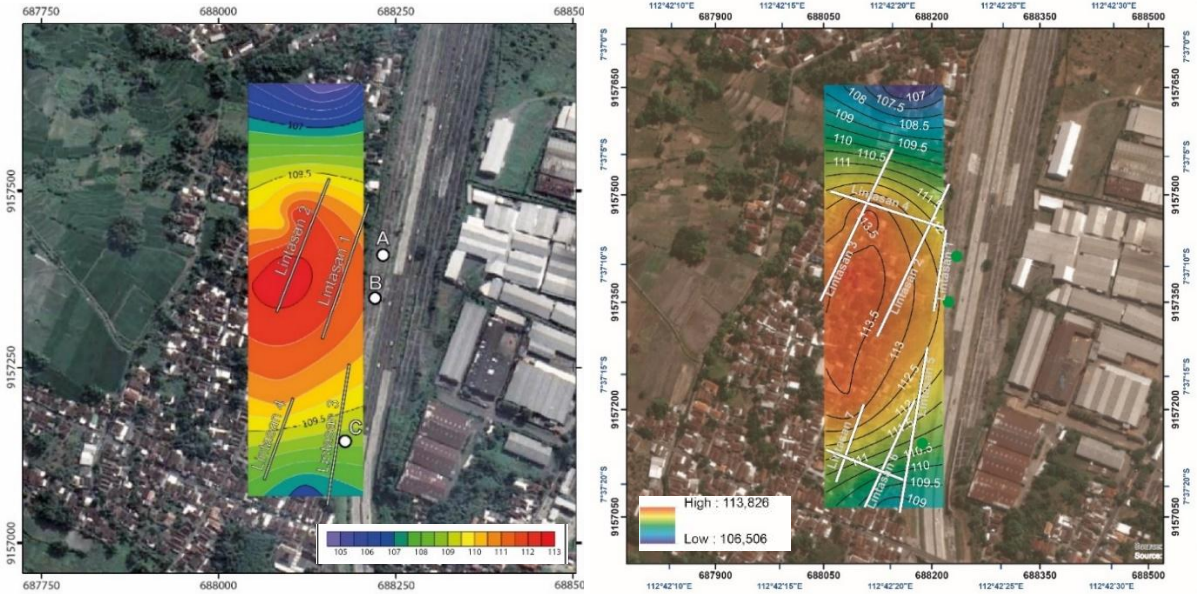
1. Introduction

Global climate change is influential in several aspects as observed in its effect on the stability of slopes against landslides in geotechnical engineering. Scholars have made efforts to correlate global climate change and landslides to determine the best mitigation system and forecast the future reinforcement of slopes to avoid future occurrences. The global warming caused in the eastern region can increase the possibility of snow melting and affect soil slope stability with the subsequent occurrence of frequent landslides. Different conditions are observed in tropical regions with the influence of climate change on rainfall intensity and duration as reported in previous studies.

Strauch et al. [1] reported that climate change could modify rainfall patterns by reducing the frequency and increasing the intensity of duration. Moreover, Chen et al. [2] showed that an increase in temperature led to heavier rainfall duration but a reduction in

frequency. These changes in rainfall patterns can affect flux boundary conditions in the soil layer and groundwater hydrology with further reduction in the value of effective and shear stress in the soil. The variations also influence the infiltration and evapotranspiration patterns of rainwater into the soil which is capable of affecting pore water pressure.

The trend shows that the rainfall infiltrating the soil on the slope has an impact on the pore water pressure and groundwater level with further reduction in the soil shear strength. The evidence of groundwater level rising due to rainfall during the dry and rainy seasons is presented in Figure 1. The difference of 2 meters was observed in the elevation between the two seasons and this confirmed the ability of rainfall to change the porewater pressure and the status of unsaturated soil to saturated. The other pieces of evidence identified are described on the Electrical Resistivity Tomography (ERT) results for the dry and rainy seasons in Figure 2. The water penetration could reduce the soil resistivity due to the content change. The relationship between resistivity and soil water content also depends on the porosity and connectivity of the soil matrix. This is because soils with high porosity and well-connected pore spaces allow freer movement of water which leads to lower resistivity values at higher content. Meanwhile, the relationship is less straightforward in compacted or poorly connected soils. The data used for the analysis was obtained from a tropical area in East Java, Indonesia in 2021 after high-intensity rain caused several landslides.



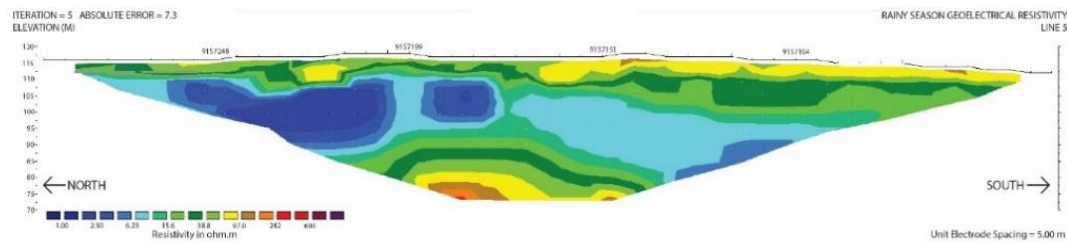


Figure 2. The Electrical Resistivity Tomography (ERT) result (upper) in the dry season and (lower) in the rainy season.

Previous studies have focused on tropical areas to determine the relationship between climate change and the number of landslide geo-disasters [3-9]. For example, Kristo et al. [4] analyzed a weather station in Singapore and reported that the rainfall intensity tended to increase over the years with a possible shift to longer duration in the future. The slope SF for the 50-year forecast showed a significant decrease due to an increase in rainfall intensity. Moreover, Vega [10] focused on Colombia and obtained a very close relationship between the variations in rainfall patterns due to global climate change, as well as La Niña and El Niño and landslide events.

Sari [9] studied the fluctuations in Pacitan, East Java for 45 years to determine the relationship between climate change, rainfall pattern, and slope stability. The results showed that the largest increase in rainfall intensity cumulative in 45 years was 8.8% with a monthly maximum of 0.75%. The condition is believed to occur due to global climate change. A day of rain with an intensity of 302 mm decreased the slope SF by 1%, a month accumulation led to a 2.8–4% reduction, while three months was 5.5%. Several previous studies showed a relationship between rainfall pattern and global climate change with a decrease in the SF for slope stability. However, the focus on tropical areas was limited to certain locations without comparison to others. Therefore, this research will be specifically conducted for tropical areas in several cities and rainfall stations for comparison.

This study was conducted to determine the pattern of changes in rain intensity over 45 years based on data at 29 rain stations in different cities of East Java from the Disaster Management Capacity of the National Agency for Disaster Management (BNPB). The focus was on the most extreme rain ever recorded in Indonesia by the Meteorological, Climatological, and Geophysical Agency (BMKG). Statistical modeling was conducted to determine fluctuations in rainfall intensity. Moreover, numerical modeling was applied with limit equilibrium and finite element method to identify the effect of changes in rain intensity, pore water pressure, and SF on the slope for the years considered. The results were expected to help understand the relationship between climate change, variations in rainfall intensity, and slope stability. The purpose was to mitigate landslide disasters due to extreme rain in tropical regions, specifically in East Java.

2. Theoretical background

2.1. Rainfall and climate change

Climate change has been a global phenomenon in the past few decades with significant influence on environmental conditions. The examples are global warming and geo-hydrological disasters which are difficult to predict and the variables of occurrence cannot be easily determined [11]. Studies are increasingly focused on the impact of climate change on changes in earthly conditions. Strauch et al. [1] reported the ability of climate change to cause less frequent rain with a more intense duration. Chen et al. [2] also reported that increasing temperature led to heavier rainfall but with reduced frequency. These changes in rainfall patterns can affect flux boundary conditions in the soil layer and groundwater hydrology with further reduction in the value of effective and shear stress in the soil. The variations also influence the infiltration and evapotranspiration patterns of rainwater which is capable of affecting pore water pressure as well as the stability of soil and ridge.

The infiltration of rainwater into an embankment can affect pore water pressure to subsequently cause landslides. Rainfall has also been identified as an important factor related to the effect of rainwater infiltration in the soil. This was reported through the study of Iverson [12] on the effect of rainwater infiltration on the occurrence of landslides. The results showed that the relationship between the pressure head and efficient drainage in a dam could lead to a high safety figure before rainfall but the value reduced sharply along with an increase in pressure head during rainfall.

Water seepage into the soil is another important factor influencing the stability of a dam. For example, Liu and Li [13] reported the significant influence of rainwater infiltration and variations in water level on embankment stability. The study also produced two important points and the first was that a faster drop in the elevation of water in a reservoir led to a greater decrease in the safety value. The speed of lowering was identified as the main key to reducing the stability of the embankment. The second point was that rain and water level fluctuations in the reservoir reduced the stability of the embankment. Moreover, the reduced safety figure was caused by increasing the total weight of the soil and pore pressure in the soil due to rain and water fluctuations.

Rainwater infiltration is further closely related to the intensity and duration of rain in several studies. There is also a current debate on the ability of intensity and duration of rain to cause landslides due to the instability of embankments. Tan et al. [14], Rahardjo et al. [15], Rahardjo et al. [16], and Hong et al. [3] argued that antecedent rainfall is a very significant influence on landslides. Meanwhile, Brand [17], Aleotti [18], and Pitts [19] identified the heavy rain that fell shortly before the landslides as the cause. These theories show that the two rainfall conditions including both the antecedent and heavy rain immediately before the landslides can lead to an increase in pore water pressure to subsequently reduce effective and shear stress in the soil. The process is capable of reducing slope stability and causing landslides.

2.2. Rainfall and hydrogeology

The relationship between rainfall and hydrogeology is fundamental to

understanding the movement and distribution of groundwater within the subsurface of the Earth. Rainfall is part of the primary sources of water infiltrating the ground and recharging aquifers which are underground layers of water-bearing rock or sediment. The infiltration occurs through the soil and fractures in rocks and the infiltrated water replenishes groundwater reservoirs through a process known as recharge. The amount and intensity of rainfall directly influence the rate of recharge which subsequently affects groundwater availability.

The type and characteristics of aquifers are very important in determining how rainfall influences groundwater levels. For example, unconfined aquifers that are not overlain by impermeable layers have the tendency of responding more quickly to changes in rainfall compared to confined aquifers bounded above and below by impermeable layers. Rainfall can also influence groundwater quality by affecting the transport of contaminants through the subsurface. This is possible because heavy rainfall events mobilize and transport pollutants from surface sources into groundwater systems to potentially affect water quality. The trend shows that rainfall is a key component of the hydrological cycle often used in describing the continuous movement of water between the atmosphere, land, and oceans. The understanding of the interactions between rainfall, surface water, and groundwater is important for managing water resources sustainably.

Hydrogeology is the study of groundwater movement and storage within geological formations. Rainfall contributes to the replenishment of groundwater storage which varies depending on factors such as the permeability of the underlying rocks and the depth of the water table. This is possible because the upper surface of the groundwater known as the water table responds to changes in rainfall patterns. During periods of high rainfall, the water table can rise as recharge exceeds discharge but declines in dry periods because groundwater is discharged through springs, wells, or streams.

Hydrology in slope areas is closely related to flow paths in the soil and the time required for rainwater to flow from the catchment area to rivers or channels. Water from rainfall can enter or infiltrate into the ground or become surface water flow. Figure 2.1 shows the difference in water flow above and into the ground in a hilly area. Surface runoff or flow is classified into two conditions and the first is Hortonian overland flow which occurs when precipitation exceeds the rate of soil infiltration. The second is the saturated overflow which occurs when the soil has reached a saturated condition. Meanwhile, subsurface stormflow is water that infiltrates and seeps into the soil layers both in unsaturated and saturated conditions [20]. Soil layers can be unconsolidated sedimentation, weathered, or hard rock. Another important point is that water flow in the soil is influenced by gravity and capillarity.

The flow can occur as a homogeneous matrix between micropores or as an inhomogeneous due to holes in the soil made by animals, plant roots, or cracks in the soil [21]. Subsurface storm flow was first described by Engler in Bronnimann [22]. Moreover, the formation of subsurface streamflow is influenced by the saturation conditions in the

soil layers, rock topography, geometry and depth of the soil layers, permeability conditions in the soil and rocks, as well as the saturation and intensity of the rainfall experienced. Subsurface storm flow often occurs in saturated and near-saturated soil conditions due to connectivity [23].

2.3. Water seepage

This study focuses on the effects of rainwater seepage into soil and the potential to trigger slope instability. The seepage of rainwater into the ground has been observed to be capable of altering the shear parameters and increasing the groundwater level with further effect on the SF of the slope. The amount of the seepage is determined by the ability of the soil to absorb water. According to Daniel et al. [24], heavy rainfall can increase surface runoff and decrease groundwater recharge due to a low absorption capacity. This scenario shows that the seepage coefficient or hydraulic conductivity is very important. Zheng et al. [25] also reported that extreme rainfall primarily contributed to groundwater and could effectively replenish deep soil layers.

He et al. [26] conducted a study using ArcGIS to simulate the changes in groundwater flow caused by rainfall seepage on slopes. The result showed that rainfall seepage changed the groundwater level and flow on the slope with further effect on slope stability. Sangrey's [27] formula Mein and Larson [28] was used to calculate rainfall recharge into the ground based on the influence of several factors as follows:

$$R = P - Q_r - E \pm S_t - S_j - S \quad (1)$$

Where, R = rainfall recharge, P = rainfall, Q_r = surface runoff, E = Evaporation, S_j = rainfall interceptions, S_t = water storage, and S = bedrock seepage. The surface runoff can be calculated through the following equation:

$$Q_r = P - I_r - S_j \quad (2)$$

Where, I_r = seepage volume.

3. Study methodology

This study was initiated with a literature review and a specific focus on the topic of global warming, changes in rainfall intensity and the impact on the geotechnical field specifically regarding landslides as presented in the flow chart in Figure 3 [29-32]. The next step was to analyze all rainfall data obtained from 28 rain stations related to the government agency (BPWS) and the Indonesian Meteorology and Geophysics Agency (BMKG). The data were compared with those related to extreme weather from NASA's Giovanni Earth Data website.

The rainfall data were analyzed using statistical methods and used as input for slope stability modeling conducted to determine the influence of rain infiltration, soil seepage conditions, soil shear parameters, and slope topography on stability based on recent study [33-35]. The statistical analysis of existing data for 45 years was also used to determine the relationship between global climate change and variations in rainfall intensity of the study regions. Lastly, a field test was conducted using ERT to validate the

226 numerical results.

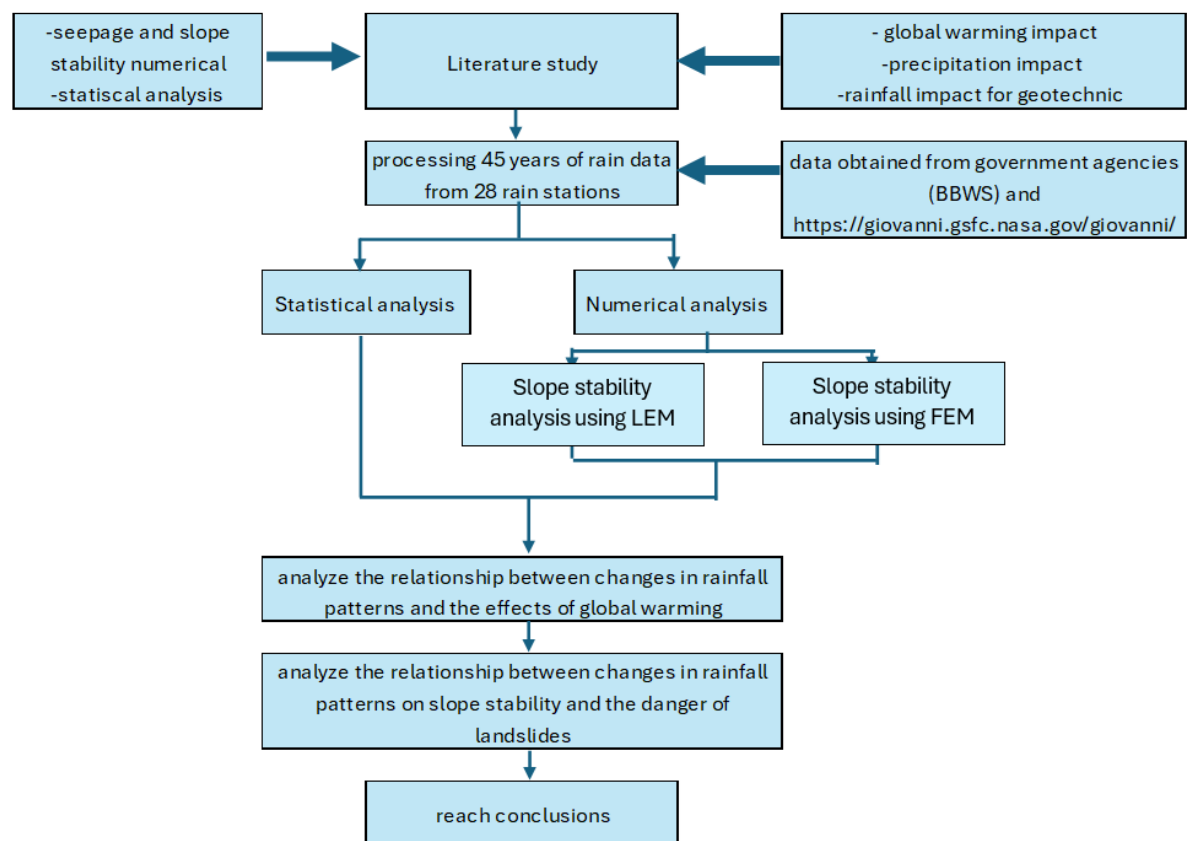


Figure 3. Study flow chart

The numerical analysis was conducted using 2D modeling coupled SLOPE/W and SEEP/W with the Limit Equilibrium Model (LEM) and the Finite Equilibrium Model (FEM) through the boundary conditions presented in Figure 4. The results are expected to determine the relationship between changes in rain patterns and rain intensity over 45 years on the issue of global warming and the subsequent impact on slope stability.

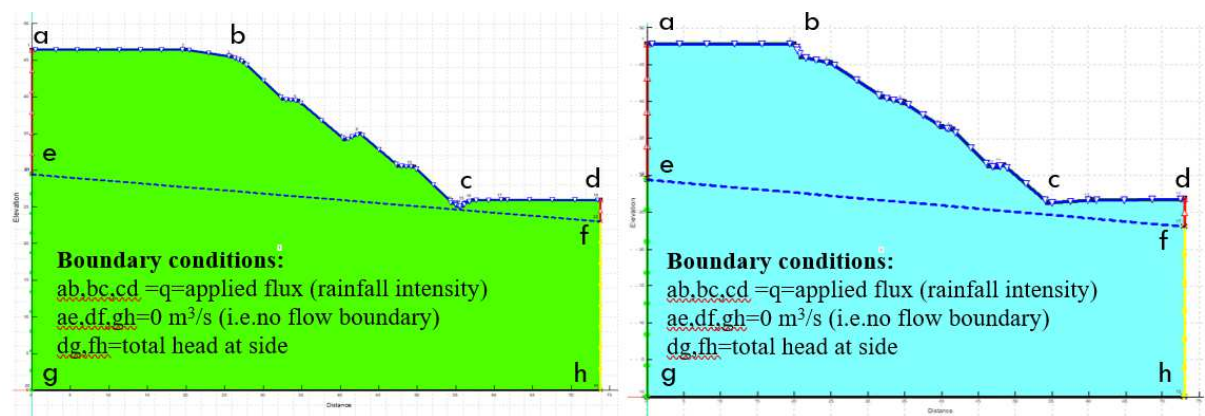


Figure 4. Boundary conditions of slope stability in 2D modeling

4. Results and discussion

4.1. Rainfall data analysis

The focus of this study was to determine the correlation between fluctuations in

rainfall intensity, frequency, and duration over 47 years on the influence of slope stability with due consideration for the effects of global weather changes in Indonesia, specifically in the East Java region. The data samples were obtained from 29 rainfall stations and presented in Table 1.

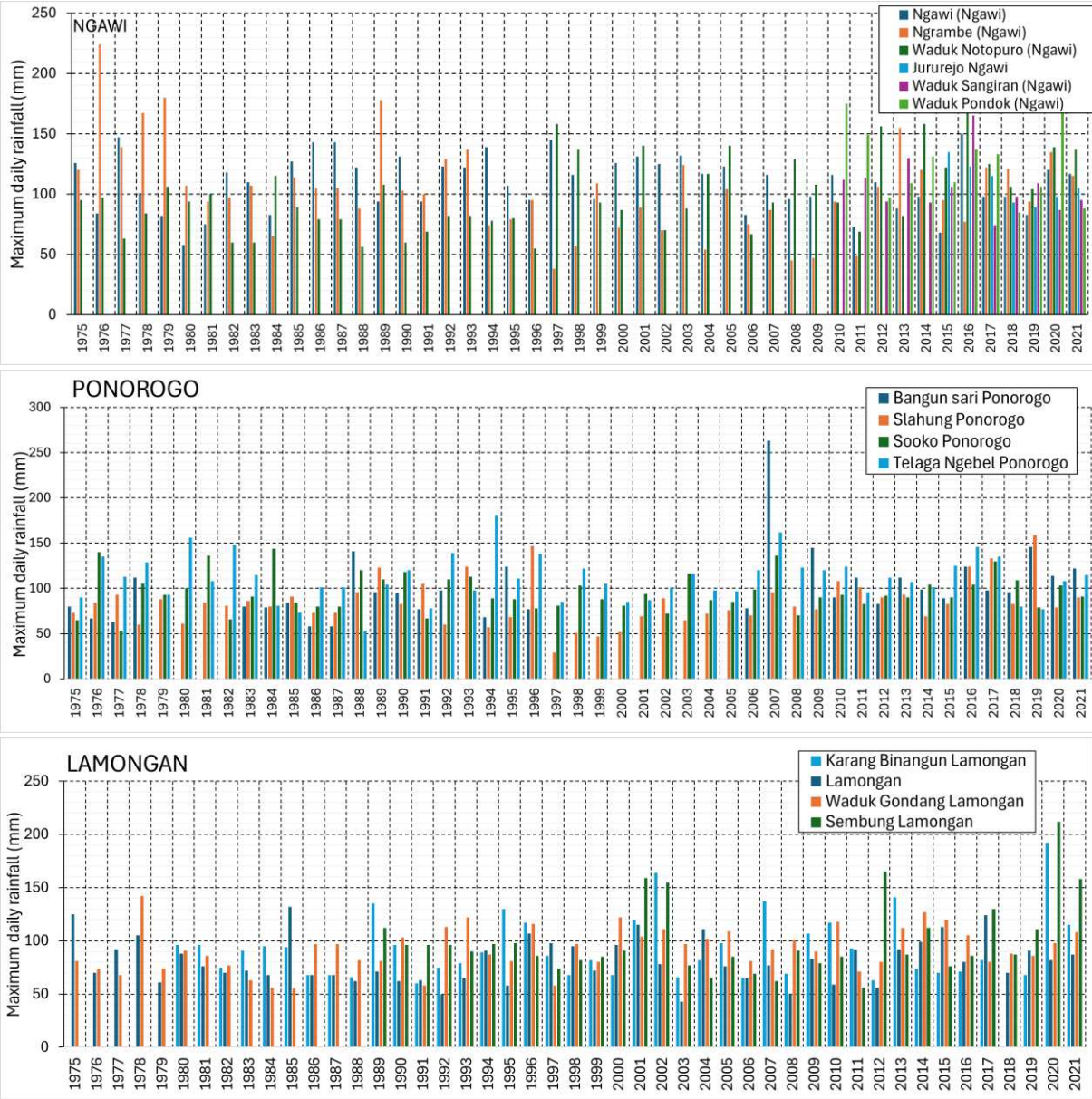
Table 1. Rainfall data

No	Location of rainfall station		Year	Year
1	Gresik	Balong panggang Gresik	2010	2021
2		Menganti Gresik	2017	2021
3	Ngawi	Jururejo Ngawi	2015	2021
4		Ngawi	1975	2021
5		Ngambe Ngawi	1975	2021
6		Waduk Notopuro Ngawi	1975	2021
7		Waduk Pondok Ngawi	2010	2021
8		Waduk Sangiran Ngawi	2010	2021
9	Ponorogo	Bangun sari Ponorogo	1975	2021
10		Slahung Ponorogo	1975	2021
11		Sooko Ponorogo	1975	2021
12		Telaga Ngebel Ponorogo	1975	2021
13	Madiun	Jatirogo Madiun	2016	2021
14		Jiwan Madiun	1976	2021
15		Waduk Dawuhan Madiun	2015	2021
16		Waduk Kedung Brubus Madiun	2013	2021
17	Lamongan	Karang Binangun Lamongan	1975	2021
18		Lamongan	1975	2021
19		Waduk Gondang Lamongan	1975	2021
20		Sembung Lamongan	1989	2021
21	Bojonegoro	Bojonegoro	1975	2021
22		Pacal Dam Bojonegoro	2016	2021
23		Padangan Bojonegoro	1975	2021
24		Pajeng Bojonegoro	2016	2021
25		Turi Bojonegoro	2016	2021
26	Pacitan	Kebon Agung Pacitan	1975	2020
27		Nawang Grindulu Pacitan	1975	2020
28		Pacitan	1975	2020

No	Location of rainfall station		Year	Year
29		Tegalombo Pacitan	2019	2020

The analysis of the data from 29 stations was used to determine the significant historical maximum daily rainfall across the studied cities. It was observed that there was 224 mm in Ngawi (1976), 220 mm in Lamongan (2020), 263 mm in Ponorogo (2007), 173 mm in Bojonegoro (2020), 156 mm in Gresik (2020), 178 mm in Madiun (2018), and 325 mm in Pacitan (1975). Furthermore, the observed maximum annual rainfall for each city was recorded as 1147 mm in Ngawi, 1002 mm in Lamongan, 998 mm in Ponorogo, 805 mm in Bojonegoro, 1020 mm in Madiun, and 1455 mm in Pacitan. The maximum daily rainfall trend across all monitored stations are presented in Figure 5.

The longest consecutive period of rainy days during the wet season was observed to be 20-21 days and occurred in January across all monitored stations. The distribution of the rainy periods is presented in the following Figure 6.



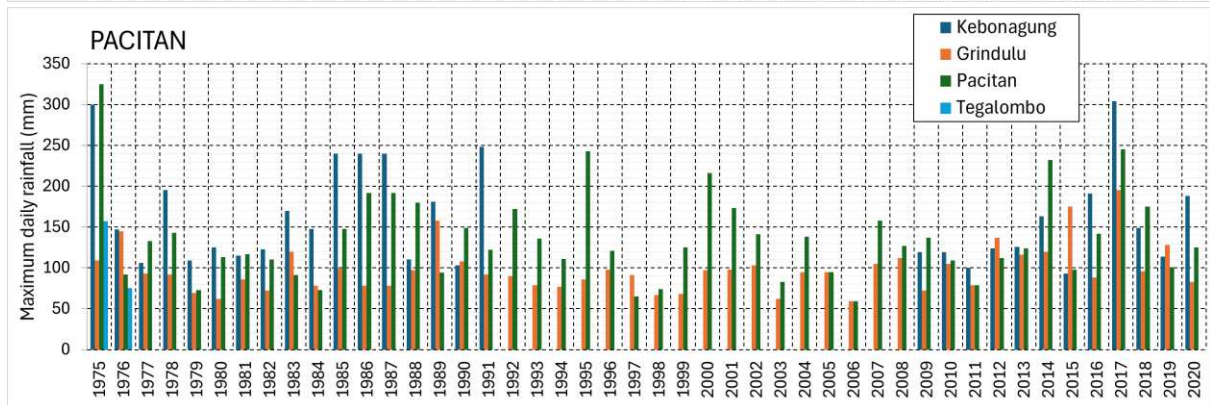
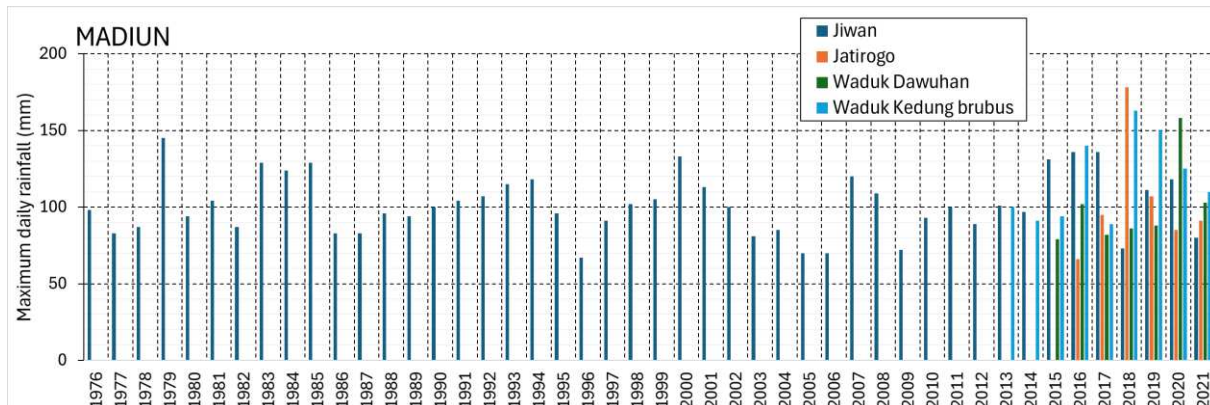
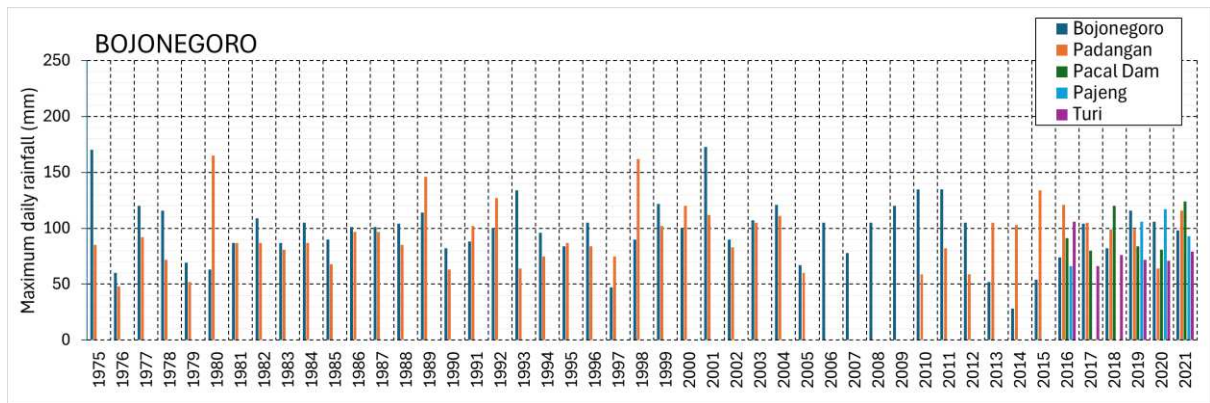
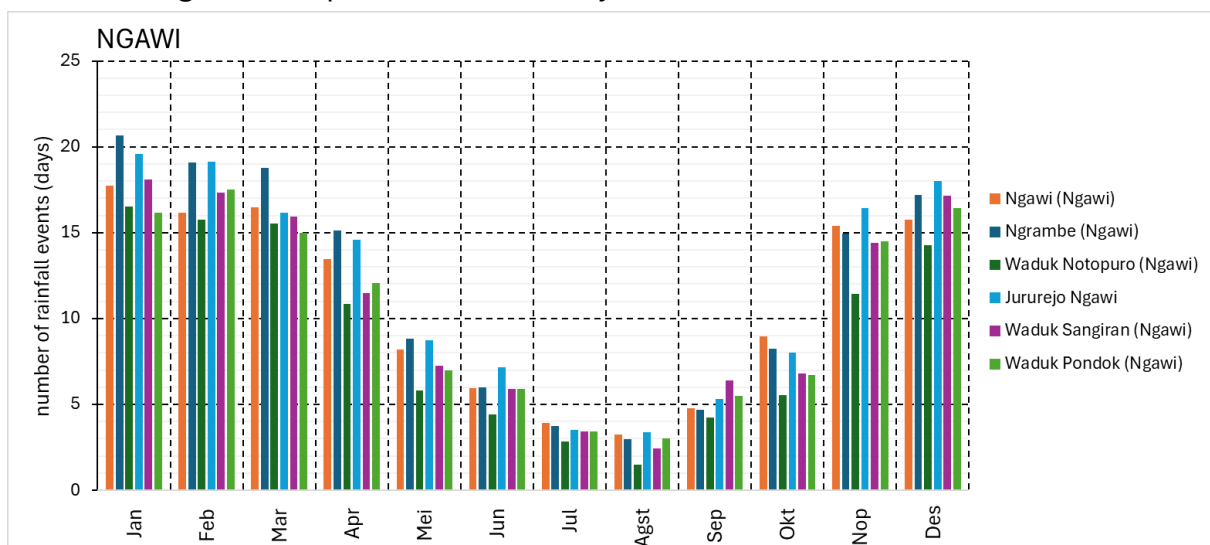
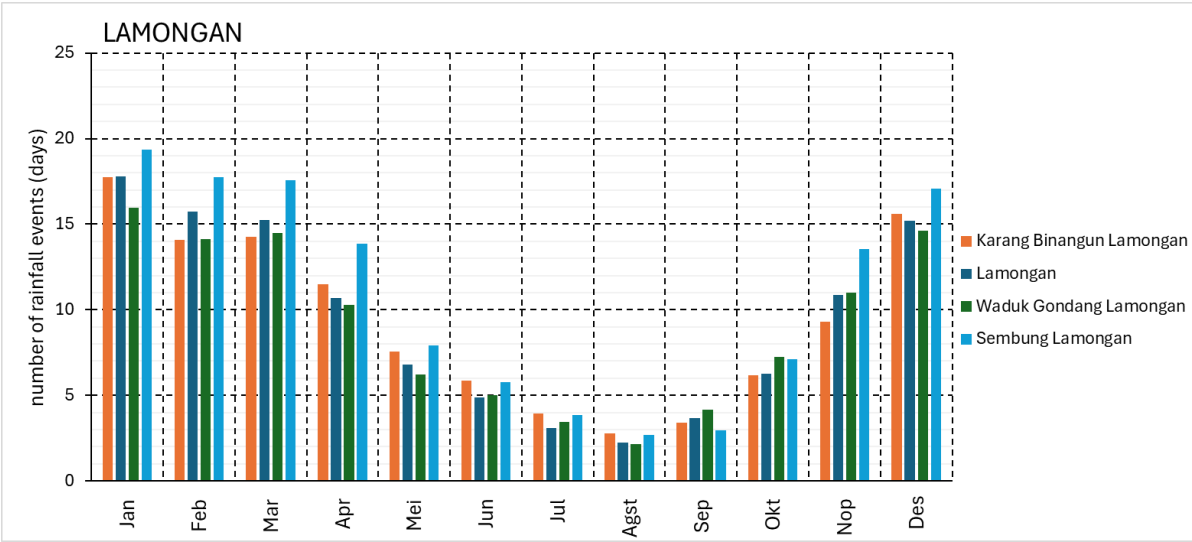
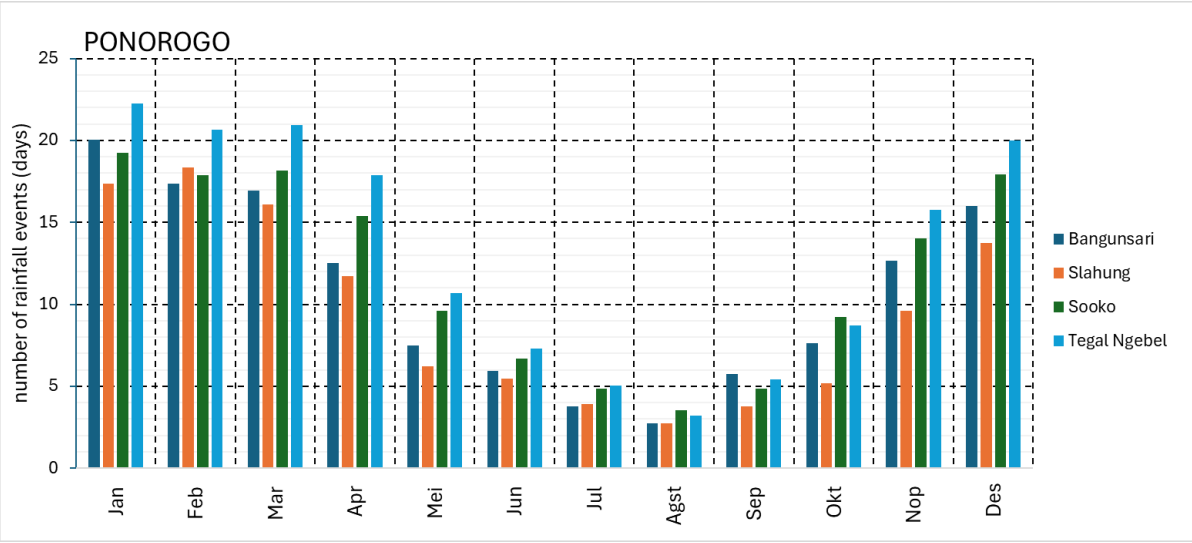


Figure 5. Graph of maximum daily rainfall at 29 monitored stations.

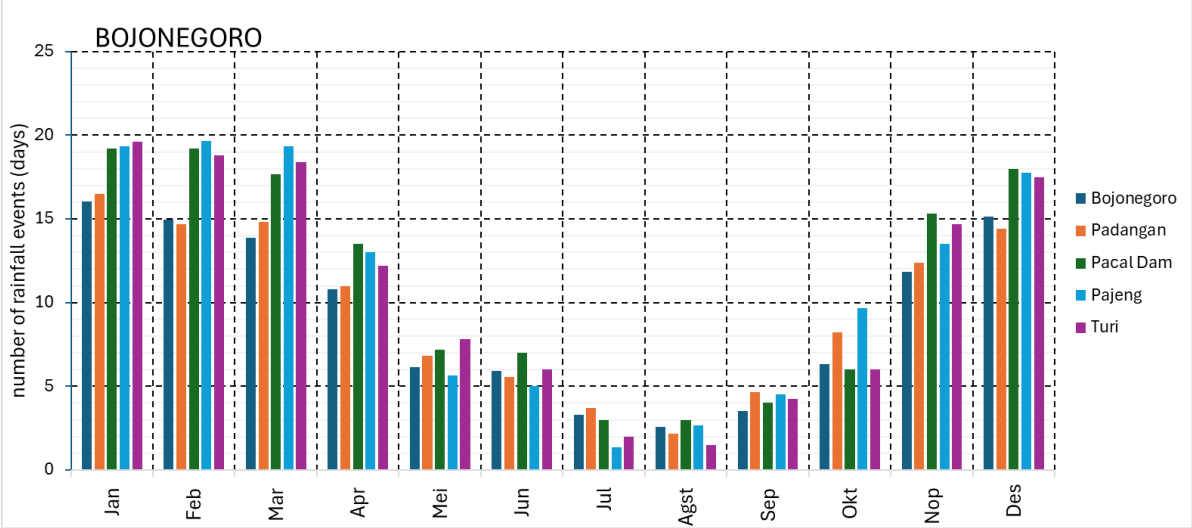




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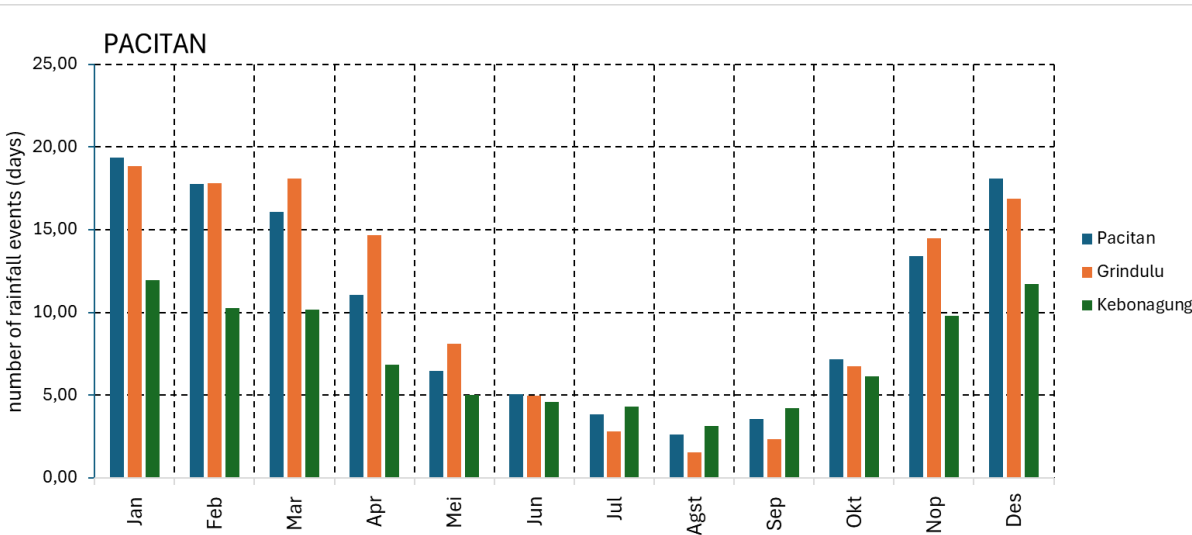
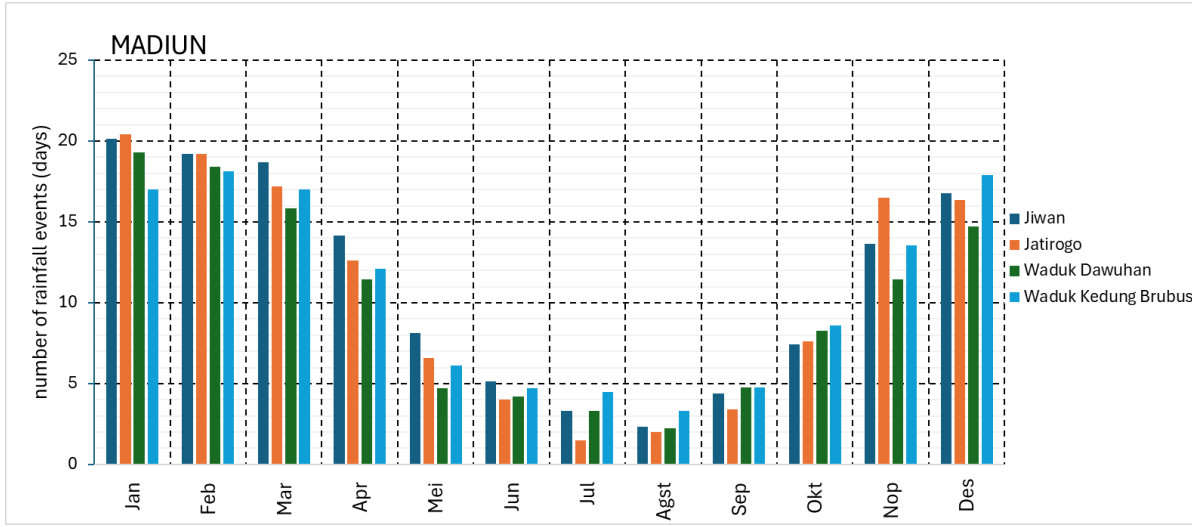
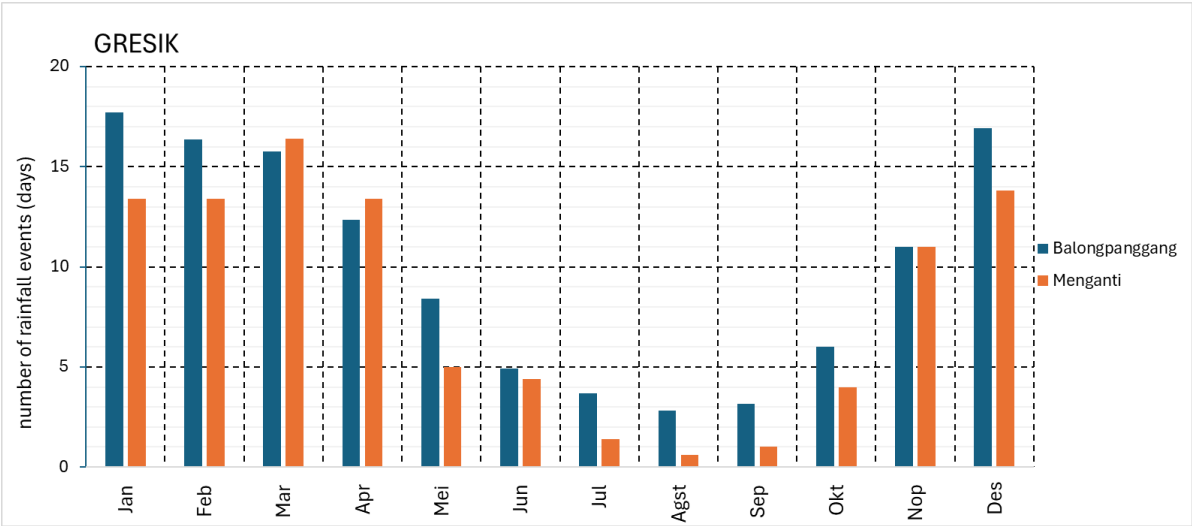


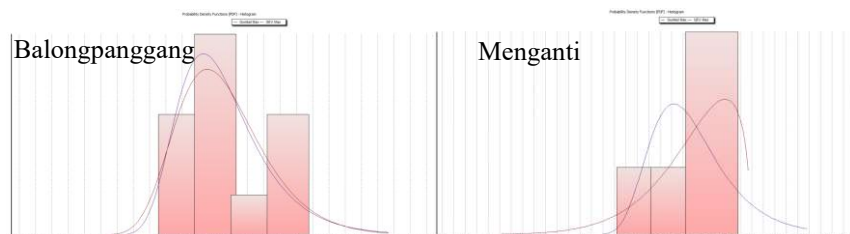
Figure 6. Rainy season at the monitored stations

A comparative analysis of the results in Figure 6 showed distinct seasonal patterns for the Madiun and Pacitan regions. The wet season was pronounced from November to

April in Pacitan with an absolute peak in January where approximately 25 rainy days were recorded which was an estimation of daily precipitation. The next was a distinct dry season characterized by a sharp decline in rainfall from May onward which led to a very dry period from June to September. The driest month was August when all stations averaged fewer than five rainy days. Similarly, the Madiun region exhibited a clearly defined wet season from November to March and also peaked in January. A dramatic decline started in April and led to a sharp dry season from May to September, with August similarly being the driest month across all stations. This synchronicity confirmed that both regions were firmly under the influence of the same overarching monsoonal system identified to have controlled the primary seasonal rhythm.

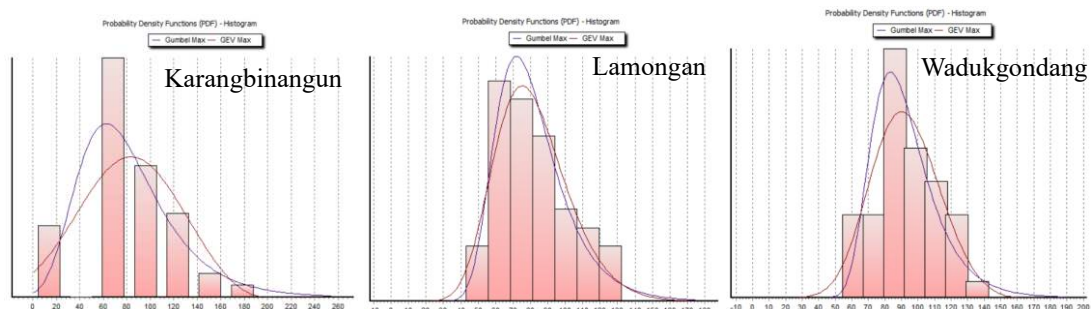
4.2. Statistical Analysis of Probability Density Function (PDF) - Gumbel Distribution and Generalized Extreme Value (GEV)

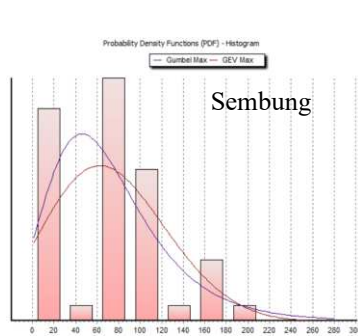
The Gumbel distribution is a probability distribution often used to model extreme values such as maximum rainfall, peak river discharge, extreme temperatures, or maximum structural loads. It is frequently adopted in hydrology, meteorology, and reliability engineering to analyze extreme events. The GEV statistical method can also be used to analyze extreme data such as maximum rainfall, extreme temperatures, or peak river discharge. This method generalizes extreme value distributions such as Gumbel, Fréchet, and Weibull within a single mathematical framework. Both methods were applied to identify extreme rainfall conditions at each rainfall station. The results of the probability distribution modeling for each rainfall station are presented in Figure 7.



	Balongpanggang	Menganti
Mean (μ)	105,54	89,2
Deviation (σ)	27,91	18,27
Skewness (ξ)	0,72932	-121.243
Kurtosis	-0,54897	140.016

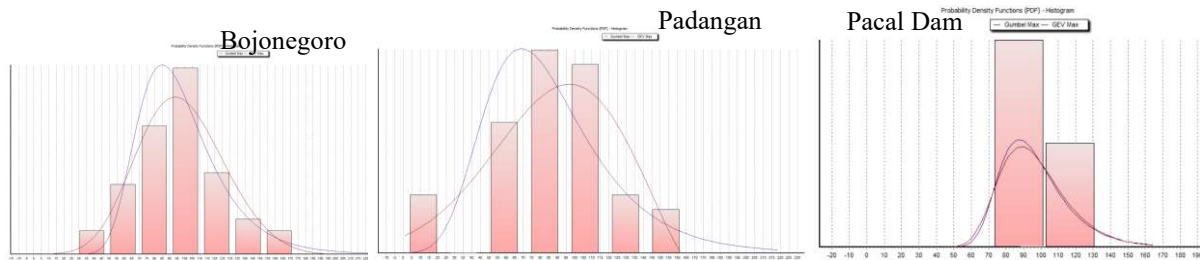
(a) Analysis of the distribution of rainfall events in the Gresik region





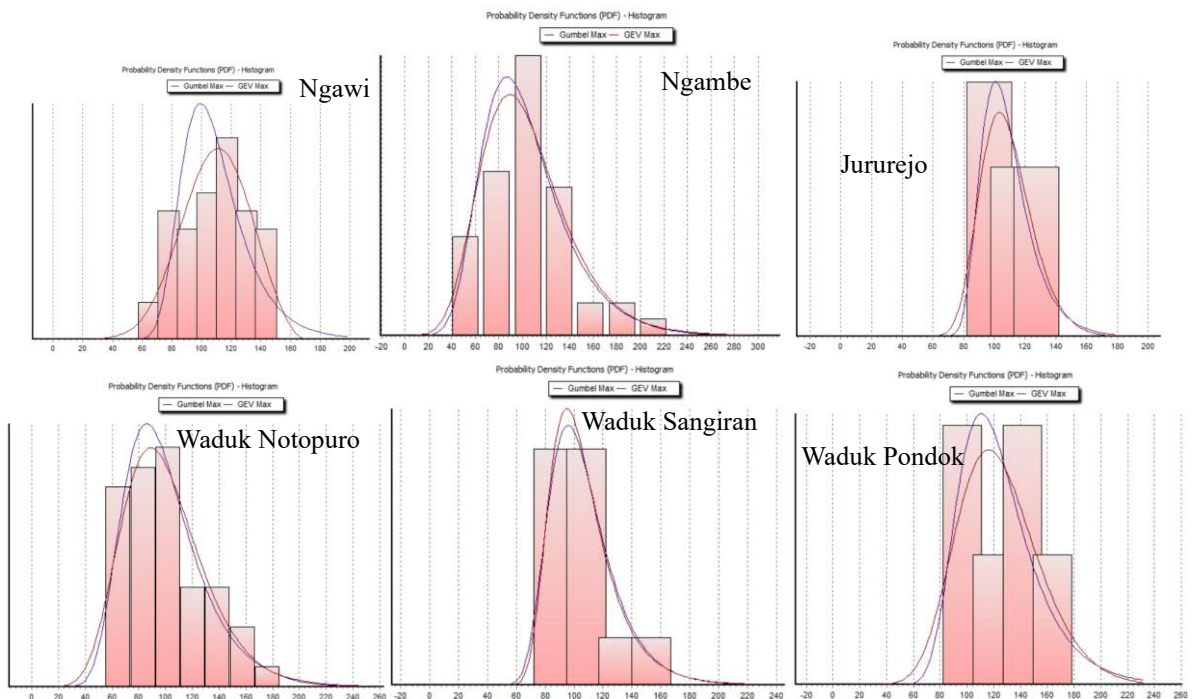
LAMONGAN	Karang Binangun	Lamongan
Mean (μ)	89,02	81,45
Deviation (σ)	35,20	21,14
Skewness (ξ)	-0,15355	0,53237
Kurtosis	0,81552	-0,29537
LAMONGAN	Waduk Gondang	Sembung
Mean (μ)	92,36	100,30
Deviation (σ)	20,27	34,36
Skewness (ξ)	0,12269	0,18597
Kurtosis	-0,37753	-0,33795

(b) Analysis of the distribution of rainfall events in the Lamongan region



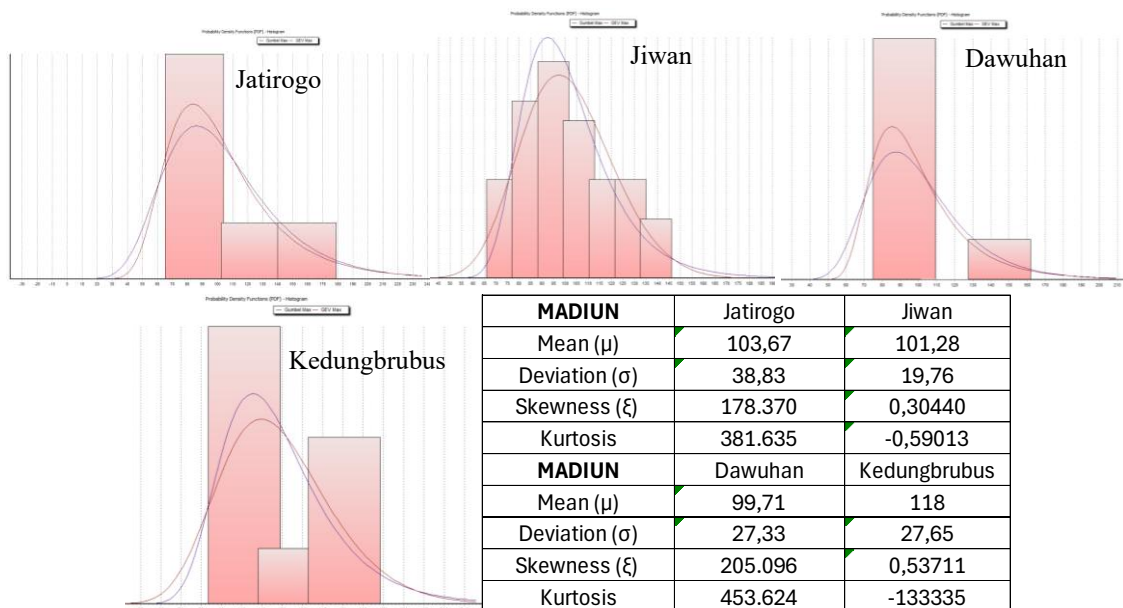
BOJONEGORO	Bojonegoro	Padangan
Mean (μ)	97,85	85,68
Deviation (σ)	28,24	37,10
Skewness (ξ)	0,18079	-0,51967
Kurtosis	109.492	100.017
BOJONEGORO	Pacal Dam	Pacel
Mean (μ)	96,67	95,50
Deviation (σ)	20,04	21,98
Skewness (ξ)	0,83673	-0,91644
Kurtosis	-182.538	0,54844

(c) Analysis of the distribution of rainfall events in the Bojonegoro region

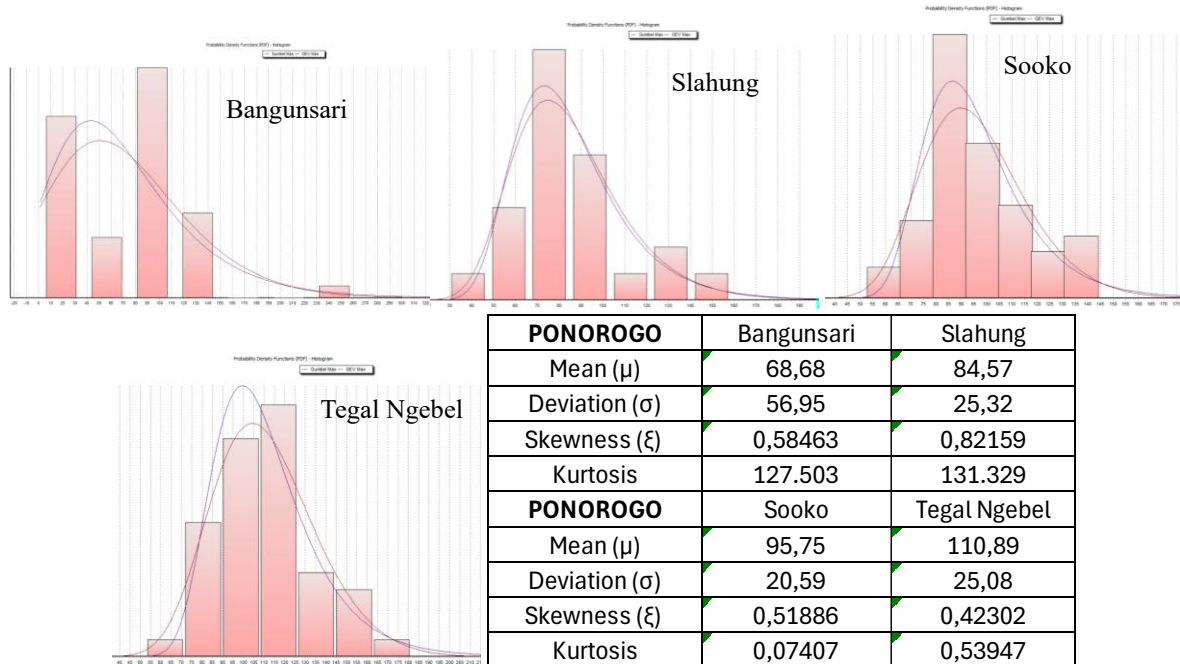


NGAWI	Ngawi	Ngambe	Waduk notopuro
Mean (μ)	109,51	103,43	99,87
Deviation (σ)	22,64	37,54	31,25
Skewness (ξ)	-0,19061	0,82066	0,69910
Kurtosis	-0,67501	142.637	-0,08074
NGAWI	Jururejo	Waduk Sangiran	Waduk Pondok
Mean (μ)	108,29	106,33	124,42
Deviation (σ)	16,82	23,42	30,47
Skewness (ξ)	0,52395	143006	0,45803
Kurtosis	-0,95432	302.443	-0,84144

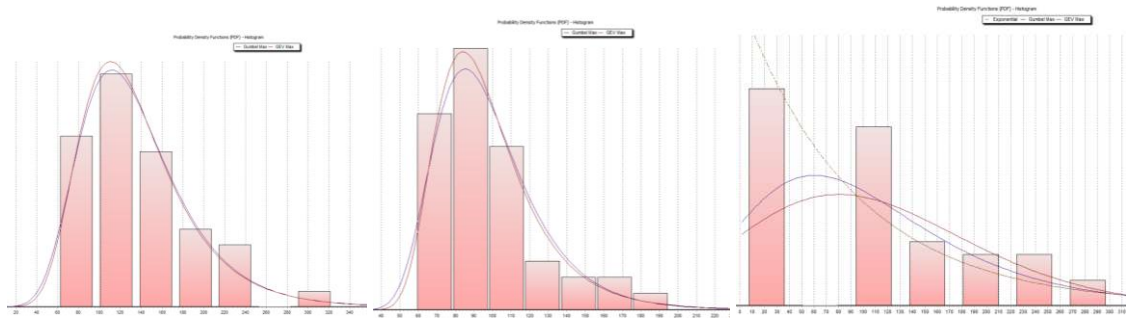
(d) Analysis of the distribution of rainfall events in the Ngawi region



(e) Analysis of the distribution of rainfall events in the Madiun region



(f) Analysis of the distribution of rainfall events in the Ponorogo region



PACITAN	Pacitan	Grindulu	Kebunagung
Mean (μ)	136,15	98,09	101,96
Deviation (σ)	54,01	28,59	92,30
Skewness (ξ)	1,3	1,47	0,37058
Kurtosis	2,29	2,68	-0,80793

(g) Analysis of rainfall distribution in the Pacitan region

Figure 7. Distribution of rainfall events using the Gumbel and GEV max methods

Some anomalies were identified in the rainfall records at several locations and characterized by exceptionally high kurtosis values. These values showed the occurrence of extremely intense rainfall events. Moreover, integrity was maintained by using raw, unmodified data in all analyses. The regions with high positive skewness such as Pacitan and Grindulu required enhanced preparedness for extreme rainfall events capable of triggering floods or landslides. This result was validated through field reports of landslides. For example, Pacitan experienced rainfall exceeding 300 mm in 2017 that led to significant slope failures [8, 9].

Detailed examination of the Pacitan and Grindulu rainfall stations showed that both regions tended to experience days or years with exceptionally high rainfall intensity as observed in the high positive skewness. Rainfall data generally clusters around the mean but the stations showed a higher probability of extreme events which was reflected through the positive kurtosis. Meanwhile, the analysis of the geographically adjacent Kebunagung station showed a more symmetrical distribution with minimal right-skewing. The data exhibited more uniform dispersion without strong central clustering as observed in the negative kurtosis compared to Pacitan and Grindulu. The statistical analysis of rainfall data showed the possibility of classifying the studied regions into the following three distinct characteristic categories:

- Regions with normal and stable distribution patterns characterized by skewness values approaching zero and low kurtosis. This category includes Karang Binangun, Lamongan, Waduk Gondang, and Sembung in Lamongan, Jiwan in Madiun, Sooko and Tegal Ngebel in Ponorogo, as well as Kebunagung in Pacitan. The regions showed predictable rainfall variability with relatively low risk of extreme events.
- Regions exhibiting extreme patterns and requiring heightened attention. This category is characterized by high positive skewness (>1) and positive kurtosis (>2) which shows vulnerability to extremely high-intensity rainfall events. Pacitan and Grindulu in Pacitan

represent primary examples because the statistical characteristics suggest potential hydrometeorological hazards such as floods and landslides.

- Regions with invalid data or anomalies. Several locations including Menganti (Gresik), Bojonegoro, Padangan, Pacal Dam (Bojonegoro), Ngambe, Waduk Sangiran (Ngawi), Jatirogo, Dawuhan, Kedungbrubus (Madiun), Bangunsari, and Slahung (Ponorogo) show abnormal skewness and kurtosis such as >100 or extreme negative values. These statistically unusual values strongly show potential errors in recording, data input, or calculation processes. Therefore, data from the regions are recommended for reverification before being used in further analysis.

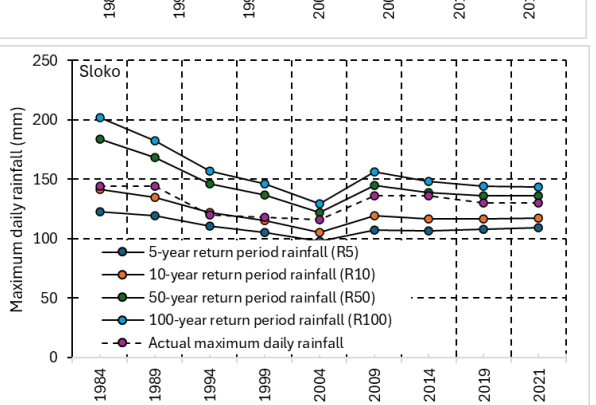
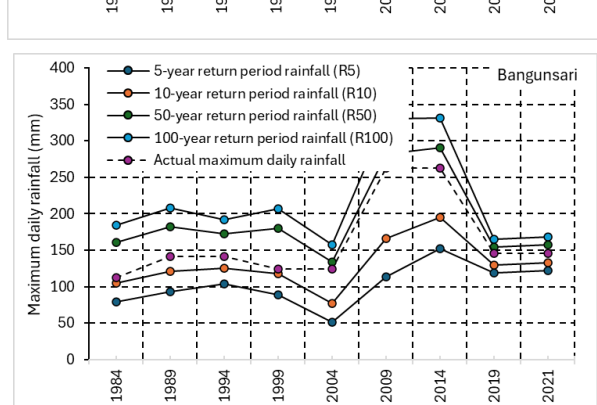
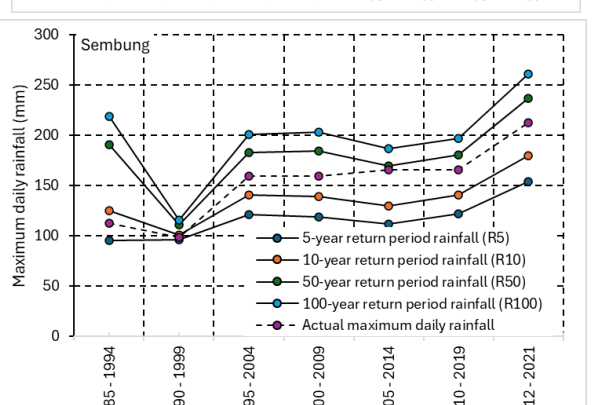
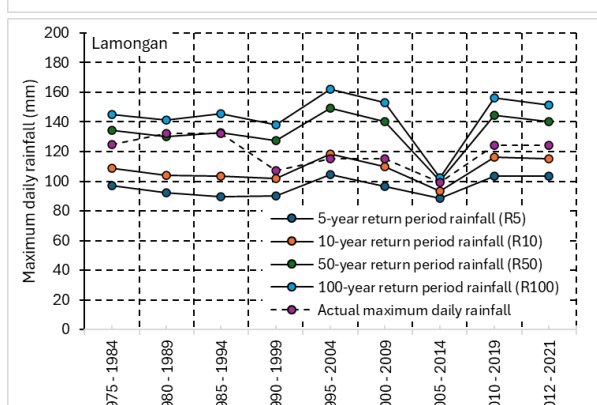
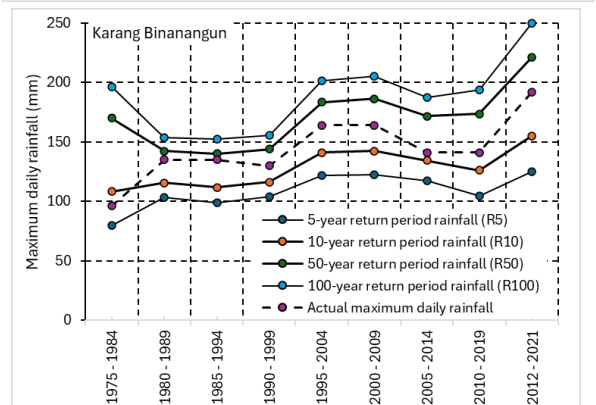
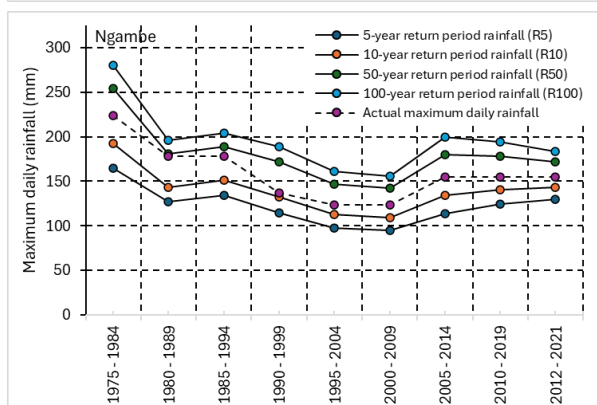
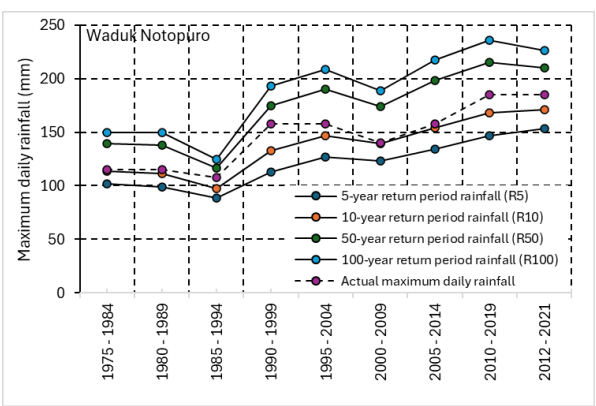
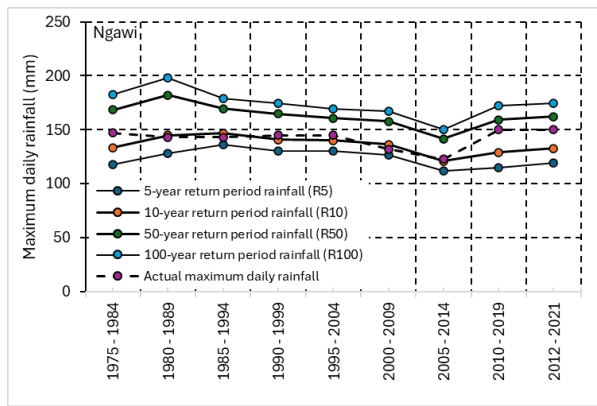
4.3. Prediction of rainfall intensity per 5, 10, 50, and 100 years and actual in the Ngawi, Lamongan, and Ponorogo regions.

This study investigated the increasing trend in rainfall intensity across the regions of Ngawi, Lamongan, and Ponorogo. The analysis focused on both actual maximum rainfall data and predicted intensities for 5-, 10-, 50-, and 100-year return periods. The charts obtained show the rising intensity trend within the reviewed regions using data representative of several rain gauge stations. A recapitulation of the predicted rainfall for the return periods is compiled in Table 1 based on maximum observations from the stations in each city.

The analysis showed that the upward trend was not uniform across the study regions. This was because only a selected number showed a significant rise in predicted rainfall. The detailed recapitulation for the specific stations with a clear increasing trend is presented separately in Table 2. This nuanced result showed the localized nature of changing rainfall patterns and reflected the importance of station-specific analysis.

The spatial variability is evident when comparing individual stations. For example, the data analysis for the Waduk Notopuro station in Figure 7b shows a significant and consistent increase in predicted extreme rainfall intensities across all return periods, specifically after the 1995-2004 period. Meanwhile, the actual maximum rainfall shows a less pronounced but variable upward trend.

The observations from the Stoko station showed a different pattern in the form of a decrease in daily rainfall. The data also presented a more complex picture as observed in a clear increase in the predicted intensity of frequent events for the 5- and 10-year return periods but the trend for more extreme, rare events at 50- and 100-year was less pronounced and had remained stable or even slightly decreased in the most recent periods.



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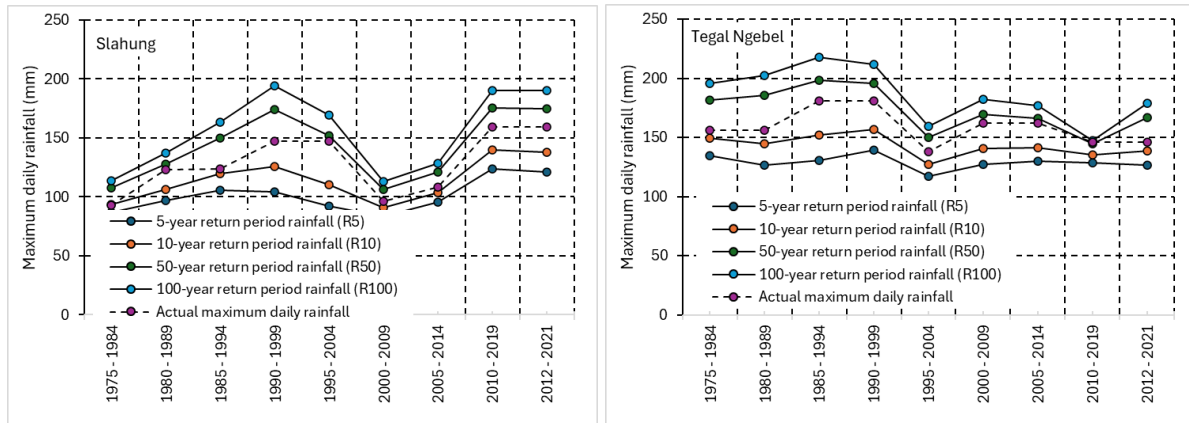


Figure 8. Maximal daily rainfall prediction

The varied results are presented in the graphs (Figure 8) from other rain stations with some showing an increasing trend while others have a decrease. Meanwhile, Table 2 shows that the rainfall trend in Pacitan city significantly increases and reaches more than 400 mm for the 100-year rainfall prediction. This condition is feared to potentially increase hydrological hazards such as floods and landslides in the region based on recent study [35],[36]. Furthermore, Table 3 shows that several other stations also have an increasing rainfall trend such as the Waduk Notopuro, Karang Binangun, Sembung, Bojonegoro, Balungpanggang, and Kedungbrubus.

Table 2. Maximum rainfall prediction in each review city.

Review Area	Actual max rain	5-year predicted max rain	10-year predicted max rain	50-year predicted max rain	100-year predicted max rain
Ngawi	224	165	192	254	280
Lamongan	212	154	180	237	261
Ponorogo	263	152	196	291	332
Bojonegoro	173	128	145	188	206
Gresik	156	103	134	157	206
Madiun	178	133	159	178	220
Pacitan	325	214	277	416	474

The recapitulation of the general results of the highest rainfall prediction analysis is presented in the following table.

Table 3. Increasing rainfall trend

Area study	rainfall station	Note
Ngawi	Ngawi	x
	Ngambe	x
	Waduk Notopuro	v
Lamongan	Karangbinangun	v
	Lamongan	x
	Waduk Gondang	x
	Sembung	v
Ponorogo	Bangunsari	x
	Sloko	x
	Slahung	x
	Tegal Ngebel	x
Bojonegoro	Bojonegoro	V
	Padangan	X
Gresik	Balongpanggung	V
Madiun	Kedungbrubus	V
Pacitan	Pacitan	X
	Kebunagung	X
	Grindulu	V

NOTE:

X = There is no increase in rainfall; the rainfall intensity is relatively the same.

V = There has been a significant increase over the last 10-20 years.

4.4. Slope stability analysis with fluctuations in rainfall intensity

The hydrological analysis was conducted using several key parameters based on historical and predictive data. Daily rainfall events with durations of 3 and 5 hours were analyzed using four intensity scenarios of 156 mm based on data from the Gresik station, 212 mm from the Lamongan station, 325 mm from the Pacitan station, and 416 mm predicted for the 50-year maximum in Pacitan. Furthermore, a 3-month rainy period with high intensity in Pacitan during 2017 was also considered to capture temporal variations in rainfall patterns.

The geotechnical parameters included two soil drainage conditions based on Rahimi's [37] study which were good and poor with the specific data variations provided in the following table. The topographic analysis focused on a cross-section at chainage 51+200 on the left side of the Malang-Surabaya transportation route. The combination of these hydrological and geotechnical parameters enabled a comprehensive evaluation of the response provided by the slope under different hydrological loading scenarios.

Table 4. The unsaturated parameter for 4.4. Slope stability analysis with fluctuations in rainfall intensity

Study Sets		Soil Type								
	Subsets	Good Drainage (GD)				Subsets	Poor Drainage (PD)			
		a	m	n	ks		a	m	n	ks
		(kPa)			(m/s)		(kPa)			(m/s)
A	A1	5	1	1	1E-04	A1	100	1	1	1E-06
	A2	10	1	1	1E-04	A2	500	1	1	1E-06
	A3	20	1	1	1E-04	A3	1000	1	1	1E-06
B	B1	10	0.5	1	1E-04	B1	100	0.5	1	1E-06
	B2	10	1	1	1E-04	B2	100	1	1	1E-06
	B3	10	2	1	1E-04	B3	100	2	1	1E-06
C	C1	10	1	1	1E-04	C1	100	1	1	1E-06
	C2	10	1	2	1E-04	C2	100	1	2	1E-06
	C3	10	1	3	1E-04	C3	100	1	3	1E-06
D	D1	10	1	1	1E-04	D1	100	1	1	1E-06
	D2	10	1	1	5E-05	D2	100	1	1	5E-07
	D3	10	1	1	1E-05	D3	100	1	1	1E-07

The results of the analysis on the changes in the slope SF due to the variations in soil conditions subjected to 90 days of real-time rainfall at different intensities were categorized into different groups. The analyses of the different groups in varying scenarios are presented as follows:

- Poor drainage soil conditions with 3-hour and 6-hour daily rainfall durations based on extreme rainfall data from 1975.
- Poor drainage soil conditions with 3-hour and 6-hour daily rainfall durations based on extreme rainfall data from 2017.
- Good drainage soil conditions with 3-hour and 6-hour daily rainfall durations based on extreme rainfall data from 1975.
- Good drainage soil conditions with 3-hour and 6-hour daily rainfall durations based on extreme rainfall data from 2017.

A summary of the SF changes across all tested variations is presented in Figures 9 to 12. The analysis of rainfall intensity over the 45 years does not show a clear or significant increasing trend that can be directly attributed to global climate change but the SF results reflect a drastic decrease when rainfall intensity increases. This is particularly critical because the region has previously experienced rainfall of light to moderate intensity which shows the potential vulnerability to more extreme events.

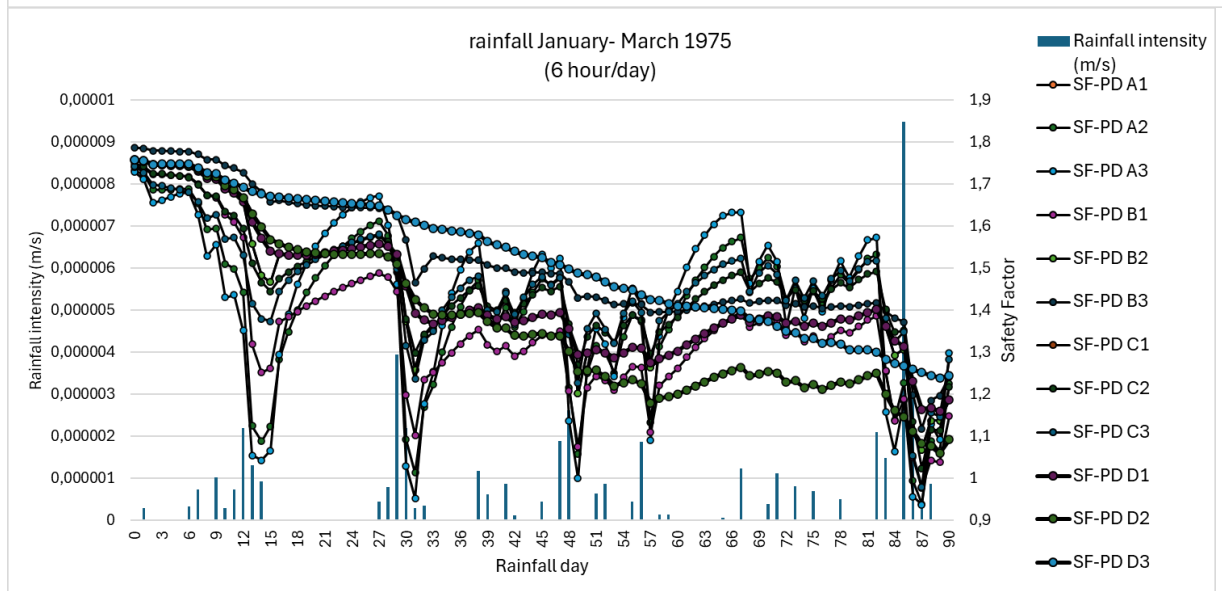
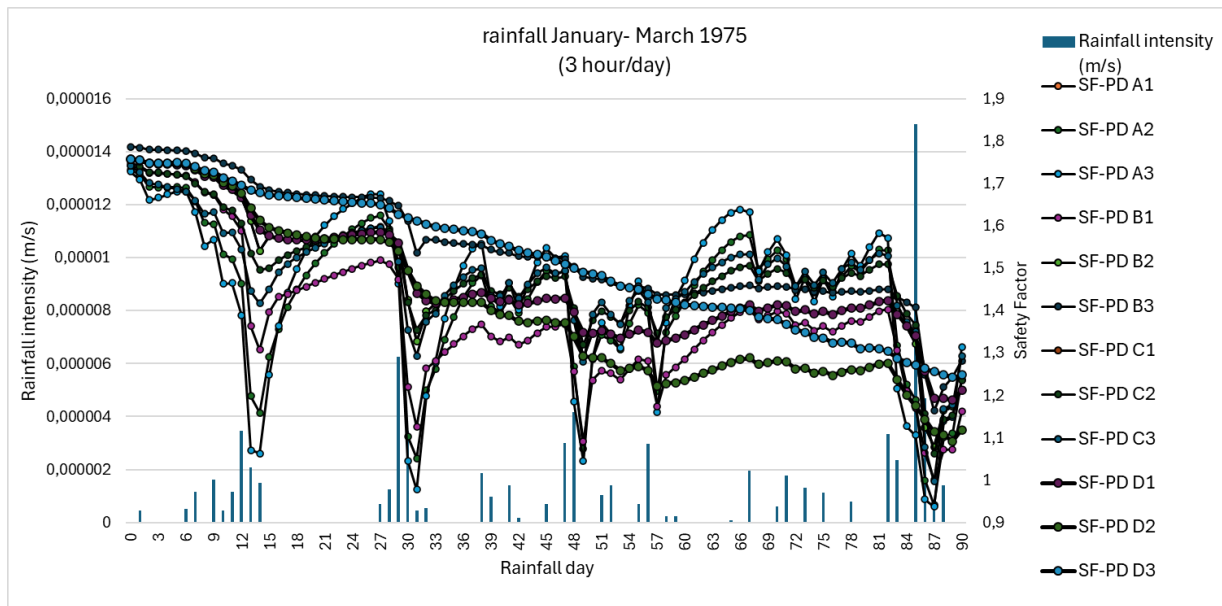


Figure 9. SF values for real-time rainfall intensity in the Pacitan region in 1976 with several variations in poor drainage soil data conditions.

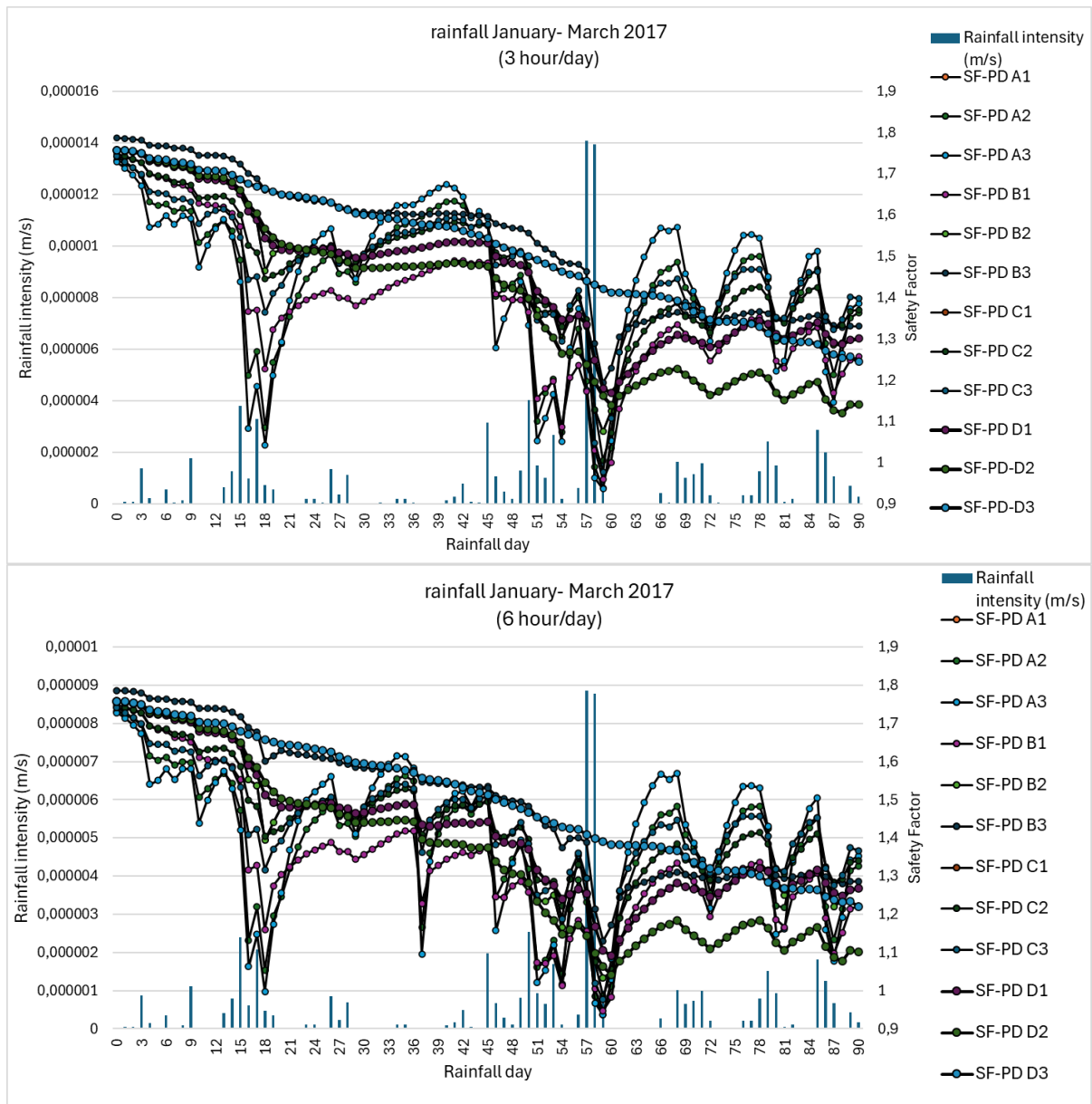


Figure 10. SF values on real-time rainfall intensity in the Pacitan region in 2017 with several variations in poor drainage soil data conditions.

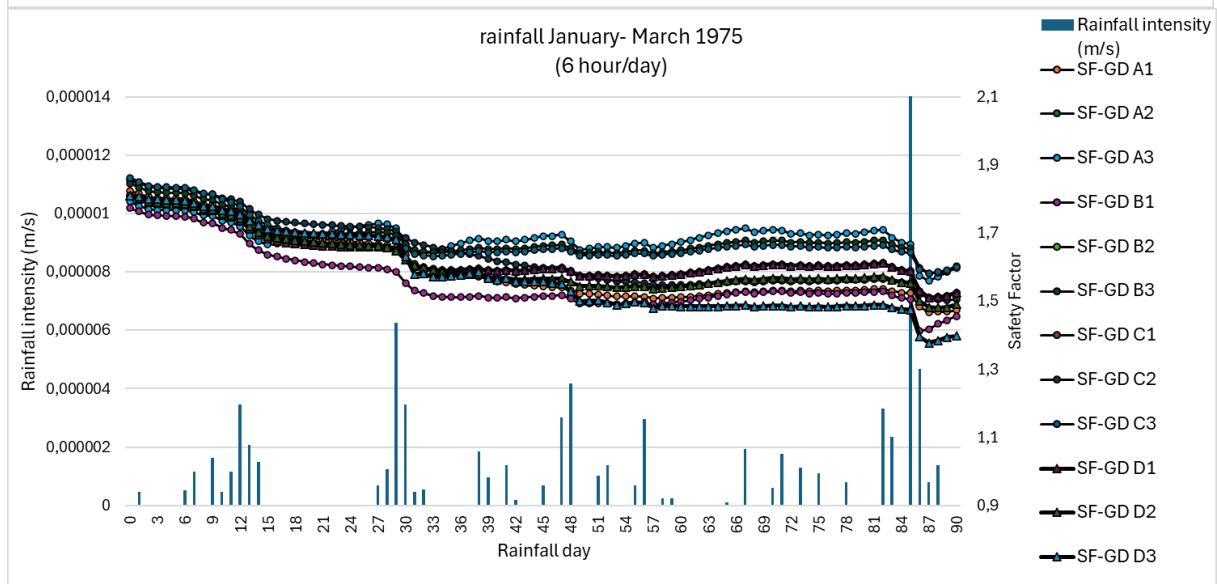
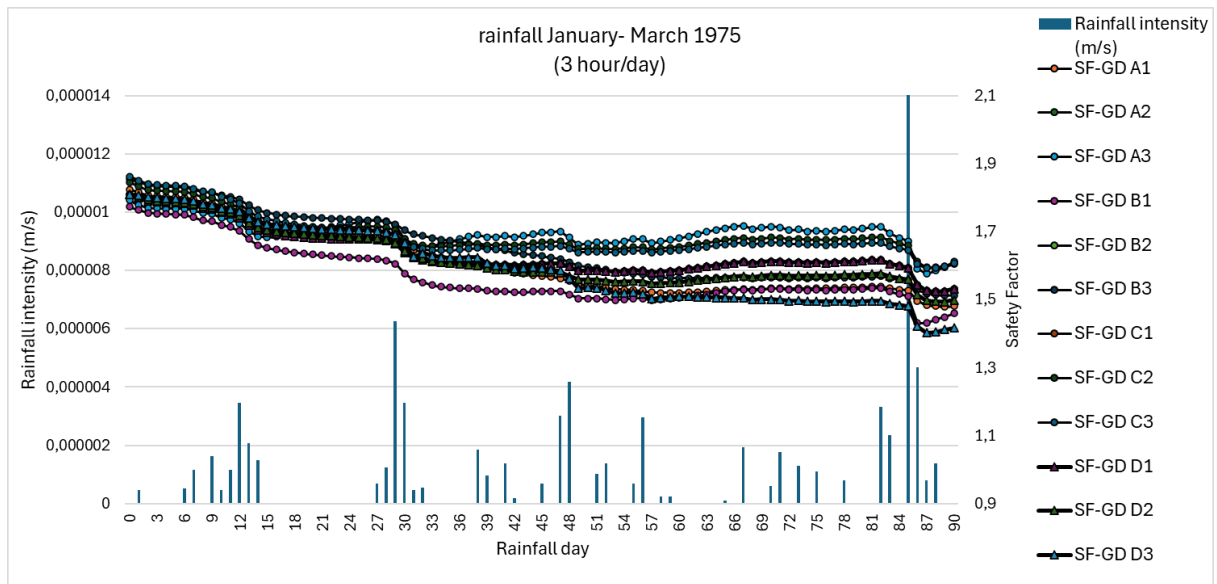
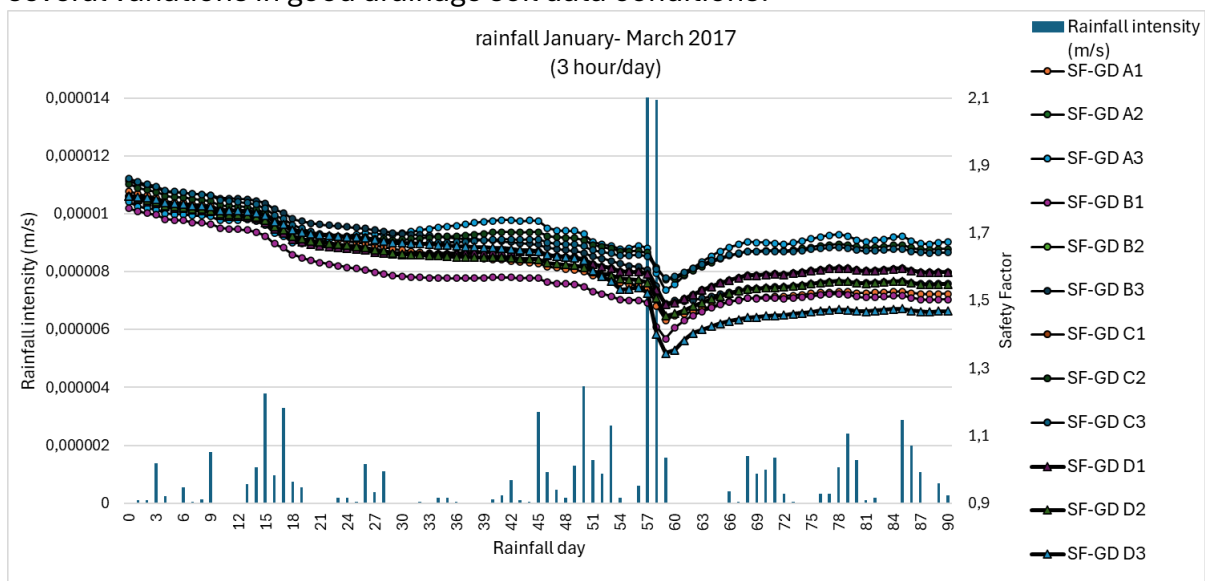


Figure 11. SF values on real-time rainfall intensity in the Pacitan region in 1975 with several variations in good drainage soil data conditions.



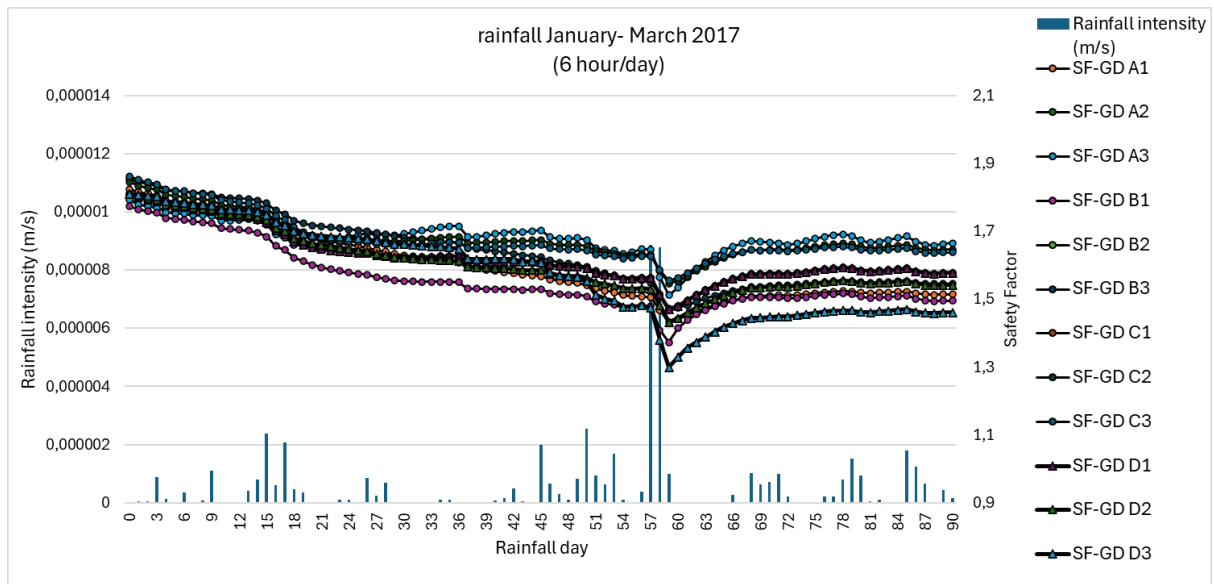
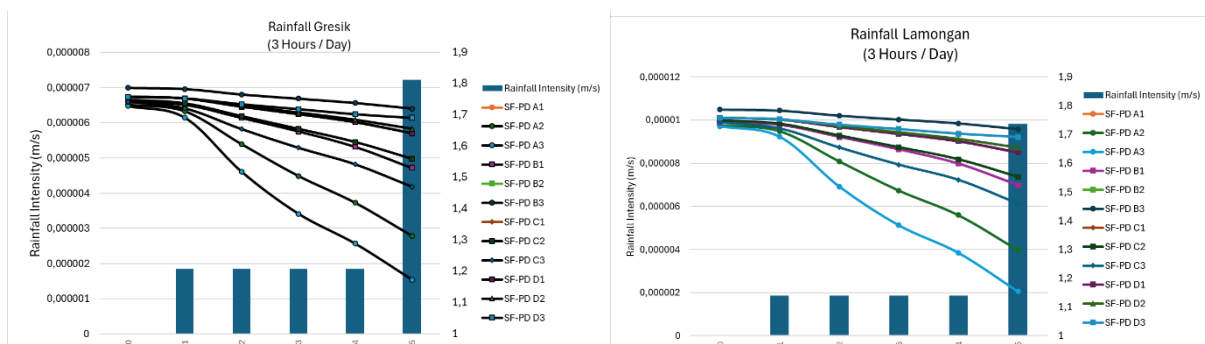


Figure 12. SF values on real-time rainfall intensity in the Pacitan region in 2017 with several variations in good drainage soil data conditions.

The results showed a significant decrease in the SF under poor drainage conditions with periods of relatively extreme rainfall. This led to a follow-up analysis specifically for poor drainage soils to simulate a single-day rainfall event of increased intensity. The analysis was conducted using four rainfall intensity scenarios, each with a duration of 3 hours per day. The subsequent recovery of the SF was not distinctly evident but a single day of high-intensity rainfall was sufficient to critically reduce the stability of the slope as observed in the decline of the values. This behavior was exclusive to poor drainage conditions. Meanwhile, a sudden one-to-two-day increase in rainfall intensity had a negligible impact on the SF under good drainage conditions. These results provide a clear explanation for the frequent landslides observed in the study regions and the surroundings during extreme rainfall events. This research is inline with the recent study [38],[39].



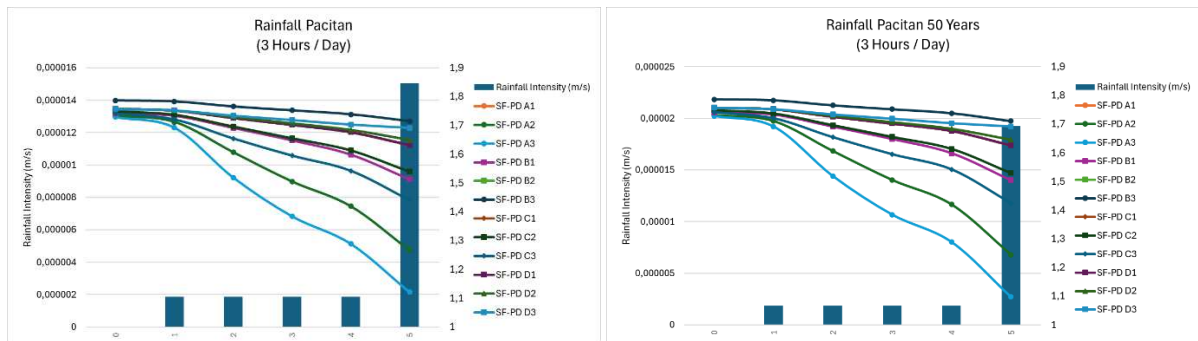


Figure 13. Results of analysis of four intensity scenarios: 156 mm based on Gresik station, 212 mm from Lamongan station, 325 mm from Pacitan station, and 416 mm predicted for 50-year maximum rainfall in Pacitan with rain for 3 hours/day.

The analyses collectively showed that the reduction of the SF factor due to rainfall was highly dependent on the drainage characteristics of the soils. Poor drainage increased the sensitivity of the soils to rainfall and led to lower SF values compared to good drainage. This sensitivity was directly governed by the ratio between the hydraulic conductivity of the soil (K_s) and the rainfall intensity. Poorly drained soil with a K_s of 10^{-6} m/s considered lower than the extreme rainfall intensity (3×10^{-5} m/s) promoted surface ponding that weakened the soil matrix. Meanwhile, well-drained soil with a K_s of 10^{-4} m/s facilitated rapid drainage of rainwater. The practical impact of this drainage capacity was evident during heavy rainfall events. On a slope with poorly drained soil, very high-intensity rainfall on days 55-56 caused a drastic decrease in the SF from 1.6 to below 1.00 which was a reflection of instability. A more extreme decrease was observed in specific soil types within the poor drainage category where Types A and B experienced a steeper decline from SF 1.4 to 0.9 compared to Types C and D from 1.6 to 1.2. The minimum SF value of 0.978 was recorded for Type A3. However, the SF reduction was less severe and the values remained stable within a safe range of 1.5 to 1.8 under good drainage conditions. The trend showed that both short-duration extreme and prolonged rainfall over five days comprising four of moderate and one of extreme intensity reduced the SF. The magnitude of the reduction varied according to soil type and this emphasized soil drainage characteristics as a key factor in assessing slope stability during and after rainfall events. The results established that inadequate drainage systems significantly increased the vulnerability of a slope to rainfall-induced failure.

5. Conclusion

In conclusion, this study comprehensively showed the critical relationship between climate-altered rainfall patterns and slope stability in a tropical setting. The following inferences were made through the series of analyses conducted:

1. Localized Rainfall Trend: Statistical analysis of 45 years of data confirmed that the impact of climate change on rainfall was not uniform. Some regions such as Pacitan showed a significant and worrying increase in extreme rainfall predictions of 416 mm for a 50-year return period while others exhibited stable or even decreasing trend. This emphasized the necessity for localized, station-specific risk assessments.

2. Drainage as the Decisive Factor: The geotechnical numerical modeling unequivocally identified soil drainage conditions as the most significant factor governing slope stability. The ratio of hydraulic conductivity (K_s) to rainfall intensity directly controlled the hydrological response. Poorly drained soils ($K_s = 10^{-6}$ m/s) were highly vulnerable to experiencing severe and rapid reductions in SF during high-intensity rainfall which potentially led to failure.
3. Mechanism of Failure: Intense rainfall under poor drainage caused surface ponding and a sharp rise in pore-water pressure which led to a drastic loss of shear strength. Specific soil types within the poor drainage category such as A and B showed a more extreme decline in SF from 1.4 to 0.9 compared to others.
4. Resilience of Good Drainage: Slopes with good drainage ($K_s = 10^{-4}$ m/s) effectively managed rainwater infiltration by maintaining SF within a stable and safe range of 1.5–1.8 despite variations in rainfall intensity and duration.
5. Implication for Hazard Mitigation: The frequent landslides in the study regions during extreme rain were directly explained by the prevalence of poor drainage conditions. Therefore, the primary mitigation strategy should focus on improving subsurface drainage. This study provided a quantitative framework for predicting slope failure and prioritized regions such as Pacitan for immediate intervention as a contribution to the essential knowledge for climate-resilient infrastructure planning in tropical regions.

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Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Putu Tantri Kumala Sari is a Lecturer and researcher at Department of Civil Engineering, Institut Teknologi Sepuluh Nopember (ITS) Surabaya Indonesia. She completed her Doctoral degree at ITS. Her research focuses on disaster risk reduction, particularly landslide mitigation, integrating geotechnical engineering approaches with community-based preparedness strategies. She has actively engaged in joint research projects with several institutions outside Indonesia, focusing on slope stability analysis, and post-landslide recovery. Her international collaborations emphasize cross-country knowledge exchange and the application of low-cost, locally adaptive technologies for landslide-prone areas. She can be contacted at tantri@ce.its.ac.id.