Characterization of Drought and Its Assessment over Sindh, Pakistan During 1951–2010

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ABSTRACT

Drought is one of the complex meteorological disasters affecting water resources, agriculture, livestock, and socioeconomic patterns of a region. Although drought prediction is difficult, it can be monitored based on climatological information. In this study, we provide high spatiotemporal resolution drought climatology, using observational, gridded precipitation data (0.5°×0.5°) from the Global Precipitation Climatological Center and soil moisture data from the Climate Prediction Center for the 60-yr period 1951–2010. The standardized precipitation index (SPI) based on a fitted Gamma distribution and Run method has been calculated from the regional drought identification model (ReDIM) for 3, 6, 9, 12, and 24 months. The results show strong temporal correlations among anomalies of precipitation, soil moisture, and SPI. Analysis of long-term precipitation data reveals that the drought vulnerability concentrates on monsoon season (July–September), which contributes 72.4% and 82.1% of the annual precipitation in northern and southern Sindh, respectively. Annual and seasonal analyses show no significant changes in the observed precipitation. The category classification criteria are defined to monitor/forecast drought in the selected area. Further analysis identifies two longest episodes of drought, i.e., 1972–1974 and 2000–2002, while 1969, 1974, 1987, and 2002 are found to be the most severe historical drought years. A drought hazard map of Sindh was developed, in which 10 districts are recognized as highly vulnerable to drought. This study helps to explain the time, duration, intensity, and frequency of meteorological droughts over Sindh as well as its neighboring regions, and provides useful information to disaster management agencies and forecasters for assessing both the regional vulnerability of drought and its seasonal predictability in Pakistan.

Key words: climatology, drought, standardized precipitation index (SPI), regional drought identification model (ReDIM), Sindh

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1. Introduction

Drought is caused naturally by the deficiency of rainfall over a prolonged period in an area, in which the lack of natural water availability leads to temporary deficiency (Vogt and Somma, 2013). It is probably the worst natural disaster, which influences and causes the largest economic loss, affecting various aspects of life with great successive and potentially hazardous consequences (Zheng, 2000; Zhang et al., 2011). Aridity is the climate characteristic used to describe a specific region (Wilhite, 2012) where the available water resources are not sufficient to fulfill the long-term water demands of the region (Spinoni et al., 2014). In addition to the societal and environmental impacts of droughts, numerous droughts can lead to desertification and land degradation. This is the situation that arose between the 1960s and 1970s in the Sahel (Zeng, 2003).

Drought is a creeping phenomenon. It develops

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gradually and propagates during the water year, which is a 12-month period from 1 October to 30 September next year, according to the Unites States Geological Survey (USGS). Its consequences persist after termination, unlike other hydrometeorological and geological disasters such as floods, cyclones, tornados, volcanic outbursts, and earthquakes (Vogt et al., 2011). In general, there are four types of drought that can be distinguished: meteorological drought, caused by the shortage of precipitation with respect to climatology over a long period in a region; agriculture drought, caused by deficiency of soil moisture and crop water needs; hydrological drought, caused by channel flow or water level in rivers, canals, or reservoirs falling below an established statistical average (Dracup et al., 1980); and socioeconomic drought, caused by the impact of previously mentioned three types of drought conditions on the supply and demand of economic goods and services (Wilhite and Glantz, 1985). Recently, a fifth category has been suggested by Mishra and Singh (2010) as drought of ground water.

Drought may affect large areas and population both socioeconomically and environmentally. About 50% of the earth's land has been drought vulnerable (Kogan, 1997). Recently, Emergency Events Database (EM-DAT, 2013) reported that more than 200 million people were affected, and 11 million had been killed by drought between 1900 and 2011. Higher temperatures may increase the number of droughts and dry conditions (Dai et al., 2004). Similarly, Sheffield et al. (2012) observed a smaller increase in the frequency of global drought.

The present study focuses on analysis of precipitation, one of the triggering factors of drought. Subsidence and higher temperature are caused by the atmospheric blocking pattern, which affects the trajectory of storm and normal precipitation (Spinoni et al., 2014). The single drought indicator method such as standardized precipitation index (SPI) uses only the precipitation input to provide early warnings of drought and help in drought severity assessment (WMO, 2012), and therefore, it does not describe the complete picture of a drought process, which also includes soil moisture response on short timescale and groundwater, reservoirs, and stream flow responses on longer terms to precipitation anomaly. However, we still choose to use SPI in this study because SPI quantifies the precipitation deficit and changes as the length of records grows, and SPI is recommended by WMO and many national hydrometeorological organizations across the world due to its simplicity and versatility.

The geographical location of Sindh, Pakistan is shown in Fig. 1. According to a government report of Pakistan (GoP, 2014), Sindh Province has a population of 42400000 and a total area of 140914 m^2 centered around 26.1°N, 68.5°E, which includes low elevation plains (250 m above sea level) and the Kirthar Range with elevations above 1000 m in the west of Sindh (UNEP, 1998). Approximately two thirds of the areas of Pakistan lie in an arid climate, including Sindh Province (Adnan, 2009). The annual rainfall is less than 200 mm in the southern parts of Pakistan, including Sindh and Baluchistan (Adnan and Khan, 2009). The intraseasonal variability of rainfall is high over Sindh, with significant floods and droughts in that region (Muslehuddin and Faisal, 2006). According to the rainfall climatology of Pakistan (1981–2010), most of the rainfall is received during the monsoon season (July–September) and summer season (May–September) is hot, with temperatures reaching up to 50°C.

The drought climatology and hazard map of Sindh has not yet been established. Therefore, this study focuses on determining the historical episode, frequency, intensity, category, type, and return period of drought, identifying the criteria of drought, and developing a drought hazard map for the 23 districts in Sindh by using the climatological datasets of rainfall and soil moisture in the past 60 years (1951–2010). This study also provides information regarding the sensitivity and behavior of soil moisture during drought years. The final results are expected to help climatologists, agro-meteorologists, agriculturists, agronomists, policy makers, and stakeholders to improve the drought preparedness and make mitigation, adaptation, and contingency plans for drought in this region.

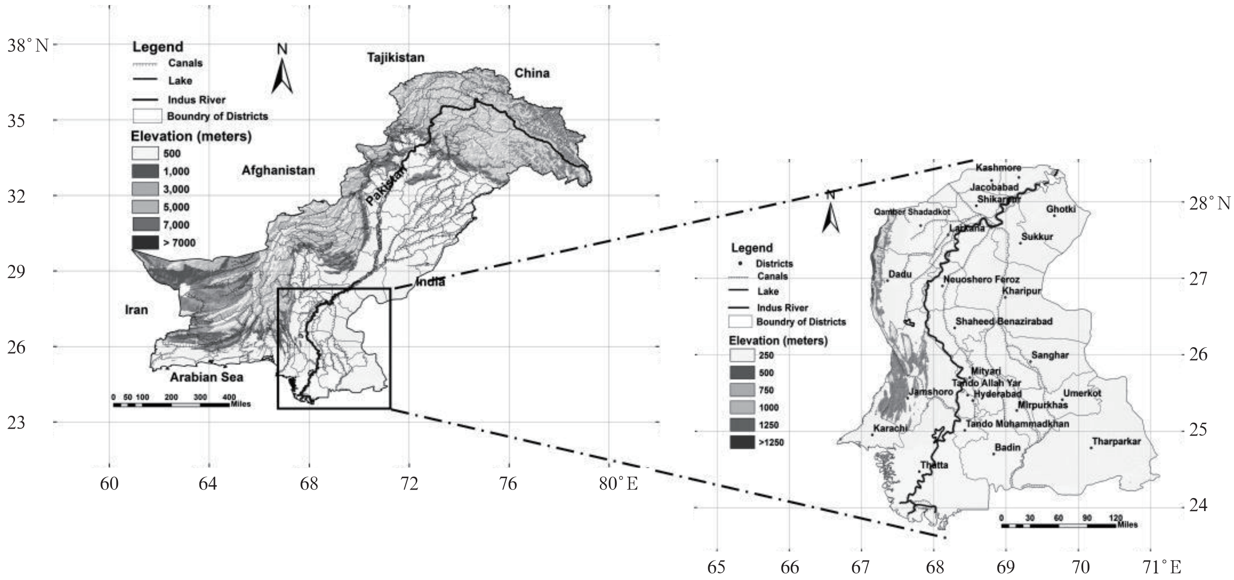

Fig. 1. Topographical map showing the geographical location of 23 districts of Sindh Province, Pakistan.

2. Methodology

2.1 Precipitation and soil moisture data

The precipitation data (version 6.0) on a resolution of 0.5°×0.5° were obtained from the Global Precipitation Climatological Center (GPCC; http://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html) (Becker et al., 2013). The dataset was selected because of the following reasons: first, it has the longest precipitation record that is spatially interpolated; second, it has a complete dataset of all gridded points after January 1951, while it ranges from January 1901 to December 2010; third, this dataset has already been used for regional and global drought studies (Becker et al., 2013); and fourth, it has a very strong correlation with the in-situ station rainfall data due to its high resolution (see details in Section 3 of this paper).

Many studies have been conducted to investigate worldwide droughts based on the GPCC datasets, such as the South African drought (Rouault and Richard, 2003), the outstanding drought in Iberian (Garcia-Herrera et al., 2007), the Qilian Mountains historical droughts (Liu et al., 2009), the European drought (Pietzsch and Bissolli, 2011), variability of the drought in Iran (Raziei et al., 2011), the historical droughts in Amazon region in the context of 2010 (Marengo et al., 2011), the SPI analysis of droughts in Africa (Kurnik et al., 2011), and the world droughts under global warming (Dai, 2011).

The GPCC monthly climatological rainfall dataset (1951–2010) with a high resolution of 0.5°×0.5°, along with the local gauging station data, were selected for monthly and annual analysis because they passed all the quality tests and allowed for better analysis of the regional drought pattern. The first soil moisture dataset (1931 to present), known as the Climate Prediction Center (CPC) soil moisture (Huang et al., 1996), plays a significant role in the real-time national drought monitoring (Svoboda et al., 2002). The monthly soil moisture dataset was produced by the Leaky Bucket model with a horizontal resolution of 0.5°×0.5° for the period 1951–2010. It worked reasonably well against the limited observations in a different region with a spatial resolution of 0.5°×0.5° from 1948 to date (Fan and Dool, 2004, 2008).

Five tests were conducted to determine the significance at the 90% and 95% confidence levels, namely, the Student t-test (Helsel and Hirsch, 1992; Maidment, 1993) for linear trends, the turning point test (Kottegoda, 1980) for randomness, the Kendall τ-test (Helsel and Hirsch, 1992; Maidment, 1993), and the Sen's slope method (Sen, 1968) to detect the magnitude of the trend.

A drought hazard map is prepared by keeping in view the geography and climatology of the selected districts of Sindh, Pakistan. The long-term data are analyzed to determine the historical drought frequency and intensity, monthly and seasonal precipitation dependencies, soil moisture anomaly, cumulative rainfall deficit, and the area deficit for each district.

2.2 Regional drought identification model (ReDIM)

Identifying the characteristics of drought over a local region is useful for planning and managing water shortage risks and for implementing preparedness and adaptation measures. A regional drought identification model (ReDIM) was adopted in this study. It uses the SPI and Run method (RM) to determine historical drought events, return period, regional drought analysis, and water deficit period (Rossi et al., 2003). Details about the RM are provided in Section 2.4.

2.3 Standardized precipitation index (SPI)

McKee et al. (1993) used SPI to monitor the status of drought in Colorado, USA by extracting information on different timescales from precipitation observations. They calculated SPI for different monthly timescales (3, 6, 12, 24, and 48 months) to reflect the temporal behavior of drought. Based on these results, the type of drought can be defined. Drought with SPI on 6-, 9-, 12-, and 24-month timescales is defined as meteorological drought, agricultural drought, hydrological drought, and hydrological drought, respectively.

To determine drought severity and excessive wetness, SPI has been used with remarkable success in several applications (Gidding et al., 2005). Data that span at least 30 consecutive years are recommended for SPI use.

The strength of drought in Sindh is classified after standardization, as shown in Table 1. The corresponding probability is calculated by using the normal probability density function for each severity. Thus, for a drought year in the Sindh region, the mild drought (SPI < -0.5), moderate drought (SPI $\leqslant -1.0$), severe drought (SPI $\leqslant -1.50$), and extreme drought (SPI $\leqslant -2.0$) have a probability occurrence of 16.5%, 9.1%, 2.7%, and 1.7%, respectively.

Table 1. Drought classification based on SPI values and the corresponding event's probability for Sindh

SPI value	Category	Probability (%)
$\geqslant 2.00$	Extreme wet	1.7
1.50 to 1.99	Severe wet	2.7
1.00 to 1.49	Moderate wet	9.1
0.50 to 0.99	Mild wet	16.5
0.49 to –0.49	Normal	40.0
–0.50 to –0.99	Mild drought	16.5
–1.00 to –1.49	Moderate drought	9.1
–1.50 to –1.99	Severe drought	2.7
$\leqslant -2.00$	Extreme drought	1.7

Source: McKee et al. (1993).

2.4 Run method (RM)

Run method is used to determine drought period and to calculate statistical characteristics of drought. Yevjevich (1967) stated that the drought period derived by RM as a function of hydrological variables remains below a threshold or critical level during consecutive number of intervals. The advantage of RM is its ability to determine the drought characteristics analytically by data generated in terms of duration and deficit if the random probability distributions of prime variables are known (Cancelliere et al., 1998; Fernández and Salas, 1999).

3. Results

The aim of this study is to conduct drought analysis for the 23 districts of Sindh Province as shown in Fig. 1. However, Pakistan Meteorological Department (PMD) has only eight meteorological stations in the whole Sindh Province. In order to fill this gap, GPCC data were used. The spatiotemporal analysis of GPCC data was performed in-situ with analysis of PMD data over eight districts of Sindh during the monsoon season (July–September) as well as annually. The spatial and temporal correlations between the GPCC data and the meteorological station rainfall data are shown in Figs. 2 and 3.

The scatter and time series graphs are plotted between the GPCC data and meteorological station data for eight districts of Sindh. The regression line shows that the coefficient of determination R^2 is 0.996 for annual rainfall, while R^2 is 0.968 for monsoon season (July–September) rainfall. Monsoon season is the main rainy season in Sindh, in which high variability in precipitation is observed. The high value of R^2 indicates that the GPCC data are well consistent with the meteorological station data in the region. Long-term analysis of rainfall during 1951–2010 shows a strong correlation between GPCC data (0.5°×0.5°) and the station data, both temporally and spatially, as shown in Figs. 2 and 3, as also suggested by Fan and Dool (2004). Based on this comparison, GPCC data can be used for Sindh districts and any other plane areas in the country where meteorological station data are not available.

The intraseasonal variability of rainfall during the monsoon season (July–September) leads to droughts and floods in this region (Muslehuddin et al., 2005). The climate normal of rainfall (1981–2010) shows that southern Sindh received 169.1 mm of rainfall, while northern Sindh received 93.3 mm during the rainy season (PMD, 2013). To determine the contribution of monsoon rainfall over Sindh, the percentage of monsoon rainfall calculated for the 23 districts is shown

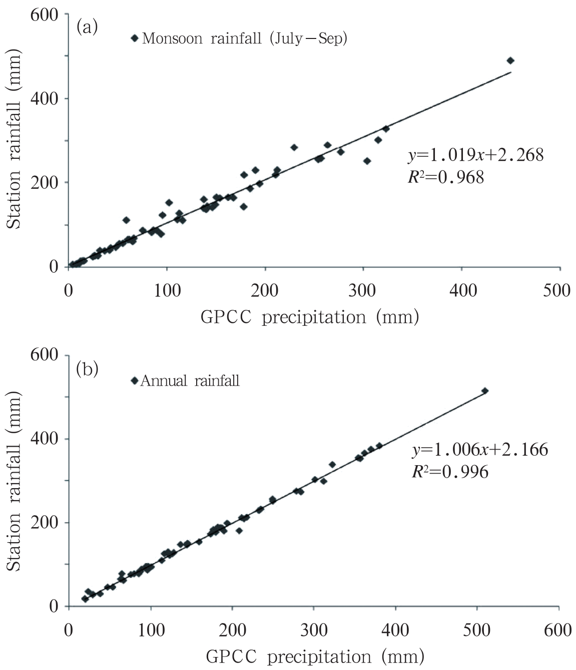

Fig. 2. Relationship between GPCC rainfall data and meteorological station rainfall data over Sindh (a) during the monsoon season and (b) annually between 1951 and 2010.

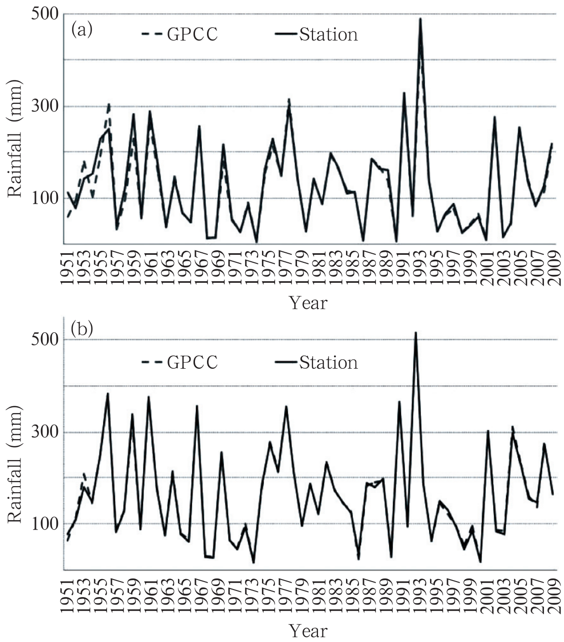

Fig. 3. Temporal relationship between the GPCC data and station data in Sindh (a) during the monsoon season (July–September) and (b) annually between 1951 and 2010.

in Fig. 4. Monsoon rainfall makes up 78.2% of annual rainfall in Sindh, with a minimum contribution of 59.3% in Kashmore and a maximum contribution of 98.1% in Tharparkar. Figure 4 also shows that the districts in southern Sindh (i.e., Badin, Mirpurkhas, Sanghar, Tando Muhammad Khan, Tharparkar, Thatta, and Umerkot) received over 80% of annual rainfall during the monsoon season, while the districts in northern Sindh received between 59% and 81% of annual rainfall during the monsoon season, with Shaheed Benzairabad receiving the largest percentage (80.3%). The analysis shows that southern Sindh depends more heavily on monsoon rainfall than northern Sindh.

Figure 5 shows strong correlations between the annual rainfall departure with 12-month SPI (abbreviated as 12-SPI, similarly for 3-, 6-, 9-SPI, etc.) (r = 0.97), rainfall departure with soil moisture (r = 0.80), and soil moisture with SPI (r = 0.77). Hence, we may determine the soil moisture departure and SPI by knowing the rainfall departure, which is a good indicator for drought monitoring as discussed by Naren-

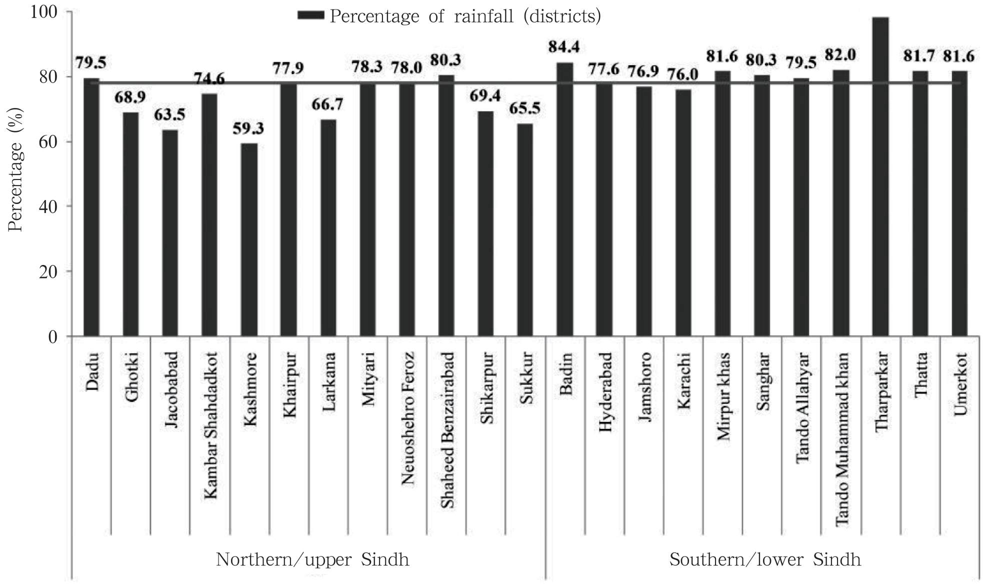

Fig. 4. Percentage of monsoon rainfall in the 23 districts of Sindh between 1951 and 2010.

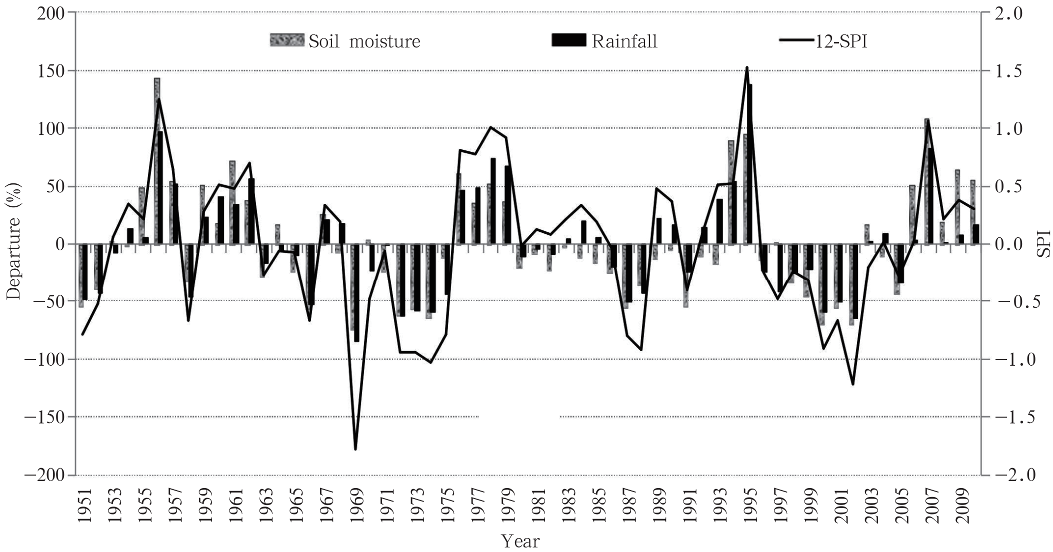

Fig. 5. Temporal comparison among 12-month SPI and percentage departure of soil moisture and rainfall in Sindh Province during 1951–2010.

dra (2008). Note: SPI is the probability of precipitation on any timescale, i.e., 1, 3, 6, 9, 12, 24, 48 months and so on, etc. whereas 12-SPI is the SPI for consecutive 12 months; 12-SPI is a comparison of the precipitation for 12 consecutive months with that recorded in the same 12 consecutive months in all previous years of available data. Ideally, SPI needs at least 20–30 consecutive years of data in order to calculate drought (Guttman, 1994). The rainfall departure, however, does not require long-term data and it works similarly to SPI.

Figure 6 shows the relationship among percentage mean area deficit, 50% quantile frequency, and 12-SPI in Sindh. The percentage mean area deficit increases with respect to SPI (tends to be negative), showing an inverse relationship between the two. The area deficit (%) increases due to negative values of SPI while positive values reduces this deficit (Wu et al., 2001). 1969

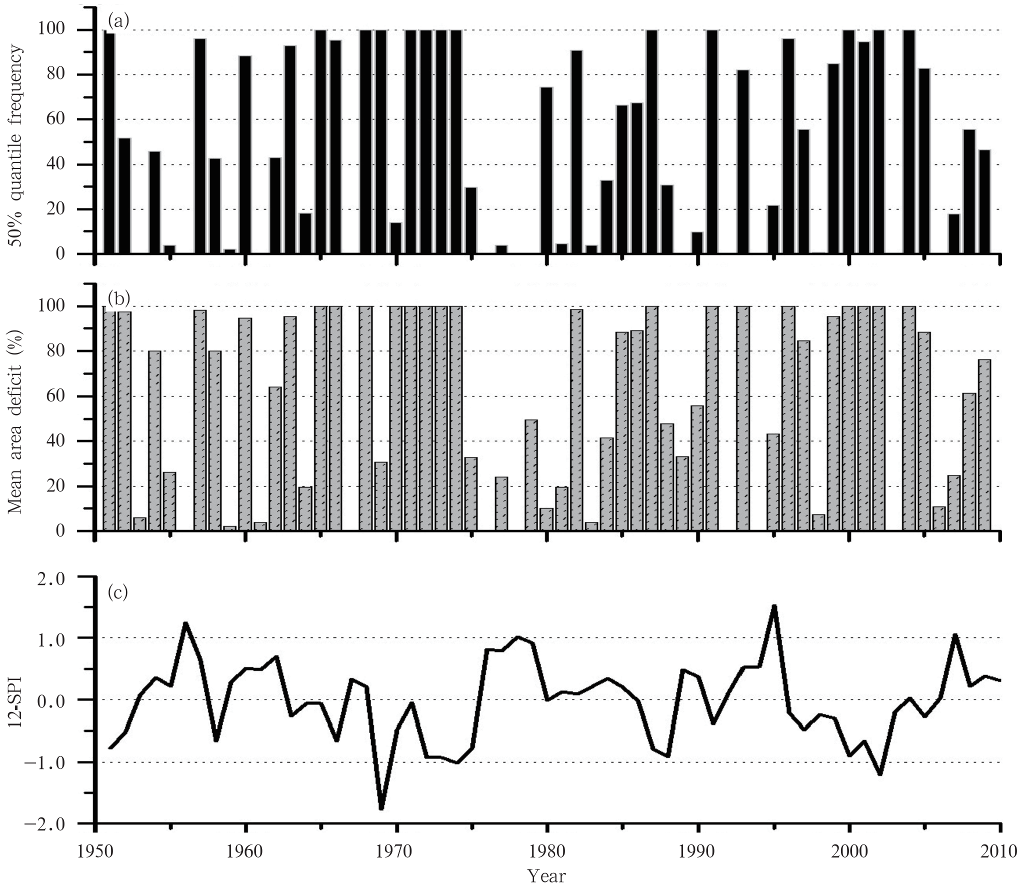

Fig. 6. Time series analysis among (a) 50% quantile frequency, (b) mean area deficit (%), and (c) 12-SPI of Sindh during 1951–2010.

is an extreme drought year in the history of Sindh Province, where the lowest 12-SPI and soil moisture departure are observed (–50 and –90%). An abrupt change from a dry period to a wet period is observed in Sindh Province in the early 1990s, similar to what was observed in Hunan Province of China (Zhang et al., 2011).

Figure 7 shows the mean deficit (MD), mean area deficit (MAD), 50% quantile frequency (QF), and 12-SPI along with the 5-yr moving average for the 60-yr period (1951–2010). There is an obvious relationship between the MD, MAD, and 50% quantile frequency deficit (QFD). Specifically, the 12-SPI is inversely proportional to MD ($r = –0.61$), MAD ($r = –0.44$), and QF ($r = –0.62$), which means that MD, MAD, and 50% QFD are in phase, while 12-SPI is out of phase with the other three variables. Therefore, the intensity of SPI (higher negative values) and time duration (3, 6, 9, 12, and 24 months) increase with MAD and MD.

Isopleths were drawn relative to each station to identify the spatial association of rainfall over the 23 districts of Sindh for the period 1951–2010. Correlation coefficients were calculated for each of the other districts to determine the degree of correlation between the annual rainfall in each region. Figure 8 shows these coefficient isopleths with Shaheed Benazirabad in the center of Sindh as the base station, as suggested by Maher (1967). There is a significant correlation between annual rainfalls in the climate zone centered on the base station. Apart from the high correlation around the base station, the pattern for other stations shows a general east-south-east and east-north-east configuration, which is most likely associated with the normal paths of moving synoptic systems. The correlation patterns did not form circles, as might be anticipated, but were approximated by ellipses. The orientation of the axes of maximum and minimum correlations does not offer a means to trace the flux of atmospheric moisture or a means to identify its sources (Yevjevich, 1967). This figure shows a high correlation among the 23 districts of Sindh, showing that all the districts receive rainfall, if a rainfall system approaches the base station.

The results from Mann-Kendall test for annual precipitation series show values that are statistically significant for $Z > 1.61$ and $Z > 1.05$ at the 95% and 90% confidence levels, respectively. The results showed no significant change at the 95% confidence level as demonstrated by Hanif et al. (2013). How-

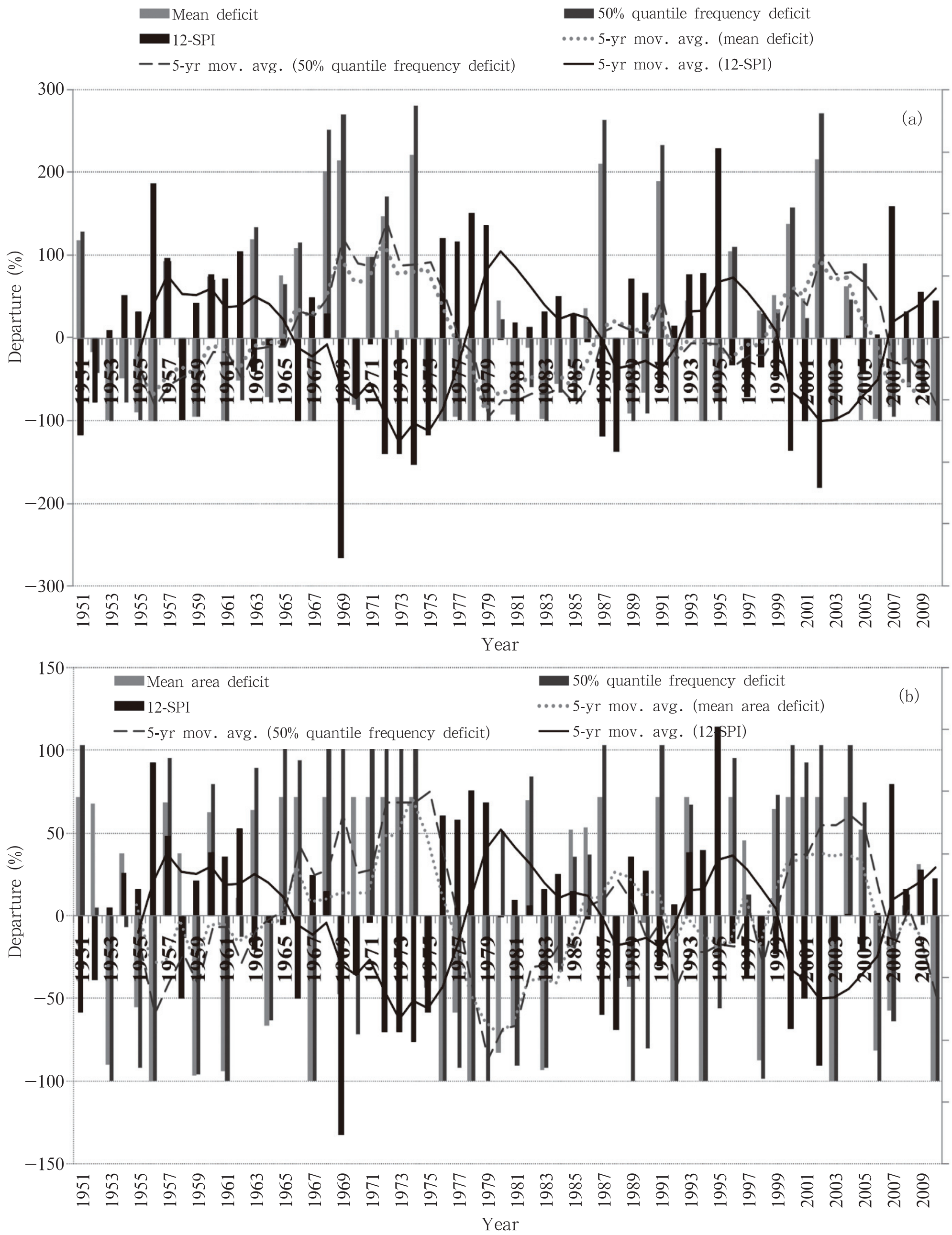

Fig. 7. Comparison between 50% quantile frequency and 12-SPI of Sindh for (a) mean deficit (%) and (b) mean area deficit (%), based on time series analysis using a 5-yr moving average.

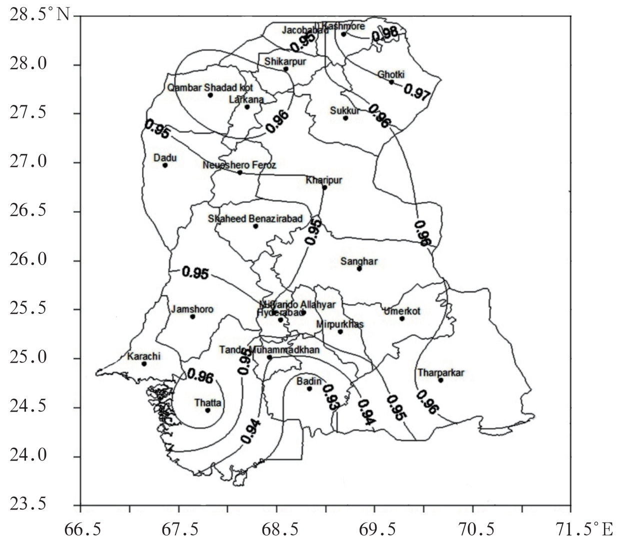

Fig. 8. Correlation coefficient isopleths of annual rainfall between the base station Shaheed Benazirabad and other stations in the 23 districts of Sindh Province during 1951–2010.

ever, a significant change was observed for the Jacobabad and Kashmore districts at the 90% confidence level. Table 2 shows a positive trend in the districts of Ghotki, Jacobabad, Kashmore, Larkana, Mirpurkhas, Sanghar, Sikarpur, Sukkur, Tharparkar, and Umerkot, and negative trends in the rest of the districts, representing almost non-significant conditions. The estimated Sen's slope (Q) shows the rising slope magnitude in the above-mentioned districts, although not a significant one. Sen's slope corresponds to Mann-Kendall test value and determines the increasing and decreasing trends and the magnitude of the slope (Mondal et al., 2012). The Student t-test and turning point test are found to be non-significant and random, respectively.

Table 3 shows strong correlations between rainfall departures and SPI. The rainfall departure and SPI were taken on the same timescale, e.g., 3 months. Table 3 indicates that the correlation between the rainfall departure and SPI becomes stronger with the passage of time as indicated by Kumar et al. (2009). Drought intensity as a function of rainfall departure was also calculated, and the results are presented in Table 4.

The intensity and category of droughts were calculated from rainfall departure (%) on 3-, 6-, 9-, 12-, and 24-month timescales by analyzing the data over 1951–2010 as shown in Table 4. The rainfall departure (%) is a simple tool for determining the intensity and category of drought. Long-term data (1951–2010)

Table 2. Results from four different statistical tests for the 23 districts of Sindh

No.	District	Mann Kendall τ-test	Sen's slope estimate (Q)	Student t-test	Turning point test
1	Badin	–0.18	–0.28	–0.2	–0.51
2	Dadu	–0.27	–0.18	–0.2	0.41
3	Ghotki	0.87	0.46	0.8	1.03
4	Hyderabad	–0.36	–0.30	–0.4	1.03
5	Jacobabad	1.23	0.69	1.0	–0.51
6	Jamshoro	–0.68	–0.62	–0.7	–0.2
7	Kambar Shahdadkot	–0.20	–0.13	–0.9	–0.82
8	Karachi	–0.71	–0.73	1.1	1.34
9	Kashmore	1.20	0.69	–0.1	0.41
10	Khairpur	–0.16	–0.06	0.4	1.03
11	Larkana	0.31	0.10	–0.3	1.03
12	Matiari	–0.40	–0.35	0.3	0.41
13	Mirpurkhas	0.30	0.24	–0.2	0.41
14	Naushahro Firoze	–0.67	–0.38	–0.2	0.41
15	Sanghar	0.47	0.46	–0.1	0.41
16	Shaheed Benazirabad	–0.25	–0.23	0.5	0.41
17	Shikarpur	0.36	0.15	0.3	1.65
18	Sukkur	0.66	0.33	0.6	1.03
19	Tando Allahyar	–0.45	–0.38	–0.3	0.41
20	Tando Muhammad Khan	–0.41	–0.44	–0.3	0.41
21	Tharparkar	0.43	0.43	0.7	0.41
22	Thatta	–0.45	–0.55	–0.6	–0.82
23	Umerkot	0.43	0.52	0.8	0.41

Table 3. Correaltion of rainfall departure with 3-, 6-, 9-, 12-, and 24-SPI for Sindh districts

Station	3-SPI	6-SPI	9-SPI	12-SPI	24-SPI
Badin	0.77	0.84	0.91	0.92	0.97
Dadu	0.91	0.93	0.94	0.94	0.98
Ghotki	0.81	0.98	0.95	0.97	0.98
Hyderabad	0.80	0.86	0.94	0.96	0.98
Jacobabad	0.78	0.85	0.93	0.94	0.96
Jamshoro	0.84	0.88	0.95	0.96	0.98
Kambar Shahdadkot	0.86	0.89	0.95	0.97	0.98
Karachi	0.86	0.90	0.96	0.95	0.98
Kashmore	0.86	0.91	0.96	0.98	0.98
Khairpur	0.94	0.87	0.94	0.95	0.98
Larkana	0.84	0.90	0.95	0.97	0.97
Mityari	0.81	0.86	0.94	0.96	0.98
Mirpur khas	0.80	0.87	0.93	0.95	0.99
Neuoshehro Feroz	0.83	0.87	0.94	0.95	0.98
Sanghar	0.79	0.87	0.93	0.96	0.99
Shaheed Benzairabad	0.79	0.84	0.92	0.94	0.98
Shikarpur	0.82	0.87	0.95	0.96	0.97
Sukkur	0.79	0.85	0.94	0.95	0.97
Tando Allahyar	0.78	0.86	0.93	0.95	0.98
Tando Muhammad khan	0.79	0.86	0.93	0.94	0.98
Tharparkar	0.87	0.91	0.95	0.97	0.99
Thatta	0.86	0.91	0.97	0.97	0.99
Umerkot	0.82	0.87	0.92	0.95	0.99
Southern Sindh	0.82	0.88	0.94	0.95	0.98
Northern Sindh	0.84	0.89	0.94	0.96	0.98
Sindh	0.83	0.88	0.94	0.95	0.98

Table 4. Drought monitoring indicator for the Sindh region

Category of drought	SPI	Departure (%)	Drought intensity
Dry period	3-SPI	–40 to –80	Mild
		> –80	Moderate
Meteorological drought	6-SPI	–40 to –65	Mild
		–66 to –80	Moderate
		–81 to –95	Severe
		> –95	Extreme
Agriculture drought	9-SPI	–40 to –65	Mild
		–66 to –80	Moderate
		–81 to –95	Severe
		> –95	Extreme
Hydrological drought	12-SPI	–40 to –60	Mild
		–61 to –75	Moderate
		–76 to –85	Severe
		> –85	Extreme
Extreme hydrological drought	24-SPI	–25 to –45	Mild
		–46 to –60	Moderate
		–61 to –75	Severe
		> –75	Extreme

show that neither severe nor extreme droughts were observed based on 3-SPI, as drought intensity depends upon the length of the timescale. Table 4 is useful in monitoring and predicting the category and intensity of drought in Sindh. The analysis shows that Sindh is highly dependent on the monsoon rainfall, and rainfall deficiency during the monsoon season may lead to droughts. Hence, on the basis of monsoon rainfall departure, drought intensity can be monitored and predicted. The following four conditions are important for monitoring and predicting drought in Sindh.

1) If monsoon rainfall departure is more than –60% or the first two quarter departure is more than –50%, mild drought might occur;

2) If monsoon rainfall departure is more than –65%, or the first two quarter departure is more than –60%, or if monsoon rainfall departure exceeds –90%, or two quarter departure exceeds –90%, moderate drought might occur;

3) If monsoon rainfall departure is more than –75% and the first quarter departure is more than –85%, or if the monsoon rainfall departure is more than –90% and the first quarter departure is more than –60%, severe drought might occur;

4) If monsoon rainfall departure is more than –85% and two quarter departure is more than –95%, or if the monsoon rainfall departure is more than –90% and the first two quarter departure is more than –80%, extreme drought might occur.

Based on 3-SPI, high frequency of mild drought is observed in southern Sindh, while moderate drought frequently occurs in northern Sindh. Figure 9 depicts that neither severe nor extreme droughts were observed with 3-SPI. The total drought frequency is higher in northern Sindh than in southern Sindh, meaning that northern Sindh is more vulnerable to drought (mild to moderate), as compared to southern Sindh.

Based on 6-SPI (termed as meteorological drought), Fig. 10 indicates that the highest frequency of total droughts is observed in northern and south-western parts of Sindh. Mild droughts are more frequent in northern parts, while moderate droughts are more frequent in central and southern parts of Sindh.

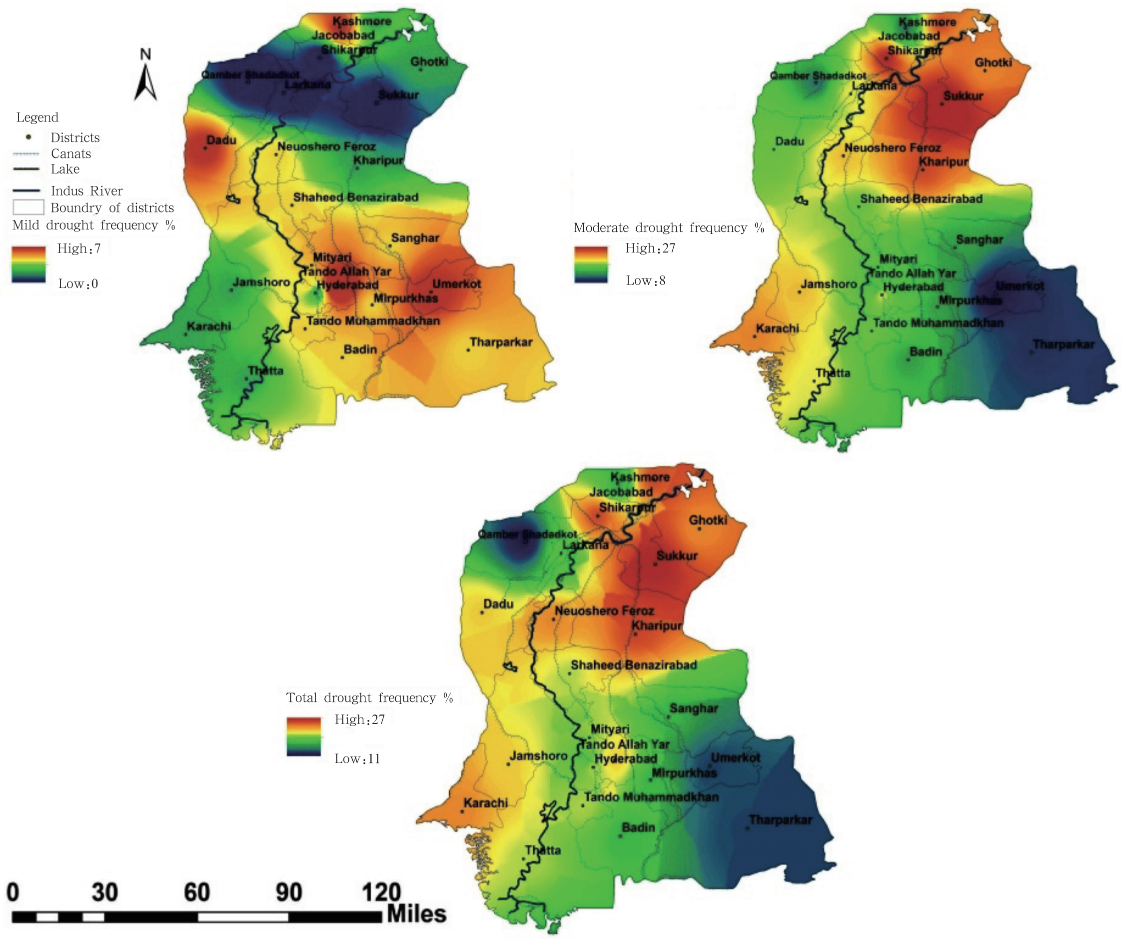

Fig. 9. Drought frequency based on 3-SPI (dry period) of Sindh over 1951–2010.

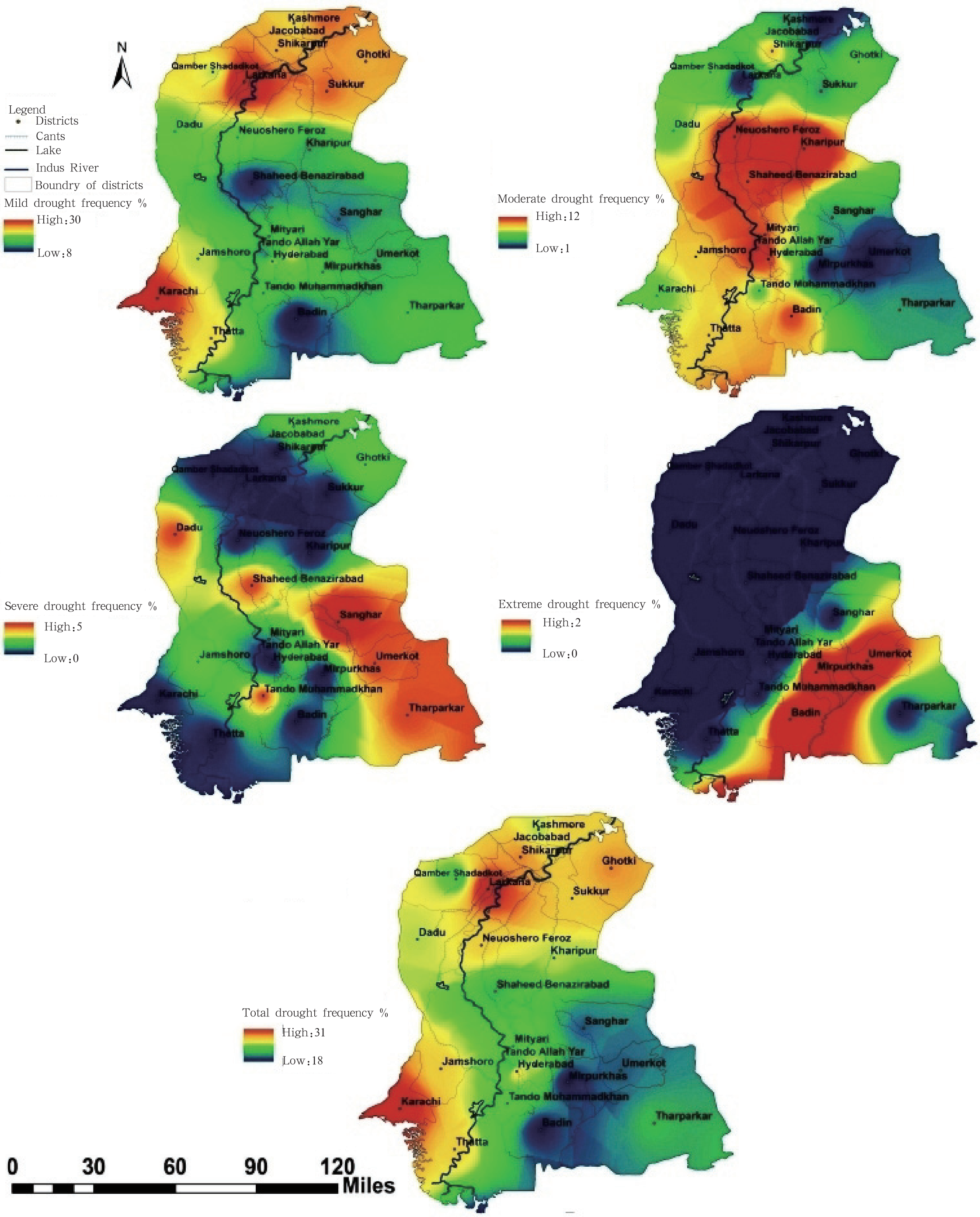

Fig. 10. Drought frequency based on 6-SPI (meteorological drought) of Sindh over 1951–2010.

Severe and extreme drought frequencies are higher in southern Sindh than in northern Sindh. Meteorological drought has higher frequency and less intensity in northern Sindh than in sourthern Sindh. Figure 10 shows that northern parts of Sindh are more vulnerable to meteorological droughts of mild to moderate intensity.

Based on 9-SPI (termed as agricultural drought), Fig. 11 shows that the drought frequency (i.e., mild to moderate and severe to extreme) is high in northern and southern parts of Sindh. The analysis also reveales that mild to moderate agricultural droughts are frequent in northern Sindh, while the intensity of these droughts is higher in southern Sindh. The total drought frequency is higher in northern Sindh than in southern Sindh. The northern Sindh receives less rain during the monsoon season than the southern part, which puts it at risk of agricultural drought.

According to climate normal of 1981–2010, the annual amount of rainfall is 128.7 mm in northern

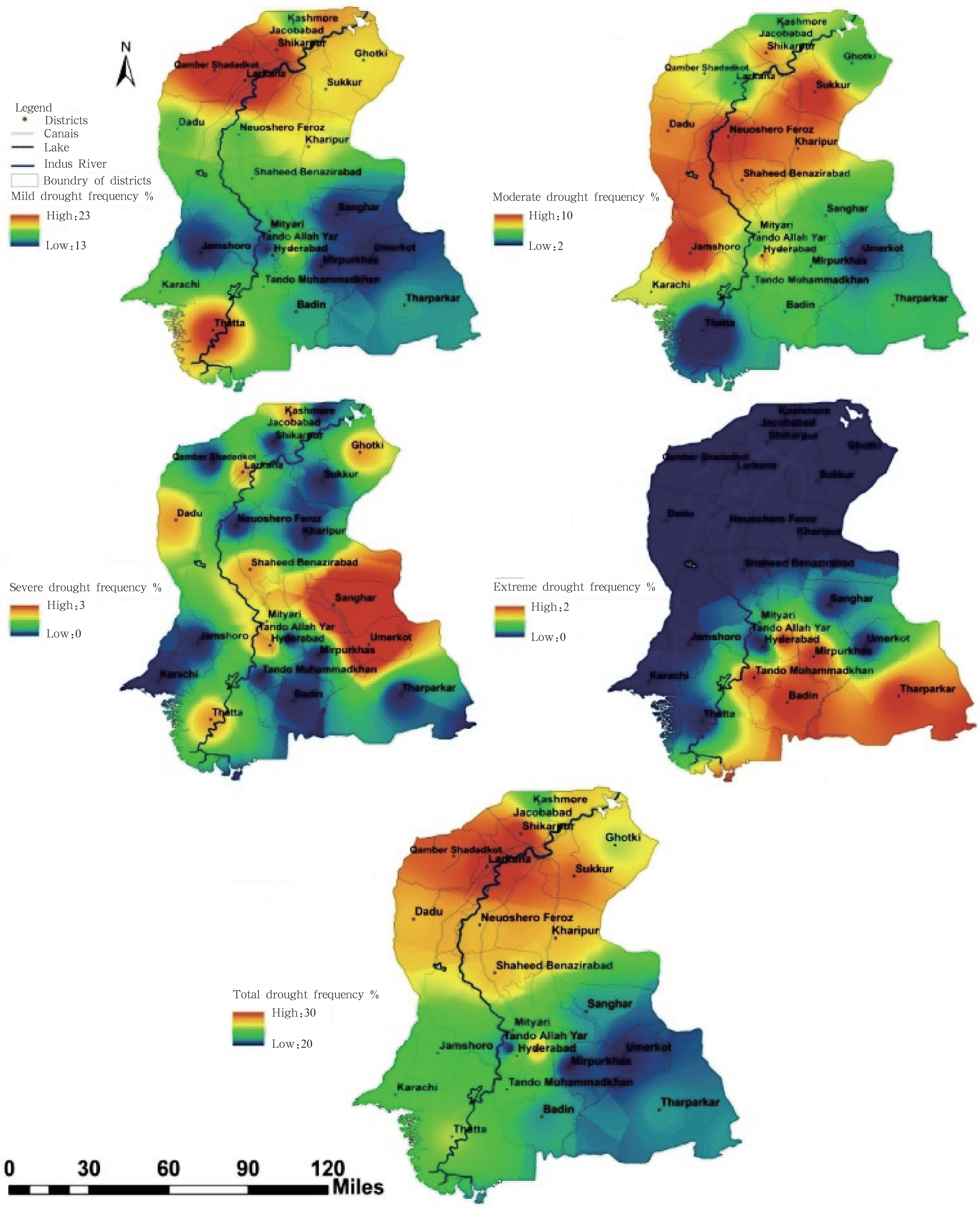

Fig. 11. Drought frequency based on 9-SPI (agriculture drought) of Sindh over 1951–2010.

parts of Sindh and 209 mm in southern parts, which means that light to moderate deficiency of rainfall may cause drought in northern parts of Sindh. The 12-SPI indicates high frequencies of mild and extreme drought in southern parts of Sindh, but high frequencies of moderate and severe drought in the northern parts (Fig. 12). The total drought frequency in northeastern and southwestern parts of Sindh is very high, suggesting that Sindh is highly susceptible to hydrological drought in the absence of monsoon rainfall.

Based on 24-SPI, Fig. 13 shows high frequency of mild, moderate, and severe drought in Sindh, while extreme drought frequency is recorded only in the northern parts of Sindh. The total drought frequency in

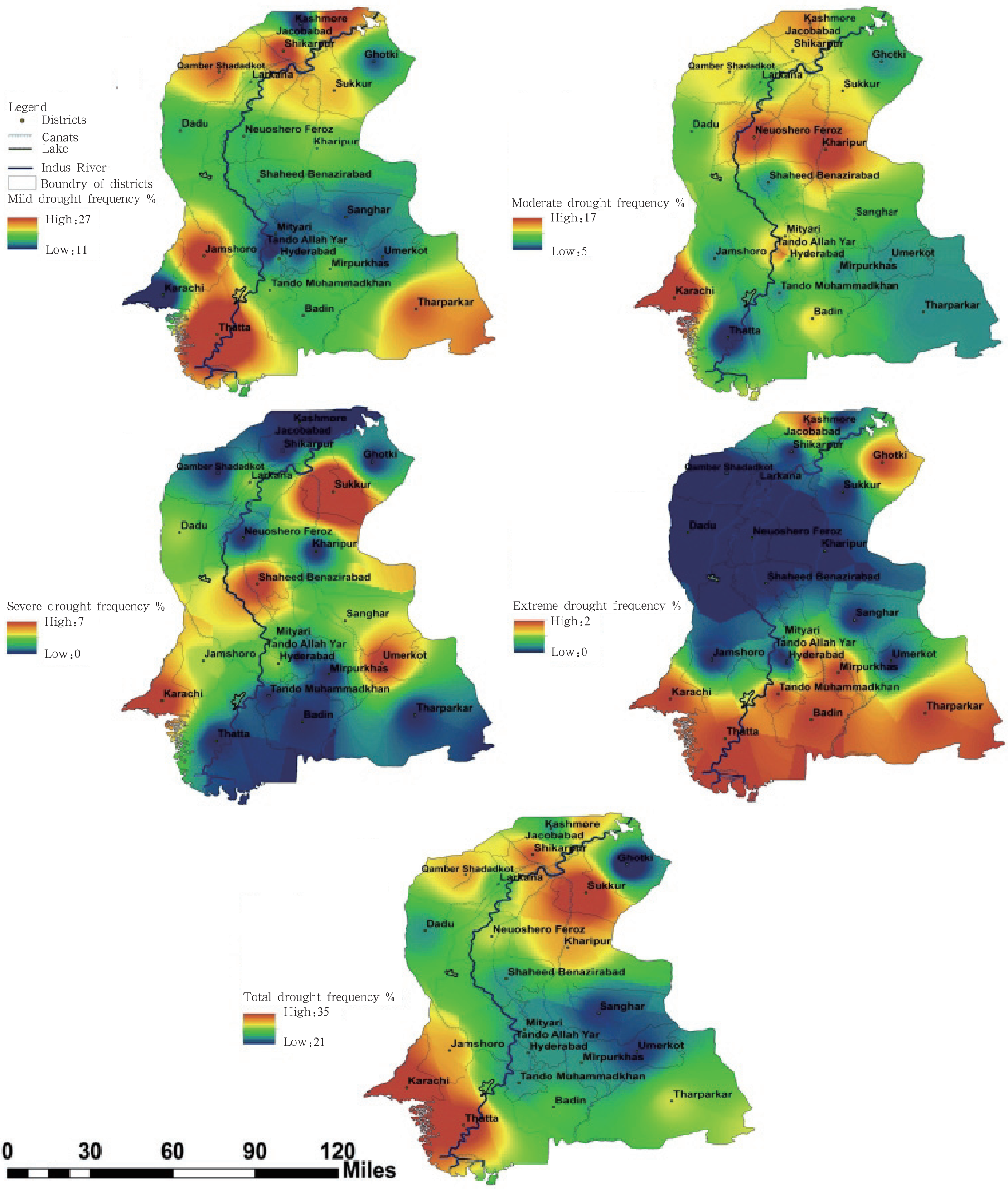

Fig. 12. Drought frequency based on 12-SPI (hydrological drought) of Sindh over 1951–2010.

southwestern parts of Sindh is very high. This implies that extreme hydrological drought is more frequent in that region.

The drought categories are defined on the basis of percentage of the affected area and intensity return period as shown in Table 5 for the Sindh region.

Each district is put into a category after the analysis of historical records during 1951–2010, as shown in Table 6. The most of the CAT-IV extreme droughts were observed in southern Sindh, where more than 80% of the area was affected.

Regional analysis in this study has identified that

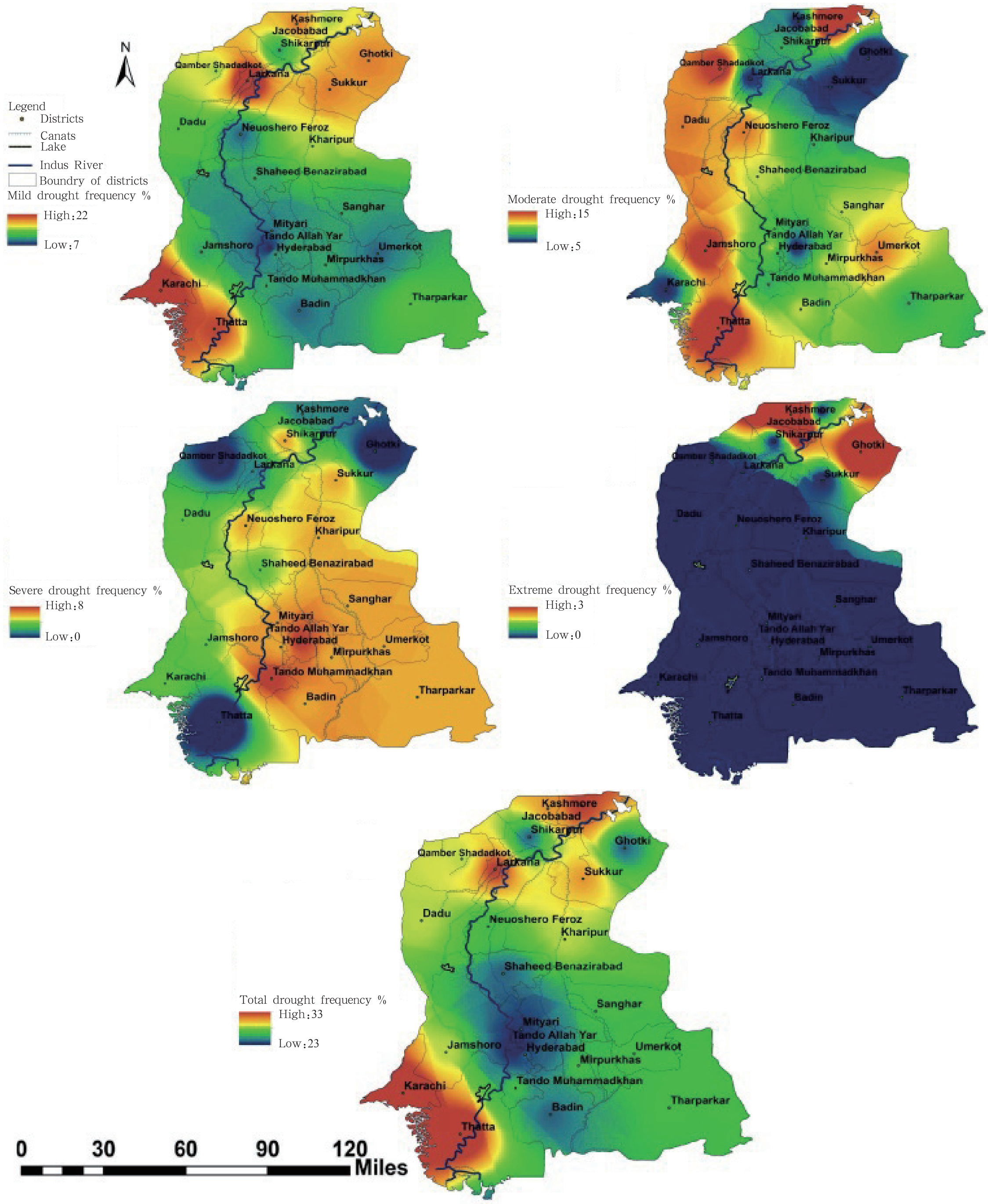

Fig. 13. Drought frequency based on 24-SPI (extreme hydrological drought) of Sindh during 1951–2010.

Table 5. Drought categories, percentage of area affected, and intensity return period for Sindh

Drought category	affected area (%)	Mild drought (yr)	Moderate drought (yr)	Severe drought (yr)	Extreme drought (yr)
CAT-I	< 40	3–4	6–10	Once in 15	Once in 20
CAT-II	40–60	5–6	11–15	16–20	21–25
CAT-III	60–80	7–8	16–20	21–30	25–35
CAT-IV	> 80	> 8	> 20	> 30	> 35

CAT-I: the percentage of area drought affected is less than 40%; CAT-II: the percent of affected area is between 40% and 60%; CAT-III: the percent of area affected is between 60% and 80%; CAT-IV: the percent of area affected is greater than 80%.

the two longest drought episodes are 1972–1974 and 2000–2002. According to SPI data, the most severe historical drought years are 1969, 1974, 1987, and 2002, where soil moisture departure (%) is below 50% in the entire province, as shown in Figs. 14a and 14b.

The drought hazard map of Sindh Province (Fig. 15) has been prepared by considering the historical records (1951–2010) of following factors in the 23 districts: dependency on seasonal/monsoon rainfall, soil moisture, SPI to calculate the drought years, frequency, intensity, return period of drought, and percentage area affected by drought. The simplest equation to calculate the drought hazard index (DHI) is as follows:

$$\mathrm{DHI} = \frac{\left(\dfrac{T_{\mathrm{d}}}{T_{\mathrm{y}}} + M_{\mathrm{Index}} + \dfrac{\mathrm{SM}_{\mathrm{J-D}}}{\mathrm{SM}_{\mathrm{annual}}}\right)}{3}, \quad (1)$$

where T_{d} is total number of droughts; T_{y} is total number of years; M_{Index} is monsoon rainfall index (see Table 7); $\mathrm{SM}_{\mathrm{J-D}}$ is soil moisture (July–December); and $\mathrm{SM}_{\mathrm{annual}}$ is annual soil moisture.

The drought vulnerability class limits and rating scores, obtained by taking the percentage of monsoon rainfall, are shown in Table 7. Based on the DHI equation (Eq. (1)), the severity class of vulnerability was developed, which varies from very low to extremely high values as describe by Asrari et al. (2012) (see Table 8).

Figure 15 shows that the southern parts of Sindh are more vulnerable to droughts than the northern parts of Sindh. The Tharparkar district is highly dependent on monsoon rainfall and extremely vulnerable to drought (once every three years). The districts of Thatta, Badin, Tando Muhammad Khan, Tando Allahyar, Dadu, Mirpur Khas, Umerkot, Sanghar, and Shaheed Benazirabad (base station) are highly vul-

Table 6. Categories and intensity of drought prone districts of Sindh

No.	District	Mild drought	Moderate drought	Severe drought	Extreme drought
1	Badin	CAT-II	CAT-I		CAT-IV
2	Dadu	CAT-II	CAT-II	CAT-IV	
3	Ghotki	CAT-III	CAT-II		CAT-IV
4	Hyderabad	CAT-II	CAT-II	CAT-IV	
5	Jacobabad	CAT-IV	CAT-I		CAT-IV
6	Jamshoro	CAT-I	CAT-II	CAT-IV	
7	Kambar Shahdadkot	CAT-II	CAT-I		
8	Karachi	CAT-IV	CAT-I	CAT-III	CAT-IV
9	Kashmore	CAT-I	CAT-II		
10	Khairpur	CAT-II	CAT-I		
11	Larkana	CAT-II	CAT-II	CAT-IV	
12	Mityari	CAT-IV	CAT-I	CAT-IV	
13	Mirpur khas	CAT-II	CAT-II		CAT-IV
14	Neuoshehro Feroz	CAT-II	CAT-I		
15	Sanghar	CAT-III	CAT-II	CAT-IV	
16	Shaheed Benzairabad	CAT-II	CAT-II	CAT-III	
17	Shikarpur	CAT-I	CAT-I		
18	Sukkur	CAT-II	CAT-I	CAT-I	
19	Tando Allahyar	CAT-III	CAT-I		CAT-IV
20	Tando Muhammad khan	CAT-II	CAT-II		CAT-IV
21	Tharparkar	CAT-II	CAT-II		CAT-IV
22	Thatta	CAT-I	CAT-III		CAT-IV
23	Umerkot	CAT-III	CAT-II	CAT-III	

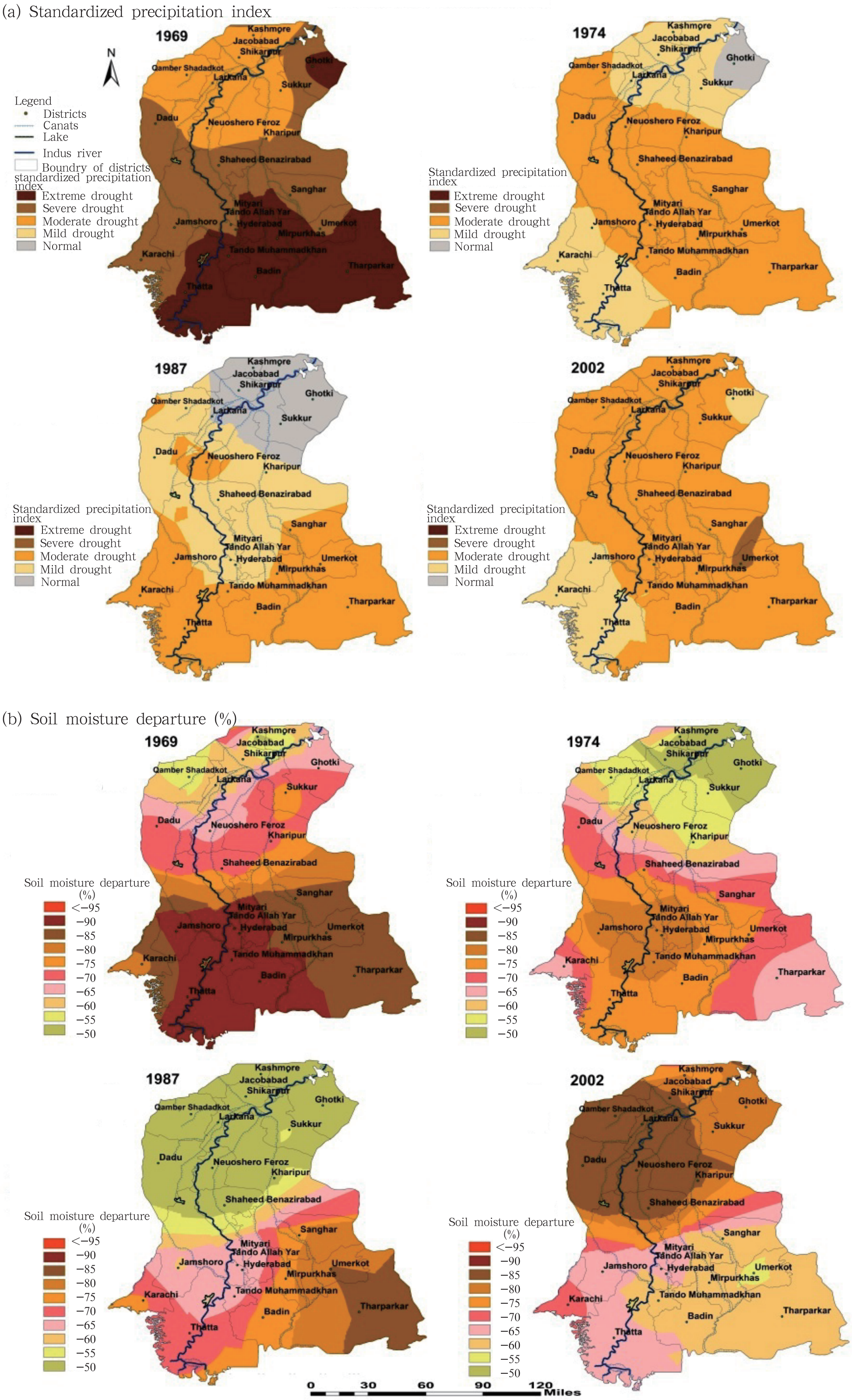

Fig. 14. (a) SPI and (b) soil moisture departure (%) for the most severe historical drought years in Sindh.

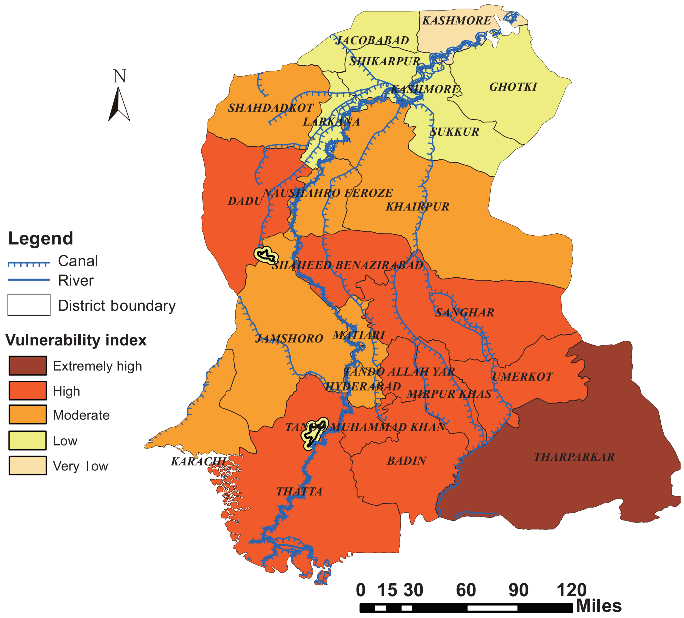

Fig. 15. Drought hazard map showing the vulnerability index for each district of Sindh.

nerable to drought as well. The western and eastern parts of Sindh districts (where no canal or river network is present) and the Kohistan region are also highly vulnerable to drought.

4. Summary

This study presents a full picture of the spatial distribution of drought and its characteristics over 23 districts of Sindh Province, Pakistan, based on SPI, soil moisture, and rainfall departure between 1951 and 2010. The results show a high correlation between the rainfall datasets of GPCC and meteorological station data, with R^2 values of 0.996 and 0.968, for both annual rainfall and monsoon season rainfall, respectively. A close relationship exists between the Mann Kendall and Sen's slope methods for statistical tests of the correlation results.

Annual and seasonal analyses show that no significant change (at the 95% confidence level) in precipitation was observed in Sindh. This region is highly dependent on monsoon rainfall (78.2%), and deficiency of monsoon rainfall is one of the major factors for the occurrence of drought. The southern part of Sindh is more vulnerable to drought than the northern part, as 82.1% of its rainfall is a result of monsoon rainfall. The drought climatologies of each district of Sindh Province are calculated on the basis of 3-, 6-, 9-, 12-, and 24-SPI along with rainfall departure and soil moisture anomaly. The rainfall departure (%) has a strong correlation with SPI, and the correlation increases as time period increases. Rainfall departure is equally a good tool as SPI for determining the intensity and severity of droughts. The 5-yr moving average results show SPI to be inversely proportional to mean deficit, mean area deficit, and 50% quantile frequency deficit of rainfall. However, severity of drought was not significant on smaller timescales of SPI ($\leqslant$ 3 months). Meteorological, agricultural, and hydrological droughts may be identified on 6-, 9- and 12-SPI, respectively.

The frequency of mild droughts has increased in northern Sindh, while intense and severe droughts are reported in southern Sindh. Regional analysis of Sindh shows that the most severe historical droughts occu-

Table 7. Criteria used for the hazard assessment of drought using percentage of normal rainfall

Indicator	Class limit and rating score			
Percentage of monsoon rainfall	> 89.0	79.1–89.0	70.1–79.0	59.0–70.0
Index value	4	3	2	1

Table 8. The severity class used in the hazard map of Sindh

Class	Extremely high	High	Moderate	Low	Very low
DHI	> 1.50	1.00–1.50	0.75–1.00	0.60–0.75	< 0.60

rred in 1969, 1974, 1987, and 2002. In this study, a drought hazard map of Sindh was developed by considering the climatological records of drought. The district of Tharparkar is extremely vulnerable to drought. Thatta, Badin, Tando Muhammad Khan, Tando Allahyar, Dadu, Mirpur Khas, Umerkot, Sanghar, Shaheed Benazirabad, and Kohsitan districts are also highly vulnerable to drought. This study is useful to policy makers, water management and irrigation departments, and disaster management agencies for preparation of contingency plans regarding drought in drought-prone areas of the country as well as neighbouring countries.

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