Natural Hazards
https://doi.org/10.1007/s11069-023-06082-y

ORIGINAL PAPER

Analyzing drought trends over Sindh Province, Pakistan

Mansoor Ahmed[1] · Ghulam Hussain Dars[2] · Suhail Ahmed[2] · Nir Y. Krakauer[3]

Received: 29 October 2022 / Accepted: 23 June 2023

Abstract

This study examines the drought patterns in Pakistan's Sindh Province (low-riparian of the Indus Basin) from 1902 to 2015 using the Standardized Precipitation Evapotranspiration Index (SPEI) on 3-month and 12-month timescales. The spatial "K"luster analysis using tree edge removal method was used to divide the study area into four zones with similar climatic characteristics. Then, the run theory was applied to characterize droughts (durations, severity, intensity, and peaks) in each zone. The non-parametric Mann–Kendall trend test was also applied to analyze statistically significant trends by zone and drought characteristic. It was found that all four zones experienced a decrease in SPEI throughout the analyzed period. The effects of climate change are more evident when we analyzed drought characteristics in two time slices, i.e., pre and post-1960. The results showed that in the post-1960 time slice, droughts increased in duration, severity, intensity, and peaks over the entire study area under both 3 and 12-month SPEI. The findings of this study can assist policymakers and water managers in devising policies for managing limited water resources under changing patterns of droughts in Sindh Province.

Keywords Drought hazard · Drought characterization · SKATER · SPEI · Sindh

✉ Mansoor Ahmed
jiskanaimansoorahmed@gmail.com

Ghulam Hussain Dars
ghdars.uspcasw@faculty.muet.edu.pk

Suhail Ahmed
suhail.ahmed9206@gmail.com

Nir Y. Krakauer
nkrakauer@ccny.cuny.edu

1 Centre for Environmental Science, University of Sindh, Jamshoro, Pakistan

2 U.S-Pakistan Center for Advance Studies in Water (USPCAS-W), Mehran University of Engineering and Technology, Jamshoro, Pakistan

3 Department of Civil Engineering and NOAA-CREST, City College of New York, New York, NY 10031, USA

Published online: 28 August 2023

1 Introduction

Pakistan is among the most vulnerable countries due to climate change. Historical data shows an increase in both rainfall and temperature over the entire country in the last 70 years. In addition, the severity and intensity of extreme events (floods, droughts, and heat waves) have also increased. Furthermore, as predicted by the climate models, future global warming could alter the water cycle and cause more extreme events, such as droughts and floods, in this region (Dars et al. 2020). Drought is one of the most complex natural hazards that affects water availability for agriculture and various socio-economic activities in a particular region (Adnan and Ullah 2020). Quantifying drought characteristics, such as duration, severity, intensity, and peak, is critical for policymakers and water managers.

Numerous drought indices have been used for this purpose, including Standardized Precipitation Index (SPI) (McKee et al. 1993), Decile Index (DI) (Gibbs and Maher 1967), Palmer Drought Severity Index (PDSI) (Palmer 1965), and Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010). Several studies have adopted these drought indices to model droughts. For example, Edossa et al. (2016) used the self-calibrated Palmer Drought Severity Index (PDSI) to analyze droughts in central South Africa. Zou et al. (2005) used PDSI derived from monthly air temperature and precipitation data from 1951 to 2003. Bazrkar et al. (2020) developed a Hydro-climatic Aggregate Drought Index (HADI) to categorize drought in colder regions. In addition, Haroon et al. (2016) applied the Drought Severity Index (DSI) and showed that the DSI could be efficiently applied only in agricultural and plain areas. Aksoy et al. (2021) developed critical drought Intensity–Duration–Frequency (IDF) curves by employing Total Probability Theorem (TPT) and Coupled Frequency Analysis (CFA). The critical IDF curves are utilized to identify more severe drought events in vulnerable regions. The study highlighted the potential of critical IDF curves in providing valuable information for regions prone to drought. In another research conducted by Won and Kim (2023) the Ecological Drought Condition Index (EDCI) based on the Normalized Difference Vegetation Index (NDVI) was evaluated to detect the effects of meteorological droughts on vegetation health. The study demonstrated the effectiveness of EDCI in detecting the impact of meteorological droughts on vegetation health.

Another research study by Wang et al. (2015) used SPI and SPEI to investigate drought severity in China by using monthly observed climatic data from 633 stations. In addition, Tirivarombo et al. (2018) used the SPEI and SPI to monitor droughts over the Kafue basin in Zambia. They also compared both indices and found that SPEI efficiently calculated the drought duration and severity. Moreover, (Jamro et al. 2019, 2020) conducted two studies on Pakistan and Balochistan Province to analyze the spatiotemporal variability of droughts using SPEI. (Xie et al. 2013; Ashraf and Routray 2015; Jamro et al. 2020) applied the Standardized Precipitation Index (SPI) over Pakistan and Balochistan Province to analyze drought trends (Adnan et al. 2015). However, under the current scenarios of increasing temperatures, the effects of climate change cannot be ignored, and the temperature cannot be assumed to be stationary in the future. The SPEI integrates the effects of climate change on temperature and precipitation and produces more reliable results than indices such as SPI that only use precipitation amounts (Jamro et al. 2019).

To our knowledge, no study has been conducted in the Sindh Province to characterize droughts and their trends using SPEI. This research aims to analyze the spatial variability of drought characteristics (drought duration, severity, intensity, and peak) using 3- and

12-month SPEI across Sindh Province, Pakistan, from 1902–2015. The studied period is also divided into two parts, pre-1960 and post-1960, to highlight the effect climate change has had on the drought characteristics of the region.

2 Materials and methods

2.1 Study area

Sindh Province lies in the southwest corner of South Asia, with the Thar Desert in the east, the mountains and hilly areas in the west, arid regions of Punjab in the north, and the Arabian Sea in the south (Abbas et al. 2018). Sindh is the second-most populous province of Pakistan and covers an area of 140,915 km^2. It has a flat topography and is situated between 23° to 30° north latitude and 66°–71° east longitude (Fig. 1). All the spatial plots are made using ArcMap. Being a lower-riparian zone, Sindh is vulnerable to floods when there is excess rainfall and droughts when there is low rainfall (Dars et al. 2021). The topography of Sindh Province can be divided into four geographic zones.

Sindh lies in the subtropical region with an arid climate. Its average summer and winter temperatures are 35 °C and 16 °C, respectively. The maximum temperature reaches 50 °C in the summer season, while minimum temperatures drop to − 1 °C in the winter (Abbas et al. 2018). Its average rainfall is about 180 mm a year, which is received mostly in the summer. Due to erratic rainfall and high potential evaporation rates, almost 80 percent of groundwater is brackish and agricultural land is affected by waterlogging and salinization (Fig. 2).

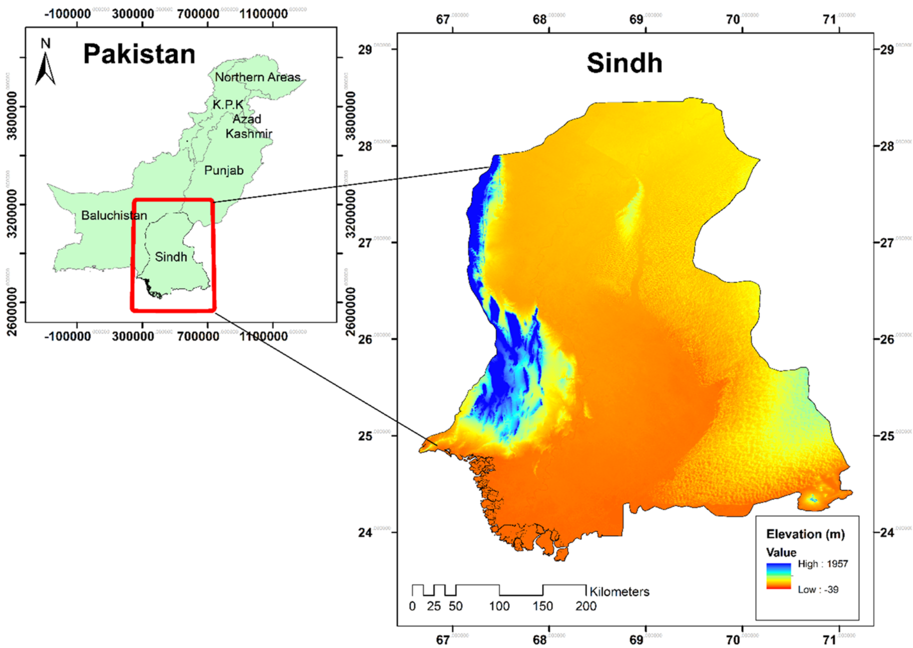


Fig. 1 The topographic map of the study area

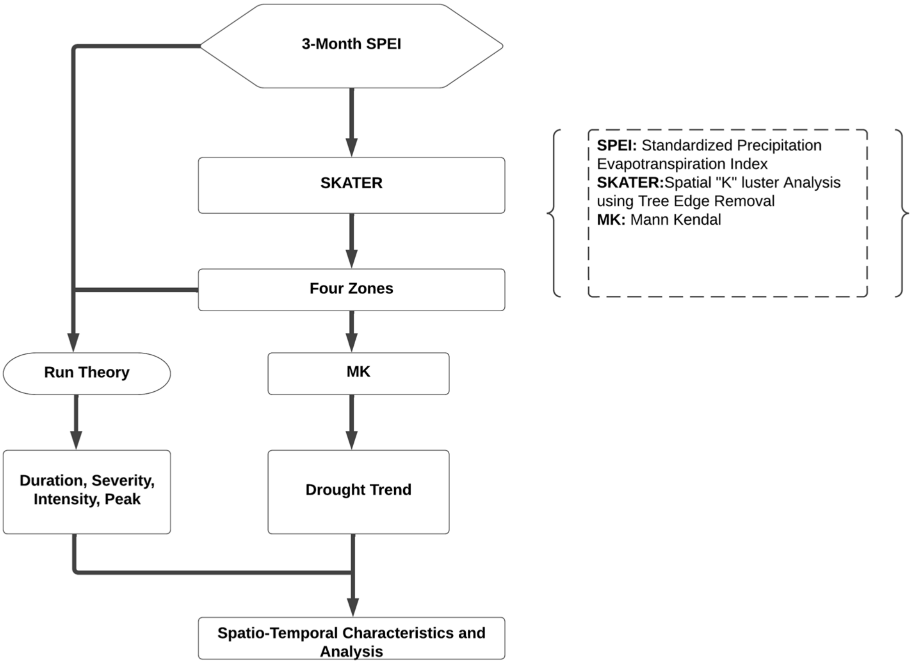


Fig. 2 Methodological framework

2.2 Climatic data

We used the gridded precipitation and potential evapotranspiration (PET) data provided by the climate research unit (CRU) (https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.06/cruts.2205201912.v4.06) at the University of East Anglia (CRU TS 3.24; (Harris et al. (2014) to compute the SPEI. The CRU data is available at a monthly temporal resolution for ten climatic variables from 1901 to 2015 at a spatial resolution of 0.5° by 0.5° (approximately 55.5 km near the equator). Many studies have used the CRU datasets over the Indus Basin region, such as Jamro et al. (2019) and Jamro et al. (2020), which showed that the CRU dataset could be used in hydrological studies over the Indus Basin and surrounding regions. In addition, Krakauer et al. (2019) concluded that despite the poor representation of the spatial variability over this region, the CRU data represented the precipitation trends quite well compared to station data.

2.3 Standardized precipitation evapotranspiration Index

Several drought indices have been used to assess drought trends, including Palmer Drought Severity Index (PDSI) (Palmer 1965), Standardized Precipitation Index (SPI) (McKee et al. 1993), and Standardized Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010). The SPEI has the advantage of incorporating the effects of temperature and hence better capturing drought risk changes in a warming climate (Vicente-Serrano et al. 2010). In this study, we have computed SPEI using R programming language. SPEI utilizes the amount of precipitation and subtracts Potential Evapotranspiration (PET). SPEI has been used and recommended by various researchers in Pakistan (Jamro et al. 2019) and around the globe (Seneviratne 2012, Touma et al. 2015; Beguería et al. 2014; Tirivarombo et al. 2018). This study analyzes the drought characteristics for the Sindh province of Pakistan using SPEI.

2.4 Drought regionalization

Regionalization is an effective technique to make homogeneous clusters based on the gridded datasets. In this study, drought regionalization has been performed using the Spatial "K" luster Analysis by utilizing the Tree Edge Removal (SKATER) algorithm using R programming language (Jamro et al. 2019, 2020; Liu et al. 2015; Assunção et al. 2006).

Jamro et al. (2019) applied the SKATER algorithm to this region for the first time. At first, SKATER employs the spatial contiguity of the dataset for producing clusters following that. As drought is a spatial phenomenon, considering spatial relationships is crucial to regionalizing drought (Assunção et al. 2006). In the SKATER algorithm, objects are represented as vertices in connected graphs, and the algorithm begins by computing adjacency relationships among objects while generating a connectivity graph. As shown in Fig. 2, each district is denoted as a vertex connected to neighboring vertices by edges. In this case, the attribute of interest is the value of SPEI, whose correlation between neighbors is characterized by a "weight" or value allotted to the particular edges. Each edge weight is directly proportional to the similarity measure between the two vertices it joins. By pruning the graph at suitable places, connected clusters are obtained.

2.5 Drought characterization

Run theory (Yevjevich 1967) is a popular and efficient technique to analyze time series. A run is a time series sequence with all indicator values below a certain threshold. Multiple thresholds have been implemented in the research studies to identify droughts. Wu et al. (2019) used an upper threshold of -0.5 to identify drought events in northeastern China. Tian and Quiring (2019) chose a -0.7 SPEI threshold for determining the droughts in Oklahoma, while Jamro et al. (2019) used a threshold of -0.5 for SPEI to identify droughts in Pakistan. In this research study, the SPEI dropping below -0.5 is considered a drought event (Table 1). After applying the SPEI thresholds to identify

Table 1 Idealized distribution and interpretation of SPEI categories (Liu et al. 2015)

SPEI	Categories
$2.0 \leq \text{SPEI}$	Extreme wetness
$1.5 \leq \text{SPEI} < 2.0$	Severe wetness
$1.0 \leq \text{SPEI} < 1.5$	Moderate wetness
$0.5 \leq \text{SPEI} < 1.0$	Slight wetness
$-0.5 < \text{SPEI} < 0.5$	Normal
$-1.0 < \text{SPEI} \leq -0.5$	Slight dryness
$-1.5 < \text{SPEI} \leq -1.0$	Moderate dryness
$-2.0 < \text{SPEI} \leq -1.5$	Severe dryness
$\text{SPEI} \leq -2.0$	Extreme dryness

drought periods, drought characteristics (drought duration, events, severity, intensity, and peak) were computed in each zone (Guo et al. 2018).

After the identification of drought events, their drought characteristics are determined. Drought Duration (DD) is the length of time, measured in months, between the beginning and end of a drought. Drought Severity (DS) is the overall amount of deficit in a drought index below a specific threshold level. It is calculated by adding up the SPEI deficit for each month during the drought. Drought Intensity (DI) is the average value of the drought index for a particular drought event, which is obtained by dividing the drought severity by its duration. Drought Peak (DP) is the minimum value that the index reaches during the entire period of the drought.

3 Drought trends

Drought trends in SPEI and drought characteristics in each zone were assessed using the non-parametric Mann–Kendall (MK) trend test (Kendall 1948) in the R programming language. Sen's method was applied to calculate the magnitude of the slope (Sen 1968). The MK test bases itself on the correlation between the actual time order and the ranks of a time series. This method is also recommended by the World Meteorological Organization (WMO) to evaluate trends in climatic studies. This method is quick and easy to use as it allows for missing values, does not require the time series to conform to a certain distribution, and has significantly lower sensitivity to outliers than parametric methods such as linear regression (Guo et al. 2018). A significance level of 0.05, which translates to a 95% confidence interval, has been chosen for all the analyses (Da Silva et al. 2015; Mahajan and Dodamani 2015).

4 Results

4.1 Drought regionalization

The study area is divided into four zones (Figs. 3, 4) using the SKATER algorithm, which is also consistent with its geography. Zone 1 comprises the upper portion of Sindh, with low annual average precipitation and high average temperature. Zone 2 is an alluvial region which is the central region and located along the Indus River. Zone 3 is a desert region comprised of the Thar Desert, Asia's third-largest and Pakistan's largest desert. Zone 4 is a coastal region connected with Balochistan province through mountain ranges. It also includes the Karachi megacity (Fig. 5).

After employing the SKATER algorithm, statistical parameters were calculated for each zone in 3-Month and 12-Month SPEI, and these showed in Table 2.

In Table 2 Mean, median, standard deviation, skewness, maximum and minimum are calculated, it can be infer from the Table 2, in 3-Month SPEI has larger mean with comparison to 12-Month SPEI; while minimum is larger in 12-Month SPEI which is −2.01 which is Zone-1.

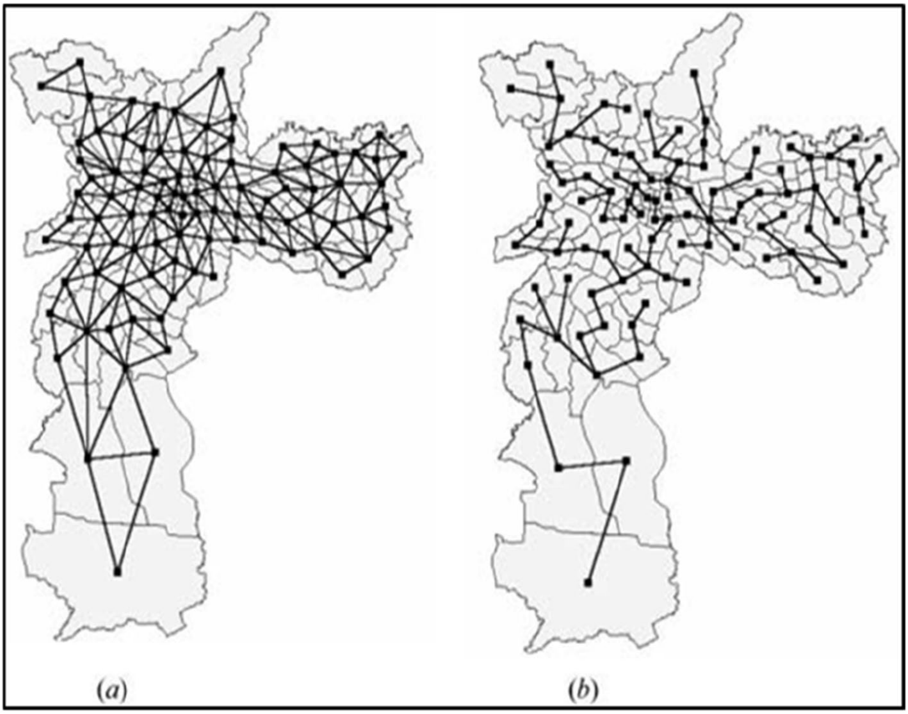
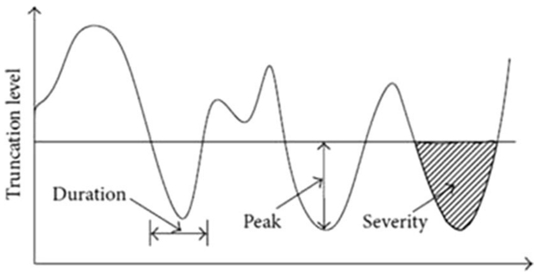


Fig. 3 **a** Connectivity graph showing adjacency relation among objects; **b** minimum spanning tree generated after cutting edges having dissimilarity

Fig. 4 Drought features extracted from the run theory



4.2 Drought characteristics

After estimating SPEI in the R programming language, droughts are identified with a threshold of −0.5 (Beguería et al. 2014). After the identification of drought events, their drought characteristics are determined. Following are the results of drought characteristics.

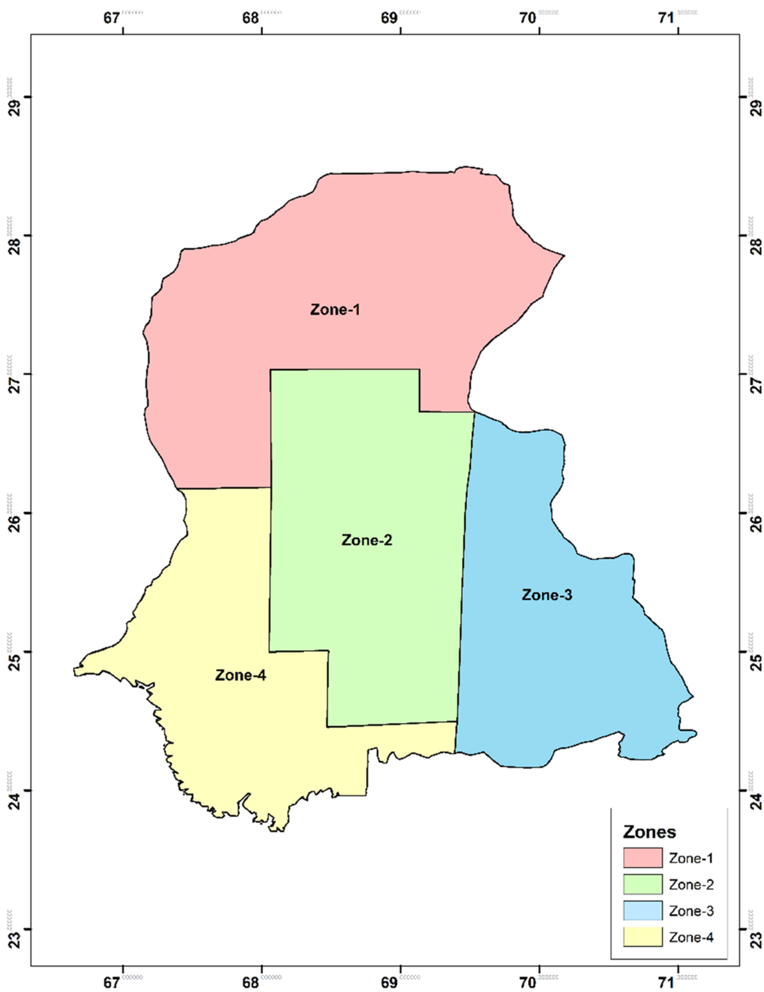


Fig. 5 Zones have been extracted by employing SKATER

Table 2 Statistical Parameters for 3-Month & 12-Month SPEI

	Mean	Median	SD	Skewness	Max	Min
3-Month SPEI						
Zone-1	0.02	−0.03	0.94	0.29	2.35	−1.75
Zone-2	0.02	−0.12	0.95	0.36	2.44	−1.56
Zone-3	0.02	−0.14	0.95	0.41	2.39	−1.75
Zone-4	0.02	−0.13	0.95	0.36	2.29	−1.58
12-Month SPEI						
Zone-1	0.009	−0.06	0.96	0.18	2.24	−2.01
Zone-2	0.008	−0.03	0.96	0.14	2.16	−1.85
Zone-3	0.005	−0.05	0.97	0.07	2.31	−1.99
Zone-4	0.008	−0.06	0.97	0.16	2.22	−1.93

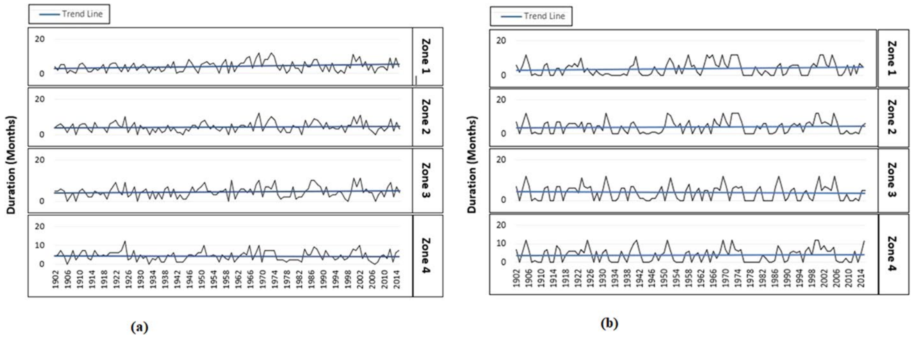


Fig. 6 Drought duration for 3-Month (**a**) and 12-Month (**b**). Trend line represents the Sen's slope

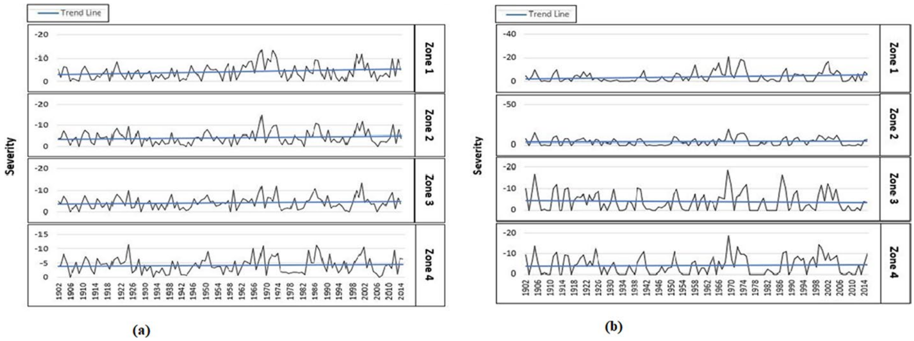


Fig. 7 Drought severity for 3-Month (**a**) and 12-Month (**b**). The trend line represents Sen's slope

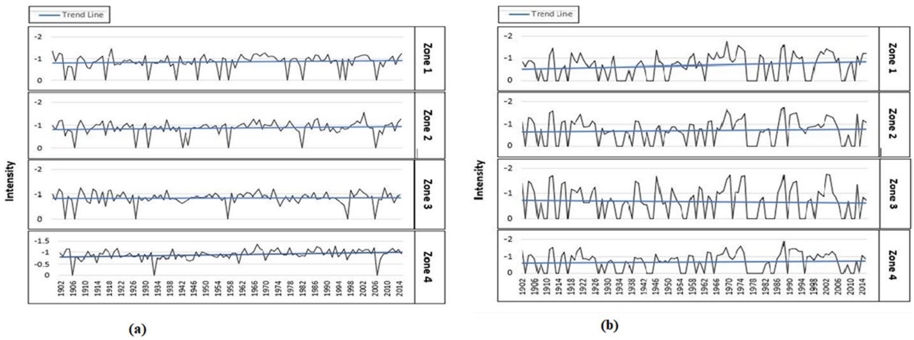


Fig. 8 Drought Intensity for 3-Month (**a**) and 12-Month (**b**). Trend line represents the Sen's slope

4.2.1 Drought duration

Drought Duration (DD) is the length of time, measured in months, between the beginning and end of a drought. The run theory was applied to analyze each zone's drought characteristics (drought events, duration, severity, intensity, and peak). These drought characteristics plots are given in Figs. 6, 7, 8, 9 for each zone's SPEI time

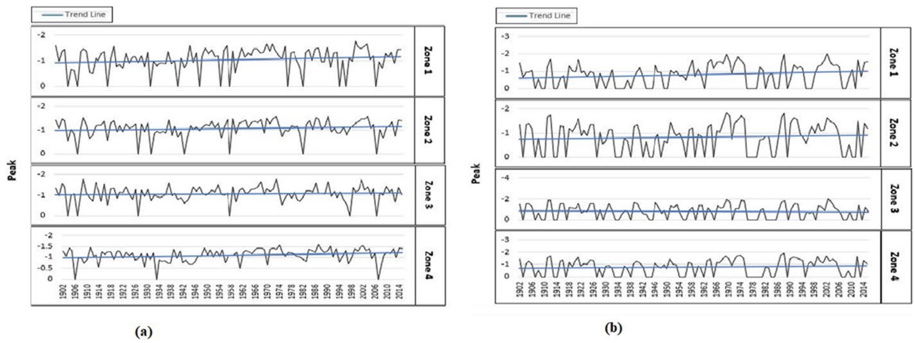


Fig. 9 Drought peak for 3-Month (**a**) and 12-Month (**b**). The trend line represents Sen's slope

series. Figure 6 shows the drought duration for 3 and 12-month SPEI timescales. The results showed an increasing trend in the drought duration in zones 1 (upper region) and 2 (central region) in both 3 and 12-month SPEI. Zone 3 (Desert region) showed an increasing (decreasing) trend in the 3-month SPEI (12-month SPEI). Moreover, a decreasing (increasing) trend was observed in zone 4 (coastal region) in 3-month SPEI (12-month SPEI). In addition, Zone 1 experienced the most prolonged drought duration of 32 months (April 1968—January 1971) in 3-month SPEI. This longest drought duration was also captured in the 12-month SPEI, for which its duration was 47 months (i.e., September 1971—July 1975).

Moreover, Zone 2 (central region) had the longest drought duration of 18 months (June 1968—January 1970) in the 3-month SPEI. In the 12-month SPEI, Zone 2 experienced the longest drought duration of 47 months (September 1971—July 1975). Zone 3 (Desert region) had the longest drought duration of 15 months (September 2001—November 2002) in the 3-month SPEI. In the 12-month SPEI, Zone 3 had the longest drought duration of 25 months (June 1986—June 1988). Zone 4 (coastal region) had the longest drought duration (October 2001—November 2002) in the 3-month SPEI. This drought duration was observed in all zones. In the 12-month SPEI, Zone 4 had the most prolonged drought duration of 35 months (September 1998 to June 2001).

4.2.1.1 Drought severity Drought Severity (DS) is the overall amount of deficit in a drought index below a specific threshold level. It is calculated by adding up the SPEI deficit for each month during the drought. The drought severity plots for 3-month and 12-month SPEI for all zones have been shown in Fig. 7. The results showed an increasing trend in the drought severity in all zones in both SPEIs, which means the drought severity is worsening over time. In 3-month SPEI, Zone 2 experienced maximum severity of −14.8 in 1969. In addition, in 2001–2002, zone 1, 2, 3 and 4 observed the maximum severity of −11.45, −11.8, −13.4, and −10.5, respectively. Moreover, in 1969 for 12-month SPEI, zone 1, 2, 3, and 4 observed the maximum severity of −21.1, −19.8, −18.8, and −18.8, respectively.

4.2.1.2 Drought intensity Drought Intensity (DI) is the average value of the drought index for a particular drought event, which is obtained by dividing the drought severity by its duration. The drought intensity plots for 3-month and 12-month SPEI for all zones have been shown in Fig. 8. The results showed an increasing trend in the drought intensity in both SPEIs except zone 3, where drought intensity is decreasing in the 12-month SPEI. In

3-month SPEI, Zone 1 to 4 suffered maximum intensity of −1.4, −1.5, −1.25, and −1.3, respectively. Similarly, in 12-month SPEI, Zone 1 to 3 suffered maximum intensity of −1.7 while zone 4 suffered a maximum drought intensity of −1.87.

4.2.1.3 Drought peaks Drought Peak (DP) is the minimum value that the index reaches during the entire period of the drought. The drought peak plots for 3-month and 12-month SPEI for all zones have been shown in Fig. 9. Similar to other drought characteristics, an increasing trend in the drought peaks was observed in both SPEIs except zone 3, where drought peaks are slightly decreasing in the 12-month SPEI. In 3-month SPEI, Zone 1 to 4 suffered drought peaks of −1.65, −1.56, −1.74, and −1.58, respectively. For 12-month SPEI, Zone 1 experienced a maximum peak of −2.0, which is very high compared to other zones. All zones observed the drought of 1999–2005 with a maximum drought peak.

Table 3 Mann–Kendall test for 3-month SPEI

Mann–Kendall trend test		
	p value	Sen's slope
Zone-1		
SPEI	0.00032	−0.00024
Duration	0.04376	0.01470
Severity	0.79866	−0.01598
Intensity	0.07929	−0.00119
Peak	0.02839	−0.00402
Zone-2		
SPEI	0.09290	−0.00011
Duration	0.49383	0
Severity	0.40086	−0.00659
Intensity	0.22537	−0.00076
Peak	0.13840	−0.00136
Zone-3		
SPEI	0.35541	−0.00006
Duration	0.21036	0
Severity	0.35840	−0.00816
Intensity	0.79328	−0.00012
Peak	0.43465	−0.00066
Zone-4		
SPEI	0.04511	−0.00013
Duration	0.78402	0
Severity	0.66468	−0.00360
Intensity	0.00048	−0.00194
Peak	0.00552	−0.00207

Statistically Significant at 95% confidence interval

Not Statistically Significant.

Table 4 Mann–Kendall test for 12-month SPEI

Mann–Kendall Trend Test		
	p value	Sen's slope
Zone-1		
SPEI	0.00172	−0.00022
Duration	0.18264	0
Severity	0.05367	−0.01085
Intensity	0.02401	−0.00179
Peak	0.02000	−0.00246
Zone-2		
SPEI	0.04984	−0.00014
Duration	0.61962	0
Severity	0.48790	0
Intensity	0.51630	0
Peak	0.49102	0
Zone-3		
SPEI	0.32997	0.00061
Duration	0.28586	0
Severity	0.39456	0
Intensity	0.60820	0
Peak	0.45989	0
Zone-4		
SPEI	0.00137	−0.00022
Duration	0.86470	0
Severity	0.68265	0
Intensity	0.48204	0
Peak	0.28823	0

Statistically significant at 95% confidence interval

Not statistically significant

4.3 Drought trends

Tables 3 and 4 show the Mann–Kendall (Mann 1945, Kendall 1948) (MK) test results for 3- and 12-month SPEI. The MK test is a statistical technique that examines whether a time series exhibits a monotonically increasing or decreasing trend, it was initially introduced by Mann in 1945 and later expanded by Kendall in 1975. The Mann–Kendall test is a non-parametric tes, it works by computing the Kendall tau rank correlation coefficient, which assesses the strength of the relationship between two variables, namely time series and time, number of steps are involved for conducting MK test; these include; calculating the Kendall tau rank correlation coefficient, analyzing the standard normal test statistic (Z) using the Kendall tau rank correlation coefficient, calculation of the p-value of the test statistic by employing a normal distribution; analyzing whether the p-value is less than the significance level (usually 0.05). If the p-value is less than the significance level, then there is evidence of a trend in the time series (Hirsch et al. 1982; Yue and Wang 2004).The p-value for SPEI in Zone 1 and Zone 4 is less than 0.05 and has a negative Sen's slope magnitude indicating a significant drying trend over the

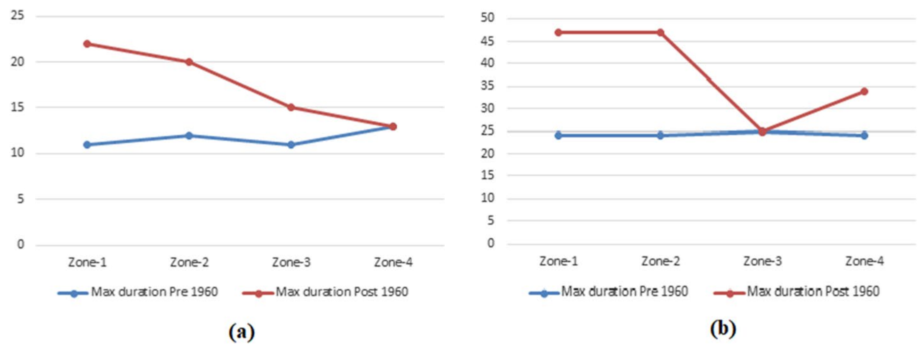


Fig. 10 Maximum drought duration for 3-month (**a**) and 12-month (**b**) SPEI

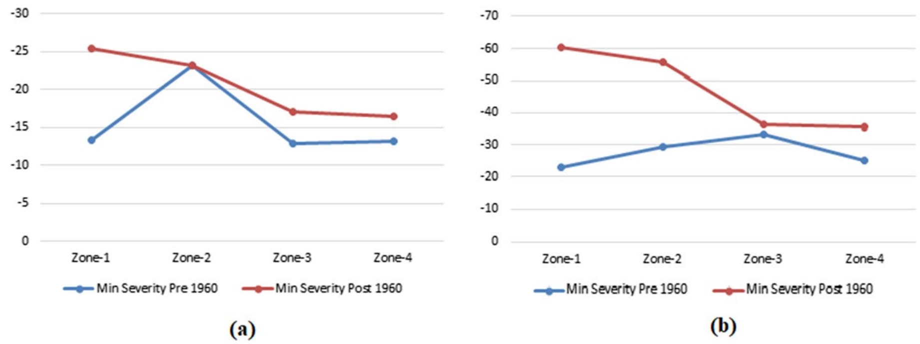


Fig. 11 Maximum drought severity for 3-month (**a**) and 12-month SPEI (**b**)

studied period. For 12-month SPEI, Zone 1, 2, and 4 also showed a significant drying trend. For drought duration, only zone 1 showed a statistically significant trend at a 95% confidence interval for 3-month SPEI, while in 12-month SPEI, it showed a non-statistically significant trend in all zones. However, drought severity showed a non-statistically significant trend for both SPEIs in all zones. Drought intensity showed a statistically significant trend in zone 4 for 3-month SPEI and zone 1 for 12-month SPEI. Moreover, the drought peak showed a statistically significant trend in zone 1 and 4 for 3-month SPEI. Additionally, in the 12-month SPEI, drought peaks showed a statistically significant trend in zone 1.

4.4 Pre and post-1960 analysis

After employing the trend analysis for the entire 1902–2015 period, the results of SPEI were divided into two parts, i.e., pre and post-1960, to evaluate the climatic changes in the study area. Figure 10 shows the maximum drought duration is increased in the post-1960 for 3-month SPEI in all zones except zone 4, where maximum drought duration is almost the same for both pre and post-1960 periods. Similarly, the maximum drought duration is increased in the post-1960 for 12-month SPEI in all zones except zone 3, where maximum drought duration is almost the same for both pre and post-1960 periods.

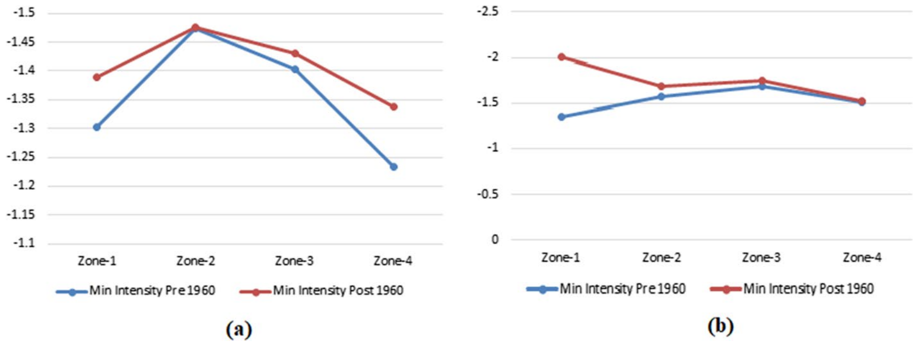


Fig. 12 Maximum drought Intensity for 3-month (**a**) and 12-month SPEI (**b**)

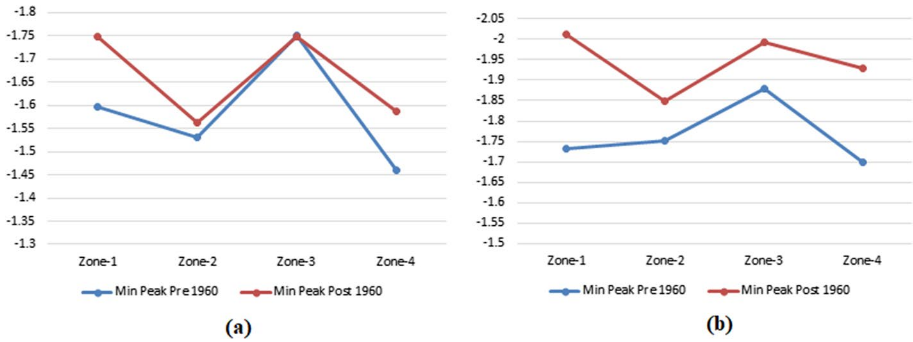


Fig. 13 Maximum drought peaks for 3-month (**a**) and 12-month SPEI (**b**)

The maximum drought severity is also increased in the post-1960 period for both SPEIs in all zones except zone 2 in the 3-month SPEI, where maximum drought severity is almost the same for both pre and post-1960 periods Fig. 11.

Figure 12 shows the maximum drought intensity is increased post-1960 for 3-month SPEI in all zones except zone 2, where maximum drought intensity is almost the same for both pre and post-1960 periods. Similarly, the maximum drought intensity is increased in the post-1960 for 12-month SPEI in all zones except zone 4, where maximum drought duration is almost the same for both pre and post-1960 periods.

Drought peaks are also higher in the post-1960 Fig. 13 for 3-month SPEI in all zones except zone 3, where drought peaks are almost the same for both pre and post-1960 periods. Similarly, the drought peaks are increased in the post-1960 for 12-month SPEI in all zones for both pre and post-1960 periods.

Spatial Efficiency Metric (SPAEF) can be estimated to compare two raster maps using spatial correlation analysis. Spatial correlation analysis is a statistical technique that measures the similarity between the spatial patterns of two raster maps (Petrovic et al. 2022; Rajbanshi and Das 2021). Several spatial correlation measures are available, but two commonly used measures are the Pearson Correlation Coefficient and Spearman's rank correlation coefficient.

The Pearson Correlation Coefficient between the two raster maps pre and post-1960 shown in the Fig. 14 is calculated using the R programming language. The Pearson

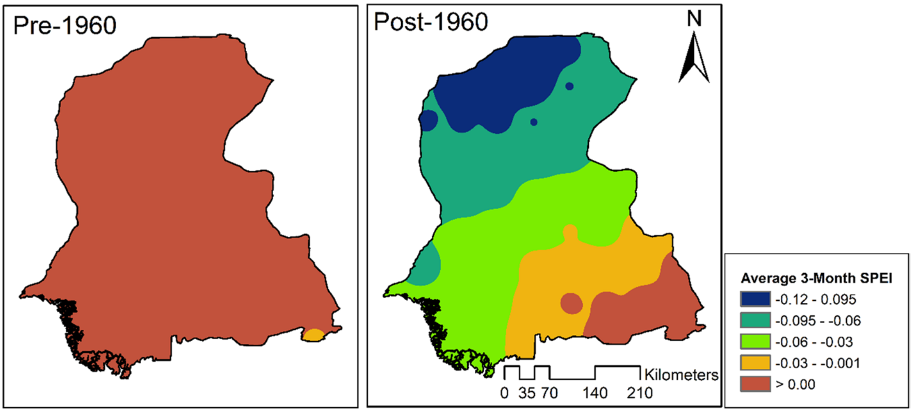


Fig. 14 Spatial efficiency metric 3-month SPEI

Correlation Coefficient values vary from −1 to 1. A high positive value, i.e., closer to 1, indicates that the two maps have similar spatial patterns. In contrast, a high negative value, i.e., closer to −1, indicates that the spatial patterns of the two maps are dissimilar. A value close to zero suggests no relationship between the two maps. This study estimated the Pearson Correlation Coefficient's value as −0.998, indicating that the pre-1960 and post-1960 raster maps are totally different.

The other spatial correlation measure is Spearman's rank correlation coefficient, which is a measure of the strength and direction of association between two variables. It is a non-parametric measure of correlation, which means it does not assume that the data follow any specific distribution. Instead, it ranks the observations of the two variables and calculates the correlation coefficient based on the ranks.

The Spearman's rank correlation coefficient varies from −1 to 1, where a value of −1 indicates a perfect negative correlation (as one variable increases, the other decreases), a coefficient of 0 indicates no correlation, and a coefficient of 1 indicates a perfect positive correlation (as one variable increases, the other also increases). Spearman's rank correlation coefficient is estimated using R programming language. We estimated the Spearman's rank correlation coefficient's value as −0.999, indicating that the pre-1960 and post-1960 raster maps are totally different.

5 Discussion

Our study aimed to examine the various aspects of drought, such as its duration, frequency, severity, intensity, and peak, in Sindh Province over 114 years (1902–2015). We utilized the CRU gridded datasets and analyzed the data using 3-month and 12-month SPEI better to understand the characteristics of drought in the region. Using the SKATER algorithm, we have classified the study area into four distinct zones based on their comparable climatic features. Different studies have employed the SKATER algorithm in their studies. For example, Liu et al. (2015) used this algorithm to analyze spatiotemporal characteristics of droughts across China using a 3-month SPEI. Jamro et al. (2019) utilized the same algorithm to identify zones and analyze drought characteristics in Pakistan.

Based on trend analysis at a 95% confidence interval, a statistically significant decreasing trend for SPEI was observed in zones 1, 2, and 4, while zone 3 displayed a positive trend. The findings of our study are consistent with those of Jamro et al. (2019), who conducted a similar analysis on droughts across Pakistan, including Sindh Province. Their results also indicated a significant decreasing trend in SPEI for Sindh Province, aligning with our findings.

The analysis of the 3-month SPEI revealed that only zone 1 exhibited a statistically significant increase in drought duration, while the other zones showed a non-significant increasing trend, except for zone 4, which showed a decreasing trend in drought duration. The study also identified prolonged drought periods in each zone, such as the one that occurred from 1968 to 1970 in Zones 1 and 2 and another prolonged drought from 2001 to 2002 in Zones 3 and 4. The 12-month SPEI analysis revealed that Zone 2 had the longest drought duration, lasting from 1971 to 1975. Similarly, all zones experienced the longest drought duration from 1986 to 1988. Zone 4, on the other hand, had the most prolonged drought duration from 1998 to 2001. Our findings are consistent with Adnan et al. (2015) wherein they assessed the drought characterization over Sindh Province employing SPI and Global Precipitation Climatology Center (GPCC) dataset and found the severe drought events in the years 1969, 1974, 1987, and 2002. These major drought events are also categorized by Jamro et al. (2019), who analyzed drought patterns in Pakistan using SPEI and took Sindh Province as a single unit. Moreover, Naz et al. (2020) quantified drought characteristics in Balochistan Province using SPI. They also reported the same drought events in the Balochistan region, adjacent to our study region. In addition, Jamro et al. (2020) have reported the same major drought events in Balochistan.

Climate change has been observed to impact the drought characteristics in all zones significantly. Dividing the SPEI results into pre- and post-1960 periods can provide insights into the impact of climate change on drought characteristics in the study area. The period of 1960 is often used as a dividing point to assess climate changes, as it was around this time that significant changes in global temperature and precipitation patterns were observed. The findings that maximum drought duration, severity, intensity, and peak have increased in the post-1960 period for both SPEIs in most zones are consistent with the expected impacts of climate change on drought characteristics. As temperatures continue to rise, the atmosphere can hold more moisture, leading to more intense precipitation events and more prolonged periods of dry weather, increasing droughts' duration. Adnan et al. (2015) found similar results, as they reported the negative effects of climate change on drought characteristics in the same area. In a recent analysis by Hosseini et al. (2021b), the authors observed an increase in the drought characteristics across the entire region of Iran, which became more pronounced following the 1950s. According to a research study conducted by Hosseini et al. (2021a), using the SPI and S-TRACK methods, there has been a significant increase in drought severity, intensity, frequency, and duration over the past four decades. In addition, a recent study has shown that the effects of droughts are becoming more apparent in West Asia, particularly after the 1960s, in terms of severity, intensity, duration, and peak (Sadeghi et al. 2022). The SPAEF for 3-Month SPEI results showed that the Pearson Correlation Coefficient and the Spearman's rank correlation coefficient were estimated as -0.998 and -0.999, respectively. These high negative values indicate that the pre-1960 and post-1960 raster maps differ from each other with more pronounced drought events in the post-1960 time period.

6 Conclusion

This study investigated different drought characteristics, including drought duration, severity, intensity, peak, and events in Sindh Province spanning 114 years, from 1902 to 2015. The drought characteristics were analyzed in two time slices, i.e., pre and post-1960 periods, to analyze the climate change effects. The results indicating that the maximum duration, severity, intensity, and peak of drought have increased in the post-1960 period for both SPEIs in most zones are in line with the anticipated effects of climate change on drought characteristics. The trend analysis using the MK test was carried out to identify significant trends in the SPEI. The analysis revealed that the SPEI has generally decreased, indicating a decrease in precipitation and an increase in the PET and, consequently, an increase in the vulnerability to drought.

We considered the 3- and 12-month SPEIs to cover both short-term and long-term meteorological drought characteristics. However, there are some limitations of this study. We used CRU datasets having 50 km spatial resolution and monthly temporal resolution. Further studies with high-resolution datasets could be conducted to produce drought projections. In addition, other drought indices could be employed, such as Palmer Drought Severity Index (PDSI), Drought Severity Index (DSI), and Crop Moisture Index (CMI). Moreover, in this study, we have used only one regionalization technique (i.e., SKATER). Comparing different regionalization techniques and adding performance metrics to evaluate the application results in future studies is recommended.

Sindh, being a low-lying region and a lower riparian of the Indus Basin, is highly vulnerable to the adverse impacts of climate change. The region is already experiencing more frequent and intense extreme weather events, such as droughts, which are likely to become more severe in the future. In this context, analyzing the drought characteristics of the region is crucial for water planners and policymakers to manage the limited freshwater resources equitably. Therefore, it is important to understand the characteristics of droughts in Sindh, including their duration, severity, and frequency.

Funding The authors have not disclosed any funding.

Declarations

Competing interest The authors have not disclosed any competing interests.

Ethical approval Hereby, I Mansoor Ahmed consciously assure that for the manuscript "Analyzing Drought Trends over Sindh Province, Pakistan" the following is fulfilled: (1) This material is the authors' own original work, which has not been previously published elsewhere. (2) The paper is not currently being considered for publication elsewhere. (3) The paper reflects the authors' own research and analysis in a truthful and complete manner. (4) The paper properly credits the meaningful contributions of co-authors and co-researchers. (5) The results are appropriately placed in the context of prior and existing research. (6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference. (7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

References

Abbas F, Rehman I, Adrees M, Ibrahim M, Saleem F, Ali S, Rizwan M, Salik MR (2018) Prevailing trends of climatic extremes across Indus-Delta of Sindh-Pakistan. Theor Appl Climatol 131:1101–1117

Adnan S, Ullah K (2020) Development of drought hazard index for vulnerability assessment in Pakistan. Nat Hazards 103:2989–3010
Adnan S, Ullah K, Gao S (2015) Characterization of drought and its assessment over Sindh, Pakistan during 1951–2010. J Meteorol Res 29:837–857
Aksoy H, Cetin M, Eris E, Burgan HI, Cavus Y, Yildirim I, Sivapalan M (2021) Critical drought intensity-duration-frequency curves based on total probability theorem-coupled frequency analysis. Hydrol Sci J 66:1337–1358
Ashraf M, Routray JK (2015) Spatio-temporal characteristics of precipitation and drought in Balochistan Province, Pakistan. Nat Hazards 77:229–254
Assunção RM, Neves MC, Câmara G, DA COSTA FREITAS, C. (2006) Efficient regionalization techniques for socio-economic geographical units using minimum spanning trees. Int J Geogr Inf Sci 20:797–811
Beguería S, Vicente-Serrano SM, Reig F, Latorre B (2014) Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. Int J Climatol 34:3001–3023
Bazrkar MH, Zhang J, Chu X (2020) Hydroclimatic aggregate drought index (HADI): a new approach for identification and categorization of drought in cold climate regions. Stochas Environ Res Risk Assess 34:1847–1870
da Silva RM, Santos CA, Moreira M, Corte-Real J, Silva VC, Medeiros IC (2015) Rainfall and river flow trends using Mann-Kendall and Sen's slope estimator statistical tests in the Cobres River basin. Nat Hazards 77:1205–1221
Dars GH, Strong C, Kochanski AK, Ansari K, Ali SH (2020) The Spatiotemporal variability of temperature and precipitation over the upper indus basin: an evaluation of 15 year WRF simulations. Appl Sci 10:1765
Dars GH, Lashari BK, Soomro MS, Strong C, Ansari K (2021) Pakistan's water resources in the era of climate change. Water Resour Pak Issues Impacts 9:95
Edossa DC, Woyessa YE, Welderufael WA (2016) Spatiotemporal analysis of droughts using self-calibrating Palmer's Drought Severity Index in the central region of South Africa. Theoret Appl Climatol 126:643–657
Gibbs WJ, Maher JV (1967) Rainfall deciles as drought indicators, bureau of meteorology bulletin No. 48.Commonwealth of Australia:Melbourne 29
Guo H, Bao A, Liu T, Ndayisaba F, Jiang L, Kurban A, de Maeyer P (2018) Spatial and temporal characteristics of droughts in Central Asia during 1966–2015. Sci Total Environ 624:1523–1538
Haroon MA, Zhang J, Yao F (2016) Drought monitoring and performance evaluation of MODIS-based drought severity index (DSI) over Pakistan. Nat Hazards 84:1349–1366
Harris I, Jones PD, Osborn TJ, Lister DH (2014) Updated high-resolution grids of monthly climatic observations–the CRU TS3. 10 Dataset. Int J Climatol 34:623–642
Hirsch RM, Slack JR, Smith RA (1982) Techniques of trend analysis for monthly water quality data. Water Resour Res 18:107–121
Hosseini A, Ghavidel Y, Farajzadeh M (2021a) Characterization of drought dynamics in Iran by using S-TRACK method. Theoret Appl Climatol 145:661–671
Hosseini A, Ghavidel Y, MOHAMMAD KHORSHIDDOUST, A. & FARAJZADEH, M. (2021b) Spatio-temporal analysis of dry and wet periods in Iran by using global precipitation climatology center-Drought Index (GPCC-DI). Theoret Appl Climatol 143:1035–1045
Jamro S, Dars GH, Ansari K, Krakauer NY (2019) Spatio-temporal variability of drought in Pakistan using standardized precipitation evapotranspiration index. Appl Sci 9:4588
Jamro S, Channa FN, Dars GH, Ansari K, Krakauer NY (2020) Exploring the evolution of drought characteristics in balochistan. Pak Appl Sci 10:913
Kendall MG (1948) Rank correlation methods.
Krakauer NY, Lakhankar T, Dars GH (2019) Precipitation trends over the Indus basin. Climate 7:116
Liu X, Wang S, Zhou Y, Wang F, Li W, Liu W (2015) Regionalization and spatiotemporal variation of drought in China based on standardized precipitation evapotranspiration index (1961–2013). Adv Meteorol
Mahajan D, Dodamani B (2015) Trend analysis of drought events over upper Krishna basin in Maharashtra. Aquat Procedia 4:1250–1257
Mann HB (1945) Nonparametric tests against trend. Econ J Econom Soc 245–259
Mckee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th conference on applied climatology, Boston, 179–183
Naz F, Dars GH, Ansari K, Jamro S, Krakauer NY (2020) Drought trends in Balochistan. Water 12:470
Palmer WC (1965) Meteorological drought. US Department of Commerce, Weather Bureau.

Petrovic D, Fersch B, Kunstmann H (2022) Droughts in Germany: performance of regional climate models in reproducing observed characteristics. Natl Hazards Earth Syst Sci 22:3875–3895

Rajbanshi J, Das S (2021) The variability and teleconnections of meteorological drought in the Indian summer monsoon season: Implications for staple crop production. J Hydrol 603:126845

Sadeghi F, Ghavidel Y, Farajzadeh M (2022) Long-term analysis of the spatiotemporal standardized precipitation evapotranspiration index for West Asia. Arab J Geosci 15:1183

SEN, P. K. (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63:1379–1389

SENEVIRATNE, S. I. J. N. (2012) Historical drought trends revisited. Nature 491:338–339

Tian L, Quiring SM (2019) Spatial and temporal patterns of drought in Oklahoma (1901–2014). Int J Climatol 39:3365–3378

TIRIVAROMBO, S., D. OSUPILE & ELIASSAN, A. P. (2018) Drought monitoring and analysis: standardised precipitation evapotranspiration index (SPEI) and standardised precipitation index (SPI). Phys Chem Earth Parts 106:1–10

Touma D, Ashfaq M, Nayak MA, Kao S-C, Diffenbaugh NS (2015) A multi-model and multi-index evaluation of drought characteristics in the 21st century. J Hydrol 526:196–207

Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J Clim 23:1696–1718

Wang W, Zhu Y, Xu R, Liu J (2015) Drought severity change in China during 1961–2012 indicated by SPI and SPEI. Nat Hazards 75:2437–2451

Won J, Kim S (2023) Ecological drought condition index to monitor vegetation response to meteorological drought in Korean Peninsula. Remote Sens 15:337

Wu R, Zhang J, Bao Y, Guo E (2019) Run theory and copula-based drought risk analysis for songnen grassland in northeastern China. Sustainability 11:6032

Xie H, Ringler C, Zhu T, Waqas A (2013) Droughts in Pakistan: a spatiotemporal variability analysis using the Standardized Precipitation Index. Water Int 38:620–631

YEVJEVICH, V. M. (1967) Objective approach to definitions and investigations of continental hydrologic droughts. An. Colorado State University, Libraries

Yue S, Wang C (2004) The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. Water Resour Manage 18:201–218

Zou X, Zhai P, Zhang Q (2005) Variations in droughts over China: 1951–2003. Geophys Res Lett, 32