




Temporal Analysis for Detection of Anomalies in Precipitation Patterns over a Selected Area in the Indus Basin of Pakistan

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Abstract—For efficient adaptation strategies, investigation of the variability in climatic data and its impact on meteorological drought is critical, particularly in semi-arid and arid regions. Innovative trend analysis (ITA), Mann–Kendall (MK) and Sen’s slope estimator (SSE) tests were employed to analyze the variations in precipitation (1981–2018) on annual, seasonal and monthly scale across 12 meteorological stations over the selected areas of the lower Indus basin (LIB) of Pakistan. The reliability of the ITA method was also compared and analyzed with both MK and SSE methods for 48 seasonal precipitation times series. Annual precipitation results indicated a significant increasing trend, i.e., 2.09 mm/year, at only one station (Rahim Yar Khan (RYK)-Khanpur), with MK test statistic $Z_{mk} = 2.09$ and Sen’s slope estimator $\beta = 2.56$. On a monthly scale, the maximum number of positive significant trends were noted during June, with Z_{mk} values of 2.01 to 3.24 and β values of 1.06–3.06, while the maximum number of negative trends was found during January, February, November and December. On a seasonal scale, ITA methods showed significant increasing trends during the summer at 12 selected meteorological stations, with trend indicator (B) values ranging from 0.22 to 2.46. Moreover, performance of the ITA method was found to be consistent with both MK and SSE test results at a verified significance level. The results of the study can help to increase our understanding of the annual, seasonal and monthly precipitation variability in the LIB that may be helpful in developing strategies for the proper management of water resources over the area.

Keywords: Climate change, precipitation variability, LIB, trend analysis, water resources management.

1. Introduction

Precipitation is an important hydrometeorological factor. Over the past few decades, as a result of the changing climate (Haider et al. 2020; Zaman et al. 2017, 2018a, b), variation in precipitation patterns has gained considerable attention in different parts of the world (Ahmad et al. 2014; Latif et al. 2018; Yang et al. 2012; Zaman et al. 2018a, b; Zhao et al. 2019). The variation in precipitation may have a substantial impact on society. Similarly, the change in precipitation patterns may directly affect the hydrological cycle that can ultimately result in extreme events such as more frequent floods and droughts. These extreme events may also influence the agricultural water supply, stormwater drainage, energy production and so on (Huang et al. 2018; Srivastava et al. 2015). It is further observed that the precipitation frequency and strength may be different for the same magnitude of precipitation (Trenberth 2011). Various researchers have noted an increased intensity and frequency of extreme precipitation events at the global and regional scale (Zaman et al. 2020). Therefore, there is an urgent need for the investigation of long-term precipitation trends for accurate assessment of water resources, drought and flood control, efficient water management and a comprehensive understanding of climate change (Huang et al. 2013, 2018).

Various studies have reported the detection of trends in hydrometeorological time series on monthly, seasonal and annual scale using various parametric and nonparametric tests (Chen et al. 2017; Djaman et al. 2017; Pingale et al. 2016). The MK and SSE tests are the two most used nonparametric tests

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for analyzing the trends of hydrometeorological time series. Similarly, the MK test and Theil–Sen's slope estimator were applied for the Giridih district in Jharkhand, India, to analyze the long-term precipitation trends, and revealed a significant positive trend during the winter season and a significant decreasing trend during the monsoon season (Kumar et al. 2016). In the South Australian region, MK and Spearman's rho (SR) tests and a linear regression technique were used to investigate the variability in precipitation, and indicated increasing trends during spring and summer, and decreasing trends during winter and autumn (Chowdhury et al. 2015). In China, variations in precipitation, evapotranspiration and runoff were analyzed using the MK test over the Heishe River Basin (Zang and Liu 2013). The MK, Theil–Sen approach and sequential MK test were also used in the Langat River Basin, Malaysia, to study the variation in precipitation, and it was found that the oscillation of up to 4 years influenced the total annual and seasonal precipitation series over the study area (Palizdan et al. 2017). The innovative trend analysis (ITA) method (a recently developed technique) was successfully used to analyze the trends in hydrometeorological time series to enable better management of water resources (Onyutha 2016; Wu and Qian 2017).

The trends of air temperature and heat waves were detected over northwestern Mexico by applying linear data adjustment, SR and ITA tests (Martínez-Austria et al. 2016). Now, the ITA test is being used extensively with reliable results, so the method has universal applicability due to its non-dependency over some restrictive assumptions as required in MK and SR tests. Mean monthly precipitation trends were detected using the ITA test over the Macta watershed in Algeria during 1970–2011, and the results indicated increasing and decreasing trends at northern and southern parts of the study area, respectively (Elouissi et al. 2016). The modified MK test and ITA method were used in the Coruh River Basin, Turkey, to analyze the trends in maximum hydrological drought variables, and showed consistent results as increasing and decreasing trends by both methods at various stations (Tosunoglu and Kisi 2017). The Intergovernmental Panel on Climate Change (IPCC) reported that increasing trends in precipitation,

including monsoon rainfall, will be seen in Central Sahel by the end of this century due to an expansion of the West African monsoon (IPCC 2012). Similarly, in the Indus valley of Pakistan, glacier melt along with precipitation and temperature variability has shown varying effects on river flows (Cheema et al. 2014; Muhammad Qasim 2013). At the same time, the lower Indus basin (LIB) is a generally arid and hyper-arid region and mainly depends upon the water supply of rivers flowing from the upper Indus plain (Hasson et al. 2014).

Various studies have been conducted on precipitation trend analysis and reported that the variability in precipitation is high on interannual and intraseasonal scales over the Indus plain of Pakistan. Latif et al. (2018) used the MK test to investigate the variations in annual and seasonal precipitation data over the upper Indus River basin in Pakistan, and decreasing trends were found in the region. Similarly, MK and SR tests were employed to detect variability in precipitation across the basin of the Swat River of Pakistan, and a maximum quantitative increase in precipitation and consistency was found in the performance of MK and SR tests (Ahmad et al. 2015). The decreasing trend in mean annual precipitation has also been observed over the coastal and arid regions (Farooqi et al. 2005). A significant warming trend with no change in precipitation was observed in the middle and lower part of the Indus plain (Ahmad et al. 2014). An increasing trend of annual precipitation at four stations and a decreasing trend at two stations in the southeast region of the upper Indus plain were observed by Ahmad et al. (2018a, b). In another study, Khattak et al. (2011) found inconsistent precipitation trends over the upper Indus River basin between 1967 and 2005. The abovementioned studies showed that the precipitation trends deviate from each other in terms of change and sometimes even direction because of the different time periods under investigation. Therefore, it is critically important that analysis of trends in precipitation be carried for different time periods to determine the future direction for water resources management.

However, most of the abovementioned studies investigated the precipitation variability over the upper Indus River basin, whereas precipitation variations in the lower reaches of Indus plains have

seldom been investigated. Moreover, to the best of the authors' knowledge, no study has been conducted for the LIB by using ITA methodology to study the variability in low, median and high values. Therefore, the precipitation variability in annual, seasonal and monthly time series was investigated over the selected area of lower Indus basin (LIB) in Pakistan using MK, SSE and ITA methods. To evaluate the reliability of the methods applied, results of the ITA test were also compared with the other two methods.

2. Study Area

The Indus Basin has a total area of 1.12×10^6 km², distributed between Pakistan, India, China and Afghanistan. The plain extends from the Himalaya mountains towards the north to the dry alluvial plains of the Sindh province of Pakistan in the south and eventually flows out into the Arabian Sea. In Pakistan, the Indus River Basin comprises about 520,000 km² (65% of the territory), including the province of Punjab, Khyber Pakhtunkhwa (KPK), most of Sindh province and some of the eastern part of Baluchistan. The climate on the lower Indus plain is divided into arid and semi-arid. The Indus plain in Pakistan is divided into upper Indus plain and lower Indus plain. The lower Indus basin is delimited by the Kirthar fold belt basin in the west and central Indus basin towards the north. The central Indus basin mainly consists of three units, i.e., Sulaimon fold belt, Sulaimon depression and Punjab Platform (Jadoon et al. 2020). The mean monthly temperature from December to February is normally 14–20 °C, whereas during March to June it is about 42–44 °C. The study area for this research consisted of 12 meteorological stations, selected carefully over the LIB (Fig. 1). The length of the precipitation data period ranged between 1981 and 2018. Details of selected stations with respect to name, data period, height from sea level and average annual precipitation are shown in Table 1. The precipitation time series data of selected stations were collected from the Computerized Data Processing Centre (CDPC), Pakistan Meteorological Department (PMD). To ensure reliability in determining the precipitation trend, meticulous data quality was mandatory. Therefore, the data quality

check and homogeneity check were carried out using numerous control approaches as explained by Zaman et al. (2020).

3. Methodology

Trend analysis involved assessing the trends of change (increasing or decreasing) or no change in a different meteorological parameter. Different methods can be used to examine the trends in hydro-climatic factors. Before the selection of any method for calculating trends, it is necessary to consider the parameters of the data, e.g., type of data, arrangement of data, sample distribution, possible kinds of trends that exist (monotonic or stepwise) and existence of continuous and seasonal variations (Cluis et al. 1989). For the present study, the trend detection in time series precipitation data (1981–2018) was performed at selected meteorological stations over the LIB. The names of meteorological stations were Multan, Dera Ghazi Khan (DG Khan), Bahawalpur, Bahawalnagar, Rahim Yar Khan (RYK)-Khanpur, Rohri, Sibbi, Larkana, Hyderabad, Badin, Karachi (AP) and Lasbella (Table 1). Nonparametric tests (MK and SSE) were used for trend detection in precipitation data because parametric test conditions can never be completely fulfilled. Moreover, nonparametric tests are highly effective even for the data having non-symmetrical distribution. These tests can also be used for seasonally variable data (Daughney and Reeves 2006; Farid et al. 2019). Furthermore, the properties of scientific phenomena such as hydrological processes are generally dynamic with non-normal distributions in nature. However, time series data must be without serial correlation before the application of the MK test (Ahmad et al. 2015; Yue et al. 2002). To overcome serial correlation, an ITA technique that is free from such restrictions is efficiently used for trend analysis. Şen (2012) employed and compared the ITA technique with the other two methods (Fig. 2). Moreover, the trends in precipitation time series from 1981 to 2018 were analyzed at $\alpha = 0.1$, $\alpha = 0.05$ and $\alpha = 0.01$ level of significance using the MK, SEE and ITA methods (Asfaw et al. 2018; Caloiero et al. 2020; Kukal and Irmak 2018; Saini et al. 2020). However, $\alpha = 0.1$ was considered

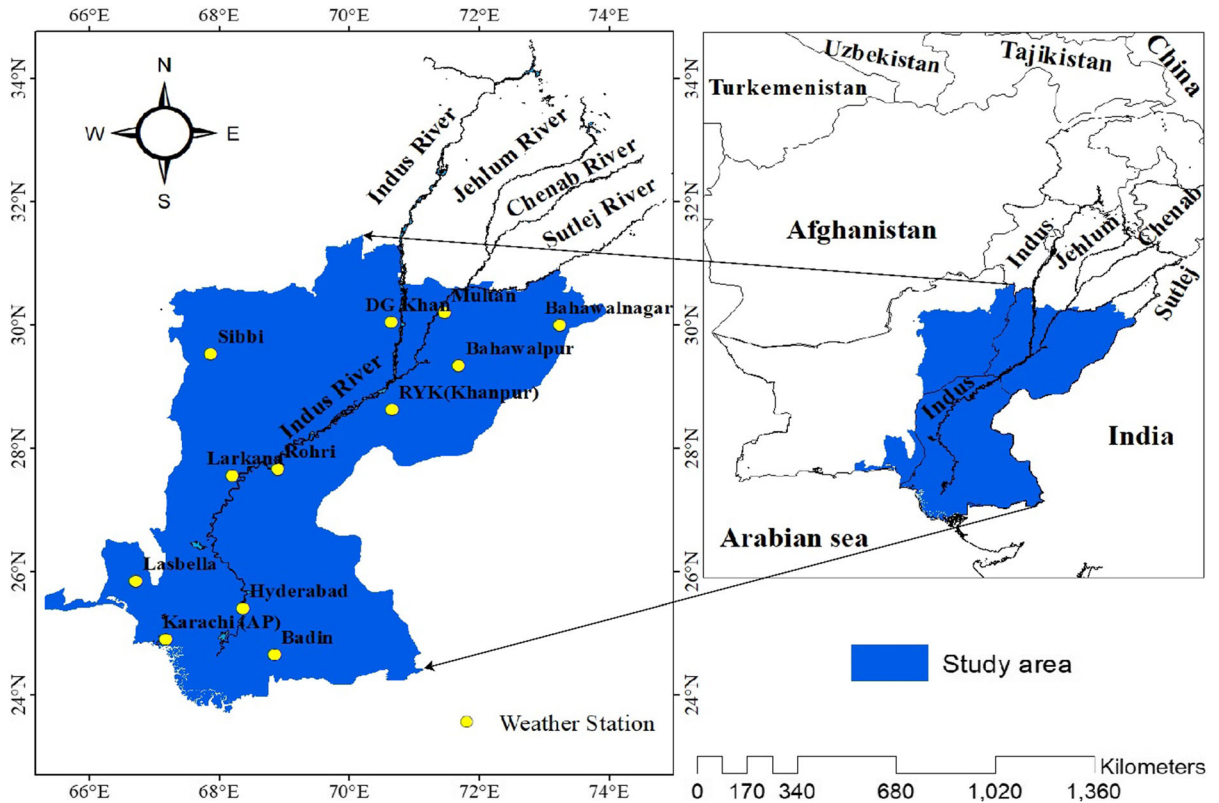


Figure 1
Location of selected meteorological stations

Table 1

Summary of basic geographic characteristics, data ranges and average annual precipitation

Sr. no.	Station	Latitude (dd)	Longitude (dd)	Data Period	Elevation (m)	Average precipitation (mm)
1	Multan	30.20	71.47	1981–2018	127	212.16
2	DG Khan	30.05	70.65	1981–2018	125	233.73
3	Bahawalpur	29.35	71.69	1981–2018	118	177.95
4	Bahawalnagar	30.00	73.24	1981–2018	157	260.75
5	RYK-Khanpur	28.63	70.66	1981–2018	90	168.99
6	Rohri	27.67	68.90	1981–2018	62	96.90
7	Sibbi	29.54	67.87	1981–2018	132	183.90
8	Larkana	27.56	68.20	1981–2018	55	114.60
9	Hyderabad	25.40	68.36	1981–2018	29	164.97
10	Badin	24.65	68.85	1981–2018	11	224.40
11	Karachi (AP)	24.90	67.17	1981–2018	35	157.64
12	Lasbella	25.85	66.71	1981–2018	145	161.25

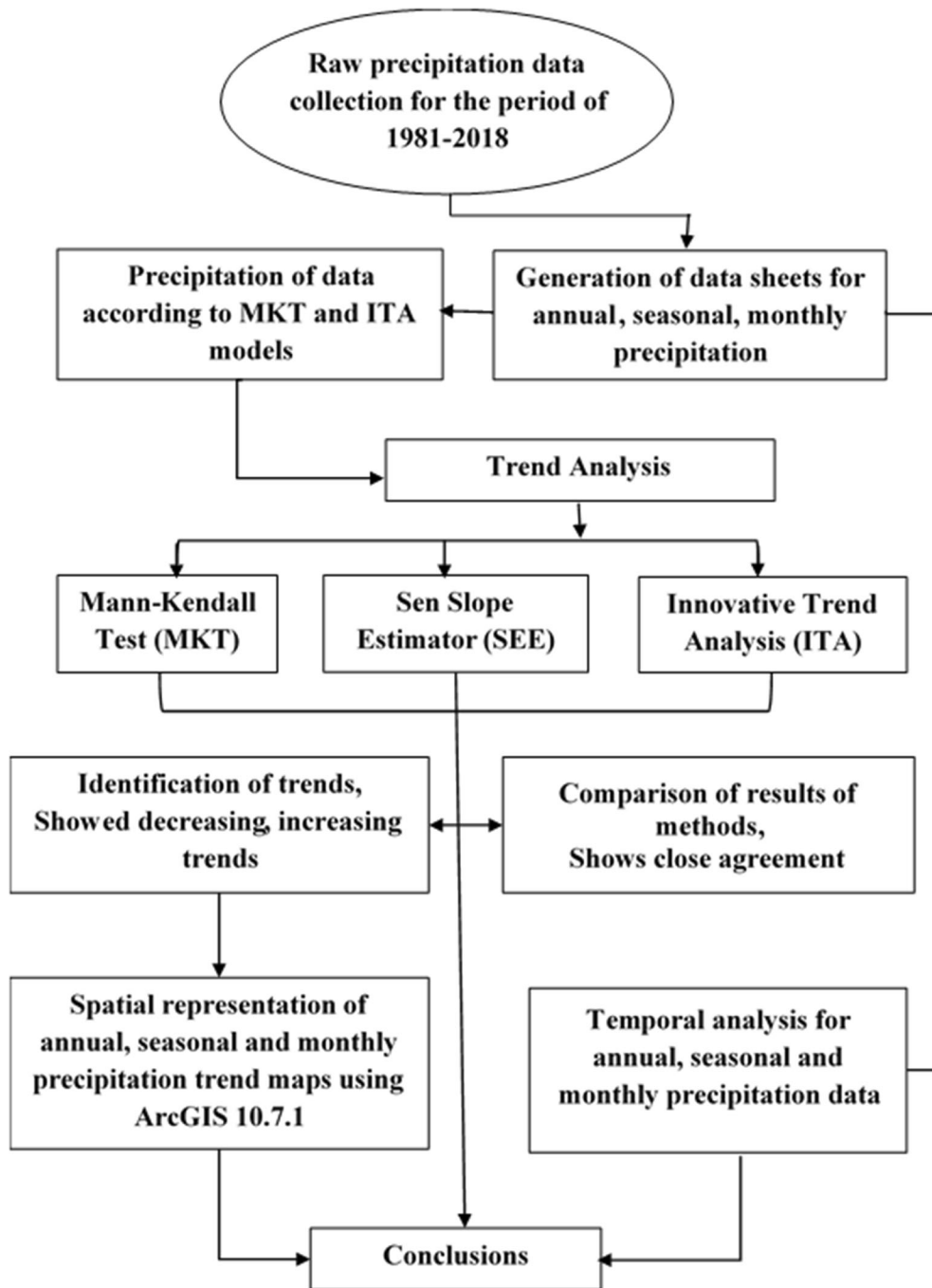


Figure 2
Steps adopted for the present study

as a threshold to identify the significant increasing or decreasing trend as used by various researchers (Ahmad et al. 2018a, b; Girma et al. 2020; Khattak

et al. 2011). Brief descriptions of each trend analysis techniques are given below as reported by different

researchers (Ahmad et al. 2015; Farid et al. 2019; Martínez-Austria et al. 2016; Shi et al. 2013).

3.1. Mann–Kendall (MK) Test

The Mann–Kendall (MK) test is a very common and reliable nonparametric test, generally employed over hydro-climatic data (Kendall 1938; Mann 1945; Martínez-Austria et al. 2016). The World Meteorological Organization (WMO) has suggested this test for assessing temporal trends over the time series data of environmental aspects (Shi et al. 2013).

The statistics of this test is are as follows:

$$\text{Statistics}(S) = \sum_{k=1}^{n-1} \binom{n}{k} \sum_{j=k+1}^n \text{Sign}((X_j - X_k)) \quad (1)$$

$$\text{Sign}(X_j - X_k) = \begin{cases} 1 & \text{if } (X_j - X_k) > 1 \\ 0 & \text{if } (X_j - X_k) = 0 \\ -1 & \text{if } (X_j - X_k) < 1 \end{cases}, \quad (2)$$

where j and k represent the observations of X_j and X_k of the time series, respectively, “Sign” denotes the signum function, and n is the length of the time series

$$V(S) = \frac{1}{18} \left[n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5) \right] \quad (3)$$

$$Z_{mk} = \begin{cases} \frac{S-1}{\sqrt{\text{VAR}(S)}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{VAR}(S)}}, & \text{if } S < 0 \end{cases}. \quad (4)$$

The increasing trend is given by the positive value of Z_{mk} , whereas a negative value of Z_{mk} indicates a decreasing trend of the time series. There are two hypotheses to be tested in the MK test. The first is the null hypothesis (H_0) which means that the concerned time series data has no trend, while the second one is the alternative hypothesis (H_1 or H_a), which means that there will be a significant trend with time.

3.2. Sen's Slope Estimator (SSE) Test

The magnitude of trends present in times series data is normally computed by Sen's slope estimator (SSE) test. The slope of n pairs of time series can be expressed by the following relation:

$$\begin{aligned} \text{Sens Slope Estimator} &= \beta \\ &= \text{Median} \left[\frac{X_j - X_k}{j - k} \right], j > k, \end{aligned} \quad (5)$$

where X_j and X_k represent the values of time series at time j and k , respectively, and for all j , it is always greater than k . The positive values of β_i indicate that the trend of the time series is increasing (upward), whereas a negative value of β_i shows a decreasing (downward) trend. If n is an odd number, then the formula of the estimated slope is

$$\beta_{\text{med}} = \beta_{[(n+1)/2]}. \quad (6)$$

If n is an even number, then the formula for an estimated slope is

$$\beta_{\text{med}} = \frac{1}{2} \left[\beta_{(n/2)} + \beta_{(n+2)/2} \right]. \quad (7)$$

At the end, β_{med} is investigated by two-tailed tests with a confidence level of $100 \times (1 - \alpha) \%$. However, the slope of a monotonic trend is determined using the nonparametric test (Partal and Kahya 2006).

3.3. Innovative Trend Analysis (ITA)

Innovative trend analysis (ITA) has recently become widely used by most researchers for trend detection over time series data (Ahmad et al. 2018a, b; Martínez-Austria et al. 2016; Onyutha 2016; Wu and Qian 2017). Figure 3 shows a description of the ITA test. This test begins with the splitting up of time series data into two equal subsets from data of the first entry to the final entry (Ahmad et al. 2018a, b; Şen 2012). Each subset of data is arranged in increasing order. If the total number of values are an odd number, then the first value is generally left out for the equal division of two subsets. The next step is to locate the first subseries (X_i) along the X -axis, while the remaining subset of data (X_j) is located along the Y -axis in an XY -coordinate system.

If the data fall in the trigon (triangular shape) down to the 1–1 line, then they will show a decreasing trend. But if data lie in the trigon above the 1–1 line, they will represent an increasing trend. It

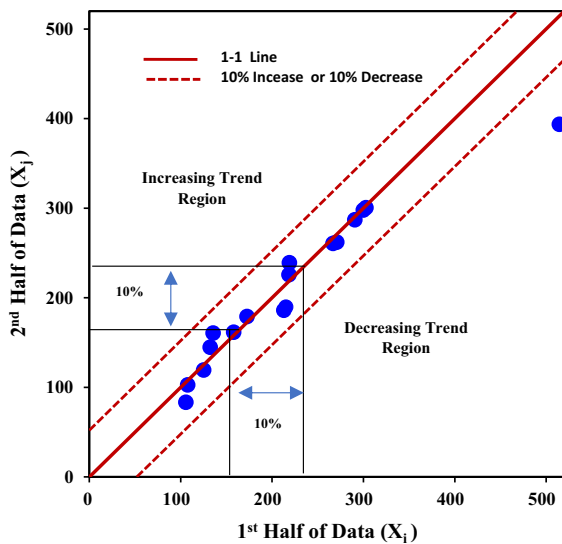


Figure 3

Illustration of increasing, decreasing and poor trend regions of the ITA method

is to be noted that the innovative feature of this method covers the comments for the data of all ranges (Ay and Kisi 2015). At the same time, the magnitude of the trend can be found by computing the average difference of X_i and X_j values at each point. Now the trend indicator value is determined by dividing the average difference from the 1-to-1 straight line by the average of the first subset of time series data. The value thus obtained is multiplied by 10% to indicate the equal scale as in the case of the MK and SSE tests with a 10% significance level. The following equation has been developed:

$$\text{Trend Indicator } (B) = \frac{1}{n} \sum_{i=1}^n 10\% \frac{(X_i - X_j)}{\mu}. \quad (8)$$

The positive value of B shows an increasing trend, while the negative value of B represents a decreasing trend.

4. Results and Discussion

4.1. Spatial and Temporal Precipitation Distribution

The spatiotemporal variations for annual, monthly and seasonal precipitation time series at 12 selected meteorological stations over the LIB are shown in

Figs. 4a–c and 5. On an annual scale, the variation in annual precipitation is not consistent at various meteorological stations (Hasson et al. 2015), as represented in Fig. 4a. However, consistency in precipitation variability was found in the northeast region of the LIB. From Fig. 4a, it is evident that a slight variation in the mean annual precipitation was observed in the southeast part, i.e., from Khanpur to Larkana. An increase in annual precipitation variation was observed from Sibbi to Badin meteorological stations. Similarly, consistent variation in precipitation was found at two stations, i.e., Lasbella and Karachi. It was also observed that Badin meteorological station showed the highest variation in annual precipitation. On a monthly scale, the variation in monthly precipitation at the 12 selected stations over the LIB is shown in Fig. 4b, which indicates that precipitation is concentrated during the months of July and August due to the monsoon season. The lowest values of precipitation were observed in the months of October–December.

Figure 4c shows the inconsistency of the variation in precipitation during four seasons in the region. However, the highest precipitation variation was noted during the summer season because of the presence of monsoonal effects in the region, whereas lowest precipitation variation was noted during autumn. The variation and inconsistency in annual precipitation at different stations may be affected by various climatic factors including monsoonal influences, warmer atmosphere and movement of moist air in the summer (Anjum et al. 2018; Waseem et al. 2020). The Pakistan Meteorological Department forecasted a slightly below normal (–10%) monsoon rainfall, with some areas expected to experience slightly above normal rainfall (+10% in the monsoon season in 2011) (Rasul 2012). It has also been reported that the precipitation regime over all of Pakistan is more erratic and is mainly controlled by the monsoon (Hartmann and Andresky 2013; Waseem et al. 2020). The spatial distribution of average annual precipitation over the study area is represented in Fig. 5. The pattern of average annual precipitation shows that the study area lies in the arid climate region (Haider and Adnan 2014). The stations located towards the northeast region of the study area

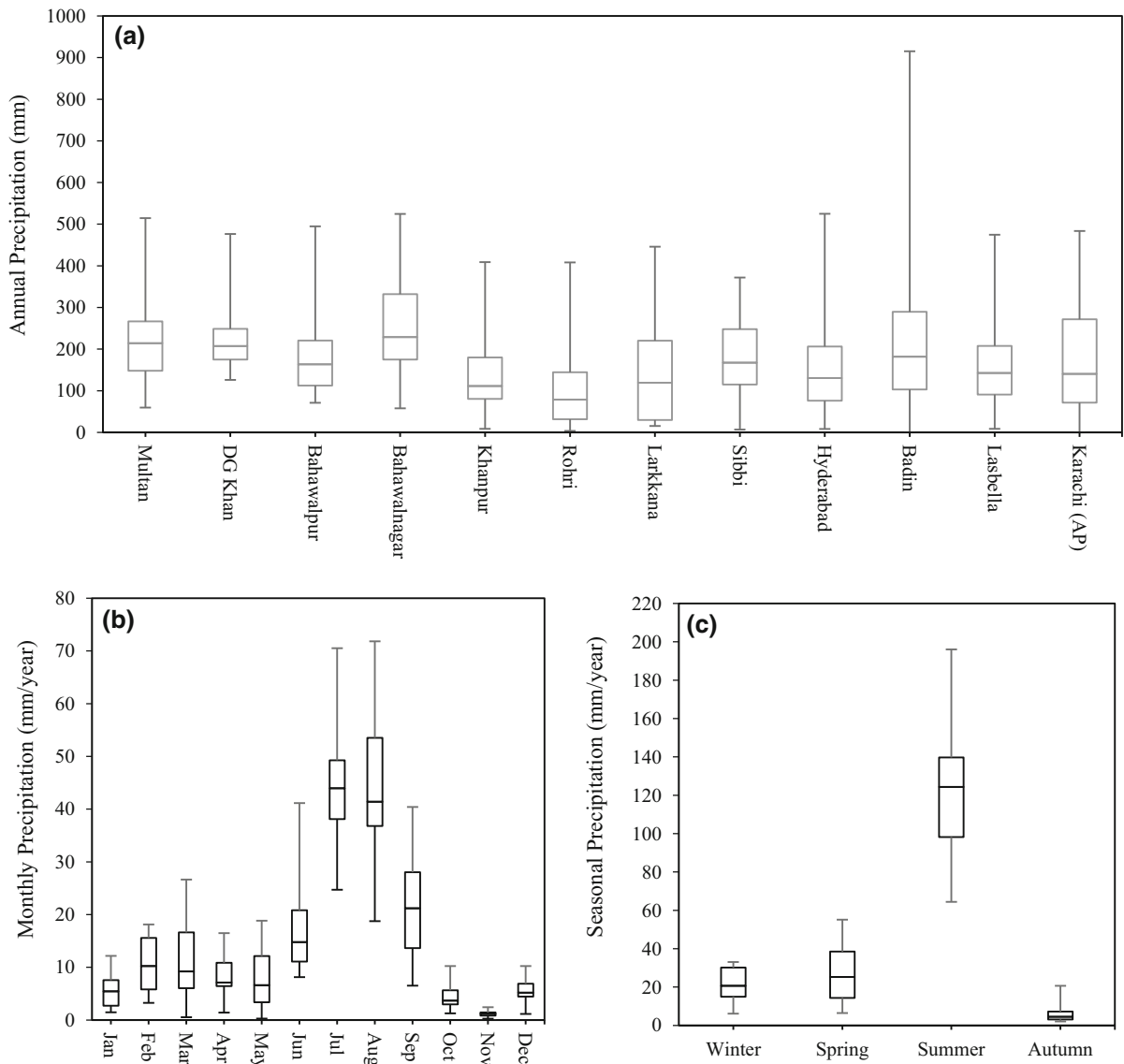


Figure 4
 Boxplot of annual, monthly and seasonal precipitation over the lower Indus plain

receive more annual precipitation relative to the central and southern parts of the study area.

4.2. Annual Precipitation Trend Analysis

Annual precipitation trends are also analyzed over the study area using MK, SSE and ITA methods, and the results are shown in Table 2. It is evident from Table 2 that most of the stations show insignificant increasing trends over study area using the MK and

SSE tests. Only one station (i.e., RYK-Khanpur) shows significant increasing trends, i.e., 2.09 mm/year which is in the southwest side of southern Punjab. Similarly, a nonsignificant increasing trend in annual precipitation of 1.33, 1.28, 1.08 and 1.05 mm/year was observed at Bahawalnagar, Sibbi, Rohri and Larkana, respectively. The decreasing trend was detected at one station (i.e., Badin as -0.45 mm/year), but it is insignificant in nature. The results of the ITA method for annual precipitation of 12

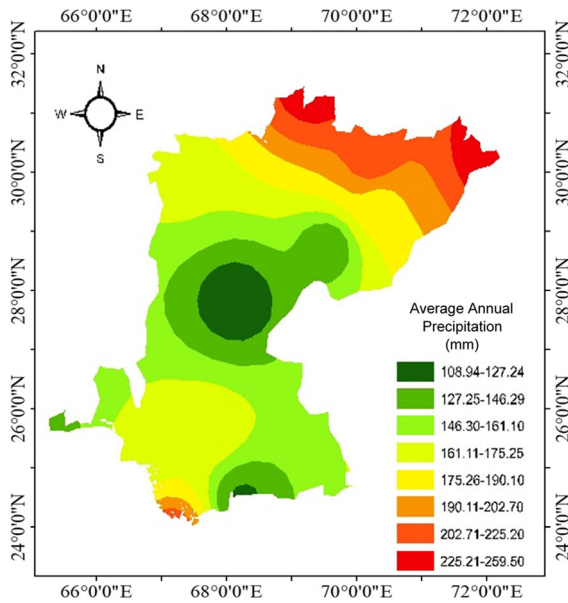


Figure 5

Spatial variation in average annual precipitation over selected stations

Table 2

MKT (Z_{mk}), SSE (β) and ITA (B) results on annual precipitation time series

Sr. no.	Station	Period	MKT test (Z_{mk})	SSE test (β)	ITA test (B)
1	Multan	1981–2018	0.30	0.47	0.21
2	DG Khan	1981–2018	0.68	1.06	0.60
3	Bahawalpur	1981–2018	0.35	0.43	0.41
4	Bahawalnagar	1981–2018	1.33	2.32	1.20
5	RYK-Khanpur	1981–2018	2.09**	2.56	2.36
6	Rohri	1981–2018	1.08	1.04	0.92
7	Sibbi	1981–2018	1.28	1.97	1.11
8	Larkana	1981–2018	1.05	1.66	1.23
9	Hyderabad	1981–2018	0.10	0.09	0.18
10	Badin	1981–2018	-0.45	-1.10	-0.57
11	Karachi (AP)	1981–2018	0.05	0.17	0.17
12	Lasbella	1981–2018	0.80	1.16	1.10
Average		1981–2018	0.72	0.99	0.74

*Trends at 10% significant level

**Trends at 5% significant level

***Trends at 1% significant level

stations selected from the study area are also given in Fig. 6 and Table 2 for more clear understanding about precipitation variation. The increasing and decreasing trends across selected sites are found inconsistent.

The results show that the value of B for annual precipitation is dominated by positive trends, and these trends are significant at $\alpha = 0.1$. This shows that the ITA method detected some other significant trends which were neglected by the MK test, also approving the ability of the ITA method to identify the hidden trends in the precipitation time series data (Wang et al. 2020). Using the ITA method, the annual precipitation is also analyzed for three categories of precipitation (low, median and high). The trend attributes are found distinctive at each station for selected precipitation categories. At the Khanpur (RY Khan) meteorological station, most of the points fall above the 10% line, which indicates the increasing trend in all the precipitation categories. The increasing trends become more dominant when the precipitation values are in the range of 124–298 mm/year. At Larkana meteorological station, the trend increases for the low-precipitation category at about 10%, and the trend decreases for the high-precipitation category (value > 400 mm/year). At Badin and Multan meteorological station, the decreasing trends become stronger when precipitation values are > 500 mm/year. These results show that the knowledge about in precipitation variability over the Indus plain is necessary for better management of available water resources (Hasson et al. 2015).

4.3. Monthly Precipitation Trend Analysis

The ITA method is used along with MK and SSE tests to analyze the monthly precipitation time series at various targeted stations over the study area. The results of three methods are presented in Table 3 which indicates the consistency of results between all three methods. Moreover, the results exhibit a mix of increasing and decreasing trends at all selected stations over the study area. The maximum number of cases of significant trends were found during the months of June and September. The maximum number of positive significant trends were noted during March, April, June and September, while the maximum number of negative trends was noted during the months of January, February, October, November and December. However, there is no single case of significant trend noted during the months of May, July and August. Figure 7 indicates

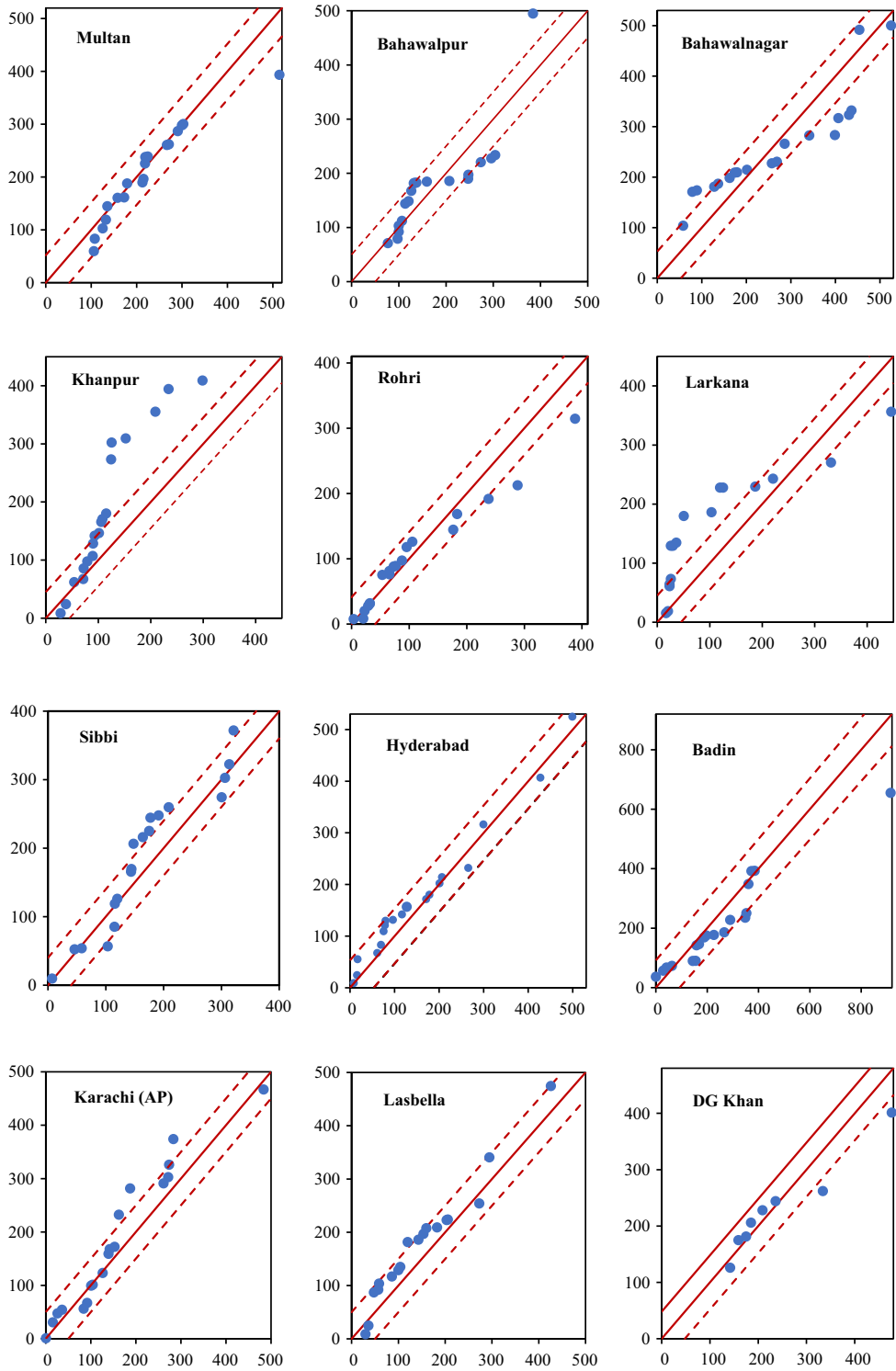


Figure 6
Results of annual precipitation trends at 12 stations using the ITA method

Table 3
Results of MKT (Z_{mk}), SSE (β) and ITA (B) results for monthly precipitation time series

Sr. no.	Station	Method	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Average
1	Multan	Z_{mk}	-1.31	0.28	-0.35	0.00	-0.29	0.97	-0.30	0.87	0.86	1.35	-0.27	0.17	0.17
		B	-1.62	0.38	-0.10	0.14	-0.32	0.73	0.73	-0.34	0.63	0.72	1.52	-0.26	0.17
2	DG Khan	β	-1.07	0.23	-0.17	0.00	-0.21	0.82	-0.20	0.58	0.61	1.21	-0.19	0.09	0.14
		Z_{mk}	-1.28	-1.53	-0.23	2.21	1.04	-0.59	1.13	0.05	-0.14	0.92	0.63	0.46	-0.52
3	Bahawalpur	B	-1.50	-1.53	-0.42	2.53	1.31	-0.80	1.11	0.13	-0.28	0.63	0.70	-0.67	0.08
		β	-1.09	-1.37	-0.27	1.19	1.46	-0.52	1.83	0.18	-0.12	0.80	0.56	-0.49	0.09
4	Bahawalnagar	Z_{mk}	-1.19	0.99	-0.39	-0.93	0.21	2.01	-1.06	0.40	1.82	0.41	-2.22	0.67	-0.10
		B	-1.54	1.01	-0.52	-1.09	0.30	2.04	-1.08	0.33	1.77	0.48	-2.14	0.76	0.03
5	RYK-Khanpur	β	-1.11	0.92	-0.23	-1.08	0.19	2.27	-0.91	0.12	1.33	0.34	-2.09	0.54	-0.14
		Z_{mk}	-1.16	0.40	-1.39	0.74	1.49	2.77	-1.03	1.33	2.66	-0.82	-2.27	-0.31	-0.30
6	Rohri	B	-1.38	0.48	-1.52	0.82	1.52	2.85	-1.46	1.17	2.70	-1.10	-2.38	-0.09	0.13
		β	-1.02	0.26	-1.14	0.67	1.12	2.02	1.16	1.54	2.30	-0.91	-0.21	-0.21	-0.32
7	Sibbi	Z_{mk}	-1.65	-0.05	0.95	1.19	-1.02	0.22	1.07	0.72	2.41	-1.83	0.04	-0.50	0.29
		B	-1.74	-0.15	0.89	1.23	-1.61	0.24	1.37	0.69	2.50	-1.80	0.22	-0.68	0.10
8	Larkana	β	-1.10	-0.03	0.82	1.16	-1.08	0.17	0.93	0.41	2.63	-1.24	0.07	0.41	0.32
		Z_{mk}	-0.62	0.00	0.55	0.70	-0.03	1.20	1.20	-1.17	1.58	-1.25	0.57	-0.43	0.14
9	Hyderabad	B	0.50	0.00	0.50	0.60	-0.01	1.05	-1.04	0.47	1.35	-1.14	0.27	-0.39	0.18
		β	-1.29	-0.55	-0.57	0.62	0.36	1.04	1.04	-0.25	0.40	1.34	-2.59	0.71	-1.70
10	Badin	Z_{mk}	-1.64	-0.67	-0.49	0.80	0.46	0.98	-0.31	0.46	1.27	-2.64	0.69	-1.99	-0.26
		B	-1.09	-0.42	-0.39	0.50	0.25	1.01	1.01	-0.12	0.44	1.04	-2.25	0.63	-1.43
11	Karachi (AP)	β	-1.52	-0.55	1.81	1.00	0.99	1.74	-0.29	1.32	1.06	0.43	0.58	0.13	0.32
		Z_{mk}	-1.17	-0.76	1.92	0.90	1.40	1.52	1.74	-0.82	1.74	1.06	0.59	0.52	0.34
12	Lasbella	B	-1.02	-0.41	1.17	1.02	1.00	1.06	-0.21	1.05	1.00	0.36	0.46	0.17	0.34
		β	-1.31	-2.11	0.55	0.39	0.65	3.24	1.11	0.45	-0.35	-1.49	-1.70	0.00	0.32
13	Karachi (AP)	Z_{mk}	-1.40	-2.35	0.82	0.31	0.70	3.08	1.05	0.69	-0.51	-1.70	0.27	0.25	0.10
		B	-1.12	-2.10	0.50	0.29	0.44	3.06	1.25	0.34	-0.24	-1.51	0.00	0.12	0.01
14	Karachi (AP)	β	-1.19	-2.28	0.98	-0.27	0.10	2.01	-0.33	1.59	1.11	-0.54	0.25	1.42	0.31
		Z_{mk}	-1.07	-2.61	1.02	-0.59	0.18	2.28	2.17	1.68	1.32	-0.42	-0.32	0.16	1.66
15	Karachi (AP)	B	-1.12	-2.03	0.80	-0.34	0.08	2.08	-0.17	1.56	1.15	-0.42	0.19	1.31	0.25
		β	-1.84	-2.14	-0.92	0.39	-1.23	-0.28	1.31	-0.87	1.31	1.55	-1.31	-0.77	0.50
16	Lasbella	Z_{mk}	-2.08	-2.06	-0.91	0.27	-1.56	-0.14	-0.82	1.40	1.68	-1.36	-1.36	-0.85	-0.50
		B	-1.51	-2.12	-0.60	0.32	-1.20	-0.12	-0.12	-0.66	0.95	1.01	-1.17	-0.69	0.43
17	Lasbella	β	-1.39	-1.33	-0.02	1.11	1.16	2.53	0.98	-0.17	2.25	0.50	0.50	1.17	0.80
		Z_{mk}	-1.40	-1.47	-0.16	1.35	1.43	2.64	0.70	-0.28	2.29	0.70	0.70	1.10	0.78
18	Lasbella	B	-1.03	-1.05	0.00	1.04	1.36	2.45	0.48	-0.12	2.01	0.45	1.09	0.91	0.47
		β													

*Trends at 10% significant level
 **Trends at 5% significant level
 ***Trends at 1% significant level

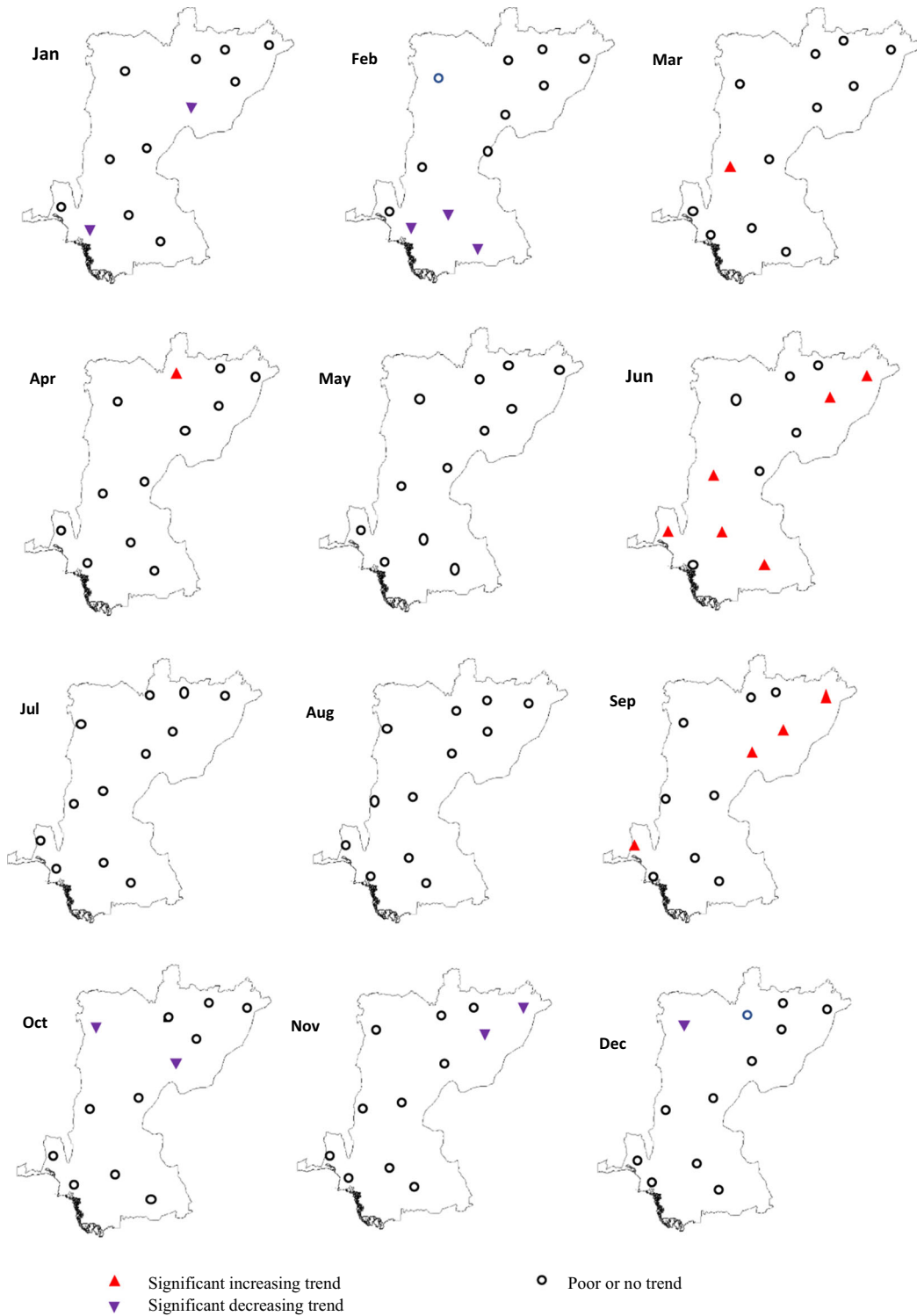


Figure 7

Location of sites with increasing, decreasing and poor trends for monthly precipitation time series using the ITA method

Table 4

Results of MK (Z_{mk}), SSE (β) and ITA (B) tests for seasonal precipitation time series

Stn. no.	Station	Winter			Spring (pre-monsoon)			Summer (monsoon)			Autumn (post-monsoon)		
		Z_{mk}	β	B	Z_{mk}	β	B	Z_{mk}	β	B	Z_{mk}	β	B
1	Multan	0.15	0.02	0.15	-0.73	-0.63	-1.05	0.70	0.48	0.75	0.44	0.20	0.39
2	DG Khan	-1.80*	-1.26	-1.84	0.62	0.58	0.69	1.17	1.07	1.06	0.79	0.03	0.83
3	Bahawalpur	0.41	0.09	0.54	-0.78	-0.26	-0.88	0.70	0.50	0.82	-0.78	-0.67	-0.76
4	Bahawalnagar	0.30	0.12	0.27	-0.03	0.00	-0.21	1.63	1.78	1.36	-1.65*	-1.01*	-1.47
5	RYK-Khanpur	-1.35	-1.32	-1.07	1.16	1.33	1.48	2.08**	2.37	2.46**	0.03	0.16	0.20
6	Rohri	0.32	0.00	0.44	0.68	0.66	0.77	0.77	0.48	0.89	-3.59***	-3.14	-3.92***
7	Sibbi	0.20	0.05	0.25	-0.48	-0.68	-0.70	1.43	1.75	1.82	-0.30	-0.25	-0.37
8	Larkana	-1.11	-1.19	-1.06	-1.00	-0.82	-0.99	1.86*	2.50	1.96*	0.02	0.12	0.19
9	Hyderabad	-2.36**	-2.30	-2.41**	0.49	0.03	0.68	0.73	0.87	0.98	-1.16	-1.23	-1.44
10	Badin	-2.14**	-2.25	-2.14**	0.38	0.00	0.32	0.73	0.52	0.86	-0.80	-0.75	-0.84
11	Karachi (AP)	0.26	0.01	0.18	-1.44	-1.01	-1.57	0.23	0.28	0.22	1.08	1.00	1.19
12	Lasbella	-0.08	0.00	-0.12	1.03	1.51	1.37	0.48	0.67	0.69	0.62	0.43	0.52
Average		-0.10	-0.25	-0.57	-0.01	0.06	-0.01	0.86	0.84	1.16	-0.01	-0.10	-0.46

*Trends at 10% significant level

**Trends at 5% significant level

***Trends at 1% significant level

the spatial distribution of monthly precipitation over the study area. During the month of June, significant increasing trends were observed at most of the meteorological stations (Bahawalnagar, Bahawalpur, Lasbella, Badin and Larkana). The increasing trend of precipitation in the month of June indicated the shifting of the monsoon from July–August to June because no trend was observed at any meteorological station during the months of July and August. The increase in precipitation in the month of June is due to the increase in air temperature. Similarly, Ali et al. (2020) investigated 35 meteorological stations over the northern, central east, central west and southern regions of Pakistan and found that the onset of the monsoon shifted towards earlier onset, from the first week of July to the last week of June.

4.4. Seasonal Trend Analysis

Like annual and monthly precipitation trend analysis, seasonal precipitation time series are examined using the MK (Z_{mk}), SSE (β) and ITA (B) tests over the study area. The study area was categorized into four seasons as winter (December–February), spring or pre-monsoon (March–May), summer or monsoon (June–September) and autumn or post-

monsoon season (October–November). The results obtained using the MK (Z_{mk}), SSE (β) and ITA (B) tests are presented in Table 4. Significant decreasing trends were observed during the winter season at DG Khan, Badin and Hyderabad, whereas an insignificant trend was found at all stations during spring precipitation over the study area. However, significant increasing trends are found during the summer season at RYK-Khanpur and Larkana. During autumn precipitation, significant decreasing trends were detected only at Bahawalnagar and Rohri, respectively. The ITA results show the significant increasing trends during the summer at 10% significance level for Multan, DG Khan, Bahawalnagar, Bahawalpur, RYK-Khanpur, Rohri, Larkana, Sibbi, Badin, Hyderabad, Karachi and Lasbella having B values of 0.75, 1.06, 1.36, 0.82, 2.46, 0.89, 1.97, 1.82, 0.86, 0.98, 0.22 and 0.69, respectively (Table 4). It is evident from Fig. 8 that at the RYK-Khanpur meteorological station, most of the points fall above the 10% line, showing a strong increasing trend in summer precipitation. Moreover, increasing trends are found at approximately 50% of the stations and decreasing trends at the remaining 50% of stations in winter, spring and autumn precipitation. Furthermore, Fig. 9 shows the

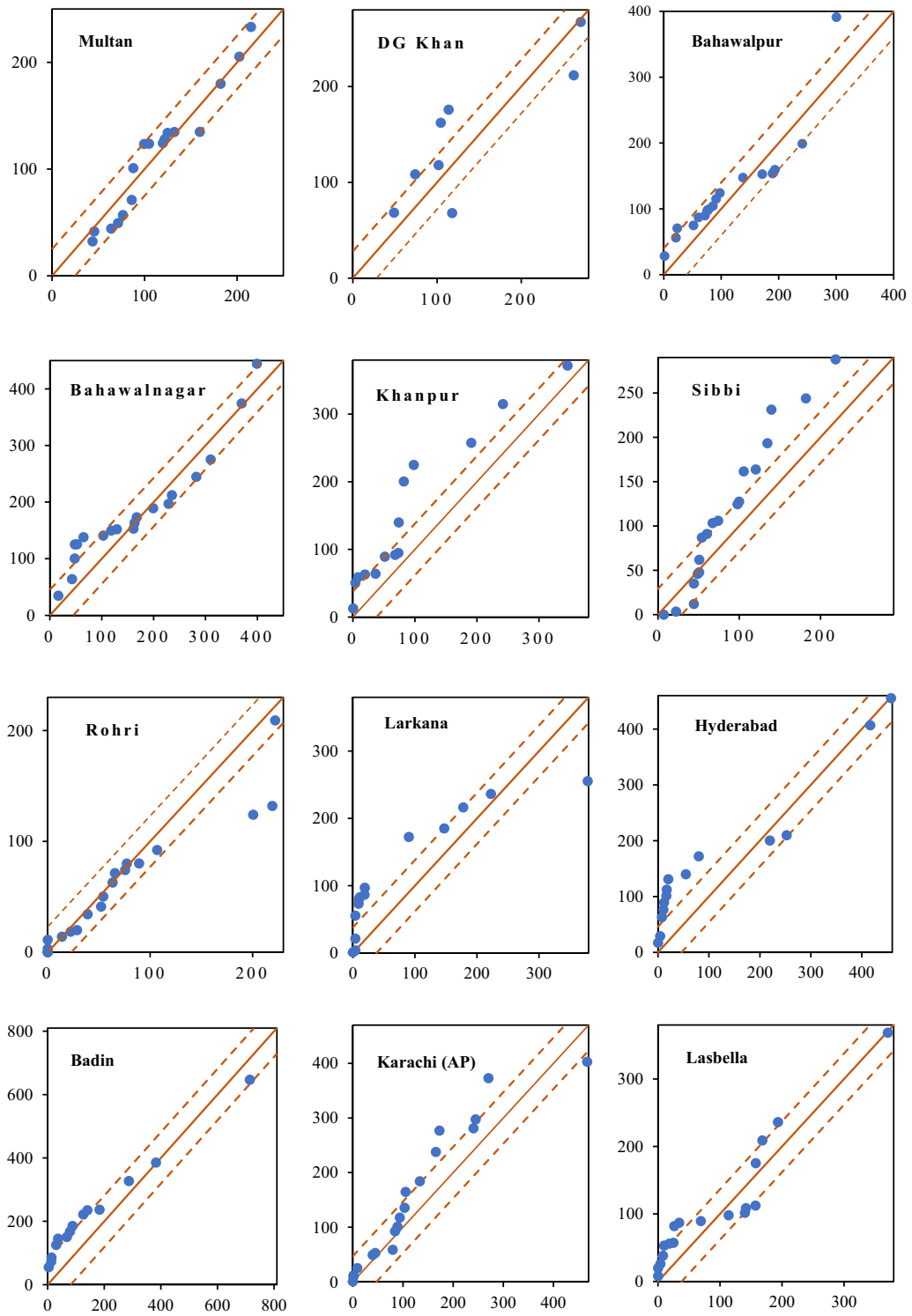


Figure 8
Results of summer precipitation trends using the ITA test

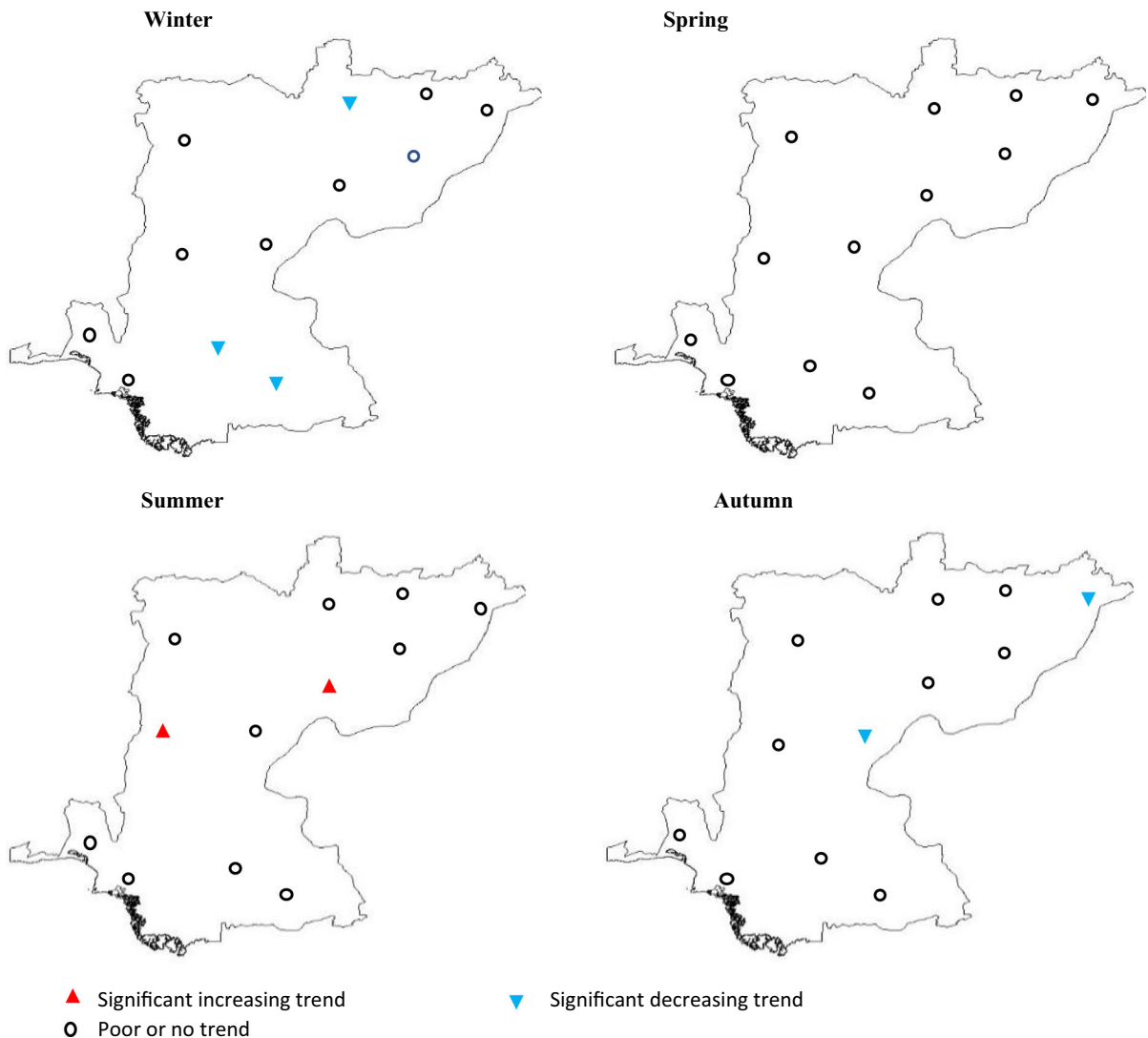


Figure 9

Location of sites with increasing, decreasing and no or poor trends for seasonal precipitation time series using the ITA method

precipitation variability on the spatial scale during the winter, spring, summer and autumn seasons over the study area. The significant decreasing trends are noted at DG Khan, Hyderabad and Badin meteorological stations during the winter season and at Bahawalnagar and Rohri meteorological stations during the autumn season.

Significant increasing trends are found at RYK-Khanpur and Larkana meteorological stations during the summer season. Overall analysis indicated that the significant increasing trends were observed only

during the summer, as the southwest wind from the Arabian Sea progresses towards Pakistan and the first monsoon rainfall prevails over Badin meteorological stations, making it the southeastern belt of the summer monsoon (Ali et al. 2020; Imran et al. 2014). Furthermore, the precipitation regime in Pakistan is more erratic and mainly controlled by the monsoon (Hartmann and Andresky, 2013; Waseem et al. 2020).

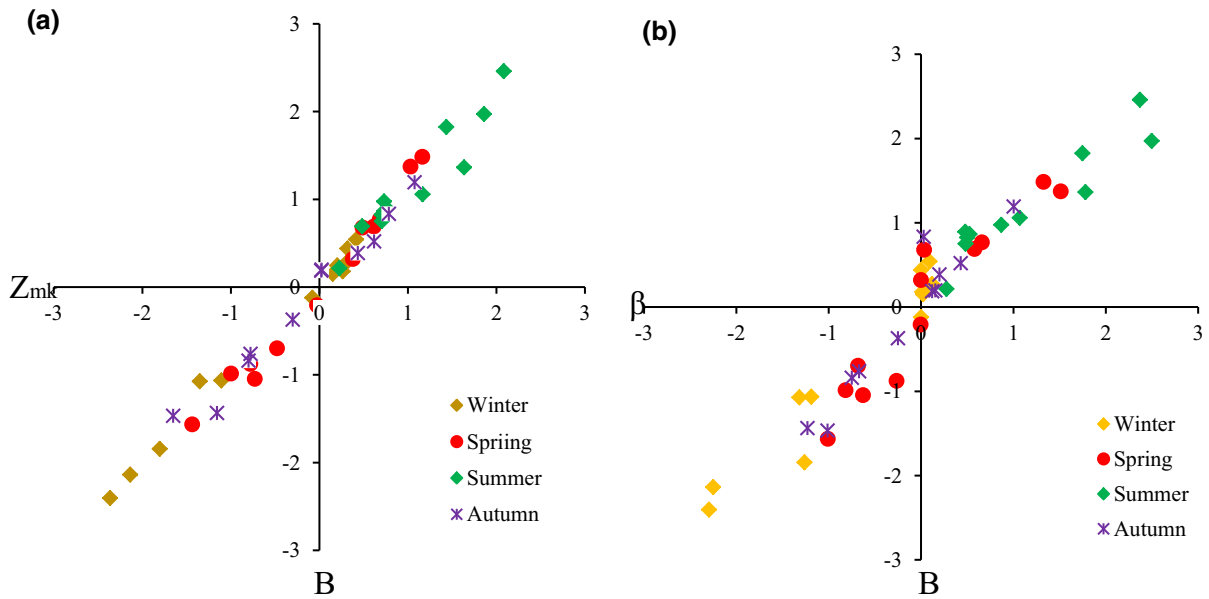


Figure 10

Scatter plots of **a** Z_{mk} of the MK test against B of the ITA method and **b** β of Sen's slope estimator against B of the ITA method

4.5. Comparison of Trend Tests

The test reliability of the ITA method was compared and analyzed with both MK and SSE methods for 48 seasonal precipitation time series. Significant trends were noted at only seven time series, and the results were found to be consistent using all three of the abovementioned methods. The test results of significant and insignificant trends were compared by plotting scatter plots between the statistic B of the ITA test and the statistic Z_{mk} of the MK test and the same between statistic B of the ITA test and statistic β of the SSE test. The results shown in Fig. 10a, b indicate that most of the points fall in first and third quadrant, representing the overall agreement among the three selected trend analysis methods.

The results also indicated a strong agreement of statistic B of the ITA method with statistic Z_{mk} of the MK test and β of the SSE test. However, ITA classifies the long-term precipitation data quantitatively into different precipitation categories (low, median and high). From the graphical representation of the ITA method, some other significant trends were also identified which were neglected by the MK test. It means that the ITA method has ability to

analyze the trends and to identify the hidden trends in the precipitation time-series data (Wang et al. 2020). Similarly, Ahmad et al. (2018a, b) compared the ITA method with both MK and SSE tests for 80 seasonal and annual time series over the upper Indus basin and recommended ITA is a reliable and effective method to analyze the trends in the hydro-meteorological data at low, median and high values.

5. Conclusions

The current study analyzed the trends in annual, monthly and seasonal precipitation time series using the MK, SSE and ITA tests over the selected areas of the LIB for the data period of 1981–2018. On an annual scale, a significant increasing trend was found at only one station, i.e., RYK-Khanpur station with $Z_{mk} = 2.09$ mm/year, $\beta = 2.56$ mm/year and $B = 2.36$ mm/year. The nonsignificant decreasing trend was detected at Badin station with $Z_{mk} = -0.45$ mm/year. The increasing rates of trends vary from 0.05 to 2.09 mm/year for the MK test and 0.17–2.56 mm/year for the SEE test. On a monthly scale, a mix of increasing and decreasing trends was

noted at all the stations. The maximum number of positive significant trends were noted during March, April, June and September, while the maximum number of negative trends were found during the months of January, February, October, November and December. On the spatial scale, significant increasing trends were observed during the month of June at most of the meteorological stations (Bahawalnagar, Bahawalpur, Lasbella, Badin and Larkana) which indicated shifting of the monsoon from July–August towards June. For seasonal precipitation, the significant increasing trends were observed at two stations (RYK-Khanpur and Larkana) during the summer only. Significant decreasing trends were investigated at three stations (DG Khan, Hyderabad and Badin) during the winter and at two stations (Bahawalnagar and Rohri) during the autumn. The results also indicated a strong agreement of statistic B of the ITA method with statistic Z_{mk} of the MK test and β of the SSE test. However, ITA seems more suitable than the other two methods for classifying the long-term precipitation data into different categories (low, median and high). The findings on precipitation variability in the present study may provide a path towards resolving future concerns and implementing a water resources management project over the LIB.

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Data Availability

The climatic and groundwater data used to support the findings of this study are available from the corresponding author upon reasonable request.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest with regard to this work.

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