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Spatio-temporal Assessment of Changing Annual and Seasonal Climate Patterns over the Major Climatic Zones of Pakistan

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Abstract

The extensive impacts of climate change on the ecology and the environment have made it one of the biggest challenges being faced by the humanity today. Apart from the temporal scale, the climate patterns also vary on the spatial scale due to the different spatial features and the latitudinal location. This necessitates investigating the changing climate patterns over the different locales to formulate a holistic climate change adaptation and mitigation strategy. Therefore, this study was conducted to briefly investigate the annual and seasonal climate trends over the major climatic zones of Pakistan during the period 1990-2022 using the MK test and Sen's slope estimator method. The results obtained from the study showed an annual mean temperature rise of about 0.1 to 1.0 °C over the Greater Himalayas and sub-Montane region, and about 0.15 to 1.2 °C over the central, southern, and the coastal parts of the country, while a declining trend was found over the Western Highlands during the study period. Seasonally, the spring season was found to be the warmest among all seasons in the country. For the summer season, a declining trend was found over the Greater Himalayas and Western Highlands, while warming increased over the other climatic zones. For the winter season, the temperature rose by about 0.1 to 1.0 °C over the Greater Himalayas and northern Balochistan, and by about 0.1 to 0.2 °C over the coastal zones. For annual precipitation, an increasing trend was found over the majority of the selected stations, whereas for the summer monsoon, a declining trend was found over the Greater Himalayas, while the other zones witnessed a significant rising trend, with the highest increment noted over the Western Highlands (100-300 mm), and about 50-150 mm in central Punjab and the lower Indus plain. For winter precipitation, the Greater Himalayas observed an upward trend (0.3-0.9 mm/year), while the southern and coastal parts of the country witnessed a declining pattern. Based on the findings, it was established that the climate patterns have varied greatly on the spatial scale over Pakistan, which necessitates the formulation of an integrated and effective climate change adaptation and mitigation strategy for the conservation of natural resources in the country.

Keywords: *Climate Change, Spatio-temporal variability, Mann-Kendall Test, Sen's slope estimator method*

1. Introduction

Climate change generally refers to the long-term changes in the normal weather patterns of an area [1]. The major anthropogenic factors generally censured for causing these long-term changes generally include the land use changes and sprawling urbanization, deforestation, and emission of toxic gases and aerosols into the air which disturbs the global heat balance (the balance between the incoming shortwave and the outgoing longwave solar radiation) and results in the occurrence of extreme meteorological events, warming air, sea, and land surface temperatures, change in wind circulation patterns, and shift in the long-term precipitation trends over an area [2]. These adverse effects of climate change pose a significant threat to the streamflows, cryosphere, agricultural production and food security, and the regional and global water balance. During the last century, the adversities of climate change have been clearly witnessed on the global as well as on the regional and local climate patterns. During the period 1906-2005, the average earth temperature warmed by about 0.74 °C [3, 4], whereas at the regional scale, the average temperature over South Asia increased by about 0.75 °C during the last century [5]. Similar warming trends were reported in a study, according to which the average global air temperature rose by about 1.1 °C with reference to the pre-industrial period (1850-1900) [6]. On the other hand, precipitation is a vital component of the hydrological cycle and significantly governs freshwater availability and the water balance on the earth's surface since water in all of its forms is received on the earth's surface via precipitation [7, 8]. Apart from air temperature, global and regional precipitation patterns have also undergone significant variations due to the changing climate patterns. During the last century, the worldwide rainfall data analysis conducted by the National Oceanographic and Atmospheric Administration (NOAA) showed a rise of about 0.04 inches/decade on the global scale [9, 10]. However, due to the highly variable nature of precipitation and its high sensitivity towards the spatial and topographical features of an area, some regions of the world also experienced a downward trend of annual and seasonal precipitation. For instance, a study conducted by Merabtene et al. (2016) revealed a declining trend of annual and winter season precipitation in Sharjah city (UAE) [11]. Similar declining trends were observed in a study conducted by Almazroui (2020) in KSA (Kingdom of Saudi Arabia), according to which the annual mean rainfall over the country dropped at the rate of about 5.89 mm/decade during the past four decades [12].

Pakistan has repeatedly been considered among the topmost countries that are highly susceptible to the unfavourable impacts of global climate change, as it lies in the region where the temperature rise is projected to be higher than the global average in the future [2, 13, 14]. Pakistan is an agrarian economy with about 24 Million hectares (Mha) of its area under cultivation, and about 88% of the country's land area lies in the arid and semi-arid zone [15, 16]. The country is geographically located in the sub-tropics and partially in the Temperate zone between the latitudes 24 to 37 °N and between the longitudes 62 to 75 °E, and has a continental type of climate with high spatial variations in the climate patterns from its north to south due to the diverse topography of country [13]. The annual mean temperature of Pakistan is about 20.65 °C, with a mean temperature of about 24 °C in the southern and the coastal parts of the country, and about 18 °C in its northern and north-western parts [17], as shown in Figure 1 (A). Similarly, the annual mean precipitation also varies across the country from about 1500 to 2000 mm over the high-altitude northern parts of the country due to the orographic effect and well establishment and intrusion of the summer monsoon and Western Disturbances over the area, while the southern parts of the country receive about 50% of the precipitation in the north, ranging from about 100-300 mm [13, 16, 17], as shown in Figure 1 (B). The weighted annual mean precipitation of Pakistan is about 300 mm [16]. Pakistan has two major rainfall seasons, the summer monsoon (July-September) and the winter precipitation (December-March). The summer monsoon contributes about 60 -70 % to the annual total precipitation of Pakistan and brings about 140.8 mm of rainfall every year on average to the country. On the other hand, the winter precipitation, which occurs due to the intrusion of moisture laden Western Depressions into the country that is formed over the Mediterranean region, contributes about 74 mm (about 30 %) on average to the annual total precipitation of country. This Western Depression has two branches, the primary and secondary Western Disturbances. The primary Western Disturbances enter into the country from Afghanistan, and cover only the north-western and the northern areas of Pakistan, while the secondary western disturbances intruding from Iran cover a comparatively larger area of the country, and bring a good amount of precipitation over northern Balochistan, Punjab, Khyber Pakhtunkhwa, Kashmir, and Gilgit-Baltistan [2, 16].

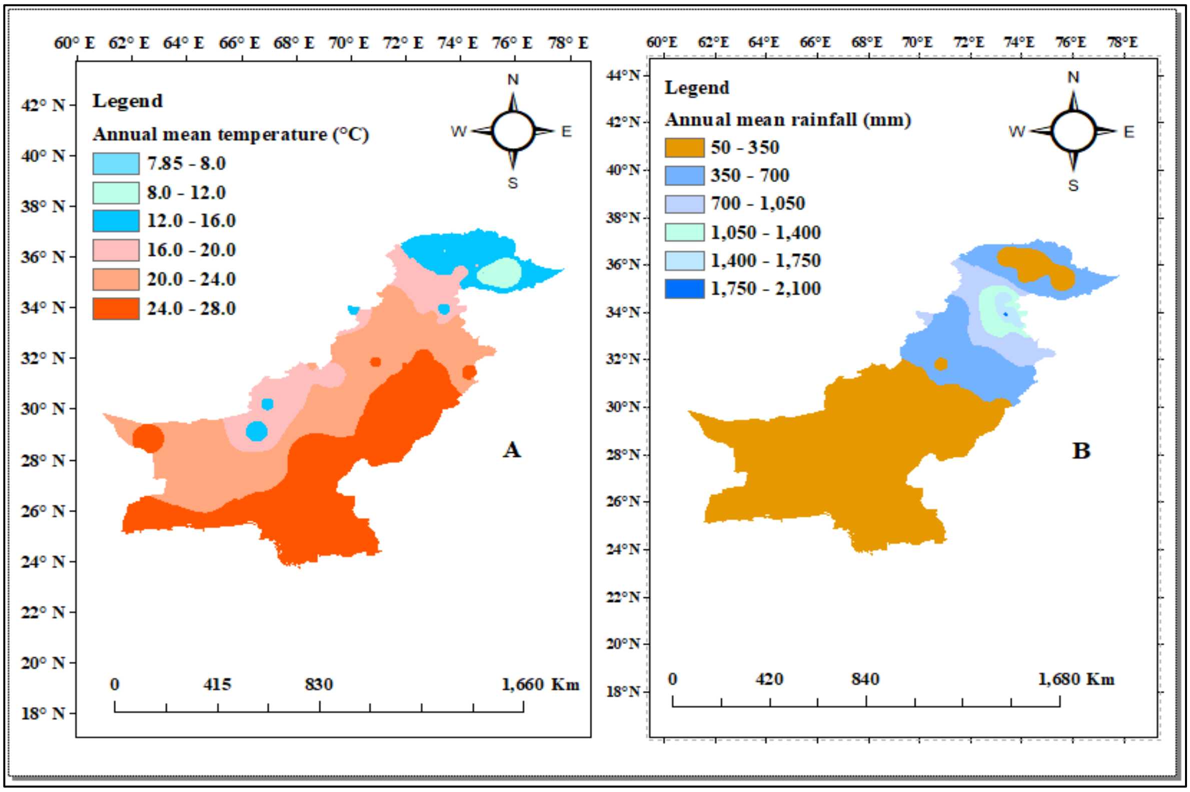

Figure 1: Map of (A) Annual mean temperature (°C) and (B) Annual mean rainfall (mm) over Pakistan, 1990-2022.
Data source: Pakistan Meteorological Department (PMD).

Pakistan generally relies on the two major sources of freshwater as the surface and groundwater resources to meet its domestic, agricultural, and industrial water needs [18]. The major source of surface water availability in Pakistan is the Indus Basin and its tributaries [18, 19]. The streamflows in the Indus Basin are mainly derived from the snow and glacier melt runoff coming from the Upper Indus Basin (UIB) lying within the vicinity of the Hindukush- Karakoram- Himalaya range, and contributes about 50-70% to the annual total flow of Indus Basin, while the remaining streamflows are contributed by the summer monsoon and the winter seasonal precipitation runoff [18]. The country receives on average about 146 MAF of runoff every year from the Indus Basin [4, 20, 21]. Out of the total annual flow of about 110 MAF of the Upper Indus Basin (UIB), about 82% (90 MAF) of flow in the UIB comes from the snowmelt runoff, while the remaining 18% (about 20 MAF) comes from the glacier melt runoff [18]. The volume of snowmelt runoff in the UIB strongly depends on the amount of winter precipitation received over the Greater Himalayas, and the spring and summer seasonal temperature patterns over the region. While the magnitude of glacier melt runoff depends on the summer seasonal temperature trends over the Greater Himalayas [18]. This clearly indicates that the climate patterns over the northern areas of the country (Greater Himalayas to be more precise) strongly govern the streamflow patterns in the Indus Basin, and ultimately the state of water security in the country.

1.1. Literature and Case studies Review

During the past decades, the adverse impacts of global climate change have been clearly evident in the local climate patterns of Pakistan [2, 14, 22-24]. As per the study conducted by the Pakistan Meteorological Department, the annual mean temperature of Pakistan rose by about 0.6 °C during the last century, at the rate of about 0.06 °C/decade, as shown in Figure 2 [2, 13, 14]. Moreover, the magnitude of warming over the country has been found to be higher in the latter half of the century as compared to the earlier half, which was reported in a study conducted by the Asian Development Bank (ADB) and the World Bank Group, according to which the annual average temperature of Pakistan increased by about 0.47 °C during the period 1960-2007, at the rate of about 0.07 °C/decade [17]. While on the seasonal scale, the warming trends have been found to be more concentrated towards the post-monsoon and winter months, whereas a declining trend of summer season temperatures has been found in Pakistan, except Balochistan [13, 17]. Apart from the temporal scale, the annual and seasonal climate trends over the country have also varied spatially over the years. This was highlighted in a study conducted by the Ministry of Climate Change (MOCC) Pakistan, according to which, the summer monsoon temperatures declined over the Greater Himalaya and north-western zones of the country, central and southern Punjab, lower Indus plain, and the coastal belt of the country during the period 1951-2000, whereas the winter and spring seasonal temperatures increased over the Greater Himalayas, central and southern Punjab, Balochistan, and the coastal belt of the country [14]. Recently, in the year 2020, Pakistan recorded about 0.22 °C higher annual mean temperature than the normal (1961-2010) *(PMD Annual Climate Report, 2020)*, whereas in 2021, the country observed about 0.99 °C higher annual mean temperature than the average (1961-1990), placing it on the 7th warmest year record across Pakistan *(PMD Annual Climate Report, 2021)*. Similarly, in the year 2022, the annual mean temperature of the country was found to be about 0.84 °C higher than the 1961-1990 average, making it the 5th warmest year on record in the country during the last six decades *(PMD Annual Climate Report, 2022)*.

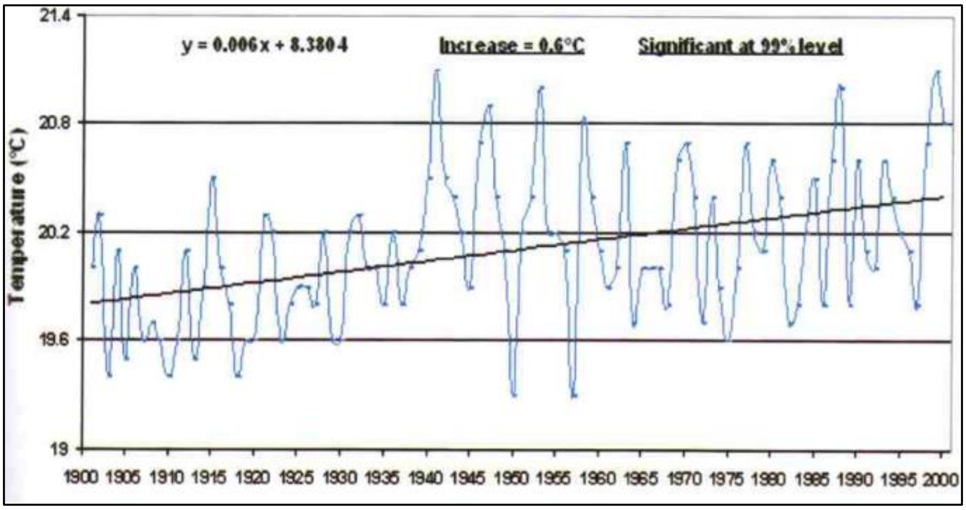

Figure 2: Annual mean temperature trend of Pakistan for the period 1900-2000.
Source: Global Change Impact Studies Centre (GCISC), 2009a.

Similar to the air temperature, the annual and seasonal precipitation patterns have also undergone significant variations across the country. According to the Pakistan Meteorological Department, the annual mean rainfall of Pakistan increased by about 63 mm (about 25%) during the period 1900-2009, at the rate of about 0.5 mm/year [2, 14]. Similarly, in an annual climate report published by PMD in 2022, a rise in the annual mean rainfall of Pakistan of about 66 mm during the period 1961-2021 was reported, as shown in Figure 3 (*PMD Annual Climate Report, 2022*). On the spatial scale, MOCC (Pakistan) reported an upward trend of summer monsoon precipitation over the country, except Balochistan and the coastal zones, while the winter precipitation showed a downward trend over the lower Indus plain, and western Balochistan during the period 1951-2000 [14]. Apart from the long-term climate variations, past studies also showed a noticeable increase in the frequency of occurrence of daily extreme and highly intense meteorological events over the country as shown in Table 1. Since the inception of the 21st century, the year 2010 in Pakistan has been marked by the occurrence of extreme flood event in the history of country, due to the occurrence of heavy summer monsoon precipitation in Khyber Pakhtunkhwa, Punjab, Sindh, and Balochistan, where the country received the highest summer monsoon rainfall since 1994 and 2nd highest during the last fifty years, inundating about one-fifth of the country's land area [25]. As per PMD, about 200 mm of rainfall was received in a single day over Khyber

Pakhtunkhwa and Punjab, whereas in Peshawar, the city witnessed a record-breaking 274 mm in a single day [25]. Further, in the year 2011, the Sindh province witnessed the highest ever recorded summer monsoon precipitation from August to September, where the province received about 271% above normal precipitation in the month of August [25]. Recently, in the year 2019, Pakistan recorded about 21% higher annual total precipitation than the normal (1981-2010), where Sindh, Punjab, and Balochistan received about 63%, 18%, and 47% respectively higher than the normal rainfall *(PMD Annual Climate Report, 2019)*. In the year 2020, the annual total rainfall over the country was found to be 38% higher than normal (1961-2010), making it the 4th wettest year since 1960. From the summer monsoon in 2020, Pakistan on a total received about 41 % higher precipitation than the normal, with Sindh, Balochistan, Gilgit-Baltistan, Khyber Pakhtunkhwa, and Punjab provinces received about 148%, 74%, 37%, 5%, and 14% respectively higher than the normal summer monsoon precipitation, where Karachi city received 231 mm in a 24-hour duration on 28th August, making it the highest one-day rainfall record *(PMD Annual Climate Report, 2020)*. Comparatively, the more extreme rainfall events were witnessed in Pakistan in the year 2022, where the country received about 77% higher annual total rainfall as compared to the normal (1961-2010), making it the highest ever since 1960s. Provincially, Balochistan received about 156% higher annual rainfall than average, while Sindh, Punjab, and Gilgit-Baltistan received about 331%, 45%, and 14% respectively higher annual precipitation than the normal. From the summer monsoon in 2022, the country on average received about 181% higher precipitation than the normal, with the magnitude of departure from the normal rainfall was found to be highest in Sindh (726%) due to the formation of extremely low thermal depression over the province, and secondly in Balochistan (590%), while Punjab, Khyber Pakhtunkhwa, and Gilgit-Baltistan received 52%, 58%, and 233% respectively higher summer monsoon precipitation than the normal *(PMD Annual Climate Report, 2022)*.

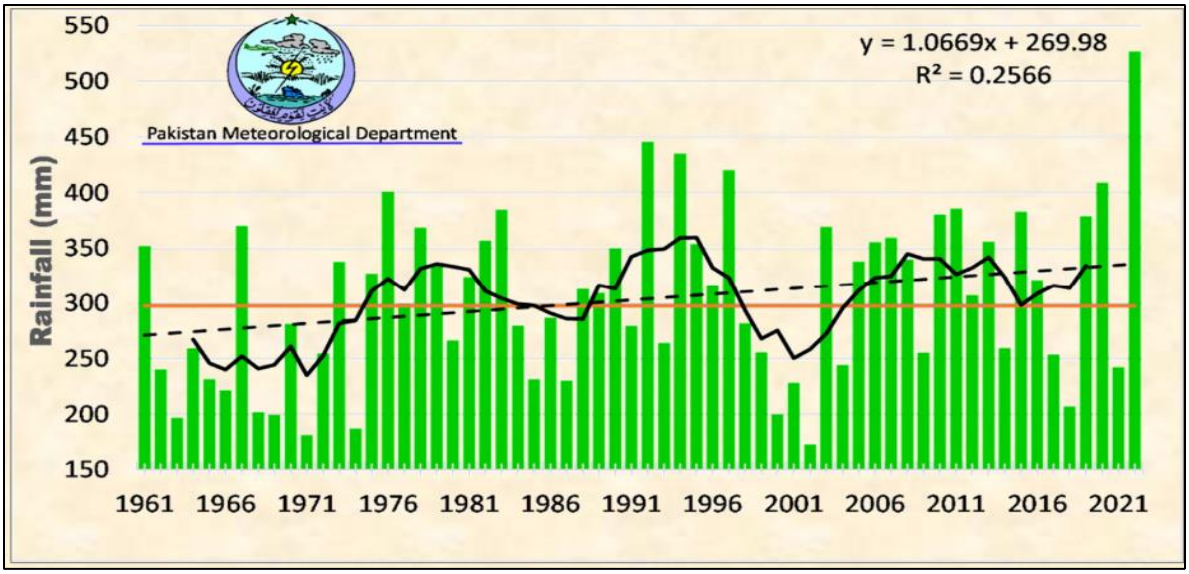

Figure 3: Annual mean precipitation trend of Pakistan for the period 1961-2021. The black line shows the 7-yr moving average, positioned over the middle year of each 7-year block. The red line shows the normal rainfall (1961-2010). The black dotted line shows the trend over the period.
Source: Pakistan Meteorological Department, Annual climate report 2022

Table 1: Frequency of occurrence of highest daily temperature and precipitation events during 1960-2000
Source: Global Change Impact Studies Centre (GCISC), 2009a.

Period	1961-1970	1971-1980	1981-1990	1991-2000
Number of stations that recorded highest daily temperature	4	12	16	20
Number of stations that recorded highest daily rainfall	6	18	11	17

In order to investigate the changing climate patterns over an area, a number of statistical methods have been used in past studies. These statistical tests are classified as parametric and non-parametric [26, 27]. The parametric tests are more effective but require the time series data to be normally distributed [26]. However, the non-parametric tests do not require the data to be normally distributed, and the outliers are better tolerated without influencing the trend [28]. The past studies showed the application of both parametric and non-parametric statistical tests for trend assessment in meteorological time series data. For example, Salma et al. (2012) used the Analysis of Variation (ANOVA) along with Dunnuett T3 test to study the rainfall trends over the different spatial zones of Pakistan, and found an overall declining trend of rainfall over the country [16]. Among the various commonly used parametric and non-parametric trend detection methods including linear regression analysis, t-test, and Spearman-Rho test, the non-parametric Mann-Kendall (MK) test has been suggested and used in numerous studies for being a reliable approach to investigate the monotonic trend in a meteorological or hydrological time series data, due to its better tolerance for the outliers and other forms of non-normality in the time series data [28-32]. As per the literature, the statistical authenticity of the resulting trend by the MK test is evaluated with the help of two parameters as Z-statistics and p-value [26, 33]. The resulting trend is termed to be statistically significant if $|Z| > |Z_{\alpha/}2|$ and $p< \alpha$. The positive value of Z-statistics depicts a rising trend in the time series, while the negative values show a declining trend [33]. Khattak et al. (2015) used the Mann-Kendall test for the assessment of temperature and rainfall patterns over the Punjab province (Pakistan), and found an increasing trend of maximum and minimum temperature over the province, where the maximum temperature over Faisalabad and Rawalpindi stations increased at the rate of about 0.01 °C/year. For rainfall, an increasing trend was found over the study area [34]. Similarly, Moazzam et al. (2022) also applied the Mann-Kendall test in a study to investigate the precipitation patterns over the northern areas of Pakistan, and reported an upward rainfall trend [35].

Apart from the nature of the trend, the magnitude of change in time series data is also a piece of important information for climate trend analysis. For this purpose, the Sen's slope estimator method has been suggested to be an effective approach due to its non-parametric nature [28, 31, 36]. Gao et al. (2020) applied the Mann-Kendall test and Sen's slope estimator method to study the nature of the trend as well as the magnitude of change in the annual, seasonal, and monthly precipitation over northern China for the period 1957-2019. The results obtained from the study showed a downward trend of monthly precipitation in January, March, April, November, and December at a 99% confidence interval, while no major change was detected on the annual scale [26]. A similar study conducted by Mersin et al. (2022) also applied the Mann-Kendall test and Sen's slope estimator method to study the annual temperature and precipitation trends in Turkey, and found a rising trend of annual mean temperature with the Sen's slope as 0.20-0.35 °C/decade, whereas the annual rainfall increased at the rate of about 4.2 to 7.9 mm/year over the country [37]. However, before the application of trend detection tests on the time series data, it is essential to first check the serial independence among the values in the time series data [27]. The serial interdependence in the time series data known as the serial or the auto-correlation refers to the relationship of a variable with itself over repeated time periods, that may show the presence of a significant trend in the time series data, even if it was present, that could mislead the analysis [26, 27]. Past studies have suggested a number of methods to remove the auto-correlation from the time series data including Pre-Whitening (PW) method, Trend Free Pre-Whitening (TFPW), and Variance Correction (VC) method [26, 27, 38]. The Pre-Whitening method has been used in numerous studies to remove the auto-correlation from the climate data [27, 31, 39, 40]. For example, Mullick et al. (2019) used the Pre-Whitening method to remove the serial correlation from the climate data, in order to investigate the temperature and rainfall trends in Bangladesh [39]. Hajani et al. (2017) also employed the Pre-Whitening approach for the removal of auto-correlation from the time series data, for the trend detection of extreme rainfall in South Wales (Australia) [41]. The method first modifies the time series data, and the trend detection tests are then applied to the corrected time series.

2. Materials and Methods

In order to adapt to short and long-term climate related hazards, a thorough understanding of variability in climate patterns in the past and the possible changes in the future over the different zones of a region is essential. Therefore, this study was conducted to comprehensively investigate the annual and seasonal climate patterns over the major climatic zones of Pakistan during the period 1990-2020. The nature of the trend was investigated in this study by using the Mann-Kendall test, whereas the rate and the magnitude of change were computed using the Sen's slope estimator method. The selection of different climatic zones of the country in this study was made to profoundly investigate and understand the spatial variations in the climate patterns over the country during the recent decades. Seasonally, the temperature trends were investigated for three seasons, spring (March -May), summer (June-September), and winter (December-February). On the other hand, the seasonal precipitation patterns were investigated for the two major rainfall seasons of the country, the summer monsoon (July-September) and winter precipitation (December-March). The methodology adopted to achieve the outcomes of the study is illustrated in Figure 4.

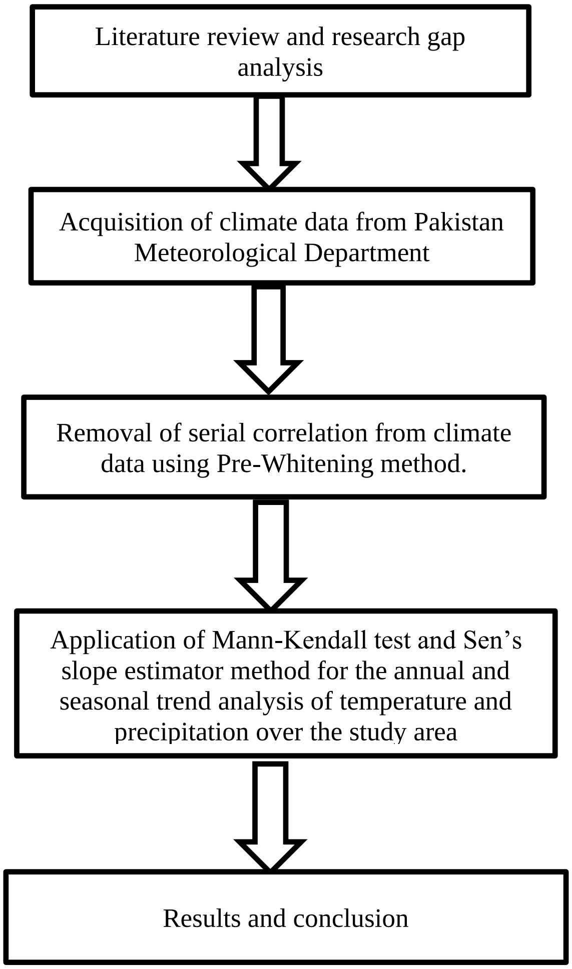

Figure 4: Flow chart describing the methodology adopted in the study.

The outcomes of this study are anticipated to help in understanding the recent annual and seasonal climate patterns over the major climatic zones of the country, and to devise an effective and holistic climate change adaptation and mitigation strategy for the conservation of natural resources in the country.

2.1. Study Area and Data

Based on the climatic and geospatial features, Pakistan is categorized into six major climatic zones as Zone I (a): Greater Himalayas, Zone I (b): Sub-montane Region, Zone II: Western Highlands, Zone III: Central and southern Punjab, Zone IV: Lower Indus plain, Zone V(a): East and northern Balochistan, Zone V(b): Western

Balochistan, and Zone VI: Coastal belt, as shown in Figure 5 [14]. Zone I (a) of Pakistan lies in the vicinity of the Himalayan-Karakoram and Hindukush (HKH) range, lying between the latitudes 35 °N to 37 °N, and characterized by having extremely cold winters with moderately warm summers. This region receives the major share of its annual precipitation from the winter precipitation (Dec-March) due to the intrusion of Western Disturbances into the country, which mainly occurs as snowfall due to the extremely low winter temperatures over the area. This zone abounds in large glaciers, with the glacial area covering about 13,680 square kilometres (about 13% of the mountain ranges in the UIB). Apart from the glaciers and the snow dominated lofty mountainous peaks, the Zone-I (a) also consists of the green valleys, copious streams, large lakes, plateaus, and forest covered areas. The Zone-I (b) is spatially situated on the southward slopes of the Himalayan range, between the latitudes 33°N to 35 °N, and with the elevation ranging from about 600 to 2000 m. The zone mainly comprises of the northern belt of Punjab and Azad Kashmir, and receives the highest amount of summer monsoon precipitation in the country, while also receiving adequate quantity of winter precipitation. The Zone-II (Western Highlands) extends from the Chitral and Swat hills in the north-southward direction and covers a large fraction of the Khyber Pakhtunkhwa (KPK) province of Pakistan. The zone is geographically located on the path of the intruding Western Disturbances into the country from the west and receives a good amount of precipitation from both summer monsoon and Western Disturbances [14].

The Zone-III (central and southern Punjab) consists of the fertile land of the Indus River and its major tributaries including Jhelum, Chenab, Beas, Ravi, and Sutlej rivers [14]. The climate of this zone is mainly semi-arid in the central part to arid in the southern part. The rivers of the Indus Basin in this zone have created an alluvial belt that is both dense and rich. These alluvial sediments cover the majority of the Punjab province in an uninterrupted strip. These floodplains comprise of flat landforms covered by a system of irrigation canals. The area is gradually sloping from northeast to southwest, with elevation ranging from about 85 m in its south to about 300 m in its extreme north. The zone receives the major share of its annual precipitation from the summer monsoon. The Zone-IV (lower Indus plain) mainly covers the Sindh province of Pakistan, and conveys streamflows from all tributaries of Indus Basin to the Arabian Sea. Similar to the Zone-III, this zone also consists of the large fertile alluvium transported and deposited by the Indus Basin. The climate of this zone is mainly arid, with the annual average rainfall ranging from about 120-250 mm. The zone also serves as an important hub for the production of major food and cash crops of the country including Rice, Wheat, Cotton, Sugarcane, pulses, fruits, and vegetables. The Zone-V (northern and western Balochistan) consists of varying physical features, but predominantly mountains and basins. The mountains in this zone are generally carved off by various ephemeral channels and hill torrents, getting water only during the precipitation in the area. The major rivers found in this zone include the Zhob, Bolan, and Mulla streams towards the northeast of the province. The climate of the zone is pre-dominantly arid to hyper-arid, with the mixed land consisting of eroded soft sedimentary rocks, tracks of sandy and gravelly wastelands with patches of loamy soil formed by the hill torrents moving the sediments from the upper situated catchment areas. In this zone, the annual precipitation is very low as the major precipitation systems of the country including the summer monsoon and western depression seldom reach the area [29]. However, the mountainous areas in northern Balochistan receive considerable precipitation in the form of snowfall from the Western Disturbances, which replenishes the surface and groundwater resources in the province. The Zone-VI (coastal area) comprises of the area situated in the proximity of the coastal belt of Pakistan. The length of Pakistan's coastal line is about 990 km long, with about 270 km lying in the Sindh province, and about 720 km lies in the Balochistan province. The part of the coastal line lying in the Sindh province consists of dense Mangrove forests, whereas the portion lying in Balochistan is mostly barren [14].

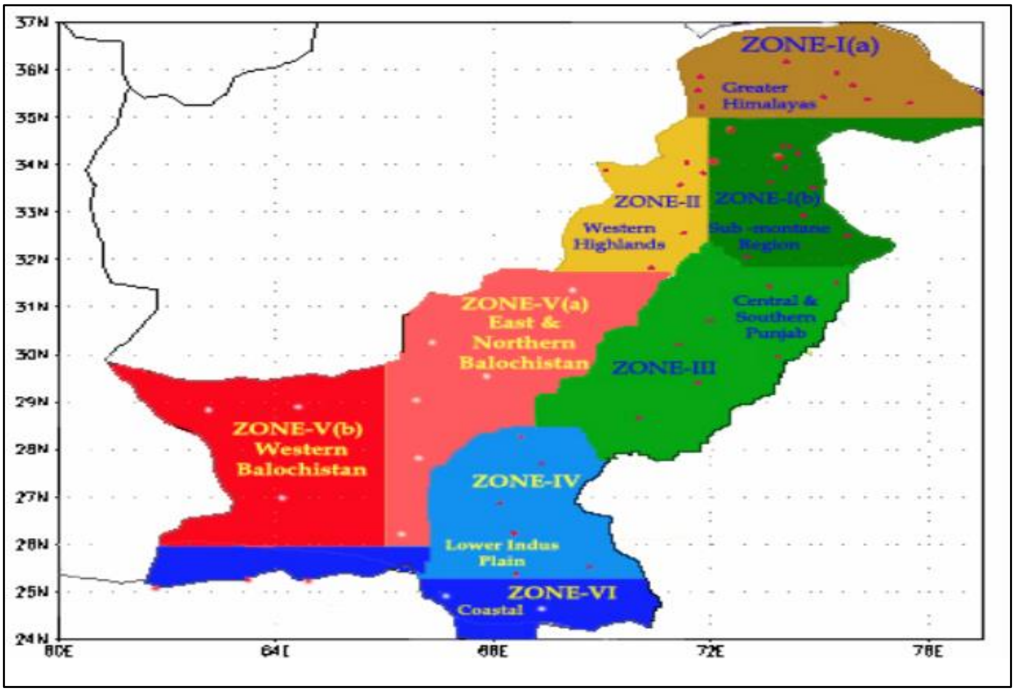

Figure 5: Description of the six major climatic zones of Pakistan.
Source: Global Change Impact Studies Centre (GCISC), 2009a

In this study, a number of 37 climate stations were selected from the six major climatic zones of the country. From Zone I (a), the stations of Astore, Gilgit, Bunji, Skardu, Chillas, and Gupis were selected. From Zone I (b), the stations of Muzaffarabad, Islamabad, Jhelum, Lahore, and Sialkot was selected. From Zone II, the stations of Dera Ismail Khan, Kohat, Parachinar, and Peshawar were taken. From Zone III, Bahawalnagar, Bahawalpur, Faisalabad, Mianwali, Multan, and Sargodha were selected. From Zone-IV, the stations of Umerkot, Hyderabad, Jacobabad, and Nawabshah were selected. From Zone-V (a), the stations of Quetta, Kalat, Khuzdar, Zhob, and Lasbela were taken, whereas, from Zone-V (b), the stations of Dalbandin, Nokkundi, and Panjgur were selected. From Zone VI (coastal belt), the stations of Badin, Jiwani, Pasni, and Karachi were taken, as shown in Figure 6.

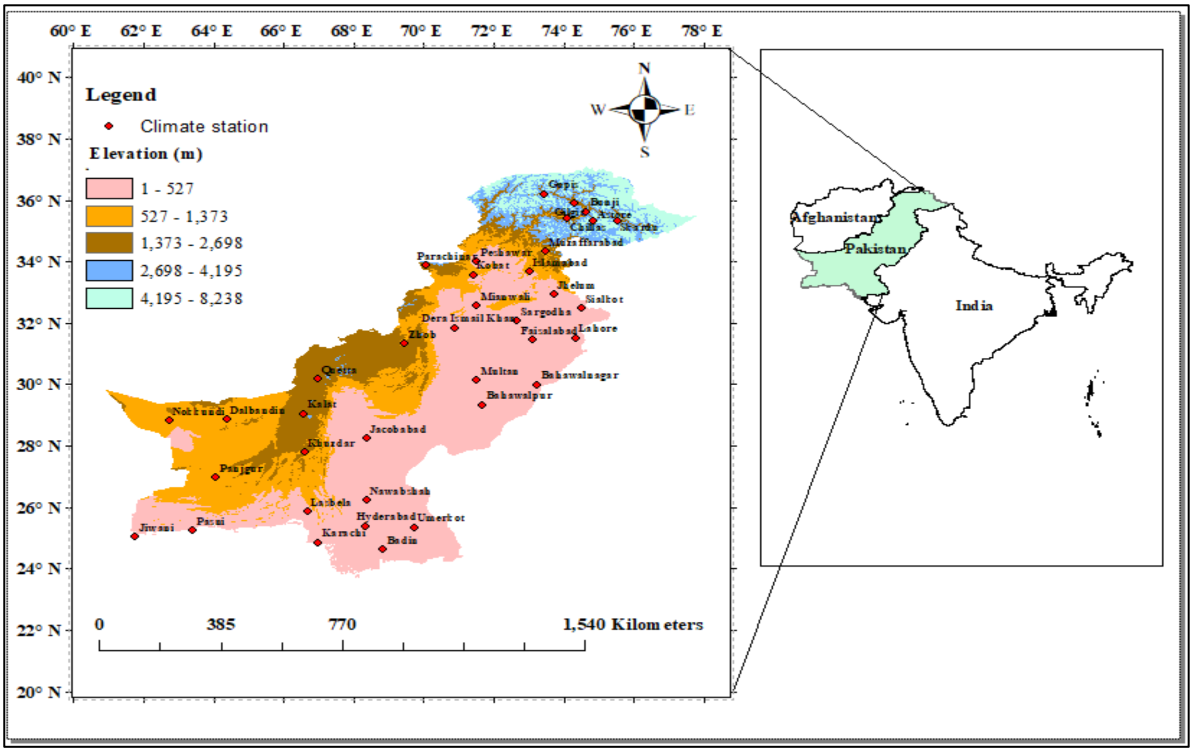

Figure 6: Description of study area showing the selected 37 climate stations from the six major climatic zones of Pakistan.

The climate data required for this study was acquired from the Pakistan Meteorological Department. The acquired data consisted of daily temperature (T_{max} and T_{min}) and rainfall (mm) for all selected stations in the study for the period 1990-2022. The geographical and climate details of the selected stations are shown in Table 2 as under:

Table 2: Geographical and climate details of the selected stations from the six major climatic zones of Pakistan.

Data source: Pakistan Meteorological Department.

Station	Latitude (°N)	Longitude (°E)	Elevation above MSL (m)	Annual mean temperature (°C)	Annual mean rainfall (mm)
Zone-I (a): Greater Himalayas					
Gilgit	35.92	74.30	1500	12.80	108
Skardu	35.32	75.55	2228	9.50	173
Bunji	35.64	74.63	1372	16.25	190
Gupis	36.22	73.44	2156	11.96	200
Astore	35.35	74.86	2168	7.85	402
Chillas	35.42	74.09	1250	17.60	254
Zone-I (b): Sub- montane Region					
Lahore	31.52	74.35	216.5	24.30	636
Muzaffarabad	34.35	73.47	702	16.70	1315
Islamabad	33.68	73.04	507	21.3	1201
Jhelum	32.94	73.72	234	23	875
Sialkot	32.49	74.52	256	22.6	972

Station	Latitude (°N)	Longitude (°E)	Elevation above MSL (m)	Annual mean temperature (°C)	Annual mean rainfall (mm)
Zone-II: Western Highlands					
Peshawar	34.01	71.52	331	22.70	404
Dera Ismail Khan	31.86	70.90	165	24.20	318
Kohat	33.58	71.44	489	21.50	504
Parachinar	33.90	70.98	1705	15.30	782
Zone-III: Central and Southern Punjab					
Multan	30.15	71.52	122	25.65	254
Bahawalpur	29.35	71.69	118	25.70	167
Bahawalnagar	30.00	73.24	163	24.50	280
Faisalabad	31.45	73.13	186	24.50	382
Mianwali	32.58	71.53	210	23.50	598
Sargodha	32.07	72.68	190	24.70	501
Zone-IV: Lower Indus Plain					
Hyderabad	25.39	68.35	13	26.80	156
Nawabshah	26.24	68.39	37	26.70	161
Jacobabad	28.24	68.38	55	27.10	223
Umerkot	25.35	69.73	19	26.50	245.5
Zone-V(a): East and Northern Balochistan					
Quetta	30.17	66.97	1719	15.70	261
Lasbela	25.87	66.71	87	25.15	200
Kalat	29.05	66.58	2015	14.10	163
Khuzdar	27.81	66.60	1231	21.50	252
Zhob	31.34	69.46	1405	19.10	285
Zone-V(b): Western Balochistan					
Dalbandin	28.88	64.39	848	22.40	80.7
Panjgur	26.97	64.08	968	22.10	109
Nokkundi	28.82	62.75	682	24.50	35.3
Zone-VI (Coastal belt)					
Badin	24.64	68.84	9	26.70	223
Jiwani	25.05	61.77	56	25.60	114
Pasni	25.25	63.41	9	26.28	115
Karachi	24.86	67.01	22	26.60	175

2.2. Methodology

2.2.1. Auto-correlation Test

In this study, before the application of trend detection tests, the existence of significant auto correlation in the given climate data was first tested at a 95% confidence interval. Therefore, the lag-1 auto-correlation coefficient (r_1) was estimated for all months in the given temperature (T_{max} and T_{min}) and rainfall time series data using Equation (1) as under [26]:

$$r_1 = \frac{\sum_{i=1}^{n-1}(X_i-\bar{X})(X_i+_1-\overline{X})}{\sum_{i=1}^{n}(X_i-\bar{X})^2} \tag{1}$$

The auto-correlation coefficient (r_1) obtained from Equation (1) was then tested for its significance at 95% confidence interval using Equation (2) as under [26]:

$$r_1\ (95\%) = \frac{-1\mp 1.96\sqrt{(n-2)}}{n-1} \tag{2}$$

Where n is the sample size, X_i is the observed value in the time series data, and $\bar{X}$ is the mean of observed values in the given time series data. As per the literature review, if r_1 for the time series is found to be within the above interval as Equation (2), then the null hypothesis is accepted, and the existence of significant auto-correlation in the time series is rejected [26]. However, if the correlation coefficient (r_1) is found to be outside the interval, then the presence of serial correlation is accepted and needs to be removed before proceeding further [27]. In this study, the Pre-Whitening method was employed to remove the serial interdependence from the time series data.

2.2.2. Pre-Whitening Method

In this study, the Pre-Whitening method was employed to remove the auto-correlation from the given time series data. This approach has been employed in different studies in the past and has been found effective to remove the auto-correlation from the time series data [27, 31, 40]. The temperature (T_{max} and T_{min}) and precipitation time series data having significant auto-correlation found were first modified by using the Pre-Whitening method as (X_2-r_1X_1, X_3-r_1X_2,…..X_n-r_1X_{n-1}), and the trend detection tests were then applied on the corrected time series [31].

2.2.3. Mann-Kendall (MK) Test

As mentioned in the literature review, the Mann-Kendall is a reliable method for the assessment of climate trends, as it does not require the normal distribution of time series data, and due to its better tolerance for outliers [16, 23, 27]. In this study, the Mann-Kendall test was applied to determine the past annual and seasonal temperature and rainfall trends over the selected stations. The statistics for the MK test including S, V(S), and Z were estimated using Equations (3)- (6) as under [26]:

$$S=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \mathrm{Sign}\left(X_j - X_i\right) \tag{3}$$

$$\mathrm{Sign}\,(X_j\text{-}X_i) = \begin{cases} +1 \text{ if } \left(X_j - X_i\right) > 0 \\ 0 \text{ if } \left(X_j - X_i\right) = 0 \\ -1 \text{ if } \left(X_j - X_i\right) < 0 \end{cases} \tag{4}$$

Where X_i and X_j are the data values in the time series i and j (with j>i) respectively, Sign (X_j-X_i) is the sign function, q is the number of tied groups, and t_p represents the number of extent p [26]. The value of S-statistics is used for the trend detection when the size of time series data (n) in the time series is less than 10 [33]. However, if n >10, then Z-statistics is calculated for the analysis of trends [33]. The value of Z-statistics was computed by employing the following mathematical equations [26]:

$$V(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)\right] \tag{5}$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & \text{if } S < 0 \end{cases} \tag{6}$$

In this study, the MK test was applied to the given time series data at a 95% confidence interval (α= 0.05), and the test results were termed as statistically significant, if |Z|> $|Z_{\alpha/2}|$ i.e., 1.96, and p-value was less than the significance level (α).

2.2.4. Sen's Slope Estimator Method

In this study, the magnitude and rate of change in the temperature (°C/year) and rainfall (mm/year) on the annual as well as on the seasonal scale over the study area were estimated using the Sen's slope estimator method. As mentioned earlier in the literature review section, this method has been applied in various studies in the past to determine the magnitude of trends in the meteorological time series data [28, 31, 36, 42]. The statistics for the Sen's slope estimator method were computed using the following equations [27]:

$$Q_i = \frac{Xj - Xi}{j - i} \quad \text{for } j>i \tag{7}$$

Where i= 1,2,3,…..N, Q_i is the estimated slope of N pairs of given data, X_i and X_j are the values of data pairs at times i and j respectively. The median of N values of slope (Q_i) was estimated as [27] :

$$Q = \begin{Bmatrix} \frac{Q(N+1)}{2} & \text{if N is odd} \\ \frac{Q\left(\frac{N}{2}\right)+Q\left(\frac{N+2}{2}\right)}{2} & \text{if N is even} \end{Bmatrix} \tag{8}$$

3. Results

3.1. Annual and Seasonal Temperature Trend Analysis

The temperature trends on the annual and seasonal scales were investigated in this study over the major climatic zones of Pakistan for the period 1990-2022, using the MK test and Sen's slope estimator method. The results obtained from the Mann-Kendall test (Z-statistics) and Sen's slope estimator method (rate of change in °C/year) are shown in Table 3 as under:

Table 3: Results Mann-Kendall (MK) test and Sen's Slope estimator method (SS) for the annual and seasonal temperature trend analysis over the major climatic zones of Pakistan for the period 1990-2022. ***Signficant trend at 95% confidence interval**

Station	Test	Annual	Spring	Summer	Winter
Zone-1(a): Greater Himalayas					
Gilgit	MK	+**2.110***	**+2.739***	-1.590	+**3.105***
	SS	+0.010	+0.024	-0.010	+0.026
Skardu	MK	+1.170	**+2.234***	-1.862	**+1.988***
	SS	+0.010	+0.027	-0.022	+0.033
Bunji	MK	**+2.470***	**+2.99***	+0.217	**+2.594***
	SS	+0.023	+0.038	+0.002	+0.029
Gupis	MK	+0.156	+0.968	-1.862	-0.983
	SS	+0.002	+0.022	-0.022	-0.016
Astore	MK	+1.700	**+2.465***	+1.105	+0.850
	SS	+0.020	+0.059	+0.010	+0.018
Chillas	MK	+0.407	+1.460	-0.680	+0.152
	SS	+0.005	+0.042	-0.015	+0.004
Zone-I (b): Sub-montane Region					
Lahore	MK	+0.316	+0.958	-1.540	-1.369
	SS	+0.005	+0.028	-0.016	-0.032
Muzaffarabad	MK	-0.889	+0.079	-0.2767	0.00
	SS	-0.010	+0.003	-0.006	NIL
Islamabad	MK	+0.375	+0.792	-0.125	+0.969
	SS	+0.008	+0.019	-0.002	+0.023
Jhelum	MK	+1.621	+1.453	+0.479	0.00
	SS	+0.022	+0.046	+0.004	NIL
Sialkot	MK	**+2.670***	**+2.010***	**+2.870***	-0.022
	SS	+0.033	+0.054	+0.026	-0.0004

Station	Test	Annual	Spring	Summer	Winter
Zone-II: Western Highlands					
Peshawar	MK	**-2.050***	-0.145	**-2.546***	+0.308
	SS	-0.030	-0.007	-0.044	+0.008
Dera Ismail Khan	MK	+0.612	+1.639	+0.256	-0.572
	SS	+0.009	+0.060	+0.004	-0.022
Kohat	MK	-1.110	-0.6001	**-2.351***	-0.145
	SS	-0.021	-0.028	-0.046	-0.004
Parachinar	MK	-1.767	-0.729	**-2.319***	-0.762
	SS	-0.033	-0.025	-0.041	-0.022
Zone-III: Central and Southern Punjab					
Multan	MK	**+2.540***	+1.917	+0.958	-0.132
	SS	+0.021	+0.055	+0.012	-0.0008
Bahawalnagar	MK	**+1.990***	**+2.750***	+0.375	-0.573
	SS	+0.029	+0.069	+0.003	-0.010
Bahawalpur	MK	+1.792	**+2.450***	+0.958	-0.220
	SS	+0.021	+0.064	+0.012	-0.003
Faisalabad	MK	**+2.535***	**+2.501***	0.00	-0.286
	SS	+0.026	+0.071	NIL	-0.006
Mianwali	MK	+0.968	**+2.15***	-1.797	+0.542
	SS	+0.015	+0.065	-0.019	+0.013
Sargodha	MK	0.00	+0.889	**-2.430***	-0.083
	SS	NIL	+0.032	-0.041	-0.001
Zone- IV: Lower Indus Plain					
Hyderabad	MK	+0.583	+1.620	-1.363	-0.908
	SS	+0.003	+0.032	-0.013	-0.014
Nawabshah	MK	**+2.790***	**+3.330***	+1.086	+1.251
	SS	+0.031	+0.086	+0.015	+0.024
Jacobabad	MK	-0.583	+0.928	-1.602	-1.793
	SS	-0.009	+0.036	-0.015	-0.053
Umerkot	MK	**+4.220***	**+3.25***	**+2.11***	+1.673
	SS	+0.037	+0.076	+0.034	+0.031
Zone-V (a): East and northern Balochistan					
Quetta	MK	+0.956	+1.670	+1.086	**+2.570***
	SS	+0.021	+0.060	+0.013	+0.057
Lasbela	MK	+0.859	+1.864	-1.443	+0.891
	SS	+0.011	+0.041	-0.013	+0.023
Kalat	MK	+1.443	+1.443	+0.535	+1.573
	SS	+0.022	+0.032	+0.006	+0.033
Khuzdar	MK	+1.378	+1.021	+0.470	+1.281
	SS	+0.023	+0.029	+0.009	+0.023
Zhob	MK	**+2.156***	**+2.335***	+1.443	+0.243
	SS	+0.021	+0.042	+0.014	+0.005
Zone- V(b): Western Balochistan					
Dalbandin	MK	+1.929	**+2.595***	+0.794	+0.243
	SS	+0.021	+0.057	+0.012	+0.005
Panjgur	MK	**+2.805***	**+2.027***	**+2.124***	+0.924
	SS	+0.032	+0.048	+0.021	+0.026
Nokkundi	MK	**+2.448***	+1.864	**+2.286***	+0.113
	SS	+0.031	+0.068	+0.029	+0.006

Station	Test	Annual	Spring	Summer	Winter
Zone- VI: Coastal Belt					
Badin	MK	**+3.085***	**+2.76***	**+2.746***	+0.438
	SS	+0.028	+0.055	+0.025	+0.004
Jiwani	MK	**+2.156***	**+2.335***	+1.443	+0.243
	SS	+0.021	+0.042	+0.014	+0.005
Karachi	MK	+1.038	+1.719	+0.210	+0.218
	SS	+0.005	+0.029	+0.002	+0.002
Pasni	MK	+1.929	**+2.595***	+0.794	+0.243
	SS	+0.021	+0.057	+0.011	+0.005

The above results obtained from the analysis showed a warming trend of annual and seasonal temperatures over the majority of the selected stations, with the magnitude of warming being higher in the southern parts of the country due to the warmer and dry climate features, as compared to the northern parts. On the annual scale, a rising trend of temperature was found over the Greater Himalayas, Sub-montane region, lower Indus plain, central and southern Punjab, northern and western Balochistan, and the coastal belt of the country, where the temperature rose by about 0.1 to 0.7 °C over the Greater Himalayas, 0.1 to 1.0 °C over the Sub-montane region, 0.4 to 1.0 °C over the central and southern Punjab, 0.1 to 1.1 °C over the lower Indus plain, 0.3 to 0.7 °C over the northern Balochistan, 0.6 to 1.0 °C over the western Balochistan, and by about 0.1 to 0.9 °C over the coastal belt of the country during the study period, as shown in Figure 7 (I). Further, these rising annual mean temperature trends were found to be statistically significant at the Gilgit, Skardu, Sialkot, Multan, Bahawalnagar, Faisalabad, Nawabshah, Umerkot, Zhob, Panjgur, Nokkundi, Badin, and Jiwani stations at 95% confidence interval, with the Sen's slope as +0.01, +0.023, +0.03, +0.02, +0.029, +0.026, +0.031, +0.037, +0.021, +0.032, +0.031, +0.028, and +0.021 °C/year respectively as shown in Table 3. However, the Zone-II i.e. the Western Highlands, showed a declining pattern of annual mean temperature, whereas at the Peshawar station, the annual mean temperature dropped at the rate of about 0.03 °C/year.

Apart from the annual temperature, the seasonal temperatures also have their respective importance and influence on the environment. As discussed earlier, the spring and summer seasonal temperatures over the high altitude glaciated and snow dominated Greater Himalayas significantly govern the cryospheric processes including the snowpack and glacial mass accumulation and ablation, and the volume of snow and glacier melt runoff, ultimately governing the water availability in the Indus Basin. Whereas the Sindh and Punjab provinces have rich growing fields of major food and cash crops of the country, the seasonal temperatures are crucial due to their considerable influence on the crop water requirements, soil moisture availability, crop water productivity, and crop yield. In this study, an upward trend of spring seasonal temperature was found over the majority of the climatic zones of the country, where the temperature rose by about 0.6 to 1.8 °C over the Greater Himalayas, 0.1 to 1.8 °C over the Sub-montane region, and by about 1.0 to 3.0 °C over the central and southern parts, and the coastal belt of the country as shown in Figure 7 (II), where significant warming trends were detected at the Gilgit, Skardu, Bunji, Astore, Sialkot, Bahawalnagar, Bahawalpur, Mianwali, Nawabshah, Umerkot, Zhob, Dalbandin, Badin, Jiwani, and Pasni stations at 95% confidence interval, with the Sen's slope as +0.024, +0.027, +0.038, +0.059, +0.054, +0.069, +0.064, +0.065, +0.086, +0.076, +0.042, +0.057, +0.055, +0.042, and +0.057 °C/year respectively, as shown in Table 3. However, over the Western Highlands, a negative trend of spring seasonal temperature was found over the majority of the stations. For the summer season, a declining temperature trend was found over the Greater Himalayas, Sub-montane region, and the Western Highlands, while over southern Punjab, the temperature rose by about 0.1 to 0.4 °C, 0.4 to 1 °C over the lower Indus plain, 0.2 to 0.4 °C over the northern Balochistan, 0.6 to 0.9 °C over the western Balochistan, and by about 0.3 to 0.8 °C during the study period, as shown in Figure 7 (III). For the winter season, an upward temperature trend was found over the Greater Himalayas, northern and western Balochistan, lower Indus plain, and the coastal belt of the country, where the temperature rose by about 0.1 to 1.0 °C over the Greater Himalayas and northern Balochistan, 0.2 to 0.8 °C over the eastern Balochistan, and by about 0.1 to 0.2 °C over the coastal belt, as shown in Figure 7 (IV). These warming winter temperature trends were found to be statistically significant at the Gilgit, Skardu, Bunji stations lying in the Zone I (a), with the Sen's slope as +0.026, +0.033, and +0.029 °C/year respectively. Conclusively, the annual mean temperature and spring seasonal temperatures were found to be increasing over the country, except in the Western Highlands. For the summer season, the Greater Himalayas and the Western Highlands showed a declining temperature trend, while for the winter season, the Greater Himalayas, northern and western Balochistan, lower Indus plain, and the coastal zones showed an upward temperature trend, which was found to be in agreement with the study conducted by the Global Change Impact Studies Center *(GCISC, 2009a)*.

Based on the results obtained from the analysis, it can be stated that the annual and seasonal temperature patterns have undergone significant spatial variations across the country during the past three decades as a consequence of the phenomenal shift in global climate patterns. As discussed earlier, the rising spring seasonal temperatures over the Greater Himalayas may result in increased melting of snowpack and glacial mass, and consequently, high streamflows over the Upper Indus Basin, resulting in increased flood events in the country, whereas the rising winter seasonal temperatures may affect the form of winter precipitation, snowpack accumulation, and the length of snow cover period. On the other hand, the warming temperature patterns (annual and seasonal) over the lower Indus plain, central and southern Punjab, and the Balochistan may result in increased heatwave events, soaring water requirements for agricultural and livestock production, and also for domestic use, thereby pressurizing the already stressed freshwater resources of the country.

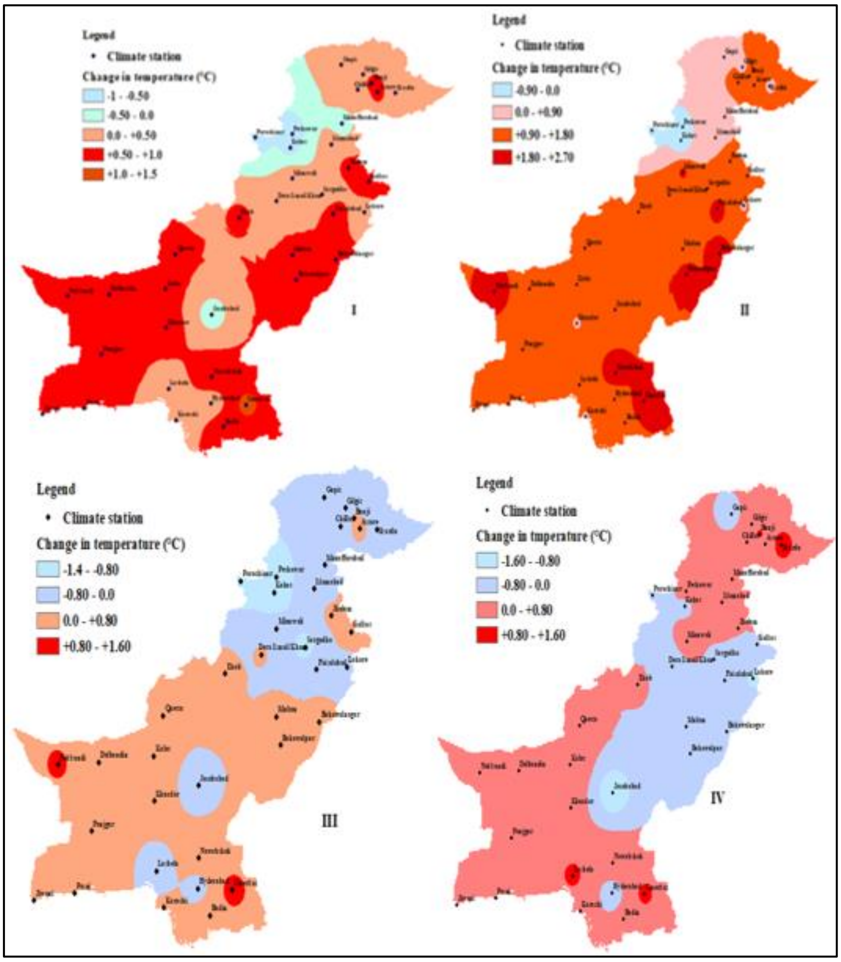

Figure 7: Magnitude of change in temperature (°C) computed by Sen's slope method for (I) Annual (II) Spring (III) Summer (IV) winter season over the major climatic zones of Pakistan, 1990-2022.

3.2. Annual and Seasonal Precipitation Trend Analysis

The precipitation patterns on the annual and seasonal scales were investigated in this study over the major climatic zones of Pakistan for the period 1990-2022 using the Mann-Kendall test and Sen's slope estimator method. The results obtained from the Mann-Kendall test (Z-statistics) and Sen's slope estimator method (rate of change in mm/year) are shown in the Table 4 as under:

Table 4: Results of Mann-Kendall (MK) test and Sen's slope estimator method (SS) for the annual and seasonal precipitation trend analysis over the major climatic zones of Pakistan for the period 1990-2022. ***Signficant trend at 95% confidence interval**

Station	Test	Annual	Summer monsoon (July-September)	Winter precipitation (December-March)
Zone-1(a): Greater Himalayas				
Gilgit	MK	+0.908	-0.085	+1.663
	SS	+0.440	-0.021	+0.319
Skardu	MK	+0.908	+1.390	+1.027
	SS	+0.980	+0.294	+0.578
Bunji	MK	+0.804	+1.089	+1.281
	SS	+0.440	+0.403	+0.297
Gupis	MK	**+2.215***	+1.704	**+2.290***
	SS	+2.535	+0.829	+0.835
Astore	MK	**-2.175***	-0.305	**-2.617***
	SS	-6.052	-0.233	-4.200
Chillas	MK	-1.835	-0.476	-1.665
	SS	-2.560	-0.166	-1.150
Zone-I (b): Sub-montane Region				
Lahore	MK	+0.450	+0.572	0.0
	SS	+2.990	+1.640	Nil
Muzaffarabad	MK	+0.651	-1.402	**+4.05***
	SS	+3.920	-5.882	+21.93
Islamabad	MK	+0.166	-1.167	+1.851
	SS	+0.594	-5.540	+4.796
Jhelum	MK	-1.639	-1.126	-0.625
	SS	-9.172	-4.507	-1.305
Sialkot	MK	-1.126	-1.402	-0.625
	SS	-9.185	-8.880	-1.375
Zone-II: Western Highlands				
Peshawar	MK	**+3.489***	**+2.628***	**+2.579***
	SS	+17.29	+4.729	+4.614
Dera Ismail Khan	MK	+1.402	**+2.430***	+0.928
	SS	+3.521	+9.936	+0.629
Kohat	MK	**+3.77***	**+2.597***	**+2.450***
	SS	+16.09	+5.060	+4.284
Parachinar	MK	**+4.36***	**+1.980***	**+3.081***
	SS	+26.36	+2.971	+7.911

Station	Test	Annual	Summer monsoon (July-September)	Winter precipitation (December-March)
Zone-III: Central and Southern Punjab				
Multan	MK	0.00	+0.098	+1.042
	SS	Nil	+0.182	+0.931
Bahawalnagar	MK	-0.375	+0.414	-0.308
	SS	-1.169	+0.884	-0.264
Bahawalpur	MK	-0.454	-0.138	-0.088
	SS	-1.290	-0.184	-0.057
Faisalabad	MK	**+2.46***	**+2.513***	+1.167
	SS	+6.527	+4.465	+0.840
Mianwali	MK	-0.889	+0.335	**-2.251***
	SS	-5.606	+1.246	-4.533
Sargodha	MK	+1.797	+1.086	+0.500
	SS	+6.279	+3.310	+0.706
Zone- IV: Lower Indus Plain				
Hyderabad	MK	+0.533	+0.770	-1.623
	SS	+1.749	+1.237	-0.300
Nawabshah	MK	+0.612	+0.375	-1.623
	SS	+0.935	+0.682	-0.300
Jacobabad	MK	**+2.034***	+1.463	**+2.231***
	SS	+9.019	+4.502	+1.435
Umerkot	MK	-0.375	+0.059	-1.490
	SS	-1.299	+0.142	-0.160
Zone-V (a): East and Northern Balochistan				
Quetta	MK	+1.446	+1.441	-0.064
	SS	+2.689	+0.397	-0.0007
Lasbela	MK	+1.510	+1.642	-0.541
	SS	+3.028	+1.977	0.00
Kalat	MK	+1.348	+1.157	+0.406
	SS	+2.343	+0.585	+0.196
Khuzdar	MK	+1.396	+1.641	+0.860
	SS	+2.447	+1.552	+0.586
Zhob	MK	**+2.04***	**+2.371***	+1.106
	SS	+3.32	+1.615	+0.586
Zone- V(b): Western Balochistan				
Dalbandin	MK	+0.136	-0.519	+0.553
	SS	0.00	0.00	+0.245
Panjgur	MK	+1.510	+1.642	-0.541
	SS	+3.028	+1.977	0.00
Nokkundi	MK	+1.510	+1.642	-0.541
	SS	+3.028	+1.977	0.00

Station	Test	Annual	Summer monsoon (July-September)	Winter precipitation (December-March)
Zone- VI: Coastal Belt				
Badin	MK	+0.355	+0.375	-0.832
	SS	+1.008	+1.164	-0.114
Jiwani	MK	+0.179	+0.267	-1.658
	SS	0.00	0.00	-0.878
Karachi	MK	+0.713	+1.052	-0.661
	SS	+2.170	+2.301	0.00
Pasni	MK	+0.195	-0.099	-1.025
	SS	0.00	0.00	-0.437

The above results obtained from the analysis showed that on the annual scale, an increasing trend of rainfall was found over the Western Highlands, lower Indus plain, northern and western Balochistan, and the coastal belt of country as shown in the Figure 8 (V), with the magnitude of rise was found be highest over the Western Highlands (about 150-800 mm) during the study period, where at the Peshawar, Kohat, and Parachinar stations, the rising trend was found to be statistically significant at 95% confidence interval, and the annual rainfall increased at the rate of about 17.29, 16.09, and 26.36 mm/year respectively as shown in the Table 4. Over the lower Indus plain, the annual rainfall increased by about 50-250 mm, where the Jacobabad station showed a significant rising trend with the Sen's slope as +9.09 mm/year. Similarly, over the northern and western Balochistan, the rainfall increased by about 70-100 mm, and about 30-60 mm over the coastal zones, while mixed trends were found over the central and southern Punjab, Greater Himalayas, and the Sub-montane region, as shown in the Figure 8 (V), where the Gupis station showed a rise of about 2.53 mm/year, while at the Astore station, the annual rainfall dropped at the rate of about 6.05 mm/year.

As discussed earlier, the summer monsoon precipitation is a major contributor to the annual precipitation of Pakistan and plays a vital role in the replenishment of surface and groundwater resources, and streamflows, supplementing the irrigation water requirements and supporting the rainfed agriculture over the country. For the summer monsoon, the analysis showed a declining trend over the Greater Himalayas and Sub-montane region, while an increasing trend was found over the Western Highlands, lower Indus plain, central and southern Punjab, Balochistan, and the coastal zone, as shown in Figure 8 (VI). Over the Western Highlands, the summer monsoon rainfall increased by about 100-300 mm during the study period, where the Peshawar, Kohat, Dera Ismail Khan, and Parachinar stations showed a significant rising trend with the Sen's slope as +4.72, +5.06, +9.93, +2.97 mm/year respectively, as shown in Table 4. In Zone-III (central and southern Punjab), the analysis showed a rise of about 50-150 mm over the stations lying in the central Punjab, where the Faisalabad station observed a significant rising trend at a 95% confidence interval, with the Sen's slope as +4.46 mm/year, while the stations lying in southern Punjab showed a slight increment. For the lower Indus Plain and Balochistan, which witnessed record high summer monsoon precipitation in recent years, the analysis showed a rising trend at all stations lying in the lower Indus plain, where the Jacobabad station showed a significant rising trend at 95% confidence interval, and the rainfall rose at the rate of about 4.5 mm/year during the study period. While over northern Balochistan, a rising trend was found at all selected stations, with a significant upward trend detected at the Zhob station, with the Sen's slope as +1.61 mm/year.

Apart from the summer monsoon rainfalls, the winter precipitation is also an important contributor to the annual total precipitation of the country (about 25-30%) and brings a good amount of precipitation over the Greater Himalayas, Western Highlands, Sub-montane region and northern Balochistan. In this study, an increasing trend of winter precipitation was found over the Greater Himalayas, Western Highlands, central Punjab, and northern Balochistan as shown in the Figure 8 (VII), where over the Greater Himalayas, the winter precipitation increased by about 10-30 mm, where the Gupis station observed a signficant rising trend with the Sen's slope as +0.83

mm/year at 95% confidence interval. Over the Western Highlands, the analysis showed a rise in the winter precipitation by about 100-250 mm as shown in Figure 8 (VII), where the rainfall increased significantly at the Peshawar, Kohat, and Parachinar stations, with the Sen's slope as +4.61, +4.28, and +7.91 mm/year respectively at 95% confidence interval. However, a declining trend of winter precipitation was found over the coastal belt, lower Indus plain, and the southern Punjab as shown in Figure 8 (VII). Conclusively, the annual mean rainfall was found to be increasing over the majority of the selected stations in the country, where the magnitude of increment was found to be highest over the Western Highlands for the annual as well as the seasonal scale. For the summer monsoon, a declining trend was found over the Greater Himalayas and the Sub-montane region, while the regions observed an increasing trend of winter precipitation that agreed with the study conducted by the Global Change Impact Studies Centre *(GCISC, 2009a)*.

Based on the results obtained from the above analysis, it can be stated that the annual and seasonal precipitation patterns in Pakistan have undergone significant changes during the last three decades. The rising summer monsoon precipitation patterns over the central and southern Punjab, Balochistan, Western Highlands, and the lower Indus plain, as witnessed by the recent summer monsoon trends, may favour the replenishment of freshwater resources, streamflows, rainfed agriculture, and meet the irrigation water demand with fewer freshwater withdrawals in the country. However, the increased intensity and amount of summer monsoon precipitation as observed during the last decade may also pose a potential threat of high rainfall-runoff inundation, which necessitates devising an effective runoff management practice over the areas. On the other hand, the rising winter precipitation patterns over the northern areas coupled with warming winter and spring seasonal temperatures (as found in this study) may result in high streamflows over the Upper Indus region, which may potentially threat the national water, infrastructure, and economic security of country in terms of intense flood events.

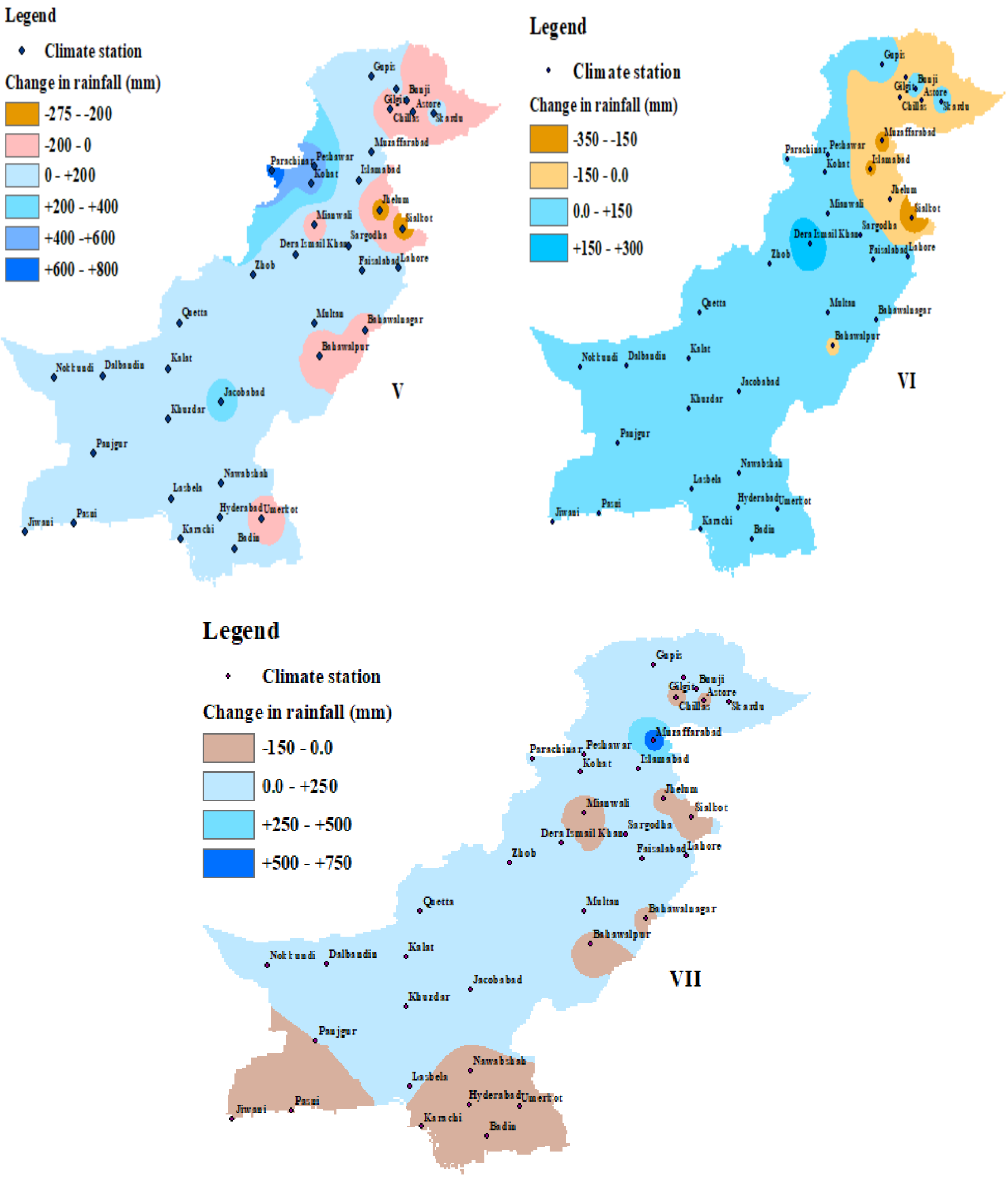

Figure 8: Magnitude of change in precipitation (mm) computed by Sen's slope method for (V) Annual (VI) summer monsoon (VII) Winter precipitation over the major climatic zones of Pakistan, 1990-2022.

4. Implication and Research Contributions

The study briefly enlightened the prevailing annual and seasonal climate patterns over the major climatic zones of Pakistan by employing the recommended statistical methods, using the latest available climate data, and incorporating the recent extreme meteorological and hydrological events that took place across the country, that provide in-depth information of the varying climate trends over the country on the temporal as well as on the spatial scale. The outcomes of the study are expected to help the policymakers and think tank of the country to devise an effective and holistic climate change adaptation policy and strategy for the country, and to protect and conserve the available natural resources (water resources to be more precise) and agriculture, and will also aid the research community by serving as a reliable benchmark to succeed the environment-serving research studies in future.

5. Conclusions

The annual and seasonal temperature and precipitation patterns over the major climatic zones of Pakistan were investigated in this study using the Mann-Kendall test and Sen's slope estimator method for the period 1990-2020. Based on the study outcomes, the following conclusions were reached:

1. The annual mean temperature is rising over the Greater Himalayas, Sub-montane region, central and southern Punjab, Balochistan, lower Indus plain, and the coastal belt of the country. However, the Western Highlands witnessed a downward trend in annual mean temperature. Spatially, the magnitude of annual and seasonal temperature rise was found to be higher over the southern and the coastal zones of the country, as compared to the northern areas.

2. Seasonally, the magnitude of warming was found to be highest for the spring season among all seasons over the country. For the spring season, the temperature over the lower Indus plain, southern Punjab, and Balochistan rose by about 1.0 to 3.0 °C, 0.6 to 1.8 °C over the Greater Himalayas, and by about 0.2 to 1.8 °C over the Sub-montane region. For the summer season, a declining trend of temperature was observed over the Greater Himalayas and Western Highlands, while the remaining zones showed an upward trend. For the winter season, a rising trend was found over the Greater Himalayas, northern and western Balochistan, the lower Indus plain, and the coastal belt of the country, whereas the remaining climatic zones observed a downward trend.

3. For the annual precipitation, a rising trend was found over the Western Highlands, lower Indus plain, central Punjab, and the coastal belt of the country, whereas mixed trends were found over the Greater Himalayas and Sub-montane region. On the seasonal scale, a downward trend of summer monsoon precipitation was found over the Greater Himalayas and the Sub-montane region, whereas the other climatic zones witnessed an upward trend, with the magnitude of rainfall rise highest over the Western Highlands. For winter precipitation, a declining trend was found over the coastal belt, southern Punjab, and the lower Indus plain, whereas the other climatic zones witnessed an upward trend of winter precipitation.

4. In a nutshell, the rising spring and winter seasonal temperatures coupled with increasing winter seasonal precipitation over the Greater Himalayas may result in increased melting of snowpack and glacial mass and consequently high glacier and snowmelt runoff over the Upper Indus region, thereby threatening the national water security. Further, the warming trends over the arid and semi-arid plains and the coastal belt of the country may result in increased heatwave events, and high domestic and agricultural water demand, thereby stressing the available freshwater resources in the country. On the other hand, the summer monsoon rainfall was found to be spatially shifted toward the north-western parts of the country. The rising summer monsoon precipitation patterns may favour the streamflows and the agriculture sector, but the high intensity and amount of precipitation may result in increased rainfall-runoff inundation. Thus, based on the findings about the prevailing climate patterns over the country, the formulation and adoption of an effective climate

change adaptation and mitigation strategy is recommended for the protection and conservation of the available natural resources in the country from the adversities of the global climate change.

5. For future works, the downscaled future climate projections over the major climatic zones can be used to assess the future possible climatic changes spatially in the coming decades over the major climatic zones of the country, for a better understanding of to cope with the coming environmental changes.

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Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

References

1. Setzer, J. and C. Higham, *Global trends in climate change litigation: 2022 Snapshot.* 2022.
2. Rasul, G., et al., *Climate Change in Pakistan: focussed on Sindh Province. Pakistan Metereological Department.* Research and Development Division, Technical Report No. PMD-25, 2012.
3. Pörtner, H.-O., et al., *Climate change 2022: Impacts, adaptation and vulnerability.* IPCC Sixth Assessment Report, 2022: p. 37-118.
4. Shah, M.I., et al., *Predicting hydrologic responses to climate changes in highly glacierized and mountainous region Upper Indus Basin.* Royal Society open science, 2020. **7**(8): p. 191957.
5. Sivakumar, M.V. and R. Stefanski, *Climate change in South Asia.* Climate change and food security in South Asia, 2011: p. 13-30.
6. Song, F., et al., *Trends in surface equivalent potential temperature: A more comprehensive metric for global warming and weather extremes.* Proceedings of the National Academy of Sciences, 2022. **119**(6): p. e2117832119.
7. Shah, S.M.H., et al., *Influence of forces on vehicle's instability in floodwaters.* Ain Shams Engineering Journal, 2018. **9**(4): p. 3245-3258.
8. Khahro, S.H., I.A. Chandio, and M.A.H. Talpur. *Data Preparation for GIS based Land Suitability Modelling: A Stepped Approach*. in *E3S Web of Conferences*. 2019. EDP Sciences.
9. Thackeray, C.W., et al., *Constraining the increased frequency of global precipitation extremes under warming.* Nature Climate Change, 2022. **12**(5): p. 441-448.
10. Khahro, S.H., et al., *Land suitability analysis for installing new petrol filling stations using GIS.* Procedia Engineering, 2014. **77**: p. 28-36.
11. Merabtene, T., M. Siddique, and A. Shanableh, *Assessment of seasonal and annual rainfall trends and variability in Sharjah City, UAE.* Advances in Meteorology, 2016. **2016**: p. 1-13.
12. Almazroui, M., *Rainfall trends and extremes in Saudi Arabia in recent decades.* Atmosphere, 2020. **11**(9): p. 964.
13. Zhongming, Z., et al., *Climate Risk Country Profile: Pakistan.* 2021.
14. Sheikh, M.M., et al., *Climate profile and past climate changes in Pakistan.* Global Change Impact Studies Center (GCISC)-RR-01, 2009.
15. Qureshi, A.S., *Groundwater governance in Pakistan: From colossal development to neglected management.* Water, 2020. **12**(11): p. 3017.
16. Salma, S., S. Rehman, and M. Shah, *Rainfall trends in different climate zones of Pakistan.* Pakistan Journal of Meteorology, 2012. **9**(17).
17. Risks, W.C., *Food Security Analysis: A Special Report for Pakistan. 2018*.
18. Yu, W., et al., *Hydrology and Glaciers in the Upper Indus Basin.* 2013.
19. Khan, A.J., M. Koch, and A.A. Tahir, *Impacts of climate change on the water availability, seasonality and extremes in the Upper Indus Basin (UIB).* Sustainability, 2020. **12**(4): p. 1283.

20. Rahman, K.U., et al., *Comparison of machine learning and process-based SWAT model in simulating streamflow in the Upper Indus Basin.* Applied water science, 2022. **12**(8): p. 1-19.
21. Yaseen, M., et al., *Spatiotemporal variability in the hydrometeorological time-series over Upper Indus River Basin of Pakistan.* Advances in Meteorology, 2020. **2020**.
22. Talpur, M.A.H., et al. *Time-Space Geography: A Creditable Transport Accessibility Measure for Rural Dwellers*. in *Applied Mechanics and Materials*. 2014. Trans Tech Publ.
23. Chandio, I.A., K.A. Rang, and M.A.H. Talpur, *Research Article Impact of the Pedestrian System on Environment and Individual Safety in MUET, Pakistan.* 2020.
24. Talpur, M.A.H., et al., *Computing travel impendences using trip generation regression model: A phenomenon of travel decision-making process of rural households.* Environment, Development and Sustainability, 2022: p. 1-24.
25. Chaudhry, Q.U.Z., *Climate change profile of Pakistan*. 2017: Asian development bank.
26. Gao, F., et al., *Trend analysis of rainfall time series in Shanxi Province, Northern China (1957–2019).* Water, 2020. **12**(9): p. 2335.
27. Latif, Y., M. Yaoming, and M. Yaseen, *Spatial analysis of precipitation time series over the Upper Indus Basin.* Theoretical and applied climatology, 2018. **131**(1): p. 761-775.
28. Agarwal, S., A. Suchithra, and S.P. Singh, *Analysis and Interpretation of Rainfall Trend using Mann-Kendall's and Sen's Slope Method.* Indian J. Ecol, 2021. **48**: p. 453-457.
29. Abdullah, A.Y.M., et al., *Extreme temperature and rainfall events in Bangladesh: a comparison between coastal and inland areas.* International Journal of Climatology, 2022. **42**(6): p. 3253-3273.
30. Alashan, S., *Combination of modified Mann-Kendall method and Şen innovative trend analysis.* Engineering Reports, 2020. **2**(3): p. e12131.
31. Ali, N., et al., *Trend analysis of precipitation data in Pakistan.* Sci Int, 2015. **27**: p. 803-808.
32. Ali, R., et al., *Long-term trends and seasonality detection of the observed flow in Yangtze River using Mann-Kendall and Sen's innovative trend method.* Water, 2019. **11**(9): p. 1855.
33. Karmeshu, N., *Trend detection in annual temperature & precipitation using the Mann Kendall test–a case study to assess climate change on select states in the northeastern United States.* 2012.
34. Khattak, M.S. and S. Ali, *Assessment of temperature and rainfall trends in Punjab province of Pakistan for the period 1961-2014.* Journal of Himalayan Earth Sciences, 2015. **48**(2): p. 42.
35. Moazzam, M.F.U., et al., *Trends of rainfall variability and drought monitoring using standardized precipitation index in a scarcely gauged basin of northern Pakistan.* Water, 2022. **14**(7): p. 1132.
36. Ali, R.O. and S.R. Abubaker, *Trend analysis using Mann-Kendall, Sen's slope estimator test and innovative trend analysis method in Yangtze river basin, China.* International Journal of Engineering & Technology, 2019. **8**(2): p. 110-119.
37. Mersin, D., et al., *Historical trends associated with annual temperature and precipitation in Aegean Turkey, where are we heading?* Sustainability, 2022. **14**(20): p. 13380.
38. Yue, S., et al., *The influence of autocorrelation on the ability to detect trend in hydrological series.* Hydrological processes, 2002. **16**(9): p. 1807-1829.
39. Mullick, M.R.A., et al., *Observed trends in temperature and rainfall in Bangladesh using pre-whitening approach.* Global and planetary change, 2019. **172**: p. 104-113.
40. Yue, S. and C.Y. Wang, *Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test.* Water resources research, 2002. **38**(6): p. 4-1-4-7.
41. Hajani, E., A. Rahman, and E. Ishak, *Trends in extreme rainfall in the state of New South Wales, Australia.* Hydrological Sciences Journal, 2017. **62**(13): p. 2160-2174.
42. Duy, V.V., S. Ouillon, and H.N. Minh, *Sea surface temperature trend analysis by Mann-Kendall test and sen's slope estimator: a study of the Hai Phong coastal area (Vietnam) for the period 1995-2020.* Vietnam Journal of Earth Sciences, 2022. **44**(1): p. 73-91.