

# Hydro-Meteorological Behavior and Intensifying Rainfall Extremes in the Kullu District, Himachal Pradesh

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## ABSTRACT

The Kullu district of Himachal Pradesh has seen significant changes in hydro-meteorological conditions over the past few years, including rainfall variability and extreme weather events. The study focuses on rainfall patterns at the Kullu and Manali stations in the district, using daily rainfall data for 20 years (2005-2024), and on the evaluation of the spatial rainfall pattern for 2020-2024 through GIS analysis. The non-parametric Mann-Kendall test and Sen's slope estimator were performed to check the trend analysis of the rainfall pattern. The findings show a weak but consistent positive trend in annual rainfall at both stations, with Sen's slope indicating a yearly rise of 6-10 mm. Seasonal analysis revealed increases in monsoon and post-monsoon rainfall, but a reduction in winter precipitation. The GIS maps of spatial rainfall indicate an expansion of high rainfall zones (>1200 mm) across the district over the past 5 years. Along with this, a slope map generated shows that the region has more than 55% of its landmass under the steep terrain category with slopes greater than 30 degrees. These results show that there has been a rise in wet years, greater rainfall magnitudes, and intensifying extreme events, indicating a wetter hydroclimatic future. These results are consistent with the IPCC AR6 reports for the western Himalayas and underscore the importance of improved monitoring, disaster preparedness, and climate-based planning in the region.

**Key words:** Kullu region, Rainfall variability, Mann-Kendall test, Sen's slope estimate, Extreme rainfall, GIS, Hydro-Meteorological hazards, Slope map

## INTRODUCTION

The increasing climate variability and rise in extreme rainfall events across mountain systems worldwide have led to more frequent hydro-meteorological disasters (Kundzewicz and Jania 2007, Loukas et al. 2021). In the Indian Himalayan Region, changing monsoon behaviour, higher moisture availability, and warming trends are intensifying climatic impacts, making these mountains highly sensitive to disturbances (Negi et al. 2012, Dimri et al. 2021). IPCC AR6 reports indicate that the Himalayas are expected to face greater rainfall variability, stronger precipitation extremes, and more frequent hydrological hazards. These shifts pose significant risks for the fragile Kullu basin, where steep terrain and human-induced pressures amplify the effects of climatic events (Prasad et al. 2016).

Kullu district, located in Himachal Pradesh, is characterized by steep slopes, narrow valleys, and a mix of humid subtropical to alpine climatic zones. The region has repeatedly experienced hydro-meteorological hazards, including cloudbursts, flash floods, landslides, and mudflows. These events have caused substantial loss of life and widespread damage to infrastructure in recent years (Thakur et al. 2023). In 2023 alone, Himachal Pradesh recorded losses exceeding 120 billion rupees due to landslides, road collapses, riverbank erosion, and structural damage. Kullu was among the worst affected, experiencing major disruptions to roads, tourism, agriculture, and local livelihoods (Chandel 2025, Kasiviswanathan et al. 2025). Similar destructive events have been observed across the state in earlier decades as well (Nagamani et al. 2024).

Globally, India accounts for 12–15% of water-related disasters, many of which occur in the Himalaya. Mountainous countries such as Nepal, Japan, China, and Indonesia also face similar challenges, with steep slopes and heavy rainfall frequently triggering natural hazards (Anonymous 2015). Such global patterns highlight how rainfall intensity, fragile terrain, and structural instability collectively drive mountain disasters.

In Kullu, these events cause loss of life, damage to homes and roads, disrupt tourism and agriculture, and create financial pressure on communities (Thakur 2021). Landslides can isolate villages, interrupt essential services, damage hydropower projects, and alter river courses. Despite several studies on Western Himalayan rainfall, long-term valley-level assessments for Kullu remain limited. With rapid development, expanding infrastructure, and increasing tourism, understanding local rainfall behaviour has become crucial.

This study addresses this gap by analysing twenty years of rainfall data supported by GIS-based rainfall maps. Using the Mann-Kendall test, Sen's slope, and IMD gridded data for 2020–2024, it examines long-term trends and spatial rainfall variation. Combined with slope and terrain assessments, the findings offer valuable insights for planning, disaster preparedness, and climate-sensitive development in the Kullu region.

## MATERIALS AND METHODS

### Study area

Kullu district (5503 km<sup>2</sup>) ranges from 1089 to 6632 m in elevation and had a population of about 0.44 million in 2011. Most residents depend on agriculture, horticulture, tourism, and hydropower projects along the major rivers. The region faces frequent climate-related disasters, including heavy rainfall, floods, landslides, and soil erosion, resulting in repeated loss of life, damage to homes, roads, and crops, and lengthy disruptions to tourism and local livelihoods.

### Data sources

Daily rainfall data for Kullu and Manali (2005–2024) were obtained from IMD Pune, quality-checked, and used to compute long-term averages of 1049.25 and

1105.83 mm, respectively. Spatial rainfall maps were created in ArcGIS using interpolation, raster classification, and zonal statistics. The slope map was prepared from DEM data downloaded from the Bhoonidhi portal (Anonymous 2025) and classified into slope categories.

### Statistical analysis

The Mann-Kendall test and Sen's slope method were used to examine long-term rainfall trends using R software (version 4.5.2) with the 'trend' and 'Kendall' package (Mann 1945, Kendall 1975, Sen 1968). The MK statistic (Z) and p-value indicate the trend's direction and statistical significance, while Sen's slope measures the rate of increase or decrease in rainfall. Positive values indicate increasing rainfall; negative values indicate declining rainfall.

### GIS analysis

GIS techniques were used to prepare annual rainfall maps (2020–2024) grouped into five ranges: <800 mm, 801–1000 mm, 1001–1200 mm, 1201–1400 mm and >1400 mm. Zonal statistics were applied to calculate the area under each rainfall class and study yearly variation. The slope map was included to understand terrain characteristics and identify areas more vulnerable to rainfall-induced hazards.

## RESULTS

### Mann-Kendall and Sen's slope trend analysis

The Mann-Kendall test results show that both Kullu and Manali have a weak increasing trend in annual rainfall. The Z-values for Kullu (1.13) and Manali (1.52) point toward a rise, but not a strong one. The p-values for both stations (0.25 for Kullu and 0.12 for Manali) are higher than the 95% confidence level, indicating that the trends are not statistically significant. Sen's slope also shows a positive value for both places, with Kullu at +6.32 mm per year and Manali at +10.03 mm per year, indicating that rainfall is increasing slightly over time, even though the change is not strong enough to be considered significant (Tables 1, 2). The present analysis showed that rainfall is becoming more irregular, with bigger swings between dry and wet years. Even though rainfall is changing, the trend is not very strong in the statistical tests because the region naturally

Table 1: Mann-Kendall and Sen's slope trend

Statistic	Kullu	Interpretation	Manali	Interpretation
Z	1.13	Weak increasing trend	1.52	Weak increasing trend
p-value	0.25	Not significant	0.12	Not significant
Sen's Slope	+6.32	Increasing	+10.03	Increasing

Table 2. Rainfall seasonal trend and Sen's slope statistics for Kullu and Manali

Season	Z-value		p-value		Sen's slope (mm/year)	
	Kullu	Manali	Kullu	Manali	Kullu	Manali
<b>Monsoon</b>	1.07	0.87	0.28	0.38	6.67	7.16
<b>Post-Monsoon</b>	0.29	0	0.77	1	0.79	0.42
<b>Pre-Monsoon</b>	1.46	1.58	0.14	0.11	5.48	8.24
<b>Winter</b>	-0.68	-0.16	0.49	0.87	-2.94	-1.87

experiences large year-to-year climatic fluctuations.

### Seasonal rainfall trends

Seasonal analysis shows increasing rainfall during the monsoon and post-monsoon seasons, marginal increases during pre-monsoon months, and a slight decline in winter precipitation. The enhanced monsoon contribution suggests rising dependence on monsoon rainfall for annual totals.

### Slope characteristic

The slope distribution of the study area indicate that moderate to steep terrain (15–45°) occupies a significant portion of the region, while gentle slopes (0–15°) are limited to valley floors. Very steep slopes above 45° occur mainly in the upper mountainous zones. Most of the area falls within steep and very steep slopes, which make the land sensitive to erosion and landslides and restrict safe construction. Only a smaller portion has gentle or moderate slopes, where farming and settlements are more feasible (Fig. 1).

### Annual rainfall variability (2005–2024)

The annual rainfall in the Kullu region does not remain constant; it varies from year to year. In Kullu, the lowest rainfall was 656.08 mm in 2009, while the highest was 1462.95 mm in 2011. At Manali, rainfall ranged from 726.87 mm in 2005 to 1369.21 mm in 2023. Overall, the years from 2015 to 2024 have been slightly wetter than the period from 2005

to 2014, suggesting the monsoon has become marginally stronger in recent years (Fig. 2).

### Spatial rainfall variability (2020–2024)

Spatial rainfall maps reveal an apparent intensification of rainfall zones across the Kullu region. In 2020, moderate rainfall (1000–1200 mm) dominated the area with isolated high-rainfall patches. By 2022 and 2023, high-rainfall zones (>1200 mm) expanded significantly across the central and western parts of the valley. This trend

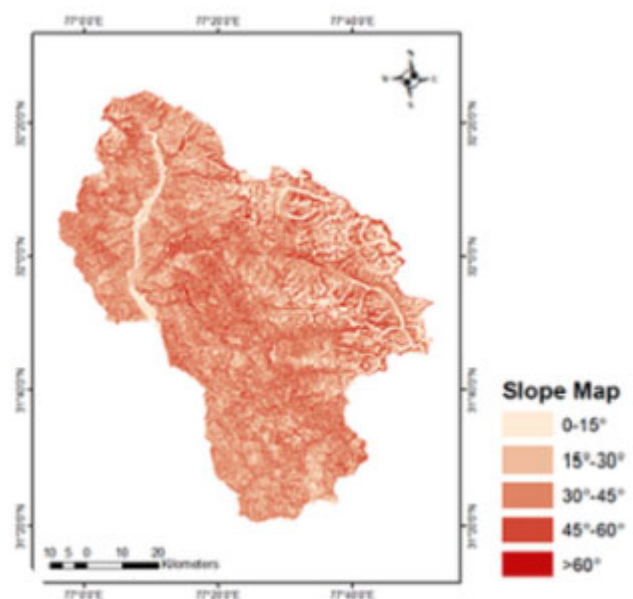


Figure 1. Slope map of Kullu

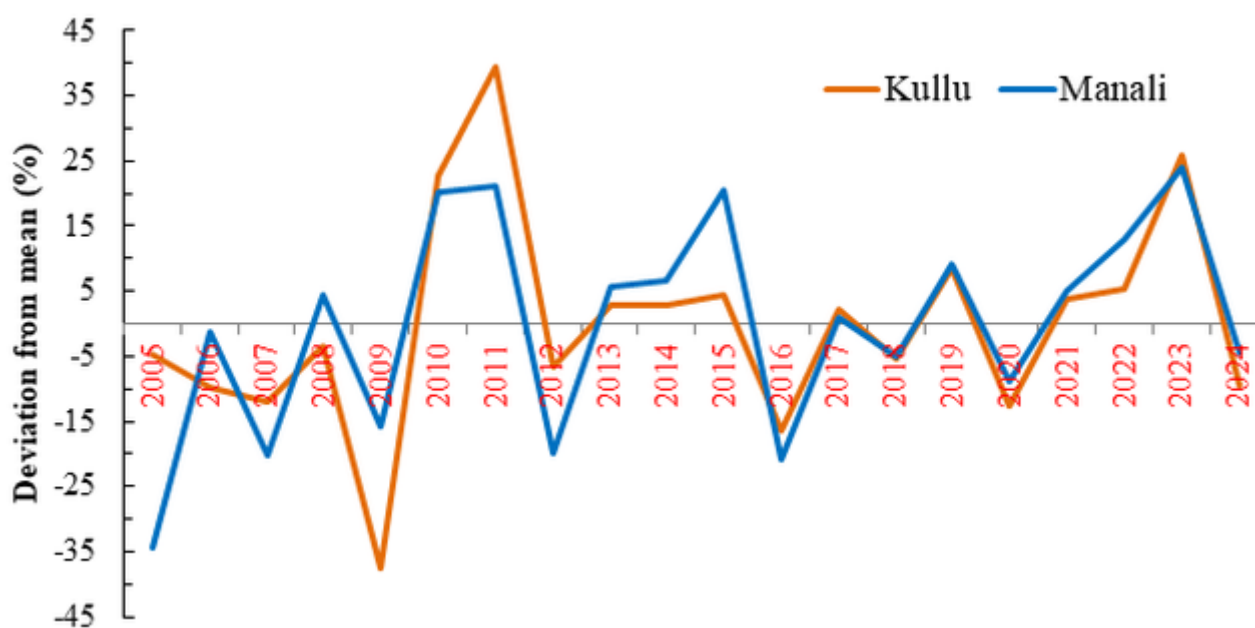


Figure 2. Deviation of annual rainfall from mean at Kullu and Manali

Table 3. Area under rainfall classes

Rainfall class (mm)	Area (km <sup>2</sup> )				
	2020	2021	2022	2023	2024
<800	69.66	172.12	90.72	43.26	1194.21
801–1000	1639.94	1083.27	849.13	837.58	2445.03
1001–1100	2460.09	1727.79	711.63	604.25	666.92
1101–1200	1160.47	1880.55	1869.92	536.38	734.93
1201–1400	167.12	631.41	1894.14	2375.92	421.85
>1400	0	2.51	81.88	1100.27	35.06

persisted into 2024 despite a slight redistribution in some areas (Fig. 3). The zonal statistics confirm that the area under high-rainfall categories (>1200 mm) expanded steadily from 2020 to 2023. Conversely, low-rainfall zones (<800 mm) contracted over time, indicating a clear shift toward wetter conditions (Table 3).

## DISCUSSION

The trend analysis shows that annual rainfall at both the Kullu and Manali stations shows a weak but increasing trend. Although the Mann–Kendall test does not indicate a statistically significant trend, the positive Sen’s slope values suggest a gradual increase in rainfall over time. In mountainous regions like

the Western Himalaya, rainfall varies greatly from year to year, often masking long-term trends in statistical analyses. Similar weak but increasing rainfall tendencies have been reported in earlier studies from Himachal Pradesh and other Himalayan regions (Jaswal et al. 2015). Seasonal analysis indicates that rainfall during the monsoon and pre-monsoon seasons has increased, while winter precipitation shows a slight declining trend. The increase in monsoon rainfall may be linked to higher atmospheric moisture availability and changes in monsoon circulation under warming conditions (Sooraj et al. 2015, Wang 2012). The rise in pre-monsoon rainfall suggests increasing convective activity during the transition season. On the other hand, the reduction in winter precipitation may be

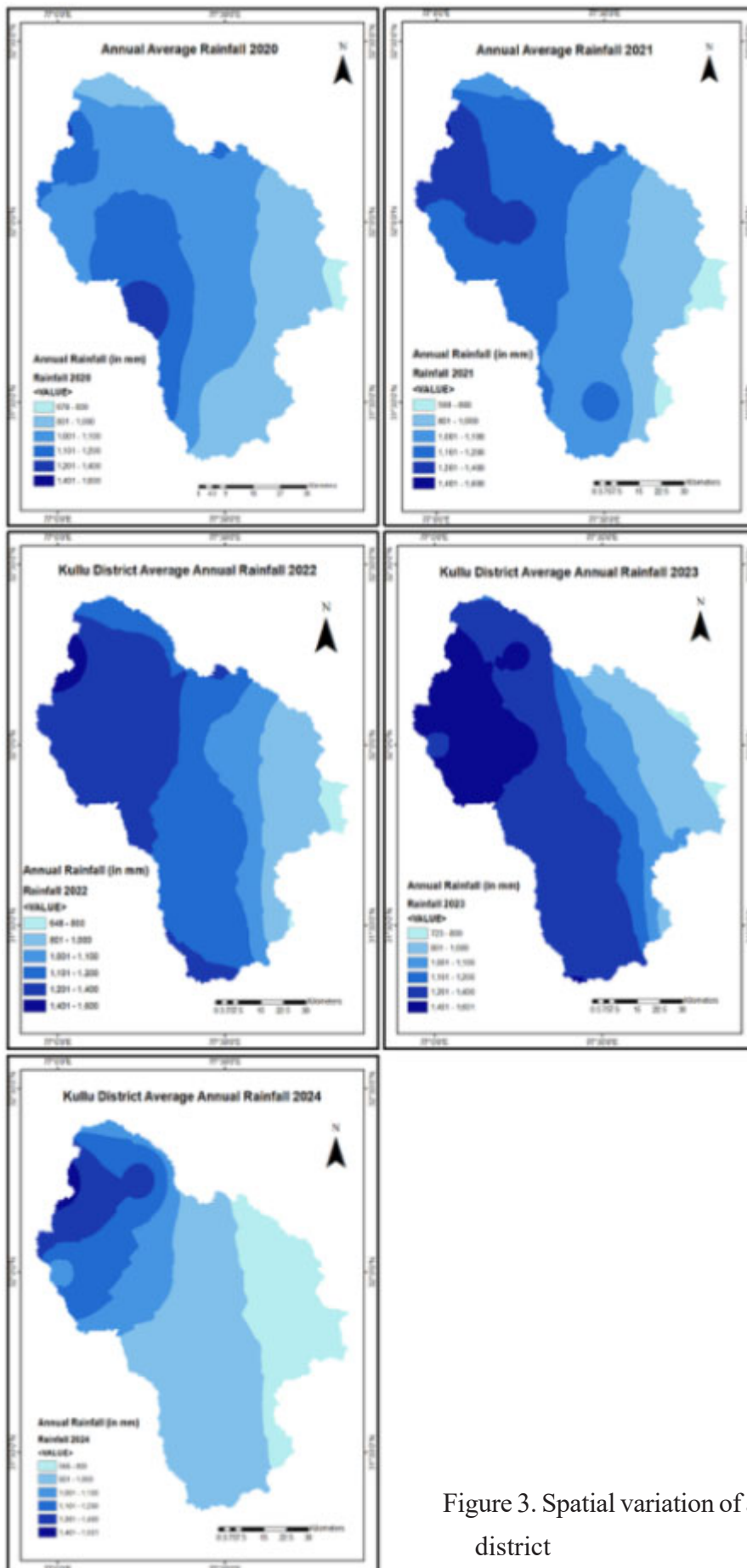


Figure 3. Spatial variation of average rainfall in Kullu district

associated with changes in the frequency or intensity of western disturbances, which are the primary source of winter rainfall and snowfall in the region (Dimri et al. 2015, Dar 2023). The analysis of annual rainfall variability highlights increasing fluctuations between dry and wet years, particularly after 2018. The growing number of wetter years in recent years indicates that rainfall behaviour is becoming more irregular and extreme, rather than steadily increasing. Similar patterns of enhanced rainfall variability and extremes have been linked to climate change impacts in mountainous regions. The occurrence of major flood and landslide events during recent wet years supports the idea that rainfall extremes, rather than mean rainfall alone, play a key role in triggering hydro-meteorological hazards.

Spatial rainfall analysis shows that high-rainfall zones have expanded across parts of the Kullu valley in recent years, while areas receiving lower rainfall have reduced. This indicates a redistribution of rainfall within the district rather than a uniform increase. Such spatial concentration of rainfall can increase localized flood risk, especially along river channels and low-lying valley areas where settlements and infrastructure are concentrated. Slope analysis reveals that a large part of the study area consists of steep to very steep terrain. In such conditions, intense rainfall can quickly lead to surface runoff, soil erosion, and slope failure. The combined effects of increasing rainfall variability and steep

slopes provide a reasonable explanation for the rising frequency of rainfall-induced landslides and flash floods in the Kullu district. The rainfall deviation pattern shows that the region has experienced a mix of normal, slightly dry, deficit, and wet years. But since 2018, wet years have become more frequent, suggesting a change in how rainfall occurs. This shift is also reflected in the recent events on the ground. The area has seen more flash floods, cloudbursts, and slope failures in the last few years, especially during the monsoons of 2021 and 2023.

The findings of this study have important implications for hydro-meteorological hazards in the Kullu district. Increasing rainfall variability and the expansion of high-rainfall zones raise the likelihood of flash floods, cloudbursts, and landslides, particularly during the monsoon season. These hazards pose risks to settlements, road networks, hydropower projects, and agricultural land located in valleys and along river corridors. Changes in seasonal rainfall patterns may also affect water availability. Reduced winter precipitation can affect snow accumulation and baseflow in rivers, while intensified monsoon rainfall may increase surface runoff and reduce groundwater recharge. This imbalance can create challenges for water resource management, agriculture, and hydropower generation.

The results highlight the need to focus on rainfall extremes rather than average rainfall in disaster risk

Table 4. Recommendations

1. Strengthen Slope Stability Measures: Areas with steep and very steep slopes should be prioritized for slope protection works, such as bio-engineering, retaining structures, controlled drainage, and reinforcement of road-cut slopes.
2. Improve Land-Use Planning: Construction activities should be restricted or closely monitored in high-risk zones, particularly steep terrain that shows repeated slope failures during heavy rainfall.
3. Enhance Rainfall and Hazard Monitoring: Install more automatic weather stations and real-time river gauge sensors to capture rapid changes in rainfall and runoff.
4. Adopt Rainfall-Based Early Warning Systems: The rise in high-rainfall areas indicates the need for rainfall threshold-based alerts for flash floods and landslides, especially during peak monsoon months.
5. Regulate Road Expansion and Tourism Development: Road widening, cutting, and infrastructure development should follow strict geotechnical guidelines to minimise slope destabilisation.
6. Encourage Nature-Based Solutions: Reforestation, watershed treatment, and slope restoration can reduce runoff and help stabilise fragile terrain.
7. Promote Community Preparedness: Local communities should be trained in disaster response practices, given the rising frequency of extreme rainfall events.

assessment and planning (Table 4). Early warning systems should consider short-duration, high-intensity rainfall events, especially in areas with steep slopes. Land-use planning should incorporate slope stability, drainage improvement, and restrictions on construction in highly vulnerable zones. At the district level, the study provides helpful scientific input for climate adaptation and disaster management planning. Integrating rainfall variability, spatial rainfall patterns, and terrain characteristics into development planning can help reduce future disaster risks and improve resilience in the Himalayan region.

## CONCLUSIONS

The overall assessment indicates that the Kullu-Manali region is gradually moving toward wetter conditions, with more wet years and higher rainfall totals in recent years. However, statistical tests do not show a strong trend. As rainfall increases and high-rainfall zones expand, areas with moderate to steep slopes respond quickly with faster runoff, soil loosening, and increased stress on roads and structures. This, along with hill cutting, unplanned construction, and growing human activity, has contributed to more frequent flash floods, landslides, and slope failures. Overall, the changing rainfall pattern and the region's sensitive terrain indicate a growing vulnerability to hydro-meteorological disasters, making careful land-use planning and slope management essential for reducing future risks.

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