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Long-Term Rainfall Variability and Seasonal Shifts in Relation to Pranatamangsa in the Rongkop Karst Region, Indonesia

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Pranatamangsa

ABSTRACT

Climate change has altered rainfall characteristics and seasonal patterns. This matter affects mostly rainfed agricultural systems in karst regions. This study aims to analyze rainfall characteristics, extreme rainfall events, seasonal shifts, and the reliability of traditional seasonal knowledge *(pranata mangsa)* in the Rongkop karst area, Indonesia. The dataset used in this study are long-term daily rainfall data from Rongkop stations for the period 1986–2021. The rainfall data then convert to *dasarian* (10-day) temporal resolution. The daily rainfall was classified into intensity categories, while seasonal onset was determined based on rainfall thresholds. Trend analysis was conducted using the Mann–Kendall test and Sen's slope estimator. The results indicate that Rongkop has moderate annual rainfall, with an average of 2012 mm, and no significant trend in total rainfall. However, there is a significant increase in the frequency of heavy rainfall events (>50 mm/day), indicating a shift towards higher rainfall intensity. Seasonal analysis shows variability in the onset of the rainy season between late August and late December, and the dry season between early February and mid-May. Seasonal duration also varies significantly, with extended dry spells and increased rainfall during the dry season. The results indicate increasing inconsistencies between traditional and observed rainfall patterns, with very high rainfall occurring during the dry season and very low rainfall during the wet season. The onset of the wet and dry seasons also exhibits significant variability beyond the expected seasonal boundaries. These findings suggest that although traditional seasonal forecasts (*pranatamangsa*) still reflect general climate patterns, their reliability for agricultural planning has declined due to increasing rainfall variability, extreme events, and large-scale climate phenomena such as El Niño and La Niña, particularly in rainfed karst areas. Therefore, integrating traditional seasonal knowledge with modern climatological analysis is crucial to support adaptive agricultural management, particularly in karst areas.

1. Introduction

Climate change has become a major global issue that affect various environmental and socio-economic sectors. The Key indicators are include increasing average temperatures, sea level rise, extreme rainfall characteristics change, and long dry seasons. The agricultural sector had impacted from these changes, spesifically in tropical regions [1]–[3]. According to the World Meteorological Organization (WMO) [4], in 2015–2020 period was recorded as the six hottest years on record. Rising temperatures increase crop water requirements, while long dry seasons reduce the water availability [5]–[7]. Furthermore, the uncertainty about the onset of the rainy season make crop planning more complicated and reduces agricultural productivity.

Climate change also threatens global food security. The Food and Agriculture Organization (FAO) reports that approximately 25% of economic losses in developing countries are caused by climate-related disasters, such as droughts, floods, and storms [8]. One common form of adaptation by farmers is selecting crop varieties that are more tolerant to climate variability [9].

Regionally, the impact of climate change is increasingly severe on vulnerable ecosystems, such as karst areas. Gunungkidul Regency is characterized by karst geological formations composed of highly permeable limestone and underground channel systems [10]. Annual rainfall in this region ranges from 1,000–3,500 mm and is heavily influenced by large-scale climate phenomena such as El Niño [11]. Due to the characteristics of the karst system,

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rainwater rapidly infiltrates into subsurface channels, limiting surface water availability. Consequently, agricultural activities in this region are highly dependent on rainfall.

Among the sub-districts in Gunungkidul Regency, Rongkop is one of the most vulnerable to severe agricultural droughts. Most agricultural land in this sub-district is rain-fed dryland, leaving farmers entirely dependent on seasonal rainfall due to the lack of irrigation facilities. Cassava is the main agricultural commodity cultivated in the region. However, farmers often experience significant losses due to the uncertainty of the onset of the rainy season. When rain falls later than expected or rainfall patterns become irregular, cassava tubers remain in the soil for longer periods, increasing the risk of rotting and reducing yields and quality.Farmers in Gunungkidul are dominated by the older generation. This generation cultivates according to the Javanese calendar, *Pranatamangsa*. *Pranatamangsa* is a traditional Javanese agricultural calendar system based on the solar cycle (*suryasengkala*), which divides the 365- or 366-day year into 12 periods *(mangsa)* with day lengths varying between 23 and 43 days. The twelve mangsa are *kasa* (first), *karo* (second), *katelu* (third), *kapat* (fourth), *kalima* (fifth), *kanem* (sixth), *kapitu* (seventh), *kawolu* (eighth), *kasanga* (ninth), *kasadasa* (tenth), *dhesta* (eleventh), and *sadha* (twelfth). Each mangsa has its own *candra* character or natural symbol based on bioclimatological signs, such as plant and animal behavior, wind direction, and specific constellations for navigation of seasonal changes. This calendar was historically inaugurated by Sri Susuhunan Paku Buwana VII of Surakarta on June 22, 1855 to provide a strong benchmark for regulating the work of farmers from year to year.

For Javanese farmers, the twelve seasons are grouped into four main time units that align with changes in planting time, namely the dry season or *mangsa katiga* (*mangsa kasa, karo, katelu*), *musim labuh* or the transitional rainy season (*mangsa kapat, kalima, kanem*), *mangsa rendheng* or the rainy season (*mangsa kapitu, kawolu, kasanga*), and *musim mareng* or the transitional dry season (*mangsa kasadasa, dhesta, sadha*). In addition to these four main seasons, farmers also recognize groupings based on transitional seasons that affect their living conditions as presented in Figure 1, namely the *mangsa terang* as the period between harvest and famine (*sadha and kasa*), the *mangsa semplah* which is interpreted as a season of hardship or despair (*karo, katelu, kapat, and kalima*), *mangsa udan* which is flanked by *semplah* and *pengarep-arep*, and *magsa pengarep-arep* as a time full of hope when animals and plants begin to reproduce (*kawolu, kasanga, kasadasa, and dhesta*). Through this periodic distribution, Javanese farmers were able to plan their lives wisely, such as learning to manage their finances and be frugal during difficult times and rejoice when welcoming a bountiful rice harvest. [12][13][14].

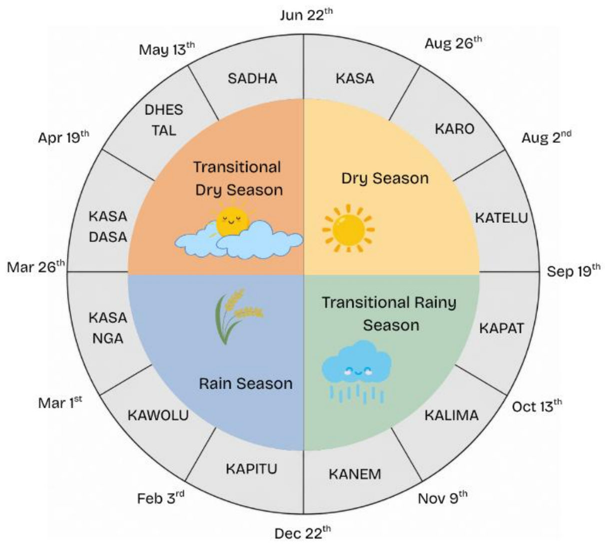


Figure 1. Pranatamangsa calendar [15]

This Prantamangsa were historically used to guide agricultural practices. However, climate change has significantly altered seasonal patterns. This shift has led to increased uncertainty in planting schedules, severe water scarcity during prolonged dry seasons, and escalating risks of total crop failure.

Despite numerous studies on rainfall variability and climate change in Gunungkidul, several critical gaps remain. Previous research in this karst region has mostly focused on regional-scale analysis, leaving a gap in localized studies. To date, there has been no specific, long-term rainfall analysis conducted specifically for the Rongkop karst area, despite its status as a drought-prone agricultural hub. Furthermore, existing literature is still limited by insufficient long-term observational data [16]. Most studies rely on monthly or annual rainfall. Dasarian temporal analysis, which is vital for precise agricultural planning, remains unexplored in this area. Additionally, the response of karst hydrological systems to extreme rainfall events under changing climate conditions is still poorly understood [17].

To address these gaps, this study aims to analyze rainfall characteristics, extreme rainfall events, and seasonal shifts specifically in the Rongkop karst area. By utilizing long-term, high-resolution rainfall data (1986–2021) at a dasarian temporal scale, this study provides the first localized climate analysis for Rongkop. The findings of this research are expected to serve as a crucial scientific foundation for local farmers to adjust their planting calendars and for policymakers to design targeted drought mitigation and climate adaptation strategies in water-scarce karst environments.

2. Methods

2.1 Study Area

This research was conducted in Rongkop District. Administratively, Rongkop District has 8 parts, namely: 1) Pucanganom; 2) Karangwuni; 3) Pringombo; 4) Semugih; 5) Petir; 6) Botodayakan; 7) Bohol; 8) Melikan. Agriculture in this area is strongly influenced by the geographical characteristics of the karst region (limestone hills) which have unique hydrological challenges. Rongkop is at an altitude of 100–300 meters above sea level with morphology in the form of conical hills, domes, valleys, and caves, but does not have underground rivers [13]. The usual planting calendar in one of the Districts in Rongkop (Karangwuni) presented in Table 1.

Table 1. Planting Calendar Estimation in Karangwuni, Rongkop [13]

Ward	Month											
	Wet					Dry			Lean		Wet	
Karangwuni	1	2	3	4	5	6	7	8	9	10	11	12
	Rice or corn				Intercropping: Corn, Cassava/Soybeans				Empty land/ Lean season			Rice or corn

According to Table 1, the wet season begins in late November. During this wet season in Karangwuni, Rongkop, farmers cultivate corn or rice. The dry season begins in June, and farmers plant less water-demanding field crops, such as corn or cassava.

2.2 Datasets

The daily rainfall data records covering the 1986–2021 period, with observations available for 27 years. These data obtained from the Department of Agriculture and Food of Gunungkidul Regency. The rainfall station location is in Rongkop to represent the study area (see Figure 2). The historical dataset originally dates back to 1952; however, the 1986–2021 period was specifically selected due to its superior data consistency and completeness.

Regarding data quality control, any missing data points within the observation period were left blank and strictly excluded from the statistical analysis to prevent artificial bias in trend detection. For temporal analysis, the daily rainfall records were aggregated into a dasarian resolution (10-day intervals), resulting in exactly three periods per calendar month (Dasarian I, II, and III). This high-resolution temporal framework allows for a more precise assessment of rainfall variability and seasonal transitions compared to standard monthly aggregations.

2.3 Rainfall Characteristics Analysis

Rainfall characteristics were analyzed based on daily rainfall data and classified into four categories as Light rainfall (<20 mm/day); Moderate rainfall (20–50 mm/day); Heavy rainfall (50–100 mm/day); and Very heavy rainfall (>100 mm/day). The frequency and percentage of each rainfall category were calculated annually to identify changes in rainfall patterns over time. In addition, the occurrence of heavy rainfall events (>50 mm/day) was analyzed to evaluate extreme rainfall behavior.

2.4 Seasonal Analysis (Onset of Rainy and Dry Seasons)

Seasonal analysis was performed using dasarian rainfall data to determine the onset of the rainy season (Awal Musim Hujan, AMH) and dry season (Awal Musim Kemarau, AMK). The criteria used in this study are defined as the onset of rainy season (AMH) occurs when rainfall exceeds 50 mm per dasarian for two consecutive periods and the onset of dry season (AMK) occurs when rainfall is less than 50 mm per dasarian for two consecutive periods. This method allows for a more detailed identification of seasonal transitions compared to monthly approaches, particularly in regions with high rainfall variability.

2.5 Analysis of Seasonal Variability

The variability of seasonal onset and duration was analyzed by examining the timing of AMH and AMK for each year. The duration of rainy and dry seasons was calculated based on the interval between onset and termination of each season.

Changes in seasonal patterns were evaluated to identify shifts in timing, duration, and variability of rainfall seasons, particularly in relation to climate variability.

2.6 Trend Analysis

Trend analysis was conducted to detect long-term changes in rainfall characteristics using the non-parametric Mann-Kendall test. This method is widely used for identifying monotonic trends in hydroclimatic time series without requiring normal data distribution.

The magnitude of the trend was estimated using Sen's slope estimator, which calculates the rate of change over time. Positive slope values indicate increasing trends, while negative values indicate decreasing trends.

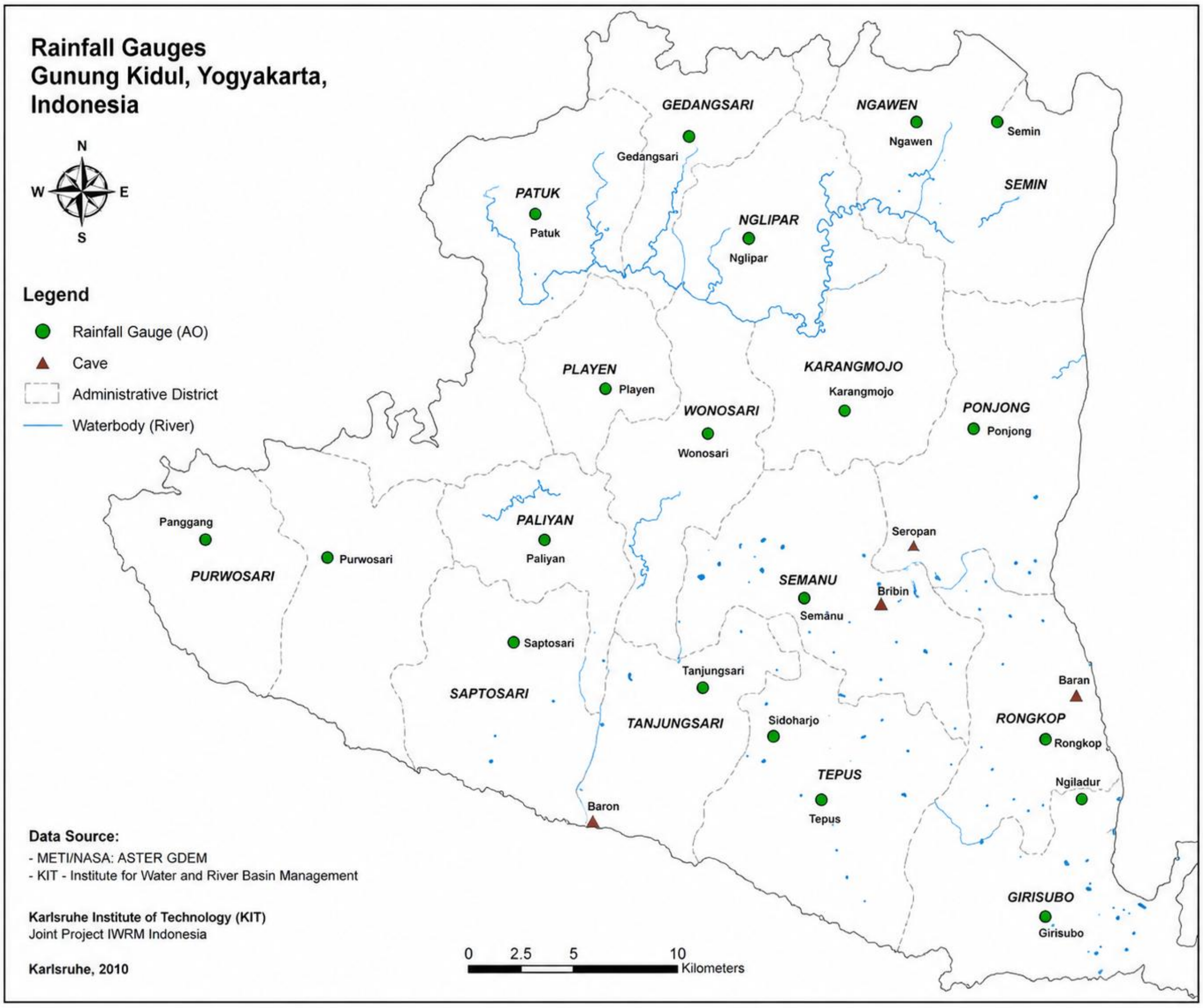


Figure 2. Distribution of rainfall stations in Gunungkidul Regency.

3. Results and Discussion

3.1 Rainfall Characteristics

The analysis of daily rainfall data in the Rongkop karst area shows that rainfall events are predominantly classified as light rainfall (<20 mm/day), followed by moderate rainfall (20–50 mm/day), heavy rainfall (50–100 mm/day), and very heavy rainfall (>100 mm/day).

The proportion of light rainfall dominates the annual rainfall distribution, indicating that most rainfall events occur at low intensity. However, an increasing tendency in the frequency of heavy and very heavy rainfall events is observed, particularly in the period after 2010. This suggests a shift in rainfall characteristics from low-intensity to high-intensity events.

Such changes in rainfall characteristics are important in karst regions, where rapid infiltration reduces surface water availability. Increasing rainfall intensity may enhance subsurface flow while also increasing the risk of soil erosion and land degradation.

3.2 Annual Rainfall Variability

The analysis of annual rainfall from 1986 to 2021 shows that the study area generally falls into the moderate rainfall category, with an average annual rainfall of approximately 2012 mm (Figure 3). Interannual variability is clearly observed, with several years classified as dry (e.g., 1997 and 2019) and wet (e.g., 2016 and 2021).

Trend analysis using the Mann-Kendall test indicates a positive trend in annual rainfall with Kendall's tau value of 0.088. However, the trend is not statistically significant at the 95% confidence level (p-value = 0.535). The magnitude of change estimated using Sen's slope is 5.48 mm/year, indicating a slight increase in annual rainfall over time.

This result suggests that total rainfall volume has not changed significantly, and rainfall variability in the study area is more influenced by interannual climate variability rather than long-term trends. Extreme dry years are associated with El Niño events, while wet years are linked to La Niña conditions, which influence rainfall patterns in Indonesia.

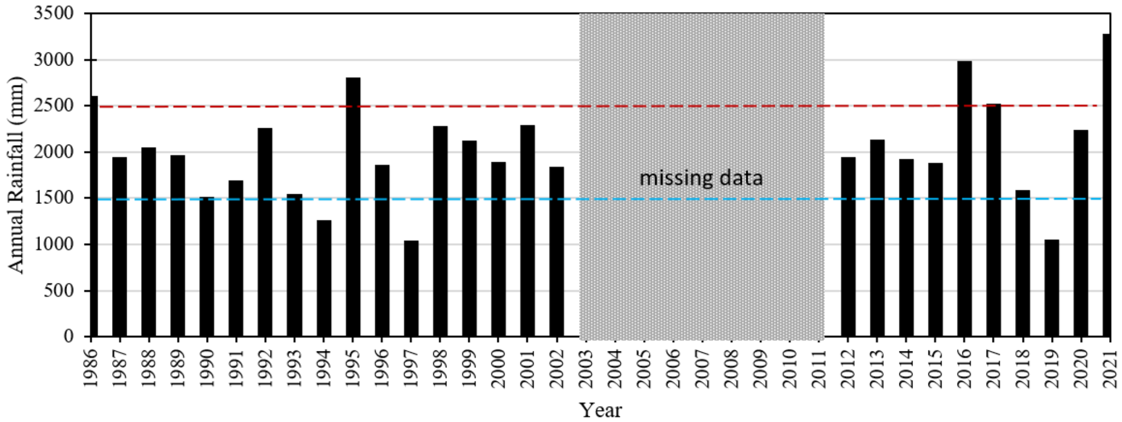


Figure 3. Annual rainfall

3.3 Trend of Extreme Rainfall Events

In contrast to annual rainfall, the analysis of heavy rainfall events (>50 mm/day) shows a significant increasing trend (Figure 4).

Based on the Mann-Kendall trend test, there is a statistically significant upward trend in the time series. This is supported by a calculated Kendall's tau of 0.465 and a positive statistic value. Because the computed two-tailed p-value of 0.001 is well below the 5% significance level, the null hypothesis of no trend is rejected in favor of the alternative hypothesis. Furthermore, Sen's slope estimator indicates a positive rate of change with a slope value of 0.200 (95% confidence interval: 0.083 to 0.308), confirming a steady, significant increase in the data over the analyzed period.

This finding highlights a shift in rainfall distribution, where total rainfall remains relatively stable, but rainfall intensity increases. Such a pattern is consistent with global climate change projections, which indicate an increase in extreme precipitation events rather than total rainfall volume.

In karst regions, increased rainfall intensity may lead to rapid infiltration into underground systems, reducing surface water availability while simultaneously increasing the risk of flash flooding and soil erosion in certain conditions.

Figure 5 indicates the dominance of low-intensity rainfall, with a gradual increase in the contribution of higher-intensity rainfall events over time.

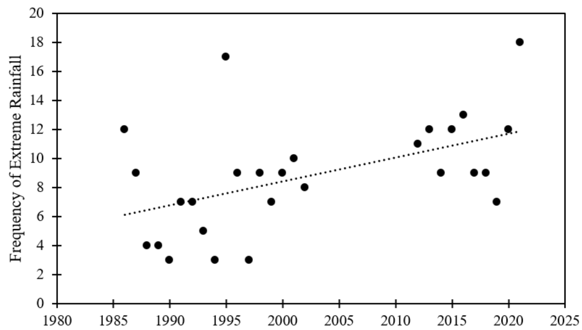


Figure 4. Annual number of extreme rainfall events (>50 mm/day) in the study area, showing an increasing trend over time.

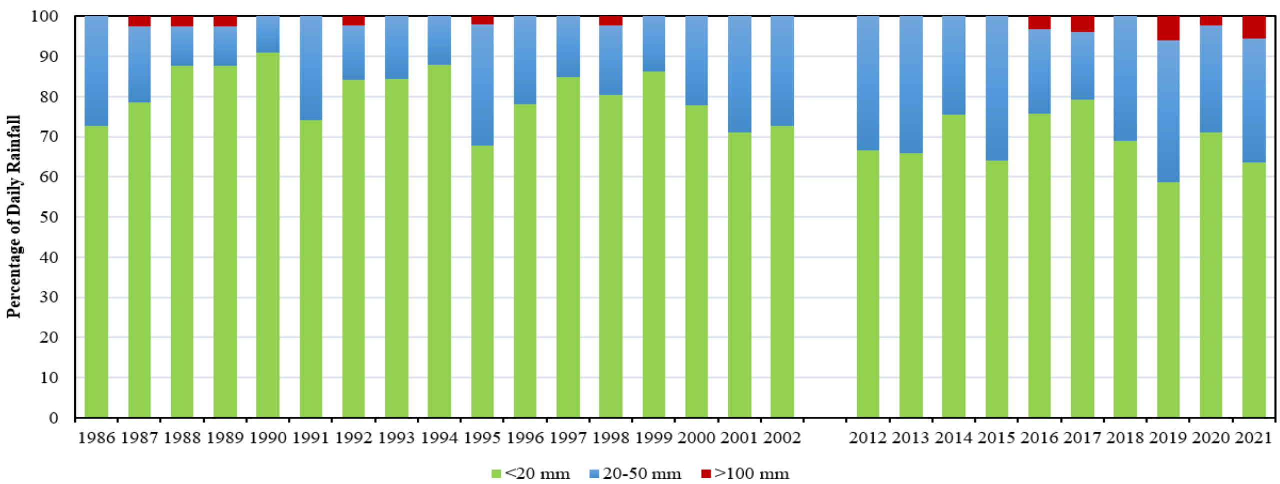


Figure 5. Percentage distribution of daily rainfall intensity (<20 mm, 20–50 mm, and >100 mm) in the Rongkop karst area from 1986 to 2021.

3.4 Monthly Rainfall Pattern

The average monthly rainfall pattern shows a clear seasonal distribution, with peak rainfall occurring in January and February, while the lowest rainfall occurs in July, August, and September (Figure 6). This pattern reflects the typical monsoonal climate of Southern Java.

However, variability in monthly rainfall is observed across years, indicating changes in seasonal distribution. In some years, rainfall occurs outside the typical rainy season, suggesting increasing irregularity in rainfall patterns.

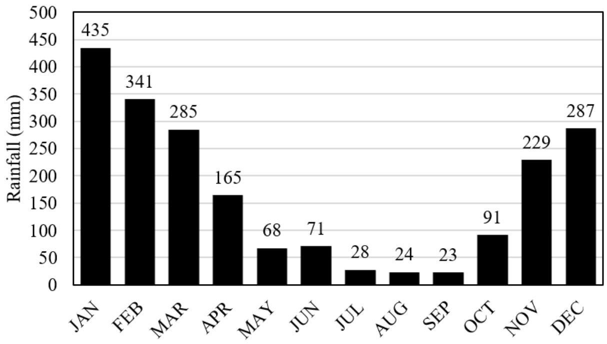


Figure 6. Monthly Rainfall Pattern

3.5 Seasonal Shift (Onset of Rainy and Dry Seasons)

The analysis of dasarian rainfall data reveals significant variability in the onset of rainy and dry seasons. The rainy season in the Rongkop karst area begins as early as the third ten-day period (dasarian) of August and as late as the third dasarian of December. Meanwhile, the dry season starts between the first dasarian of February and the second dasarian of May.

The duration of the dry season averages 212 days, while the rainy season lasts approximately 151 days. The longest dry seasons were recorded in 1997, 2013, and 2019, which are associated with El Niño events.

These results indicate that seasonal patterns are becoming increasingly irregular, which poses challenges for agricultural planning. Farmers who rely on traditional seasonal calendars such as *pranata mangsa* may face difficulties in adapting to these changes.

3.6 Implications for Karst Agriculture and Climate Variability

The findings of this study demonstrate that climate change impacts in the study area are not primarily reflected in changes in total rainfall, but rather in the increasing intensity and variability of rainfall events.

The significant increase in heavy rainfall events, combined with shifting seasonal patterns, may lead to increased hydrometeorological risks, including soil erosion, crop failure, and water management challenges. In karst regions, where water rapidly infiltrates into subsurface systems, these changes can exacerbate water scarcity during dry periods despite increased rainfall intensity.

These findings are consistent with previous studies indicating that climate change tends to increase rainfall variability and extreme events rather than total rainfall. Therefore, adaptation strategies in karst agricultural systems should focus on improving water management, adjusting planting calendars, and enhancing resilience to climate variability.

3.7 The Reability of Pranatamangsa

The accuracy of the Pranatamangsa is assessed by the stability of the rainfall amount during each mangsa period. Rainfall dynamics within the Pranatamangsa framework exhibit highly structured hydro-meteorological fluctuations, with shifting patterns that follow the apparent solar cycle and the monsoon wind system. Based on historical data for the 1986–2021 period, monthly and seasonal rainfall quantities divide 12 *mangsa* into four main groups that have a strong correlation with the cumulative rainfall thresholds of low (<100 mm/ mangsa), medium (100–300 mm/ mangsa), and high (>300 mm/ mangsa).

***Mangsa Katiga* (dry season)**

The dry season was identified in *Mongso Kasa*, *Karo*, and *Katelu*. Rainfall during this period is shown in Figure 7. The Dry Season is consistently in the Very Low rainfall category, with an average cumulative accumulation of only 75.3 mm. The dynamics of air and soil humidity dropped sharply starting from *Kasa* (41.3 mm) to reaching the driest point in *Karo* (16.5 mm) and *Katelu* (17.5 mm), where all three were well below the low threshold of 100 mm. This characteristic forces the agricultural sector to shift from high water deficit crops to secondary crops or leave the land in a fallow state to break the pest cycle. Although generally dry, this group has sharp anomalous dynamics, both in the form of wet dry phenomena and absolute drought. In years with a negative Indian Ocean dipole or coastal La Niña, such as 1986, 1992, and 2016, wet anomalies occurred with dry accumulations reaching 241–266 mm, *Katelu* alone contributed 249 mm of rain. Conversely, in 1991, 1994, 1997, 2012, 2015, 2018, and 2019, extreme dry anomalies occurred with accumulations of 0 mm for three consecutive years, triggering prolonged droughts and irrigation water crises.

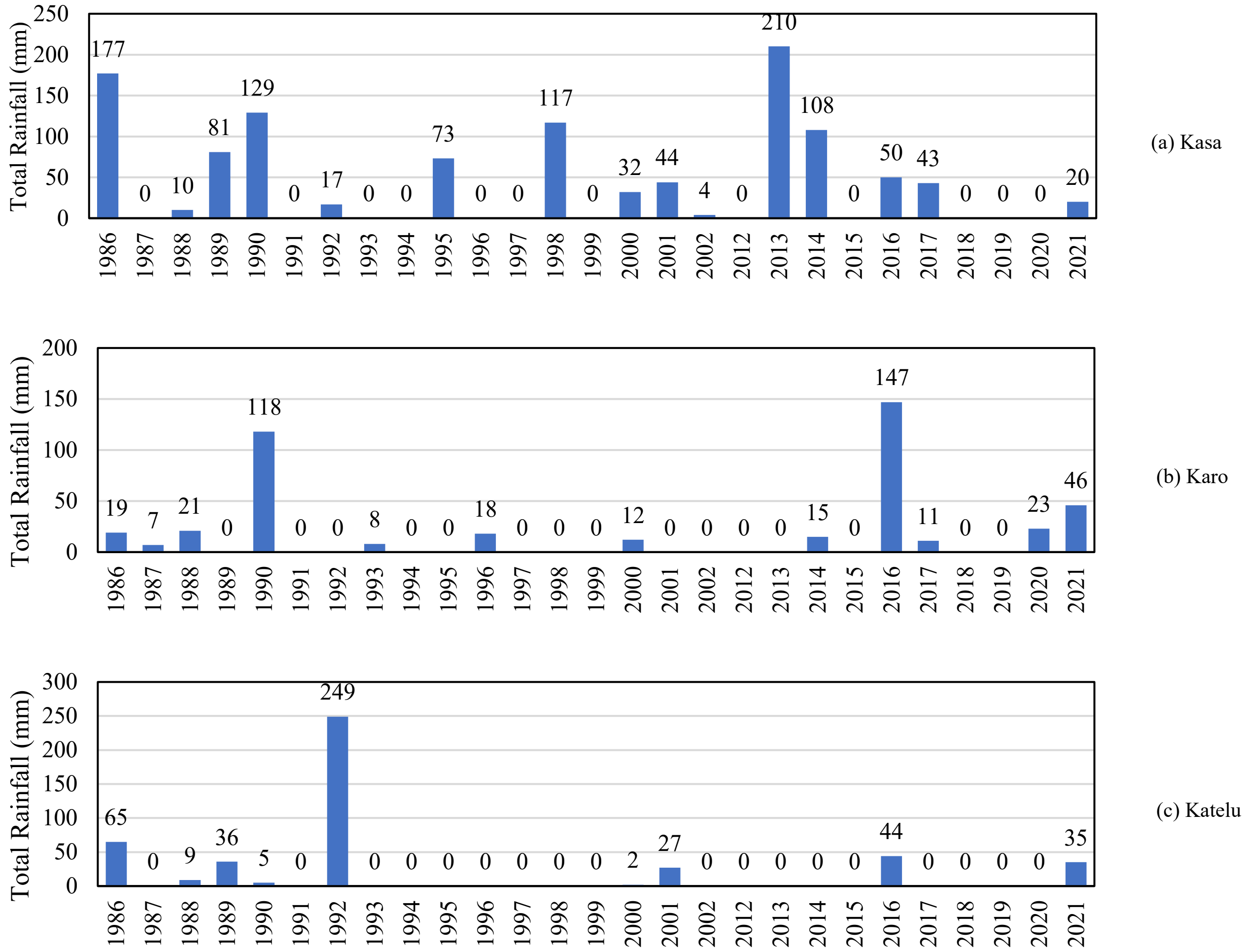
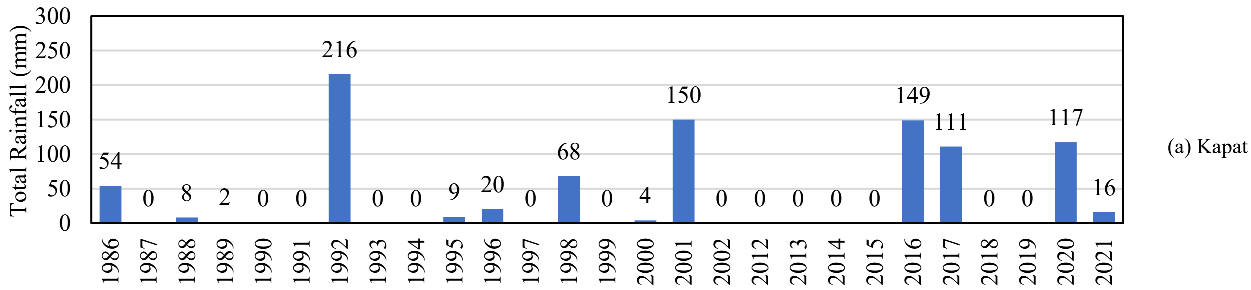


Figure 7. Total rainfall in *Mongso Ketigo* from 1986 to 2021

Musim Labuh (Transitional Rainy Season)

Musim Labuh is identified by the *Kapat*, *Kalima*, and *Kanem*. Cumulative rainfall in these monsoons is shown in Figure 8.

Musim Labuh represents a transitional phase with high rainfall accumulation, a cumulative average of 517.9 mm, which increases from month to month. The dynamics begin with *Kapat* (34.2 mm), which falls into the Low category. Next, *Kalima* (112.1 mm) shifts to the Moderate category, marking the start of land cultivation, and culminates with *Kanem* (371.6 mm), which jumps to the High category, signaling the end of the transition period and the official start of the rainy season. Anomalies in this transitional group are crucial for the accuracy of the early-season planting schedule. In 2017 and 2021, very wet transitional anomalies occurred with cumulative totals reaching 1,145–1,177 mm. In 2021, *Kanem* recorded an extreme rainfall of 902 mm. On the other hand, due to the impact of strong El Niño in 1997 and 2019, this transition period experienced a failed transition with accumulated rainfall reaching only 36–40 mm, which caused a delay in the national simultaneous planting schedule.



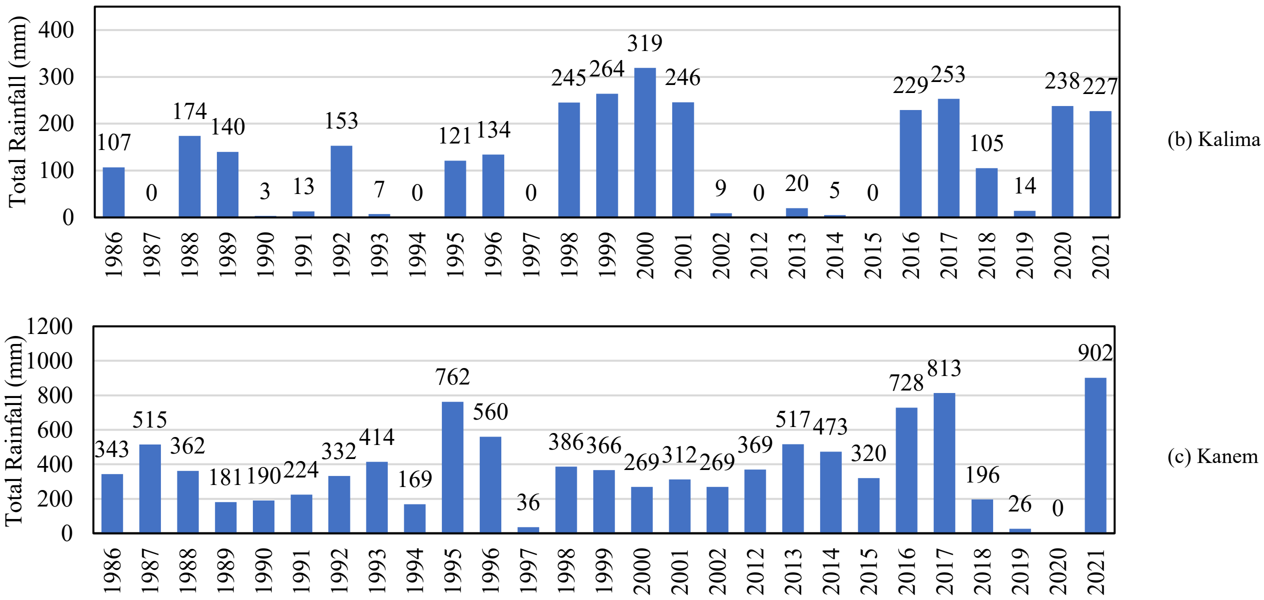
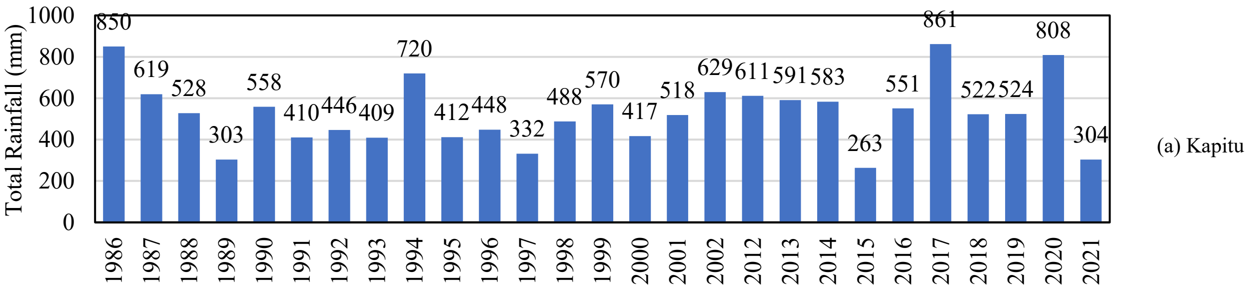


Figure 8. Total rainfall in *Mongso Ketigo* from 1986 to 2021

Mangsa rendheng (Rainy Season)

Mangsa rendheng was identified in the *Kapitu*, *Kawolu*, and *Kasanga* season. Rainfall in these period is shown in Figure 9.

Mangsa rendheng is characterized by a dominant Very High water accumulation, with a cumulative average reaching 1,073.9 mm per season. Rainfall dynamics during this period test land resilience due to the gradual, massive water supply, starting with the highest peak in *Kapitu* (average 528.7 mm), which is categorized as High, then gradually decreasing in *Kawolu* (314.9 mm) and *Kasanga* (230.3 mm), which are categorized as Medium. This excess water supply provides the main foundation for the rice planting phase (long-term drought), but also poses the risk of inundation and flooding in areas with poor catchment areas. These results are consistent with previous research which showed that Mangsa Kapitu was the period with the highest rainfall [18]. The anomaly in this mangsa is markedly contrasting due to the influence of global climate interactions such as La Niña and El Niño. In 2020, an extreme wet anomaly occurred with total seasonal rainfall reaching 1,700 mm, while *Kasanga*, which usually begins to subside, actually surged to 503 mm due to the strong La Niña phenomenon. Conversely, during El Niño events in 1997 and 2013, accumulated seasonal rainfall experienced a significant deficit, reaching a low of around 692–694 mm, drastically reducing water supplies during the vegetative growth period of rice plants.



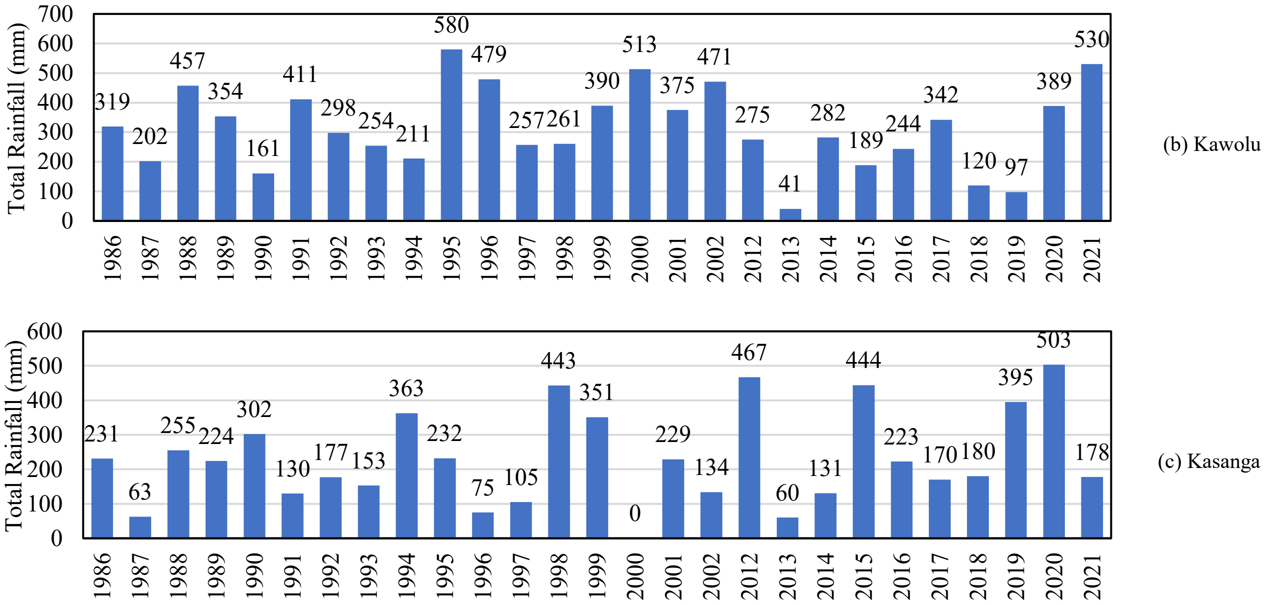
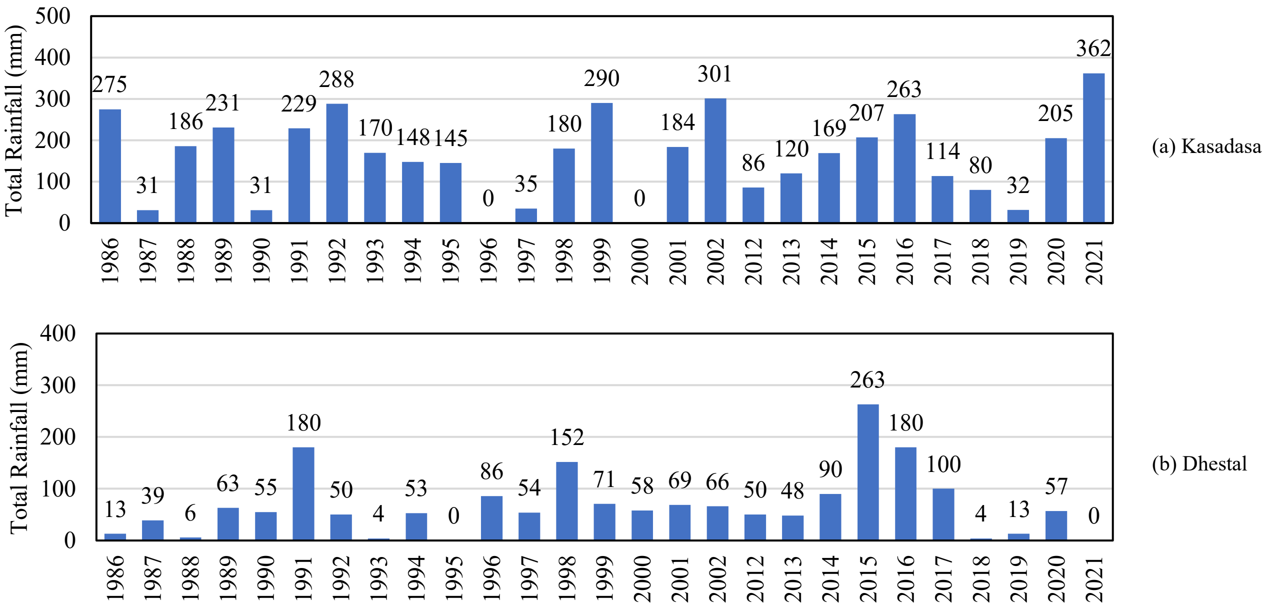


Figure 9. Total rainfall in *Mongso Udan* from 1986 to 2021

Mangsa Mareng (Transitional Dry Season)

Mangsa mareng was identified in *Kasasadasa*, *Dhestal*, and *Sadha*. Rainfall in these period is shown in Figure 10.

Mangsa mareng reflects a gradual moisture release phase, with accumulated rainfall in the Moderate category, with a cumulative average of 327.7 mm. Rainfall decreases steadily from *Kasasadasa* (161.6 mm) in the Moderate category, then decreases to *Dhestal* (67.6 mm) and *Sadha* (98.6 mm), both of which are in the Low category. Anomalies in *mangsa mareng* generally trigger crop uncertainty due to prolonged or abruptly shortened seasons. In 2016 (794 mm) and 2013 (600 mm), extreme wet Mareng anomalies occurred; in 2013, Sadha recorded up to 432 mm of rainfall, potentially disrupting the drying process of crops. In contrast, in 2019 (45 mm) and 2018 (85 mm), the transition to the dry season was very rapid and dry, which often made it difficult for farmers to utilize the remaining soil moisture.



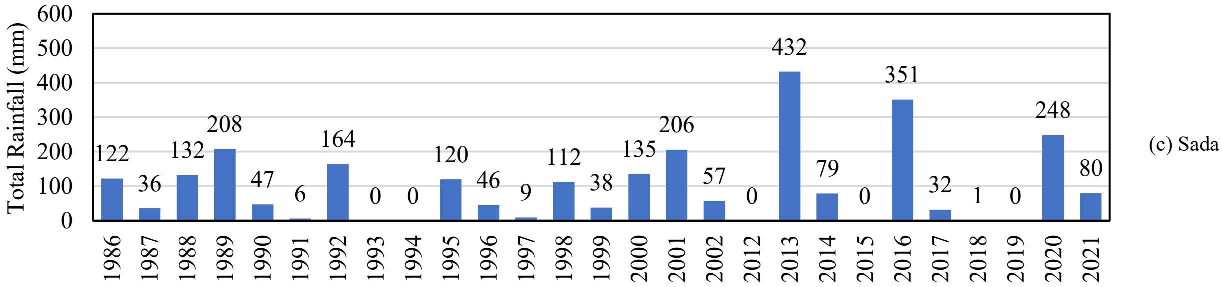


Figure 10. Total rainfall in *Mongso Udan* from 1986 to 2021

The analysis of rainfall distribution based on *pranatamangsa* indicates that the general seasonal pattern is still recognizable, where peak rainfall occurs during *Kanem* and *Kapitu*, while low rainfall is observed during *Karo*, *Katelu*, and *Kapat*. However, significant variability and anomalies are evident across the study period.

Several *mangsa* that are traditionally classified as dry exhibit unusually high rainfall, such as *Katelu* in 1992 and *Kapat* in 1992. Conversely, some wet *mangsa* show very low rainfall, such as *Kawolu* in 2013 and *Kasanga* in 2000 which is almost 0 . This indicates that rainfall distribution within traditional seasonal periods is becoming increasingly irregular. Figure 11 illustrates the Pranatamangsa calendar and the rainfall characteristics.

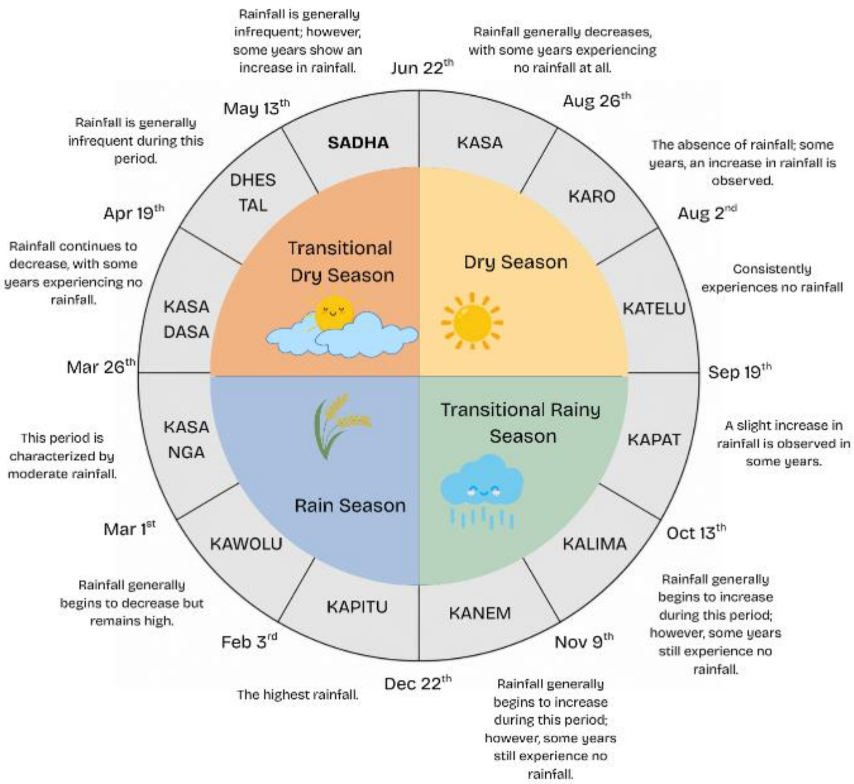


Figure 11. Pranatamangsa calendar and the rainfall characteristics.

The analysis of seasonal onset further supports this finding. The onset of the rainy season (AMH) does not consistently occur within the expected mangsa period, indicating a temporal shift in seasonal cycles. Similarly, the onset of the dry season (AMK) shows variability that deviates from traditional seasonal boundaries.

These inconsistencies suggest that while *pranatamangsa* still represents the general climatic pattern. However, according to the survey, only a third of farmers still consider paranata mangsa relevant, while the rest said it was not or needed to be re-evaluated [19]. its reliability has decreased due to increasing rainfall variability and extreme events. The observed increase in extreme rainfall events, as identified by the Mann-Kendall analysis, further supports this conclusion.

This condition reflects the impact of climate variability, particularly large-scale climate phenomena such as El Niño and La Niña, which influence rainfall distribution in the region. As a result, traditional seasonal indicators may no longer be sufficient for agricultural planning, especially in rainfed karst areas that are highly dependent on rainfall patterns [20].

4. Conclusions

This study demonstrates that the Rongkop karst area is characterized by moderate annual rainfall, with an average of approximately 2012 mm during the period 1986–2021. Although no significant trend is observed in total annual rainfall, there is a clear increase in the frequency and proportion of heavy (>50 mm/day) and very heavy (>100 mm/day) rainfall events. This shift toward higher rainfall intensity indicates an increasing risk of hydrometeorological hazards, which may negatively affect agricultural productivity in rainfed karst systems.

The analysis of dasarian rainfall reveals significant variability in seasonal patterns. The onset of the rainy season varies widely, occurring between the third ten-day period of August and the third ten-day period of December, while the dry season begins between the first ten-day period of February and the second ten-day period of May. The duration of both seasons is also highly variable, with prolonged dry seasons observed in 1997, 2013, and 2019, which are associated with El Niño events. In addition, the increasing occurrence of heavy rainfall during the typical dry season suggests growing seasonal irregularity, likely influenced by more frequent La Niña events.

The comparison between observed rainfall patterns and the traditional seasonal system (*pranata mangsa*) indicates that the general seasonal structure is still recognizable, particularly in distinguishing wet and dry periods. However, significant deviations are identified, including increased rainfall during traditionally dry mangsa and reduced rainfall during expected wet periods. These findings suggest that the reliability of *pranata mangsa* as a seasonal indicator has decreased due to increasing climate variability and extreme rainfall events.

Overall, this study highlights that climate change in the study area is manifested not through changes in total rainfall, but through increasing rainfall intensity and seasonal unpredictability. As a result, traditional seasonal knowledge alone is no longer sufficient for agricultural decision-making. Therefore, it is essential to integrate *pranatamangsa* with modern climatological analysis to improve the accuracy of seasonal prediction and enhance the resilience of agricultural systems in karst regions.

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