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Analyzing Precipitation Trends in the Cholistan Desert, Pakistan: A Statistical and GIS-Based Study

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KEYWORDS

- desert precipitation variability
- Mann–Kendall trend test
- Sen Slope Estimator
- arid environment
- Cholistan Desert

ABSTRACT

Climate change is driving significant shifts in temperature and precipitation patterns globally, with far-reaching socio-economic and environmental impacts, especially in arid regions. This study examines precipitation variability and long-term trends from 1980 to 2020 in Pakistan's Cholistan Desert, a region where water scarcity poses critical challenges for local communities and ecosystems. Using data from five meteorological stations, we applied a combination of Geographic Information System (GIS) techniques and statistical analyses to assess both seasonal fluctuations and annual trends in precipitation. The results reveal notable spatial variability in precipitation trends across the Cholistan Desert. Positive trends, indicating increased precipitation over time, were observed in the northwestern areas, particularly at the Bhagla, Khanpur, and Fort Abbas stations. In contrast, significant negative trends were detected in the southwestern areas, represented by the DinGarh and MaujGarh stations, where precipitation has steadily decreased over the study period. These contrasting trends reveal the diverse impacts of climate change within the desert pointing out the areas that may face heightened water scarcity. The ongoing shifts in precipitation necessitate targeted water management and climate adaptation strategies to address the challenges posed by these shifting precipitation patterns. For areas with declining trends, strategies focused on rainwater harvesting and conservation will be critical. Regions experiencing increased precipitation may require infrastructure improvements to manage and store water more effectively.

Introduction

Climate change is a pressing global issue that is driving unprecedented shifts in temperature and precipitation patterns, with profound impacts on ecosystems, agriculture, water resources, and human livelihoods. Since the industrial era, global average temperatures have risen significantly, with the Intergovernmental Panel on Climate Change (IPCC) reporting an increase of approximately 1.1°C above pre-industrial levels, mainly due to human activities (IPCC, 2021). This warming trend is accompanied by more frequent and intense extreme weather events, including droughts, floods, and storms, which affect billions of people worldwide and strain resources, particularly in vulnerable regions (Amouzay et al., 2023). Precipitation patterns have also been notably altered, with

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regions such as Africa, South America, and parts of Asia experiencing significant increases or decreases in rainfall, leading to both flood risks and severe drought conditions (Nordhaus, 2018; Wagesho et al., 2013).

In South Asia, climate variability has become more pronounced over the past few decades, marked by erratic monsoon patterns, longer dry spells, and more intense rainfall events. The region is experiencing an increase in the frequency of extreme weather events, driven by changes in atmospheric circulation and the influence of warming oceans. Recent studies have shown that South Asia's annual monsoon season has become less predictable, with some areas receiving above-average precipitation and others suffering from prolonged droughts (Deng et al., 2019; Ghorbani et al., 2021). These shifts in precipitation not only affect agricultural productivity but also increase the risk of water scarcity in arid and semi-arid areas where communities rely on seasonal rains for survival (Singh & AchutaRao, 2019). South Asia is particularly vulnerable due to its dense population, high dependence on agriculture, and limited resources for climate adaptation (Balogun et al., 2023).

Pakistan, as part of this climate-sensitive region, faces severe consequences from these shifts in climate. The country has witnessed a rise in extreme weather events, including both intense monsoonal flooding and prolonged droughts (Abbas et al., 2023). In its Sixth Assessment Report, the IPCC highlighted that Pakistan is among the countries most vulnerable to climate impacts due to its diverse geography, reliance on agriculture, and already stressed water resources (IPCC, 2021). Research indicates that Pakistan's annual mean temperature has increased by approximately 0.6°C in recent decades, accompanied by variable rainfall patterns, resulting in increased aridity in some areas and unexpected flooding in others (Baig et al., 2022; Hussain & Abbas, 2019). The impact on water resources has been particularly acute in arid and semi-arid zones, where even small reductions in rainfall can lead to severe water shortages, affecting both human and ecological systems (Arshad et al., 2022; Xu et al., 2011).

The Cholistan Desert in South Punjab, Pakistan, is an arid region that relies heavily on seasonal precipitation for water resources. Covering an area of approximately 26,000 square kilometers, it forms part of the larger Thar Desert ecosystem and is characterized by extremely low and erratic rainfall. Local communities in this region depend on rainwater harvesting techniques, such as using natural depressions and artificial ponds, or *tobas*, to capture and store rainfall for use during dry periods. However, as precipitation patterns continue to shift, the desert's limited water resources are increasingly at risk. The region's population, livestock, and limited agricultural activities are highly vulnerable to the impacts of climate change, as changes in precipitation can exacerbate already challenging conditions (Rahman & Dawood, 2017; Dawood et al., 2018).

Despite the pressing need to understand precipitation trends in the Cholistan Desert, few studies have focused specifically on this region. Research on climate variability in Pakistan has generally concentrated on major river basins and highland areas, such as the Indus Basin and northern mountains, where water resources play a vital role in national agriculture and hydropower. To address this gap, this study investigates long-term precipitation trends in the Cholistan Desert over a 40-year period (1980–2020), using data from five meteorological stations. By employing GIS techniques and statistical analyses – including the Mann-Kendall Trend (MKT) test and Theil-Sen's Slope (TSS) estimator – this study aims to detect seasonal and annual precipitation trends across different parts of the desert. Understanding these trends is crucial for designing effective water resource management strategies and informing policy decisions aimed at increasing the resilience of local communities to climate variability. The findings from this study contribute insights for managing water resources in arid regions and enhance our understanding of climate variability within the Cholistan Desert. These results can assist policymakers, resource managers, and the scientific community in developing adaptive strategies to address water scarcity and ensure sustainable water availability in the face of changing climate patterns. By shedding light on the effects of climate change in one of Pakistan's most water-stressed regions, this research adds to the broader scientific literature on arid-zone climate dynamics and provides a foundation for future studies on climate adaptation in vulnerable ecosystems.

Characteristics of the Study Area

The Cholistan Desert, situated in Southern Punjab, Bahawalpur Pakistan (Figure 1), encompasses a vast expanse of arid landscape, extending between latitudes 27° 42´ to 29° 45´ North and longitudes 69° 52´ 30 to 75° 24´ East. Spanning an estimated 2.6 million hectares (26,000 km^2), it comprises two distinct regions: Greater Cholistan spans approximately 18,130 km^2, while Lesser Cholistan covers roughly 7,770 km^2 (Rafique & Hassan, 2015). The desert stretches an impressive 481 km in length and 193 km in width, dominating two-thirds of the Bahawalpur Division's landmass. A predominantly sandy terrain, the Cholistan Desert bears resemblance to Great India's Rajputana Desert, extending to the Indian border and lying southwest of the now-dry course of the Hakra River. Lesser Cholistan, on the other hand, extends from the termination point of the Sutlej River northeastward to the Hakra River (Akram et al., 2008; Hassan et al., 2021).

Beyond its geographical features, the Cholistan Desert exhibits unique human and natural aspects. Human settlements in the desert primarily consist of nomadic tribes, such as the Cholistanis (Malik et al., 2017), who rely on traditional livelihoods like animal husbandry, particularly camel rearing, to sustain their communities. These nomads traverse the desert landscape in search of water and pasture for their livestock, forming an integral part of the desert's cultural fabric (Haider et al., 2021). Rainwater is primarily collected in naturally low-lying areas or in man-made small pools, such as depressions locally known as *tobas* (Rasheed et al., 2018). In the arid landscape of the Cholistan Desert, rainfall serves as the sole source of drinking water for both humans and livestock. However, these water bodies, or *tobas*, typically retain water for only a maximum of four to five months before evaporating or being absorbed into the ground. Moreover, the salinity of underground water sources in the region tends to be high (Mumtaz, 1982). There are approximately 2000 small and large *tobas* scattered across the desert (Figure 1) (Rasheed et al., 2018). However, only around half of these *tobas*, roughly 1000, remain functional, while the others have become filled with silt and sand, reaching the land surface (Hussain & Abbas, 2019).

The size and storage capacity of each toba vary based on its dimensions, including length, width, and depth. Additionally, the amount of rainwater collected in these tobas fluctuates depending on the size of their catchment areas. On average, the water storage capacity of these tobas ranges between 500 and 1000 cubic meters (equivalent to 0.1 to 0.2 million gallons) (Malik et al., 2017). Therefore, the total water storage capacity of approximately 1000 tobas in the Cholistan Desert is estimated to be around 0.5 million cubic meters (or 80 million gallons) according to the Capital Development Authority (CDA) in 2022 (Imran et al., 2023).

According to the Köppen climate classification, the Cholistan Desert (Arid, Semi-arid) falls under the **"BWh"** climate type, which denotes a **hot desert climate**. Characterized by extremely low and erratic annual rainfall and high temperatures, especially during summer. Climate-wise, the Cholistan Desert experiences distinct

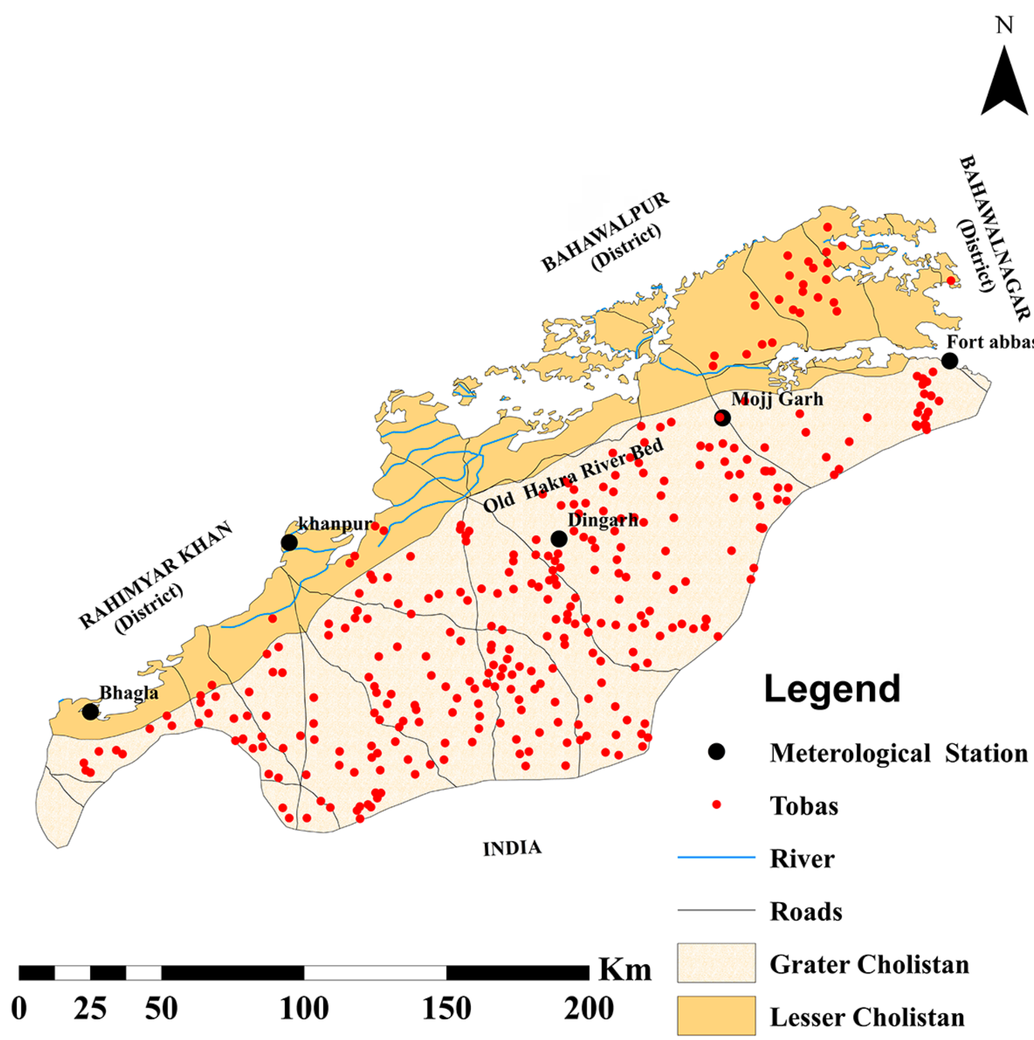

Figure 1. Location Map of the Cholistan Desert, South Punjab, Pakistan.
The shapefiles used in this map were downloaded from DIVAGIS.COM.

seasonal variations, with the summer monsoon season typically receiving more rainfall compared to the winter months. This wet season brings relief to the parched landscape, rejuvenating water sources and fostering temporary vegetation growth. Relative humidity levels fluctuate between 50% and 58%, influencing local climatic conditions and ecosystem dynamics (Haider et al., 2021). Understanding the climatic factors in the Cholistan Desert is vital for sustainable development and environmental conservation efforts in the region. As such, this study aims to delve into the complex interactions shaping the desert's hydrological patterns and their implications for water resource management and community livelihoods.

Material and Methods

Data Collection

This study utilized precipitation data spanning a 40-year period (1981–2020), obtained from the Pakistan Meteorological Department (PMD), including its main office in Lahore and regional office in Bahawalpur. Five meteorological stations were selected for data collection: Din Garh, Mauj Garh, Bhagla, Khanpur, and Fort Abbas (Figure 1). These stations were chosen based on key criteria to ensure comprehensive spatial coverage and representative data for the Cholistan Desert (Khan et al., 2020).

The selected stations provide broad spatial coverage across the desert, capturing precipitation variability influenced by local climatic conditions. Each station is positioned near areas with significant human and livestock populations, making them essential for monitoring precipitation trends and assessing water resource availability in this water-scarce region. The 40-year dataset enables a robust analysis of long-term precipitation trends, critical for understanding the impacts of climate change on water resources in the Cholistan Desert.

Data Processing and Analysis

Before conducting statistical analyses, the collected rainfall data underwent thorough preprocessing steps. This involved data cleaning to remove any inconsistencies or outliers, as well as data aggregation to calculate yearly mean rainfall values for each meteorological station.

Mann-Kendall Trend Test

The Mann-Kendall test, a robust non-parametric method, was applied to assess long-term trends in the rainfall time series data (Mann, 1945; Kendall, 1948). This widely used test is particularly suited for climatological and hydrological studies, as it does not rely on assumptions about the underlying distribution of the data. The MKT was applied to detect monotonic trends in precipitation, providing statistical outputs such as the Kendall (Tau) value, p-value (at 95% confidence), and z-statistics. A positive z-score indicates an increasing trend in the time series, while a negative z-score suggests a decreasing trend. Eq. (i) gives (Dawood & Shirazi, 2022) a simplified expression of the Mann Kendall Test.

$$S=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n-1} Sign(T_j-Ti) \quad \text{(i)}$$

$$Sign\left(t_j-t_i\right)=\begin{cases} 1 & T_i-T_i \quad >0 \\ 0 & T_j-T_i \quad =0 \\ -1 & T_j-T_i \quad <0 \end{cases} \quad \text{(ii)}$$

The variance can be expressed as follow:

$$Var(S)=\frac{n(n-1)(2n+5)-\sum_{i=1}^{n} t_i(t_i-1)(2t_i+5)}{18} \quad \text{(iii)}$$

Initially, the precipitation data was calculated using Addinsoft XLSTAT 2014 and were analyzed using MKTM and SSE against null hypothesis (H_o) to a 95% significance level. The application of the MKT in climate studies has been well-documented in the literature. Previous research by Bannayan et al. (2020), Wang et al. (2020), and Yu et al. (2024) utilized the MKT to analyze precipitation trends, highlighting its effectiveness in detecting significant trends without requiring data to conform to specific distributions.

Theil Sen's Slope (TSS) Method

The Theil Sen's slope method, another robust technique, was utilized to further analyze the temporal changes in rainfall patterns (Sen, 1968; Yu et al., 2024). This method calculates the slope or direction of change in the time series data, providing insights into the magnitude and direction of trends. The TSS method is particularly valuable for its ability to handle outliers and non-linear data, making it well-suited for climate data analysis.

The magnitude of the temporal precipitation data's slope (T_i) is expressed (Dawood et al., 2024) as Eq (iv):

$$F(t)=Q_t+B \quad \text{(iv)}$$

- where Q represents the slope's magnitude, and B denotes a constant. However, the magnitude of the slope is calculated differently (v), to assess the slope for the temporal rainfall data:

$$Qi = \frac{X_i + X_j}{j - k} \quad \text{(v)}$$

- here, X_i and X_j represent pairs of precipitation data, respectively, with i=1,2,3,4,5,6, 7,...,N, and among time, denoted by j and k (where $j>k$). The median of the N values of Ti is calculated as Eq. (vi),

$$Q_{med} = \begin{cases} \frac{Q_{\left[\frac{N+1}{2}\right]}}{} & (if\ N\ is\ odd) \\ \frac{Q_{\left[\frac{N}{2}\right]} + Q_{\left[N+\frac{2}{2}\right]}}{2} & (If\ N\ is\ even) \end{cases} \quad \text{(vi)}$$

Consequently, if N is odd, the Theil Sen's slope (TSS) is computed as: $Q_{med} = T(N + 1)/2$. On the other hand, if N is even, TSS is calculated as: $Q_{med} = T(N+2) + T(N+2)/2$. Finally, Q_{med} is determined using the non-parametric model (MKT) to ascertain magnitude. In the context of Theil Sen's slope (TSS), Q_{med} represents the median of the calculated slopes (Qi). It serves as a measure of central tendency for the set of slopes derived from the pairwise differences in precipitation data over time. This median slope (Q_{med}) is then used to characterize the overall trend or direction of change in the rainfall data. If Qi is positive, it suggests an increasing trend in precipitation, whereas a negative Qi indicates a decreasing trend. Geographic Information System (GIS) technology was used for the spatial interpolation and finally expressing the slope of the detected trend as different maps.

Spatial Interpolation Technique GIS

All spatial maps of precipitation were prepared using the widely adopted Inverse Distance Weighted (IDW) technique in ARCGIS software. IDW is a common spatial interpolation method for creating rainfall maps and is straightforward to implement within a GIS environment (Nath et al., 2024). In GIS, spatial interpolation estimates unknown values at specific geographic locations based on known values from surrounding areas (Hu et al., 2019). Precipitation data were first computed in Microsoft Excel and then interpolated in ArcGIS, using various tones and shades to illustrate precipitation variability across the region. This color-coded approach effectively presents climate data and highlights geographic differences. Temporal rainfall data were interpolated into a raster format, enabling the analysis of geostatistical relationships among sites (Ozturk & Kilic, 2016). GIS was utilized to develop spatial databases and prepare result maps, ensuring accurate representation of precipitation trends.

Results

Analysis of the Annual Precipitation

The Mann-Kendall Trend test was employed to analyze the mean annual rainfall data collected from meteorological stations including Din Garh, Mauj Garh, Bhagla, Khanpur, and Fortabbas. For Din Garh station, encompassing the years 1980 to 2020, the mean annual rainfall was recorded at 2.196 mm, with a standard deviation (SD) of 1.582 mm. Notably, the year 1984 witnessed the highest annual rainfall of 5.477 mm, while the lowest was observed in 2009 at 0.196 mm (Table 1). Applying the MKT test to 40 years of rainfall data from the Din Garh station revealed a significant declining trend, with Kendall's Tau (τ) computed as -0.410 at a significance level of 0.05. The associated p-value (< 0.0001) indicates statistical significance, leading to the acceptance of the null hypothesis (Ho) and suggesting a significant negative trend. Additionally, Sen's slope for Din Garh was calculated as -0.088, further indicating a negative downward trend (Figure 2).

Similarly, at Mauj Garh station, the standard deviation was found to be 1.245 mm, with minimum, maximum, and mean rainfall values of 0.321 mm, 4.555 mm, and 1.900 mm, respectively. The calculated Kendall's tau (τ) of -0.4410 suggests a slight negative trend in rainfall data, with a p-value (< 0.0001) indicating statistical significance and the acceptance of Ho, implying a significant decreasing trend. Sen's slope for Mauj Garh was determined as -0.059, corroborating the negative downward trend observed. In contrast, Bhagla station recorded a comparatively lower annual mean rainfall of 0.9841 mm, with 2017 witnessing the highest recorded rainfall of 3.568 mm and 1983 experiencing the lowest at 0.186 mm. Interestingly, the MKT test results for Bhagla station revealed no discernible pattern in rainfall, with a calculated Kendall's tau of 0.5154 indicating a positive trend (p-value = 0.000637) at a significance level of 0.05. This rejection of the null hypothesis suggests a statistically significant positive trend in rainfall data.

The dataset from the Khanpur meteorological station exhibits considerable variability in precipitation levels, characterized by a mean of 3.1063 mm and a standard deviation of 3.6069 mm. Rainfall measurements range from a minimum recorded value of 0.114 mm to a maximum of 15.073 mm. For Khanpur station, the estimated Kendall's tau was found to be 0.4615, suggesting a slightly positive temporal rainfall trend with a corresponding p-value of 0.000144. Additionally, Sen's slope was calculated as

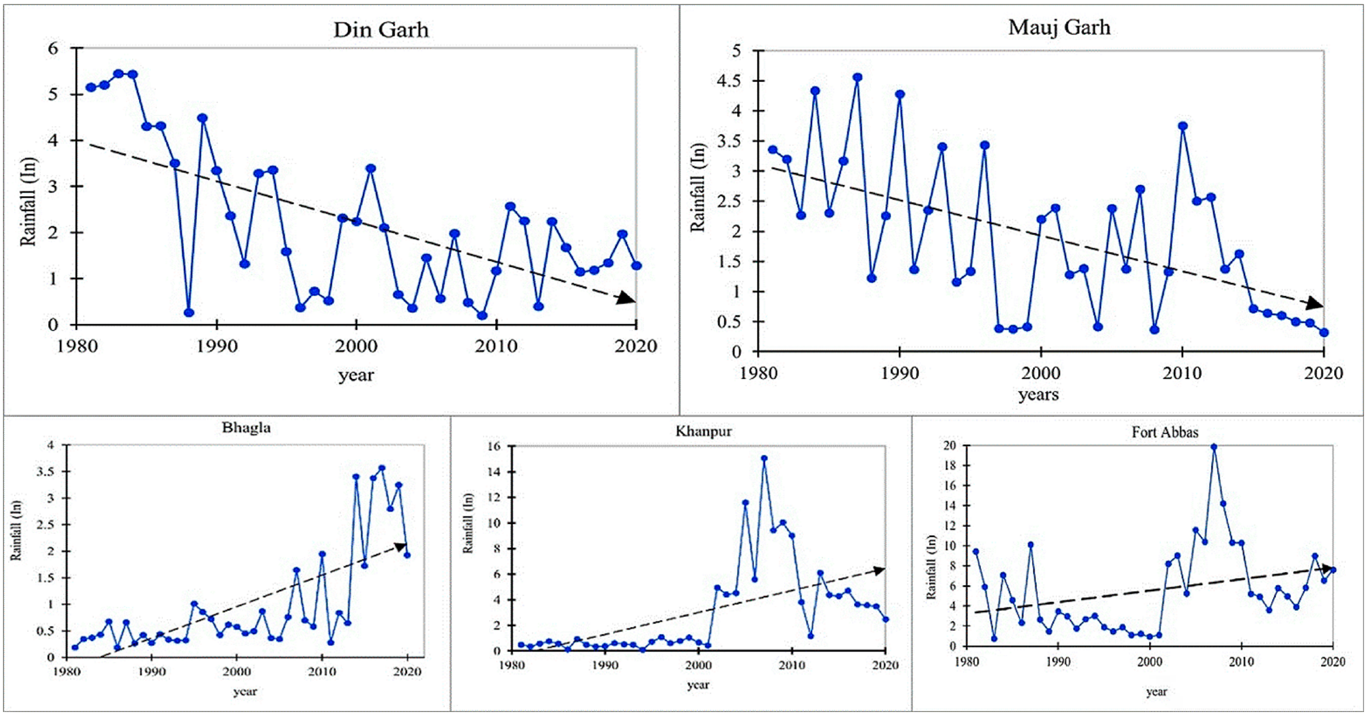

Figure 2. Mean annual rainfall trend (1980-2020) across the selected meteorological stations

0.1102 for the Khanpur station, indicating a positive slope and signaling a visible rising trend in rainfall over the past 40 years. This positive Sen's slope, reflecting an anticipated increase in rainfall intensity per unit of time, corroborates the findings of Kendall's Tau. Furthermore, employing the Mann-Kendall test, analysis of 40-year rainfall data from the Fort Abbas meteorological station reveals a notable and statistically significant increasing trend in rainfall. The dataset, characterized by a mean of 5.597 mm and a standard deviation of 4.202 mm, exhibits significant variability in rainfall amounts, ranging from 0.740 mm to 19.850 mm. The MKT results indicate a strong statistical trend of increasing rainfall, supported by a low p-value of 0.015 and a positive Kendall's tau of 0.196, indicating rejection of the null hypothesis (Table 1).

SSTD (Statistically Significant Trend Detected)

The application of Theil-Sen's slope (TSS) estimator to the annual time series data of rainfall revealed distinct trends across meteorological stations. Din Garh and Mauj Garh stations exhibited a negative slope magnitude (Figure 2), indicating a decreasing pattern in rainfall. Specifically, for Din Garh, the Sen's slope was calculated as Q = -0.088, illustrating a negative downward trend in precipitation (Figure 3). Similarly, Mauj Garh station displayed a negative SSTD (Statistically Significant Trend Detected) slope with Q = -0.059, indicating a downward trend in rainfall. Conversely, Bhagla, Khanpur, and Fort Abbas stations demonstrated positive slope magnitudes, signifying an increase in rainfall pattern. The Sen's slope for Bhagla station was Q = 0.0318, indicating a visible rising trend in rainfall over the past 40 years (Figure 2). Similarly, Khanpur station exhibited a positive slope with Q = 0.1102, suggesting a notable upward trend in rainfall intensity. These positive Sen's slopes align with Kendall's Tau's findings and provide further support for the observed trends.

Furthermore, Fort Abbas station displayed a positive Sen's slope of Q = 0.098, indicating an estimated increase in rainfall intensity over the four-decade period. This quantifies the size of the trend, corroborating the over-

Table 1. Results of Mann Kendall trend test on mean annual rainfall (1980-2020)

Met station	Mean rainfall (mm)	SD	Kendall's tau	P-value	alpha	Sen's slope	TSS remarks	MK test remarks	Model Interpretation
Din Garh	2.196	1.58	-0.410	0.0001	0.05	-0.088	Decreasing trend	Accept H_o	SSTD
Mauj Garh	1.900	1.24	-0.4410	0.0001	0.05	-0.059	Decreasing trend	Accept H_o	SSTD
Bhagla	0.9841	0.98	0.5154	0.0006	0.05	0.0318	Rising trend	Reject H_o	SSTD
Khanpur	3.1063	3.606	0.4615	0.0001	0.05	0.1102	Rising trend	Reject H_o	SSTD
Fort Abbas	5.597	4.202	0.196	0.015	0.05	0.098	Rising trend	Reject H_o	SSTD

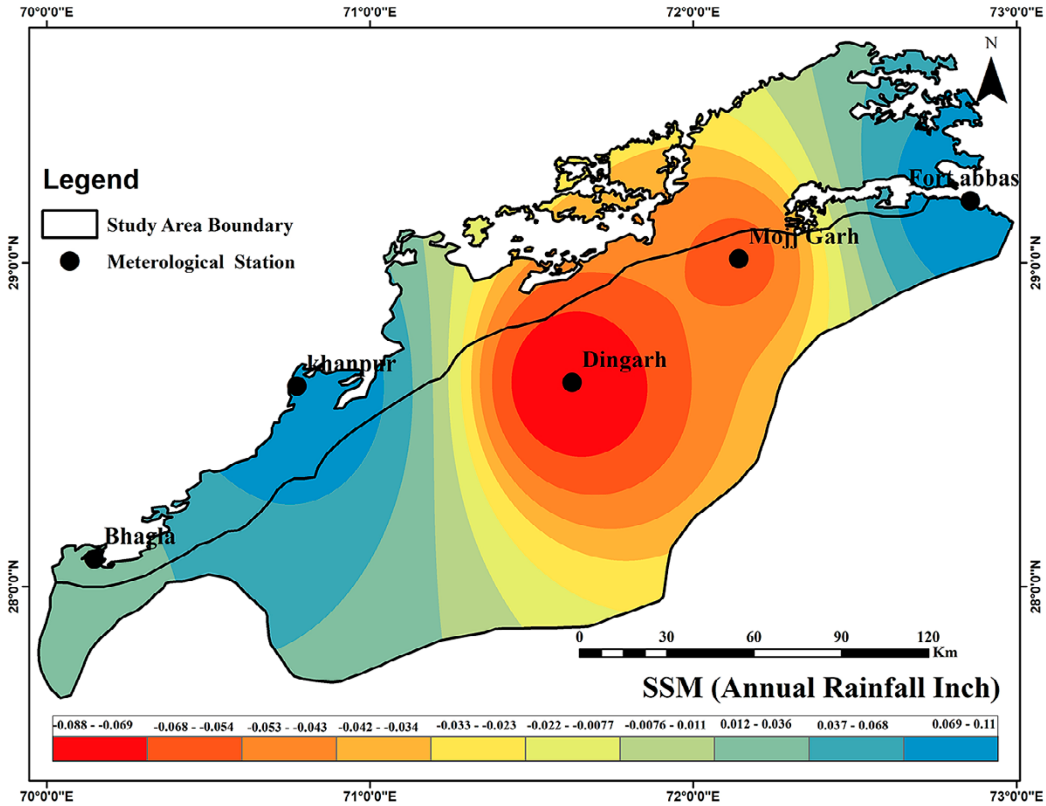

Figure 3. Cholistan Desert, slope magnitude for annual precipitation (Inches).

all findings. Moreover, the subsequent analysis highlights the relationship between precipitation patterns and slope magnitude at an annual scale. It indicates that changes in precipitation trends are associated with variations in slope magnitude, reflecting the dynamic nature of rainfall pattern over time (Table 1).

Analysis of Mean Monthly Precipitation

The analysis revealed significant variations in mean monthly precipitation across different meteorological stations (Figure 4). Bhagla meteorological station recorded the highest mean monthly precipitation of 11 mm in June, closely followed by 43 mm in July. Conversely, October and November witnessed the lowest monthly rainfall. Similarly, Din Garh station experienced substantial precipitation in January (5.5 mm) and July (43 mm) throughout the period 1980–2020. Conversely, Fort Abbas station reported the highest mean monthly rainfall of 54 mm, 58 mm, and 86 mm in July, August, and September, respectively, while January recorded 22 mm during the same period.

In contrast, Khanpur station registered the lowest mean monthly rainfall of 2.9 mm in June, 18 mm in July, and a minimum recorded rainfall of 0.7 mm in October, with December recording 5.1 mm betweenn1980-2020. Mauj Garh station data revealed 6.2 mm of rainfall in June, 45 mm in July, and 60 mm in September, with a significant drop to 1.3 mm in October, indicating considerable variation compared to other stations. Similarly, Bhagla station experienced the highest mean monthly rainfall of 60 mm in September and the lowest of 1.1 mm in October (1980–2020). Furthermore, both Mauj Garh and Fort Abbas stations recorded the lowest mean monthly rainfall of 3.5 mm in December and the highest of 72 mm in September. These findings underscore the presence of substantial variations in rainfall patterns among meteorological stations, attributed to factors such as geographical location, altitude, and temporal intervals.

Precipitation Seasonality in the Cholistan Desert

The Cholistan Desert exhibits marked seasonality in precipitation, with extended dry periods interrupted by infrequent rainfall, predominantly during the summer monsoon season (July to September). Over the study period from 1981 to 2020, this seasonal precipitation pattern has shown considerable variability, influencing the region's water availability and environmental conditions. Analysis of precipitation data using the Standardized Precipitation Index (SPI) at DinGarh and MaujGarh meteorological stations indicates a gradual increase in drought severity (Figure 5). Severe drought events were documented in the years 1981, 1988, 1997, 1999, 2002, 2007, 2018, and 2019, with prolonged dry spells particularly common during the early spring and summer months. These dry periods, exceeding several consecutive months in some years,

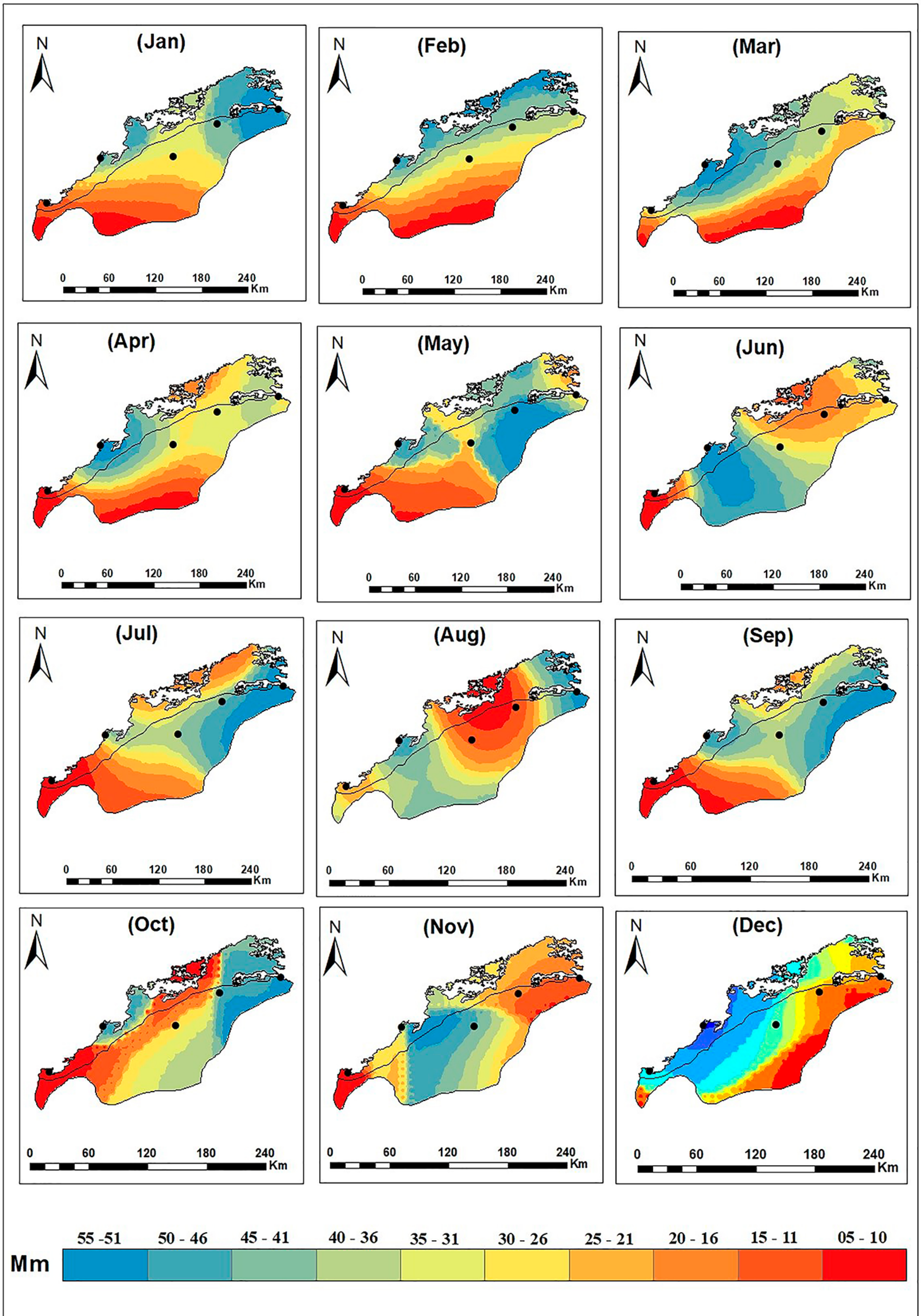

Figure 4. Spatial distribution of mean monthly rainfall (mm) for 12 months marked as Jan to Dec

reveal the challenges of sustaining adequate water levels in surface storage structures like *tobas* and *kunds*, which rely heavily on the limited monsoon rains.

Precipitation seasonality also varies across different parts of the Cholistan Desert, as illustrated by differences among the selected meteorological stations. DinGarh, generally dry year-round, experienced brief wet periods in years like 1982, 1993, and 2007, which temporarily improved water storage and vegetation conditions. Conversely, MaujGarh encountered more severe dry spells in years such as 1983, 1990, and 2020, with near-total precipitation deficits contributing to extreme aridity. Bhagla and Khanpur stations similarly recorded prolonged dry spells in 1981, 1983, 1986, 1994, and 2002, punctuated by occasional wet years like 2005 and 2007, which offered temporary relief.

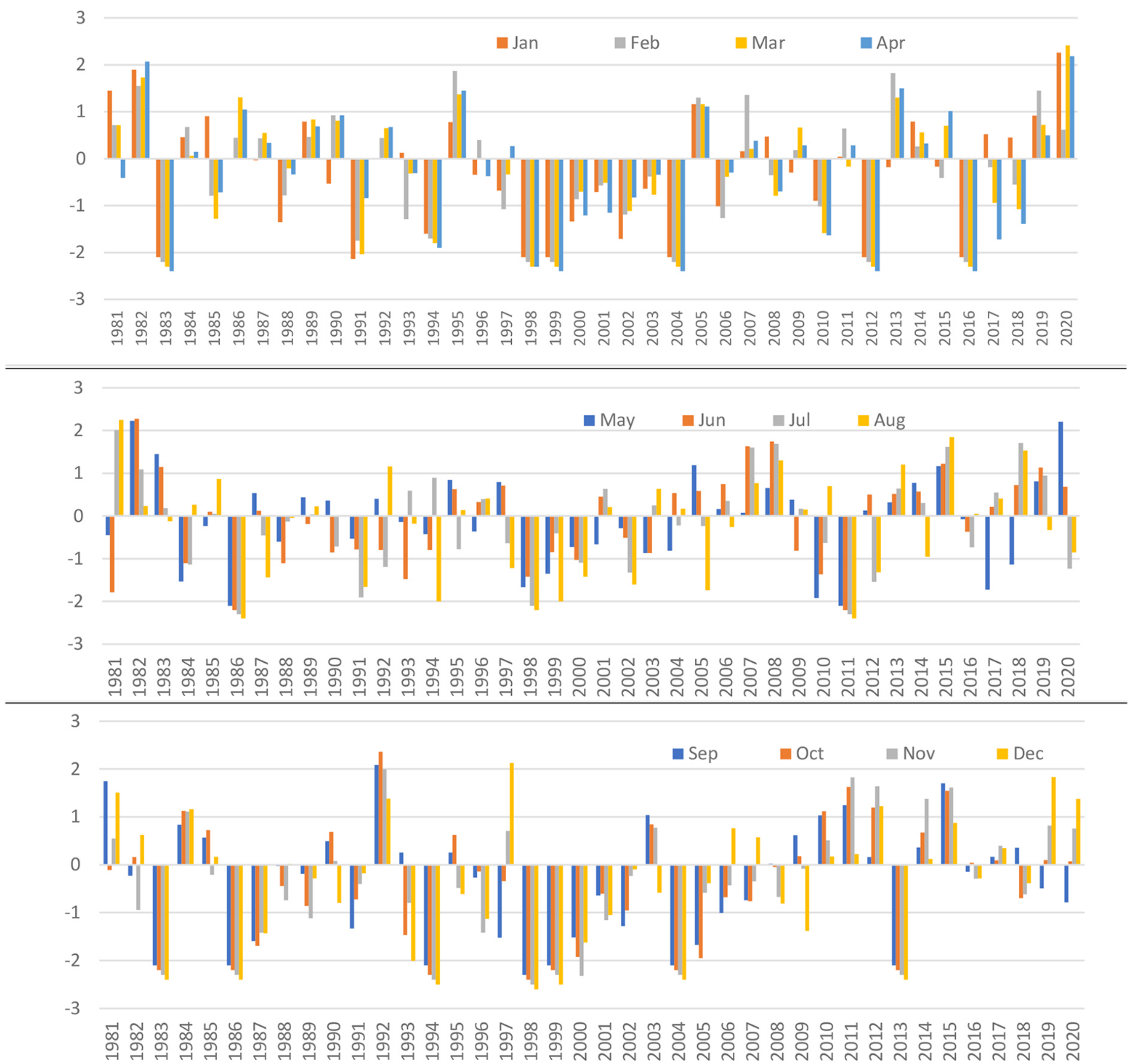

Figure 5(a). Seasonality and drought analysis of the Cholistan Desert using SPI. *Fort Abbas precipitation seasonality*

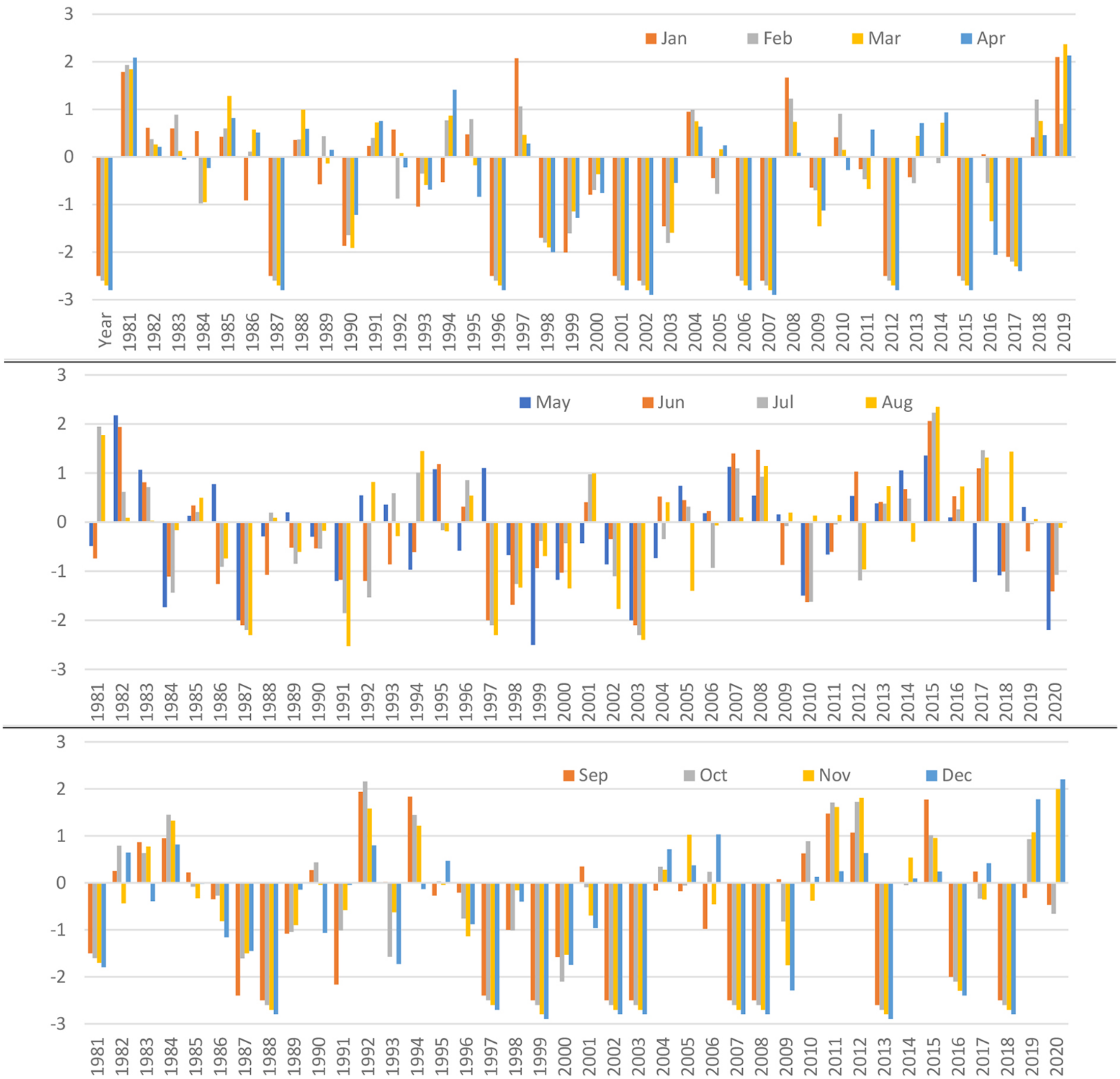

Figure 5(b). Seasonality and drought analysis of the Cholistan Desert using SPI. *DinGhar precipitation seasonality*

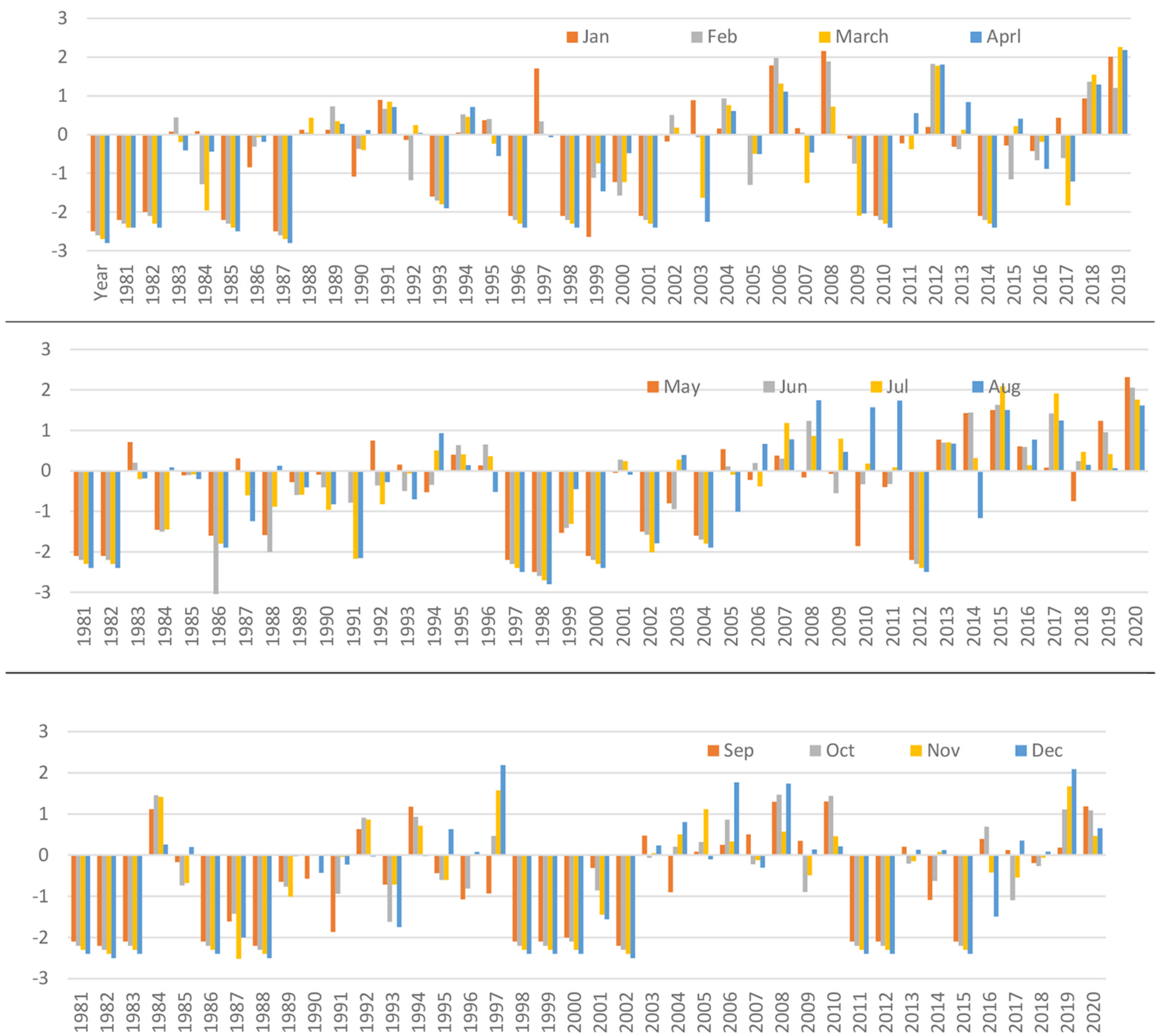

Figure 5(c). Seasonality and drought analysis of the Cholistan Desert using SPI. *Bhagla precipitation seasonality*

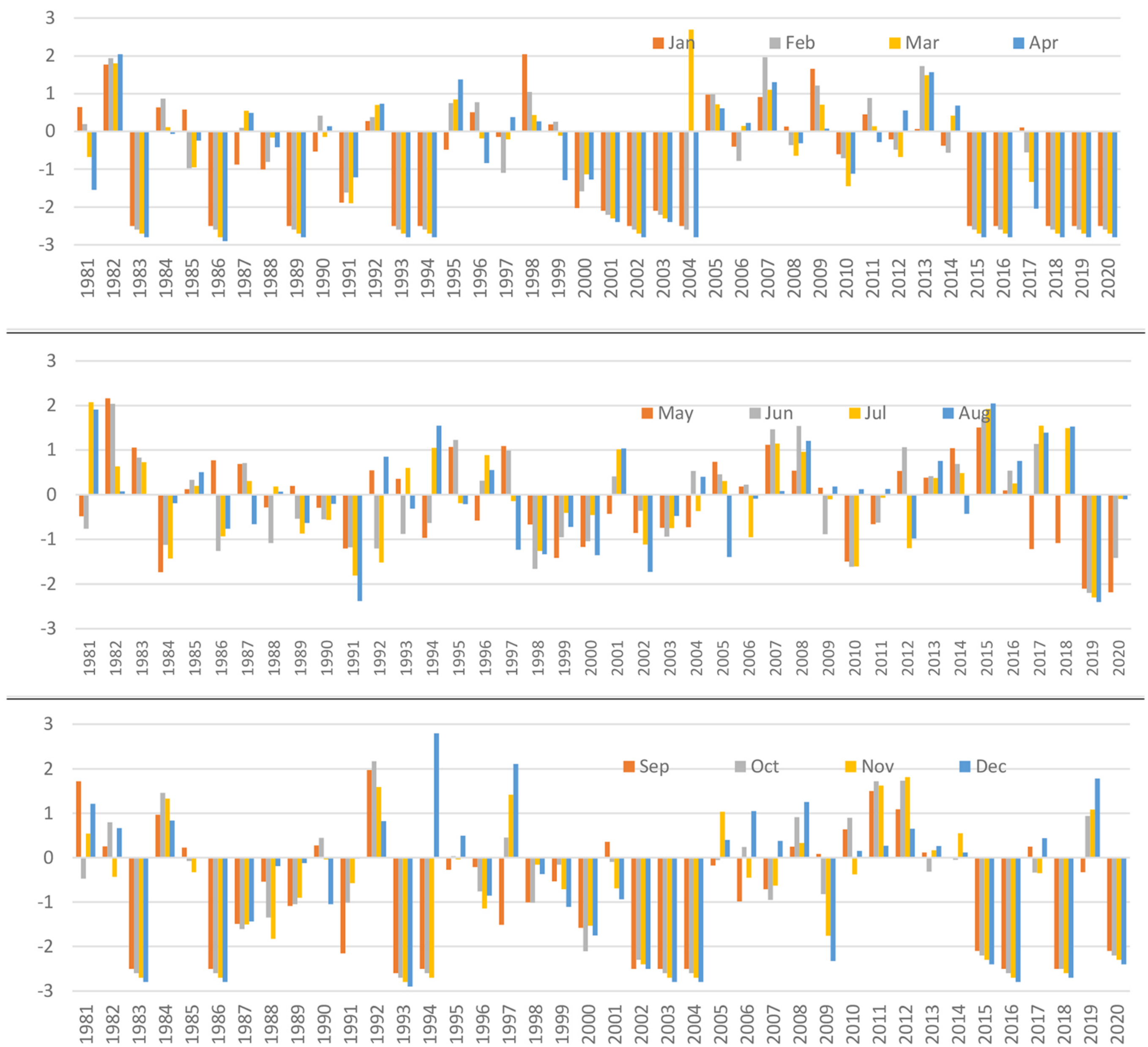

Figure 5(d). Seasonality and drought analysis of the Cholistan Desert using SPI. *MoujGarh precipitation seasonality*

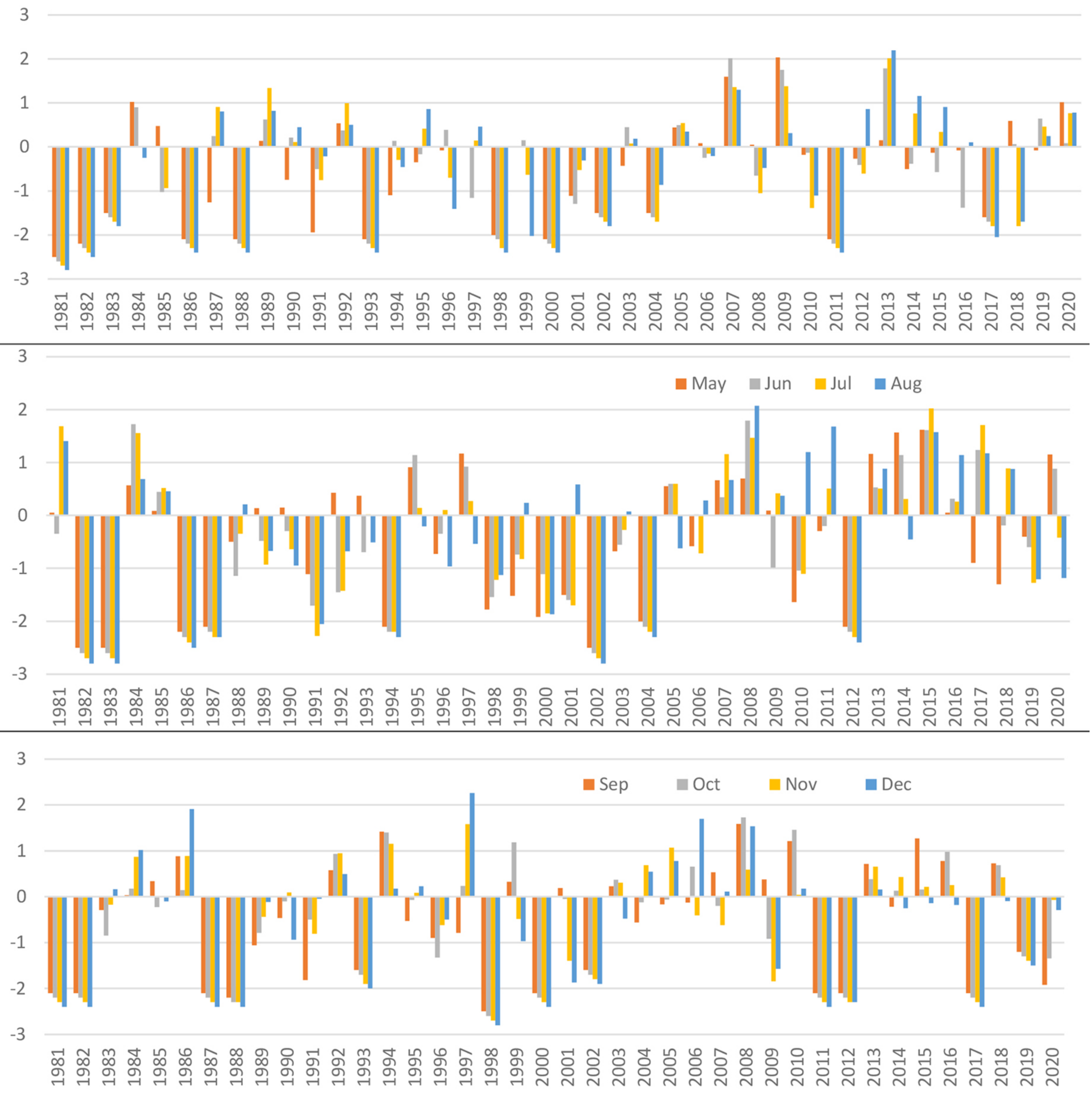

Figure 5(e). Seasonality and drought analysis of the Cholistan Desert using SPI. *Khanpur precipitation seasonality*

Discussion

The results indicate that Din Garh and Mauj Garh stations exhibit significant declining trends in annual rainfall, as evidenced by negative Kendall's Tau values and negative Sen's slopes. Specifically, Din Garh showed a Kendall's Tau of -0.410 (p-value < 0.0001) and a Sen's slope of -0.088, while MaujGarh displayed a Kendall's Tau of -0.441 (p-value < 0.0001) and a Sen's slope of -0.059. Conversely, Bhagla, Khanpur, and Fort Abbas stations demonstrated significant increasing trends in annual rainfall. Bhagla's Kendall's Tau was 0.5154 (p-value = 0.000637) with a Sen's slope of 0.0318, Khanpur's Kendall's Tau was 0.4615 (p-value = 0.000144) with a Sen's slope of 0.1102, and Fort Abbas's Kendall's Tau was 0.196 (p-value = 0.015) with a Sen's slope of 0.098. Hussain and Abbas (2029) also reported similar trends with rainfall variability ranging from 100 mm to 200 mm, while occasionally reaching to 300 mm. The analysis of mean monthly rainfall patterns also revealed significant seasonal variability across the stations. For instance, Bhagla and Fort Abbas stations recorded the highest mean monthly rainfall during the monsoon months (June to September), with Bhagla peaking at 11 mm in June and 43 mm in July, and Fort Abbas recording 54 mm, 58 mm, and 86 mm in July, August, and September, respectively. In contrast, the lowest rainfall was observed in the dry months of October and November.

The hypothesis of this study postulated that there are significant spatial and temporal variations in annual and monthly rainfall patterns across the study area driven by a combination of climatic and geographical factors. This hypothesis was tested using the Mann-Kendall (MK) trend test and Theil-Sen's Slope (TSS) estimator applied to rainfall data from five meteorological stations. The results support the hypothesis, confirming significant spatial and temporal variations in rainfall patterns. The observed trends in annual and monthly rainfall, along with the varying slope magnitudes, explain the influence microclimate factors. The spatial variability also reveals the complex interplay of local and regional climatic influences.

The declining trends observed at Din Garh and Mauj Garh stations indicate a worrying reduction in annual rainfall. These trends suggest an increasing aridity in the proximal areas, potentially exacerbating desertification processes. This is consistent with broader climate change predictions that arid regions will become drier due to altered atmospheric circulation patterns and reduced moisture availability (Haider et al., 2021). The significant negative trends at these stations highlight the urgent need for enhanced water conservation strategies. The reduction in rainfall at these locations poses severe risks for both local agriculture and the availability of potable water, directly impacting the livelihoods of communities dependent on these water sources (Wahla & Kazmi, 2022).

The spatial variability in precipitation trends observed in the Cholistan Desert reflects similar patterns seen in other arid regions around the world, where climate change often drives complex patterns of both increasing and decreasing rainfall across short distances. For instance, studies in the Sahara Desert and the adjacent Sahel region reveal a heterogeneous rainfall distribution, with some areas experiencing intensified dryness while others exhibit a "greening" effect due to seasonal increases in precipitation (Badr et al., 2016; Biasutti, 2019). In India's Thar Desert, research has documented both spatial and temporal variations in rainfall, influenced by shifts in monsoon intensity and direction, which are shaped by microclimatic and atmospheric factors similar to those impacting the Cholistan Desert (Saini et al., 2022; Singh & Choudhary, 2023). The Rub' al Khali region in the Arabian Desert also shows variable precipitation trends, with slight increases in some areas attributed to the influence of the Indian Ocean Dipole (IOD). However, the overall trend in the region leans toward reduced precipitation, which further exacerbates water scarcity (Almazroui et al., 2012). In contrast, the Atacama Desert in South America predominantly exhibits declining rainfall patterns, largely influenced by the Pacific Decadal Oscillation (PDO) and El Niño events, resulting in intensified aridity (Houston & Hartley, 2003).

Conversely, the increasing rainfall trends at Bhagla, Khanpur, and Fort Abbas stations suggest a different microclimatic influence. These areas show positive slopes in their annual rainfall patterns, indicating a trend towards wetter conditions. This spatial variability within the Cholistan Desert can be attributed to localized climatic factors and possibly the influence of the Indian monsoon as also suggested by (Wariss et al., 2013), while similar localized trends can be observed in other surrounding deserts such as Nara Desert in Sindh as reported by (Qureshi & Bhatti 2008).

The significant seasonal variability in monthly rainfall further suggests the challenges of water resource management in the Cholistan Desert. The pronounced peaks during the monsoon months (June to September) contrast sharply with the dry periods experienced throughout the rest of the year. This variability necessitates effective rainwater harvesting and storage systems to capture and utilize the monsoon rains efficiently. The existing rainwater harvesting practices, as mentioned in Hussain and Abbas (2019), including the use of tobas and kunds, are vital but require significant improvements to address seepage, evaporation, and contamination issues. Climate change impacts in the Cholistan Desert are evident through the observed trends in rainfall. The increasing temperature and changing precipitation patterns align with global climate change models predicting more extreme weather events, including both severe droughts and intense rainfall periods (Bashir and Hanif 2018). These changes necessitate adaptive strategies that enhance resilience to climate variability. Improved meteorological monitoring, coupled with advanced modeling techniques, can provide better predictions, and inform more effective water management policies.

Water scarcity remains a critical issue in the Cholistan Desert, directly linked to the observed rainfall trends (Afzal & Rizwan 2017). The areas experiencing declining rainfall trends are likely to face heightened water scarcity, exacerbating the challenges of sustaining local populations and their agricultural activities. The results from this study unveil the vulnerability of the region to prolonged dry spells, with the majority of rainfall occurring during the monsoon season (July to September). However, this monsoon rainfall is often inconsistent, leading to extended periods of drought, especially in early spring and summer, which poses significant challenges for maintaining water levels in traditional storage systems such as tobas and kunds. The gradual increase in drought severity observed at DinGarh and MaujGarh stations, as indicated by the Standardized Precipitation Index (SPI), underscores the pressing issue of water scarcity, which is exacerbated by climate variability.

The spatial variation in precipitation seasonality across different parts of the desert further complicates water resource management. For instance, DinGarh experienced sporadic wet years, providing brief but essential relief for water storage, whereas MaujGarh encountered more frequent and severe droughts, leading to greater environmental stress. Similarly, stations like Bhagla and Khanpur, which experienced prolonged dry spells interrupted by only occasional wet years, reveal the uneven distribution of precipitation across the desert. This variability emphasizes the need for tailored water management practices in different regions of Cholistan. Improving and expanding rainwater harvesting infrastructure, as well as enhancing drought resilience through sustainable water storage and conservation practices, would be essential for adapting to the area's increasingly unpredictable precipitation patterns.

Conclusion and Research Prospects

This study delved into the analysis of rainfall patterns in the Cholistan Desert, located in South Punjab, Pakistan, utilizing temporal rainfall data collected from meteorological stations including DinGarh, MaujGarh, Bhagla, Khanpur, and Fort Abbas. Through advanced GIS technology and statistical modeling, trends and fluctuations in rainfall were examined, shedding light on the changing precipitation dynamics in the region. The analysis revealed notable trends in annual rainfall across various meteorological stations. Particularly, a significant upward trend in precipitation was observed at Fort Abbas, Bhagla, and Khanpur stations, indicating an increase in rainfall over the study period. Conversely, DinGarh and MaujGarh stations showed less significant trends, suggesting a more stable or declining rainfall pattern. Furthermore, the application of Theil-Sen's Slope (TSS) method provided deeper insights into the temporal trends of precipitation. Positive Sen's slopes were identified at Bhagla, Khanpur, and Fort Abbas stations, indicating an increasing trend in rainfall intensity over the past four decades. Conversely, Din Garh and Mauj Garh stations exhibited negative Sen's slopes, signifying a decreasing trend in precipitation. The analysis of mean monthly rainfall patterns highlighted significant variations across different months and meteorological stations. While certain months like July and September experienced substantial rainfall, others such as October and November recorded minimal precipitation. These variations underscore the complex interplay of seasonal and geographical factors influencing rainfall distribution in the Cholistan Desert.

This study provides insights into the spatio-temporal trends of rainfall variability in the Cholistan Desert. The observed trends indicate a shift in precipitation patterns, with some areas experiencing an increase while others show a decline in rainfall intensity over time. These findings have significant implications for water resource management and agricultural practices in the region. Climate change-induced fluctuations in precipitation pose a substantial challenge to the already scarce water resources in the Cholistan Desert. The occurrence of extreme weather events like droughts and heatwaves further exacerbates the vulnerability of local communities, threatening their livelihoods and well-being. Moving forward, it is imperative to conduct further research to better understand the underlying drivers of rainfall variability in the Cholistan Desert and its broader implications for climate change adaptation and mitigation strategies. The integration of remote sensing technology and advanced modeling techniques can enhance our ability to monitor and predict changes in precipitation patterns, thereby informing more effective decision-making processes and resource allocation efforts. Addressing the challenges posed by climate change and water scarcity requires a multi-disciplinary approach, involving collaboration between scientists, policymakers, and local communities. By fostering greater awareness and understanding of climate-related risks and vulnerabilities, we can work towards building resilience and sustainable development in the Cholistan Desert and beyond.

The Cholistan Desert, with its harsh arid-to-semi-arid climate and remote location, presents several limitations for this study. The availability of meteorological data is limited, as there are few stations in the region, many of which lack long-term, continuous records and modern monitoring technologies. These stations cover only a portion of the vast desert, which restricts the spatial comprehensiveness of the data.

To improve future investigations of precipitation trends in the Cholistan Desert, efforts should focus on enhancing data quality and spatial coverage. Expanding the network of meteorological stations and upgrading existing ones with advanced technologies would enable more accurate and frequent data collection. Additionally, integrating high-resolution satellite imagery with ground-based data can provide a broader view of precipitation patterns. Employing advanced techniques, such as machine learning models, could also help capture complex precipitation variations that may be missed by traditional methods.

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