



Regional Rainfall Disparities and Monsoon Dynamics in Kerala: Insights for Climate Adaptation

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Abstract

This study analyses seventy years (1951–2020) of rainfall patterns in Kerala, focusing on long-term variability, extreme events, monsoon divergence, and seasonal rainfall concentration. Monthly rainfall data from 83 stations across all 14 districts were used to create a time series at both district and state levels, based on arithmetic means. Statistical tools such as the Seasonality Index (SI), Precipitation Concentration Index (PCI), Pettitt test, Mann-Kendall trend test, and Sen's slope estimator were applied to assess temporal and spatial rainfall trends. The results reveal notable intra-state variations. Northern districts like Kasaragod, Kannur, and Wayanad exhibit higher rainfall seasonality and concentration, making them more vulnerable to water stress and extreme events. In contrast, southern coastal regions benefit from more evenly distributed rainfall due to the combined influence of the Southwest and Northeast monsoons. Although statewide trends do not show a statistically significant decline in rainfall, some districts, particularly Wayanad, have experienced notable decreases, posing risks to agriculture and local ecosystems. The study also identifies changes in the timing of monsoon onset and withdrawal, especially post-1990s, indicating increased climatic variability. Overall, the findings point to evolving rainfall dynamics in Kerala, with critical implications for agriculture, disaster preparedness, and water management. The study underscores the need for localized climate adaptation strategies to address the region-specific impacts of changing monsoon patterns and rainfall distribution.

Keywords: Rainfall variability, Monsoon dynamics, Seasonality Index (SI), Precipitation Concentration Index (PCI), Climate adaptation, Kerala.

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1. INTRODUCTION

The problem of climate change and extreme weather occurrences has been a primary global concern in recent decades (Samantray & Gouda, 2024). Natural climatic variability can lead to extreme weather and localized climate change. Extreme weather would still occur because of natural variability even in the absence of anthropogenic climate change (Samantray & Gouda, 2024). Kerala, along with the states of northeastern India, receives the first monsoon rainfall each year; it is one of the few places in India with the highest monsoon rainfall (Pal & [Tabbaa](#), 2009). The State of Kerala is located in the far southwest of the Indian subcontinent. It is bounded to the north by Karnataka State, to the east by Tamil Nadu, and to the west by the Arabian Sea. It encompasses the area of the subcontinent that is defined by longitudes 75° and 77° east and latitudes 8° and 13° north (Guhathakurta et al., 2020). The geographical terrain can be classified into three zones on a longitudinal profile: the high land, the mid land, and the low land, which includes the coastal plain. The state is renowned for its geographic orientation, which makes the weather pattern unique in this part of the Indian subcontinent. It has been honoured with the first showering of the Indian summer monsoon rainfall (Nair et al., 2013). There are over 50 large dams distributed primarily throughout the Western Ghats and about 44 rivers that flow through Kerala, generating water for hydroelectric power generation and agriculture (Ramasamy et al., 2019).

Although the area was less vulnerable to widespread flooding and landslides in previous decades, it is now more susceptible to severe floods and inundation (along the lowlands and coastal plains, floodplains, and large flat-bottom valleys of the river systems) and landslides across the steep slopes of the Western Ghats (Sudheer et al., 2023). In the recent decade, several climate-related disasters have occurred, among which the 2018 flood and the 2024 Wayanad landslide are prominent. The most severe flooding experienced by Kerala since 1924 occurred in August 2018. Over 400 people lost their lives in the terrible flood and landslides that followed, which impacted 5.4 million people. The Kerala government commissioned a post-disaster evaluation, which calculated the economic loss to be over \$3.8 million (Hunt & Menon, 2020). July 30, 2024, saw the most recent and devastating landslide. In the Meppadi Grama Panchayat in the Wayanad district, the villages of Punchirimattam, Chooralmala, and Mundakkai were all affected by these landslides. More than 350 people died, more than 200 of them were presumed to be buried beneath the debris (Azad et al., 2024).

Due to heavy rainfall events, flash floods, and landslides, the whole district of Kerala is vulnerable; therefore, Understanding Kerala's rainfall patterns has become increasingly important in light of the state's growing climate variability. Extreme rainfall results in landslides, flash floods and crop damage that significantly impact society, the economy and the environment. Although the prediction of such extreme weather events is still fraught with uncertainties, an appropriate assessment of likely future trends would help in setting up infrastructure for disaster preparedness (Goswami et al., 2006). To effectively adapt to climate change and establish effective policies, an integrated, district-level analysis encompassing seven decades (1951–2020) that takes into account seasonality, precipitation concentration, trend in rainfall and rainfall extremes is lacking. The present study aims to provide a comprehensive assessment of Kerala's rainfall dynamics over seven decades (1951–2020). It aims explicitly to evaluate long-term variability and extremes, investigate divergence trends between the Southwest and Northeast monsoons, and analyse rainfall seasonality and concentration patterns among districts using the Seasonality Index (SI) and Precipitation Concentration Index (PCI). The study also plans to assess changes in indicators of monsoon onset and withdrawal. Additionally, the study intends to evaluate changes in indications of monsoon onset and withdrawal. The results of this approach have the potential to be highly relevant to Kerala's agricultural planning, climate adaptation, and control of its water resources.

2.LITERATURE REVIEW

Climate change results in unpredictable and severe precipitation events globally. In this context, the rise of extreme precipitation events presents serious challenges to natural ecosystems and human populations. (Du et al., 2025). The United Nations Strategy for Disaster Reduction (UISDR, 2002) finds that the frequency of storms, floods, droughts, and landslides has tripled in the previous 30 years as a result of global warming and climate change. India has been facing multiple challenges associated with different negative consequences on agriculture, water resources, forestry and biodiversity, public health, coastal management, and increasing temperatures (Balasubramanian & Birundha, 2012).

The risk of flooding is primarily driven by variations in rainfall on an annual and monthly basis. The increase in precipitation further increases the population's susceptibility to these disasters (Pohk-seh et al., 2024). Flash floods and cloudbursts generally are brought on by intense rainfall, which is subsequently accompanied by debris flow or landslides, often leading to the obstruction of river systems (Joshi & Kumar, 2006).

Vulnerability and sustainability are predominantly local concerns, depending upon the quantity and temporal distribution of precipitation received in a location. Therefore, rainfall patterns must be examined from a regional point of view (Goswami & Ramesh 2007). Among all the shocks that affect households, natural disasters are the most important. Natural hazards are considered as one of the major drivers of prevalence of food insecurity and undernourishment in developing countries because farmers are more exposed and vulnerable to climate induced disasters (Pham et al., 2020).

The state of Kerala, located in the southern region of India's west coast, has recently suffered disastrous landslides and floods (Raj & Sofi, 2023). According to the study of Pal and Al-Tabbaa (2009), Kerala's rainfall extremes emphasize the growing severity of off-seasonal climate anomalies, encompassing pre-monsoon droughts and post-monsoon floods. Utilizing long-term gridded precipitation data and non-parametric trend analysis from 1954 to 2003, researchers identified notable intra-regional and seasonal fluctuations in extreme rainfall patterns. A study of the long-term pattern of rainfall from 1871 to 2005 indicated a substantial decrease in southwest monsoon rainfall, accompanied by an increase in post-monsoon precipitation in the State of Kerala, commonly referred to be the "Gateway of the summer monsoon." Precipitation during the winter and summer seasons exhibited a insignificant upward trend. Rainfall in June and July exhibited a notable declining tendency, but an increasing trend was observed in January, February, and April (Krishnakumar et al., 2009, Thomas & Prasannakumar, 2016).

Despite being a water-abundant state, the state receives around 3000 mm of yearly precipitation. The state continues to have water scarcity and associated issues throughout the summer months due to its varied physiographic configuration, ranging from the coastal region to the Western Ghats (Shyam, 2022). The agriculture sector is one of the most important sectors that is affected by climatic extremes. Climate change impacts the agriculture sector in numerous ways. It is globally recognized that climate change in Kerala is particularly severe in the areas of crop production, horticulture, coastal areas, forests, and health (Thomas, 2023). Kerala is among the most populated states in India, which makes it highly susceptible to damage and losses due to calamities. Floods are the predominant natural hazards in the state. Approximately 14.5% of the state's geographical area is susceptible to flooding. From June 1 to August 18, 2018, Kerala endured its most catastrophic floods since 1924. During this period, the state experienced cumulative rainfall that above its normal average by 42% (Somwal, 2024).

Even though many studies have been conducted during the past years, an elaborate district-wise study has not been done. Climate change and extreme climatic issues like the rise in temperature and extreme rainfall events causing flooding and landslides are common in recent periods; it is essential to understand the spatial and temporal rainfall variability. Consequently, we can adapt region-specific climate strategies and mitigate risks associated with natural disasters.

3. RESEARCH OBJECTIVES AND HYPOTHESES

The primary objective of the present study is to provide a comprehensive assessment of rainfall dynamics in Kerala over a seven-decade period from 1951 to 2020. Using the Seasonality Index (SI) and Precipitation Concentration Index (PCI), the study aims to assess long-term variability and extreme rainfall events. It also analyses divergence trends between the Southwest and Northeast monsoon seasons, and examines spatial variations in rainfall seasonality and concentration across all the fourteen districts in Kerala. In addition, the study seeks to assess changes in indicators related to monsoon onset and withdrawal over time. By addressing these aspects, the study aims to generate insights relevant to agricultural planning, climate adaptation strategies, and effective water resource management in Kerala.

4. RESEARCH METHODOLOGY

4.1 Data Sources

For this study, the fourteen districts in the entire state of Kerala, which is located in the southernmost part of India, are selected. Monthly rainfall data for various stations from 1951 to 2020 is considered for the analysis of the mean, variability, and trend pattern of all fourteen districts. Monthly rainfall data for various stations is collected from the data portal of the Indian Meteorological Department (IMD). From the monthly station-wise data, a monthly district-wise rainfall series has been constructed by calculating the arithmetic average of all the station rainfall values within the district (Guhathakurta et al., 2020). The total number of rain gauge stations used for this study is 83. From the district-wise average value, the annual rainfall data of the state was also constructed.

4.2 Methods

4.2.1 Seasonality Index

The seasonality index (SI), developed by Walsh and Lawler in 1981, is a statistical tool for estimating rainfall seasonality. Using mean monthly and mean yearly rainfall data, the seasonality index is computed as follows:

$$\overline{SI} = \frac{1}{\overline{R}} \sum_{n=1}^{n=12} \left| x_n - \frac{\overline{R}}{12} \right|$$

Where \overline{SI} represents the seasonality index, \overline{R} is mean annual rainfall and x_n is mean monthly rainfall for month n .

Table1: Seasonal Precipitation Regimes

| <i>SI</i> | Precipitation regime |
|-----------|---|
| < 0.19 | Precipitation spread throughout the year |
| 0.20–0.39 | Precipitation spread throughout the year, but with a definite wetter season |
| 0.40–0.59 | Rather seasonal with a short drier season |
| 0.60–0.79 | Seasonal |
| 0.80–0.99 | Markedly seasonal with a long dry season |
| 1.00–1.19 | Most precipitation in less than 3 months |
| > 1.20 | Extreme seasonality, with almost all precipitation in 1–2 months |

Source: Walsh and Lawler (1981)

From the table 1 it is clear that a low value of the seasonality index suggests a type of rainfall regime with a shorter dry season, whereas a high value indicates that the majority of the rain falls during a few months (two to three months).

4.2.2 Precipitation Concentration Index (PCI)

Precipitation Concentration Index (PCI) (Oliver, 1980), an indicator of the concentration of rainfall is calculated using the following equation;

$$PCI \text{ annual} = \frac{\sum_{i=1}^{12} P_i^2}{(\sum_{i=1}^{12} P_i)^2} \times 100$$

Here P_i , is the monthly precipitation in the i .th month.

The uniform distribution of rainfall over a period of the year is shown by PCI values less than 10. Seasonality is indicated by values between 10 and 20, and irregular precipitation throughout the year is indicated by values more than 20 (Table 2).

Table 2: Classification of Precipitation Concentration Index

| Precipitation Concentration Index (PCI) | Temporal PCI Concentration |
|---|----------------------------|
| <10 | Uniform |
| 11-15 | Moderate |
| 16-20 | Concentrated |
| >20 | Very Concentrated |

Source: (Oliver, 1980)

4.2.3 The Pettit Change Point Test

Pettitt test is used to examine the occurrence of abrupt changes in climatic records (Pettit, 1979). It can be performed as follows;

*The statistic U_k is calculated using the following equation:

$$U_k = 2 \sum_{i=1}^k M_i - k(n + 1),$$

Where M_i is the rank of the i -th observation when X_1, X_2, \dots, X_n in the series are arranged in ascending order.

*The statistical change point test (SCP) is defined as: $K = \max_{1 \leq k \leq n} |u_k|$

* A break/ change point occurs at which U_k attains a maximum value of K .

The critical value is given by:

$$K_{\alpha} = [- \ln \alpha \times (n^3 + n^2) / 6]^2$$

4.2.4 Mann Kendall test (M-K Test)

The MK test is a non-parametric test commonly used to analyse the existence of trends in climatic variables (Mann,1945; Kendall 1975; Wang et al.,2020). This statistical method is primarily used to test the alternative hypothesis of the existence of a monotonic increasing or decreasing trend against the null hypothesis of no trend by using hydro-climatic time series data (Barai & Kalunge, 2021).

The Mann-Kendall test statistic(S) is calculated using the formula that follows (Mann, 1945)

$$S = \sum_{k=1}^n \sum_{j=k-1}^n \text{sign}(X_j - X_k)$$

Where, X_j and X_k are the annual values in year's j and k , $j > k$ respectively and X_k represent the data point at time k . here sign denotes the sign function.

Sign = +1 if $x_j - x_k > 0$

0 if $x_j - x_k = 0$

-1 if $x_j - x_k < 0$

The normalized test statistic Z is calculated using the following formula,

$$Z = \frac{(S+1)}{\sqrt{\text{variance}(S)}} \text{ if } S > 0$$

$$Z=0 \quad \text{if } S=0$$

$$Z = \frac{(S-1)}{\sqrt{\text{variance}(S)}} \text{ if } S < 0$$

In this study, the value of test statistics is computed at confidence level of 99, 95 and 90 per cent. At the 99 per cent significance level, the Null hypothesis of no trend is rejected if $|Z| > 2.575$; at the 95 per cent significance level, the Null hypothesis of no trend is rejected if $|Z| > 1.96$ and at the 90 per cent significance level, the Null hypothesis of no trend is rejected if $|Z| > 1.645$.

4.2.5 Sen's slope method

Sen (1968) established a simple non-parametric method that can be used to estimate the true slope, or change per unit of time, in a time series that exhibits a trend. To derive an estimate of the slope Q_t , the slopes of each pair of data were computed.

$$Qt = \frac{x_j - x_k}{j - k}, i=1,2, 3,..N, j>k$$

As many slope estimates, Qt, as $N = n(n-1)/2$, must be calculated if the time series contains n values of xj. This N values of Qt's median is the Sen's estimator of slope (Barai & Kalunge, 2021). The N values of Qt were ranked from the smallest to the largest and the Sen's estimate was computed as follows:

$$Qt = Q \frac{(N+1)}{2} \text{ If N is odd}$$

$$Qt = \frac{1}{2} Q \frac{(N)}{2} + Q \frac{(N+1)}{2}, \text{ If N is even}$$

Qt is the trend's magnitude, and it is the median of all slope values. Increased rainfall is indicated by positive values, and decreasing rainfall is shown by negative values.

4.2.6 Coefficient of Variation

From the mean and standard deviation, coefficient of variation (CV) is calculated as follows:

$$\text{Coefficient of Variation (CV)} = \frac{\text{Standard Deviation}}{\text{Mean}} \times 100$$

5.RESULTS AND DISCUSSIONS

5.1 Intra annual seasonality

Table 3: District wise SI and PCI

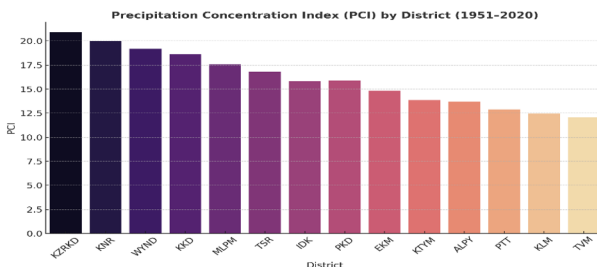
| District | SI (Seasonality Index) | PCI (Precipitation Concentration Index) |
|----------|------------------------|---|
| ALPY | 0.607 | 13.68 |
| EKM | 0.656 | 14.84 |
| IDK | 0.723 | 15.85 |
| KKD | 0.783 | 18.62 |
| KLM | 0.520 | 12.47 |
| KNR | 0.869 | 20.00 |
| KTYM | 0.611 | 13.87 |
| KZRKD | 0.916 | 20.92 |
| MLPM | 0.765 | 17.56 |
| PKD | 0.693 | 15.87 |
| PTT | 0.537 | 12.88 |
| TSR | 0.752 | 16.81 |
| TVM | 0.490 | 12.08 |
| WYND | 0.828 | 19.17 |

Source: Author's own computation

The Seasonality Index (SI) and the Precipitation Concentration Index (PCI) for each district in Kerala are displayed in the table 3, emphasizing spatial variations in the distribution of rainfall. A distinct spatial pattern may be seen throughout Kerala in the Seasonality Index (SI) values. Kasaragod (0.916), Kannur (0.869), and Wayanad (0.828) are examples of northern districts that are classified as highly seasonal, indicating a significant degree of rainfall variability and a considerable reliance on the Southwest monsoon. Due to the combined effect of the Southwest and Northeast monsoons, southern coastal districts such as Thiruvananthapuram (0.490) and Kollam (0.520) exhibit mild seasonality, indicating a more balanced rainfall regime. The intermediate SI values in mid-region districts like Alappuzha, Kottayam, and Pathanamthitta suggest a pattern of rainfall that transitions between the high seasonality in the north and the relatively uniform distribution in the south.

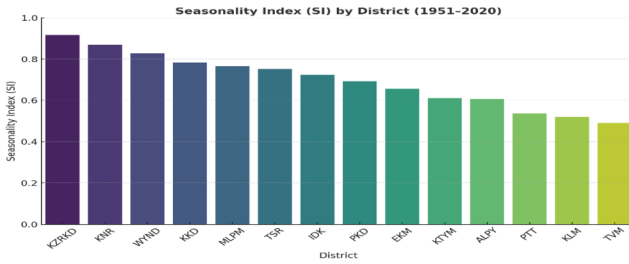
Northern districts, particularly Kasaragod (20.9), Kannur (20.0), and Wayanad (19.2), show strong concentration when the precipitation concentration index (PCI) is calculated. This implies that the majority of rainfall occurs during a few peak months, making them extremely vulnerable to severe monsoonal bursts and dry spells. The high PCI of 18.6 in Kozhikode further supports this northern concentration. On the other hand, southern coastal districts like Thiruvananthapuram (12.1) and Kollam (12.5) had lower PCI values, which suggests that the Northeast monsoon's increased contribution has resulted in a more even distribution of rainfall over the months. With the north mainly depending on the Southwest monsoon and the south enjoying the advantages of twin monsoon systems. The indices show notable intra-state variation in rainfall parameters overall, which has consequences for agriculture, disaster preparedness, and water resource management.

Figure 1: Precipitation Concentration Index- District wise



Source: Author's own computation

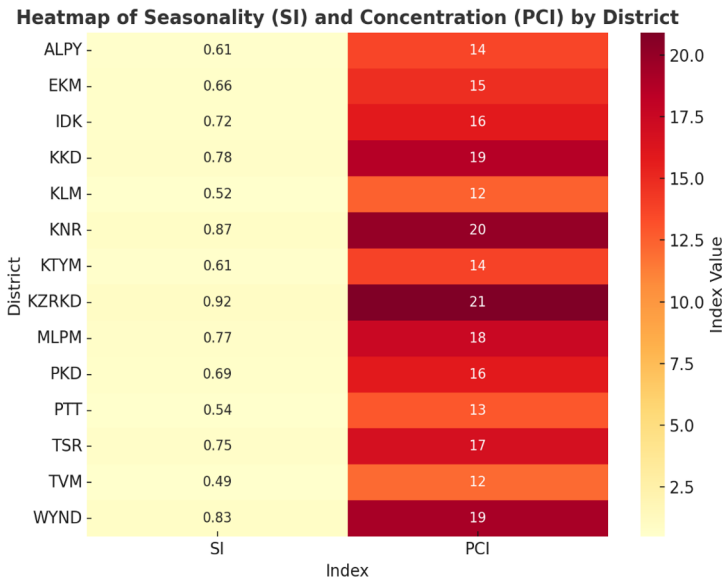
Figure 2: Seasonality Index (SI)- District wise



Source: Author’s own computation

The bar charts for the seasonality index and precipitation index are displayed in Figures 1 and 2, respectively. According to Figure 1, the Southwest Monsoon dominates the seasonal rainfall regimes in Kasargod, Kannur, Wayanad, and Kozhikode. Trivandrum, Kollam, and Pathanamthitta have the least amount of seasonality because of the extra rainfall during the Northeast Monsoon. Figure 2 confirms that rainfall is concentrated in fewer months in the northern and Ghat districts (Kasargod, Kannur, Wayanad, and Kozhikode) (PCI ~19–21). Trivandrum and Kollam, two southern coastal districts, exhibit lower concentration (PCI ~12), indicating a more evenly distributed rainfall.

Figure 3: Heatmap of SI & PCI



Source: Author’s own computation

Two distinct indicators (SI and PCI) are compared across different districts using the figure 3 heatmap. The key is the colour intensity: greater values are represented by darker colours (red and maroon) and lower values by lighter colours (yellow). According to the precipitation concentration index, the districts with the darkest colours on the map are Kasargod, Kannur, Kozhikode, and Wayand.

5.2 Divergent Trends in Southwest and Northeast Monsoons

The divergent trends in Southwest and northeast monsoons based on Pettitt test, Sen's slope and Mann Kendall's test is described in table 4. The Pettitt test indicated a possible break in 1964 for Kerala overall, although it was not statistically significant. The Sen's slope of -18.9 mm/decade suggests a weak drying tendency. It indicates that although there might be some drying pressure at the state level, it is not strong enough to be regarded as a significant change in the climate.

With a significant break in 1970 ($p = 0.0003$), Wayanad exhibits the most crucial signal. A Sen's slope of -147 mm/decade suggests intense, rapid drying. According to the Mann-Kendall test, Wayanad is a hotspot of susceptibility to declining rainfall, which is statistically significant ($p < 0.001$). This finding is consistent with broader evidence of rainfall declines in the highland areas of Kerala, which could have a significant impact on ecosystems, hydrology, and agriculture.

Table 4: Divergent Trends in Southwest and Northeast Monsoons

| Scale / District | Break Year (Pettitt) | Sen's Slope (mm/decade) | Mann-Kendall Significance | Interpretation |
|--------------------------|-------------------------------------|-------------------------|------------------------------------|----------------------------------|
| Kerala | 1964 (ns) | -18.9 | Not significant ($p = 0.48$) | Weak non-significant drying |
| Wayanad | 1970 ($p \approx 0.0003$) | -147 | Significant ($p < 0.001$) | Strong drying, highly vulnerable |
| Idukki | 1987 ($p \approx 0.09$, marginal) | $+21$ | Not significant | Slight increase, not significant |
| Thrissur | 1999 (ns) | -47.7 | Not significant | Moderate drying, not significant |
| Trivandrum | (not specified) | Negative slope | Not significant | Persistent drying, weak evidence |
| Kasargod, Kannur, | (varies) | Negative slopes | Not significant | Moderate drying |

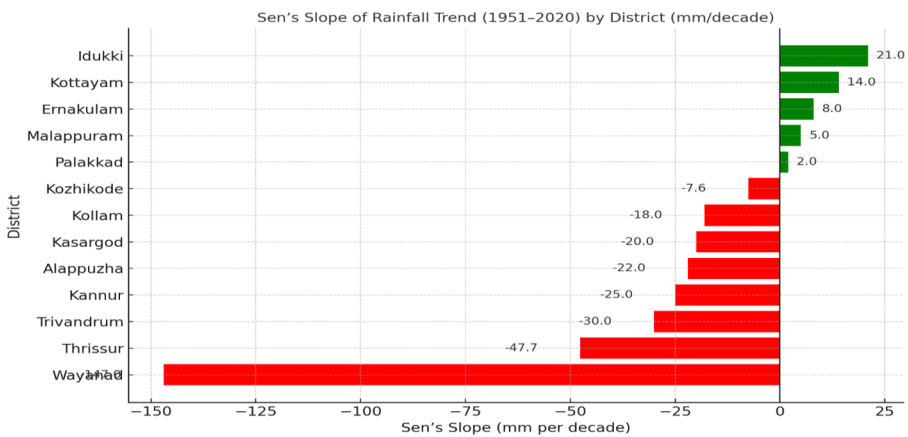
| | | | | |
|--|----------|--------------------------------|-----------------|-------------------------|
| Kozhikode, Kollam, Alappuzha | | | | |
| Kottayam, Malappuram, Palakkad, Ernakulam | (varies) | Slight positive/neutral slopes | Not significant | Stable / small increase |

Source: Author’s own computation

With a moderate positive slope (+21 mm/decade), Idukki shows an insignificant break year in 1987. However, rather than showing a substantial rising trend, this rise is statistically insignificant ($p = 0.67$), suggesting rainfall stability. Although not statistically significant ($p = 0.16$), the 1999 break in Thrissur corresponds to a moderate negative slope (-47.7 mm/decade). While there is no statistical proof, Trivandrum also exhibits a continual drying tendency, which is represented by a negative slope.

Figure 4 illustrates the long-term rainfall trends across districts using Sen’s Slope estimator, expressed in millimetres per decade. The coastal and northern districts, including Kasargod, Kannur, Kozhikode, and the coastal districts Kollam, and Alappuzha, generally show negative slopes, indicating mild drying; however, none of these are statistically significant. On the other hand, the slopes of Kottayam, Malappuram, Palakkad, and Ernakulam are slightly positive or close to neutral, suggesting either minor increases in rainfall or relative stability. These disparate results at the district level demonstrate how Kerala’s rainfall patterns vary geographically, with some areas experiencing increased vulnerability and others remaining mostly untouched.

Figure 4: Sen’s Slope -District Wise



Source: Author’s own computation

Table 5: Seasonal pattern of Southwest & Northeast Monsoon

| Season | Break Year | Sen's Slope (mm/decade) | MK Test | Interpretation |
|---------------------------------|-----------------|----------------------------|--|-------------------------------------|
| Southwest Monsoon (JJAS) | 1975 (ns) | -10 | Not significant ($\tau = -0.039$, $p = 0.63$) | Gradual weakening of main monsoon |
| Northeast Monsoon (OND) | 1991 (marginal) | +2.6 | Not significant (weak positive) | Slight strengthening, esp. in south |

Source: Author's own computation

While analysing the seasonal pattern of the southwest and northeast monsoons (Table 5), a slight decreasing trend is observed in the southwest monsoon, which accounts for the majority of Kerala's annual rainfall. The Pettitt test identifies a potential break of southwest Monsoon in 1975; however, it is not statistically significant. The Sen's slope indicates a modest decrease of -10 mm per decade, although this decline is not statistically significant according to the Mann-Kendall test ($\tau = -0.039$, $p = 0.63$). It implies that, although there are indications of a decrease in rainfall during June-July-August-September (JJAS rainfall), the trend is not a significant long-term decrease, but rather a mild one that falls within the range of natural variability.

The Northeast Monsoon, on the other hand, shows a slight break in 1991, which is when the rainfall patterns in southern Kerala began to change. Although statistical significance is not confirmed by the Mann-Kendall test, the Sen's slope of +2.6 mm per decade indicates a minor increasing trend. A possible intensification of October-November-December (OND rainfall), especially in the southern districts, is indicated by this small positive signal. This pattern aligns with local and regional findings that OND is becoming increasingly significant in Kerala's seasonal rainfall distribution, although the difference is not statistically significant.

5.3 Monthly Trend in District Rainfall.

The significant negative trend results are listed in Table 6, and the significant positive trend results are listed in Table 7. The July rainfall showed significant decreasing trends for 7 districts, Wayanad with 99 percent significance and Sen's slope -9.88 mm precipitation.

Kannur, Kasargod, Thrissur, Kollam, and Thiruvananthapuram are also showing significant decreasing trends with a 95 percent significance level, while Kozhikode shows a significant decreasing trend of a 90 percent significance level. Alappuzha, Kottayam, and Wayanad also show significant negative trends for the June month with a 95 percent significance level. Wayanad district shows a significant decreasing trend of August rainfall, also with a 90 percent significance level. Thrissur, Palakkad, and Kannur are the districts where the decreasing trend in precipitation for the month of April is evident. At a 95% significance level, precipitation in May also shows a falling trend in Palakkad and Thrissur.

Table 6: Districts showing Significant Negative Trends

| District | Month/Season | Z | Significance Level | Q |
|-----------|-----------------------|--------|--------------------|---------|
| Kasargod | July | -2.453 | ** | -3.919 |
| Kannur | April | -2.007 | ** | -4.809 |
| | July | -2.453 | ** | -3.91 |
| Kozhikode | July | -1.754 | * | -3.71 |
| Wayanad | Annual | -3.771 | *** | -14.73 |
| | Southwest | -3.680 | *** | -13.02 |
| | June | -2.038 | ** | -3.177 |
| | July | -4.46 | *** | -9.888 |
| | August | -1.804 | * | -2.366 |
| Palakkad | April | -2.35 | ** | -0.733 |
| | May | -2.210 | ** | -1.041 |
| | Past 30 year – Annual | -1.96 | * | -22.40 |
| | April | -2.048 | ** | -0.5807 |
| | May | -2.195 | ** | -1.95 |

| | | | | |
|--------------------|------|---------|----|-------|
| Thrissur | July | -2.18 | ** | -3.84 |
| Kottayam | June | -1.992 | ** | -2.45 |
| Alappuzha | June | -1.992 | ** | -2.45 |
| Kollam | July | -2.0178 | ** | -1.8 |
| Thiruvananthapuram | July | -2.13 | ** | -1.52 |

Source: Authors own computation

*** significant at 99 percent, ** significant at 95 percent, * significant at 90 percent

Table 7: Districts Showing Significant Positive Trends

| District | Month | Z | Significance Level | Q |
|--------------------|-----------|-------|--------------------|--------|
| Wayanad | March | 1.946 | * | 0.2545 |
| Malappuram | March | 1.648 | * | 0.114 |
| | September | 1.647 | * | 1.381 |
| Thiruvananthapuram | November | 1.987 | ** | 1.0777 |

Source: Authors own computation

*** significant at 99 percent, ** significant at 95 percent, * significant at 90 percent

Only three districts showed significant positive trends of rainfall over various months, which are Wayanad, Malappuram, and Thiruvananthapuram (table 7). Malappuram and Wayanad showed an increase in the summer rainfall in the month of March with a 90 percent significance level. Even though both the districts showed a positive trend, the Sen's slope value is comparatively low as it takes the values 0.2545 and 0.114 mm per month.

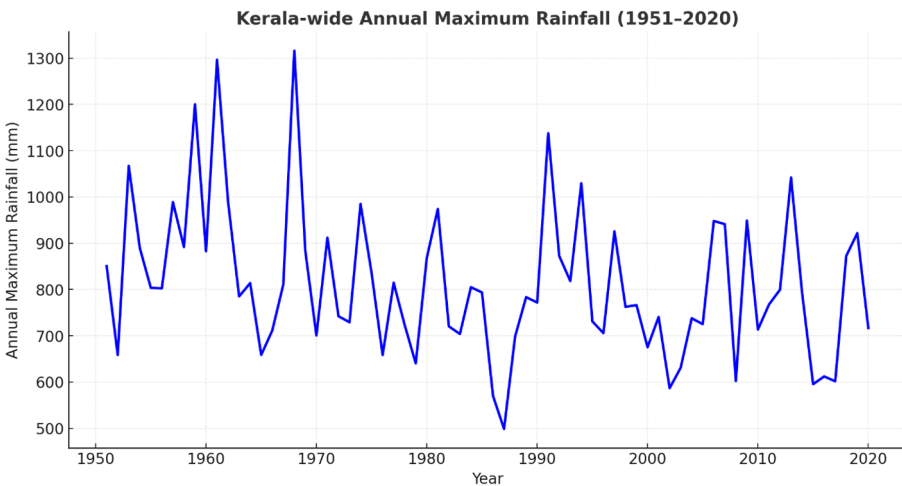
September rainfall also showed a positive trend for Malappuram district with a 90 percent significance level. Whereas November rainfall for Thiruvananthapuram district showed a significant positive trend with 95 percent significance.

5.4 Rainfall Variability and Extremes

Kerala's annual maximum rainfall from 1951 to 2020 is depicted in the figure 5. Its extreme degree of year-to-year unpredictability is its most important aspect. The annual maximum

rainfall trend, when averaged across districts, exhibited episodic extremes rather than a distinct monotonic increase or decrease. Extremely powerful monsoon seasons were evident in the late 1950s and late 1960s, when the highest rainfall maximums (over 1300 mm) were recorded. A significant trough, with a record low of about 500 mm, was observed in the mid-1980s, indicating a time of less intense rainfall occurrences. The rainfall maximums after the peak in the 1990s seem to be less powerful overall, but they still fluctuate significantly, underscoring the region's extreme rainfall events' unpredictability.

Figure 5: Kerala-Wide Annual Maximum Rainfall



Source: Author's own computation

5.5 District-Level Weather Extremes

The district-level weather extremes are shown in table 8. The rainfall CV values for the southern, central, and northern districts of Kerala show distinct spatial differences. With comparatively low CV values, southern districts like Trivandrum (Mean CV \approx 88.81, Max CV \approx 94.35) and Pathanamthitta (Mean CV \approx 83.36, Max CV \approx 89.82) show consistent rainfall with slight variations. Kottayam (Mean CV \approx 92.62, Max CV \approx 101.93) and Ernakulam (Mean CV \approx 101.10, Max CV \approx 110.89) are examples of central districts that exhibit relatively more variation but remained within a comparatively stable range.

The northern districts, on the other hand, show significantly greater CV values, which are indicative of extremely seasonal and unpredictable rainfall patterns of particular importance to

their great variability are the districts of Kasaragod (Mean CV \approx 131.77, Max CV \approx 140.90), Kannur (Mean CV \approx 130.46, Max CV \approx 136.26), and Wayanad (Mean CV \approx 127.77, Max CV \approx 143.08). Similarly, very high maximum CV values have been obtained in Malappuram (Mean CV \approx 121.02, Max CV \approx 153.36) and Thrissur (Mean CV \approx 118.50, Max CV \approx 153.55), showing significant rainfall variability.

Table 8: District-Level Weather Extremes

| District | Mean CV | Max CV |
|----------|-------------|-------------|
| ALPY | 95.26454608 | 113.0302163 |
| EKM | 101.1013731 | 110.8964936 |
| IDK | 109.5394987 | 143.5308855 |
| KKD | 125.0362902 | 131.207205 |
| KLM | 86.96795388 | 114.3859637 |
| KNR | 130.4691155 | 136.2649442 |
| KTYM | 92.62309318 | 101.9393245 |
| KZRKD | 131.7773433 | 140.9021887 |
| MLPM | 121.0200967 | 153.36281 |
| PKD | 112.8649897 | 128.7895376 |
| PTT | 83.36158345 | 89.82895973 |
| TSR | 118.5038636 | 153.5598503 |
| TVM | 88.81380137 | 94.35994478 |
| WYND | 127.7774161 | 143.0871496 |

Source: Author's own computation

5.6 The Onset and Withdrawal Pattern of Monsoon

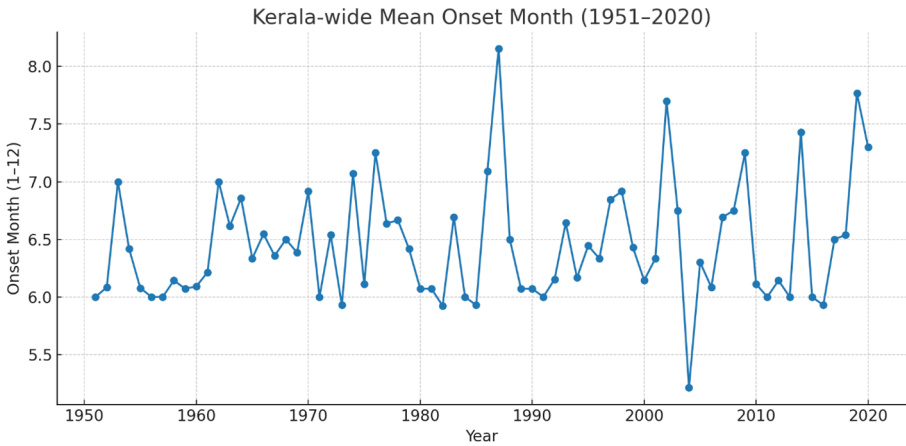
The interannual variability of the onset and withdrawal pattern of the monsoon over the years is shown in figure 6 and figure 7.

The monsoon onset months for the entire state of Kerala from 1951 to 2020 show significant interannual variability, with onset generally taking place between June (month 6) and July (month 7). Around June, with only a little delay into July, the monsoon onset stayed comparatively constant over the early decades (1950-1970s).

This period of time can be considered as having relatively less variability, indicating a more predictable onset phase. There was a significant increase in the variability in onset months starting in the early 1980s. The most notable instance occurred in 1987–1988, resulting in a significant delay, with the mean onset shifting to around August (month 8). During this time, the regular monsoon cycle was disturbed by the well-known drought of 1987, which was closely associated with an El Niño event. The onset months have been extremely fluctuating

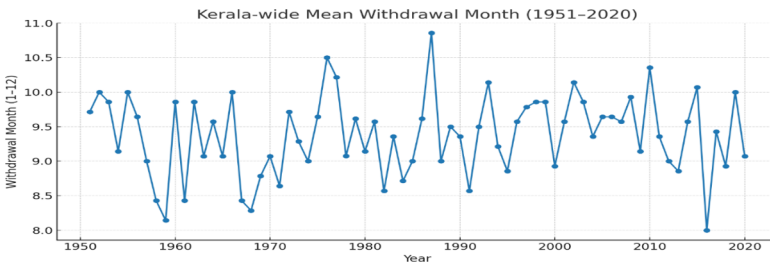
over the last 20 years (2000–2020), with some years exhibiting early arrivals (May 2003) and others registering delays into late July. The lack of a steady long-term trend toward either an earlier or later arrival suggests that monsoon timing is becoming increasingly unpredictable. The results indicate that although there has been no systematic shift in the mean onset month, the increasing dispersion of onset dates creates difficulties for the state's agriculture and water resource management, as farming calendars are strongly dependent on the consistency of monsoon rainfall. According to the climatological norms for the retreat of the southwest monsoon over Kerala, the withdrawal usually takes place around October (month 10). Nonetheless, the data shows notable variations from year to year, with withdrawal months varying from August (month 8) to November (month 11).

Figure 6: The Onset Pattern of Monsoon



Source: Author's own computation

Figure 7: The Withdrawal Pattern of Monsoon



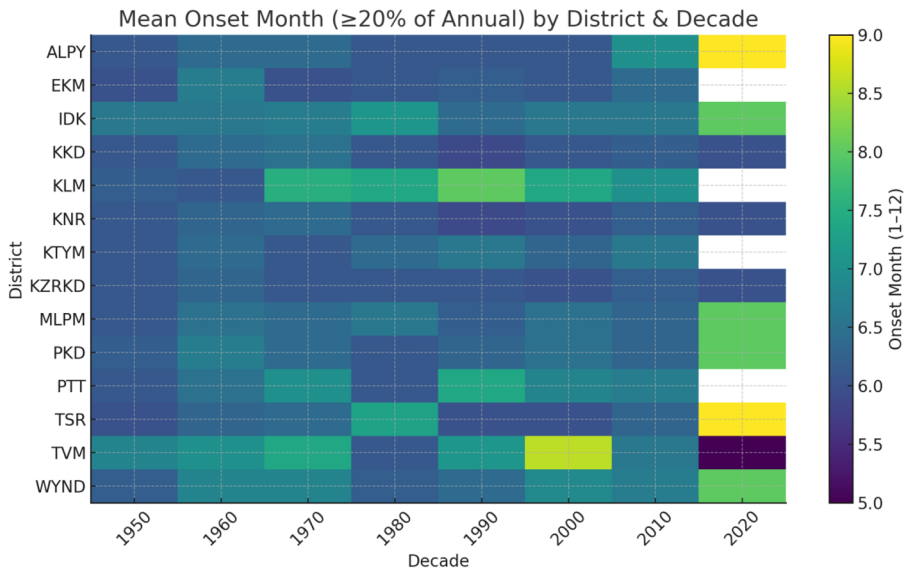
Source: Author's own computation

When the temporal trend is examined in greater detail, it becomes clear that early withdrawals were quite prevalent in the 1950s and 1960s, frequently taking place by September. On the other hand, there was more variation in the following decades, especially in the 1970s and 1980s, with instances of retreats that occurred both earlier and much later. The 1987 El Niño event, well known for its extensive effects on drought, coincided with one of the most significant delayed withdrawals (Krishnamurti et al., 1989).

While the mean withdrawal month continued to cluster around October starting in the 1990s, there were more frequent outliers, with some years showing both abnormally early and late occurrences.

With exceptional late retreats in November, the 2000s decade (2000-2010) was characterized by a series of withdrawals that were almost regular, usually occurring in October. Following 2010, there is an increase in variability, with trends of late withdrawals (2011, 2017, 2019) and early withdrawals (2016) alternating. This is indication of an unpredictable phase in which the monsoon does not withdraw according to a regular pattern.

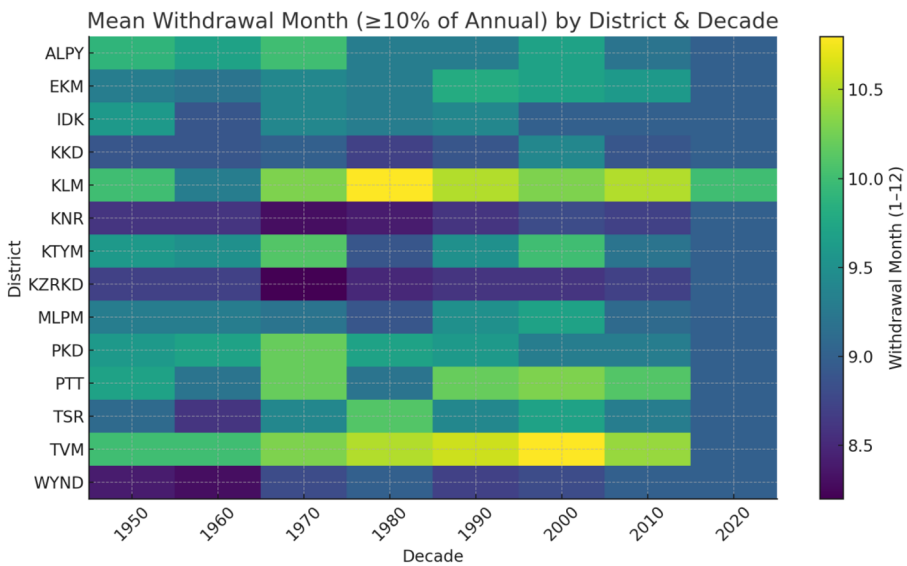
Figure 8: District wise Decadal Shifts in Monsoon Onset



Source: Author's own computation

District wise analysis of monsoon onset (figure 8) shows that Thrissur (TSR) and Alappuzha (ALPY) exhibit a particularly significant delay in the most recent decades, with the mean onset month shifting to as late as August or September, whereas Trivandrum (TVM) shows an early onset. District wise analysis of withdrawal (figure 9) suggests that while northern districts like Wayanad (WYND) and Kannur (KNR) typically exhibit earlier withdrawal patterns in multiple decades, districts like Kollam (KLM) and Thiruvananthapuram (TVM) show comparatively late withdrawal patterns, frequently extending into October and November. There is an apparent temporal variation between the decades, suggesting that withdrawal timings are impacted by broader environmental factors rather than being static.

Figure 9: Decadal Shifts in Monsoon withdrawal- District wise



Source: Author’s own computation

6.POLICY IMPLICATIONS

The research yields significant policy ramifications for climate-oriented planning and sustainable development in Kerala. The observed long-term fluctuations in precipitation, the growing disparity between the southwest and northeast monsoons, and the rising frequency of climatic extremes underscore the urgent need for micro-level, region-specific, and seasonally adapted water resource management plans. The districts of Kasargod, Kannur, and Wayanad exhibit significant rainfall seasonality and concentration, as indicated by the SI and PCI,

necessitating targeted interventions in local planning. The local level planning must include rainwater harvesting, better reservoir operation methods, and a better groundwater recharge mechanism to mitigate flood risks during peak monsoon months and water stress during the summer season. The shifts in monsoon onset and withdrawal over the 1990s highlight growing climatic unpredictability, demanding improvements in climate monitoring, early warning systems, and catastrophe planning frameworks. The present variation in Kerala's rainfall patterns requires the integration of region-specific climate adaptation strategies into long-term agricultural planning, environmental conservation, and water resource management policies.

7.CONCLUSION

The comprehensive examination of seasonality, monsoon dynamics, and rainfall variability a cross Kerala reveals significant intrastate differences that are influenced by both fundamental climatic factors and geographic location. With rainfall concentrated in a few peak months, northern districts like Kasaragod, Kannur, and Wayanad continue to be highly seasonal, rendering them especially susceptible to water stress and climate extremes, according to the Seasonality Index (SI) and Precipitation Concentration Index (PCI). The combined effect of the Southwest and Northeast monsoons, on the other hand, benefits southern coastal districts by ensuring a more evenly distributed rainfall. Kerala does not show a statistically significant decline in rainfall in general, according to long-term trend analysis employing the slope approaches developed by Pettitt, Mann-Kendall, and Sen. However, there are some districts, like Wayanad, where rainfall has significantly decreased, endangering ecosystems and agriculture. With delayed onsets and changed withdrawal dates in some districts after the 1990s, changes in monsoon commencement and withdrawal further highlight growing unpredictability and reflect larger indicators of climatic variability. All of these findings pointed to a slow but substantial change in Kerala's rainfall regime, which has consequences for agriculture, disaster preparedness, and longterm water resource management. Plans for climate adaptation that are suitable for that region are therefore necessary.

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