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Original Research

A study of precipitation changes from 1990 to 2020 in the Leh district of Ladakh using Innovative Trend Analysis

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ABSTRACT

Precipitation plays the most important role in the hydrological cycle and water resource management in climate-sensitive regions. Identifying the long-term changes in precipitation is essential for understanding the regional climate dynamics. The innovative trend analysis (ITA) method was used to study the seasonal and annual trends in precipitation over the Leh district from 1990 to 2020. The ITA results showed a statistically significant negative monotonic trend in annual precipitation at -2.45 mm. On seasonal scale the ITA results showed significant monotonic decreasing trend in precipitation in spring (March-May) (-3.50 mm), winter (December-February) (-2.29 mm), and summer season (June-August) (-2.03 mm), however, the autumn season (September-November) showed non-monotonic insignificant decreasing trend (-0.05 mm). The winter and spring seasons contributed largely to the overall decline of precipitation. The High coefficients of variation in seasonal data indicate strong interannual variability, and the percentage bias values suggest deviations in seasonal precipitation behaviour. The results highlight a shift toward decline and erratic seasonal rainfall, which can have negative implications for water management in the region. Since the communities in the region depend on winter precipitation (snowfall) for water availability, artificial glaciers are the only adaptive measures to mitigate the water stress. Results from the present study can guide future initiatives aimed at mitigating the implications of changing precipitation on rural livelihoods and other sensitive ecosystems in the Himalayan region.

INTRODUCTION

Global warming is witnessed by scientific communities all over the world. The Intergovernmental Panel on Climate Change (IPCC) also informed global rise in temperature in their Fifth Assessment Report. Since the pre-industrial era, human activities have played a substantial role in warming the global temperature, which will continue to rise and affect climate dynamics (Masson-Delmotte et al. 2022; Ahmed et al. 2025; Pranto et al. 2024). The changes in climatic parameters are particularly noticeable in high-altitude mountainous regions such as the Himalayas, the Rockies, and the Alps. Climate change significantly impacts both natural environments and human societies (Monreal and Stotter, 2014; Hagedorn et al. 2019; Kohler et al. 2014). The Himalayan belt is facing abnormal changes in both temperature and precipitation (Singh et al. 2016; Kumar et al. 2024). As a result, these regions are highly exposed to extreme weather events like cloud bursts, short-term flooding and water shortages (Gautam et al. 2013; Ahsan et al. 2022; Pant et al. 2018; Norris et al. 2020). One of the most significant challenges in the 21st century is climate change (Abhumhadi et al. 2012), particularly the change in precipitation and its implications (Carter et al. 2021; Huq et al. 2015). The variability in precipitation significantly affects the sensitive ecological regions and particularly the livelihood of the communities in these regions. These communities are reliant on subsistence agriculture and glacier meltwater for irrigation. The abnormal pattern of precipitation and climate variability highlights the critical importance of the study of precipitation change in Ladakh, where the communities are severely dependent on snowmelt or glacier meltwater for agricultural and domestic purposes (Norphel and Tashi, 2015; Shaheen et al. 2013; Tuladhar et al. 2023; Khan et al. 2024). Numerous studies (Paul et al. 2017; Longobardi and Villani, 2010; Sayemuzzaman and Jha, 2014; Addisu et al. 2015; Gajbhiye et al. 2016; Asfaw et al. 2018; Gao et al. 2020; Pastagia and Mehta, 2023) have highlighted the rainfall variability across different geographical regions, employing both parametric and non-parametric methods. Some of the well-known techniques across climate change studies are the Mann-Kendall test, Sen's slope estimator, Spearman's rho, and linear regression methods. In these methodologies the data should be independent of each other and should be normally distributed but sometime data are not independent of each other and are serially correlated, (Moshfika et al., 2022; Aziz et al., 2003; Barua et al., 2013) therefore to address the limitations of serially correlated data, Sen (2012) introduced a novel trend analysis method which is innovative trend analysis (ITA) method. Various researchers in various fields have used this method and highlighted the advantages of using this method over traditional methods. It is the ability of this method that a sub-trend is also visible, which is not visible with the MK test or MMK test (Poddar et al. 2023). The applicability of this method is universal compared to the MK or MMK tests, making it an important methodology for trend detection in different contexts (Mallick et al. 2022; PZ and KV, 2021; Tosunoglu and Kisi, 2017).

In the study region, the communities are reliant on subsistence agriculture and pastoralism. Therefore, glaciers and snow-melting water play a major part in the sustenance of these communities in this cold desert environment (Gondhalekar et al. 2015; Nusser et al. 2019). The variations in precipitation patterns, particularly in the winter seasons (December to February), directly affect the availability of irrigation water in the sowing season (May and June) (Tuladhar et al. 2023). The region is also facing other hydrological challenges like cloud bursts and flash floods, particularly in August, affecting livelihoods (Kumar and Saizen, 2023; Tuladhar et al. 2023; Barrett and Bosak, 2018). Therefore, finding precipitation change in a longer timeframe (1990-2020) is necessary to comprehend the vulnerability of the study region to water shortages and intense climatic events. The objective is to find the temporal variations in precipitation from 1990 to 2020 and to find whether the trend is monotonic or non-monotonic, by employing the innovative trend analysis (ITA) method.

2. STUDY AREA

The study area is Leh district (Fig. 1), between the Karakoram and Zanskar ranges. Geographically, it stretches from 34°17' North latitude to 77°58' East longitude, at an average altitude of 3500 meters above sea level in the Trans-Himalayan region (Chevuturi et al. 2016). It is a cold, arid desert that receives little rainfall, particularly in the summer months, influenced by the Indian monsoon and snowfall in the winter, under western disturbances. The seasonal range of temperature is high in this region, during the winter season, the temperature drops to -28 degrees Celsius and rises to 35 degrees Celsius in the summer (Thayyen et al. 2013). The aridity of the region is attributed to its location within the rain shadow of high mountain ranges which have surrounded the district from all sides (Sant et al. 2011; Chevuturi et al. 2016; Juyal, 2014). Consequently, the vegetation in the region is limited to riverbanks and streams. Therefore, this region's rural communities rely on agriculture and livestock. The cultivation of Wheat and barley is carried out during the summer season, which is the major crop of the region. The locals also grow fruits like apricots, apples, and watermelons and vegetables like peas, potatoes, cabbage, and others during the summer months. Since the communities primarily depend on snow melt water, the winter precipitation plays a significant role in water availability for irrigation during the sowing period. Understanding the changing precipitation pattern and water availability is critical in this ecologically sensitive region.

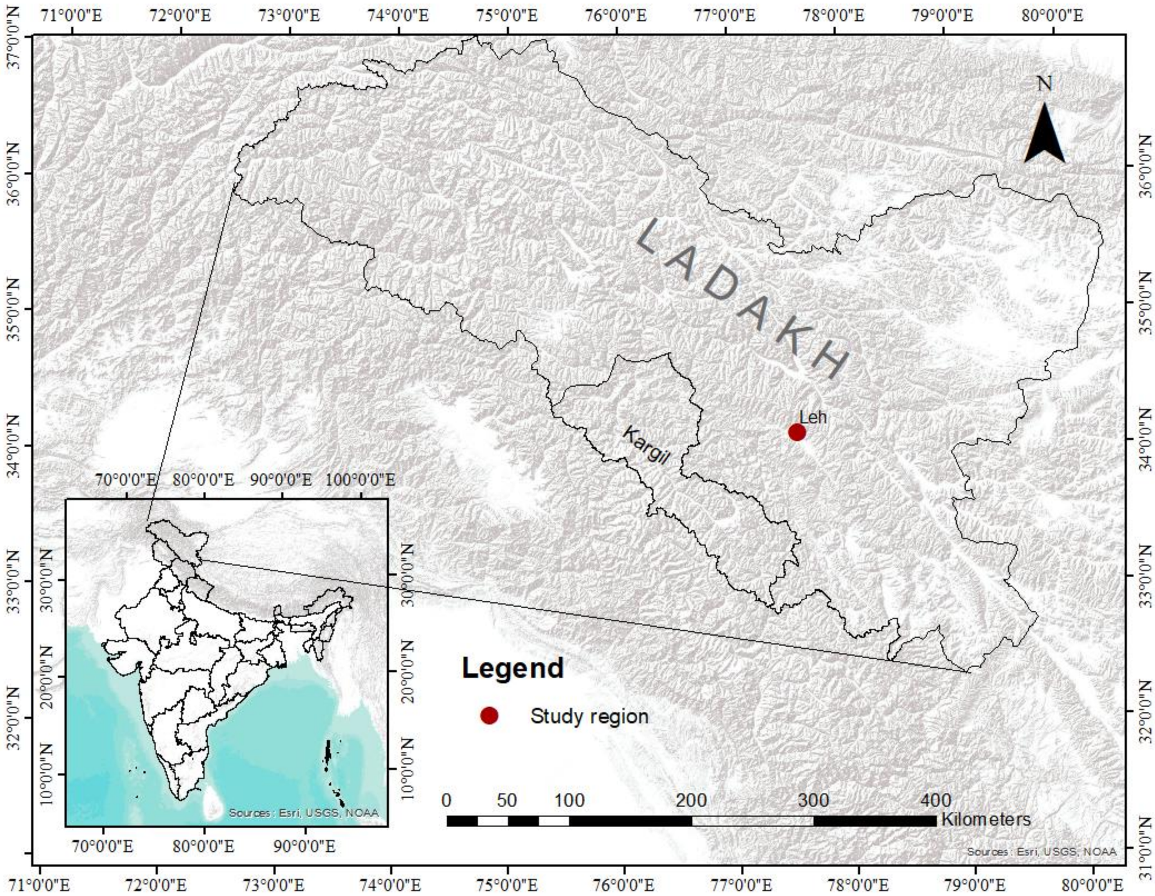


Figure 1: Map study area of the Leh district in Ladakh.

2. MATERIALS AND METHODS

2.1. Data sources

The IMD daily gridded datasets (0.25×0.25 degree) were collected from 1990 to 2020 to carry out this study. The data were collected using the Python console IMDLIB packages in QGIS software. After collecting the data for each year, the data was analysed to find the missing data. The multiple imputation method in SPSS software was used to substitute the missing data (Miro et al. 2017). The software is known for statistical analysis (Khalifeloo et al. 2015). The data was then used to find out the distinct trends in precipitation patterns over the last 30 years using the Innovative trend analysis (ITA) method.

2.2. Innovative trend analysis

In this study, the innovative trend analysis (ITA) method was used to find out the changes in precipitation over the last three decades, i.e. from 1990 to 2020, in the study region; this method was introduced by Sen (2012). Unlike traditional approaches such as the MK or mMK, the ITA works without assumptions regarding serial autocorrelation, normality, or record length (Caloiero et al. 2018). The ITA data from 1990 to 2020 was separated into two equal parts, i.e., the first half from 1990 to 2004, and the second half from 2005 to 2020, then these data were organized in an ascending order. After organizing the data, we used the Cartesian coordinate system and plot the first half data (1990-2004) on the X-axis (horizontal) and the other half data (2005-2020) on the Y-axis (vertical) (Singh et al., 2021; Caloiero, 2020; Wang et al. 2020) to create the scatter plot. The ITA method helps in visualizing the trend in the data. A diagonal 45° line (1:1 line) was drawn on the scatter plot (Fig. 2) to represent trendless or no trend. If the data points aggregate on the 45° line, then it signifies trendless, and if the scatter points aggregate above the 45° line, then it indicates an increase in trend (Fig. 3), and if the data points aggregate below the 45° line, then it signifies a decrease in trend (Sen, 2012). The distance of scatter points from the 45° line serves as a degree of magnitude of the trend, i.e. the trend is either monotonic or non-monotonic (Figure 3).

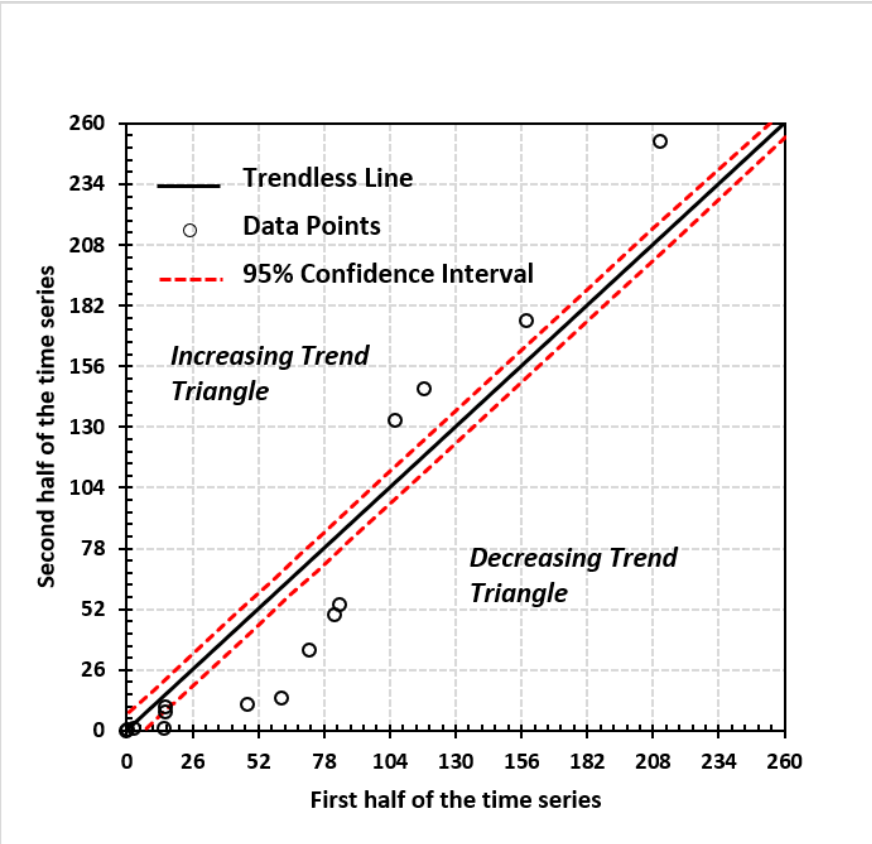


Figure 2: Illustration of increasing trend and decreasing trend triangle and trendless line (45°) of ITA.

To provide the indicator for trend analysis, the standardization of average variation was necessary. It involves multiplication of the indicator by 10 to facilitate interpretation. The representation of the innovative trend analysis is defined as (Equation I):

$$\boldsymbol{B} = \frac{1}{n}\sum_{i=1}^{n}\frac{10(y_i - x_i)}{\bar{X}} \qquad \text{I}$$

The first and second-half data are denoted by yi and xi, respectively (Equation II). Additionally, X represents the first half's mean, while B is a trend indicator. A Positive B value signifies a positive trend (Increasing trend) in the data, whereas a negative B value signifies a negative trend (Decreasing). In cases where the original time series data exhibits anomalies, the initial observation is excluded before dividing it into two halves. This exclusion ensures that the more recent data from the series is fully utilized for analysis.

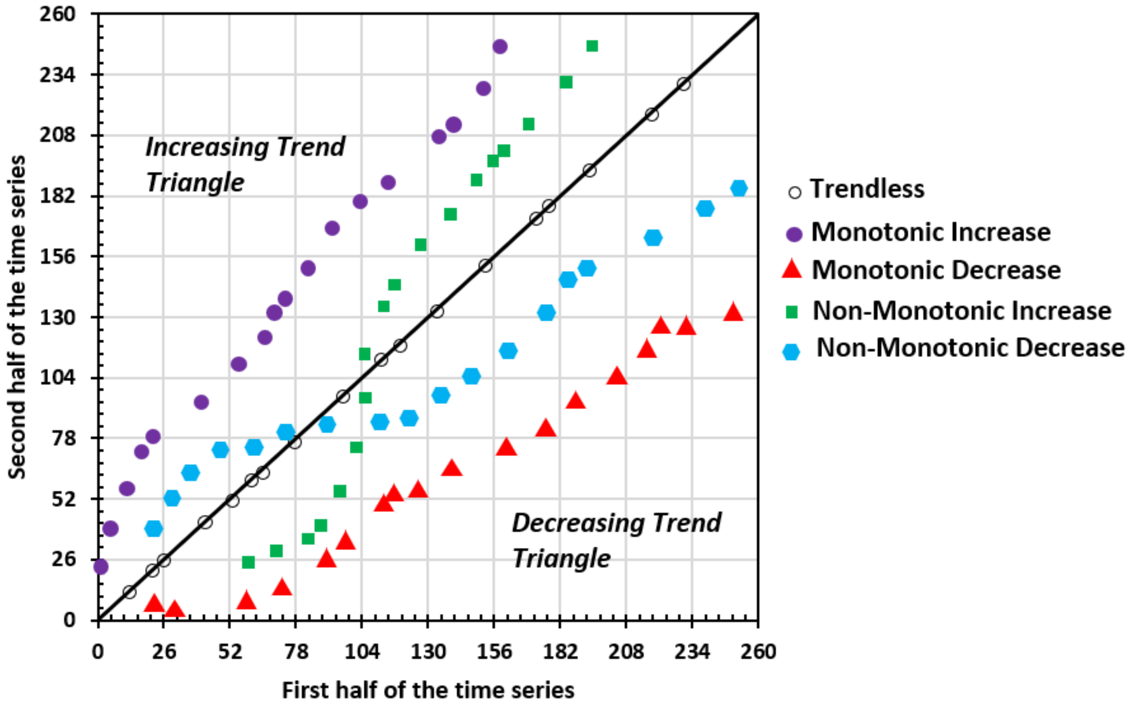


Figure 3: Illustration of monotonic and non-monotonic trends.

2.3. Percent Bias

Percent Bias approach (Equation II) is widely utilized to find out the percentage change in the time series between two halves. (Poddar et al. 2023; Das et al. 2021; Mandal et al. 2021).

$$PB = 100 - \sum_{i-1}^{n}\frac{R_i}{M_i} \times 100 \qquad \text{II}$$

where *PB* denotes Percent Bias, while *n* stands for the total data series. *Mi* and *Ri* denote the values which were found in the first half and second half data series. An upward trend in data is shown by positive scores and a downward trend in the data is shown by negative scores.

3. RESULTS

3.1. Annual and monthly precipitation

Monthly and annual precipitation data for 1990–2020 in the Leh district show significant temporal variability (Table 1; Figure 6). The Monthly precipitation showed wide-ranging values, with mean precipitation varying from as low as 12.74 mm in October to a high of 82.72 mm in August. August also recorded the highest monthly maximum precipitation (730.43 mm), highlighting its importance as the major contributor to the annual rainfall budget. Other months with relatively higher average precipitation included March (58.69 mm), February (50.98 mm), and July (44.13 mm), while minimal precipitation was observed during June (20.95 mm), November (17.03 mm), and October (12.74 mm).

The standard deviation (SD) values reflect the dispersion of precipitation events, with the most significant variability again observed in August (158.95 mm), followed by March (86.98 mm) and February (73.38 mm). These variations point toward the irregular and erratic nature of precipitation events in the region. The coefficient of variation (CV), which represents relative variability, was remarkably high in nearly all months, notably in January (4584.14), February (3221.76), and March (2809.79), indicating extreme variation in precipitation from year to year. Positive skewness was observed in all months, suggesting that precipitation events were typically lower than the mean, with occasional extreme rainfall or snowfall events. November (3.41), May (2.24), and August (2.90) exhibited the highest skewness values, indicating the presence of infrequent but intense events. Similarly, high kurtosis values in these months particularly in November (11.06), August (9.29), and May (5.60) further confirm the leptokurtic nature of the precipitation distribution, implying a sharp peak and heavy tails.

The analysis of annual precipitation adds further understanding into the long-term climatic behaviour of the region. The mean annual precipitation during the 30-year period was 461.73 mm, with a substantial standard deviation of 537.19 mm. The high variability is evident in the coefficient of variation (CV = 1.16), and the positively skewed distribution (skewness = 2.44) indicates that most years experienced below-average precipitation, interrupted by occasional years of high precipitation. The kurtosis value of 0.92 suggests a platykurtic distribution at the annual scale, with a flatter peak and thinner tails compared to the more leptokurtic monthly distributions.

Table 1: Statistical analysis of precipitation (MM).

Months	Min	Max	Total	Mean	SD	CV	Skewness	Kurtosis
Jan	0	260.27	1313.15	42.36	67.71	4584.14	1.93	3.20
Feb	0	224.50	1580.25	50.98	73.38	3221.76	1.38	0.49
Mar	0	282.06	1819.51	58.69	86.98	2809.79	1.29	0.41
Apr	0	176.93	1242.70	40.09	59.39	2605.11	1.28	0.05
May	0	202.29	851.18	27.46	46.72	2718.08	2.24	5.60
Jun	0	135.09	649.48	20.95	32.71	1274.63	2.04	4.04
Jul	0	264.26	1368.03	44.13	70.22	2253.57	1.99	3.24

Aug	0	730.43	2564.40	82.72	158.95	2867.09	2.90	9.29
Sep	0	197.43	1102.08	35.55	52.73	1453.28	1.75	2.44
Oct	0	96.22	395.01	12.74	22.68	733.93	2.27	5.43
Nov	0	189.20	527.95	17.03	45.27	-50.75	3.41	11.06
Dec	0	186.33	899.79	29.03	58.43	935.77	2.13	3.08
Annual	0	1764.22	14313.53	461.73	537.19	1.16	2.44	0.92

3.2. Innovative trend analysis of annual precipitation

Figure 4 shows the innovative trend graph of annual precipitation trends. The analysis reveals a consistent and statistically significant decreasing monotonic direction in annual precipitation. The observation indicates this that most data points lie below the 45° line, indicating a deviation from a constant trend. Moreover, most of the data points fall below the 5% confidence interval, providing further evidence of the significance of the observed trend. Specifically, the innovative trend analysis indicates a monotonic decreasi20ng trend in annual precipitation, with a notable negative slope. The calculated slope represents a decrease of approximately -2.45 mm in annual precipitation. The percent bias analysis also shows a substantial 49% change in annual precipitation.

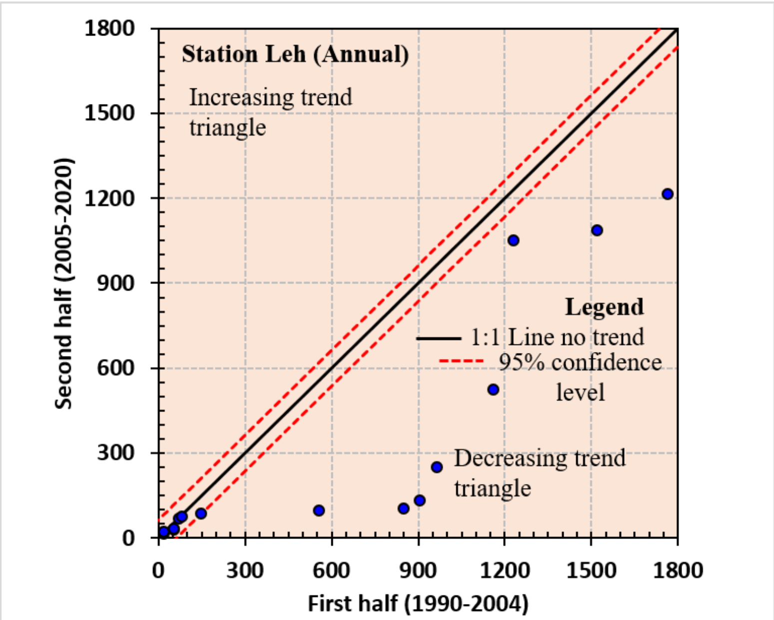
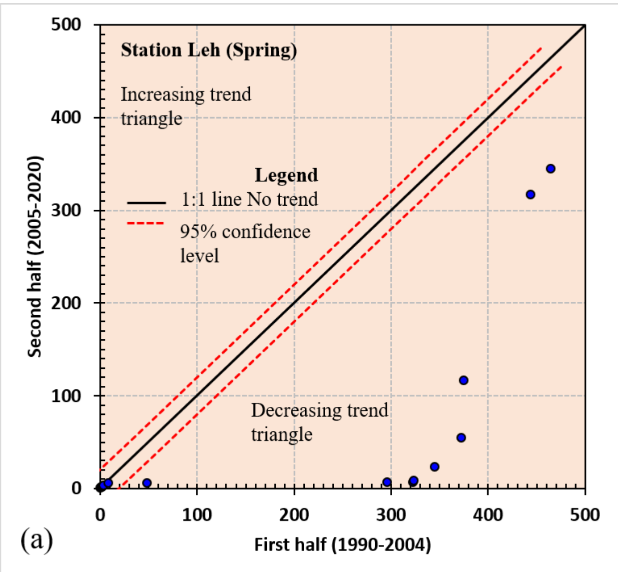


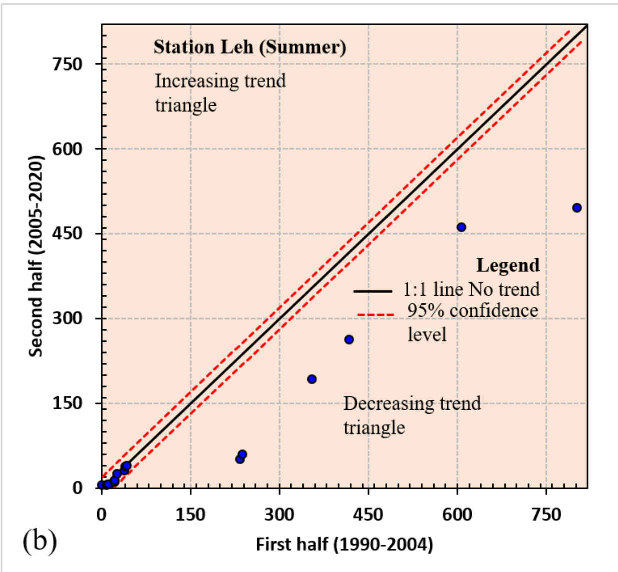
Figure 4 : ITA plot showing the annual precipitation (MM)

3.3. Seasonal precipitation

The seasonal variability of precipitation was different in different seasons. In Figure 5a, the scatter plot of spring season precipitation, the data points lie predominantly below the 45 °line, signifying a decreasing monotonic trend in spring precipitation. This observation is consistent with a negative trend in spring precipitation. Moreover, the majority of data points fall below the 95% confidence interval, suggesting statistical significance at a 95% confidence level. The percent bias calculation reveals a substantial 70.01% change in precipitation levels in our analysis.

This significant decrease highlights the importance of understanding and addressing shifts in precipitation patterns. Furthermore, the slope analysis yielded a -3.50 mm decrease in spring precipitation. This finding further supports the observed downward trend in spring precipitation levels, highlighting potential impacts on water resources. In Figure 5b, the distribution of precipitation during the summer season is presented. The data points representing precipitation levels consistently fall below the 45° line, inside the decreasing triangle. The scattering of data points indicates a noticeable declining trend in precipitation from 1990 to 2020. The trend appears monotonic, characterized by a consistent decline without significant fluctuations. Furthermore, statistical analysis reveals that the trend falls below the 5% confidence interval, confirming its significance with high statistical certainty. A notable 40.45% change in precipitation was observed after calculating the per cent bias. Specifically, there was a decrease of -2.03 mm in precipitation during the summer season, as determined by the slope analysis. These findings provide evidence of a significant and monotonic reduction in summer precipitation levels. The scatter plot in Figure 5c illustrates the precipitation trends during the autumn season. We identified a non-monotonic trend, characterized by the dispersion of data on both sides of the 45° line. This pattern shows variability in precipitation levels rather than a consistent directional trend. We calculated a percent bias of 1.07 upon further examination, indicating a minimal deviation from the expected precipitation values. Additionally, utilizing equation 5 to calculate the slope of the trend, we observed a slight decrease in autumn precipitation. Specifically, the calculated slope revealed a decrease of -0.05 mm in precipitation.





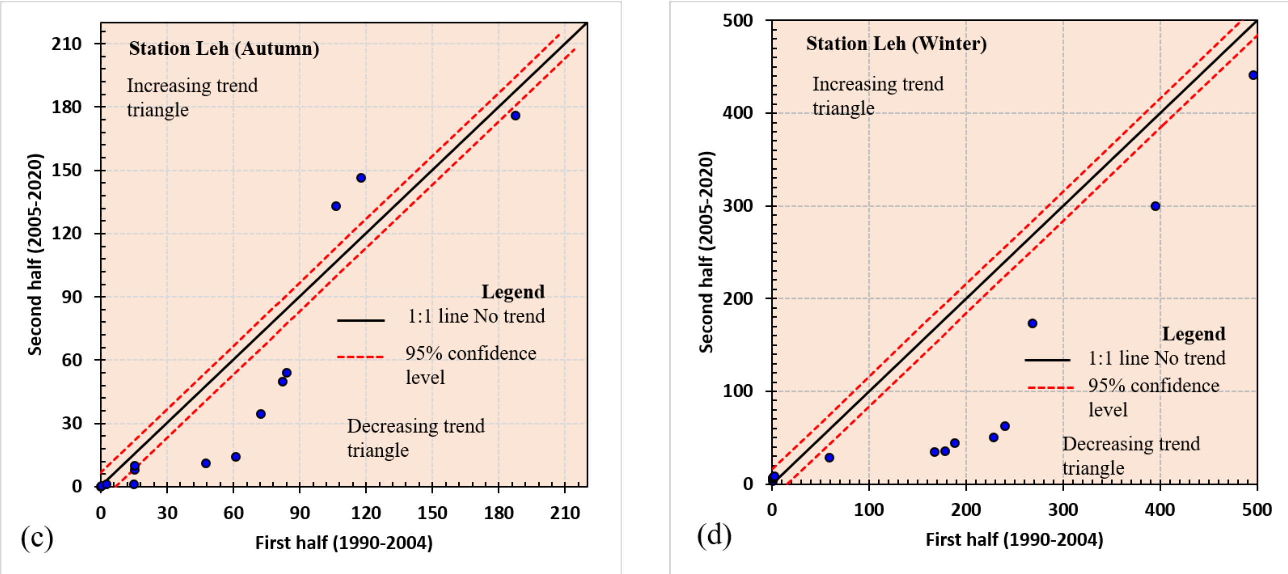


Figure 5: a. plot showing the spring precipitation (MM), b. ITA plot showing the summer precipitation (MM), c. ITA plot showing the autumn precipitation (MM), d. ITA plot showing the winter precipitation (MM)

Figure 5d illustrates the winter precipitation trend analysis, where the data points consistently fall in the decreasing triangle. This suggests a noticeable declining trend in winter precipitation from 1990 to 2020. Furthermore, statistical analysis reveals that this trend is monotonic, with a high confidence level. Most data points lie below the 5% confidence interval, which shows the trend's 95% confidence level. In addition to trend analysis, we computed the percent bias of the precipitation trend, revealing a substantial 45.77% change in winter precipitation over the years. Also, the slope identification yielded a -2.29 mm decrease in winter precipitation, signifying a consistent decline. The present study specifies that the significant changes in precipitation occur during the spring and winter, with a high percentage of change observed in these periods. The significant decrease in precipitation highlights the potential for future water shortages in the region if current trends persist. The variability of the trend highlights the demand for practical measures to address water-related implications and adaptation strategies in Leh, particularly in rural areas.

Table 2: Statistical outcomes of annual and seasonal precipitation

Climatic variable	Precipitation				
	Spring	Summer	Autumn	Winter	Annual
Minimum	0.00	0.00	0.00	0.80	15.49
Maximum	464.44	801.77	367.44	495.93	1765.22
Mean	126.24	147.80	65.32	118.58	461.73
SD	168.5	210.5	83.8	141.6	537.19
CV	8133.0	6395.3	2136.5	7411.2	1.16
Slope of Innovative trend	-3.50*	-2.03*	-0.05	-2.29*	-2.45*
Percent Bias (%)	70.01	40.45	1.07	45.77	49.00
Innovative trend pattern	#	#	##	#	#

* Statistically significant trends at the 95% confidence level
# Monotonic decreasing trends

Non-Monotonic decreasing trends

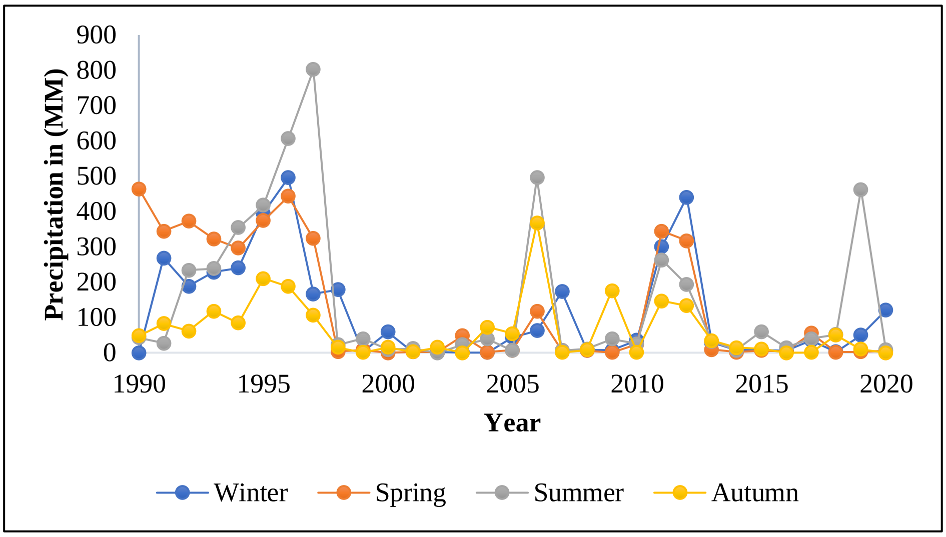


Figure 6: Annual and seasonal precipitation over 1990 to 2020

4. Discussion

The application of innovative trend analysis (ITA) method exhibited significant trends in both seasonal and annual precipitation in the study region (Figure 4 and Figure 5). The results show that the region is experiencing a decreasing trend in precipitation across the year, suggesting a shift in precipitation patterns over time. Statistically significant monotonic decreasing trends dominate the seasonal scale in spring, summer, and winter, with the highest decline observed in spring. The annual precipitation also shows significant declining trend in precipitation, suggesting a long-term dry condition. Among the four seasons, summer and spring shows significant declines, with slopes of –2.03 mm/year and –3.50 mm/year respectively, both statistically significant at the 95% confidence level. The high percent bias values in spring (70.01%) and summer (40.45%) support the degree of deviation from the baseline mean, signaling increasing unpredictability in seasonal precipitation. The winter also shows a significant decreasing trend (–2.29 mm/year) in precipitation, which could have major implications for accumulation of snow and availability of irrigation water during sowing season of May and June (Tuladhar et al. 2023; Kumar and Saizen, 2023; Namgyal et al. 2025; Paljor and Murari, 2022). Shafiq et al. (2016) studied the precipitation pattern change from 1901 to 2000 and reported distinct trends compared to our findings, they found a negative trend in summer precipitation and positive trend in late winters precipitation which is not the case in our study, the differences could be the results of application of different methods of analysis and scale of study period. However, the results of present study align with previous studies, such as Chevuturi et al. (2018); Angmo and Mishra (2009); Ahmad et al., (2018), they also observed declining trend in precipitation in the study region. Chevuturi et al. (2018) employed many datasets to compare the monthly and daily precipitation trends. They observed varied precipitation trend among the datasets and interpreted that there was a decline in precipitation before 1970s and increase in precipitation after 1970s till 1995 and again declining precipitation after 1995 to 2012. Angmo and Mishra (2009) analyzed the meteorological data of the Leh town from 1973 to 2008 and observed declining trend in precipitation from November to March, they also validated the results from the local communities. The results of Angmo and Mishra (2009) align particularly with our results of decline in precipitation in winter and spring season. The decline in winter precipitation was also reported by Vinod and Mahesha (2024). Singh and Bhatla (2024) studied precipitation change in the region across nine decades and three tricades and found decreasing trend in precipitation from 1962 to 1991 and 1992 to 2021, which is similar to the results on decreasing trend in precipitation from 1990 to 2020. The decrease in precipitation in the region particularly during winter and spring seasons can have broader implications for water resources and livelihood of the communities, since the local population are solely depended on snow and glacier melt water for irrigation. Artificial glaciers and community-based water managements strategies need to be strengthened to minimize the negative implications of water shortages (Paljor et al., 2022; Muller et al., 2020; Namgyal and Sarkar, 2023; Namgyal et al., 2025). While ITA has showed both monotonic and non-monotonic trends, limitations still remain. The analysis relies solely on gridded datasets, (0.25×0.25 degree) which can be improved with higher resolution datasets, which may not fully represent the variability, especially in topographically diverse landscapes of Leh region. Additionally, no station data were analysed and compared, which may further clarify the observed changes in precipitation. Future research should focus on integrating station datasets and examining correlations with atmospheric drivers and runoff modelling.

5. Conclusions

Significant monotonic decreasing trends were found in spring, summer, and winter, while autumn showed a non-monotonic decreasing trend. The annual trend, though statistically significant, displayed subtle nonlinearity, indicating occasional deviations from the broader drying trend. the observed decline in precipitation particularly in critical growing and recharge seasons demands for the integration of these trends into regional water management strategies, agricultural planning, and climate adaptation policies. In future research should incorporate station spatial datasets, explore relationships with atmospheric circulation indices, and integrate socio-ecological vulnerability assessments to support the climate resilience planning in the region.

6. Key takeaways for stakeholders

- The precipitation in the region is steadily decreasing threatening water security and subsistence agriculture.
- The policy makers and stakeholders must act on early signals of climate stress, particularly in regions where communities are dependent on snow-dependent.

Author Contributions:

P. N.; Writing – original draft, Software, Methodology, S. S.; Writing – review & editing, Investigation, R. K.; Writing – review & editing. Supervision.

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Conflicts of Interest:

The authors declare no conflicts of interest.

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