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Recent Rainfall Patterns and Their Consequences in Kerala: A Comprehensive Review

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Abstract: *Kerala, located on the southwest coast of India, has experienced increasingly erratic rainfall patterns in recent years, driven by global climate change, monsoonal variability, and anthropogenic influences. This review synthesizes recent findings on rainfall variability in Kerala, examines the socio-economic and environmental consequences of such changes, and discusses the associated vulnerabilities and recommended adaptation strategies. Using recent case studies and climatological data, the implications for agriculture, infrastructure, health, and disaster preparedness are examined.*

Key Word: *Rainfall variability, Floods, Climate change, Landslides, Monsoon*

I.INTRODUCTION

The Indian state of Kerala, located on the southwestern coast of India, consists of 14 districts and features a 580 km coastline, extensive agricultural lands, and the ecologically sensitive Western Ghats, a UNESCO World Heritage Site. Its topography and location make it highly sensitive to climatic variations. Kerala receives its first rains in late May or June and has an average annual rainfall of approximately 3107 mm, with orographic effects causing variability from 1250 mm in lowlands to over 5000 mm in the highlands.

Kerala is the first Indian state to receive monsoon rains, as the Southwest monsoon splits into Arabian Sea and Bay of Bengal branches, due to the Western Ghats. The state has 44 major rivers, most of which are monsoon-fed and characterized by fast flow and seasonal fluctuation, making it highly vulnerable to flooding. Kerala has experienced a series of consecutive extreme events—notably in 2018, 2019, 2020, and 2024—with widespread impacts on livelihoods, infrastructure, and ecosystems. These recurring flood events underscore the urgent need for resilient strategies and informed planning.

II.RAINFALL TRENDS IN KERALA

1. Temporal and Spatial Patterns

Analysis of rainfall data from 1901 to 2022 reveals notable changes in monsoon behavior. Early onset and late withdrawal, coupled with increased short-duration high-intensity rainfall events, have altered Kerala's hydrological profile. Notably, rainfall during June has decreased while the intensity during July–September has increased. Furthermore, a decline in the number of rainy days has been observed in many districts, despite a higher total rainfall— indicating a shift towards more intense downpours in shorter periods.

Table 1: Monthly Rainfall Distribution Trends (2010–2024)

Month	Avg Rainfall (mm)	Trend
June	640	Decreasing ↓
July	820	Increasing ↑
August	870	Increasing ↑
September	690	Increasing ↑

2. Recent Extremes

- In May 2025, Kerala recorded 126.7 mm of rainfall, the highest in 124 years.
- In July 2024, Wayanad received over 572 mm of rainfall in 48 hours, triggering catastrophic landslides.
- Ernakulam district recorded 20 cm of rain in a single day in June 2022, leading to urban flooding and the closure of public institutions.
- The 2018 flood was one of the worst in a century, with August rainfall exceeding 164% of the norm.

3. Drivers of Rainfall Variability

Rainfall anomalies in Kerala have been attributed to a complex interplay of global and regional climatic, ecological, and anthropogenic factors. One of the primary drivers is global warming, which alters atmospheric circulation patterns and intensifies the hydrological cycle. Warmer oceans and increased surface temperatures contribute to higher evaporation rates and moisture content in the atmosphere, resulting in more intense but uneven precipitation events. This has led to the increased frequency of short-duration, high-intensity rainfall observed in Kerala in recent years. A weakening of the Indian summer monsoon circulation, linked to warming in the Indian Ocean and a declining land- sea thermal contrast, has also been documented. These changes lead to erratic monsoon onset, prolonged breaks, and disrupted intra-seasonal rainfall distribution. The shifting location of the Intertropical Convergence Zone (ITCZ) and altered monsoon trough dynamics further complicate rainfall predictability. Land-use changes—notably deforestation, hill-cutting, and urban expansion — have substantially modified local microclimates. These activities reduce evapotranspiration, increase runoff, and undermine the natural water-absorbing capacity of the terrain, especially in the Western Ghats. This contributes to reduced orographic rainfall efficiency and an increased incidence of landslides and flash floods in hill districts. Urban centers like Kochi and Thiruvananthapuram have seen the emergence of urban heat islands, caused by extensive concrete infrastructure and diminished green spaces. These localized hotspots interact with monsoonal moisture to trigger convective storms, leading to frequent, and intense urban flooding. On a broader scale, convective atmospheric waves such as the Madden-Julian Oscillation (MJO) significantly influence intra-seasonal rainfall variability by enhancing or suppressing convection across the Indian subcontinent. The Indian Ocean Dipole (IOD) also plays a pivotal role; positive IOD phases (warmer western Indian Ocean) strengthen monsoon activity over southwest India, while negative phases dampen it. In addition, solar activity cycles, including fluctuations in sunspot numbers and total solar irradiance, are thought to influence long-term monsoon behavior. Lower solar activity is associated with weaker monsoon currents and irregular rainfall patterns, although this relationship remains under continued investigation.

Together, these dynamic and interlinked factors have disrupted Kerala's historical rainfall regularity, contributing to the dual challenge of drought spells and extreme precipitation events, both of which pose serious threats to agriculture, water security, and disaster preparedness in the region.

III.CONSEQUENCES OF RAINFALL EXTREMES

1. **Flooding and Infrastructure Damage -** The 2018 and 2019 floods caused damage exceeding USD 5.5 billion, displacing over 1.4 million people. Urban areas such as Kochi and Thiruvananthapuram frequently experience waterlogging due to poor drainage systems. Major roads, bridges, and rail networks face recurrent disruptions, affecting daily commutes and emergency services. Additionally, the collapse of poorly maintained buildings has led to casualties and long-term displacement.

2. **Landslides and Geohazards -** The Western Ghats region, especially Wayanad and Idukki, has seen a rise in landslide events. Increased slope modification, deforestation, and construction have worsened the situation. In 2020, the Pettimudi landslide claimed 66 lives. The high vulnerability zones identified by the Geological Survey of India (GSI) emphasize the need for stricter land-use regulation. Soil loosening due to heavy rain and unplanned tourism activities have also contributed to slope instability.

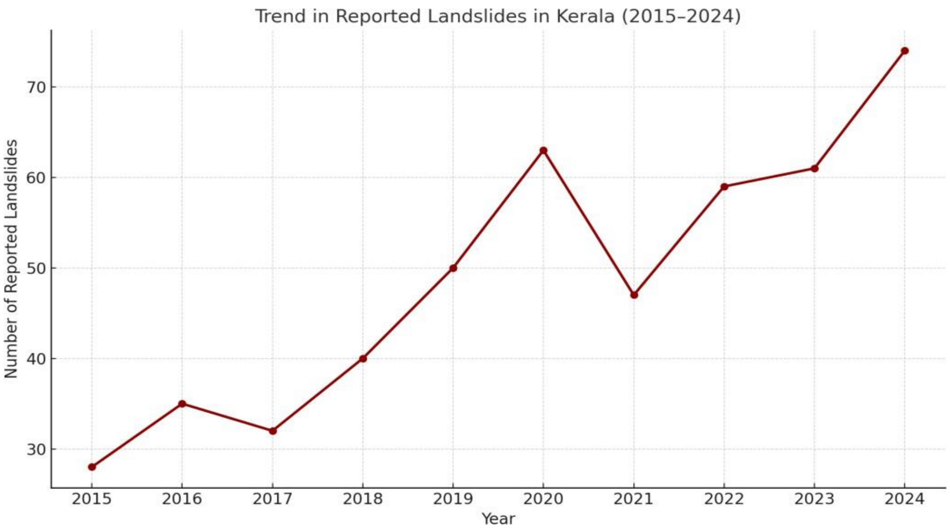

Figure 1: Trend in Reported Landslides in Kerala (2015–2024)

3. **Agricultural Impacts -** Rice, banana, and pepper yields have declined in flood-prone districts. Flash floods damage paddy fields, disrupt planting schedules, and erode topsoil. Traditional farming calendars are no longer reliable, and crop insurance claims have increased. Climate-resilient crop varieties are being trialed to mitigate losses. However, farmers face barriers in adopting new technologies due to cost and lack of awareness. Organic farming practices are being re-evaluated to ensure climate compatibility.

4. **Public Health and Nutrition -** Floods have led to outbreaks of leptospirosis and dengue. Malnutrition rates in children increased in flood-affected districts due to disrupted food supply and sanitation. The stress on primary health centers during flood periods leads to resource constraints. Additionally, stagnant water contributes to vector-borne diseases, and there has been a noted rise in mental health issues such as PTSD and anxiety following repeated displacement.

IV.VULNERABILITIES AND RISK FACTORS

Ecological Fragility: Kerala's dense population and development pressures have compromised ecological buffers such as wetlands and forests. Wetland reclamation for real estate and agriculture has significantly reduced water retention capacity, increasing runoff and flood intensity. Encroachment into river banks and hill slopes has made many regions susceptible to flash floods and debris flows.

Flood Vulnerability by District: Simulated data shows that Pathanamthitta, Idukki, and Wayanad face the highest levels of flood vulnerability. These areas are also most affected by terrain-related risks and inadequate drainage infrastructure.

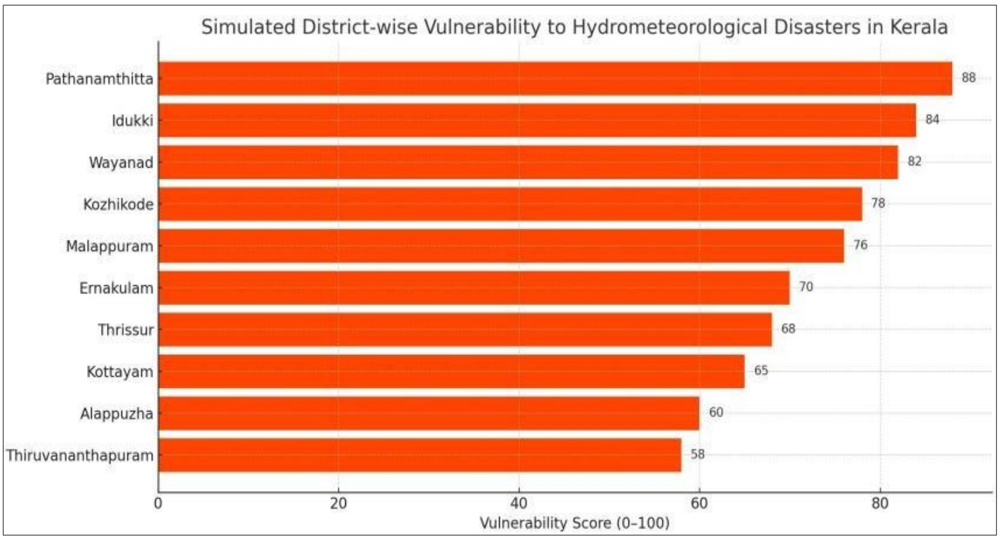

Figure 2: Simulated Flood Vulnerability by District

Governance Gaps: Despite repeated disasters, urban planning and disaster management systems have not sufficiently evolved. Many local bodies lack climate-risk zoning and resilient infrastructure frameworks. The lack of data-sharing between agencies and poor coordination during emergencies amplify the impact of disasters. Environmental impact assessments (EIAs) are often bypassed in favor of rapid development.

V.ADAPTATION AND MITIGATION STRATEGIES

1. **Early Warning Systems -** Investments in Doppler radar, real-time flood forecasting models, and mobile alert systems have shown promise but remain underutilized in remote areas. Community-based alert networks are gaining traction and can bridge the last-mile communication gap. Enhanced collaboration between IMD, KSDMA, and local governance bodies is essential.

2. **Land Use and Urban Planning -** Policy measures to restrict construction on slopes and flood plains must be strictly enforced. Integrated watershed management is essential. Urban local bodies must update building codes, regulate hill station tourism, and prioritize green infrastructure like rain gardens and pervious pavements.

3. **Agricultural Innovations -** Climate-resilient varieties (e.g., KAUM 179-1 rice) and alternate wet-dry irrigation methods are being promoted. Farmer resilience indices can help target assistance. Hydroponics, rooftop farming, and AI-based crop monitoring tools are being explored in research hubs such as Kerala Agricultural University.

4. **Community Engagement and Education -** Public awareness campaigns, community-based disaster preparedness, and school curriculum integration are crucial for long-term resilience. NGOs and panchayats must work in tandem to build local capacity. Periodic mock drills, climate literacy programs, and disaster volunteer teams can greatly reduce vulnerability.

VI.CONCLUSION

Kerala's changing rainfall patterns represent a clear manifestation of climate variability and underscore the need for comprehensive adaptation strategies. With increasing extremes, the state's ecological, infrastructural, and socio- economic systems are under stress. A multi-pronged, science-driven, and participatory approach is essential for sustainable resilience. The integration of traditional ecological knowledge with modern climate science can offer innovative solutions.

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