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Characterization of seasonal droughts in Balochistan Province, Pakistan

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Abstract Droughts are usually destructive when they coincide with crop growing season. Cross-seasonal drought characterization can better inform drought mitigation efforts. The present study relies on precipitation data from the Global Precipitation Climatology Centre to reconstruct historical droughts during different climatic seasons in Balochistan province, Pakistan. We identified seasonal drought events based on the standardized precipitation index for each season. The distribution of reconstructed drought events was analyzed to determine their seasonality and to calculate their return periods. Using these return periods, we constructed seasonal drought maps. The study revealed that early winter droughts are frequent in the north of Balochistan, where the return periods of moderate, severe, and extreme droughts are 7, 21, and 55 years, respectively. Severe and extreme late winter droughts are more frequent in the upper north, with return periods of 16 and 35 years, respectively. Early summer droughts occur more frequently in the east, returning every 8, 20, and 60 years; late summer droughts occur in the northeast, with moderate, severe, and extreme droughts returning every 8, 22, and 65 years, respectively. Rabi droughts are more frequently in the central and northeaster regions of Balochistan, while more severe kharif droughts occur primarily in the eastern regions. These seasonal droughts were found to be positively correlated with variations in the seasonal rainfall throughout the study area. The findings of this study contribute to our understanding of seasonal drought characteristics and help to inform drought mitigation planning.

Keywords Seasonal droughts · Standardized precipitation index · Gridded precipitation · Cropping seasons · Geographical information system · Balochistan

1 Introduction

Despite being a typical and recurrent phenomena occurring across the climate spectrum (Wilhite et al. 1986), droughts remain among the most damaging and least understood of all natural hazards (Pulwarty and Sivakumar 2014). Such damage is particularly acute in the agricultural sector where the dependency on water resources creates a vulnerability to drought conditions (Zhang et al. 2012; Telesca et al. 2013; Liu and Hwang 2015). Moreover, the rural economies of developing countries tend to be highly dependent upon agriculture, leaving vast populations at the mercy of seasonal rainfalls (Ashraf et al. 2014; Miyan 2015). Droughts can have a devastating effect on the livelihood of agricultural communities and it is often difficult for these communities to return to normal once a drought has subsided (Osbahr et al. 2008).

Pakistan's long latitudinal extent gives rise to considerable variability in seasonal rainfall. Nonetheless, even relatively minor deviations in seasonal mean rainfall can result in water scarcity and predispose the country to economic and humanitarian disasters (Sheikh 2001). Droughts have been observed to occur every four out of

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10 years in Pakistan (Anjum et al. 2012), with the province of Balochistan being among the most drought prone regions. Severe droughts were recorded in 1967–1969, 1971, 1973–1975, 1994, and 1998–2002, having a devastating effect on the economy and on people's livelihoods. The protracted 1998–2002 drought reduced rain-fed crop yields by 60–80 %, irrigated crop yields by 15–20 %, and led to the deaths of approximately two million animals (FAO/WFP 2002; Sarwar 2008).

Drought is a multivariate phenomenon, characterized by its frequency and severity (Reddy and Ganguli 2013). Asian countries have seen a marked increase in the frequency and severity of droughts in recent years (Wang et al. 2012). According to a recent Intergovernmental Panel on Climate Change (IPCC) study, the production of rice, maize, and wheat in many parts of Asia has declined over recent decades due to increasing water stress attributed to a combination of increasing temperatures, the increasing frequency of El Niño events, and a reduction in the number of rainy days (Bates et al. 2008). There is growing concern about the increasing frequency and severity of droughts in Pakistan. Zahid and Rasul (2012) reported a significant increase in the frequency of heat waves across Balochistan, an indicator of forthcoming drought. Nonetheless, few attempts have been made to study droughts in this region. Previous studies have been limited to describing the impact of droughts and adaptation measures for livestock (Shafiq and Kakar 2007), agriculture (FAO/WFP 2002), soil degradation and rangeland productivity (Islam et al. 2004), vegetation cover (Ashraf et al. 2011), desertification (Ali 2006), future drought mitigation strategies (Ahmad et al. 2004), and farmers' coping and adaptation measures (Ashraf et al. 2014). Thus far, no attempts have been made to characterize the region's droughts. Such quantification has implications for mitigating the impact of droughts in the region, especially during crop growing seasons.

Number of studies have been carried out for the quantification of droughts, in different parts of the world. More than 50 drought indices have been developed using different variables for this purpose (Kim et al. 2011; Huang et al. 2014; Li et al. 2014b). Most of these indices lead to a general characterization of droughts without giving any indication of drought risk for particular periods. Predicative characterization is important because severe droughts are not necessarily destructive unless they coincide with crop growing seasons. For example, Mishra and Cherkauer (2010) reported that despite a history of severe droughts in the United States, such as those occurring in the 1930s and 1950s, the 1988 drought was the most costly to date having occurred during the crop growing season. This emphasizes the need of drought characterization during crop growing seasons.

The objective of the present study is to characterize Balochistan's droughts across the four climatic seasons, namely early winter, late winter, early summer, and late summer; and the two major cropping seasons, kharif and rabi. Using gauged-based precipitation data provided by the Global Precipitation Climatology Centre (GPCC) (Becker et al. 2013), we calculate the standardized precipitation index (SPI) (McKee et al. 1993), per the recommendations of the World Meteorological Organization (WMO), for the characterization of meteorological droughts (WMO 2012). The SPI is calculated in the last month of a given season with a time period that spans the entire season to define seasonal rainfall deficits. Negative SPI values are separated from the SPI series for the determination of a time series of drought events for each season. The time series of drought events is then fitted with various distributions to identify the function that best describes the seasonal droughts. Annual maximum series (AMS) approach is used to calculate the return period of droughts during different seasons. Finally, the return periods with various severities are interpolated to map droughts for each climatic and crop growing seasons. The findings of this study and the resultant maps can serve to guide interventions aimed at disaster risk reduction in Pakistan's drought prone Balochistan province.

The structure of this paper is described thusly; in the next section, we provide a brief description of the study area including its climate, topography, and agricultural output. This is followed by a description of the data and the methods used in this study, after which we present our results. This follows the discussion and conclusion sections, where results are analyzed and conclusions are derived.

2 Study area

Balochistan is a province of Pakistan with a mountainous and arid desert terrain, located between 30.12°N and 67.01°E. Figure 1 illustrates the topography and administrative subdivisions of Balochistan. The province comprises an extensive basin of rough terrain divided into several plateaus that vary by height and ruggedness. Geographically, Balochistan can be divided into four distinct zones: upper highlands, lower highlands, plains, and deserts. The topography of the study area, as shown in Fig. 1b, reveals significant variations over a short distance, with mountains dominating the terrain.

The climate of the province varies between hyper-arid, arid, and semi-arid (Fig. 2a). Daily mean temperatures vary from 10 °C in the winter to 35 °C in summer, occasionally rising above 50 °C during summer. The annual average evapotranspiration in the area is about 3000 mm. Rainfall
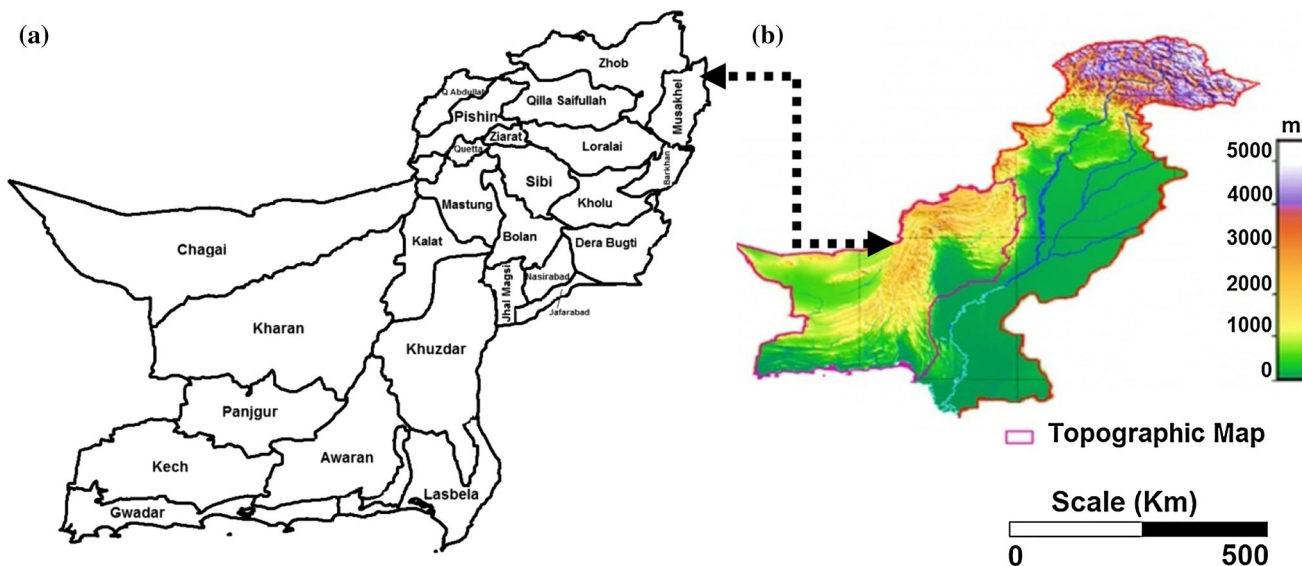
Fig. 1 **a** Administrative boundary map of Balochistan province, Pakistan; and **b** the topography of Balochistan
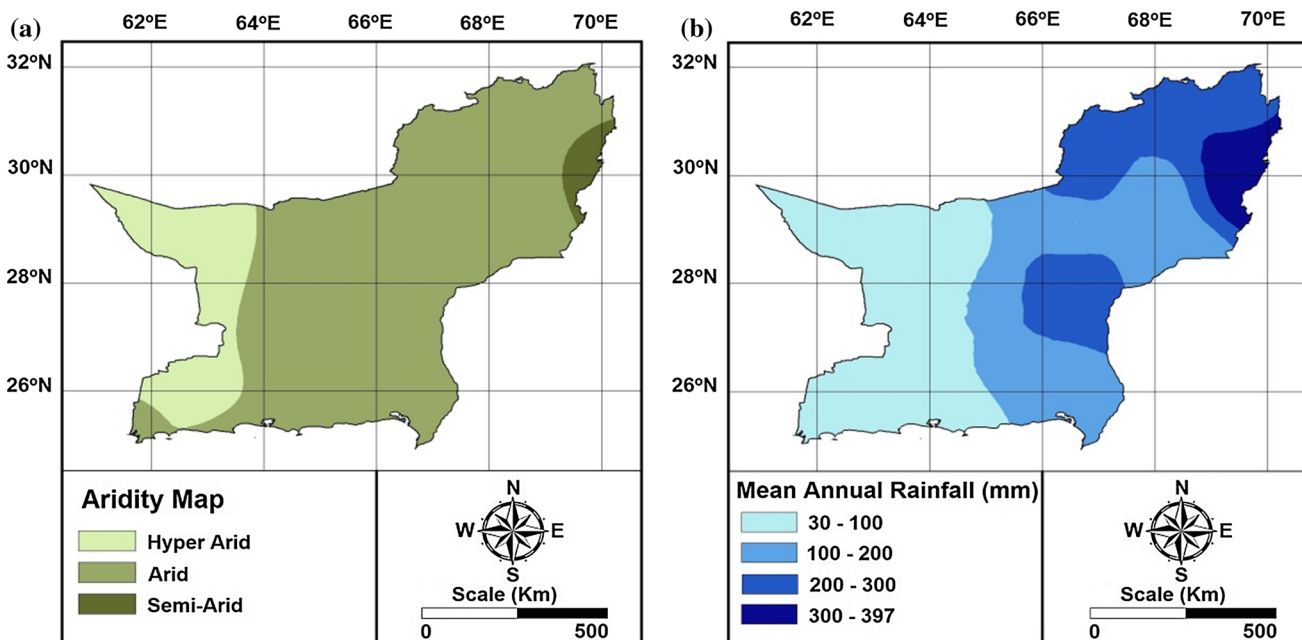

Fig. 2 Maps of **a** climatic zones; and **b** spatial distribution of mean annual rainfall in the study area

is scant and unevenly distributed, ranging from 30 mm in the southwest desert to 397 mm in the northeast. The spatial distribution of mean annual rainfall is shown in Fig. 2b. The region's four seasons are divided thusly: (a) early winter (November–January); (b) late winter (February–April); (c) early summer (May–July); and (d) late summer (August–October) (Snead 1968). As can be seen in Fig. 3, the seasonal distribution of rainfall varies considerably across climatic zones.

Monsoon winds and western depressions are, respectively, the main sources of rainfall during summer and

winter. About 58 % of the province's total rainfall occurs during the winter due to western depressions originating in the Mediterranean Sea. Western disturbances travel eastward along the higher latitudes, resulting in the 34–36°N regions receiving maximal rainfall due to the topography of the Himalaya Mountains. These disturbances induce secondary rainfall in the 25–30°N lower latitudes where most of the land area of Balochistan is located (Sheikh 2001). Secondary disturbances, moreover, extract moisture from the Arabian Sea and result in most of Balochistan receiving light to moderate rainfall (Gils and Baig 1992). Another
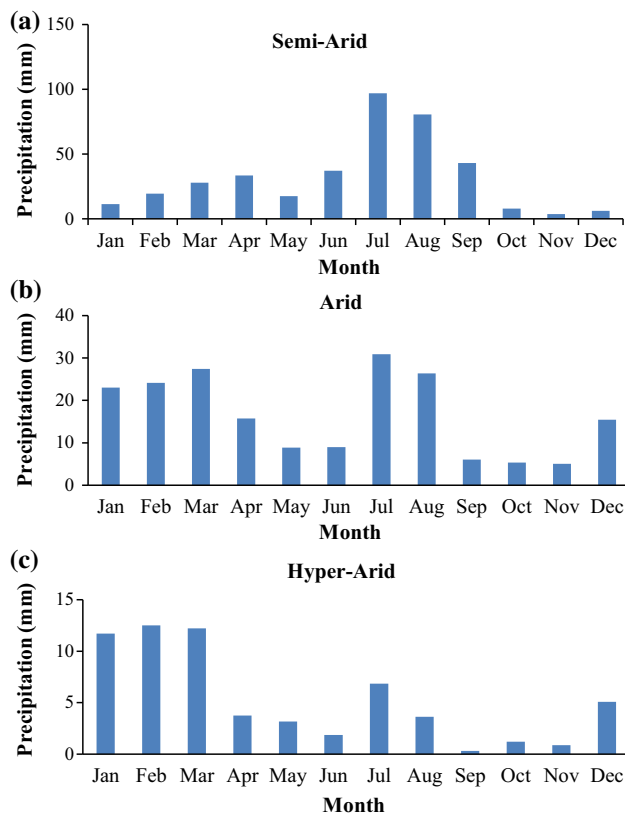
(a)

(b)

(c)

Fig. 3 Seasonal distribution of rainfall in different climatic zones **a** semi-arid; **b** arid; and **c** hyper-arid

31 % of the total rainfall occurs during the monsoon season; however, the distribution of the monsoon rainfall varies widely across the region. Monsoonal winds, entering the region from the southeast corner of the province, blow in moist air from the Bay of Bengal from August to October. The direction of these winds results in the southeastern part of the province receiving significantly more rainfall during the monsoon season. As the monsoon continues on its journey across the province, the air moisture content reduces and the monsoon rainfall gradually decreases from east to west.

Balochistan has two distinct cropping seasons, kharif and rabi. Kharif season begins in May when the soil moisture content from rainfall sources is sufficient to support rain-fed or un-irrigated crops, and ends in September. Major kharif seasonal crops include cotton, sugarcane, rice, and maize. The exact timing of the rabi cropping season varies by latitude and is influenced by the subsiding of the monsoon. However, on average, the rabi season usually begins sometime around November and ends in March. Rabi seasonal crops tend to be somewhat region-specific and include wheat, barley, peas, gram, and mustard (FAO 2014).

Majority of the Balochistan's population (85 %) live in the rural areas and rely on agriculture as their main source of income (Ashraf et al. 2014). Agriculture and livestock industries employ about 67 % of the labor force and account for 50 % of the gross domestic profit (GDP) of the province (Hussein 2004). Rangelands provide about 90 % of livestock feed requirements (Shafiq and Kakar 2007).

2.1 Data and sources

Precipitation is obviously of paramount importance in the characterization of droughts. Monthly precipitation data from fourteen meteorological stations located in the study area are collected from Pakistan Meteorological Department for the study. Reliable monitoring of droughts requires long-term and continuous precipitation data (Li et al. 2014b); therefore, the homogeneity of the precipitation data provided by the 14 meteorological stations was assessed via the standard normal homogeneity test (SNHT) (Alexandersson 1986), Buishand range test (1982), Pettitt test (1979), and Von Neumann ratio test (1941). Much of the data from the stations were found to be inhomogeneous and incomplete. In addition, we determined that the ratio of synoptic stations to total land area (347,190 km^2) was too few and that stations were not well distributed across the province. Consequently, as the topography of the area varies widely, it is not possible to define the spatial extent of droughts in the area using so few rain gauges.

Gridded gauged-based precipitation data are considered where long-term reliable observation data are not available (Uppala et al. 2008). Gridded gauge-based precipitation datasets are developed through the interpolation of all available previous observations (Schneider et al. 2014) and numerous gridded precipitation datasets have been developed for climatological studies over the past two decades (Li et al. 2014a). In the present study, we relied on the monthly gridded precipitation dataset as provided by the GPCC (Becker et al. 2013). GPCC data possess a number of distinct advantages, including (a) the dataset is of sufficient quality and covers a wide-enough time span for hydrological analysis, such as calculating the return period of droughts; (b) it is a climate model-derived dataset based on the highest number of collected precipitation records; and (c) the dataset is continuous, without missing data since January 1951 (Spinoni et al. 2014). Furthermore, the GPCC uses smart interpolation techniques, accounting for the systematic relationship between elevation and station observations, thus facilitating more accurate estimations drought return periods (Schneider et al. 2014). Xu et al. (2015) reported that GPCC datasets perform better than satellite-based tropical rainfall measuring mission (TRMM) datasets. These advantages make GPCC gridded datasets suitable for regional and global drought-related studies. For example, GPCC gridded dataset were used by Garcia-Herrera et al. (2007) to analyse droughts over the
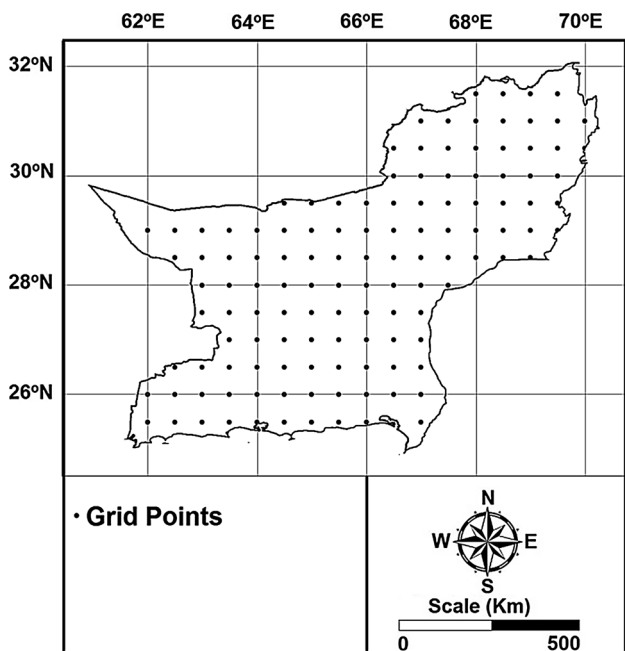
Fig. 4 Grid points indicating the collection of reanalysis rainfall data

Iberian Peninsula, by Hossein et al. (2012) to evaluate the variability of droughts over Korea, by Raziei et al. (2015) to reconstruct droughts over Portugal, and by Spinoni et al. (2014) to analyse the frequency, duration, and severity of droughts across the globe.

The GPCC produces several products at differing spatial resolutions (Schneider et al. 2014). The present study uses the 0.5° spatial resolution GPCC full data reanalysis product (version 6) (Schneider et al. 2011). This dataset includes monthly precipitation data for the period 1961–2010, collected from 130 grid points covering the study area (Fig. 4). Several studies point to a strong correlation between the GPCC gridded rainfall data and observed data from nearby stations (Teegavarapu 2012; Lovino et al. 2014). We observed a similarly strong correlation between the GPCC gridded data and the data available from the synoptic stations in the study area. A detailed statistical summary of the monthly GPCC precipitation data from 130 grid points spread across the study area is provided in Table 1. This table shows that the mean

annual rainfall in the study area is 160.98 mm. The table also shows that there is considerable seasonal variation in rainfall across the study area. Balochistan receives about 60 % of its rainfall during late winter and early summer. The GPCC precipitation data for the last 50 years reveal that maximum and minimum rainfalls in the study area are experienced in early summer. Therefore, the greatest standard deviation in seasonal rainfall occurs in early summer. Conversely, the least standard deviation in rainfall is observed in early winter. The rainfall data for each station were found to be positively skewed, although never by more than two standard deviations. A negative kurtosis of −0.01 is found in the late winter rainfall data, while the late summer rainfall data were found to possess a very high positive kurtosis.

3 Methodology

The incidence of droughts during the various climatic and crop growing seasons was reconstructed by estimating the SPI for the corresponding season at each grid point. For example, to reconstruct historical late summer droughts (August–October), we retrospectively computed the 3 month SPI for the month of October from 1961 to 2010. Negative SPI values for a particular season were separated to prepare the time series of drought events for that season. Frequency distribution of drought events was then analyzed to estimate drought return periods and their severity. Finally, drought maps were prepared for the various climatic and crop growing seasons by interpolating the return periods with the severity of each drought. Below, we present a more detailed description of the methods used in the present study.

3.1 Standardized precipitation index (SPI)

The SPI is a widely used drought index based on the probability of precipitation for multiple timescales (McKee et al. 1993). The SPI involves comparing the precipitation for a given period with the precipitation during the same period in all previous years, for which there are data

Table 1 Statistical summary of precipitation at 130 grid points for the period 1961–2010

Description	Annual (mm)	Early winter (mm)	Late winter (mm)	Early summer (mm)	Late summer (mm)
Mean	160.98	34.67	51.53	50.32	29.86
Standard deviation	72.27	16.46	23.47	33.17	26.11
Skewness	0.80	1.22	0.95	1.04	1.39
Kurtosis	0.46	1.56	−0.01	0.86	2.45
Minimum	38.86	11.15	18.23	6.47	1.28
Maximum	395.59	83.98	117.34	163.84	132.10

available in the historical record. Consequently, the SPI facilitates the temporal analysis of droughts. To compute SPI, monthly rainfall data at each grid point are fitted to a gamma probability distribution function:

$$g(x) = \frac{1}{\beta^{\alpha} \Gamma(\alpha)} \chi^{\alpha-1} e^{-x/\beta} \quad \text{for} \quad x > 0 \qquad (1)$$

where $\alpha > 0$ is a shape parameter, $\beta > 0$ is a scale parameter, $x > 0$ is the amount of precipitation, and $\Gamma(\alpha)$ defines the gamma function.

Gamma distribution parameters, α and β, for each station and timescale are estimated according to a maximum likelihood solution

$$\alpha = \frac{1}{4A} \left(1 + \sqrt{1 + \frac{4A}{3}} \right)$$
$$\beta = \frac{\bar{x}}{\alpha}, \qquad (2)$$

where

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n}$$

$n =$ number of precipitation observations.

This allows for the distribution of rainfall at the station to be represented mathematically by way of a cumulative probability function:

$$G(x) = \int_{0}^{x} g(x)dx = \frac{1}{\beta^{\alpha} \Gamma(\alpha)} \int_{0}^{x} x^{\alpha-1} e^{-x/\beta} dx. \qquad (3)$$

As the gamma function for $x = 0$ is undefined and a precipitation distribution may be zero, the cumulative probability becomes

$$H(x) = q + (1-q)G(x) \qquad (4)$$

where q is the probability of zero. The cumulative probability $H(x)$ is then transformed to the standard normal distribution to yield the SPI (McKee et al. 1993).

As the precipitation rate is fitted to a gamma distribution for different monthly timescales, the resulting function represents the cumulative probability of a rainfall event occurring at a station during a given dataset month and during whatever timescale has been defined. This allows for establishing drought classification per SPI values

Table 2 Drought classification according to SPI

SPI	Drought severity
SPI > −1.0	Mild drought
−1.5 < SPI ≤ −1.0	Moderate drought
−2.0 < SPI ≤ −1.5	Severe drought
SPI ≤ −2.0	Extreme drought

according to the system as described by McKee et al. (1993) (see Table 2). Further details of the SPI algorithm can be found in McKee et al. (1993). SPI values are computed according to the last month of a season with a timespan covering the course of the season to define the rainfall deficit of the entirety of that season. In the present study, drought events were computed for 3- and 6-month timespans, with the computed periods coinciding with the end of each climatic and cropping season.

3.2 Return period

The return period is a useful statistic for characterizing droughts (Bonaccorso et al. 2003). The return period for a drought is defined as the average time between two consecutive droughts (Shiau and Shen 2001). A seasonal drought event is a single event in a year. Therefore, the return period of a seasonal drought is calculated as the inverse of the probability of drought occurring in a year. In the present study, we used a combination of parametric frequency distribution and non-parametric non-exceedance probability procedures for the estimation of seasonal drought return periods. Frequency analysis of drought magnitude was carried out using the AMS approach. The AMS is based on a single drought event each year, provided that it exceeds a given threshold. In the present study, a negative SPI value (i.e., less than zero) was considered indicative of a drought. Years without droughts were assigned a value of zero. Thus, the length of the resultant series is equal to the number of years for which SPI values are available. Much like SPI values, AMS values can also be zero. In such cases, the drought frequency analysis is based on the non-zero values combined with a correction factor that accounts for the number of zero values in each series. Tallaksen et al. (1997) analyzed the frequency of stream flow droughts using AMS to assess extremes of drought duration in two Danish catchments. Vicente-Serrano and Beguería-Portugués (2003) estimated the frequency distribution of AMS in the annual number of days without precipitation to predict the risk of extremely dry periods in the middle Ebro Valley of northeastern Spain. Silva et al. (2015) used the peaks-over-threshold model with generalized Pareto distributed peak magnitudes for flood frequency analysis in the Itajaí River Basin in southern Brazil. These studies relied on conditional probability procedures for frequency analysis due to the presence of zero values in the observation series. A similar conditional probability procedure was used in the present study for the frequency analysis of the AMS of the SPI in order to estimate the return period of meteorological droughts. Non-exceedance probability (F') has been used to account for the number of zero values (Vicente-Serrano 2006; Santos et al. 2011):

$$F' = q + (1 - q)F \qquad (5)$$

where F is the non-exceedance probability value obtained by using frequency analysis on the non-zero values, and q is the probability of a zero value, calculated as the ratio of time intervals without drought to the total number of time intervals in the recording period (Santos et al. 2011).

The drought events are fitted using normal, lognormal, gamma, and extreme value I distributions, with the gamma distribution having been selected based on the results of Kolmogorov–Smirnov (K–S) and Chi-square tests. The return period of a drought with particular severity is calculated thus

$$T(x) = \frac{1}{1 - F'(x)}. \qquad (6)$$

3.3 GIS mapping

A drought is a dynamic phenomenon that changes over time and space (Patterson et al. 2013). Therefore, a complete analysis of drought requires the study of both its spatial and temporal extents. Hydrological investigation over a large area requires the assimilation of information from multiple sites, each with a unique geographic location (Shahid et al. 2000). A geographical information system (GIS) is used in this study to map drought hazards during different cropping seasons in Balochistan. The GIS stores the spatial location of each sampling point and provides a means with which to relate to the sampling data.

Kriging is a family of estimators used to interpolate spatial data. Universal kriging, also known as 'kriging with a trend', is generally used when the data have a strong trend that can be modeled through simple functions (Lefohn et al. 1987); therefore, universal kriging would not be appropriate in this instance as the topography of the study area is too rough to give rise to any strong trends (Ahmed et al. 2014). Consequently, ordinary kriging is used in the present study for the surface interpolation of drought return periods.

Surface interpolation is optimally performed by way of kriging based on spatially dependent variance, generally expressed as a semivariogram. Surface interpolation using kriging depends on the semivariogram selected, which must be fitted with a mathematical function or model (Ahmed et al. 2014). In the present study, an exploratory spatial data analysis was performed to compare four semivariogram models—circular, spherical, exponential, and Gaussian—to identify the best method for estimating interpolation weight. Spherical and exponential models were found to underestimate the values, whereas Gaussian and circular models overestimated the values. Nonetheless, Gaussian and exponential models were chosen as these

models led to the smallest root mean square error in nearly all cases.

4 Results and discussion

We investigated drought hazards in Balochistan province based on the frequency of different categories of drought occurring during the climatic and cropping seasons. The SPI was calculated for 3- and 6-month timespans. The negative SPI values were fitted with gamma distribution; however, by specification, gamma-distributed random variables can never be negative. Therefore, negative SPI values were transformed to positive values before being fit via gamma distribution. The distribution function of the fitted gamma distribution is used to calculate the non-exceedance probability of droughts with different severities. The resultant probability values were then corrected using Eq. (5), and then used in Eq. (6) to determine the return periods of droughts with various severities. For example, negative SPI values are found in 25 years out of 50 years in three-month SPI time series in the month of October at a grid point. The negative SPI values are separated and transformed into positive values. The transformed positive values are then fitted with gamma distribution to calculate the non-exceedance probability values for droughts with different severities. For example, the non-exceedance probability value for severe late summer droughts was found to be 0.71 from the fitted gamma distribution. This value is used in Eq. (5) to arrive at the corrected non-exceedance probability value of 0.85, which yields a return period of severe late summer droughts of 7 years at that grid point.

4.1 Spatial pattern of return periods of droughts

The return periods of moderate, severe, and extreme droughts for each climatic and cropping season was calculated for each grid point and the values were then used to prepare corresponding maps by using a geostatistical analysis tool of ArcMap 10.0. Droughts during different climatic and cropping seasons are discussed below.

4.1.1 Early winter droughts

A significant portion of Balochistan's rainfall is received during the winter. Most districts of Balochistan receive more than 25 % of total rainfall and the coastal regions in the southwest receive more than 45 % during early winter. The 3-month SPI is calculated in the month of January to identify droughts during early winter (November–January). The spatial distribution of droughts during early winter is illustrated in Fig. 5 and the percentage of land area

frequently affected by different categories of drought is presented in Table 3.

Figure 5a shows that moderate droughts occur in a small area to the north of the province with a 5–6 year return period. In the central and the northern regions, it occurs with a return period of every 7–8 years. As shown in Table 3, 8.09 % of the province is affected by moderate droughts with a return period of 5 years. Severe droughts primarily occur in the northern regions and in a northwest stretch (Fig. 5b). Extreme early winter droughts (Fig. 5c) follow a similar pattern to severe droughts, occurring once every 22–54 years in the northwest. Table 3 shows that percentage of land area affected by frequent severe and extreme droughts is 22.63 and 22.51 %, respectively.

4.1.2 Late winter droughts

The province receives more than 21 % of its total rainfall during late winter. Some western districts receive more than 50 % of their total rainfall during late winter. There-fore, drought during this season has a greater impact on agriculture in these areas. The spatial distribution of droughts during late winter is shown in Fig. 6. It can be observed from Fig. 6a that moderate droughts are frequent in about 83 % of the province except for a small pocket in the northeast. The spatial distributions of severe (Fig. 6b) and extreme (Fig. 6c) droughts are more or less same. These late winter droughts occur more frequently in the upper north of the province. Nevertheless, severe droughts have a larger spatial extent (25.29 %) as compared to extreme droughts (18.32 %).

4.1.3 Early summer droughts

The spatial distribution of moderate, severe, and extreme drought return periods during early summer is presented in

Table 3 Percentage of frequent affected areas by each category of drought during each season

Seasonal droughts	Area (%) experiences frequent droughts		
	Moderate	Severe	Extreme
Early winter	8.09	22.63	22.51
Late winter	83.03	25.29	18.32
Early summer	45.04	26.80	15.74
Late summer	36.76	27.73	18.97
Rabi	56.16	45.57	22.08
Kharif	56.75	25.31	23.00

Fig. 7. Figure 7a shows that moderate early summer droughts are more frequent in the eastern region as compared to other parts of the province. The spatial distribution of moderate and severe droughts (Fig. 7b) is more or less similar. However, the area affected by frequent moderate droughts (45.04 %) is greater than that of severe droughts (26.8 %). Moreover, the frequency of moderate droughts is also higher as compared to severe droughts. Moderate droughts occur once every 6–7 years in the eastern region of the province, while severe droughts occur once every 13–19 years. The spatial pattern of extreme droughts (Fig. 7c) is similar to that of moderate and severe droughts. Extreme early summer droughts occur more frequently in 15.74 % of the province, particularly in the southeastern and northeastern regions, while the western region appears to be less drought prone in early summer, with each cate-gories of drought being less frequent in these areas.

4.1.4 Late summer droughts

The eastern and northern regions of the province receive more than 20 % of their annual rainfall during the late
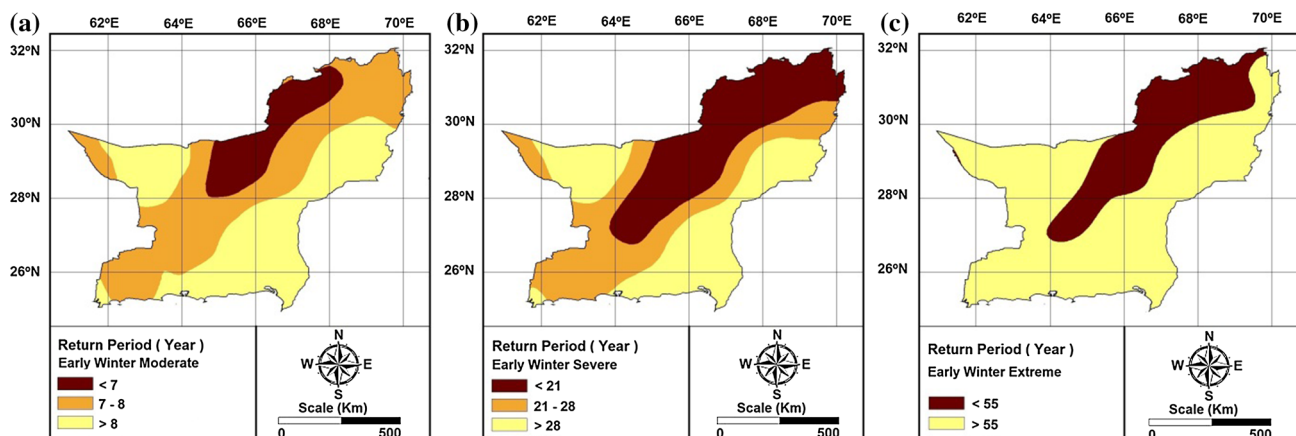

Fig. 5 Return periods of early winter (November–January) droughts in Balochistan with **a** moderate, **b** severe, and **c** extreme severities
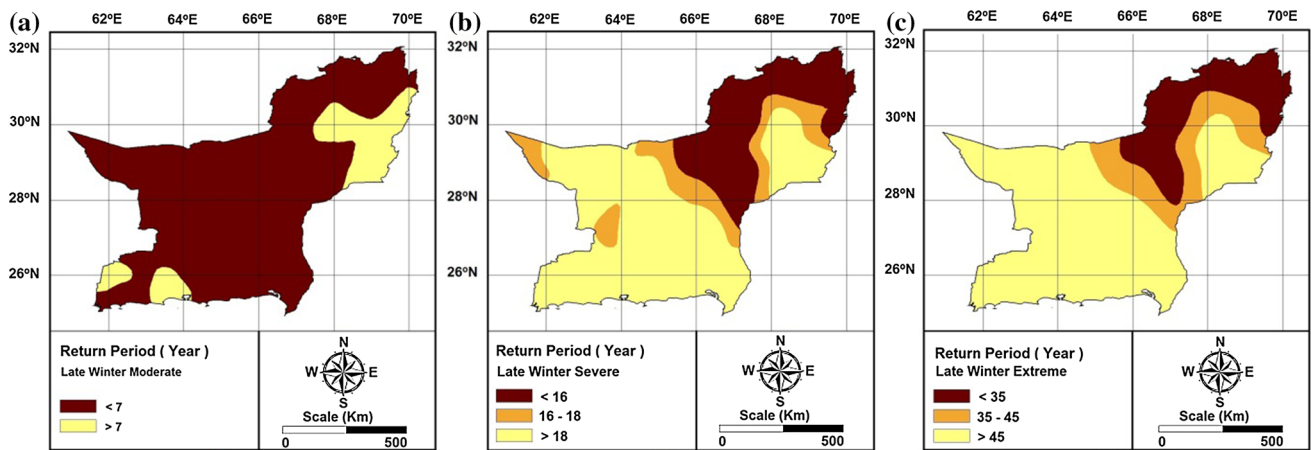
Fig. 6 Return periods of late winter (February–April) droughts in Balochistan with **a** moderate, **b** severe, and **c** extreme severities
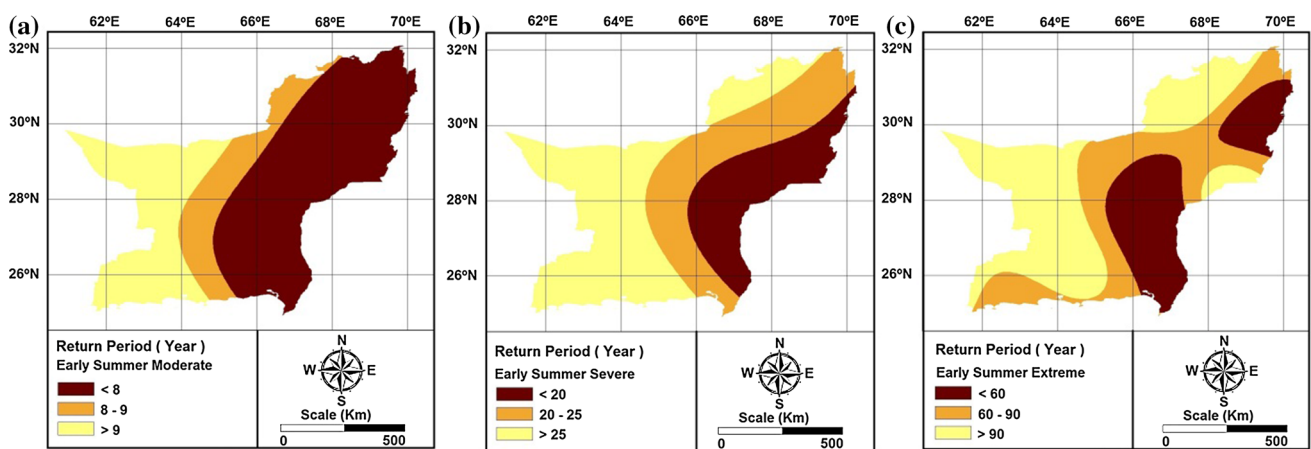

Fig. 7 Return periods of early summer (May–July) droughts in Balochistan with **a** moderate, **b** severe, and **c** extreme severities

summer months. The return period of moderate late summer droughts (Fig. 8a) varies between 6 and 7 years in the eastern region, and 10–15 years in the western region. Severe droughts (Fig. 8b) frequently occur in the northeast region of the province, which covers 27.73 % of the total area, and return on average once in 15–21 years. The distribution pattern of extreme droughts is similar to that of severe droughts. Return period of extreme late summer droughts (Fig. 8c) in the northern region is 23–64 years. All categories of late summer drought occur less frequently in the western region of the province. Overall, the results demonstrate that the spatial distribution of late summer drought varies widely with severity. However, the north and northeast regions appear to be more prone to late summer droughts.

4.1.5 Rabi droughts

Rabi crops are sown in autumn or early winter to be harvested in spring or early summer. A significant portion of the province's rainfall (55 %) occurs in the rabi season. Some parts of Balochistan, such as the south and southwest, receive more than 70 % of their annual rainfall during the rabi season. Therefore, rainfall during the rabi season plays an important role in regional agriculture and food security. The spatial distribution of the return periods of moderate, severe, and extreme droughts during rabi season is shown in Fig. 9.

The distribution of rabi droughts varies widely with severity. Figure 9a shows that, with the exception of the upper northwest region, moderate rabi droughts occur frequently throughout Balochistan. These moderate droughts are more frequent in the coastal regions, which account for almost 56.16 % of the total land area of the province. The return period of severe drought (Fig. 9b) is unlike that of moderate drought, and occurs mostly in the central and some northern regions of Balochistan. The spatial pattern of extreme droughts (Fig. 9c) is similar to that of severe droughts, but extreme rabi droughts occur more frequently over a smaller spatial extent (22.08 %) as compared to
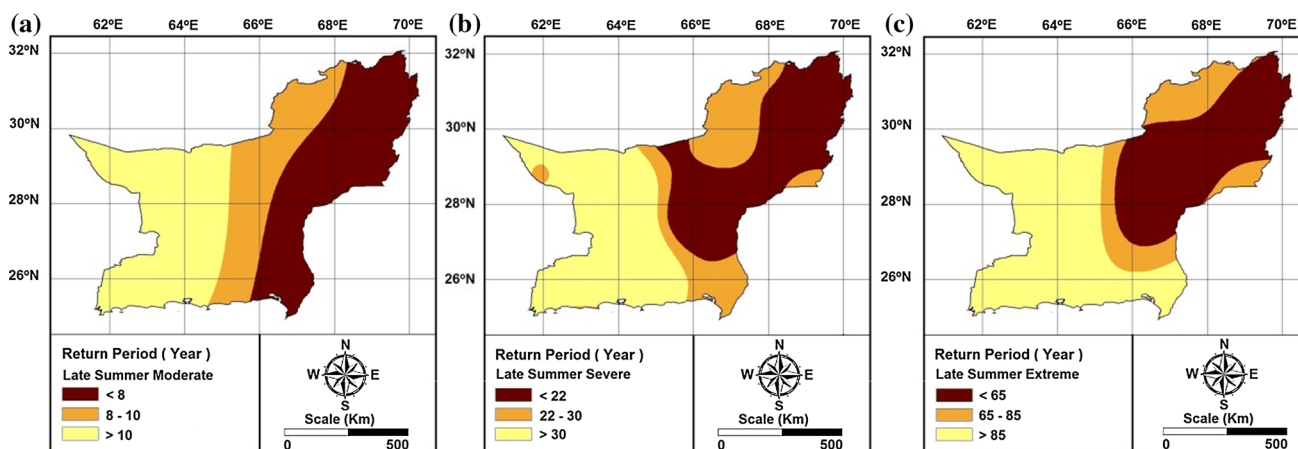
Fig. 8 Return periods of late summer (August–October) droughts in Balochistan with **a** moderate, **b** severe, and **c** extreme severities
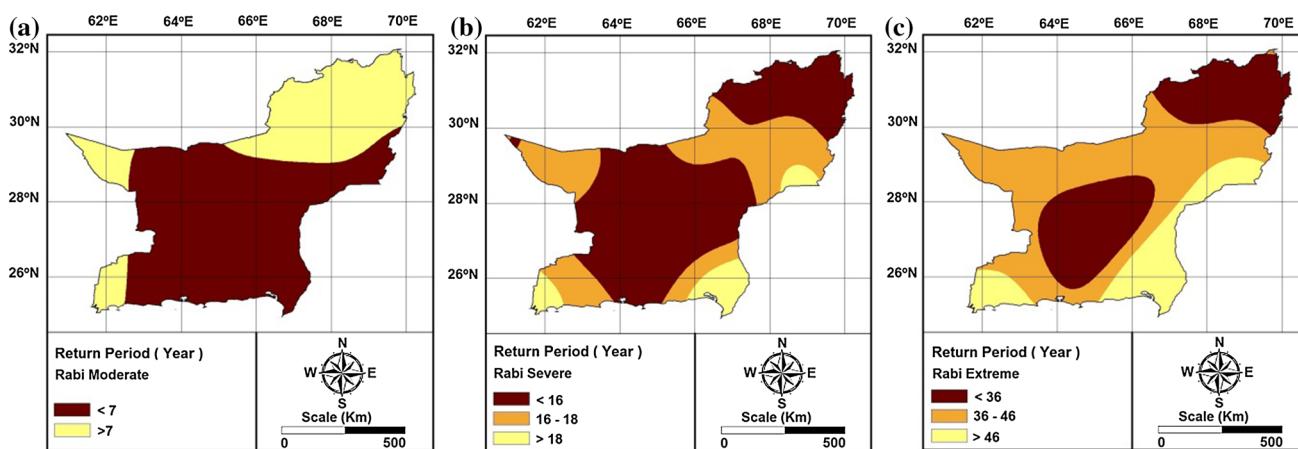

Fig. 9 Return periods of rabi (November–April) droughts in Balochistan with **a** moderate, **b** severe, and **c** extreme severities

severe rabi droughts (45.57 %). These extreme rabi droughts occur frequently, every 16–35 years, in some central and northern regions of Balochistan.

4.1.6 Kharif droughts

Most of the crops in Balochistan are harvested during the kharif season. On average, the province receives 45 % of its total rainfall during kharif season. The northern and eastern districts receive more than 50 % of their total rainfall during this season. The spatial distribution of the return periods for moderate, severe, and extreme droughts during kharif season is shown in Fig. 10. As can be observed in the figure, kharif droughts share somewhat similar characteristics regardless of their severity. Nonetheless, their spatial extents vary considerably. The percentages of land area that experiences frequent moderate, severe, and extreme kharif droughts is 56.75, 25.31, and 23.0 % respectively. The distribution of the return period for moderate, severe, and extreme kharif droughts shows that they mostly occur in the northeast and

east of Balochistan, and less so in the southwest and northwest. In most cases, the return period of moderate kharif droughts (Fig. 10a) is 6–7 years, including some parts of Makran coastline. However, some southwestern parts of the province are also affected by frequent moderate kharif droughts.

The return period for severe drought (Fig. 10b) is between 13 and 16 years in the northern and the northeastern regions, and more than 22 years in the northwest and some coastal regions in the south. Extreme kharif droughts occur less frequently as compared to moderate and severe droughts (Fig. 10c), once in 26–44 years in the northeast and the eastern regions of Balochistan. Extreme kharif droughts occur less frequently in the western region of the province.

4.2 Relationship of droughts with mean and standard deviation of rainfall

Non-parametric Kendall-tau correlation analyses were conducted to understand the association between the
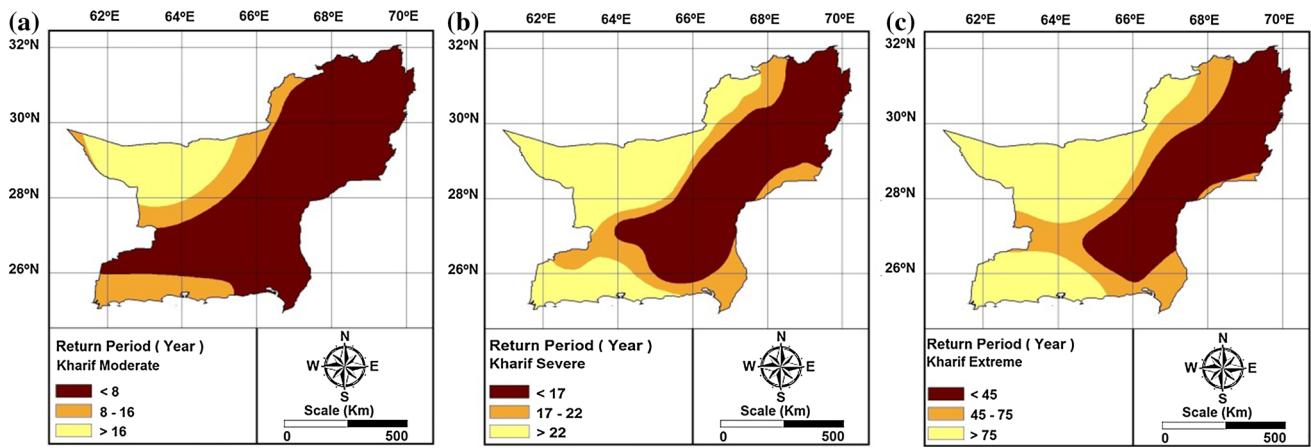
Fig. 10 Return periods of kharif (May–October) droughts in Balochistan of **a** moderate, **b** severe, and **c** extreme severities

Table 4 Correlation of drought return periods with mean and standard deviation of rainfall

Season	Moderate		Severe		Extreme	
	Seasonal rain	Standard deviation	Seasonal rain	Standard deviation	Seasonal rain	Standard deviation
Kharif	−0.121	−0.093	**−0.189**	−0.062	**−0.177**	−0.050
Rabi	**0.244**	**0.234**	−0.074	0.003	**−0.217**	−0.119
Early Winter	**−0.366**	**−0.287**	**−0.426**	**−0.309**	**−0.414**	**−0.284**
Late Winter	−0.025	−0.069	**−0.479**	**−0.276**	**−0.502**	**−0.260**
Early Summer	**−0.314**	**−0.203**	**−0.492**	**−0.324**	**−0.424**	**−0.367**
Late Summer	**−0.531**	**−0.490**	**−0.524**	**−0.404**	**−0.429**	**−0.280**

Bold number represents significant correlation at 99 % level of confidence

droughts and the average and standard deviation of rainfall in the region. For this purpose, the return periods of moderate, severe, and extreme droughts in each season were correlated with the average and standard deviation of rainfall in that season, the results having been presented in Table 4. Significant correlations indicative of a 99 % level of confidence are presented in bold in the table.

Negative correlations were found between the return periods of seasonal drought and mean seasonal rainfall in almost all cases. The return periods of moderate droughts were found to be significantly negatively correlated with seasonal rainfall during the early winter, early summer, and late summer periods. On the other hand, moderate severe droughts were found to be positively correlated ($r = 0.244$) with rainfall in the rabi season. Moreover, the return periods of severe droughts were also found to be significantly negatively correlated with the amount of seasonal rainfall in all seasons except for the rabi season. On the other hand, a significant negative correlation was found between the return periods of extreme drought and seasonal rainfall for all seasons. The highest negative

correlation of seasonal rainfall with the return periods of moderate ($r = -0.531$) and severe ($r = -0.490$) drought was found in late summer. However, the highest negative correlation of seasonal rainfall with the return periods of extreme drought ($r = -0.502$) was found in late winter.

Similar correlations were observed between the return periods of seasonal droughts and the standard deviation of seasonal rainfall. Negative correlations were found between the return periods of moderate droughts and the standard deviation of seasonal rainfall in early winter, early summer, and late summer; notwithstanding, this correlation was positive ($r = 0.234$) for the rabi season. The return periods of severe and extreme droughts were found to be negatively correlated with the standard deviation in seasonal rainfall for all seasons except for kharif and rabi. The highest negative correlations with standard deviation in seasonal rainfall were with the return periods of moderate ($r = -0.490$) and severe ($r = -0.404$) droughts during late summer. On the other hand, the highest negative correlation in the standard deviation of seasonal rainfall with the return periods of extreme drought ($r = -0.367$) was found in early summer.

Scatter plots were prepared to better illustrate the relationship between the return periods of seasonal droughts and the mean and standard deviation of seasonal rainfall. Because the seasonal rainfall series contains a disproportionate number of extreme values as compared to the drought return period series, plot points were prepared in log scale to better illustrate the data. The scatter plots between the return periods of droughts in late summer and the mean and standard deviation in late summer rainfall are shown in Fig. 11. The figure shows that most of the points fall close to regression line.

The negative correlation between drought return period and mean seasonal rainfall suggests that droughts occur more frequently in areas that receive above average rainfall for a particular season. Therefore, if the southern region was to receive above average early summer rain, the probability of the southern region experiencing early summer drought increases. Similarly, the negative correlation between drought return period and standard deviation in seasonal rainfall indicates that droughts occur more frequently in areas with greater year-to-year variation in rainfall. These findings are consistent with those reported by Sönmez et al. (2005), Shahid (2008), and Gallant et al. (2013).

5 Discussion

Other climatic factors, such as high temperature, high wind, low relative humidity, high evaporation, deforestation, and desertification can contribute to the occurrence of drought in a region (Sönmez et al. 2005; Gallant et al. 2013). However, precipitation constitutes the critical factor in the occurrence of drought and, therefore, allows for a better understanding of the process by which drought occurs (Vrochidou and Tsanis 2012). The present study only considered precipitation in the characterization of seasonal droughts. The study revealed that the return periods for droughts in different climatic and cropping seasons varied across the study area.

While winter droughts occur throughout the province, their return periods are less frequent in the northwest of the province. Therefore, the northwest region of Balochistan experiences droughts more frequently during winter. Winter rainfall in Balochistan is the result of western disturbances that travel eastwards at higher latitudes between 30° and 60°N. Sheikh (2001) reported that the winter rainfall in Pakistan fails when the western disturbance travels at 35°N or above. In such a situation, no secondary disturbances form below the 30°N latitude, resulting in drought striking the northern regions of Pakistan. The findings of the present study confirm these observations by Sheikh (2001). We observed that the return period of

winter droughts was more frequent in those regions with an abundance of winter rain. Regions experiencing the highest rainfall also experience the greatest variation in rainfall (Tabari et al. 2012). The correlation analysis revealed that the drought return period is inversely associated with the mean and standard deviation of rainfall, indicating that droughts are more frequent in areas where the standard deviation and the amount of winter rainfall are high.

The summer droughts occur due to a paucity of monsoonal rainfall. The monsoon enters Balochistan via an eastern aspect, resulting in the eastern part of the province receiving more rainfall during the monsoon. Summer droughts also occur predominantly in the eastern regions of Balochistan when the monsoon system fails to bring enough rainfall to these parts of the province (Chaudhry and Rasul 2012). The monsoon rainfall in Pakistan varies considerably in time, space, duration, and intensity (Saha 2010; Ganguli and Reddy 2014). These variations in monsoon rainfall often lead to disastrous floods and droughts in the monsoon-dominated areas. The results of this study also show that the frequency of summer drought is higher in the monsoon-dominated areas of the province. The correlation analysis revealed an inverse association in the summer drought return period and the mean and standard deviation of summer (i.e., monsoonal) rainfall. This indicates that summer droughts occur more frequently in the areas where the mean and standard deviations of summer rainfall are high. The summer droughts have a severe effect on local populations and ecosystems, especially on agriculture-dependent populations in the region (Dabo-Niang et al. 2014). The province's agricultural sector has suffered severe losses in the past due to summer droughts. The most severe droughts witnessed by the region occurred between the years 1998 and 2002. Ahmad et al. (2004) reported that these droughts resulted in the loss of 50–80 % of Balochistan's arable land and a 50 % loss in agricultural productivity between 1998 and 2002.

Precipitation increases with elevation. As the drought return period in the study area is inversely related to the volume of rainfall, the mountainous regions of Balochistan were found to be more prone to frequent droughts (Allamano et al. 2009). Much of the northeastern and eastern region is situated 1000 m above the mean sea level. Almost 95 % of agriculture in this area is rain-fed. The population density is also high in these regions (56 people per square kilometer) due to the ready availability of water and higher incomes when crop harvests are successful. Recurrent droughts, however, have a deleterious effect on the livelihoods and social structures of those living in these higher elevation regions.

Droughts in Balochistan have occurred many times in the past with devastating results. A lack of proper drought mitigation measures has exaggerated their impact on
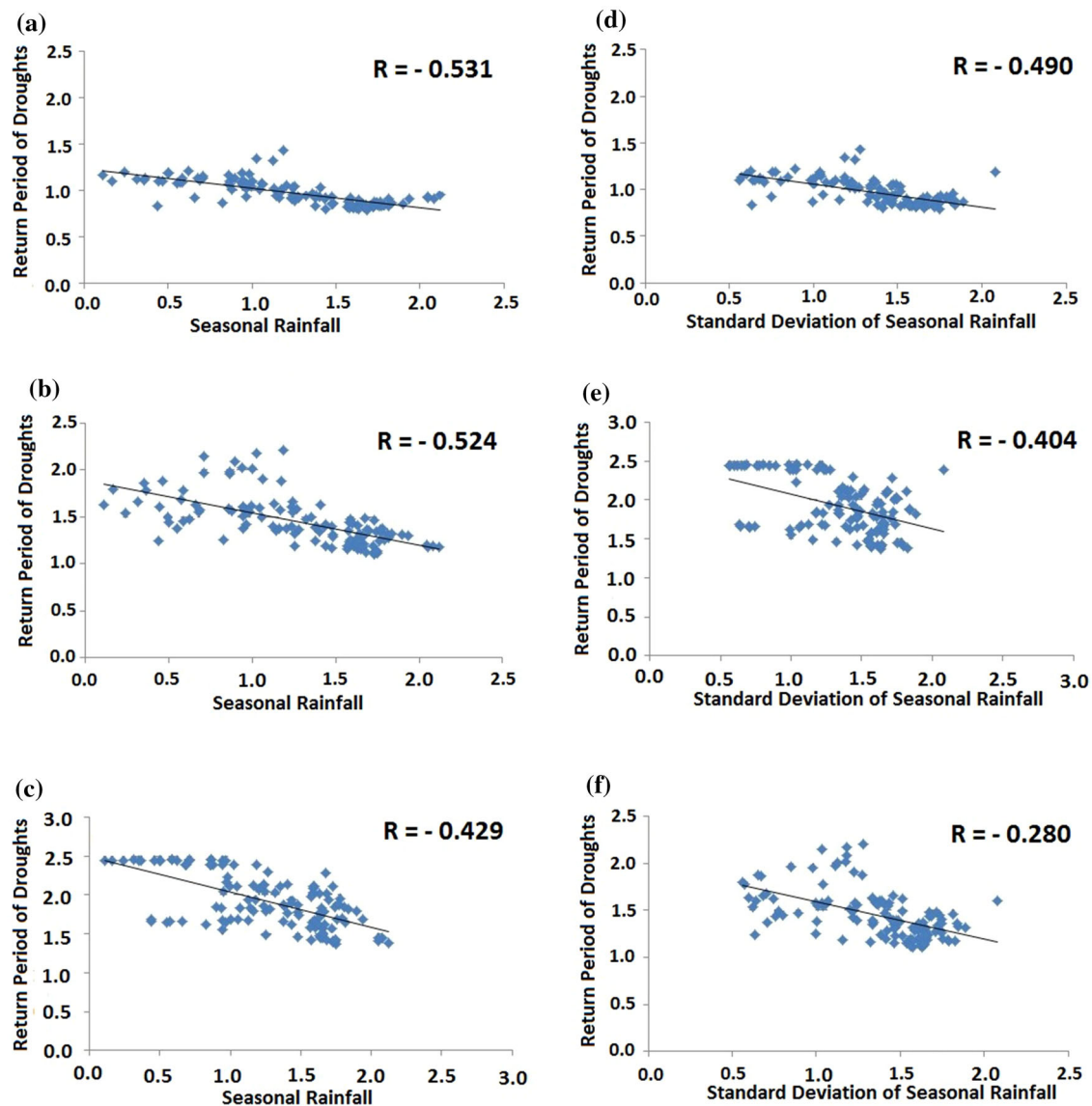
Fig. 11 Scatter plots showing association between seasonal rainfall and return periods of (**a**) moderate; (**b**) severe; (**c**) extreme droughts; standard deviation in seasonal rainfall and return periods of (**d**) moderate; (**e**) severe; (**f**) extreme droughts

society. Drought monitoring is essential for drought preparedness and mitigation in the region. Similar to other natural hazards, drought risk depends on a combination of natural forces and the degree to which a population is vulnerable to the effects of drought. Therefore, comprehensive drought studies, such as their intensity, frequency, magnitude, as well as their spatial and temporal patterns, are required in order to better inform drought mitigation planning.

Several drought studies have been carried out in recent years in Balochistan (Ahmad et al. 2004; Ali 2006; Shafiq and Kakar 2007; Ashraf et al. 2011, 2014). Most of these studies have focused on adaptive capacity and capabilities

to cope with droughts. Few attempts have been made to identify drought hazard zones in Pakistan. Anjum et al. (2012) analyzed the existing literature and rainfall maps of Pakistan to identify drought prone zones, concluding that the frequency of drought is much higher in Balochistan and Sindh provinces as compared to the rest of Pakistan. Mazhar and Nawaz (2014) used annual mean rainfall data from 36 stations across Pakistan for mapping meteorological drought intensity, finding that Balochistan was one of the most arid parts of the country and had the highest probability of extreme meteorological droughts. Pasha et al. (2015) assessed severe droughts in Sindh province, on the border of Balochistan, through the analysis of media

reports and concluded that the prolonged absence of rainfall and sheer negligence on the part of administrative authorities contributed to the devastating drought of 2014. However, each of these studies cited above limited their identification of drought prone areas to annual rainfall deficits and media reports. None of these studies sought to characterize droughts. The only effort to understand the return period of droughts in Pakistan was made by Xie et al. (2013), who investigated the spatiotemporal variability of droughts between 1960 and 2007 by calculating the SPI for 3-, 6-, and 12-month timescales. However, Xie et al. (2013) characterized overall drought patterns in Pakistan without giving any indication of how droughts differed across seasons or cropping periods. Droughts are particularly devastating in Pakistan when they occur during crop growing seasons (Ahmad et al. 2004). Therefore, the characterization of drought hazards during different climatic and cropping seasons is essential for the development of effective adaptation and coping strategies (Wang et al. 2012). The drought maps prepared in the present study can be used to identify drought prone areas during different climatic and crop growing seasons. The maps can also help in guiding effective adaptation and mitigation planning in Balochistan, which is one of the most drought prone regions of Pakistan.

Pakistan is looking toward the efficient management of droughts and other natural disasters. A number of organizations, such as the Pakistan Meteorological Department, are investigating drought monitoring and early warning systems. Several new organizations have also been established in Balochistan for drought and other disaster risk management purposes, such as the Provincial Disaster Management Authority (PDMA), to promote disaster risk management approaches through coordination and collaboration to prevent or minimize damage; and the Arid Zone Research Centre (AZRC), to conduct research on farm level adaptation to droughts. The Provincial Assembly of Balochistan, the province's peak governing body, has also prepared a Provincial Disaster Risk Management Plan (PDRMP), which identifies the risk to environment, and outlines the key institutional and programming components of effective disaster risk management, emergency response, and recovery.

However, a major limitation in Pakistan's current approach to drought monitoring is the lack of coordination among the various organizations and poor policy implementation. Therefore, the following major recommendations are made to improve drought preparedness and mitigation in the region:

1. Improvement in the coordination between different government and non-governmental organizations is required in order to enhance the capability of drought knowledge/information dissemination between departments.

2. The majority of farmers in rural areas are illiterate and they possess little knowledge about crop water requirements. Therefore, greater awareness is required among farmers of crop water management practices to cope with droughts.

3. Government initiatives are needed to encourage the modern irrigation techniques and floodwater harvesting to cope with droughts.

4. The development of drought forecasting and early warning systems should be considered a priority.

6 Conclusions

The arid climate and rough topography of Balochistan, coupled with high rainfall variability, contribute to the province's vulnerability to droughts. This study has revealed that the return period of droughts during different climatic and cropping seasons varies considerably across the province. While early winter droughts are more frequent in the northwest region, late winter droughts occur throughout almost the entire province. The early and late summer droughts occur more frequently in the east and in the northeast regions, while rabi and kharif droughts are more frequent in the central, northern, and northeastern regions. As the return period provides a measure of the likelihood of a drought event, the maps prepared for this study can be used for proper adaptation and mitigation measures. The findings of this study are expected to benefit a number of stakeholders, particularly disaster management and agricultural organizations, and development/planning authorities, to improve their understanding of drought patterns in the province.

Drought is a complex phenomenon that should be studied more comprehensively. Further studies might help to elucidate the socioeconomic impact of drought in the region. As groundwater is one of the main sources of irrigation in Balochistan, future studies might look to investigate the propagation of meteorological drought to groundwater. Future studies could also be conducted to identify the geographical distribution of drought risk through the analysis of human and environmental vulnerability to drought during different seasons. Moreover, projected precipitation data could be used to investigate the pattern of future droughts in the context of climate change and variability.

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