
**MODELING OF DAILY RAINFALL DYNAMICS IN MANADO CITY
NORTH SULAWESI**

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ABSTRACT

This study aims to analyze and model the daily rainfall dynamics in Manado City, North Sulawesi, during the period of January to March 2026. An in-depth understanding of daily-scale rainfall variability is crucial for mitigating hydrometeorological disasters in vulnerable urban areas like Manado. The research methods employed encompass descriptive statistical analysis and time series modeling, utilizing trendlines and forecasting based on daily empirical data. The results indicate that February 2026 was the period of the highest and most consistent rainfall intensity, recording an average of 4.756 mm/day and a median of 1.5 mm. Conversely, March 2026 registered the lowest average intensity at 2.903 mm/day with a median of 0 mm, yet it exhibited the most extreme atmospheric uncertainty, characterized by the highest coefficient of variation reaching 193.07%. From a physical perspective, these fluctuations are driven by complex interactions among regional sea surface temperatures, monsoonal wind flows, and local orographic factors that trigger convective energy release. Identified environmental impacts include a high risk of soil saturation in February, which accelerates surface runoff, alongside the potential for sudden flash floods in March resulting

from sporadic precipitation spikes of up to 22.60 mm during otherwise dry periods. Despite technical limitations involving data gaps on specific dates, such as March 6, 2026, this modeling continues to provide a robust characterization of local atmospheric behavior. This study concludes that flood management strategies in Manado City must transition from a reliance on monthly averages to the rigorous monitoring of extreme daily values to establish a more precise and adaptive early warning system.

INTRODUCTION

Rainfall phenomena represent crucial variables in environmental physics and hydrology studies, particularly within the Indonesian Maritime Continent, which exhibits highly complex ocean-atmosphere interactions (Pujiastuti & Nurjani, 2018; Stephanie et al., 2019). The rainfall dynamics in this region are influenced by multiscale phenomena, ranging from global drivers such as the El Niño-Southern Oscillation and the Indian Ocean Dipole to regional occurrences like the Madden-Julian Oscillation (Bakri et al., 2021; Lestari et al., 2016). Specifically, North Sulawesi is situated in a transitional zone significantly influenced by the monsoon wind system, resulting in highly dynamic temporal variability in rainfall distribution between the dry and wet seasons (Pujiastuti & Nurjani, 2018).

Manado City, as the epicenter of economic growth in North Sulawesi, faces profound challenges regarding weather anomalies and shifting precipitation patterns. Recent studies indicate an upward trend in the mean annual rainfall alongside an increase in the maximum daily precipitation intensity in this region over the past few decades (Wallah et al., 2025). The city's topographical characteristics, directly bordering coastal areas, coupled with the presence of the Tondano Watershed, render Manado highly vulnerable to hydrometeorological disasters (Mananoma et al., 2024). Data indicate that maximum daily rainfall in Manado can reach extreme thresholds of 240 mm/day to 520 mm/day for return periods of 10 to 50 years, which physically exceeds the current capacity of the urban drainage system (Tahmid, 2020).

A primary constraint in environmental risk management within this region is the lack of precise daily rainfall prediction models. Most available data are on a monthly scale, whereas disastrous events such as flash floods are frequently triggered by daily rainfall anomalies characterized by short durations but high intensities (Robertson et al., 2008; Supriyadi, 2024). Efforts to generate daily data from monthly records via stochastic approaches are continuously being developed to overcome the limitations of continuous field observations (Supriyadi, 2024). Various methodologies, such as the Autoregressive Moving Average, have

been implemented in Manado; however, they frequently encounter difficulties in capturing the non-linear fluctuations associated with extreme weather events (Pakkung et al., 2024; Stephanie et al., 2019).

Uncertainties in daily rainfall estimations pose significant risks for infrastructure planning and flood early warning systems (Fitrianto et al., 2022; Wallah et al., 2025). To date, the integration of statistical modeling with local atmospheric physical characteristics in Manado requires more in-depth study to enhance the accuracy of daily predictions (Pakkung et al., 2024). Therefore, this study aims to model the daily rainfall dynamics in Manado City utilizing a more comprehensive approach. By fostering a deeper understanding of distribution patterns and the probability of extreme precipitation events, this research is anticipated to provide theoretical contributions to environmental physics and practical insights for disaster mitigation in North Sulawesi.

METHODS

This study employs a quantitative research design utilizing a modeling approach aimed at developing a model of daily rainfall dynamics in Manado City, North Sulawesi, based on historical meteorological observation data. The research was conducted within the administrative boundaries of Manado City, geographically situated on the northern coast of Sulawesi Island. The region is characterized by a tropical maritime climate exhibiting high rainfall variability, driven by ocean-atmosphere interactions and local topographical conditions. The secondary data utilized in this study consist of daily rainfall records obtained from the North Sulawesi Province Meteorology, Climatology, and Geophysical Agency (BMKG) via the BMKG Data Online system (<https://dataonline.bmkg.go.id>). The analyzed data comprise daily rainfall observations from meteorological stations, selected for specific observation periods based on data completeness and continuity.

Data collection was executed through documentation techniques by downloading the daily rainfall data from the official BMKG database. Subsequently, a verification process was conducted to ensure data consistency, completeness, and overall quality prior to analysis. The research phases commenced with a literature review to identify advancements in studies related to climate change, tropical precipitation dynamics, and extreme rainfall events in North Sulawesi. This was followed by data collection and preprocessing, which involved examining missing values, identifying outliers, correcting recording errors, and compiling the database into a tabular format.

Following data preparation, a descriptive statistical analysis was performed to determine the general characteristics of daily rainfall by calculating the mean, median, maximum, minimum, range, standard deviation, and coefficient of variation. To identify changing patterns in rainfall over time, a time series analysis was conducted using temporal graphs and trend analysis based on linear regression. The variability of daily rainfall was analyzed by observing temporal fluctuation patterns, the frequency of precipitation events, and the distribution of daily rainfall intensity throughout the observation period.

The modeling of daily rainfall dynamics employed a time series approach, utilizing moving average and trend regression methods to illustrate precipitation trends and identify evolving precipitation patterns over time. All data processing and analyses were performed using Microsoft Excel software. The modeling results were then descriptively evaluated to interpret the characteristics of daily rainfall dynamics in Manado City and correlate them with regional climate variability phenomena influencing precipitation formation in North Sulawesi. Through this approach, the research aims to generate a scientific representation of daily rainfall dynamic patterns, which can serve as a foundational basis for hydrometeorological risk assessments and climate-based disaster mitigation planning in Manado City.

RESULTS AND DISCUSSION

General Description of the Study Area and Research Data

Manado City is the capital of North Sulawesi Province, located in the northern part of Sulawesi Island, geographically situated within the coordinates of 1°29'–1°39' N and 124°40'–124°50' E. This area covers approximately 157 km² with diverse landscape characteristics, ranging from coastal areas directly bordering the Celebes Sea to hilly regions and undulating plains in the southern and eastern parts of the city. These geographical conditions place Manado City in an atmospheric environment heavily influenced by interactions between oceanic and topographical factors, resulting in relatively high rainfall variability throughout the year. As a region situated within a tropical maritime climate system, the precipitation pattern in Manado City is influenced not only by the Asia-Australia monsoon circulation but also by global climate phenomena such as the El Niño–Southern Oscillation (ENSO), the Southern Oscillation Index (SOI), and the Indian Ocean Dipole (IOD), which can modify both the spatial and temporal distribution of rainfall in the North Sulawesi region.

Climatologically, Manado City is classified as a region with relatively high annual rainfall, where precipitation events tend to be distributed throughout the year. This condition is driven

by the presence of warm waters surrounding the Celebes Sea and the Molucca Sea, which serve as the primary sources of water vapor for convective cloud formation. Furthermore, the orographic uplift effect caused by the hills and mountains surrounding the Manado area additionally increases the probability of moderate to high-intensity rainfall events. These characteristics render Manado City one of the regions vulnerable to extreme hydrometeorological events, particularly urban flooding triggered by high-intensity, short-duration rainfall or high daily rainfall accumulations.

The data utilized in this study consist of daily rainfall records derived from meteorological observations obtained from the Meteorology, Climatology, and Geophysical Agency (BMKG) via the BMKG Data Online system. These data represent the daily precipitation conditions in the Manado City area during a specified observation period, determined based on data availability and continuity. Prior to analysis, all data underwent a quality control process encompassing the identification of missing values, the examination of recording consistency, and the verification of measurement unit congruity to ensure the validity of the subsequent analytical results.

The characteristics of the daily rainfall data utilized in this study demonstrate a fluctuating nature with high intensity variations over time. This variability is a common characteristic of tropical precipitation systems influenced by both local and regional atmospheric dynamics. Therefore, a time series analysis approach was selected to identify rainfall change patterns, temporal trend tendencies, and daily precipitation dynamics developing over the observation period. Through this analysis, it is anticipated that a more comprehensive understanding of the rainfall characteristics in Manado City will be achieved, serving as a foundation for developing daily rainfall dynamic models and evaluating hydrometeorological risks in tropical coastal urban areas.

The general description of the study area and the characteristics of the research data form an essential foundation for interpreting the modeling results discussed in the subsequent section. An understanding of the geographical and climatological conditions, along with the observation data characteristics, enables the identification of relationships between daily rainfall variability and the atmospheric driving factors influencing the regional climate system in North Sulawesi. Consequently, the research findings obtained not only depict statistical rainfall patterns but also provide a physical explanation for the precipitation dynamics occurring in Manado City.

Descriptive Statistical Analysis

Table 1. Results of Descriptive Statistical Analysis of Daily Rainfall. (January–March 2026)

Month	Number of Data	Mean	Median	Maximum	Minimum	Data Range	Standard Deviation	Coefficient of Variation (%)
January 2026	31	4.355	0	27.30	0	27.3	7.995	183.60
February 2026	28	4.756	1.5	22.50	0	22.5	6.165	129.63
March 2026	30	2.903	0	22.60	0	22.6	5.606	193.07

Based on Table 1, the characteristics of daily rainfall in Manado City during the period from January to March 2026 indicate a high degree of variability. Generally, the mean daily rainfall experienced monthly fluctuations, with the highest mean occurring in February 2026 at 4.756 mm/day, followed by January 2026 at 4.355 mm/day, while the lowest mean was recorded in March 2026 at 2.903 mm/day. These results indicate that rainfall intensity tended to decrease towards the end of the observation period.

The median values of daily rainfall exhibit a different pattern compared to the means. In January and March 2026, the median was 0 mm, whereas in February 2026, it was 1.5 mm. Median values that are lower than the means signify that most days during the observation period experienced low rainfall or no precipitation at all, while a few high-intensity rainfall events caused an elevation in the mean values. This condition indicates a positively skewed data distribution, which is a common characteristic of daily rainfall data in tropical regions.

The maximum rainfall recorded during the study period occurred in January 2026 with a value of 27.30 mm, while February and March reached 22.50 mm and 22.60 mm, respectively. Meanwhile, the minimum value for all months was 0 mm, indicating the presence of days without rain during the observation period. The magnitude of the data range, which spans from 22.5 to 27.3 mm, demonstrates a relatively significant discrepancy between the minimum and maximum rainfall conditions within a single month.

The variability of daily rainfall data can also be observed through the standard deviation values. January 2026 possessed the highest standard deviation at 7.995 mm, followed by February at 6.165 mm and March at 5.606 mm. Standard deviation values that are relatively large compared to the means imply that daily rainfall has a high degree of data dispersion and

fluctuates significantly from day to day. Consequently, although the mean daily rainfall is classified as low, higher-intensity rainfall events still frequently occur at certain times.

The level of data variance is further elucidated by the coefficient of variation (CV) values, all of which exceed 100%. The highest coefficient of variation occurred in March 2026 at 193.07%, followed by January at 183.60% and February at 129.63%. According to statistical criteria, a coefficient of variation value above 100% signifies a very high degree of heterogeneity; therefore, the daily rainfall distribution during the study period can be categorized as highly variable. The high coefficient of variation values indicate that the daily rainfall pattern in Manado City during January–March 2026 was unstable and heavily influenced by strong atmospheric fluctuations.

Overall, the descriptive statistical results suggest that the primary characteristics of daily rainfall in Manado City during the January–March 2026 period include an asymmetrical distribution, a dominance of days with low or no rainfall, and the presence of relatively high-intensity rainfall events that result in massive data variability. These characteristics confirm that daily rainfall dynamics in Manado City are fluctuating and complex, thus necessitating a time series modeling approach capable of more representatively capturing temporal changes and precipitation variability.

Rainfall Analysis

1. Rainfall Analysis for January 2026

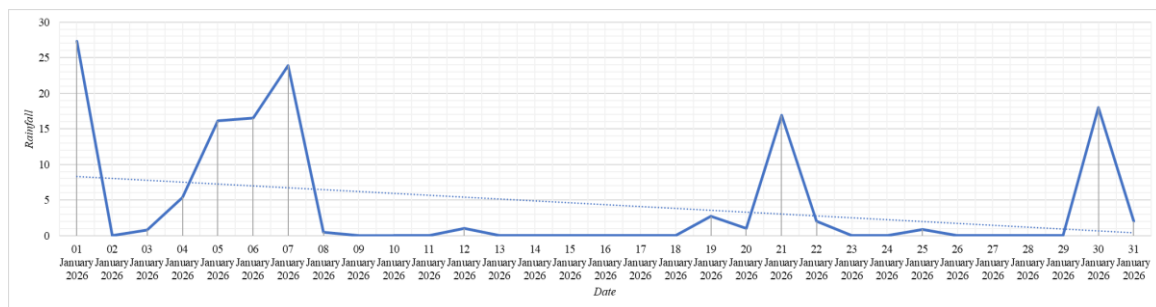


Figure 1. Forecast and Trend Analysis of Rainfall in January 2026.

The data represented in Figure 1 regarding the estimated model output (forecast) and rainfall trendline in Manado City for the January 2026 period provides the following in-depth descriptive analysis from an environmental physics perspective: The visualization of daily rainfall dynamics in January 2026 reflects highly complex and stochastic tropical atmospheric behavior. This pattern indicates that the rainfall distribution in the Manado region does not occur gradually but is rather dominated by massive releases of convective

energy over short durations. This characteristic is highly typical of coastal areas influenced by strong monsoon circulations, where the interaction among land, sea, and atmosphere creates sharp intensity fluctuations.

Specifically, the initial phase of January 2026 marks the period with the most prominent hydrometeorological activity. The highest intensity peak was recorded exactly on January 1, reaching 27.5 mm/day. This sharp surge indicates saturated water vapor in the atmosphere at the beginning of the year, which physically has the potential to trigger rapid surface runoff if not balanced by an adequate soil infiltration system. A second significant fluctuation emerged shortly after, on January 7, with a high intensity of 24 mm/day.

A particularly interesting phenomenon to examine from a physical standpoint is the emergence of a fairly persistent dry spell in the middle of the month. Observed from January 8 to 18, 2026, rainfall intensity dropped drastically, touching a baseline close to zero. During these approximately eleven days, the Manado region was predicted to experience a significant pause in precipitation. From an atmospheric physics perspective, this condition indicates a disruption or obstacle in the flow of moist air masses, resulting in a temporary decline in convective cloud growth activity despite occurring during the wet season.

Following this dry phase, the graph again shows an increase in rainfall activity in the third decade of January, with moderate peaks occurring on January 21 (~17 mm/day) and January 30 (~18 mm/day). Although fluctuating once more, the intensities no longer reached the extreme levels seen at the beginning of the month.

The linear trendline analysis provides an overview of weather development throughout the month. The trendline exhibits a consistent negative slope, starting from a predicted average of approximately 8 mm in early January and gradually decreasing to reach a nadir of about 1 mm at the end of the month. Statistically, this downward trend signals that the probability of high-accumulation rainfall events in Manado tended to decay over time throughout January 2026.

In conclusion, although the trendline indicates a downward tendency, physical environmental risks remain anchored in the daily variability demonstrated by sharp surges early in the month. The intensity peaks between 24 and 27.5 mm/day represent critical parameters that must be monitored in flash flood disaster risk management, considering Manado's topographical characteristics, which are vulnerable to overflows from the Watershed. This explanation emphasizes that monthly averages are insufficient to depict actual threats; rather, daily dynamics determine the stability of the region's hydrological ecosystem.

2. Rainfall Analysis for February 2026

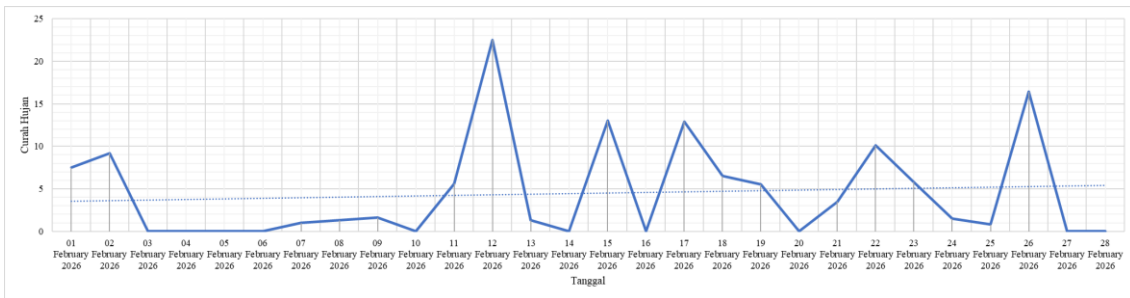


Figure 2. Forecast and Trend Analysis of Rainfall in February 2026.

Climatologically, as illustrated in Figure 2, February 2026 represents a crucial period where Manado City reached its peak hydrometeorological activity compared to January and March. Descriptive statistical data reveal that this month recorded the highest average daily rainfall at 4.756 mm/day. Physically, this figure indicates that the supply of moisture and latent energy in the atmosphere was at a highly active level. What distinguishes February from the other months is its median value, which reached 1.5 mm. Compared to January and March, which have a median of 0 mm, this value indicates that in February, rainfall events occurred more frequently and evenly throughout the day, rather than merely as brief surges at specific times. Examining the trendline visualization reveals that while daily intensities fluctuated, the general trend indicates a notably high stability of water accumulation from the beginning to the middle of the month. Although the recorded maximum value was 22.50 mm—slightly lower than January's peak of 27.30 mm—the data variability in February tended to be more "regular," with a coefficient of variation of 129.63%. In environmental physics, this value reflects high heterogeneity yet simultaneously demonstrates that rainfall distribution was more temporally dispersed. Physically, this imposes a sustained hydrological burden on the urban drainage system in Manado.

An essential point to note in interpreting this graph is the data discontinuity on February 5, 8, and 23, 2026. Because the North Sulawesi BMKG did not conduct measurements on these dates, there are information "gaps" in the time series. Technically, the resulting trendline performs mathematical interpolation to bridge these voids. As researchers, we view these dates as uncertainty variables; it is entirely possible that higher peaks of convective energy occurred on these days but were not empirically recorded. Consequently, the forecast model for this period must be interpreted with heightened caution.

The daily fluctuation pattern depicted by the forecast graph illustrates the dynamic interaction between monsoon winds and sea surface warming around North Sulawesi. With a standard

deviation of 6.165 mm, the data distribution indicates that extreme rainfall surges remain a tangible threat despite the seemingly low average. Every ascent on the graph symbolizes the process of heat release into the atmosphere, which strengthens local circulation, whereas sharp declines following peaks indicate a phase of atmospheric pressure stabilization.

In conclusion, the rainfall phenomenon in Manado during February 2026 is characterized by the most consistent intensity within the first quarter of the year. The presence of missing data on February 5, 8, and 23 serves as a limitation for high-precision analysis; nevertheless, the existing trend provides a strong signal that the region was in a water-saturated state. Understanding these figures is vital for determining flood risk thresholds, where higher rainfall frequency (reflected by the 1.5 mm median) can lead to faster soil saturation compared to other months.

3. Rainfall Analysis for March 2026

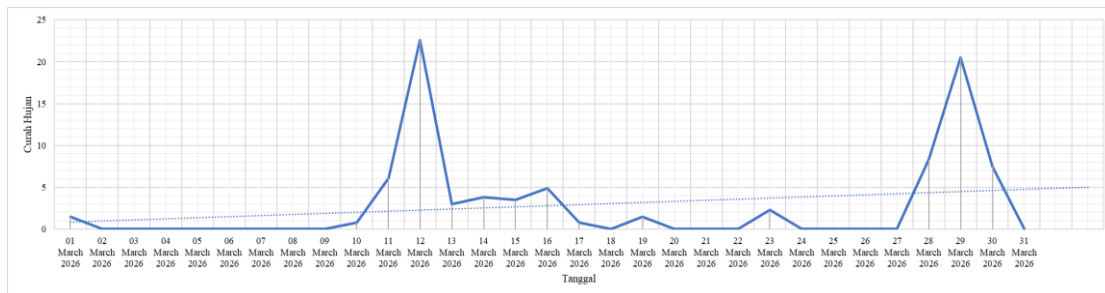


Figure 3. Forecast and Trend Analysis of Rainfall in March 2026.

Physically, March represents a fascinating transitional phase in North Sulawesi's atmosphere, where the climate system begins to shift from the peak of the wet season toward more stable conditions, yet continues to harbor high convective energy. Empirical data shows that the average daily rainfall for this month was recorded at 2.903 mm per day. Compared to February, this indicates a significant decrease in water mass accumulation in the troposphere. This decline is physically associated with the weakening of monsoonal air mass thrust and changes in solar radiation distribution, which influence evaporation on the sea surface surrounding Manado.

The most crucial phenomenon requiring physical dissection is the median value, which touches 0 mm—an indicator that sharply contrasts with the maximum intensity reaching 22.60 mm. In environmental physics, this zero median informs us that, statistically, the vast majority of days in March 2026 were actually rainless, or the rainfall that did occur had such an insignificant volume that it was not detected as notable precipitation. However, the presence of a substantially large maximum value indicates that the mechanism of latent

energy release via the condensation process still occurred sporadically and intensely. This condition reflects a "spiky" atmospheric character, filled with sudden surges; meaning that although the weather tended to be dry for extended periods, the potential for short-term heavy rainfall remained a real physical threat to surface hydrological stability.

The level of atmospheric uncertainty in March 2026 is clearly reflected in the coefficient of variation, which reached 193.07%—the highest value in the first quarter of the year. From a physics perspective, this high variability, supported by a standard deviation of 5.606 mm, demonstrates that the environmental system was in a state of extreme heterogeneity. This implies that fluctuations between dry days and heavy rainfall events were highly irregular, causing the trendline to fluctuate heavily and struggle to form a stable linear pattern. This irregularity is a manifestation of complex interactions between local factors, such as land-sea breezes and mountainous topography, with regional factors, resulting in precipitation predictions for this month possessing a higher degree of entropy or chaos compared to preceding months.

In this modeling process, the record indicating a lack of measurements by the North Sulawesi BMKG on March 6, 2026, serves as a critical limiting variable for the accuracy of this scientific description. Technically, the loss of data at a single point in time within a continuous dataset causes a discontinuity in the physical analysis. The trendline observed in the figure is compelled to perform mathematical interpolation or point connection to fill the void on the 6th. As physicists, we perceive this as an "information gap" where atmospheric phenomena that may have occurred—whether extreme rainfall peaks or exceptionally dry conditions—were not empirically recorded. Therefore, interpretations of daily dynamics around that date must be conducted cautiously, as the model lacks a direct observational basis for that specific day.

Overall, the analysis of the forecast graph and trendline for March 2026 illustrates an environmental system moving toward a new equilibrium point while still harboring the potential for hydrometeorological disturbances. The decline in average rainfall to 2.903 mm must not cause us to overlook the fact that data variability is extremely high, meaning the risk of disasters such as local flash floods persists due to sudden precipitation peaks. An in-depth understanding of these figures is vital in environmental risk management in Manado City, as it provides a scientific basis for early warning systems that, even if rainfall frequency decreases (as indicated by the zero median), the physical intensity of a single rainfall event can severely overburden soil infiltration capacity and existing urban drainage systems.

Comparison of Rainfall in January, February, and March 2026

Rainfall fluctuations in Manado City from January to March 2026 serve as a tangible manifestation of energy and mass transfer dynamics in the tropical atmosphere. In January, the environmental system began to exhibit convective activity with an average rainfall of 3.435 mm per day and a maximum peak reaching 27.30 mm, although the frequency was still relatively intermittent with a median of 0 mm. Entering February, there was an escalation in intensity, where the average rainfall significantly increased to 4.756 mm per day. The physically crucial point in February was the shift in the median value to 1.5 mm, signifying that rain occurred much more frequently and consistently compared to the other months. However, in March, the atmospheric system exhibited a transitional phase with the average dropping to 2.903 mm, yet possessing the highest level of uncertainty or coefficient of variation at 193.07%, reflecting a highly heterogeneous and unpredictable atmospheric condition.

The physical factors underlying these changes are closely related to regional atmospheric thermodynamic mechanisms, where sea surface warming around the North Sulawesi waters triggers intensive evaporation, providing water vapor as the primary fuel for the hydrological cycle. In February, the high rainfall frequency (median 1.5 mm) was caused by air mass convergence and sustained latent heat release, creating stable convection cells over the Manado region. Meanwhile, in March, despite the declining average, the sharp fluctuations with a standard deviation of 5.606 mm indicate mesoscale disturbances causing convective energy to be released suddenly in the form of short-duration heavy rains. The interaction between monsoon winds and the hilly topography surrounding Manado strengthens the orographic process, where air masses are forced upwards, cool, and condense into raindrops with extremely varying intensities each month.

The environmental impacts of these physical dynamics are highly significant, particularly concerning soil infiltration capacity and urban drainage systems. The conditions in February pose the highest risk from a hydrological standpoint; with continuous high rainfall frequency, the soil reaches water saturation more rapidly, thereby reducing infiltration capability and increasing surface runoff volume, which triggers inundation flooding. On the other hand, the characteristics of March, which possess extremely high variability (CV 193.07%), present a threat in the form of sudden flash floods. Despite its lower average, the maximum rainfall peak remains high (22.60 mm) during the March period, which can inflict shock loads on unprepared drainage systems. Therefore, understanding these physical rainfall profiles is vital for disaster management and spatial planning in Manado to anticipate environmental

degradation and infrastructure damage caused by these extreme shifts in precipitation patterns.

CONCLUSION

This study concludes that rainfall patterns in Manado City from January to March 2026 were highly variable, with February emerging as the most vulnerable period due to more frequent and evenly distributed precipitation (averaging 4.756 mm/day with a median of 1.5 mm). Conversely, March recorded a lower precipitation volume (averaging 2.903 mm/day), yet it proved to be the most unpredictable due to the frequent occurrence of sudden heavy downpours amidst dry conditions. From a physical perspective, these phenomena are driven by warm sea surface temperatures and wind currents transporting substantial amounts of water vapor to the Manado mainland. Consequently, the high rainfall frequency in February resulted in rapid soil saturation, thereby diminishing its water infiltration capacity, while sudden precipitation spikes in March posed a significant risk of overwhelming the city's drainage capacity. Therefore, flood prevention strategies in Manado City must not rely solely on monthly average data; rather, they require strict vigilance and proactive measures against extreme and erratic daily rainfall fluctuations.

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