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International Journal of Innovations in Science & Technology

RESEARCH & INNOVATION DIVISION

IJIST

Assessing Eight Years of Monsoon Rainfall Patterns in Karachi, Pakistan: Study of the Intense Rainfall Events

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Citation | Zaineb. S, Bashir. M, "Assessing Eight Years of Monsoon Rainfall Patterns in Karachi, Pakistan: Study of the Intense Rainfall Events", IJIST, Vol. 6 Issue. 2 pp 621-631, June 2024

Received | May 03, 2024, **Revised |** June 04, 2024, **Accepted |** June 06, 2024 **Published |** June 09, 2024.

Rainfall plays a pivotal role in regulating water levels in reservoirs, which can lead to overflow or drought, depending on the unpredictability of rainfall patterns. In 2020 and 2022, Sindh experienced seven episodes of normal to heavy rains, causing flooding and disrupting major highways such as Gwadar-Karachi. This study evaluates daily and cumulative rainfall data in Karachi for the months of June, July, and August from 2016 to 2023. The rainfall data is divided, focusing on the monsoon rains over the eight-year period. Among these years, the highest recorded rainfall of 93.099mm occurred on August 11, 2019, while the lowest rainfall of 0.001mm was noted on July 26, 2016, and June 18, 2017. The yearly (2016-2023) cumulative rainfall for the study period was 114.6mm, 187.0mm, 34.9mm, 310.5mm, 347.9mm, 285.3mm, 761.4mm, and 167.6mm respectively. Notably, the cumulative rainfall and the frequency of rain events were highest in August 2020 and 2022. The monthly data revealed that Karachi experienced exceptionally heavy rainfall in August 2020 and 2022, resulting in significant disruption and chaos in the city. Moreover, when considering the data across the years, it becomes evident that Karachi faced unprecedented rainfall in 2020 compared to the preceding years. This research represents the first comprehensive analysis of the intense rainfall events in August 2020 and 2022 in Karachi. It identifies trends in rainfall patterns that led to flood-like conditions in the city. This study provides a detailed and quantitative understanding of rainfall occurrences during the monsoon season. Such insights are invaluable for assessing flood risks in Karachi, Pakistan.

Keywords: Flood; Rainfall; Cumulative rainfall; Monsoon; Precipitation; Linear regression coefficient.

Introduction:

Karachi, the most densely populated city in Pakistan, is located on the coastline of Sindh Province, with precise coordinates at 24.860°N and 67.0011°E. The city is bordered by the "Dadu District" in the northeast, the "Thatta District" in the southeast, the "Lasbella District" to the west, and the expansive "Arabian Sea" to the south. Climate change significantly impacts rainfall patterns, with varying effects across regions and diverse perceptions among those dependent on these patterns for their livelihoods [1][2]. Fluctuations in precipitation directly influence floods, droughts, water resources, and ecosystem services, consequently, altering the hydrological cycle and impacting the environment and society.

Flood is a natural disaster, marked by its widespread agricultural devastation and the harm to infrastructure, the environment, and communities. Climate change, intensified snow and glacier melting, and prolonged periods of rainfall are major causes of the severity of floods [3]. Additionally, human activities, topographical features, socio-economic vulnerabilities, and deforestation collectively influence the frequency and intensity of flood occurrences [4]. In Karachi, the presence of two major rivers, Lyari and Malir, serve as natural drainage systems for urban runoff, directing water toward the sea. During Heavy Precipitation Events (HPEs) the monsoon season from July to August led Karachi into a flood-like situation in 2020, and 2022. The consequences were devastating, resulting in the loss of lives and the destruction of thousands of homes. The city experienced devastating loss of lives and the destruction of thousands of homes.

The frequency and intensity of precipitation hold a vital role in the management of agriculture, water resources, and ecosystems. Meteorological systems induce Heavy Precipitation Events (HPEs) originating from offshore and moving towards the bluff coastal hills, a phenomenon commonly observed near the Arabian Sea area. This phenomenon is attributed to the persistent mesoscale connective system, which can trigger heavy rainfall, leading to flash floods [5]. Predicting flood events and enhancing forecasting performance poses a challenging task [6]. To address this, statistical methods are employed to assess the likelihood of rainfall and floods due to climate change [7]. Research conducted by [7] examines flood formation conditions in various regions; such as along the Belarus River and Wadi Umm Sidr, using simulated rain flood hydrographs and flood discharge modeling. Similarly, [8] estimated the total flood volume, duration, infiltration rate, and transmission rate of a significant flash flood in 2016. Furthermore, 2D hydrodynamic models are utilized to enhance flood resilience by generating inundation maps [9]. The authors in [10] examined rainfall patterns in China and their correlation with flood damage between 2000 and 2015. They investigated the spatial and temporal variations in annual rainfall, providing valuable insights for flood control policies in China. Identifying change points in precipitation data and modeling series trends before and after these breakpoints are additional areas of study aimed at understanding and predicting precipitation-related events. In a separate study, [11] established a relationship between rainfall and runoff and created storm hyetographs for studying storm patterns in the area. Researchers employ a multivariate dynamic regression model to establish the relationship between rainfall and runoff in diverse environmental conditions, aiming to address water-related challenges [12]. Additionally, studies conducted by [13] emphasize the evolving spatio-temporal patterns of rainfall and temperature in the semi-arid Logone River basin. These trends are crucial for evaluating future disaster scenarios and developing effective mitigation strategies.

Previous studies have emphasized the crucial role of accurate data on the historical frequency and spatial occurrence of flash floods, critical for effective flood risk management in localities [14]. Given the recent rainfall conditions experienced in Karachi, particularly in August 2020 and 2022, there is a pressing need for a detailed analysis of these rainfall events concerning their timing. Such analysis can provide precise information necessary for evaluating potential flash flood hazards in the future.

Objectives:

In this study, we analyzed the variations in rainfall during June, July, and August in Karachi from 2016 to 2023 on a national scale. Daily rainfall data from NASA's Power Data Access Viewer were utilized for this study. Trend detection of rainfall events was carried out using curve-fitting techniques. The eight-year data evaluation enabled authors to quantitatively assess the rainfall patterns that contributed to the flood-like situation in Karachi in 2020 and 2022 respectively. This analysis offers a detailed and clear study of rainfall occurrences during the monsoon season. These insights provide valuable information for flood risk assessment and flood control management strategies in Karachi, Pakistan.

Novelty:

Using advanced data sources, studying on a national scale, and applying curve-fitting techniques for trend detection along with the focus on flood events collectively incorporate the novelty and significance of the study's findings, presenting a pioneering contribution to understanding Karachi's rainfall patterns and aiding in flood risk management strategies.

Material and Methods:

The rainfall data utilized in this study was sourced from the freely accessible Power Data Access Viewer NASA. Several satellite-based products are available globally, including CMORPH (Climate Prediction Centre morphing technique), TRMM (Tropic Rainfall Measuring Mission), and GPM (Global Precipitation Measuring) [15]. In this research, we employed MERRA-2 (The Modern-Era Retrospective Analysis for Research and Application version 2), which focuses on historical climate analysis across various weather and climate time scales. MERRA-2 is based on the Goddard Earth Observing Model version 5 (GEOS-5)), a NASA reanalysis product providing comprehensive atmospheric data. Key atmospheric variables relevant to the study were extracted from the MERRA-2 dataset. These included: Surface temperature, Precipitation (used in this study), Surface pressure, Wind components, Humidity, and radiation. The dataset was retrieved at a daily temporal resolution to capture 24h 24-hour variability and trends. Moreover, the data was attained at a spatial resolution of $0.5° \times 0.625°$, certifying detailed spatial coverage. To match the study area's grid, bilinear interpolation was useful to support MERRA-2 data with the particular geographical coordinates of the study region [16]. It was selected over other reanalysis choices for various reasons, including its advanced methodologies, comprehensive data assimilation, high resolution, and extensive evaluation.

Flow of Study:

The flow of the study consists of four steps also shown in Figure 1. (1). Daily rainfall data for June, July, and August from 2016 to 2023 was obtained from NASA's Power Data Access Viewer. (2) After data collection, the dataset is prepared for further analysis. At this phase, the division of the eight years data into the monsoon season and the months of June, July, and August has been carried out for data visualization and plotting graphs (3). The prepared data undergoes data analysis using curve-fitting techniques to identify trends and patterns in rainfall occurrences over the eight-year period from 2016 to 2023. (4). Results were explained with historical data and climate projections to evaluate flood risks and inform policy approvals. To enhance the study's reliability, a linear curve fitting method is used for analyzing precipitation trends across different locations and periods. The following are the specific techniques used:

Techniques:

Linear Curve Fitting: A linear regression model is used for the precipitation time series data within the study area. This includes fitting a straight line to the data, where the slope of the line designates the rate of change in precipitation.

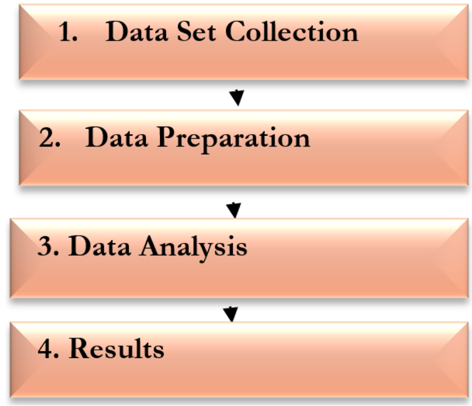

Figure 1: Flow of Methodology

Trend Analysis:

The linear trends were analyzed to detect increases or decreases in precipitation. This method allowed us to measure the direction and magnitude of precipitation changes over the study period. The study concentrated on 10 different towns within Karachi, as illustrated in Figure 2A and Figure 2B, with specific details about their locations (latitude and longitude) provided in Table 1. The choice of Baldia Town, Hameedabad, Sadar Town, Korangi Town, Landhi Town, Bin Qasim Town, Malir Town, Gulshan Iqbal, North Nizamabad, and Gulshan Mayamar was made to cover the geographical diversity areas of Karachi. This ensures an inclusive understanding of rainfall trends by including various parts of the city, from densely populated urban places to more suburban and semi-rural regions, giving varied topographical features and socio-economic environments. This diverse selection is made randomly which helps in analyzing how aspects like urbanization, infrastructure, and topography influence the city's rainfall patterns. The analysis covered eight years, evaluating the temporal variation of rainfall occurrence. The aim was to detect and analyze time series data to discern recent trends in rainfall patterns in Karachi, Pakistan.

Table 1: List of Towns of Karachi locations with latitude and longitude

#	Towns of Karachi	Latitude/Longitude (N°/E°)	#	Towns of Karachi	Latitude/Longitude (N°/E°)
1	Baldia Town	24.9525/66.955	**6**	Bin Qasim Town	24.8596/67.4005
2	Hameedabad	24.8610/66.9905	**7**	Malir Town	24.8937/67.2163
3	Sadar Town	24.8532/ 67.0167	**8**	Gulshan Iqbal	24.9204/67.1344
4	Korangi Town	24.8387/67.1209	**9**	North Nizamabad	24.9372/67.0423
5	Landhi Town	24.8406/67.1948	**10**	Gulshan Mayamar	25.0221/67.1346

Result and Discussion:

Climate change deeply influences overflow patterns, impacting the probable maximum flood. Rainfall, being a fundamental input to river basins, significantly affects water capacity and the likelihood of flooding, especially during intense and record-breaking rainfall events. Thus, this study aims to assess the changes in the frequency and occurrence of rainfall, specifically focusing on the significant rainfall events in Karachi during August 2020 and 2022. The study presents a comparison between daily and cumulative rainfall values within the specified duration, conducting an analysis to identify trends and variances in rainfall patterns.

Rainfall Variability of Different Locations at Different Time Scales:

Figure 2A and Figure 2B present a spatio-temporal analysis of precipitation in ten distinct towns of Karachi, on six random dates: 7 July, 30 July, 7 August, and 27 August 2020, 10 August, and 17 August 2022. The different colors of the circles in Figure 2 depict the intensity and fluctuations in rainfall events. Notably, the size of circles represents the magnitude of rainfall that steadily increases, reaching its peak in August 2020 and 2022.

Daily and Cumulative Rainfall Variability of August (2016-2023):

Figure 3A and Figure 3B exclusively illustrate the distribution of daily and cumulative rainfall in Karachi for the years 2016-2020 and 2021-2023 respectively, specifically focusing on August. The daily peak rainfall values for 2016-2023 are recorded as 20.3mm, 31.1mm, 1.19mm, 93.0mm, 34.2mm, 40.0mm, 91.9mm, and 33.0mm respectively. Correspondingly, the cumulative rainfall figures stand at 90.7mm, 67.2mm, 4.71mm, 213.9mm, 251.9mm, 2.7mm, 289.9mm, and 0.18mm for August in the years 2016-2023. A comparative analysis between the rainfall data of August 2020 and 2022 and that of August in the years 2016-2019, 2021, and 2023 reveals that the cumulative rainfall values and the frequency of rainfall events (as shown in Table 2) were notably higher in August 2020 and 2022.

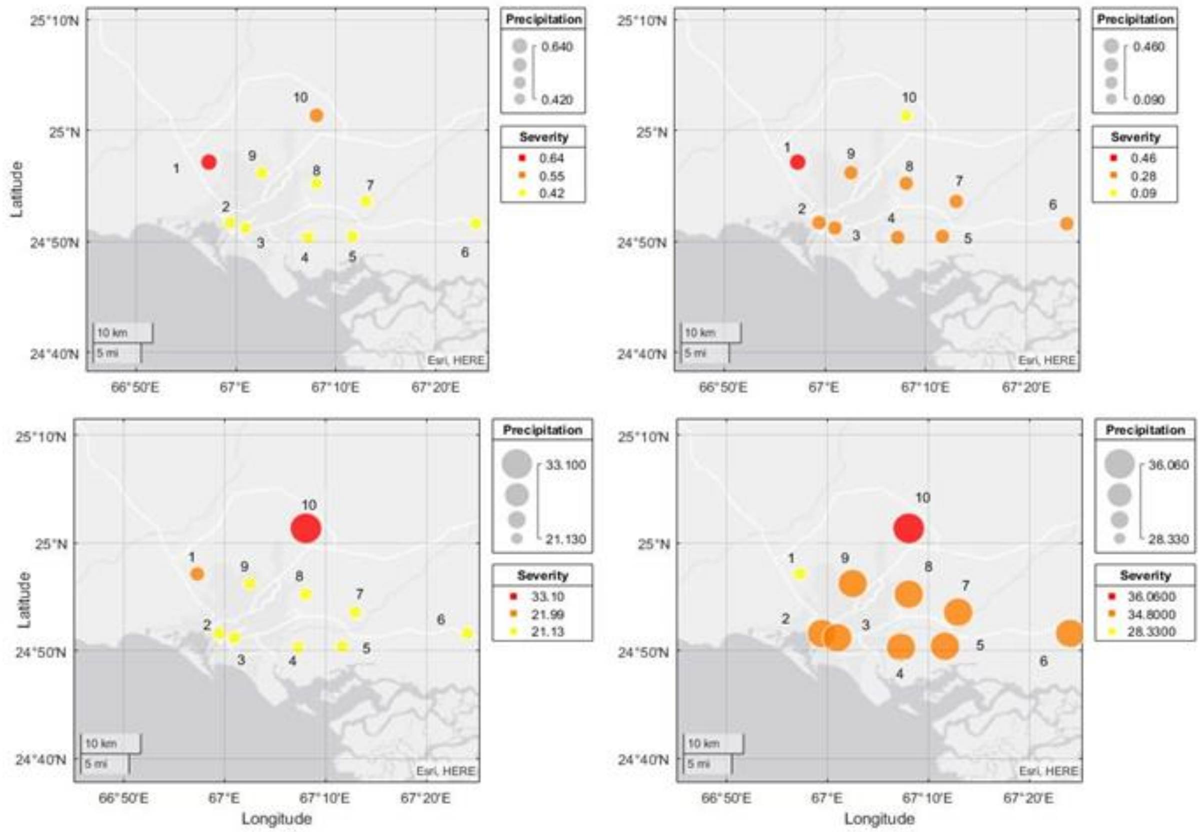

Figure 2A: Precipitation distribution across the study site in Karachi on four specific dates (a)14 July, (b) 30 July, (c) 7 August, and 27 August 2020

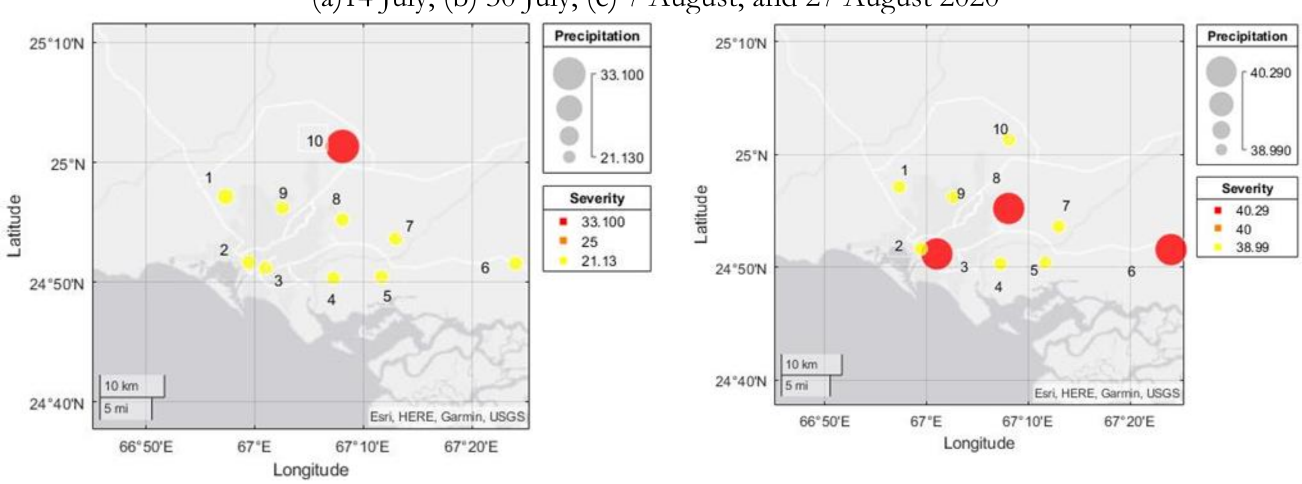

Figure 2B: Precipitation distribution across the study site in Karachi as of (a) 10 August, (b) 17 August 2022

Table 2 presents the weekly cumulative rainfall, the frequency of rainfall events, and their average values for August during the period 2016-2023, focusing on raindrops larger than 0.5mm. It's noteworthy that although the daily peak rainfall on August 11, 2019, was higher at 93.0mm compared to August 2020(34.2mm on 27) and 2022 (47.2mm on 24), subsequent daily rainfall values in August 2019 decreased. In contrast, the daily rainfall values in August 2020 and 2022 exhibited a consistent increase over time. This consistent rainfall led to water accumulation in rivers and nullahs, culminating in the record-breaking rains in August 2020, and 2022 which paralyzed and inundated Pakistan's largest city. This sudden and unexpected variation in rainfall patterns was a result of changing climate conditions, creating flood-like situations in August 2020 and 2022. Conversely, the climate in previous years, particularly in 2017 and 2018, was relatively drier in comparison.

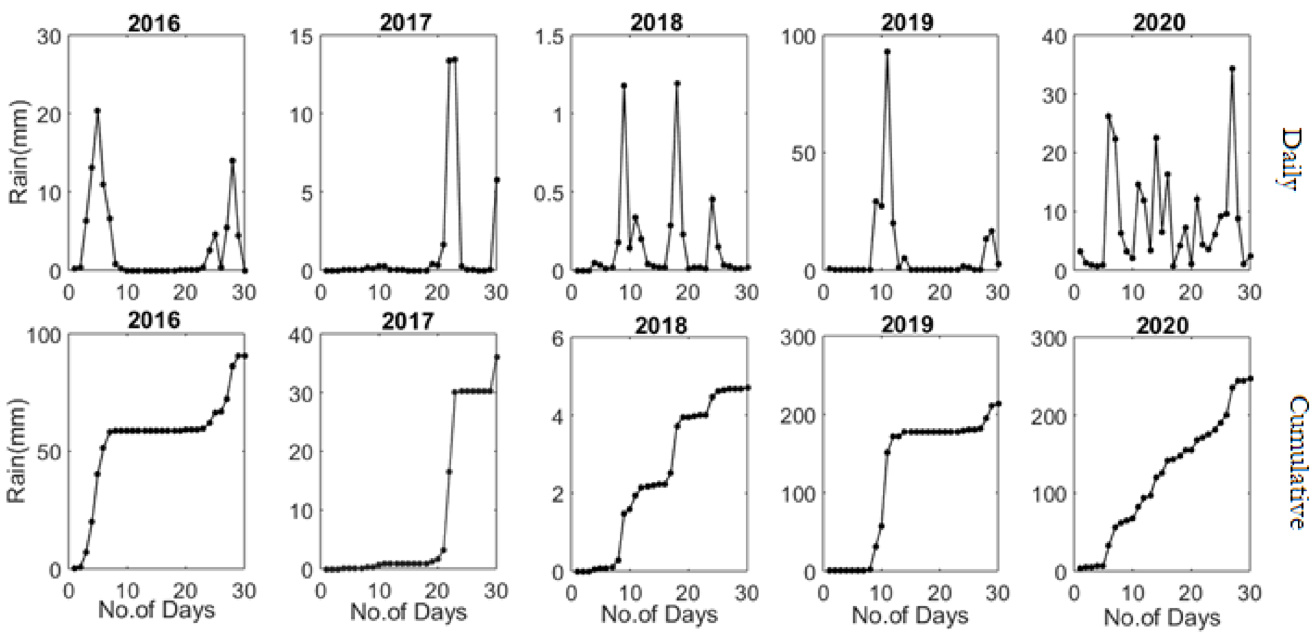

Figure 3A: Daily and cumulative rain in August 2016-2020 for Karachi during August.

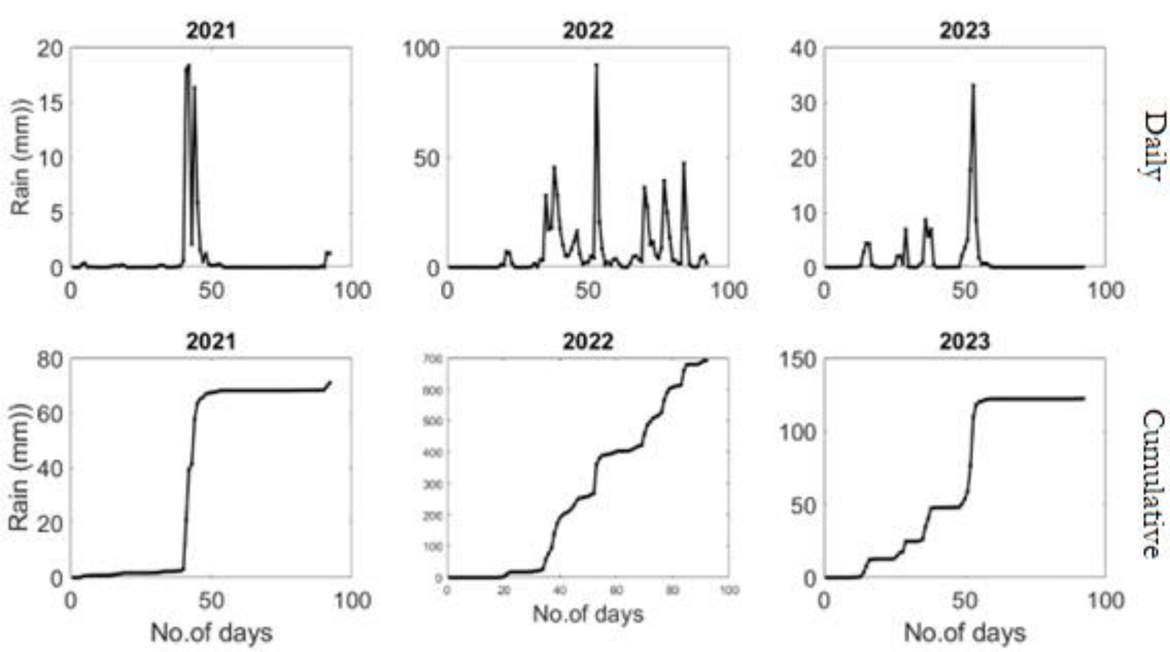

Figure 3B: Daily and cumulative rain in August 2021-2023 for Karachi

Table 2: Weekly values of cumulative rainfall, frequency, and average of August 2016-2023

August	week				Average
Frequency	**1st**	**2nd**	**3rd**	**4th**	
2016	5	1	0	5	2.75
2017	0	0	1	4	1.25
2018	0	1	1	0	0.5
2019	1	6	0	5	3
2020	7	7	7	10	7.75
2021	0	0	0	2	0.5
2022	7	7	7	10	7.75
2023	0	0	0	0	0.00
Rain(mm)					
2016	58.0	0.87	0.17	31.7	22.68
2017	0.05	0.86	2.29	64.0	16.8
2018	0.10	2..09	1.77	0.73	1.17
2019	1.30	176	0.27	36.0	53.3
2020	55.6	63.8	48.0	84.3	62.9
2021	0.0	0.0	0.07	2.72	0.855
2022	16.16	98.02	94.53	81.21	72.48
2023	0.04	0.00	0.00	0.14	0.15

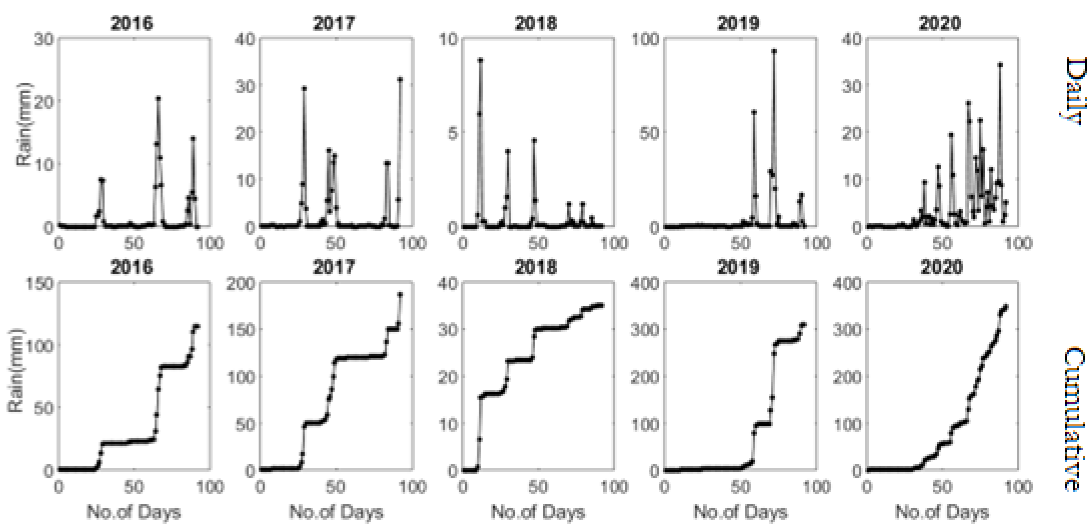

Figure 4A: Daily and cumulative rainfalls of Karachi in June-August 2016 -2020

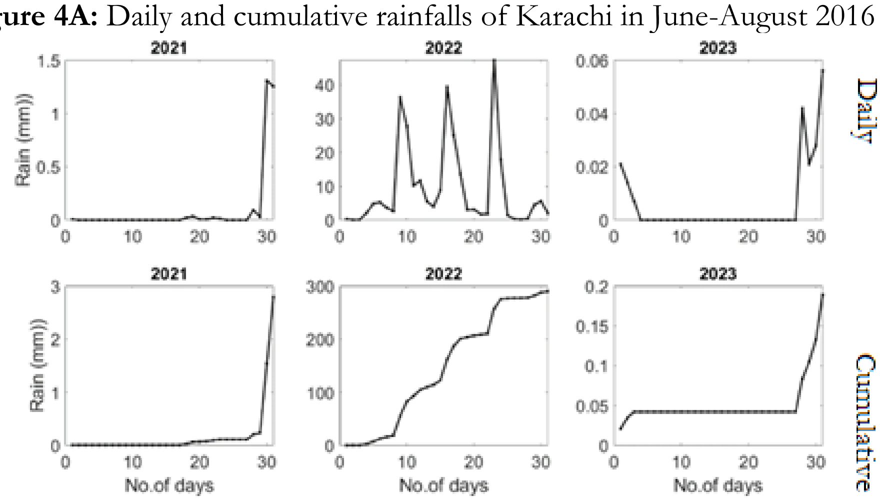

Figure 4B: Daily and cumulative rainfalls of Karachi in 2021 -2023

Daily and Cumulative Rainfall Variability for Monsoon 2016-2020:

In this section, we conduct a comparative analysis of eight years (2016-2023) focusing on the months of June, July, and August. The daily and cumulative rainfall data for these three months over the eight-year period is depicted in Figure 4A and Figure 4B. The cumulative rainfall values for June-to-August (monsoon period) are reported as 114.6mm, 187.0mm, 34.9mm, 310.5mm, 347.9mm, 71.0mm, 693.5mm, and 122.4mm for the years 2016-2023, respectively. Notably, the figure highlights the exceptional rainfall recorded in August 2022. Figures 3 and 4 collectively highlight the spatio-temporal trends in rainfall, which significantly impact water availability in rivers. Understanding these trends is of paramount importance in flood assessment, emphasizing the critical role of such knowledge in managing flood risks effectively.

Trend Analysis of Rainfall for Five Years in Karachi:

Table 3 presents the results of the linear fit analysis conducted on both daily and cumulative rainfall data for the study period in Karachi. The linear fit equation used is y=mx+c, where 'x' represents the day of the month or year, 'm' denotes the trend line slope, and 'y' indicates the average value of rainfall occurrence.

Table 3A: The linear fit and stats for June-to-August rainfalls for five years in Karachi

	2016	2017	2018	2019	2020
June Daily	Y=0.1149x-1.066 R^2=0.2812 SSE=75.86	Y=0.2756x-2.616 R^2=0.1921 SSE=717.7	Y=0.01553x+0.5351 R^2=0.04699 SSE=114.8	Y=0.0104x-0.06148 R^2=0.1821 SSE=1.091	Y=0.004996x-0.0172 R^2=0.1564 SSE=0.3026
June cumulative	Y=0.384x-3.474 R^2=0.3533 SSE=606.7	Y=0.7516x-6.638 R^2=0.3018 SSE=2938	Y=0.8183x-1.823 R^2=0.7892 SSE=402.1	Y=0.1086x-0.9172 R^2=0.7097 SSE=10.85	Y=0.05923x-0.3587 R^2=0.8045 SSE=1.915
July Daily	Y=0.04889x+0.001361 R^2=0.1283 SSE=0.4029	Y=0.02438x+1.872 R^2=0.002336 SSE=629.6	Y=0.003737x+0.1663 R^2=0.001623 SSE=21.3	Y=0.4713x-4.519 R^2=0.1492 SSE=3141	Y=0.09643x+1.496 R^2=0.3826 SSE=579.7
July cumulative	Y=0.07471x-0.3131 R^2=0.8908 SSE=1.698	Y=3.3x-18.55 R^2=0.8595 SSE=4414	Y=0.3334x-2.031 R^2=0.7916 SSE=73	Y=1.72x-16.87 R^2=0.3649 SSE=12760	Y=3.26x-11.26 R^2=0.9536 SSE=1282
August Daily	Y=-0.1189x+4.831 R^2=0.04391 SSE=763.7	Y=0.2942x-2.538 R^2=0.176 SSE=1005	Y=-0.001809x+0.1809 R^2=2.657 SSE=0.003044	Y=-0.2029x+10.15 R^2=0.01054 SSE=9577	Y=0.0616x+7.141 R^2=0.004393 SSE=2138
August cumulative	Y=2.065x+23.33 R^2=0.6885 SSE=4742	Y=1.508x-12.95 R^2=0.6512 SSE=3020	Y=0.194x-0.5291 R^2=0.945 SSE=5.436	Y=8.058x-2.28 R^2=0.7687 SSE=48450	Y=8.77x-15.22 R^2=0.9859 SSE=2737
June-August Daily	Y=0.0320x-0.2421 R^2=0.06376 SSE=976.6	Y=0.02907x+0.6814 R^2=0.01997 SSE=2691	Y=-0.008348x+0.7685 R^2=0.0309 SSE=141.8	Y=0.109x-1.694 R^2=0.05477 SSE=13310	Y=0.1231x-1.94 R^2=0.2608 SSE=2786
June-August	Y=1.224x-21.54 R^2=0.8342	Y=2.026x-20.19 R^2=0.9165	Y=0.365x+6.586	Y=3.617x-88.12	Y=3.666x-81.38

cumulative	SSE=19330	SSE=24280	R^2=0.8524 SSE=1499	R^2=0.7128 SSE=342100	R^2=0.82 SSE=191400

Table 3B: The linear fit and stats for June-to-August rainfalls for 2021-2023 in Karachi

	2021	2022	2023
June Daily	Y= -0.002x+0.100 R^2= 0.06617 SSE=0.2418	Y=0.049-0.150 R^2= 0.6161 SSE=83.16	Y= 0.06473x-0.1814 R^2=0.1155 SSE=72.08
June cumulative	Y=0.060x+0.160 R^2=0.9043 SSE=0.863	Y=6.89x+5.815 R^2=0.7093 SSE=565.4	Y=7.395x+7.89 R^2=0.8674 SSE=242.5
July Daily	Y=-0.7715x +2.146 R^2=0.021 SSE=810.3	Y=-1.752x+12.44 R^2=0.0091 SSE=9991	Y=1.024x+3.148 R^2=0.0228 SSE=1347
July cumulative	Y=27.05x+41.13 R^2=0.7985 SSE=5538	Y=125.9x+214.3 R^2=0.9576 SSE=21080	Y=33.51x+41.35 R^2=0.8337 SSE=6716
August Daily	Y=-0.1428x+0.090 R^2=0. 201 SSE=2.43	Y=0.04948x+9.353 R^2=0.000005 SSE=4809	Y=-0.0051x+0.0060 R^2=0.1411 SSE=0.00486
August cumulative	Y=0.274x+0.1869 R^2=0.2422 SSE=7.048	Y=106.5x+149.2 R^2=0.9681 SSE=11210	Y=0.019x+0.0521 R^2=0.3332 SSE=0.02195
June-August Daily	Y=- 0.07362+0.7722 R^2=0.005 SSE=919.2	Y=3.18x+7.539 R^2=0.0533 SSE=16340	Y=-0.1569x+1.33 R^2=0.0013 SSE=1622
June-August cumulative	Y=29.06x+37.85 R^2=0.7857 SSE=20960	Y=238.2x+266.6 R^2=0.9448 SSE=301900	Y=48.68x+66.02 R^2=0.8922 SSE=26070

When the trend line slope is positive, it indicates an increasing trend, while a negative slope signifies a decreasing trend. In the analyzed data, the daily minimum slope was -0.05, observed in August 2023, whereas the maximum slope recorded was 0.2942 for August 2017. Notably, although August 2017 had the highest daily maximum slope, the magnitude of rainfall and the cumulative slope were highest in August 2022. The R^2 values serve as indicators of goodness-of-fit, representing the variance between the given data and the fitted values. Additionally, the SSE values represent the sum of the squares of residuals, indicating the expected deviation from the actual data. Importantly, Tables 3A and 3B highlight that the daily and cumulative slope values of rainfall in August 2020 surpassed those of the entire study duration. This underscores the record-breaking nature of the rainfall in August 2020, which led to a flood-like situation in Karachi. The substantial increase in rainfall during August 2020 and 2022 stands out as an anomaly in contrast to the historical data. These spikes in precipitation can be indorsed to numerous factors, containing unusual monsoonal activity and prospective impacts from broader climate change patterns. This deviance from the standard identifies the increasing variability in weather patterns, which is a hallmark of climate change.

Conclusion:

This paper presents an eight-year analysis of monsoon rainfall patterns and flood risks in Karachi, Pakistan with a focus on the intense rainfall events that occurred in August of 2020 and 2022. It gives a comparative analysis of rainfall data spanning eight years, covering the months of June, July, and August. The primary objective of this research is to assess the alterations in the occurrence and frequency of rainfall, with a specific focus on the substantial rainfall events in August 2020 and 2022. The rainfall data used in this research comprises average values from 10 different towns within the study area. Over the eight-year period, the daily peak rainfall values were recorded at 20.3mm, 31.1mm, 1.19mm, 93.0mm, 34.2mm, 40.0mm, 91.9mm, and 33.0mm while the yearly cumulative rainfall for the work period stood at 114.6mm, 187.0mm, 34.9mm, 310.5mm, 347.9mm, 71.0mm, 693.5mm, and 122.4mm respectively. Notably, these findings exhibit a significant increase in cumulative rainfall in 2022, with a rise of 83.4%, 73.0%, 94.9%, 55%, 49.8%, 89.7%, and 82.2% when compared to the other studied years. Furthermore, the analysis highlights the remarkable surge in both the magnitude of rainfall and cumulative slope, particularly in August 2020 and 2022. This study highlights the notable shifts observed in daily and cumulative rainfall values, trends, slopes, and rainfall frequency, all of which were notably higher in 2020 and 2022, especially during the month of August, when compared with the preceding years in Karachi, Pakistan.

Acknowledgment: We are thankful to the Department of Physics, University of the Punjab, Lahore, Pakistan.

Author's Contribution: All authors contributed significantly.

Conflict of Interest: There exists no conflict of interest for publishing this manuscript in IJIST.

Declaration: We declare that the manuscript has not been published or submitted to any other journal.

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