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Original Article

Drought variability assessment using standardized precipitation index, reconnaissance drought index and precipitation deciles across Balochistan, Pakistan

Avaliação da variabilidade da seca usando o índice de precipitação padronizado, índice de seca de reconhecimento e decis de precipitação no Baluchistão, Paquistão

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Abstract

Drought variability analysis is of utmost concern for planning and efficiently managing water resources and food security in any specific area. In the current study, drought spell occurrence has been investigated in the Balochistan province of Pakistan during the past four decades (1981-2020) using standardized precipitation index (SPI), reconnaissance drought index (RDI), and precipitation deciles (PD) at an annual timescale. Precipitation and temperature data collected from 13 synoptic meteorological stations located in Balochistan were used to calculate the SPI, the RDI, and the PD for calculation of drought severity and duration. Based on these indices, temporal analysis shows adverse impacts of drought spells in Nokkundi during 1991-1993, in Barkhan, Dalbandin, Quetta stations during 1999-2000, whereas Barkhan, Dalbandin, Lasbella, Sibi during 2002-2003, Zhob during 2010-2011, Kalat and Khuzdar during 2014-2015, and Panjgur during 2017-2018. Also, the aridity index for each station was calculated based on the UNEP method shows that major part of Balochistan lies in the arid zone, followed by the hyper-arid in the southwestern part and the semi-arid zones in the northeastern part of the province. SPI and RDI results were found more localized than PD, as PD shows extensive events. Furthermore, principal component analysis shows a significant contribution from all the indices. For SPI, RDI, and PD, the first three principal components have more than 70% share, contributing 73.63%, 74.15%, and 72.30% respectively. By integrating drought patterns, long-term planning, and preparedness to mitigate drought impacts are only possible. The RDI was found more suitable and recommended in case of temperature data availability.

Keywords: drought variability, standardized precipitation index, reconnaissance drought index, precipitation deciles, principal component analysis.

Resumo

A análise da variabilidade da seca é de extrema importância para o planejamento e gestão eficiente dos recursos hídricos e da segurança alimentar em qualquer área específica. No estudo atual, a ocorrência de períodos de seca foi investigada na província do Baluchistão, no Paquistão, durante as últimas quatro décadas (1981-2020), usando índice de precipitação padronizado (SPI), índice de seca de reconhecimento (RDI) e decis de precipitação (PD) em uma escala anual. Dados de precipitação e temperatura coletados de 13 estações meteorológicas sinóticas localizadas no Baluchistão foram usados para calcular o SPI, o RDI e o PD para cálculo da severidade e duração da seca. A análise temporal mostra os impactos adversos dos períodos de seca em Nokkundi durante 1991-1993 e na maior parte da província de 1999 a 2004. Além disso, o índice de aridez para cada estação foi calculado com base no método do PNUMA. Os resultados de SPI e RDI foram encontrados mais localizados do que PD, pois PD apresenta eventos extensos. Além disso, a análise de componentes principais mostra uma contribuição significativa de todos os índices. Para SPI, RDI e PD, os três primeiros componentes principais têm mais de 70% de participação, contribuindo com 73,63%, 74,15% e 72,30%, respectivamente. O planejamento e a preparação de longo prazo para mitigar os impactos da seca só são possíveis por meio da integração dos padrões de seca.

Palavras-chave: variabilidade da seca, índice de precipitação padronizado, índice de seca de reconhecimento, decis de precipitação, análise do componente principal.

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1. Introduction

Pakistan is an agricultural country heavily dependent on rainfall for its livelihood and economy (Mahmood et al., 2020; Praveen and Sharma, 2019). Pakistan is reported to face many types of natural disasters, such as earthquakes, floods, droughts and famines, landslides, heatwaves, and many more as a result of having various climatic zones and unstable geological settings (Ashraf and Routray, 2013; Qaisrani et al., 2019; Sajjad et al., 2014). Balochistan, the largest province of the country, covers 44% of the total area has a diverse climate with the major part in arid and hyper-arid zones and with a small semi-arid northeastern part. The average temperature ranges from 0 °C in winter to 35 °C in summer but sometimes exceeds 50 °C in specific areas (Ahmed et al., 2016). Agriculture and livestock husbandry are directly affected by low rainfall, whereas global warming is exponentially increasing water demand within the province, resulting in drought events (Qaisrani et al., 2021). The same is evident globally in higher evaporation rates and decreasing surface and groundwater levels because of rising temperatures (Cassardo, 2014). So, global warming is one of the dominant factors in increasing frequency and duration of drought especially in regions where the precipitation rate is already low (Chou et al., 2019; Zahid and Rasul, 2012). Apart from natural factors, human activities such as urbanization, overexploitation of groundwater, industrialization, ever-changing human needs, and increasing population are also involved in annoying the drought impacts. Mostly, the people in Balochistan live in rural areas and the impacts of drought become worst in such areas (Ashraf et al., 2014; Miyan, 2015).

It was reported in the literature that in Pakistan average rainfall decreases with increasing distance from the sea (Adnan and Khan, 2009). The dominant field of the economy within the province is livestock husbandry and agriculture, which are directly impacted by the drought events within the province. Also, livelihood is badly disturbed by a shortage of water and related factors imposed by the climatic extremes. The increasing population and industrialization culture require improved planning of resources. Low rainfall, geographic location, geomorphological characteristics, poor mass awareness of water use, global warming, poor watershed management, and lack of resource planning, all contribute to a bad situation. Proper drought monitoring and variability assessment is a key concern to enable addressing the current state and to evaluate future scenarios.

According to the census of 2017, the population of Balochistan reached 12.3 million with an annual growth rate of 3.37%, while it was recorded as 6.56 million in 1998. On the other hand, increasing heatwaves in the province are considered as major threats of drought impacts (Kim et al., 2017; Masood et al., 2015; Rauf et al., 2017; Zahid and Rasul, 2012). Another study reported that temperature rises continuously threatening the Southeastern, low plains, and North-eastern part of Balochistan. These temperatures cause heatwaves, low humidity, a high rate of evaporation, low soil moisture, and the ultimate result is recurring droughts (Zahid and Rasul, 2007). Also, the recorded variability in water resources is very high in Balochistan (Young et al., 2019). This is due to the large differences in altitude within the province, which causes rainfall variability.

While, drought is an essential creeping part of the climate and occurs in all climatic zones with long-lasting adverse impacts (Osbahr et al., 2008), assessing its variability will help in preparedness and proper planning of resources. Droughts are considered as the deadliest disasters. Therefore, their risk assessment is of keen concern, however, this process contains many stages including from monitoring to mitigation (Chou et al., 2019). Drought monitoring is one of these steps. In the current study, more focus was paid to monitoring drought events in Balochistan. Many drought indices have been designed to quantify drought impacts, but only a few are perfect for a specific area such as Pakistan. Fifteen different indices were assessed in a study and they found SPI, SPEI, and RDI more suitable for Pakistan (Adnan et al., 2018). Also, a combination of indices for drought assessment gives better results (Buttafuoco et al., 2016; Akbari et al., 2016). Therefore, SPI, RDI, and PD were selected for the current study. Standardized Precipitation Index (SPI) is one of the best options when limited station data is available, and also it is the standardized index that can be normalized (Mckee et al., 1993). It has been used by Pakistan Meteorological Department (PMD) for drought monitoring purposes (Xie et al., 2013). As PMD only deals with shorter timescales such as 1-3 months, it considers meteorological drought for the ease of farmers, hydroelectric power production, water resource managers, and other stakeholders. Also, many other indices exist today for drought monitoring and characterization. A previous study in the arid zone of the Balochistan province exists and suggests longer timescales to avoid fluctuations in results (Qaisrani et al., 2021).

The current study investigates the temporal variability of drought at an annual timescale in the Balochistan province of Pakistan. It covers majorly hydrological drought as 9-12 months timescales refers to hydrological droughts, although covering meteorological and agricultural types of droughts. This study aims to assess the dry periods with different drought intensities by evaluating the performance of three drought indices. The scope of this study is to monitor and characterize droughts specifically in Balochistan province from 1981 to 2020. Although different indices were applied and investigated for Pakistan, this work only focuses on the Balochistan scenario using these three indices. As Balochistan province faced severe drought conditions in the near past for agriculture, livestock, and drinking water. Therefore, this study will help the government and other stakeholders to understand a clearer picture of the situation and adopt sustainable strategies for pre-planning in-drought actions, and post-management. These above-mentioned characteristics are well explained using different classes of the drought categories. The study used standardized Precipitation Index (SPI), Reconnaissance Drought Index (RDI), and Precipitation Deciles (PD) for drought assessment during 1981-2020. SPI and PD only require precipitation as input data, whereas the RDI needs temperature data for the calculation of potential evapotranspiration (PET). Monthly temperatures are available only at 13 stations within the province which can be used for the calculation of PET in this study. Also, this study uses precipitation data available with PMD for 40 years for index calculation. SPI is extensively used in the literature for drought monitoring and analysis in most parts of the world because of its standardized nature (Mckee et al., 1993; Qaisrani et al., 2021; Xie et al., 2013). It is simple to calculate as compared to many other indices and helps in assessing drought severity. However, SPI has limitations as it only considers single input, therefore multiple indices give a better picture of the drought using temperature and evapotranspiration (Khan et al., 2021). RDI is an important index that uses water balance in terms of input and output. World Meteorological Organization (WMO) also recommended SPI and RDI for drought characterization (Hayes et al., 2011). PD is used for the first time in Balochistan to check its appropriateness for this area, although it was also used for South Central Asia in a study (Adnan et al., 2016) The performance of three indices was evaluated in this study which will help in climate change adaptation and water resource management within the province.

2. Materials and Methods

2.1. Study area

Balochistan is the largest province in Pakistan, located between approximate latitudes 24 to 33° N and longitudes 61 to 71° E with diverse climatic zones. Climate zones range from semi-arid to hyper-arid. The hyper-arid zone is the most vulnerable to rainfall, with an average of less than 15 mm (Ahmed et al., 2019). The topography of the province varies strongly over short distances from the mountainous areas (Ahmed et al., 2016). Rough terrain makes an extensive part of the province containing several plateaus with varying heights and ruggedness. Two significant sources of rainfall are the Monsoon and the western depression. Monsoon causes summer rainfall, and the latter causes winter precipitation in the eastern and northeastern parts of the province. The western depression causes rainfall in the lower region of the province (Ahmed et al., 2016). The annual precipitation ranges from 200 to 350 mm, including snow in the winter and heavy rain during summer (Naz et al., 2020).

2.2. Data collection and analysis

The precipitation data for the current study was collected from Pakistan Meteorological Department (PMD) from 1981 to 2020, as observed at 13 weather stations named Barkhan, Dalbandin, Jiwani, Kalat, Khuzdar, Lasbella, Nokkundi, Ormara, Panjgur, Pasni, Quetta, Sibi, and Zhob within the province. The mentioned duration for data collection was due to its availability with PMD. Only for Ormara station, the temperature data for the periods 1981-1994 and 2016-2020 were missing, therefore for this specific station data included in this study for 1995-2016. These stations and their characteristics (elevation, latitude, and longitude) are shown in Figure 1 and Table 1.

The data was assembled, and the SPI, the RDI, and the PD were calculated using Drought Indices Calculator

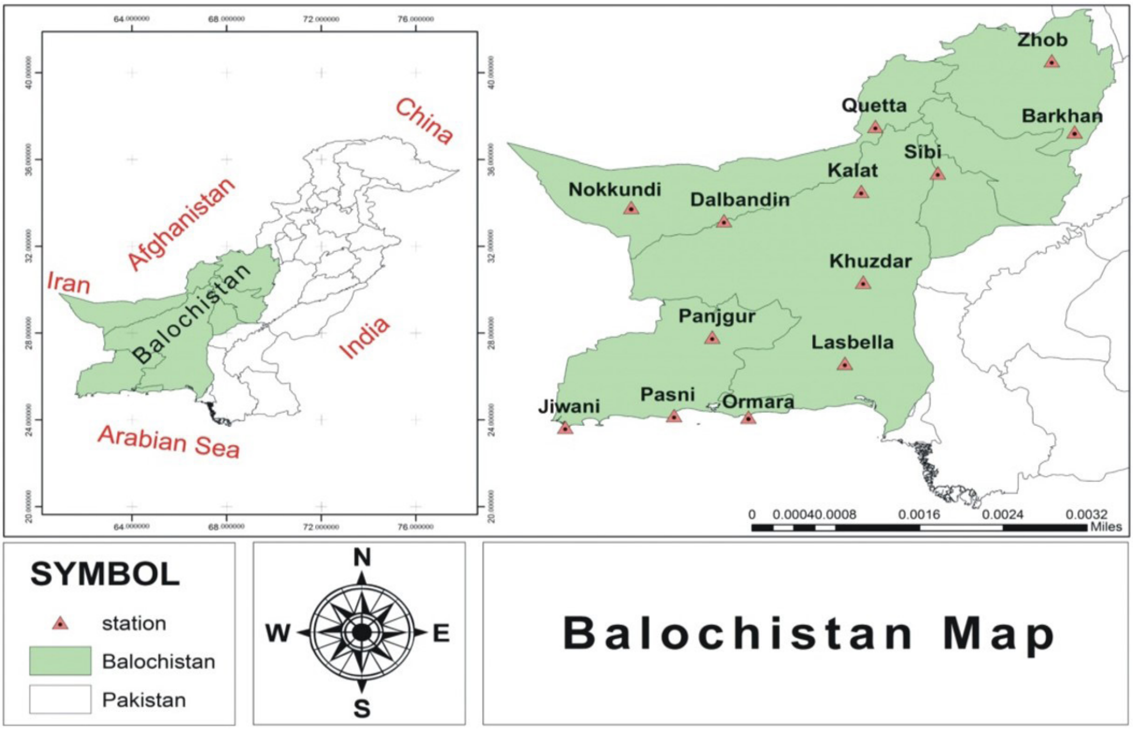

Figure 1. Situation map with synoptic weather stations.

Table 1. Study station details.

S.#	Station	S. S	Lat (°N)	Long (°E)	A. Max. T (°C)	A. Min.T (°C)	A. PRCP. (mm)	Elevation (MSL)	Data
1	Barkhan	BKN	29.88	69.72	28.44	14.84	34.9	1,098	1981-2020
2	Dalbandin	DBN	28.53	64.24	32.39	14.03	6.9	848	1981-2020
3	Jiwani	JWI	25.07	61.80	30.46	21.22	8.4	57	1981-2020
4	Kalat	KLT	29.02	66.35	22.20	5.65	18.1	2,015	1981-2020
5	Khuzdar	KZD	27.50	66.38	29.07	15.08	22.3	1,231	1981-2020
6	Lasbella	LSB	26.14	66.10	35.48	18.84	13.9	87	1981-2020
7	Nokkundi	NKD	28.82	62.75	32.80	17.52	3.0	679	1981-2020
8	Ormara	ORM	25.30	64.60	30.56	18.46	7.0	7	1995-2016
9	Panjgur	PGR	26.58	64.06	30.37	15.23	7.5	968	1981-2020
10	Pasni	PSI	25.26	63.47	31.47	19.92	8.3	10	1981-2020
11	Quetta	QTA	30.11	66.57	25.13	8.62	22.0	1,626	1981-2020
12	Sibi	SIB	29.33	67.53	35.15	19.24	15.6	133	1981-2020
13	Zhob	ZHB	31.21	69.28	26.72	11.99	23.5	1405	1981-2020

S.S: short symbol; A. Max. T: average maximum temperature; A. Min. T: average minimum temperature; A. PRCP: average precipitation; MSL: mean sea level.

(DrinC) software (version 1.7) developed by the Centre for the Assessment of Natural Hazards and Proactive Planning and Laboratory of Reclamation Works and Water Resources Management at National Technical University of Athens. DrinC can calculate drought indices at various time scales using precipitation and temperature as input data in a specific format and gives output in the form of Excel spreadsheets (Tigkas et al., 2015), however in the current study three indices are calculated at an annual timescale.

2.3. Standardized Precipitation Index (SPI) calculation

Index calculation can be done manually using appropriate equations or using software tools specifically designed for this purpose. SPI is a commonly used index that was developed in a prior study (Mckee et al., 1993), and it is useful for any drought event (i.e., meteorological to hydrological because of its calculation at various timescales) based on past precipitation data (Chen et al., 2017; Shahabfar and Eitzinger, 2013; Thomas et al., 2015b). DrinC calculates SPI as a "rolling" index based on monthly data (Tigkas et al., 2015). The long-term rainfall record for a specific period is fit with a probability distribution, which is further converted to a normal distribution. Gamma distribution is a good fit with the long-term time series (Mckee et al., 1993). Periodical sums of precipitation usually follow the gamma distribution. As a result, the sequence of precipitation was normalized using the transformation function f (P) given below and the SPI can be expressed as follows (Mckee et al., 1993) (Equations 1-2):

$$f\left(P\right)= X=\sqrt[3]{P} \tag{1}$$

$$SPI=\frac{X-X_m}{\sigma} \tag{2}$$

Where 'P' denotes the element of precipitation sequence, 'X' shows the Precipitation noted at the given station in mm, 'X_m' is the Precipitation mean (mm) and 'σ' represents Standard deviation measured in mm (Adnan et al., 2018; Sharma et al., 2009).

SPI by its sign indicates whether the precipitation is above or below the long-term mean, with positive and negative values respectively. As the SPI is normalized, it can be compared across different locations, irrespective of the absolute values of precipitation (Guttman, 1998). It uses standard deviation to express deviation from the long-term mean. The classification of drought conditions is given in Table 2 (Tigkas et al., 2015).

2.4. Reconnaissance Drought Index (RDI) calculation

RDI is an index used to calculate water deficiency as it takes PET into account by considering monthly maximum and minimum or mean temperatures at an observation point. It is useful for drought determination across various climatic characteristics (Thomas et al., 2015a; Tsakiris et al., 2007). The following equation calculates the initial value for the i-th year on a time basis of k months (Equation 3).

$$\propto_k^{(i)}=\frac{\sum_{j=1}^{k} P_{ij}}{\sum_{j=1}^{k} PET_{ij}}\ ,i=1\left(1\right)N\ and\ j=1\left(1\right)k \tag{3}$$

Where, α_k is the initial value of RDI, P_{ij} and PET_{ij} show precipitation and potential evapotranspiration for the j-th month of i-th year and 'N' shows the number of years covered by collected data.

The initial value of RDI follows gamma or lognormal distribution depending upon time scale and location (Tigkas et al., 2015). If the distribution is lognormal, then

Table 2. The classification of SPI to named categories (source: Tigkas et al., 2015).

SPI/RDI range	Category label
≥ 2.0	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderate drought
-1.5 to -1.99	Severe drought
≤ -2.0	Extreme drought

the Standardized RDI can be calculated using equation Equation 4.

$$RDI_{st}^{(i)} = \left(y^{(i)} - \bar{y} \right) \Big/ \hat{\sigma}_y \quad (4)$$

Where $y^{(i)} = ln\,\alpha_k^{(i)}$, $\bar{y}$ is the arithmetic mean, and $\hat{\sigma}_y$ shows standard deviation.

Drought severity categories based on RDI are given in Table 2. If the gamma distribution is assumed, then the gamma probability function is fit to the given frequency distribution of the initial value of α_k. For short-term periods, the cumulative precipitation may be assumed zero. In such a case, RDI_{st} is computed based on composite cumulative distribution, gamma probability function, and probability of zero precipitation.

RDI_{st} with positive values represents wet periods or no drought while negative values represent drought spells.

2.5. Precipitation Deciles (PD) calculation

Precipitation Deciles (PD) were developed by Gibbs and Mahar and are used to examine droughts (Barua et al., 2011; Gibbs and Maher, 1967). This measure has been widely used by many researchers in drought determination where output results show the climatic situation for a specific area ranging from 'much below normal' to 'much above normal' (Keyantash and Dracup, 2002; Lana and Burgueño, 2000; Wilhite et al., 2007). It requires fewer input data, is relatively easy to calculate, and can be applied for data-scarce areas. Using this method, long-term precipitation data is arranged in descending order for making a cumulative frequency distribution. It is computed by dividing the monthly precipitation distribution into 10% parts. A sum of three months of precipitation is ranked against the record of total climate data. If the sum falls within the lowest three months decile data, the region is declared as drought-stricken, while if it lies within the fourth decile, the condition is normal, however, if the total precipitation is in or above the eighth decile, the drought is over. It ranges from 1^{st} to 10^{th} decile while the labeling is shown in Table 3.

Table 3. The classification of PD to named categories (source: Tigkas et al., 2015).

PD range	Category
1-2 Deciles	Much below normal
3-4 Deciles	Below normal
5-6 Deciles	Near normal
7-8 Deciles	Above normal
9-10 Deciles	Much above normal

2.6. Aridity Index (AI) and Potential Evapotranspiration (PET) calculation

The aridity index represents the climatic conditions of a specific location or area based on total precipitation and potential evapotranspiration. It is a key indicator for the degree of dryness and drought characterization using Equation 4, and Table 4 has been adopted by the United Nations Environment Program (UNEP) (Li et al., 2017) (Equation 5).

$$AridityIndex\left(AI\right) = P \big/ PET \quad (5)$$

Where 'P' denotes 'mean annual precipitation and 'PET' is the mean annual evapotranspiration.

Potential evapotranspiration (PET) is very important for calculating RDI. It uses either mean temperature data or maximum and minimum temperature values, depending upon the method Hargraves method, Thornthwaite, or Penman-Monteith (Anderson and French, 2019; Hargreaves, 1994; Thornthwaite, 1948). Hargraves method was adopted in this study to calculate PET, requiring monthly maximum and minimum temperatures as input data and it can be calculated using Equation 5 (Hargreaves and Samani, 1985) (Equation 6).

$$PET = cH \times 0.408\, R_0 \times \left(T + 17.8\right)\sqrt{T_{max} - T_{min}} \quad (6)$$

Here cH stands for Hargreaves coefficient with a standard value of 0.0023, R_0 represents the solar radiation at the given latitude, the value 0.408 is a constant (reciprocal of the latent heat flux of vaporization at 20 ℃), T is the mean temperature, and T_{max} and T_{min} are maximum and minimum temperatures respectively.

3. Results and Discussions

Based on calculated PET values and climatic conditions, Lasbella station had the highest PET of 1990.60 mm while Jiwani station had the lowest PET of 1427.70 mm, both in an arid climate.

Several existing indices are used for drought monitoring, including SPI, RDI, and PD, in the literature (Guo et al., 2018; Marini et al., 2019; Merabti et al., 2018; Mukherjee et al., 2018; Spinoni et al., 2015). Potential evapotranspiration informs about the water demand for agriculture and the conservation of water resources. RDI and SPI on an

Table 4. The classification of aridity index to named categories (source: Boschetto et al., 2010; Li et al., 2017).

Aridity Index (AI) range	Category
AI < 0.05	Hyper-arid
0.05 <AI < 0.2	Arid
0.2 < AI < 0.5	Semi-arid
0.5 < AI < 0.65	Dry sub-humid
0.65 < AI > 0.75	Humid
AI > 0.75	Hyper-humid

annual scale show similar variabilities, while PD shows more moderate to severe events than the other indices, as can be seen in Figures 2, 3, and 4, respectively (Ramkar and Yadav, 2018). For overall drought categories shown in Table 5, SPI shows 57.53% as moderate, 20.55% as Severe, and 21.92% as extreme, droughts while RDI shows 53.42%, 22.85%, and 21.43% as moderate, severe, and extreme, respectively. However, PD shows 3.31%, 66.88%, and 29.80% as moderate, severe, and extreme, respectively. It is clear from these results that the SPI and the RDI show similar results while PD gives different and extensive percent for the severe category.

Similar studies in Iran show that the RDI is more sensitive than the SPI because of its input data. Evapotranspiration cannot be neglected while monitoring drought in any region (Jamshidi et al., 2011). In another study, authors used DrinC which monitors drought in Sistan and Baluchistan provinces of Iran using RDI and SPI and recommended RDI for its better results for temperature data (Province and Iranshahr, 2018; Shokoohi and Morovati, 2015).

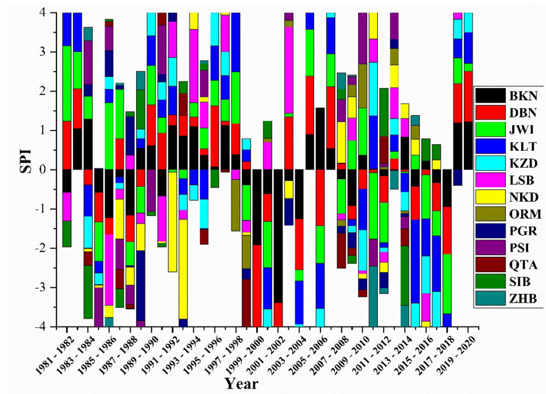

Figure 2. SPI on an annual scale for the years 1981-2020.

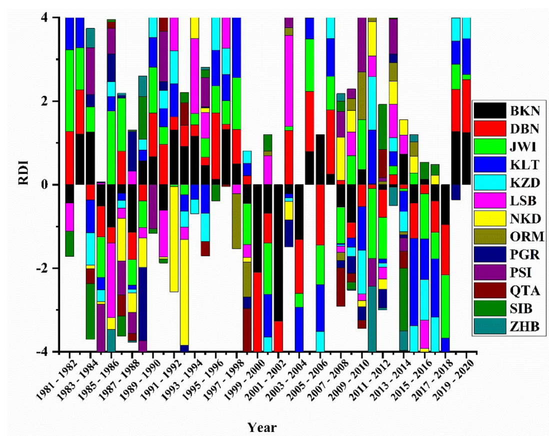

Figure 3. RDI on an annual scale for the years 1981-2020.

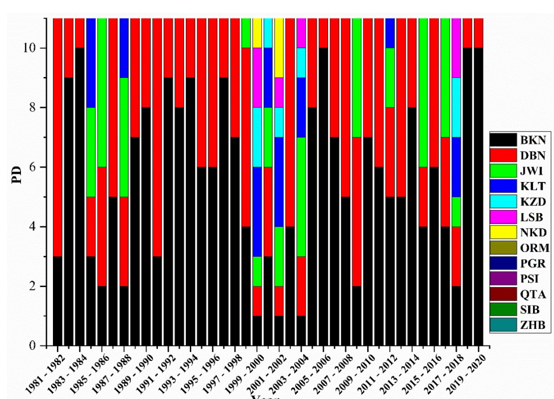

Figure 4. PD on an annual scale for the years 1981-2020.

3.1. Temporal analysis of drought

Figures 2-4 show temporal variations of drought in the study area during the period 1981-2020. However, for the Ormara station, the period was 1995-2016 because of consistent data being available for the said duration. All drought indices show moderate to extreme drought events at all thirteen stations in different years. These graphs show extreme drought events for Nokkundi station during 1991-1993, for Barkhan, Dalbandin, Quetta stations during 1999-2000, at Barkhan, Dalbandin, Lasbella, Sibi during 2002-2003, at Zhob during 2010-2011, at Kalat and Khuzdar during 2014-2015, and at Panjgur during 2017-2018.

Severe drought events are visible for Pasni station during 1984-1985, for Lasbella during 1985-1986, for Panjgur during 1988-1989, for Jiwani, Lasbella, Panjgur, and Pasni during 1999-2000, for Nokkundi, Sibi, and Zhob during 2003-2004, for Jiwani during 2010-2011, and Jiwani and Pasni during 2017-2018.

Regarding moderate drought events, although all the indices show several events during these 40 years, PD shows more of this type of events than the other two indices. A detailed summary showing number of drought events with different severity categories is given in Table 5.

3.1.1. Standardized precipitation index

The temporal analysis results using SPI for all stations during 1981-2020 are shown in Figure 2, which shows the severe drought in Nokkundi during 1991-1993, severe to extreme droughts at Barkhan, Jiwani, Lasbella, Panjgur, Pasni, Dalbandin, and Quetta during 1999-2000 and at Nokkundi, Sibi, Zhob, Lasbella, and Panjgur during 2003-

Table 5. Number of droughts in months based on various drought categories.

Station	SPI			RDI			PD		
	M	S	E	M	S	E	M	S	E
BKN	0	1	1	3	1	2	0	8	3
DBN	3	0	2	3	0	2	1	8	2
JWI	4	4	0	3	3	0	0	8	4
KLT	6	0	1	6	0	1	0	8	5
KZD	6	0	1	6	0	1	0	8	3
LSB	1	2	2	1	2	2	0	8	4
NKD	2	1	2	2	1	2	1	8	4
ORM	3	0	1	3	0	0	0	4	2
PGR	0	2	2	0	2	2	1	9	2
PSI	5	3	0	4	3	0	1	8	4
QTA	5	0	1	5	0	1	0	8	3
SIB	1	1	1	1	2	1	0	8	4
ZHB	3	1	2	2	2	1	1	8	5
Sum	42	15	16	39	16	15	5	101	45
St. Dev.	0	1.281	0.725	1.870	1.165	0.800	0.506	1.165	1.050
Mean	3.230	1.153	1.230	3	1.230	1.153	0.384	7.769	3.461

M: moderate; S: severe; E: extreme.

2004, while Jiwani, Pasni, and Panjgur had severe drought during 2017-2018.

The SPI shows no moderate event for Barkhan and Panjgur stations. Similarly, for Dalbandin, Kalat, Khuzdar, Ormara, and Quetta no severe event was found. However, Jiwani and Pasni were the only stations where extreme events were not reported. The maximum events reported were moderate (Kalat and Khuzdar), severe (Jiwani) and extreme for Dalbandin, Lasbella, Nokkundi, Panjgur and Zhob.

3.1.2. Reconnaissance drought index

The temporal analysis results using RDI for all stations during 1981-2020 are shown in Figure 3, showing that Nokkundi was severely affected during 1991-1993, while Barkhan, Dalbandin, and Quetta were during 1999-2000, Barkhan, Dalbandin, Lasbella, and Sibi were during 2001-2002, Lasbella and Panjgur were during 2003-2004, Zhob was during 2010-2011, Kalat and Khuzdar were during 2014-2015, and Panjgur was during 2017-2018.

The RDI shows more moderate events for Kalat and Khuzdar followed by Quetta and Pasni stations, while more severe events were detected for Jiwani and Pasni stations than other stations, and more extreme events were shown for Barkhan, Dalbandin, Lasbella, Nokkundi, and Panjgur. On the other hand, no moderate spell for the Panjgur station, no severe event for Dalbandin, Kalat, Khuzdar, Ormara, and Quetta, and similarly no extreme events for Jiwani, Ormara, and Pasni stations.

3.1.3. Precipitation deciles

The temporal analysis results using PD for all stations during 1981-2020 can be seen in Figure 4. Overall, PD shows more affected areas than SPI and RDI. Like the other indices, it shows the extreme drought in Nokkundi during 1991-1993, and severe to extreme drought during 2001-2002, 2003-2004, and 2017-2018.

The above-mentioned drought indices give reliable results especially considering limited available data with the government. The changing climate impacts on water resources are notable in Balochistan demonstrating negative trends in almost all stations (Naz et al., 2020). Frequent drought spells are expected in the arid zone of Balochistan (Naz et al., 2020; Qaisrani et al., 2021).

From Table 5, it is very clear that PD shows an extensive number of drought months although it considers only precipitation as drought input. However, the importance of temperature is well known in drought occurrence; therefore, RDI is more reliable among these three indices.

The PD shows no moderate events for Barkhan, Jiwani, Kalat, Khuzdar, Lasbella, Ormara, Quetta, and Sibi, however many severe and extreme events were detected for all stations, although category classes for the PD are different from other both indices.

3.1.4. Comparison of drought indices

Drought index comparison is important for any specific region or area (Pathak and Dodamani, 2020; Zarei et al., 2019). RDI results are more reliable than SPI because it considers temperature data and precipitation while SPI takes only precipitation as input. Literature shows that SPI is not much effective for the correlation of agricultural production. RDI gives significant results for drought existence if it coincides with crop production season. Also, it is an important index for its validity in agricultural risk assessment (Khan et al., 2021). However, both indices show almost similar patterns. On the other hand, results taken from PD are relatively poor, showing extensive events at all stations with mixed results. Based on results obtained during the temporal study of drought events, RDI is more suitable than the other two indices, where a previous study shows similar results (Adnan et al., 2018).

3.2. Aridity index

The aridity index (AI) is an important index used to explain an area's climatic characteristics (Tabari and Aghajanloo, 2013). It was calculated using the UNEP method in DrinC software while calculating RDI for specific locations. The AI for each location and their respective climatic conditions at each station can be seen in Table 6.

3.3. Principal Component Analysis (PCA) of drought

PCA is used in drought analysis to summarize and interpret several variables (Gocic and Trajkovic, 2014). It has been widely reported in the literature for drought variability analysis in different parts of the world (Martins et al., 2012; Raziei et al., 2009). It is one of the very useful nonparametric linear tools for compression and orthogonalization of data. It will produce a new set of uncorrelated variables which describe the total variation of a large number of interrelated variables (Sigdel and Ikeda, 2010). In this study, PCA was applied to compare different indices i.e., SPI, RDI and PD (Georgios, 2016). It was applied separately to the calculated values of SPI, RDI, and PD, across all stations, using the Past statistical package version 4.03. A Scree plot of eigenvalues (%) and scatter plot between PC1 and PC2 are shown in Figure 5, Figure 6, and Figure 7 respectively. PCA is a nonparametric multivariate technique used to identify the smallest dimensionality that can explain a given variability (Sigdel and Ikeda, 2010; Xie et al., 2013). It is based on the estimation of the eigenvalues and eigenvectors. In PCA, either covariance matrices or correlations are applied (Gocic and Trajkovic, 2014). In this study, PCA across the thirteen synoptic weather stations was applied, and only eigenvalues greater than 1.0 were included in the Scree plot (Sigdel and Ikeda, 2010). These PCs are unrotated components showing the percentage of variance. Whereas scree plots help in determining the number of principal components applicable for retaining rotation (Demšar et al., 2013; Abdi and Williams, 2010). A summary of the variance explained by individual components is shown in Table 7. It is worth mentioning that although number of components displayed is 13, however, only first three components are considered as these show the highest variability in drought patterns.

Table 6. Aridity index calculated for the study stations.

S. No.	Station	Aridity Index	Climatic Condition
1	Barkhan	0.26	Semi-arid
2	Dalbandin	0.04	Hyper-arid
3	Jiwani	0.07	Arid
4	Kalat	0.15	Arid
5	Khuzdar	0.15	Arid
6	Lasbella	0.08	Arid
7	Nokkundi	0.02	Hyper-arid
8	Ormara	0.05	Arid
9	Panjgur	0.05	Arid
10	Pasni	0.06	Arid
11	Quetta	0.17	Arid
12	Sibi	0.10	Arid
13	Zhob	0.18	Arid

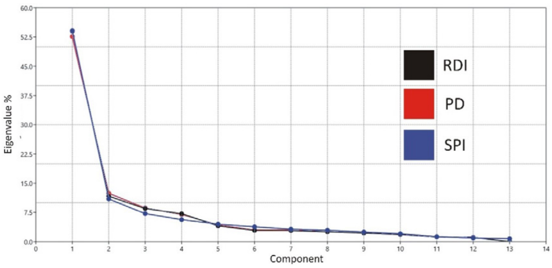

Figure 5. Scree plot for PCs using SPI, RDI, and PD data across 13 stations.

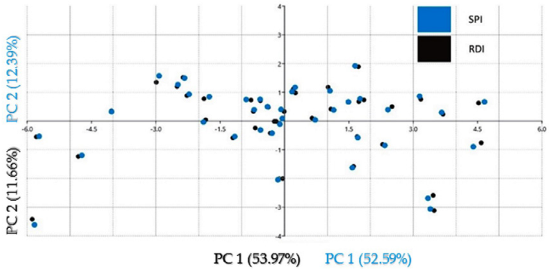

Figure 6. Scatter plot for PCs using SPI and RDI.

Table 7. Proportion of variance explined by each principal component.

PC	SPI	RDI	PD
	% Variance	% Variance	% Variance
1	52.591	53.971	54.137
2	12.394	11.663	10.965
3	8.6413	8.5126	7.2015
4	6.9769	7.1723	5.6456
5	4.2942	4.0858	4.5225
6	3.0225	2.9	3.8452
7	2.9913	2.8646	3.238
8	2.6124	2.5313	2.9624
9	2.2084	2.2043	2.492
10	1.8868	1.8242	2.0302
11	1.247	1.1894	1.2604
12	1.1337	1.0809	0.93588
13	2.43E-31	1.71E-31	0.76427

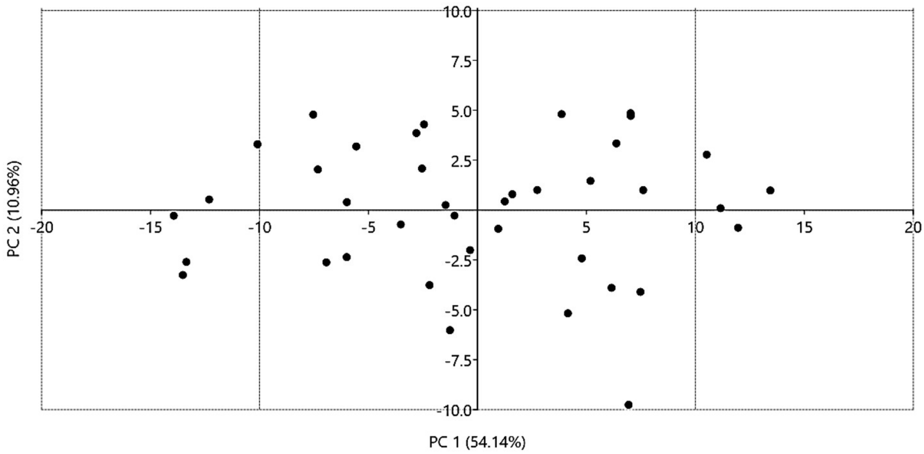

Figure 7. Scatter plot for PCs using PD.

3.3.1. PCA on SPI

PCA for the SPI values was applied and the Scree plot and scatter plot at 95% ellipses of PCs can be seen in Figure 5 and Figure 6 respectively. Only PC1, PC2, and PC3 were considered, and these explained the variance of 73.63% of the total variability. Among these PCs, PC1, PC2 and PC3 contributed 52.59%, 12.39%, and 8.65% respectively.

3.3.2. PCA on RDI

PCA for RDI was done and Scree plot and scatter plot at 95% ellipses of PCs can be seen in Figure 5 and Figure 6. Only PC1, PC2, and PC3 were considered, and these explained the variance of 74.15% of the total variability. The individual contributions by PC1, PC2, and PC3 were 53.97%, 11.66%, and 8.52% of the total variance.

3.3.3. PCA on PD

PCA for PD was done and Scree plot and scatter plot at 95% ellipses of PCs can be seen in Figure 5 and Figure 7 respectively. PC1, PC2, and PC3 explained the variance of 72.30% of the total variability, and their contributions were 54.14%, 10.96%, 7.20%, respectively.

4. Conclusion

A comprehensive study about drought monitoring in the Balochistan province of Pakistan was conducted using three different indices SPI, RDI and PD for a period of 40 years followed by aridity index calculation identified extreme drought events during 1991-1993, 1999-2000, 2001-2004. PCA on SPI and RDI, individually across the weather stations, gave very good results although the RDI results are more comprehensive and RDI is recommended if temperature data are available. PD results were mixed, and this index is only recommended if data are scarce. The loading values for the first three components are very high which show that the score of these components represents the long-term drought variability in the Balochistan. Based on the aridity index, it is concluded that a major part of Balochistan lies in the arid zone, followed by the hyper-arid in the southwestern part and the semi-arid zones in the northeastern part of the province. This study gives a clear picture to the water resource managers and policymakers. Preparedness and adopting sustainable strategies to mitigate drought impacts on livelihood are important. The Constitution of a drought forecasting and management body at the provincial and national level is recommended for pre-drought planning, in-drought actions, and post-drought management. Accumulation of surface water and conservation of groundwater through national policy on a priority basis is required. More importantly, remote sensing techniques may give long-term data for the calculation of near-real-time results in drought assessment for future studies.

Since the economy of Balochistan greatly depends upon livestock and agriculture, and regional and global climate changes are continuously adding pressure on agriculture and the environment. Land degradation, rising needs of people and other environmental challenges need to be handled efficiently. Therefore, some sustainable water resource management techniques are suggested. These include the construction of dams, smart irrigation, rainwater harvesting, greywater recycling, and other locally adopted techniques. A detailed realistic study within the province for combating the worst situation of dry spells is recommended in the context of climate change.

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