

Original Research

Hydroclimatic Variability and Precipitation Extremes in Sindh under a Changing Climate

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Abstract

Sindh Province, Pakistan, is highly vulnerable to hydroclimatic extremes, necessitating a detailed understanding of its precipitation patterns for effective water management. This study assesses spatiotemporal precipitation dynamics across Sindh from 2001 to 2024 by integrating satellite-based CHIRPS data, in situ observations from the Climate Knowledge Portal (CKP), and CMIP6 climate model projections. Validation results show strong agreement between CHIRPS and ground data ($R \approx 0.87$, $d \approx 0.93$), confirming the satellite product's reliability in data-sparse regions. Findings reveal a pronounced southeast-northwest precipitation gradient, with coastal districts receiving higher rainfall (up to 485.72 mm) compared to the interior plains. The region exhibits high interannual variability ($CV = 50.32\%$), driven by the South Asian summer monsoon and modulated by ENSO and the Indian Ocean Dipole. While decadal analysis shows a modest upward trend in mean annual precipitation (from 167.17 mm in 2001-2010 to 271.25 mm in 2021-2024), precipitation extremes have intensified significantly. Future projections suggest that, although mean precipitation remains relatively stable, the intensity of extreme events is likely to rise. These results provide a



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scientific foundation for disaster preparedness and the development of climate-resilient policies in Sindh.

Keywords

Precipitation dynamics; climate change; Sindh; climate hazards group infrared precipitation with station data (CHIRPS); Climate Knowledge Portal (CKP)

1. Introduction

Climate change represents a paramount global challenge, altering atmospheric circulation patterns and, consequently, precipitation regimes worldwide. It is one of the most pressing challenges of the 21st century, significantly affecting the Earth's climate systems and hydrological cycles [1-3]. It influences regional water and energy cycles and threatens food and water security in arid regions [4, 5]. The anthropogenic emission of greenhouse gases raises atmospheric temperatures, leading to adjustments in global precipitation patterns and temperatures [6, 7]. Rising global temperatures, increased atmospheric moisture, and intensified weather systems have combined to produce unpredictable rainfall patterns, leading to prolonged droughts in some areas and devastating floods in others [8]. One of the most evident consequences of climate change is the disruption of precipitation patterns worldwide. These patterns serve as significant indicators of climate change's impact, providing critical insights into how shifting climatic conditions reshape our environment. By tracking where, when, and how heavy rain or snow falls, we gain a clearer understanding of the profound ways global warming alters natural systems, affecting ecosystems, agriculture, and communities worldwide [9]. The studies [10-12] serve as compelling evidence that climate change has severe impacts on a country's atmosphere and environment. The increasing climate variability in Pakistan is particularly evident in erratic monsoons, changing rainfall patterns, and the rising frequency of extreme events such as cloudbursts, flash floods, and prolonged dry spells [13]. The integration of agriculture, with its sensitive hydrological dependency on a country's structure, renders it highly vulnerable to these changes. Over the past two decades, Pakistan has consistently ranked among the top 10 nations most affected by climate-change disasters, according to the Global Climate Risk Index [14]. In addition to jeopardizing both short-term food production and long-term water sustainability, disturbances to precipitation cycles directly affect cropping patterns, groundwater recharge, river flows, and rural livelihoods.

Sindh is one of Pakistan's provinces and is consistently at risk from climate change. It is situated in the lower Indus Basin and characterized by an arid-to-semiarid climate. Sindh receives limited and highly variable rainfall, most of which occurs during the monsoon months [15]. Annual precipitation in Sindh ranges from about 100 mm in the southern arid regions to approximately 400 mm in the northern parts, with most rainfall occurring during the summer monsoon season between July and September [16]. Over the last two decades, extreme droughts and heavy rainfall events have alternated across the province, influencing agriculture. These changes have made urban infrastructure, ecosystems, and human settlements more susceptible to the effects of climate change. However, monsoon rainfall is not only limited but has become highly erratic over time. Studies have indicated that the timing and intensity of monsoonal precipitation in Sindh have

changed, with increasing instances of dry spells and prolonged heavy downpours, both of which pose challenges for agriculture and water resource management [17]. Historically, Sindh has suffered from dual vulnerability; on one hand, prolonged droughts, such as those observed in the Tharparkar and Umerkot districts, have led to severe water scarcity and agricultural losses; on the other, flash floods like the devastating monsoon floods of 2010 and 2022 have inundated large swathes of cropland and settlements [18]. For instance, the 2022 flood impacted approximately 70% of Sindh's districts, submerging large areas for weeks and displacing millions of people [19]. These extremes indicate a changing climate in the region, in which traditional rainfall patterns no longer hold, necessitating a reassessment of hydrological planning and disaster preparedness in the province [18]. The northern districts, such as Larkana, Khairpur, and Sukkur, often receive higher rainfall compared to the coastal regions, such as Badin and Thatta, which are prone to both saline intrusion and desertification [20]. Meanwhile, other districts, such as Tharparkar, Umerkot, and Sanghar, have experienced repeated drought conditions. At the same time, urban centers like Karachi and Hyderabad have been affected by sudden, high-intensity rainfall events that overwhelm existing infrastructure and cause flash flooding [21]. Temporal shifts have also been observed: the onset of the monsoon season has become less predictable, and the number of rainy days has decreased, even as the intensity of rainfall on individual days has increased. This is associated with global warming and regional climatic disturbances such as the Indian Ocean Dipole and ENSO events [22]. Scientific assessments reveal a worrying trend. According to a detailed climate risk profile by the Asian Development Bank [23], Sindh is projected to experience further decreases in rainfall reliability and increases in both dry spells and days with intense rainfall under future climate scenarios.

Many areas of Sindh lack sufficient ground-based meteorological stations, and interpreting changes in rainfall patterns from satellite data poses an additional challenge. In such circumstances, satellite products like CHIRPS offer a practical alternative. CHIRPS combines infrared satellite imagery with valid substitute station data and is specifically designed to monitor rainfall trends in data-sparse regions [24]. Its high temporal and spatial resolution makes it suitable for detecting both long-term trends and short-term events in precipitation, which is essential for regions like Sindh, where chronic water shortages and sudden floods coexist. By integrating gridded satellite data with ground-observed datasets and long-term projections, this study aims to provide a more comprehensive understanding of precipitation dynamics in Sindh from 2001 to 2024. The inclusion of future projections (2025-2050) based on global climate models (GCMs) from the World Bank's Climate Knowledge Portal ensures that this analysis is not just retrospective but also forward-looking. This will assist local governments and development planners in designing adaptation strategies that reflect the region's evolving climatic realities, from managing irrigation demands to flood risk mapping. The study also validates the CHIRPS data against observed precipitation to ensure accuracy and reliability, enabling analysis of how rainfall has changed over time and how it might evolve in the coming decades. The primary objective of this study is to understand the changing nature of precipitation in Sindh in the context of a warming climate. By identifying trends, anomalies, and projected shifts, this study provides evidence-based insights that are vital to climate-resilience planning, water resource management, and agricultural policy formulation in the region.

2. Materials and Methods

2.1 Study Area

Sindh, the southeastern province of Pakistan, lies between latitudes 23°35' N and 28°30' N and longitudes 66°42' E and 71°01' E, bordering the provinces of Balochistan and Punjab to the west and north, and sharing an international border with India to the east (Figure 1). The province opens onto the Arabian Sea to the south, providing a 250 km coastal edge that enhances its ecological and economic importance. Geographically, Sindh lies within the Lower Indus Basin, a critical agroecological zone in South Asia. This basin not only significantly contributes to Pakistan's food production but also holds strategic importance for water resource management and regional climate dynamics. Sindh covers approximately 140,914 square kilometers and is home to over 47 million people [25]. The Indus River, which flows through the province, is the region's lifeline; however, the province remains water-stressed. Despite the presence of the Indus, water scarcity has become a recurring issue in Sindh, particularly in the tail-end districts such as Badin, Thatta, and Tharparkar [16]. In these areas, seasonal variability in river flow, upstream withdrawals, and climate-induced shifts in precipitation contribute to a chronic freshwater shortage for agriculture and domestic use [26].

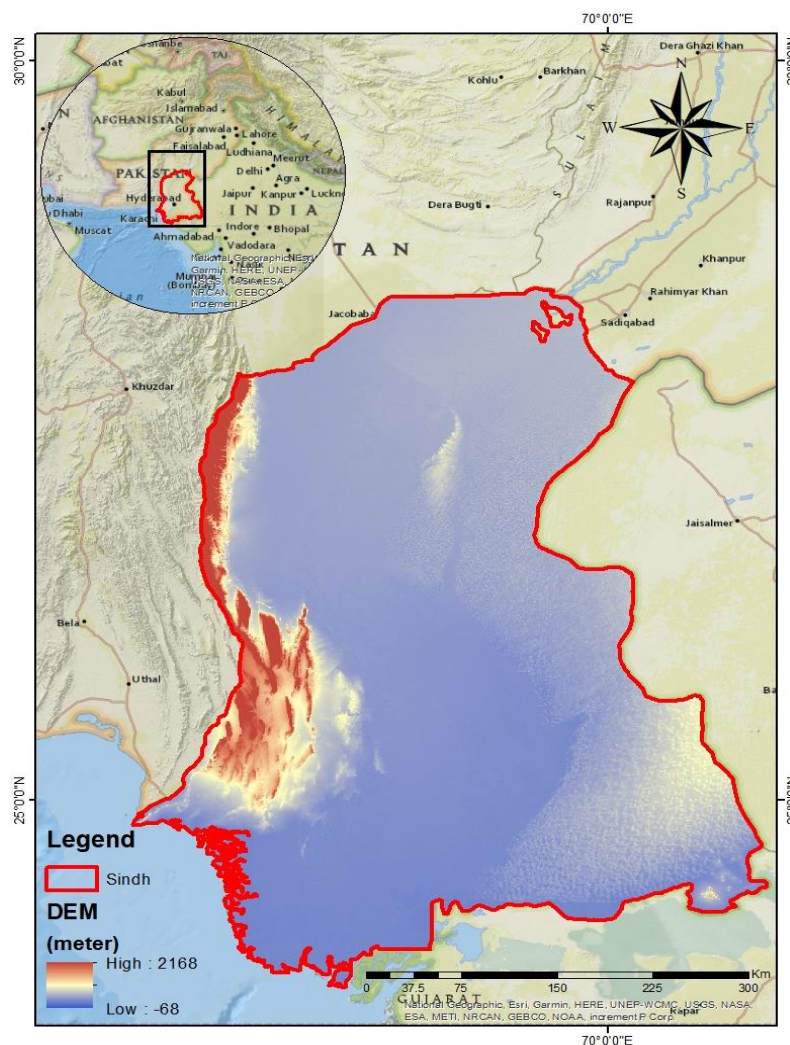


Figure 1 Map of the study area (Sindh).

Groundwater in Sindh is abundant due to the naturally high water tables, especially in irrigated areas [27]. However, its quality is often poor, marked by high salinity and contamination from fluoride and other harmful elements, rendering it unsuitable for drinking or irrigation without treatment [28]. Meanwhile, surface water resources are limited, with availability largely depending on seasonal rainfall, which is becoming increasingly unpredictable due to climate change. As a result, precipitation has become a critical component of Sindh's hydrological balance, influencing crop cycles, groundwater recharge, and water security for rural communities. Most regions of Sindh experience arid to semi-arid climatic conditions, with annual rainfall often falling below 250 mm, primarily concentrated during the monsoon months from July to September [17]. This limited seasonal window makes the region highly sensitive to rainfall anomalies. Even slight changes in the intensity or timing of monsoon rains can lead to devastating floods or severe droughts, both of which have occurred in recent decades. The 2022 floods, for instance, devastated large agricultural areas, while frequent droughts in Tharparkar continue to cause crop failure and malnutrition [18]. Given these dynamics, understanding the spatiotemporal variability of precipitation in Sindh is crucial not only for scientific research but also for effective water resource management, climate adaptation planning, and sustainable agriculture.

2.2 Data Collection

2.2.1 Precipitation Data

Precipitation data were obtained from the Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) dataset, accessed via the Google Earth Engine (GEE) cloud-computing platform, with a spatial resolution of 5 km (https://developers.google.com/earth-engine/datasets/catalog/UCSB-CHG_CHIRPS_DAILY). The CHIRPS dataset was selected for this study due to its strong reputation for producing reliable, high-resolution rainfall estimates. Covering the period from 1981 to the present, CHIRPS blends satellite imagery with ground-based station data to produce rainfall estimates at approximately 5 km spatial resolution, making it ideal for regional climate studies and hydrological assessments [24]. In this study, CHIRPS was chosen as the primary precipitation dataset due to its accessibility, spatiotemporal consistency, and demonstrated reliability for climate studies in semi-arid and monsoonal regions.

2.2.2 Observed and Projected Data

The study utilized observed and projected rainfall data obtained from the Climate Knowledge Portal (CKP) of the World Bank (<https://climateknowledgeportal.worldbank.org/>). CKP provides historical data, whereas the study has gathered data covering its study period from 2001 to 2024 (<https://climateknowledgeportal.worldbank.org/country/pakistan/climate-data-historical>). CKP also provides mean projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6) for the period 2024-2100. In contrast, the study used SSP5 8.5 projections from 2025 to 2050 to encompass precipitation projections for the next two decades (<https://climateknowledgeportal.worldbank.org/country/pakistan/climate-data-projections>). CKP is frequently utilized in peer-reviewed studies focusing on climate change impacts across developing countries [29, 30].

2.3 Methodology

2.3.1 Data Acquisition and Preprocessing

Precipitation data were obtained from the CHIRPS data via Google Earth Engine (GEE) for the period 2001-2024. The data were extracted at monthly and annual temporal resolutions to capture interannual and intraannual variability across the study area. The methodological framework of the study shown in Figure 2.

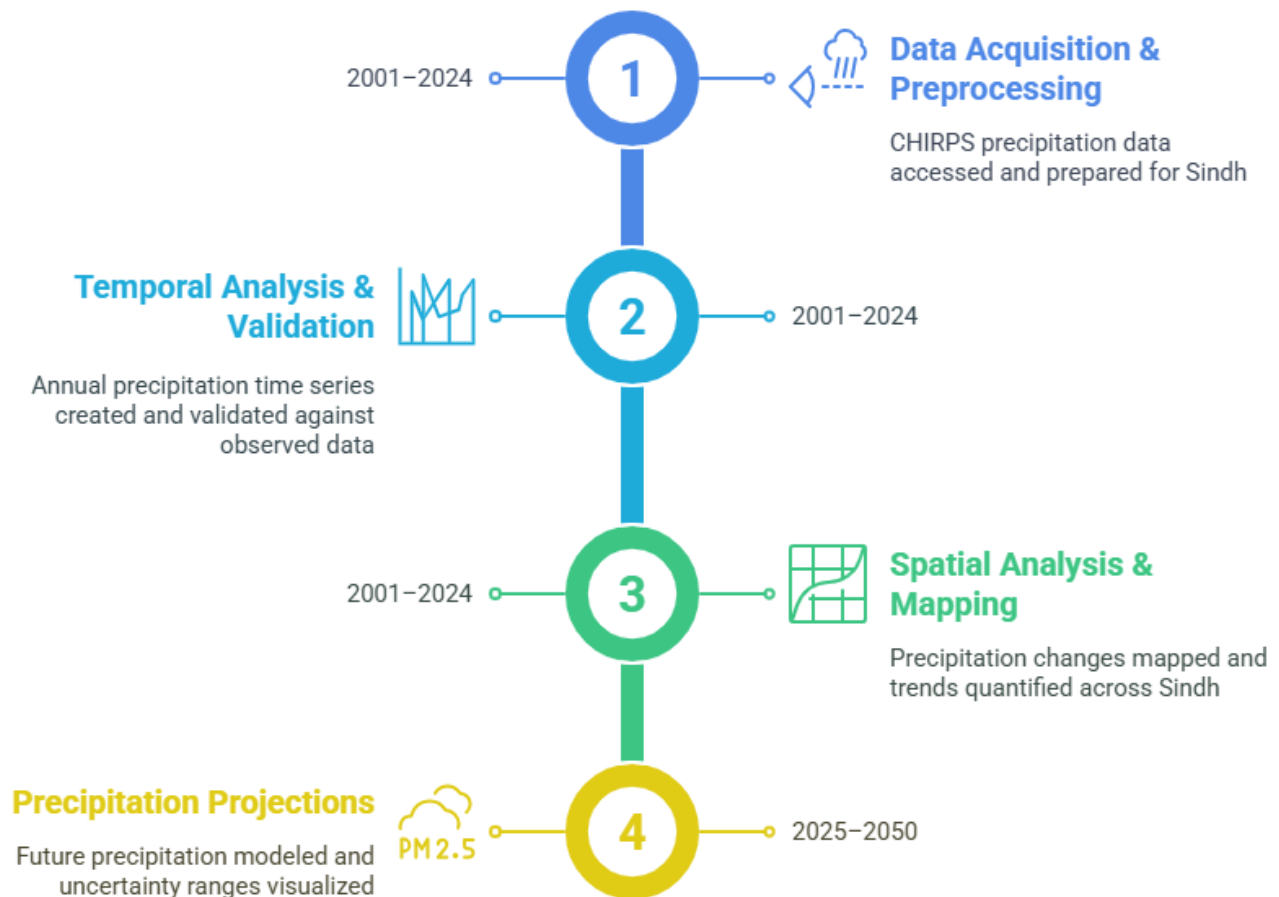


Figure 2 Methodology Framework of the study.

2.3.2 Spatial Analysis of Precipitation Dynamics

The spatial distribution and magnitude of precipitation change were mapped using GIS tools. Each grid point was analyzed to detect changes in precipitation intensity and distribution over time. Color-coded visualization techniques were applied to enhance the interpretability of spatial patterns and variations in precipitation magnitude across the region. This integrated methodology provides a detailed visualization of how precipitation patterns in Sindh have evolved over the past two decades and how they may continue to change, aiding in climate impact assessments and policy planning.

2.3.3 Temporal Analysis and Validation

Annual precipitation values for each year during the study period were extracted to construct a time series. These CHIRPS-based values were validated against ground-based observed precipitation data obtained from the CKP using temporal graphs. This comparison facilitated the assessment of the accuracy and reliability of the CHIRPS dataset in representing observed precipitation trends. To evaluate the performance of orbital (satellite-derived) precipitation against surface observations, a set of widely used statistical indicators was employed, including the root mean square error (RMSE), Pearson correlation coefficient (R), Willmott's index of agreement (d), and percent bias (Pbias). RMSE quantifies the overall magnitude of errors, R measures the strength of linear association, d assesses the degree of agreement between datasets, and Pbias indicates systematic overestimation or underestimation by the satellite product. Additionally, precipitation projections for 2025 to 2050 were generated using Python. Temporal graphs were developed to illustrate projected trends and associated uncertainty ranges, providing insights into potential future climatic shifts.

2.3.4 Rainfall Variability and Climate Indicators

To further assess rainfall variability and its potential linkage with climate change, three widely used precipitation-based indices were employed: the Standardized Precipitation Index (SPI), the coefficient of variation (CV), and decadal rainfall analysis. Monthly precipitation data were used to compute SPI at 3-, 6-, and 12-month time scales (SPI-3, SPI-6, and SPI-12), representing short-, medium-, and long-term moisture conditions, respectively. The SPI was calculated by fitting a gamma probability distribution to the aggregated precipitation series and subsequently transforming it to a standard normal distribution following the methodology recommended by the World Meteorological Organization. Positive SPI values indicate wetter-than-normal conditions, while negative values indicate varying degrees of drought. Rainfall reliability was assessed using the coefficient of variation (CV), calculated as the ratio of the standard deviation to the mean annual precipitation, expressed as a percentage. Higher CV values indicate greater interannual variability and lower rainfall reliability. In addition, decadal rainfall analysis was conducted by grouping annual precipitation into three periods (2001-2010, 2011-2020, and 2021-2024) to examine long-term changes in rainfall characteristics under a changing climate.

3. Results

3.1 Spatial Dynamics

The CHIRPS-derived maps clearly reveal that Sindh's rainfall is neither spatially uniform nor temporally constant. Spatially (Figure 3), a pronounced southeast-northwest gradient emerges: coastal and low-lying districts such as Badin, Thatta, Karachi East and West, and Tharparkar regularly record the highest mean annual totals (isolated grid cells peaking around 485 mm), driven by intense monsoonal incursions and occasional cyclonic moisture inflow. In contrast, the interior plain districts like Larkana, Shikarpur, Sukkur, and Khairpur receive markedly less rainfall (often below 300 mm), reflecting their greater distance from the Arabian Sea and a semi-arid climate regime. Transitional zones in Sanghar, Umerkot, and Mirpurkhas show intermediate values (300-600 mm), underscoring

how subtle topographic undulations and land-cover differences shape localized convective activity. Figure 4 illustrates that the 2001-2024 series shows significant interannual volatility. Exceptional wet years, including 2011, 2012, 2020, and especially 2022, stand out with widespread surges of 20-40% above the long-term mean, particularly enhancing rainfall in the southeast by up to 150 mm compared to neighboring years. These wet pulses coincide with strong monsoon seasons and, in 2022, with record-breaking cyclonic events. Conversely, drought-prone years such as 2002, 2004, 2006, and 2018 exhibit region-wide deficits of 15-30%, with the interior districts falling below 200 mm and coastal zones lacking as much as 700 mm. The alternating sequence of wet and dry years highlights the basin's sensitivity to large-scale climate oscillations (ENSO, Indian Ocean Dipole). It underscores the substantial uncertainty for agricultural planning and water management [31]. Collectively, these spatiotemporal patterns not only chart two decades of climatic variability but also identify hotspots of hydrological risk and resilience across Sindh.

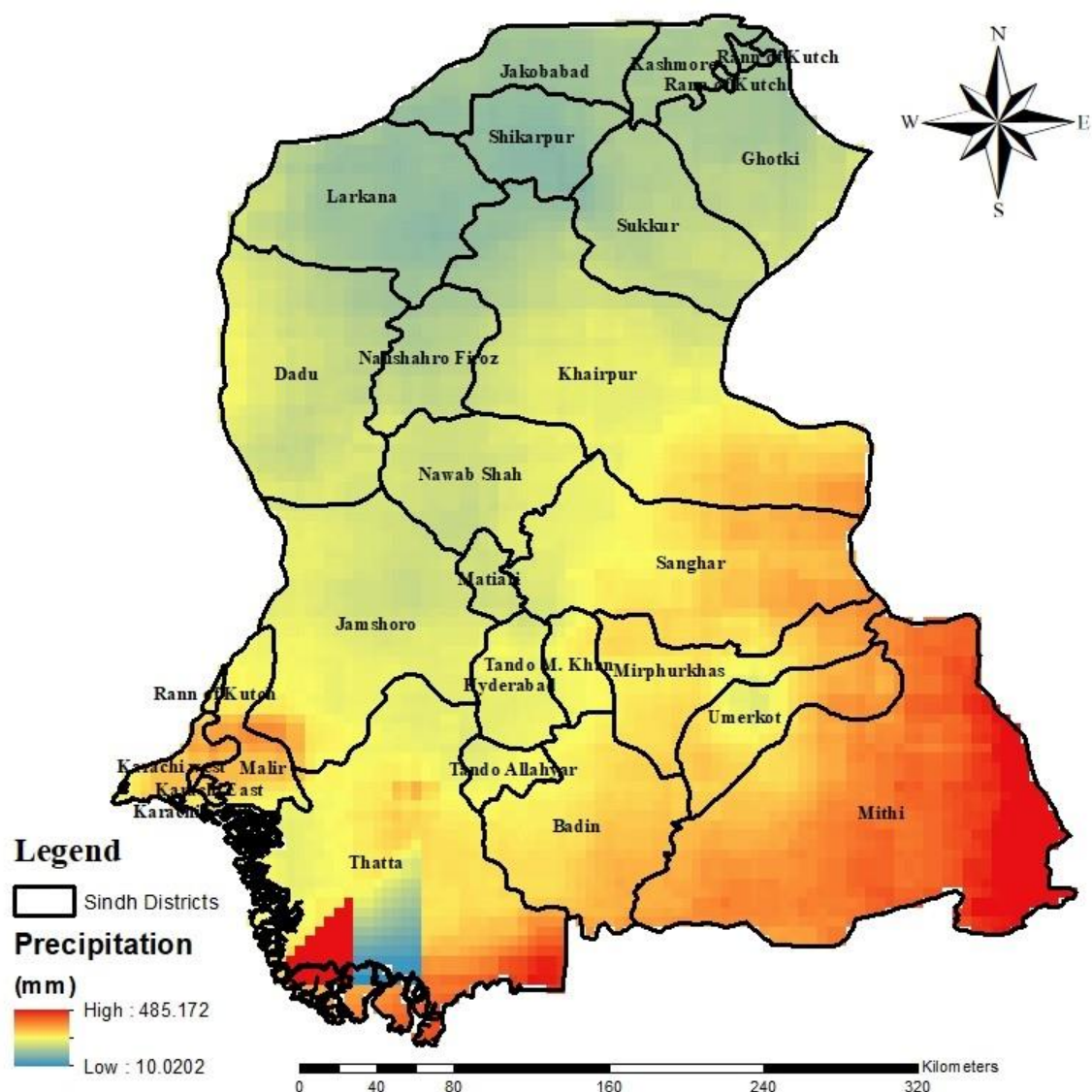


Figure 3 Spatial Average Pattern of Precipitation across the study area from 2001 to 2024.

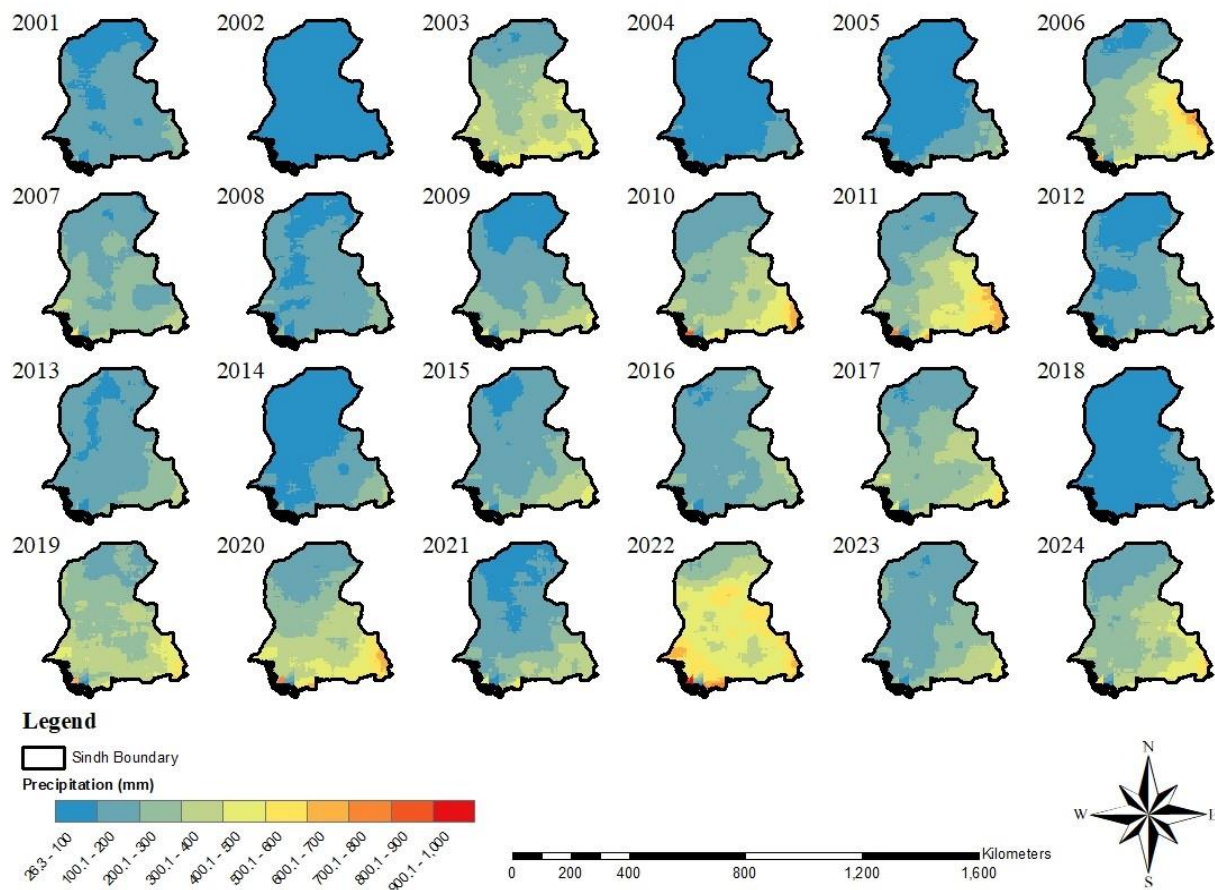


Figure 4 Spatial Annual Patterns of Precipitation from 2001 to 2024.

The comparison between CHIRPS-derived and in situ (CKP) annual precipitation (Figure 5) reveals a strong, nearly linear relationship, underscoring the reliability of the gridded CHIRPS dataset for Sindh. The least-squares trendline (slope ≈ 0.78 , intercept ≈ 5 mm) accounts for almost 90% of the variance ($R^2 = 0.89$), highlighting that CHIRPS slightly underestimates the highest rainfall totals (points above 300 mm) by 10-20 mm. The comparison between orbital precipitation estimates and surface observations shows strong agreement. The RMSE was 49.73 mm, indicating moderate deviations between the two datasets. A high Pearson correlation coefficient ($R = 0.87$) reflects a strong linear relationship between orbital and surface precipitation. Furthermore, the Willmott index of agreement ($d = 0.93$) indicates excellent overall agreement. The percent bias ($Pbias = 8.33\%$) suggests a slight overestimation of precipitation by the orbital product. Overall, these results confirm the reliability of satellite-derived precipitation data for capturing interannual rainfall variability in the study region. These statistics confirm that CHIRPS captures both the magnitude and year-to-year variability of observed precipitation across Sindh's diverse climate zones. However, extreme events may be marginally smoothed in the satellite product.

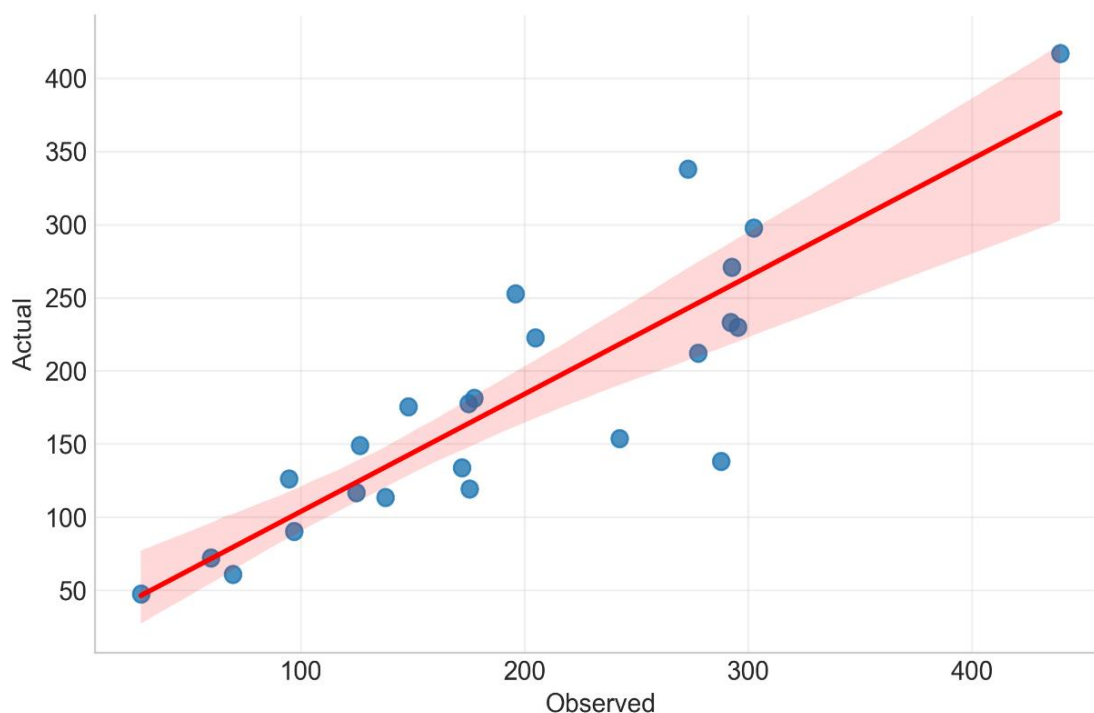


Figure 5 Comparison of CHIRPS and CKP Annual Precipitation from 2001 to 2024.

3.2 Temporal Dynamics

The temporal results for the province of Sindh reveal more significant outcomes. Figure 6 presents monthly precipitation data from 2001 to 2024 separately. The vast majority of Sindh's annual precipitation occurs during the southwest monsoon season, which lasts from July to September, with peak monthly totals occurring in August when monsoon circulation is strongest. While July is climatologically the wettest month nationally, contributing the most significant single-month fraction of annual rainfall across Pakistan, the unprecedented 2010 floods in southern Pakistan were preceded by anomalously intense monsoon rains in late 2009 and early 2010, driven by La Niña-induced moisture surges, resulting in record-level inundation of Sindh's Indus floodplain [32]. Conversely, several years have fallen well below normal, reflecting drought-like conditions. Broadly, the 2000-2005 period stands out as the most severe five-year drought in South Pakistan's recorded history, with cumulative precipitation deficits approaching 75% in arid zones [33]. Large-scale modes of variability, such as ENSO and the Indian Ocean Dipole, modulate these wet and dry extremes. El Niño years often correlate with weakened monsoon flow and below-average rainfall in Sindh, whereas La Niña tends to enhance moisture transport into the Arabian Sea and adjoining provinces [34]. These detailed patterns, which include strong monsoonal rainfall clustering, pronounced interannual volatility driven by climate oscillations, and an upward trend in extreme events, underscore the critical need for adaptive water management and resilient agricultural planning in Sindh.

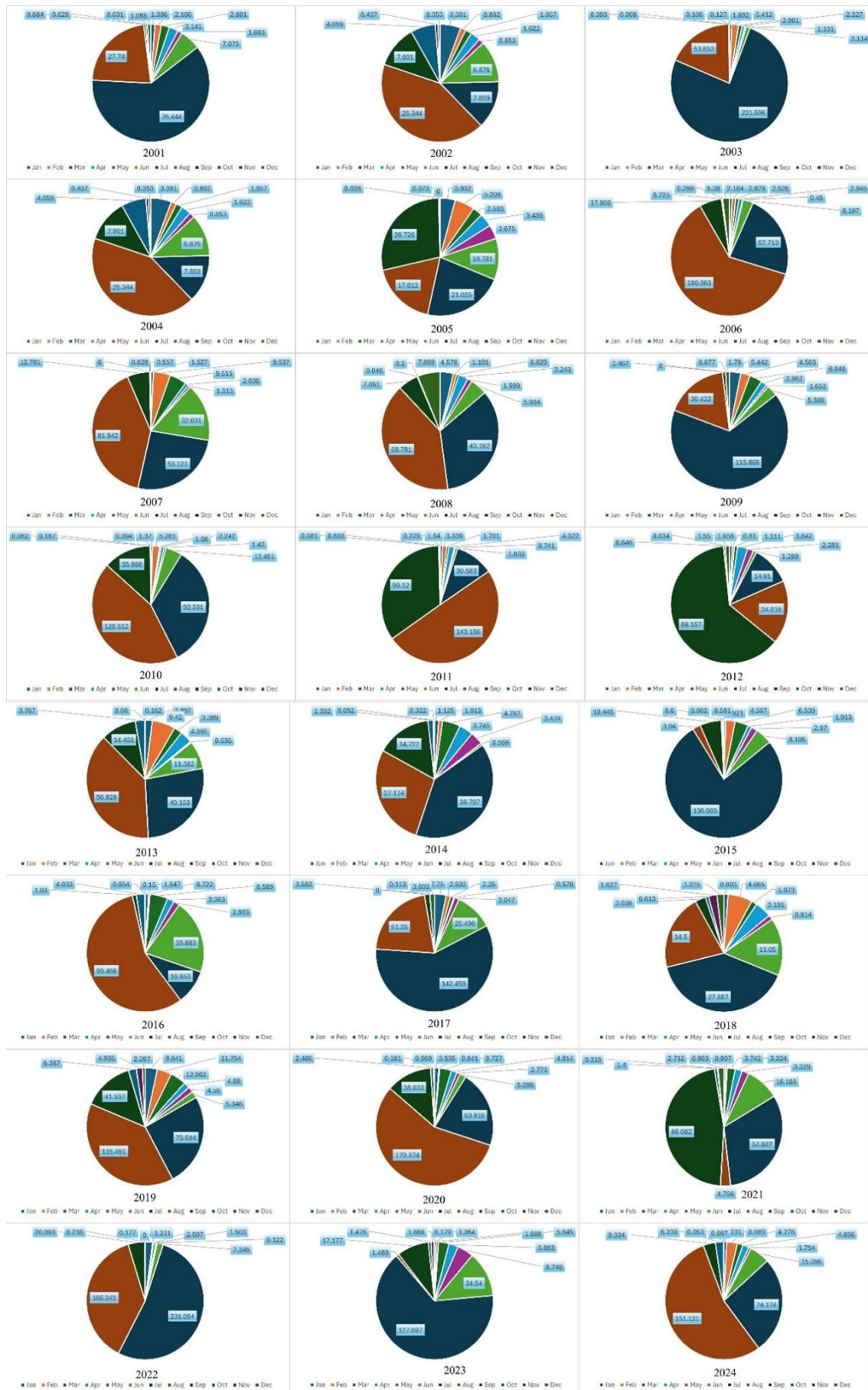


Figure 6 Monthly Variations in Precipitation from 2001 to 2024.

Figure 7 shows annual CHIRPS-derived precipitation compared to in situ CKP observations for Sindh from 2001 to 2024, revealing an almost one-to-one correspondence (correlation coefficients consistently greater than 0.70). The least-squares regression yields a slope near unity (≈ 0.78 - 0.85) and a slight negative bias (-3 to -5 mm/yr), indicating that CHIRPS marginally underestimates extreme high-rainfall years by 10-20 mm on average [35]. Overlaid on this validation is a five-year moving-average trend line, which exhibits a modest upward trend in mean annual precipitation (approximately +5 mm per five-year period), suggesting a gradual intensification of the hydrological cycle in the region [36]. Figure 8 presents multi-model CMIP6 projections of annual precipitation for Sindh under standard greenhouse gas scenarios, alongside the 5-95% uncertainty envelope. Across the ensemble, mean precipitation remains effectively stationary through mid-century, with projected changes within ± 3 % of the 2001-2024 baseline (± 20 mm/yr) [36]. The extensive uncertainty range, spanning roughly 10% to 12% of mean precipitation, reflects divergent model responses to monsoon dynamics and ocean-atmosphere interactions, particularly the Indian Ocean Dipole and ENSO teleconnections [37]. Despite negligible mean shifts, specific high-emission scenarios (e.g., SSP5-8.5) project slight increases in extreme precipitation intensity by 2040-2050, with RX5day (maximum five-day rainfall) rising by 5-8% relative to historical values [4]. Future studies should focus on high-resolution regional downscaling, formal attribution of extreme events, socioeconomic impact assessments, and the development of machine-learning-based forecasting tools to support resilient water resource planning in Sindh.

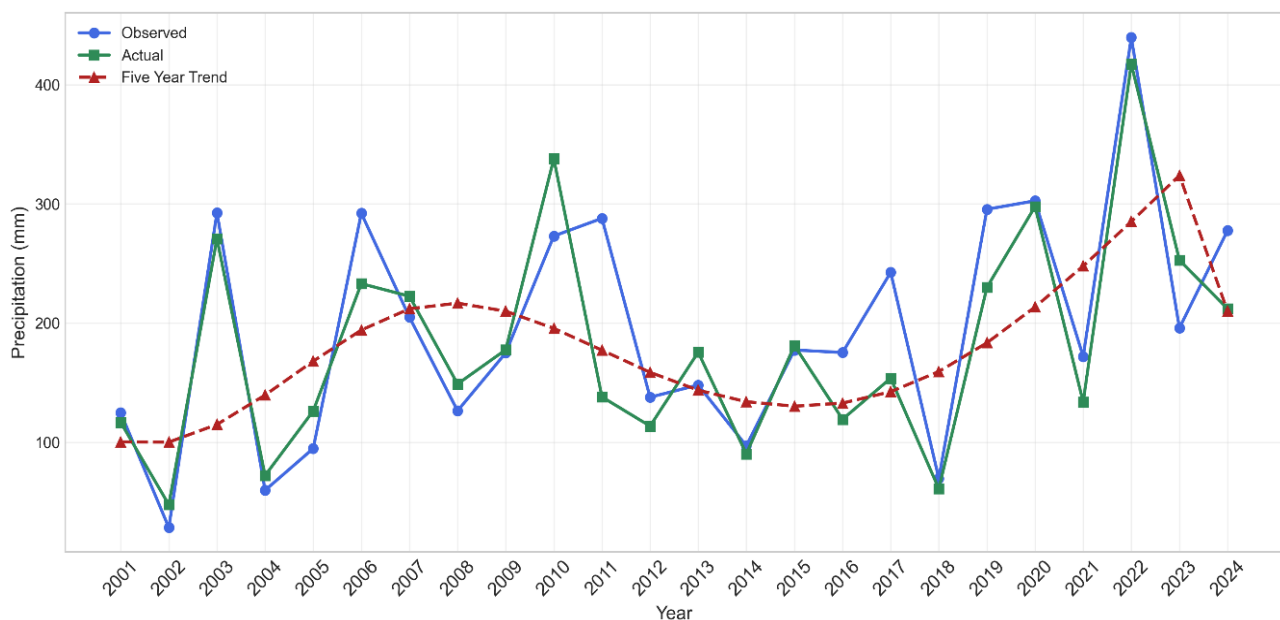


Figure 7 Annual Variations of Precipitation and Validation from 2001 to 2024.

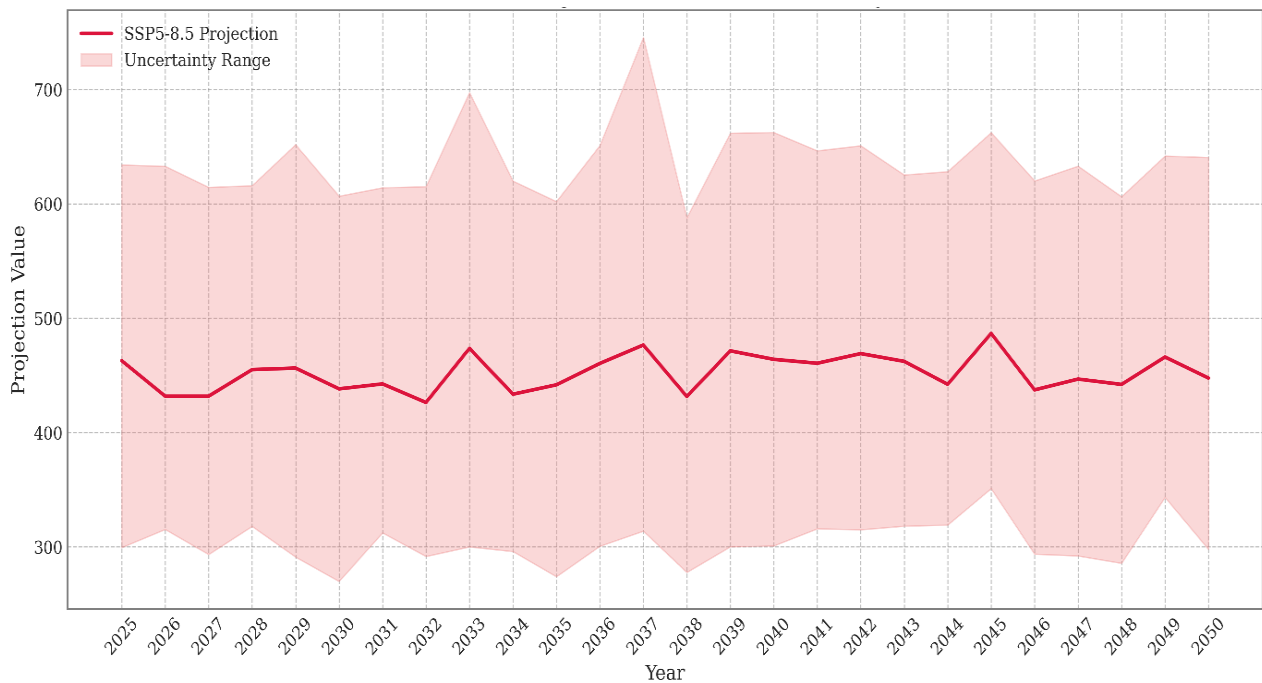


Figure 8 Annually SSP-8.5 Scenario Projections with Uncertainty from 2023 to 2050.

The SPI analysis reveals pronounced temporal variability in precipitation across the study period (Figure 9). The SPI-12 time series shows several episodes of moderate to severe drought, indicating prolonged rainfall deficits at the annual scale. These dry phases are interspersed with relatively wet periods, reflecting substantial interannual variability in precipitation. The persistence of low SPI-12 values in recent years suggests an increasing tendency toward persistent dry conditions, which are associated with regional climate variability and changing precipitation regimes.



Figure 9 Temporal variation of the 12-month Standardized Precipitation Index (SPI-12) derived from monthly precipitation data during 2001-2024. Horizontal dashed lines represent drought severity thresholds.

The coefficient of variation (CV) of annual rainfall was estimated at 50.32%, indicating high interannual variability and relatively low rainfall reliability in the study area. This level of variability suggests increased uncertainty in water availability, which may pose challenges for water resource planning and management. Decadal rainfall analysis further illustrates notable changes in precipitation characteristics (Figure 10). The mean annual rainfall increased from 167.17 mm during 2001-2010 to 193.37 mm during 2011-2020, and then rose further to 271.25 mm during 2021-2024. However, the most recent decade also exhibits the highest standard deviation (120.96 mm), indicating enhanced rainfall variability despite higher mean precipitation.

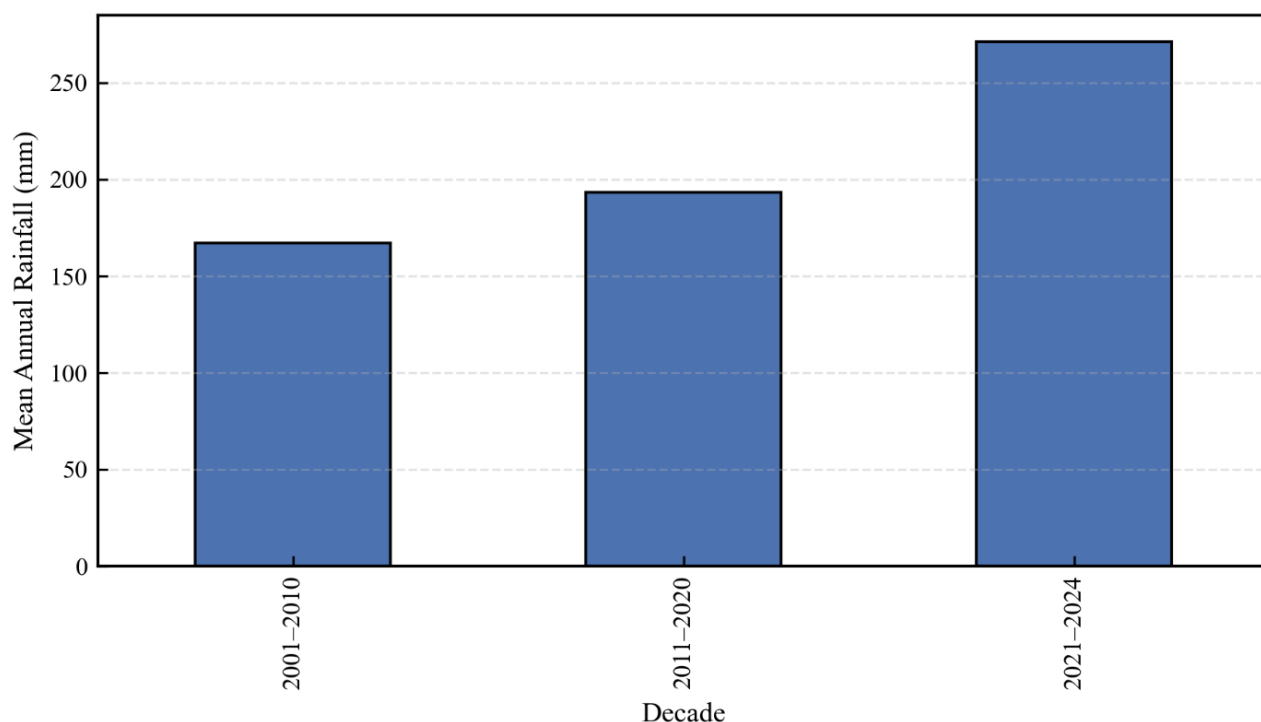


Figure 10 Decadal variation in mean annual precipitation.

4. Discussion

4.1 Spatial and Temporal Variability of Precipitation

The spatial precipitation patterns derived from CHIRPS data indicate clear gradients across Sindh, with higher precipitation in southern and coastal districts and lower values in the inland and northern regions. Such spatial contrasts are well documented in previous studies and are commonly attributed to proximity to the Arabian Sea, local moisture availability, and orographic influences (e.g., monsoon-driven rainfall enhancement along coastal belts). The corrected spatial averages, ranging from approximately 10.02 mm to 485.72 mm, fall well within climatologically plausible limits and align with earlier satellite- and gauge-based assessments over southern Pakistan. Temporally, annual and monthly analyses reveal substantial interannual variability, as reflected by the high coefficient of variation (50.32%). This degree of variability underscores Sindh's hydroclimate's sensitivity to large-scale atmospheric drivers and underscores the importance of long-term datasets for distinguishing short-term fluctuations from longer-term trends. Decadal rainfall statistics further suggest a gradual increase in mean precipitation in recent decades, particularly since 2010, although variability remains pronounced.

4.2 Satellite-Gauge Consistency and Dataset Reliability

Validation of CHIRPS precipitation against CKP observations shows strong agreement, with correlation coefficients exceeding 0.70, a high index of agreement ($d = 0.93$), and moderate RMSE values. The slight positive Pbias (8.33%) and minor underestimation during extreme rainfall years are consistent with known limitations of satellite precipitation products, particularly under intense convective conditions. Nevertheless, the overall correspondence confirms that CHIRPS reliably

captures regional-scale precipitation dynamics in Sindh, supporting its application in hydroclimatic assessments where dense gauge networks are unavailable.

4.3 Extreme Precipitation and Climate Change Signals

While mean precipitation is relatively stable, multiple indicators point to an increase in precipitation extremes. The SPI analysis at different accumulation scales highlights more frequent wet anomalies in recent years, and the moving-average trend suggests a modest intensification of the hydrological cycle. This pattern-stable means combined with increasing extremes has been widely reported in climate change literature and reflects changes in rainfall intensity rather than total volume. Such behavior has significant implications for flood risk, water resource management, and infrastructure resilience in vulnerable regions such as Sindh. It is important to emphasize that projected changes are interpreted as ensemble-consistent tendencies rather than deterministic outcomes. Uncertainties associated with climate models, emission scenarios, and internal variability remain, and results should therefore be viewed as indicative of plausible future conditions rather than precise forecasts.

4.4 Role of Regional Atmospheric Circulation

Regional atmospheric circulation plays a critical role in shaping precipitation variability over Sindh. The dominant driver is the South Asian summer monsoon, which governs seasonal rainfall distribution and interannual variability. Variations in monsoon strength, onset timing, and moisture transport from the Arabian Sea strongly influence precipitation totals, particularly in southern and eastern districts. In addition, large-scale climate modes, such as the El Niño-Southern Oscillation (ENSO), modulate monsoon behavior, often suppressing rainfall during El Niño phases and enhancing it during La Niña conditions. Western disturbances also contribute to winter and pre-monsoon precipitation, particularly in northern Sindh, though their influence is generally weaker than that of the monsoon. The interaction of these circulation systems, combined with regional warming, likely contributes to the observed increase in precipitation extremes despite relatively stable mean values.

4.5 Implications for Water Resources and Policy

The identified variability and emerging intensification of extreme precipitation events have direct implications for water resource management, flood risk, and climate adaptation planning in Sindh. Increased rainfall extremes may exacerbate flooding, particularly in low-lying and coastal districts, while high interannual variability poses challenges for agricultural planning and water allocation. The quantitative findings of this study provide a scientific basis for strengthening early warning systems, improving infrastructure resilience, and integrating climate information into regional development strategies.

5. Conclusions

Reliable characterization of precipitation variability is fundamental for sustainable water-resource management and climate adaptation in Sindh Province, a region highly vulnerable to hydroclimatic extremes. This study presents a comprehensive assessment of spatiotemporal

precipitation dynamics across Sindh for the period 2001-2024 by integrating satellite-based CHIRPS data, in situ CKP observations, statistical validation, and climate model projections.

The results reveal pronounced spatial and temporal variability in precipitation, with a strong seasonal dominance of the South Asian summer monsoon. More than 70% of annual rainfall occurs between July and September, with August representing the peak rainfall month. Spatial analyses indicate a clear southeast-northwest precipitation gradient, with higher mean annual precipitation in southern and coastal districts and substantially lower values across the interior plains. Corrected spatial averages show precipitation ranging from approximately 10.02 mm in the driest regions to 485.72 mm in wetter zones, reflecting realistic hydroclimatic conditions across the province.

Interannual variability is high, as indicated by a coefficient of variation exceeding 50%, underscoring Sindh's sensitivity to large-scale atmospheric drivers. Exceptional wet years, such as 2009/10, 2020, and 2022, produced markedly above-average rainfall and contributed to widespread flooding, whereas prolonged dry conditions during the early 2000s resulted in severe rainfall deficits. The five-year moving average indicates a modest upward trend in precipitation (approximately +5 mm per five years), suggesting a gradual intensification of the regional hydrological cycle.

Validation results demonstrate strong agreement between CHIRPS and CKP observations, with a high correlation ($R \approx 0.87$), strong index of agreement ($d \approx 0.93$), and moderate RMSE (~ 50 mm). Although CHIRPS slightly underestimates precipitation during extreme rainfall years, its overall consistency confirms its suitability for long-term regional precipitation monitoring and trend analysis in data-sparse environments.

Climate projections derived from CMIP6 ensembles suggest no statistically significant change in mean annual precipitation in the near term; however, indicators point to a potential increase in extreme rainfall intensity. This combination of stable means and intensifying extremes has important implications for flood risk, infrastructure resilience, and water-resource planning.

Overall, this study provides a robust, data-driven understanding of precipitation behavior in Sindh and highlights the value of integrating satellite observations, ground measurements, and climate projections. The findings provide a scientific foundation for adaptive water management, disaster preparedness, and climate-resilient policy development in one of Pakistan's most climate-sensitive regions.

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Author Contributions

Conceptualization, M.H. and M.A.; methodology, M.H.; software, M.H.; validation, M.H., M.A.; investigation, C.L. and J.X.; resources, C.L.; writing—original draft preparation, M.A.; writing—review and editing, M.H.; visualization, M.H.; supervision, C.L. and J.X. All authors have read and agreed to the published version of the manuscript.

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Competing Interests

The authors have declared that no competing interests exist.

Data Availability Statement

The data used in this study were downloaded from the public platforms of the Climate Knowledge Portal and Google Earth Engine. They can be accessed via the following websites: (<https://climateknowledgeportal.worldbank.org/>) and (https://developers.google.com/earth-engine/datasets/catalog/UCSB-CHG_CHIRPS_DAILY).

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