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Assessment Of Precipitation Patterns Using Meteorological Observations

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Abstract: ***Understanding the distribution of precipitation is essential for effective water resources management and regional planning in regions with diverse topography and climatic conditions.***
This study analyzes precipitation patterns across northwestern Pakistan using daily rainfall records collected from Meteorological Department, Pakistan for the past two decades. Rainfall events were classified into five categories based on daily precipitation amounts, from non to heavy. The occurrence for each category was calculated to examine spatial variability in precipitation distribution for the selected area. The results revealed considerable spatial heterogeneity in precipitation occurrence across the study area.
The northern mountainous region exhibited the highest record of less precipitation events (753 days), attributed to orographic lifting mechanisms and westerly disturbances. The southern region demonstrated the greatest number of non-precipitation days (4,884 days) and the lowest total precipitation occurrence, reflecting arid to semi-arid conditions. The central region displayed transitional characteristics with the highest moderate (135 days), heavy (24 days), and extreme heavy (8 days) precipitation events, suggesting a convergence zone influenced by both monsoon and westerly systems. These results improve the understanding of regional precipitation patterns and their spatial variability.
The results also underscore the need for spatially differentiated management strategies that account for regional differences in rainfall characteristics.
Keywords: Precipitation Pattern, daily rainfall, Analysis, topography, heterogeneity

I. INTRODUCTION

Precipitation is one of the most important components of the hydrological cycle and plays a vital role in water resources management, agriculture, ecosystem sustainability, and disaster risk reduction [1], [2]. The spatial and temporal distribution of precipitation directly influences water availability and hydrological processes across different regions [3]. Understanding precipitation patterns is particularly important in areas characterized by diverse topography and climatic conditions, where rainfall distribution can vary significantly over short distances [4], [5].

Pakistan is situated in a transitional zone where multiple climatic regimes converge, resulting in a complex and diverse environmental landscape [6]. The country exhibits substantial climatic and geographical diversity, ranging from arid plains to mountainous regions [7].

Monsoon precipitation constitutes a significant portion, approximately 70 to 80% of the total annual precipitation, making it vital for freshwater ecosystems, reservoir replenishment, and hydroelectric power generation [6]. The northwestern region of Pakistan experiences pronounced variations in precipitation due to complex terrain, including the Hindu Kush range, and atmospheric circulation systems such as western disturbances and monsoon incursions [1], [8]. These variations influence regional water resources and contribute to both drought and flood-related challenges [9]. The topographic complexity of the area, characterized by steep elevational gradients from the plains to the high mountains, significantly influences the spatial distribution of precipitation through orographic lifting mechanisms [8].

Recent studies have revealed that precipitation extremes in Pakistan are becoming more pronounced. Increasing trends in heavy and very heavy precipitation days have been observed in monsoon-dominated eastern and central regions, while some mountainous and arid areas show declining trends [10]. Percentile-based indices, including R95pTOT and R99pTOT, indicate growing tendencies toward intense rainfall events across parts of Pakistan, highlighting an increasing of extreme precipitation as shown in Table 1.

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Table 1: Precipitation intensity indices.

Name	ID	Definition	Units
Wet days	R1 mm	Days count with precipitation > 1 mm	Days
Heavy precipitation days	R10 mm	Days count with precipitation > 10 mm	Days
Very heavy precipitation days	R20 mm	Days count with precipitation > 20 mm	Days
Mean precipitation amounts on a wet day	SD11	Days count with precipitation > 50 mm	mm
Maximum 1-day precipitation	Rx1 day	Maximum1-day precipitation amount	mm
Very wet days	R99p TOT	Days with precipitation > 95 percentile	mm
Extremely wet days	R99p TOT	Days with precipitation >99 percentile	mm

The region's vulnerability to such climatic variability is underscored by Pakistan's ranking as the eighth most affected country globally by climate-related disasters, with losses exceeding US$3.7 billion from 2000 to 2019 due to floods and droughts [6].
Despite numerous investigations on rainfall trends and climate variability, studies focusing specifically on precipitation pattern and detailed distribution analysis in northwestern Pakistan remain limited. Therefore, this study aims to investigate precipitation patterns across northwestern Pakistan using rainfall observations for the selected area. The findings contribute to a better understanding of rainfall variation and provide useful information for hydrological assessments and regional planning.

II. METHODOLOGY

The study was conducted in Pakistan, covering north-west regional stations located across different climatic zones as shown in **Figure 1**. The region includes mountainous northern areas, central valleys, and southern plains, providing diverse precipitation characteristics suitable for spatial analysis [11], [12]. The study area encompasses stations at varying elevations, allowing for the assessment of topographic influences on rainfall distribution [13], [14].

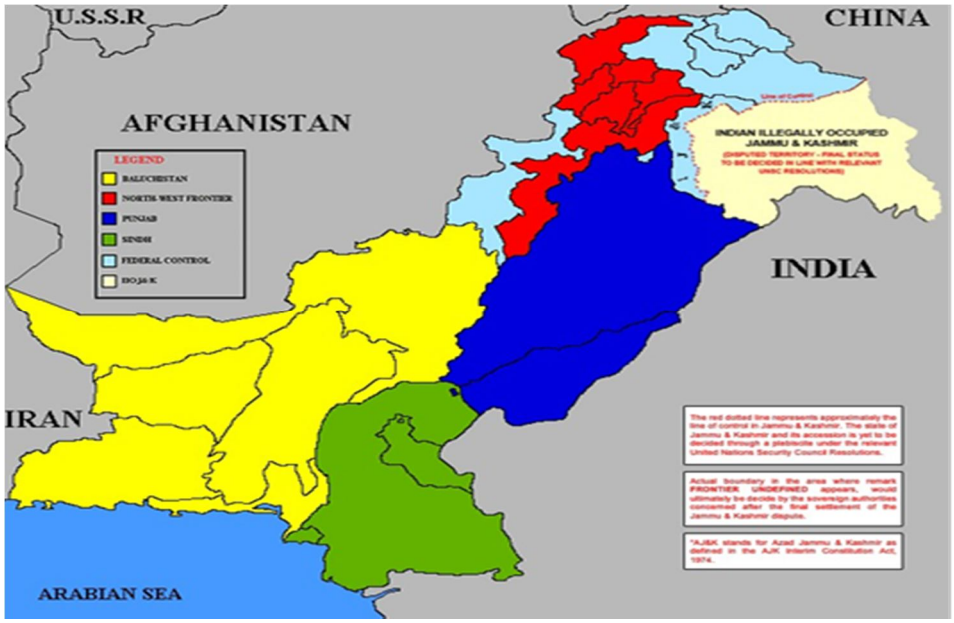

Figure 1: Selected Meteorological Stations in Pakistan

A. Data Collection

Daily precipitation data were obtained from the meteorological stations of the Pakistan Meteorological Department (PMD) for the past two decades. The dataset was subjected to quality checks to identify missing and inconsistent records before analysis [15]. The selection of meteorological stations was based on data availability.

B. Precipitation Pattern

Rainfall observations were divided into precipitation pattern based on daily rainfall amounts. The classification varying from non - precipitation to heavy precipitation [16]. The occurrence for each category was calculated for all meteorological stations to evaluate regional precipitation characteristics [17].

III. RESULTS

A. Overview of Precipitation Depth Distribution

The analysis of daily precipitation records from the selected meteorological stations across was carried out to analyze the pattern. The number of occurrences for each precipitation category varied considerably among the three regions of the study area (northern, central, and southern), indicating substantial spatial heterogeneity in rainfall characteristics. as described in **Table 2**.

Table 2: Counting of precipitation occurrence for Pakistan

Level	Northern	Southern	Central
Non	4620	4884	4581
Less Precipitation	753	476	727
Intermediate Precipitation	87	99	135
Heavy Precipitation	10	14	24
Extreme heavy Precipitation	5	2	8

B. Regional Patterns in Precipitation

1) Northern Region

The northern mountainous region recorded 855 precipitation days (15.6% of the observation period), with less precipitation events (0-15 mm) dominating at 753 days (88.1% of all precipitation events). Intermediate precipitation occurred on 87 days (10.2%), while heavy and extreme heavy events were relatively infrequent at 10 days (1.2%) and 5 days (0.6%), respectively. The occurrence of extreme heavy precipitation days indicates the potential for high-intensity rainfall events in mountainous areas, likely attributed to orographic enhancement mechanisms.

2) Southern Region

The southern region recorded highest of non-precipitation days at 4,884 days (89.2% of the observation period), with total precipitation events occurring on only 591 days (10.8%). Less precipitation dominated at 476 days (80.5% of precipitation events), followed by intermediate events on 99 days (16.7%), while heavy and extreme heavy events were observed on 14 days (2.4%) and 2 days (0.3%), respectively. The low occurrence of precipitation events in the southern region is consistent with the arid to semi-arid climatic conditions prevalent in this area.

3) Central Region

The central region recorded 894 precipitation days (16.3% of the observation period), with less precipitation events dominating at 727 days (81.3% of precipitation events). The region exhibited notably higher number of intermediate (135 days, 15.1%), heavy (24 days, 2.7%), and extreme heavy (8 days, 0.9%) precipitation events compared to both northern and southern regions. The greater number of intermediate and heavy precipitation events in the central region suggests a transitional climatic zone that receives substantial moisture from both monsoon and westerly systems.

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IV. DISCUSSION

The analysis of precipitation patterns of the study area revealed considerable spatial variability in rainfall distribution among the northern, central, and southern regions. The findings demonstrate distinct regional differences in precipitation occurrence and levels, reflecting the complex interplay of topographic features and atmospheric circulation systems [13], [14].

The northern mountainous region exhibited a greater number of less precipitation events (753 days) compared to other regions, consistent with the influence of orographic lifting mechanisms that enhance rainfall in high-altitude areas [13]. This pattern aligns with previous studies documenting higher precipitation occurrence in elevated northern regions of Pakistan due to westerly disturbances and orographic effects [8]. The frequent less precipitation events in the north contribute to sustained soil moisture and support diverse ecosystems, although extreme events were relatively rare.

The southern region demonstrated the highest occurrence of non-precipitation days (4,884 days) and the lowest number of total precipitation events (591 days), reflecting the predominantly arid to semi-arid climatic conditions prevalent in this area [7]. This finding is consistent with the expected rainfall distribution in lowland regions that experience rain-shadow effects and limited moisture availability [12]. The relatively higher proportion of intermediate precipitation events in the southern region (16.7% of precipitation events) compared to the north (10.2%) suggests that when rainfall does occur, it tends to be more intense, potentially leading to flash flood risks [10].

The central region exhibited transitional characteristics, with the highest number of intermediate (135 days), heavy (24 days), and extreme heavy (8 days) precipitation events among all regions. This pattern suggests that the central zone receives substantial moisture from both monsoon and westerly systems, resulting in a mixing of precipitation regimes [10]. The elevated number of heavy and extreme heavy precipitation in the central region raises important considerations for flood risk management and infrastructure planning, as intense rainfall events can lead to rapid runoff and flooding. These findings are consistent with recent studies documenting increasing trends in heavy precipitation days in monsoon-dominated regions of Pakistan.

V. CONCLUSION

This study analyzed precipitation patterns using daily rainfall records from selected meteorological stations for which data has been collected. The division of precipitation events into five categories revealed considerable variation among the northern, central, and southern regions. The northern mountainous region exhibited the highest number of less precipitation events (753 days), attributed to orographic lifting and westerly disturbances. The southern region demonstrated the greatest number of non-precipitation days (4,884 days) and the lowest total precipitation numbers, reflecting arid to semi-arid conditions. The central region displayed transitional characteristics with the highest number of intermediate (135 days), heavy (24 days), and extreme heavy (8 days) precipitation events, suggesting a convergence zone influenced by both monsoon and westerly systems. The observed patterns highlight the significant influence of topography, elevation gradients, and regional atmospheric circulation on precipitation distribution.

VI. RECOMMENDATIONS

The elevated frequency of heavy precipitation in the central region necessitates enhanced early warning systems, real-time rainfall monitoring, improved forecasting, and community-based disaster preparedness to reduce flash flood vulnerability.

Climate change adaptation plans should incorporate projected changes in precipitation intensity, considering potential implications for water availability, flood risk, and agricultural productivity in long-term development strategies for northwestern Pakistan.

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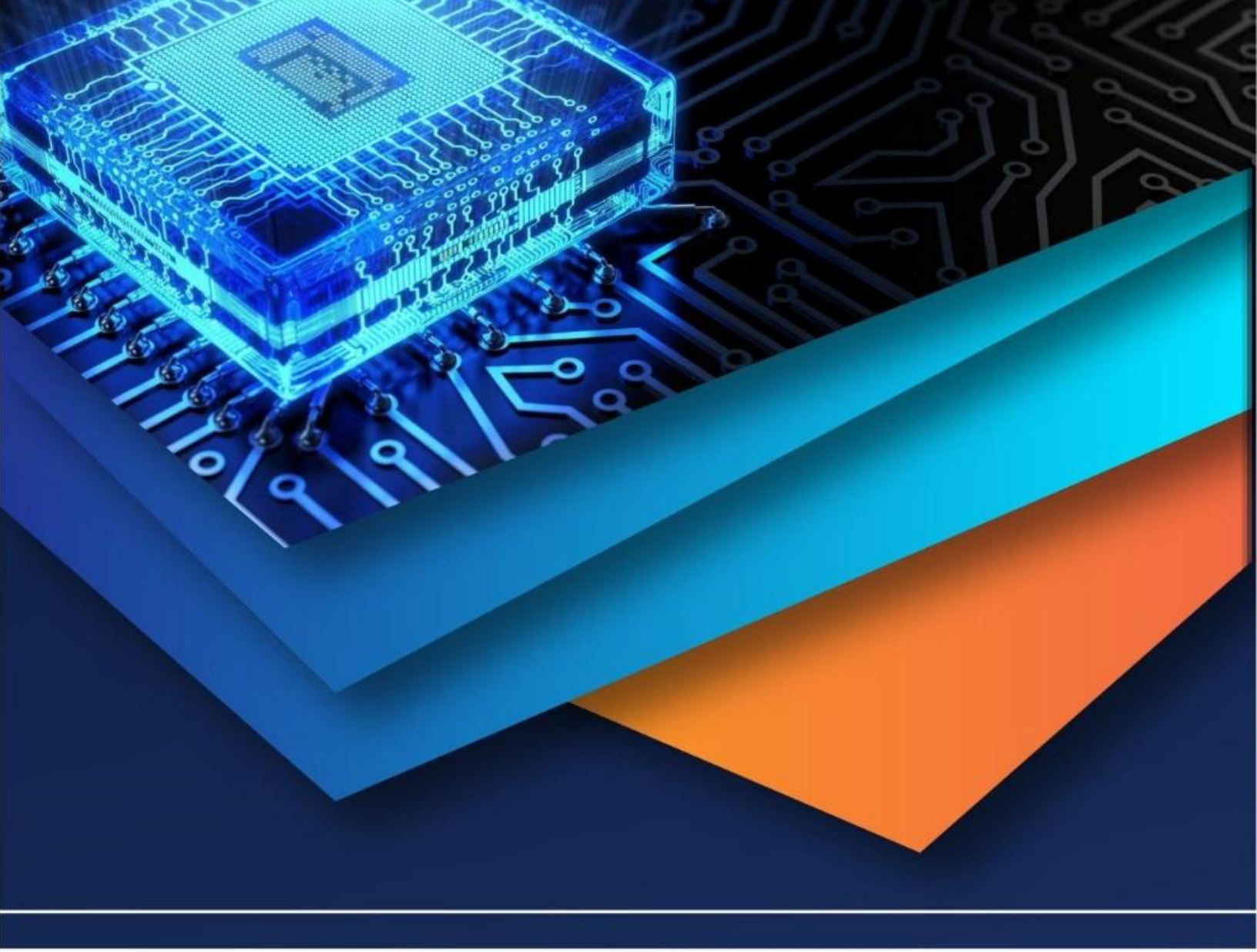

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