Original Research Article

Analysis of Meteorological Drought for Selected Districts of Saurashtra Region of Gujarat

ABSTRACT

Drought, in particular, is a complex and recurring phenomenon triggered by insufficient precipitation or changes in its distribution, often resulting in decreased water availability. It evolves slowly, affecting large populations' access to food and water, disrupting the entire hydrological cycle, and causing long-term economic losses. The present study attempts a comprehensive analysis of meteorological drought characteristics for selected districts (Junagadh, Amreli, Jamnagar, and Rajkot) in the semi-arid Saurashtra region of Gujarat. The analysis of meteorological drought was performed using rainfall (RF), maximum temperature (Tmax), and minimum temperature (Tmin) data from four stations (each district has one station) for the 43 years duration (1981–2023). The Standardized Precipitation Evapotranspiration Index (SPEI) is utilized across multiple timescales to assess the number of drought affected years, occurrence of drought and drought parameters (total drought duration, magnitude, and intensity). The meteorological drought incidence varied significantly across Junagadh, Amreli, Jamnagar and Rajkot, with Junagadh experiencing droughts in 29% of years, Amreli in 32%, and higher rates in Jamnagar (37%) and Rajkot (36%). The most severe drought years in the four districts were 1987 and 2002, with additional major droughts occurred in 1985, 1986, 1987, 1993, 2002 and 2012. These districts also faced consecutive droughts from 1985 to 1987 and again from 1999 to 2002.Analysis of drought parameters in Junagadh, Amreli, Jamnagar and Rajkot districts showed that drought duration (DD) ranged from 29.46% (Junagadh) to 35.85% (Jamnagar) of months, drought magnitude (DM) varied between -37.58% (Jamnagar) and -34.10% (Junagadh), and drought intensity (DI) spanned from -1.17 (Rajkot) to -1.04 (Junagadh). The analysis of drought occurrence in all districts shows that mild and moderate droughts have been most frequent while severe and extreme droughts have been less common. The study's findings enhance water managers' understanding of how climate change influences drought patterns in the region, thereby assisting policymakers in conducting effective drought risk assessments.

Keywords: Meteorology Drought Analysis, SPEI, Occurrence of Drought, Drought Magnitude, Drought Severity, Drought Intensity

1. INTRODUCTION

More people than any other natural hazard is affected by drought, which is regarded by many as being the most complicated but least understood of all natural hazards [9]. A universal definition of drought is generally hampered by large-scale geographical temporal diversity in the timing and duration of drought impact. However, Wilhite and Glantz (1985) divided the different types of droughts into four categories: meteorological (lack of precipitation), hydrological (drying of surface water storage), and agricultural (lack of root zone soil moisture), and socio-economic (loss of water supply for socio-economic purposes) [27].

Over the major portions of India, the South-west monsoon is responsible for around 70% of the nation's yearly rainfall. The possibilities for agricultural output are determined by its timely occurrence in a consistent distribution and with a normal intensity [18]. Due to the complete lack of monsoon rains (64 mm total) till August 2002, the drought of 2002 is regarded as the worst in the past 100 years and was called the most intense drought. In contrast to the 650 mm average rainfall in the north western area of India, 102 mm of rain fell during the kharif in 1987. Its effects on people, livestock and natural resources, notably in the year 2002, have been documented in states like Haryana, Rajasthan, Punjab, Uttar Pradesh, Odisha, Madhya Pradesh, Gujarat, Tamil Nadu, Karnataka and Kerala [20;21]. According to Gautam (2014), the year 2002, which affected approximately 30 meteorological sub-divisions of India, would be remembered as the year of severe drought at the start of the twenty-first century. This drought that once in 1899, 1918, 1972, and 1987 were very similar [6].

Gujarat is a region of India that experiences severe droughts every three to four years. Arid and semi-arid climate zones cover a large portion of Gujarat, which experiences frequent droughts. Additionally, it has been noted that droughts have become more frequent and intense in the state over the years, leading to severe drinking water shortages [19]. In Gujarat state, 99 administrative blocks and more than 60% of its land are located in drought-prone areas. Nine major droughts affected Gujarat between 1977 and 2012, covering anywhere between 23% to over 90% of the country's land [26]. Gujarat had seven heat waves from 1978 to 1999 that killed 34 people, most frequently from March to May. In this state, drought occurred twice or three times every five years, and every ten years, there were two to three severe and extensive droughts, oftentimes in quick succession. Gujarat saw 15 significant droughts between the years of 1981 and 2010 (i.e., 1982, 1985, 1986, 1987, 1990, 1991, 1993, 1995, 1998, 1999, 2000, 2001, 2002, 2004 and 2009), according to statistics kept by the India Meteorological Department (2015) [13]. Heat waves and high temperatures are also common throughout most of these dry years, especially in northern Gujarat. In this time, the area had moderate to severe heat waves in 1990, 1995, 2001, 2002, 2004, and 2010. Meteorological droughts and heat waves have an impact on water supplies and resources, harm the health of the plants and lower the agricultural production [5].

The Saurashtra region of Gujarat has great variation in its rainfall patterns, which has a significant effect on the local ecology, agriculture, and water supplies. In arid and semi-arid region, water is a major barrier to intense irrigation [16]. Due to its arid and semi-arid environment, Saurashtra is vulnerable to drought occurrences. The most extreme drought year was determined to be 1987, with additional drought years being 1986, 1991, 2000, 2002, and 2013. In 1986 and 1987 were two consecutive years of high severity drought in Saurashtra, as well as 1990 to 2002 .The different areas in Saurashtra are projected to experience mild drought once in three years, moderate drought once in nine to eleven years, severe drought once in 29 to 44 years, and extreme drought once in 98 to 174 years [17].

Many drought indices were developed in the previous century by combining weather factors like rainfall, evapotranspiration, and temperature which are indicators or variables used to describe drought conditions. Many climate researchers used the multi-scalar drought index in their drought studies, such as the Standardized Precipitation Index (SPI). The fundamental drawback of SPI is that it only uses precipitation data and ignores other crucial factors, particularly temperature. Although precipitation is the primary cause of drought, new research have shown the significance of temperature in understanding current trends in water resources.

The Standardized Precipitation Evapotranspiration index (SPEI), a new drought indicator, has been created lately to measure the drought status [24]. The SPEI is a better approach for

analyzing how drought frequency is impacted by climate change because it takes both temperature and precipitation into consideration. Comprehending the temporal and spatial variability of drought is becoming increasingly important for better planning of mitigation methods and readiness against it.

Drought damages crop water balance and results in inadequate soil moisture. The Standardized Precipitation Evapotranspiration Index (SPEI) is one of the most widely used indicators in drought monitoring. Vicente-Serrano *et al*. (2010) initially suggested the Standardized Precipitation Evapotranspiration Index (SPEI) as an enhanced drought measure that is particularly appropriate for research on how global warming affects drought severity [24]. Similar to the Palmer Drought Severity Index (PDSI), the SPEI takes into account how reference evapotranspiration affects the severity of droughts. However, because the SPEI is multi-scalar, it is used to identify various types of droughts and their effects on various systems [25].

To represent the multi temporal aspect of the SPI, the SPEI integrates the influence of PET to change in evaporation demand along with temperature changes and trends. Research indicates that the annual precipitation and potential evapotranspiration (PET) have a mathematical difference that is less than zero [11]. Consequently, it might not be enough to monitor droughts for India using a drought index that is only based on precipitation data. The SPEI is computed similarly to the SPI but with the addition of moisture stresses brought on by evapotranspiration.

By computing at different temporal scales based on the probability of precipitation and potential evapotranspiration (P-PET) differences, SPEI is able to depict the multi-temporal nature of hydrological, meteorological, and agricultural droughts [24]. Homdee *et al.* (2016) evaluated the SPI and SPEI approaches and concluded that the SPEI approach was more accurate [12].

Therefore, considering the above facts, a study was planned to analyze meteorological drought characteristics in selected districts (Junagadh, Amreli, Jamnagar, and Rajkot) of Saurashtra, Gujarat. The findings of this study aim to provide water managers with a deeper understanding of how droughts in the study area are influenced by climate change. These insights will be valuable for policymakers and in conducting drought risk assessments.

2. MATERIAL AND METHODS

2.1 Description of Study Area

This study was conducted in the selected districts (Junagadh, Amreli, Jamnagar, and Rajkot) of Saurashtra region of Gujarat State, India. Saurashtra, also known as Kathiawar, is situated on the western coast of India, between 20°30' to 23°N latitude and 69° to 72°E longitude. This peninsula region along the Arabian Sea comprises about one-third of Gujarat State and covers 11 districts. The area covers 6.49 million hectares, of which 3.91 million hectares (60%) are used for agriculture, with 1.78 million hectares being irrigated. Seasonal rainfall is vital for agricultural productivity, as a significant portion of the irrigated land relies on groundwater [2]. The study area's location is shown in Figure 1.

The region of Saurashtra experiences frequent droughts because of its semi-arid and arid environment. A protracted period of below-average rainfall causes moisture stress and water shortages, which in turn leads to droughts. The south-west monsoon brings precipitation to all part of the Saurashtra. Due to the region's location in the south-western monsoon's periphery, rainfall has been incredibly uneven and erratic. The region's average yearly rainfall varies greatly, with the southern Junagadh area receiving 800 mm and the northern portion receiving 400 mm. Typically, the monsoon begins in the middle of June and ends until the middle of September. In much of the area, the months of June through September get over 95% of the yearly precipitation. June receives around 10–15% of the yearly rainfall, July receives over 40%, August receives 30%, and September receives 10–20%. The months of July and August have the most days with rain. The rainy days range from 20 in Jamnagar to 37 in Junagadh district. The entire region is classified as dry land and drought prone area. [1].

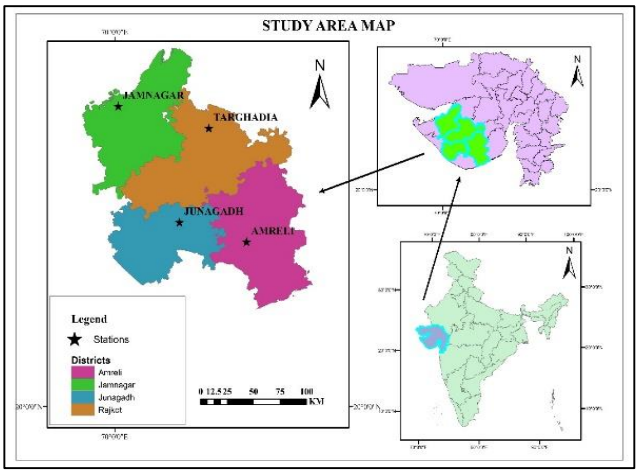

Fig. 1 Location of the study area

The region has significant seasonal variations in average temperature. The summer season has a high temperature of above 42°C and a low temperature of 25°C. During the winter, the highest temperature can reach 34°C while the lowest temperature can occasionally drop below 8°C.The months with the lowest and highest recorded temperatures are respectively January and May. Places near the coastline have comparatively low temperatures. The diurnal range of temperature is least in the months of July and August, while it is more in the winter. The range is higher for places like Rajkot and Amreli [1].

2.3 Data Collection

The daily rainfall, maximum and minimum temperature data of 4 stations for the selected districts of Saurashtra, which means each district has one station, totalling four stations for the duration of 1981 to 2023 (43 years), were used for computing the meteorological drought using the SPEI index. The data was collected from various meteoroidal stations of Junagadh Agricultural University.

2.4 Computation of Standardized Precipitation Evapotranspiration Index

Vicente Serrano *et al*. (2010) developed the Standardized Precipitation Evapotranspiration Index (SPEI) based on the SPI [24]. The monthly difference between precipitation and PET is used by the SPEI. This illustrates a simple climatic water balance [23], from which the SPEI is derived by calculating it at different time scales. Researchers often utilise the Thornthwaite (1948) technique to compute PET, subject to the availability of data [24]. The Thornthwaite technique, which only requires data on monthly mean temperature, was used to calculate PET. With this approach, the monthly PET (mm) is calculated by

$$PET = 16K\left(\frac{10T}{I}\right)^{m} \quad \ldots(2.1)$$

where, T represents monthly-mean temperature (°C), and I represents heat index (°C), heat index (I) is computed as the summation of 12 monthly heat index values, obtained from mean monthly temperature (T_i) using the formula

$$I = \sum_{i=1}^{12}\left(\frac{T_i}{5}\right)^{1.514} \quad \ldots(2.2)$$

Where m is a coefficient which depends on I.

$$m = (6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.79 \times 10^{-2} I + 0.492) \quad \ldots(2.3)$$

K is a coefficient of correction which is dependent on the latitude and month,

$$K = \left(\frac{N}{12}\right)\left(\frac{NDM}{30}\right) \quad \ldots(2.4)$$

Where NDM is the total number of days in the given month and N is the maximum number of sun hours computed as:

$$N = \left(\frac{24}{\pi}\right)\omega_s \quad \text{...(2.5)}$$

Where, ω_s is the hourly angle of the sun rising and it is estimated from latitude and solar declination.

The climate–water balance was calculated as follows:

$$D_i = P_i - PET_i \quad \text{...(2.6)}$$

Where, D_i is the i_{th} month moisture deficit (mm), P_i is the i_{th} month precipitation (mm), and PET_i is the i_{th} month potential evapotranspiration (mm).

The value of D_i were aggregated on different time scales:

$$D_n^k = \sum_{i=0}^{k=1} (P_{n-i} - PET_{n-i}) \ , n \geq k, \quad \text{...(2.7)}$$

Where, k is the monthly timescale and n is the number of calculations.

Following the Vicente Serrano *et al*. (2010) approach, the log-logistic distribution F(x) was applied to transform the original D series into standardized units at different timescales [24].

The probability density function of a three parameter log-logistic distributed variable is expressed as

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left[1 + \left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]^{-2} \quad \text{...(2.8)}$$

Where, α, β and γ represent the scale, shape, and origin parameters, respectively, for D values in the range $(\gamma > D < \infty)$.

Parameters of log-logistic distribution can be obtained following different procedures. Among them, the L-moment procedure is the most robust and easy approach. When L moments are calculated, the parameters of the Pearson III distribution can be obtained following.

$$\beta = \frac{2w_1 - w_0}{6w_1 - w_0 - w_2} \quad \text{...(2.9)}$$

$$\alpha = \frac{(w_0 - 2w_1)\beta}{\Gamma\left(1 + \frac{1}{\beta}\right)\Gamma\left(1 - \frac{1}{\beta}\right)} \quad \text{...(2.10)}$$

$$\gamma = w_0 - \alpha\Gamma\left(\frac{1+1}{\beta}\right)\Gamma\left(\frac{1-1}{\beta}\right) \quad \text{...(2.11)}$$

The log-logistic distribution adapted very well to the series for all time scales.

The probability distribution function of the D series, according to the log-logistic distribution is given by

$$F(x) = \left[1 + \left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1} \quad \text{...(2.12)}$$

The F(x) values for the D series at different time scales adapt very well to the empirical F(x) values at the different observatories, independently of the climate characteristics and the time scale of the analysis.

With F(x) the SPEI can easily be obtained as the standardized values of F(x).

SPEI has been calculated as follows:

$$SPEI = W - \frac{c_0 + c_1 w + c_2 w^2}{1 + d_1 w + d_2 w^2 + d_3 w^3} \quad \text{...(2.13)}$$

Where, $W = \sqrt{-2In(P)}$ for P ≤ 0.5 and $W = \sqrt{-2In(1-P)}$ for P > 0.5

P is the probability of exceeding a determined D value, P = 1− F(X)

The constants are c_0 = 2.515517, c_1 = 0.802853, c_2 = 0.010328, d_1 = 1.432788, d_2 = 0.189269, d_3 = 0.001308.

The average value of SPEI is 0, and the standard deviation is 1. The SPEI is a standardized variable, and it can therefore be compared with other SPEI values over time and space. An SPEI of 0 indicates a value corresponding to 50% of the cumulative probability of D, according to a log-logistic distribution. The positive SPEI values indicate the wet condition and negative SPEI values indicate the drought condition. The classification of drought category based on SPEI is depicted in Table 1. The researchers utilized the same drought classification analysis that has been applied in Gujarat, Iran, and Maharashtra [22; 15; 28].

Table 1. Drought severity classification by SPEI drought indices

SPEI value	Category
≥ 2.0	Extremely wet
1.5 to 1.99	Severely wet
1.0 to 1.49	Moderately Wet
0.5 to 0.99	Mild wet
− 0.49 to 0.49	Near normal
− 0.5 to − 0.99	Mild drought
− 1.0 to − 1.49	Moderate drought
− 1.5 to – 1.99	Severe drought
≤ − 2.0	Extreme drought

The SPEI was calculated based on 1-month (June, July, August and September), 3-month (June to August and July to September), and 6-month (June to November) time scales for the four districts. The SPEI values were obtained at multiple time scales for the four districts. These values were used to assess the percentage occurrence of drought for each category, the number of drought years for each drought category, and drought parameters (total drought duration, magnitude, and intensity).

3 Results and Discussion

3.1 Meteorological drought analysis of Junagadh district

The drought severity of Junagadh by 1 month SPEI index for June, July, August and September for 1981 to 2023 can be observed from Fig 2. The number of years under no drought and various drought severity categories for June, July, August and September out of 43 years under study are given in Table 2

It can be observed from Fig. 2 and Table 2 that in the month of June, out of the total 43 years under study, 13 years were identified as drought years. Among these, 2 years (1981 and 1982) experienced extreme drought. Additionally, 6 years were under moderate drought and 5 years were under mild drought. In the month of July, 11 years were noted as drought years.

Table 2: Number of years under various drought severity categories based on SPEI at 1 month time scale in four districts of Saurashtra

District	No. of years under drought category				
	No drought	Mild	Moderate	Severe	Extreme
June					
Junagadh	30	5	6	0	2
Amreli	29	8	6	1	0
Jamnagar	27	8	8	0	0
Rajkot	28	6	8	1	0
July					
Junagadh	32	3	4	4	0
Amreli	29	8	2	4	0
Jamnagar	26	7	10	0	0
Rajkot	31	3	7	2	0
August					
Junagadh	28	7	7	1	0
Amreli	31	3	7	2	0
Jamnagar	31	5	5	2	0
Rajkot	29	4	9	1	0
September					
Junagadh	28	7	6	2	0
Amreli	31	4	6	1	0
Jamnagar	24	13	6	0	0
Rajkot	27	9	5	2	0

Among these, 4 years (1986, 1987, 2002, and 2012) experienced severe drought, 4 years experienced moderate drought, and 3 years experienced mild drought. The analysis revealed that a greater number of drought years were identified in June compared to July. This finding is consistent with the results of Pandya (2023) [17], who also observed a higher number of drought conditions in June as revealed by the SPEI index. The 15 years were noted as drought years for August, out of which the year 1993 was under severe drought and 7 years experienced moderate drought while 7 years were under mild drought. In the month of September, 2 years (1982 and 1987) were under severe drought and 6 years experienced moderate drought while 7 years were under mild drought.

The drought severity of Junagadh by SPEI index based on three monthly timescale of June to August and July to September for 1981 to 2023 can be observed in Fig 3. The number of years under no drought and various drought severity categories for June to August and July to September out of 43 years under study are given in Table 3. In the months of June to August, an extreme drought was observed in the year 1982. The years 1985, 1993, and 2012 experienced severe droughts, respectively and 3 years were observed under moderate drought years while five years experienced mild drought. In the months of July to September, the years 1986, 1987, and 1993 experienced severe droughts and 4 years were under moderate drought, while five years were observed as mild droughts.

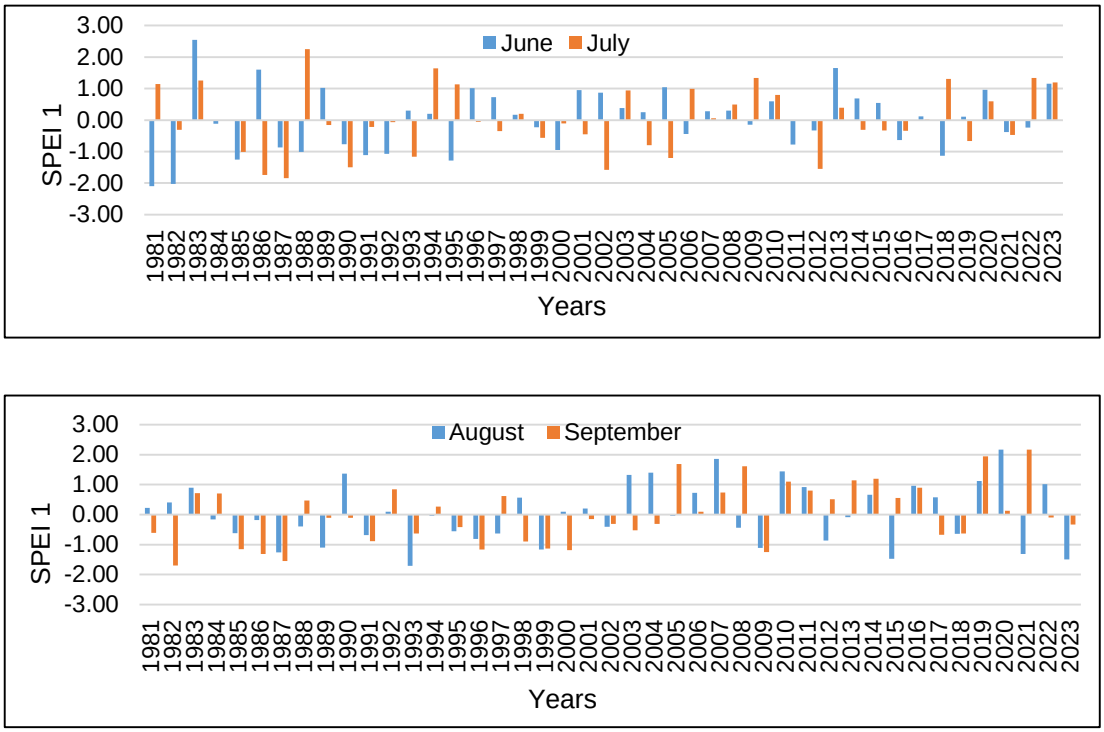

Fig. 2.: Drought severities of Junagadh district for monthly time scales of June, July, August and September

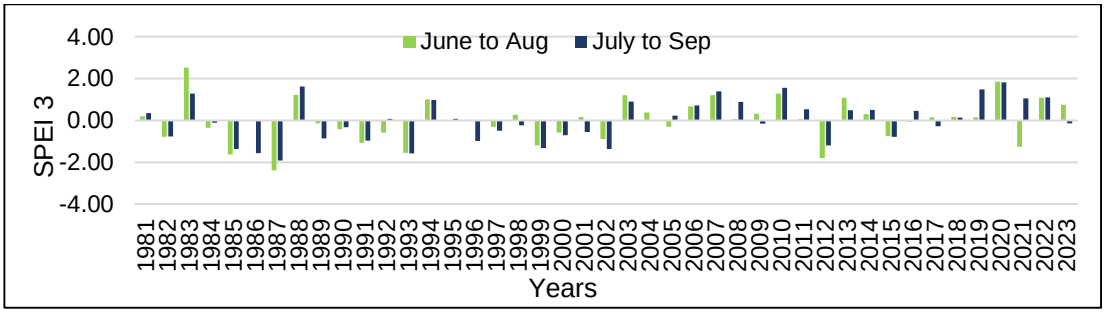

Fig. 3: Drought severities of Junagadh district for three monthly time scales of June to August and July to September

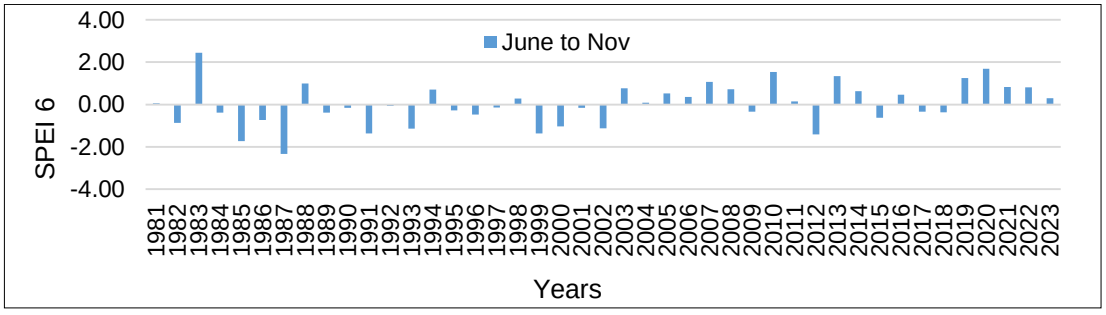

Fig. 4: Drought severities of Junagadh district for six monthly time scales of June to November

Table 3: Number of years under various drought severity categories based on SPEI at 3 month time scale in four districts of Saurashtra

District	No. of years under drought category				
	No drought	Mild	Moderate	Severe	Extreme
June to August					
Junagadh	31	5	3	3	1
Amreli	29	6	5	3	0
Jamnagar	29	7	4	3	0
Rajkot	29	7	4	3	0
July to September					
Junagadh	28	8	4	3	0
Amreli	28	6	7	2	0
Jamnagar	29	6	6	2	0
Rajkot	27	9	4	3	0

Table 4: Number of years with no drought and various drought severity categories based on the 6 month SPEI timescale over 43 years of study for the months of June to November in four districts of Saurashtra

District	No. of years under drought category				
	No drought	Mild	Moderate	Severe	Extreme
Junagadh	32	3	6	1	1
Amreli	29	6	6	1	1
Jamnagar	27	8	6	1	1
Rajkot	26	8	6	3	0

The drought severity of Junagadh by SPEI index based on six monthly timescale of June to November for 1981 to 2023 can be observed in Fig 4. The number of years under no drought and various drought severity categories are displayed in Table 4.

It can be observed from Table 4 as well as Fig. 4 that the 11 years were under drought years. The extreme drought was observed in 1987 and severe drought was observed in 1985 while 6 years were under moderate drought. The consecutive severe drought years were recorded from 1999 to 2000, spanning a period of two years. A similar result was indicated by [7] that the years 1999 and 2000 were the worst as consecutive occurrences of drought in successive two years in India.

Overall, at the 1-month time scale, 1% year, 4% years, 13% years and 13% years were affected by extreme, severe, moderate and mild droughts respectively. At 3-month time scale, 1% year, 7% years, 8% years and 15% years were affected by extreme, severe, moderate and mild droughts respectively. At 6-month time scale, 2% year, 2% years, 14% years and 7% years were affected by extreme, severe, moderate and mild droughts respectively. The years 1981, 1982, 1985, 1986, 1987, 1993, 2002, and 2012 exhibited notably higher levels of drought severity (severe to extreme drought category) in Junagadh district. Hirapara *et al*. (2021) also identified 2002 as a year classified under the category of a disastrous drought in Junagadh district [10]. Roy *et al.* (2007) identified four significant drought events in Gujarat during the years 1982, 1985, 1986, and 1987 [19].

Table 5: Occurrence of historic drought categories (percentage) for four districts of Saurashtra at multiple time scales

District	Category	1 month SPEI	3 month SPEI	6 month SPEI
Junagadh	Mild	12.79	15.11	6.98
	Moderate	13.37	8.13	13.95
	Severe	4.07	6.97	2.33
	Extreme	1.16	1.16	2.33
Amreli	Mild	13.37	16.28	13.95
	Moderate	12.79	13.95	13.19
	Severe	4.65	5.81	2.33
	Extreme	0	0	2.33
Jamnagar	Mild	19.19	15.12	18.60
	Moderate	16.86	11.67	13.95
	Severe	1.16	5.81	2.33
	Extreme	0	0	2.33
Rajkot	Mild	12.79	18.60	18.60
	Moderate	16.86	9.30	13.95
	Severe	3.79	6.97	6.98
	Extreme	0	0	0

These findings are consistent with the drought patterns observed in the Junagadh district. The consecutive drought years were identified from 1985 to 1987, spanning a period of three years in Junagadh. Similar conclusions were drawn by Bandyopadhyay and Saha (2016) [3], who noted continuous dry conditions from 1985 to 1987 in Gujarat. Likewise, Pandya (2023) reported consecutive drought years (1985 to 1987) in the Saurashtra region [17]. The year 1987 was observed under extreme drought category. Bandyopadhyay *et al.* (2016) also concluded that during the monsoon season of 1985, 1986 and 1987, lack of sufficient rainfall resulted in severe to extreme meteorological drought in various parts of the Gujarat [4]. The worst condition was in 1987, when barring some small parts, the entire Gujarat suffered from a spell of intense drought.

The percentage occurrence of drought in each category in Junagadh, as shown in Table 5, indicates that mild and moderate droughts occurred most frequently, while severe and extreme droughts occurred least frequently across all time scales. In Junagadh, mild and moderate droughts were most frequent, notably at the 3-month (15.11%) and 6-month (13.95%) time scale, while severe and extreme droughts were least frequent across all periods.

For Junagadh district, drought parameters for seven duration were evaluated at multiple time scale from 1981 to 2023 and are presented in Table 6. At 1-month time scale, the total drought duration (DD), drought magnitude (DM) and drought intensity (DI) were found to be 31.40 % of the months, -34.49 % of the months and -1.10 respectively.

Table 6: Drought parameters (drought duration and magnitude both as % of months and drought intensity) for seven durations according to the timescale in four districts of Saurashtra from 1981 to 2023

District	Time scale	Month	Total drought duration	Total drought magnitude	Total drought Intensity
Junagadh	1 month	June	30.23	-34.86	-1.15
		July	25.58	-31.65	-1.24
		August	34.88	-35.86	-1.03
		September	34.88	-35.58	-1.02
	3 month	June to Aug	27.91	-33.58	-1.20
		July to Sep	34.88	-38.14	-1.09
	6 month	June to Nov	25.58	-31.95	-1.25
Amreli	1 month	June	32.56	-31.26	-0.96
		July	32.56	-35.53	-1.09
		August	27.91	-33.21	-1.19
		September	25.58	-29.14	-1.14
	3 month	June to Aug	32.56	-35.63	-1.09
		July to Sep	34.88	-38.56	-1.11
	6 month	June to Nov	32.56	-37.30	-1.15
Jamnagar	1 month	June	37.21	-36.79	-0.99
		July	39.53	-40.44	-1.02
		August	27.91	-32.02	-1.15
		September	44.19	-37.49	-0.85
	3 month	June to Aug	32.56	-36.51	-1.12
		July to Sep	32.56	-35.42	-1.09
	6 month	June to Nov	37.21	-38.19	-1.03
Rajkot	1 month	June	34.88	-36.93	-1.06
		July	27.91	-34.16	-1.22
		August	32.56	-36.49	-1.12
		September	37.21	-36.77	-0.99
	3 month	June to Aug	32.56	-35.77	-1.10
		July to Sep	37.21	-38.23	-1.03
	6 month	June to Nov	39.53	-39.65	-1.00

3.2 Meteorological drought analysis of Amreli district

The drought severity of Amreli by SPEI index for June, July, August and September for 1981 to 2023 can be observed from Fig 5. The number of years under no drought and various drought severity categories for June, July, August and September out of 43 years under study are given in Table 2.

It can be observed from Fig. 5 and Table 2 that in the month of June, out of the total 43 years under study, 15 years were identified as drought years. Among these, severe drought was observed in 1982. Additionally, 6 years were under moderate drought and 8 years were under mild drought. In the month of July, 14 years were noted as drought years. Among these, severe drought was observed in year 1986 , 1987, 2002 and 2012, 2 years (1990 and 1999) were observed as moderate drought with SPEI value of -1.32 for 1990 and -1.11 for 1999, and 8 years were under mild drought. The July month is experienced more severe drought as compared to June month like Junagadh district. The 12 years were noted as drought years for August, out of which the 2 years under severe drought were observed in year 1993and 2023. The years 1999, 1987, 2015, 2009, 1996, 1985, and 1995 were noted as moderate drought years. In the month of September, one year (1987) was observed as severe drought year and years 1991, 2000, 1882, 2009, 2001, 1986 and 2018 were experienced moderate drought.

The drought severity of Amreli by SPEI index based on three monthly timescale of June to August and July to September for 1981 to 2023 can be observed in Fig 6. The number of years under no drought and various drought severity categories for June to August and July to September out of 43 years under study are given in Table 3. In the months of June to August, severe drought was observed in year 1985, 1987 and 2012.The 5 years were observed as moderate drought years and 7 years were under mild droughts. The consecutive drought years were recorded from 1999 to 2000, spanning a period of two years. A similar result was indicated by Guhathakurta *et al.* (2003) that the years 1999 and 2000 were the worst as consecutive occurrences of drought in successive two years in India [7]. In the months of July to September, the years 1986 and 1987 were experienced severe droughts and the 7 years were under moderate drought while six years were observed as mild droughts. From Fig. 6, the consecutive drought event was identified from 1999 to 2002(four years) and 1985 to 1987 (three years) in July to Sep. Gupta et al. (2011) also highlighted the effect of persistence of droughts from 1999 to 2002 in the country [8]. Additionally, Pandya (2023) also identified the three (1985 to 1987) and four (1999 to 2002) consecutive drought years in the Saurashtra region [17].

The drought severity of Amreli by SPEI index based on six monthly timescale of June to November for 1981 to 2023 can be observed in Fig 7. The number of years under no drought and various drought severity categories are displayed in Table 4.It can be observed from Table 4 as well as Fig.7 that the 14 years were under drought years. The extreme drought was observed in 1987 and severe drought was observed in 2000 while 6 years were under moderate drought. The consecutive drought was observed from 1984 to 1987.

Overall, at the 1-month time scale, 5% years, 12% years and 13% years were affected by severe, moderate and mild droughts respectively. At 3-month time scale, 6% years, 14% years and 14% years were affected by severe, moderate and mild droughts respectively. At 6-month time scale, 2% year, 2% years, 14% years and 14% years were affected by extreme, severe, moderate and mild droughts respectively. The years 1982, 1985, 1986, 1987, 1993, 2000, 2002, 2012 and 2023 exhibited notably higher levels of drought severity (severe to extreme drought category) in Amreli district. Roy et al. (2007) identified four significant drought events in Gujarat during the years 1982, 1985, 1986, and 1987 [19]. These findings are consistent with the drought patterns observed in the Amreli district. The consecutive drought years were identified from 1985 to 1987, spanning a period of three years in Amreli. Similar conclusions were drawn by Bandyopadhyay and Saha (2016), who noted continuous dry conditions from 1985 to 1987 in Gujarat [3]. Likewise, Pandya (2023) reported consecutive drought years (1985 to 1987) in the Saurashtra region [17]

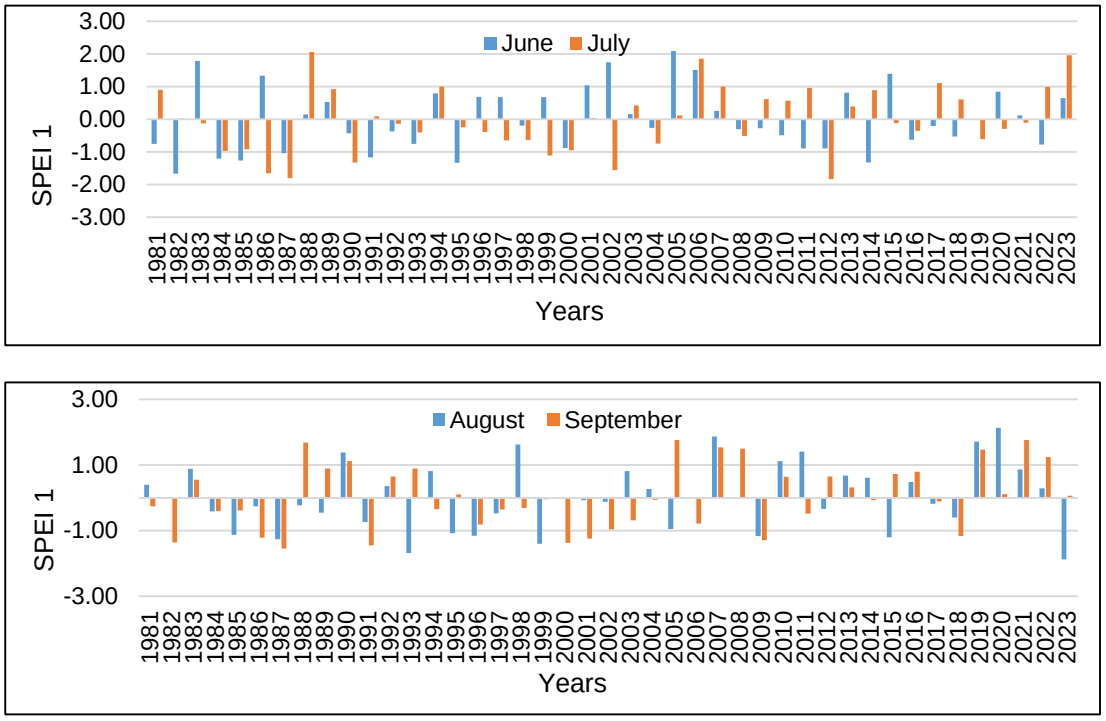

Fig. 5: Drought severities of Amreli district for monthly time scales of June, July, August and September

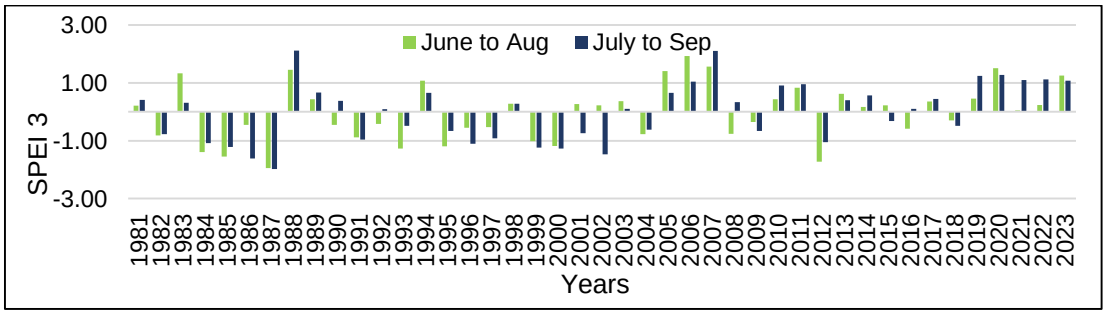

Fig. 6: Drought severities of Amreli district for three monthly time scales of June to August and July to September

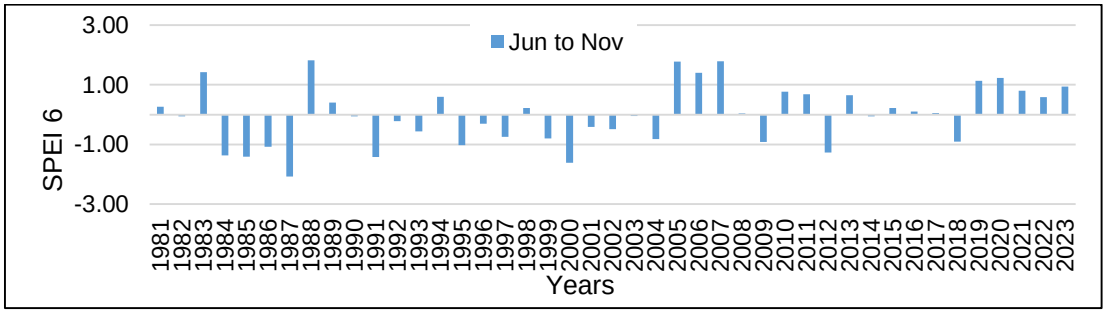

Fig. 7: Drought severities of Amreli district for six monthly time scales of June to November

The year 1987 was observed under extreme drought category. Bandyopadhyay et al. (2016) also concluded that during the monsoon season of 1985, 1986 and 1987, lack of sufficient rainfall resulted in severe to extreme meteorological drought in various parts of the Gujarat [4]. The worst condition was in 1987, when barring some small parts, the entire Gujarat suffered from a spell of intense drought.

The percentage of occurrence of drought for each category in Amreli, which can be observed from Table 5. Amreli exhibited frequent mild droughts at 3 months (16.28%) and moderate droughts at 3 months (13.95%), with severe and extreme droughts occurring infrequently, predominantly over longer periods. The highest percentage of mild drought occurrences was observed across all time scales compared to other drought categories. Similar findings were concluded by Kebede et al. (2019) and Pandya (2023).

Drought parameters for seven durations in Amreli district were analyzed at various time scales from 1981 to 2023, as shown in Table 6. At 1-month time scale, the total DD, DM and DI were found to be 29.65 % of the months, -32.28 % of the months and -1.10 respectively. At 3-month time scale, the total DD, DM and DI were found to be 33.72%, -37.09 % of the months and -1.10 respectively. At 6-month time scale, the total DD, DM and DI were found to be 32.56%, -37.30% of the months and -1.15 respectively.

3.3 Meteorological drought analysis of Jamnagar district

The drought severity of Jamnagar by SPEI index for June, July, August and September for 1981 to 2023 can be observed from Fig 8. The number of years under no drought and various drought categories for June, July, August and September out of 43 years under study are given in Table 2

It can be observed from Fig. 8 and Table 2 that in the month of June, out of the total 43 years under study, 16 years were identified as drought years. No incident of extreme or severe drought was exhibited. The 8 years were under moderate drought and 8 years were under mild drought. In the month of July, 17 years were noted as drought years. No incident of extreme or severe drought was also exhibited in month of July. The 10 years were observed as moderate drought and 7 years were under mild drought. The 12 years were noted as drought years for August, out of which the 2 years under severe drought were observed in year 1987 and 1993. The 5 years were noted as moderate drought years. In the month of September, 19 years were under drought year. The 6 years were observed under moderate drought and 13 years were noted as mild drought. The consecutive drought was identified from 1999 to 2003. Gupta et al. (2011) also highlighted the effect of persistence of droughts from 1999 to 2002 in the country [8].

The drought severity of Jamnagar by SPEI index based on three monthly timescale of June to August and July to September for 1981 to 2023 can be observed in Fig 9. The number of years under no drought and various drought severity categories for June to August and July to September out of 43 years under study are given in Table 3. In the months of June to August, severe drought was observed in year 1987, 1999 and 2012.The 4 years were observed as moderate drought years and 7 years were under mild droughts. The consecutive drought years were observed from 1985 to 1987 and from 1988 to 1989. Bandyopadhyay and Saha (2016) also reported a continuous dry spell of dry condition from 1985 to 1987 in Gujarat [3]. In the months of July to September, the years 1987 and 1999 were experienced severe droughts and the 6 years were under moderate drought, while six years were observed as mild drought years. The consecutive drought years were observed from 1985 to 1987 and from 1988 to 1989. Bandyopadhyay and Saha (2016) also reported a continuous dry spell of dry condition from 1985 to 1987 in Gujarat [3].

The drought severity of Jamnagar by SPEI index based on six monthly timescale of June to November for 1981 to 2023 can be observed in Fig 10. The number of years under no drought and various drought severity categories are displayed in Table 4.

It can be observed from Table 4 as well as Fig. 10 that the 16 years were under drought years. The extreme drought was observed in 1987 and severe drought was observed in 1999 while the 6 years were under moderate drought.

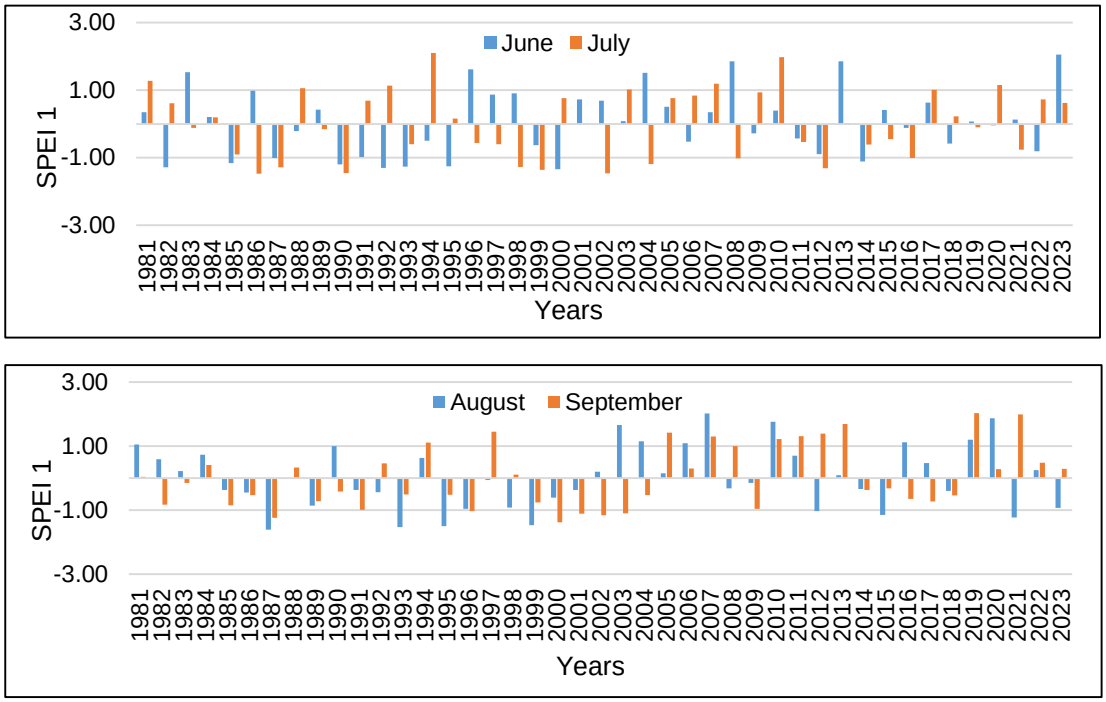

Fig. 8: Drought severities of Jamnagar district for monthly time scales of June, July, August and September

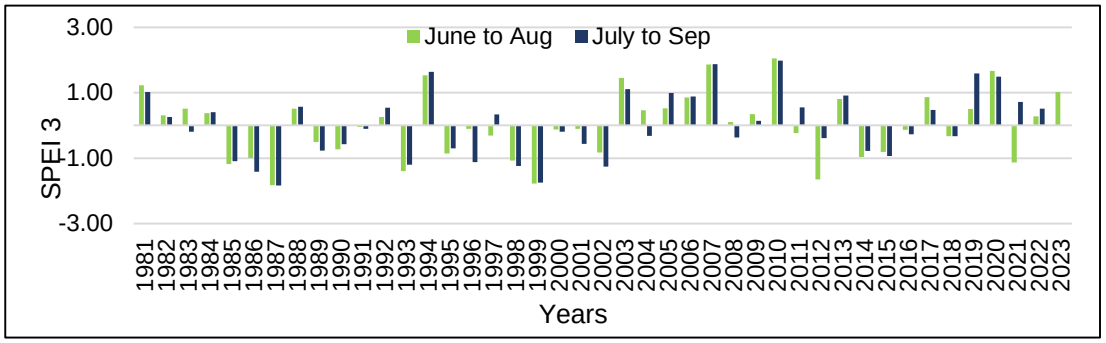

Fig. 9: Drought severities of Jamnagar district for three monthly time scales of June to August and July to September

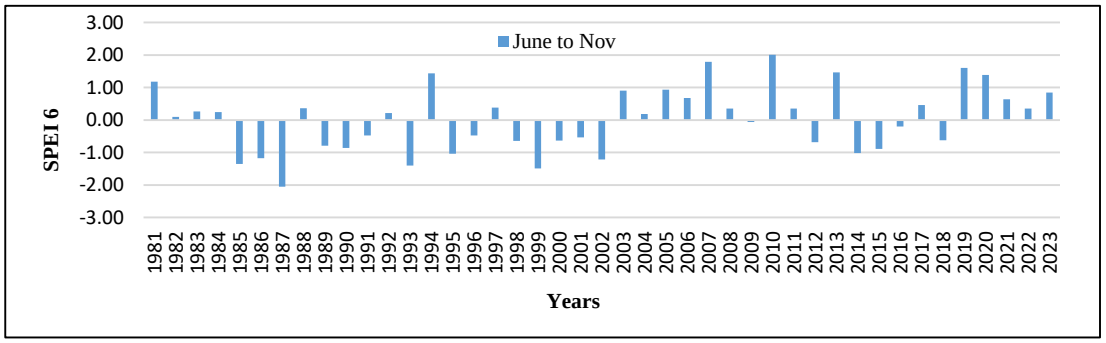

Fig. 10: Drought severities Jamnagar district for six monthly time scales of June to November

Eight years were also observed as having a mild drought. The years 1985 to 1987 (3 years) and 1998 to 2002 (5 years) were identified as periods of consecutive drought.

Overall, at the 1-month time scale, 1% year, 17% years and 19% years were affected by severe, moderate and mild droughts respectively. At 3-month time scale, 6% years, 12% years and 15% years were affected by severe, moderate and mild droughts respectively. At 6-month time scale, 2% years, 2% years, 14% years and 19% years were affected by extreme, severe, moderate and mild droughts respectively. The years 1986, 1987, 1993, 1999, 2002 and 2012 exhibited notably higher levels of drought severity (severe to extreme drought category) in Jamnagar district. The consecutive drought years were identified from 1985 to 1987, spanning a period of three years in Jamnagar. Similar conclusions were drawn by Bandyopadhyay and Saha (2016), who noted continuous dry conditions from 1985 to 1987 in Gujarat [3]. Likewise, Pandya (2023) reported consecutive drought years (1985 to 1987) in the Saurashtra region [17]. The year 1987 was observed under extreme drought category. Bandyopadhyay et al. (2016) also concluded that during the monsoon season of 1985, 1986 and 1987, lack of sufficient rainfall resulted in severe to extreme meteorological drought in various parts of the Gujarat [4]. The worst condition was in 1987, when barring some small parts, the entire Gujarat suffered from a spell of intense drought.

The percentage of occurrence of drought for each category in Jamnagar can be observed from Table 5. Jamnagar experienced a high occurrence of mild droughts at the 1-month (19.19%) and 6-month (18.60%) time scales, with moderate droughts also noticed at the 1-month time scale (16.86%). Severe and extreme droughts occurred least frequently.

Drought parameters for seven durations in Jamnagar district were analyzed as per time scale from 1981 to 2023, as shown in Table 6. At 1-month time scale, the total DD, DM and DI were found to be 37.21 % of the months, -36.69 % of the months and -1.00 respectively. At 3-month time scale, the total DD, DM and DI were found to be 32.56 %, -35.97 % of the months and -1.10 respectively. At 6-month time scale, the total DD, DM and DI were found to be 37.21 %, -38.19% of the months and -1.03 respectively.

3.4 Meteorological drought analysis of Rajkot district

The drought severity of Rajkot by 1 month SPEI index for June, July, August and September for 1981 to 2023 can be observed from Fig 11. The number of years under no drought and various drought severity categories for June, July, August and September out of 43 years under study are given in Table 2.

It can be observed from Fig. 11 and Table 2 that in the month of June, out of the total 43 years under study, 15 years were identified as drought years. The severe drought was observed in 1995. The 8 years were under moderate drought and 6 years were under mild drought. In the month of July, 12 years were noted as drought years. Among these, severe drought was observed in year 1986 and 2002. The 7 years were observed as moderate drought The 14 years were noted as drought years for August, out of which the one year under severe drought was observed in year 1993. The nine years were noted as moderate drought years. In the month of September, 16 years were under drought year. The severe drought was observed in year 1986 and 1987.The 5 years under moderate drought was observed and 9 years were noted as mild drought. The consecutive drought was noticed from 1999 to 2003.

The drought severity of Rajkot by SPEI index based on three monthly timescale of June to August and July to September for 1981 to 2023 can be observed in Fig 12. The number of years under no drought and various drought severity categories for June to August and July to September out of 43 years under study are given in Table 3. In the months of June to August, severe drought was observed in year 1985, 1987 and 2012.The years 1986, 1993, 1995 and 1999 were observed as moderate drought years and 7 years were under mild droughts. In the months of July to September, the years 1986, 1987 and 2002 were experienced severe droughts and the 7 years were under moderate drought, while 9 years were observed as mild drought years.

The drought severity of Rajkot by SPEI index based on six monthly timescale of June to November for 1981 to 2023 can be observed in Fig 13. The number of years under no drought and various drought severity categories are displayed in Table 4.

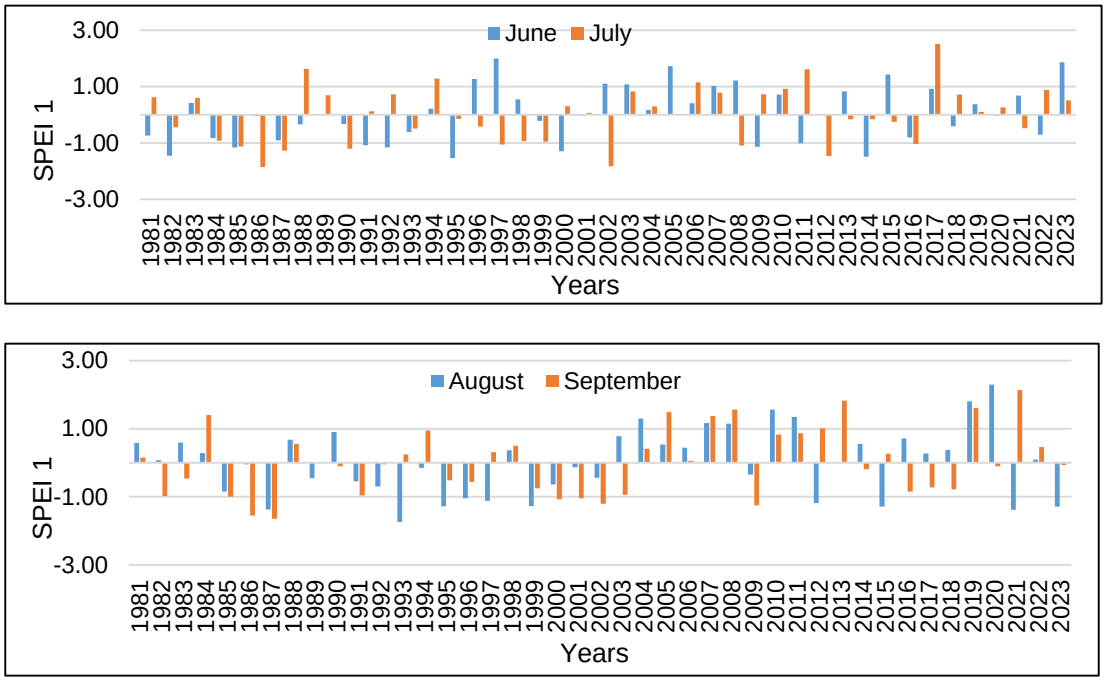

Fig. 11: Drought severities of Rajkot district for monthly time scales of June, July, August and September

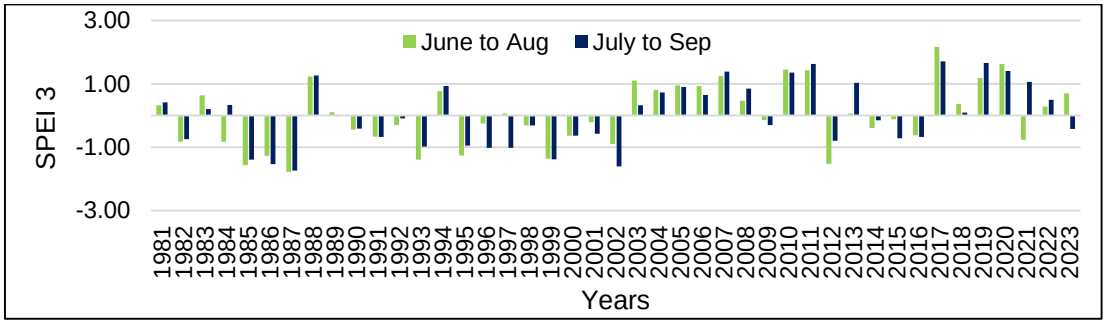

Fig. 12: Drought severities of Rajkot district for three monthly time scales of June to August and July to September

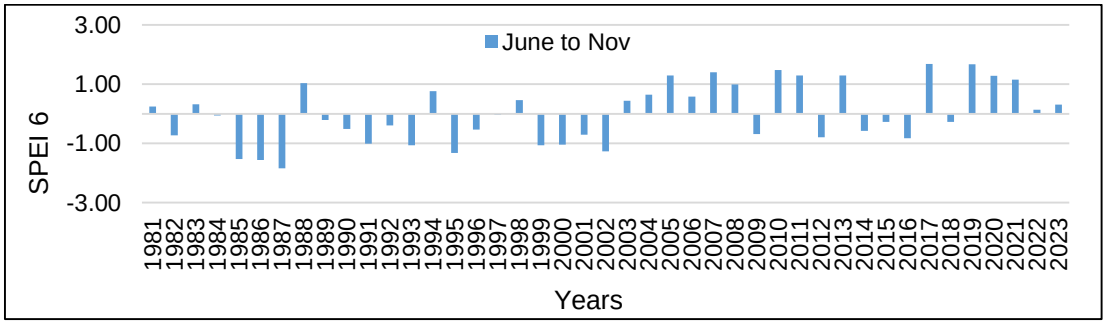

Fig. 13: Drought severities of Rajkot district for six monthly time scales of June to November

It can be observed from Table 4 as well as Fig. 13 that the 17 years were observed as drought years. The severe drought was observed in 1999, 1886, and 1987. The 6 years were under moderate drought while eight years were also observed as having a mild drought. It can be observed from Fig. 13, the consecutive drought was noted from 1985 to 1987 and 1999 to 2002, spanning a period of three years and four years respectively in Junagadh district. Bandyopadhyay and Saha (2016) also reported a continuous dry spell of dry condition from 1985 to 1987 in Gujarat [3]. Gupta et al. (2011) also highlighted the effect of persistence of droughts from 1999 to 2002 in the country [8].

Overall, at the 1-month time scale, 3% year, 17% years and 13% years were affected by severe, moderate and mild droughts respectively. At 3-month time scale, 7% years, 9% years and 19% years were affected by severe, moderate and mild droughts respectively. At 6-month time scale, 7% years, 14% years and 19% years were affected by severe, moderate and mild droughts respectively. The years 1985, 1986, 1987, 1993, 1995, 2002 and 2012 exhibited notably higher levels of drought severity (severe to extreme drought category) in Rajkot district. The consecutive drought years were identified from 1985 to 1987, spanning a period of three years in Rajkot. Similar conclusions were drawn by Bandyopadhyay and Saha (2016), who noted continuous dry conditions from 1985 to 1987 in Gujarat [3]. Likewise, Pandya (2023) reported consecutive drought years (1985 to 1987) in the Saurashtra region [17]. The year 1987 was observed under extreme drought category. Bandyopadhyay et al. (2016) also concluded that during the monsoon season of 1985, 1986 and 1987, lack of sufficient rainfall resulted in severe to extreme meteorological drought in various parts of the Gujarat [4]. The worst condition was in 1987, when barring some small parts, the entire Gujarat suffered from a spell of intense drought.

The percentage of occurrence of drought for each category in Rajkot, which can be observed from Table 5. The highest percentage of occurrence of mild drought was observed at both 3 and 6 month time scales (18.60%).The percentage of occurrence of moderate drought was maximum at 1 month time scale (16.86%) followed by at 6 month time scale (13.95%).

Drought parameters for seven durations were assessed in Rajkot district across the time scale from 1981 to 2023, as indicated in Table 6. At 1-month time scale, the total DD, DM and DI were found to be 33.14 % of the months, -36.09 % of the months and -1.10 respectively. At 3-month time scale, the total DD, DM and DI were found to be 34.88%, -37 % of the months and -1.06 respectively. At 6-month time scale, the total DD, DM and DI were found to be 39.53%, -39.65 % of the months and -1.00 respectively.

4. Conclusion

The analysis of drought incidence over the historical period reveals significant variability in the number of drought-affected years across the regions of Junagadh, Amreli, Jamnagar, and Rajkot. Junagadh experienced drought events in 29% of the years, indicating the lowest incidence among the four regions. Amreli had drought events in 32% of the years. Conversely, Jamnagar and Rajkot exhibited higher drought incidence, with 37% and 36% of the years affected, respectively.

The years 1987 and 2002 were found as the most disastrous drought years of four districts and the years 1985, 1986, 1987, 1993, 2002 and 2012 were other major drought years with varying severities of severe and extreme droughts across four districts. These four districts experienced severe consecutive droughts twice, from 1985 to 1987 and again from 1999 to 2002.

The analysis of drought occurrence shows that mild and moderate droughts have been the most frequent across the four districts while severe and extreme droughts have been less frequent.

The analysis of drought parameters during historical period revealed that across the districts of Junagadh, Amreli, Jamnagar, and Rajkot, the average total drought duration (DD) ranged from 29.46% to 35.85% of the months. Junagadh district had the shortest duration, and Jamnagar district had the longest duration. The average drought magnitude (DM) varied between -37.58% and -34.10%, with Jamnagar district showing the greatest magnitude and

Junagadh the smallest. Drought intensity (DI) ranged from -1.17 to -1.04, with Junagadh district recording the highest and Rajkot district the lowest.

REFERENCES

1. Anonymous. Status Report of Junagadh Agricultural University (2014-15 and 2015-16). Published by Director of Research, Junagadh Agricultural University, Junagadh-362001(Gujarat) (Publication No. 3-1-21). 2016. Accessed 13 September 2023. Available: http://www.jau.in/attachments/book/status_report_2016.pdf
2. Anonymous. District-wise Area, Production and Yield of Important Food and Non-food Crops in Gujarat State for 2018-19, 2019-20 and 2020-21. Department of Agriculture, Farmers' Welfare, Government of Gujarat. 2020. Accessed 15 September 2023. Available: https://dag.gujarat.gov.in/estimate.htm
3. Bandyopadhyay N, Saha AK. A comparative analysis of four drought indices using geospatial data in Gujarat, India. Arabian Journal of Geosciences.2016; 9: 1-11.
4. Bandyopadhyay N, Bhuiyan C, Saha AK. Heat waves, temperature extremes and their impacts on monsoon rainfall and meteorological drought in Gujarat, India. Natural Hazards. 2016; 82: 367-388.
5. Bhuiyan C, Saha AK, Bandyopadhyay N, Kogan FN. Analyzing the impact of thermal stress on vegetation health and agricultural drought–a case study from Gujarat, India. GIScience and Remote Sensing. 2017; 54(5): 678-699.
6. Gautam RC, Bana RS. Drought in India: its impact and mitigation strategies– a review. Indian Journal of Agronomy. 2014; 59(2): 179-190.
7. Guhathakurta P. Droughts in districts of India during the recent all India normal monsoon years and its probability of occurrence. Indian Journal of Meteorology, Hydrology & Geophysics. 2003; 54(2): 542-545.
8. Gupta AK, Pallavee T, Sehgal VK. Drought disaster challenges and mitigation in India: strategic appraisal. Current Science. 2011;100(12): 25.
9. Hagman G, Beer H, Bendz M, Wijkman A. Prevention better than cure. Report on human and environmental disasters in the Third World. 1984;2.
10. Hirapara JG, Singh M, Singh PK. Assessment of drought duration and severity during kharif season in junagadh district under south-saurashtra agro-climatic zone of Gujarat. 2021.
11. Hogg EH. Climate and the southern limit of the western Canadian boreal forest. Canadian Journal of Forest Research. 1994; 24(9): 1835-1845.
12. Homdee T, Pongput K, Kanae S. A comparative performance analysis of three standardized climatic drought indices in the Chi River basin, Thailand. Agriculture and Natural Resources. 2016; 50(3): 211-219.
13. IMD.2015;Accessed on 13.09.2023. Available: http://www.imdpune.gov.in weather forecasting/glossary. pdf.
14. Kebede A, Raju JP, Korecha D, Takele S, Nigussie M. Drought sensitivity characteristics and relationships between drought indices over Upper Blue Nile basin. Journal of Water and Land Development. 2019; 43 (X-XII): 64-75.
15. Mishra S, Chauhan M. Performance evaluation of two meteorological indices for drought assessment in Jalna. International Journal of Current Research. 2019;11(01): 521 -525.
16. Pandya PA, Rank HD. Summer sesame response to irrigation methods and mulching. Research on Crops. 2014;15(4): 810-815.
17. Pandya PA. Development of Drought Forecasting Indices and Crop Yield Modeling using Remote Sensing and GIS. Ph.D. Thesis (Published). Junagadh Agricultural University, Junagadh; 2023.
18. Reddy GR. Principles of crop production. Kalyani Publishers. New Dehi-110002. 2008; 43-47.

19. Roy AK, Hirway I. Multiple impacts of droughts and assessment of drought policy in major drought prone states in India. *Gujarat, India*: Centre for Development Alternatives; 2007.
20. Samra JS. Review and analysis of drought monitoring, declaration and management in India. Working Paper 84. International Water Management Institute, Colombo, Sri Lanka; 2004.
21. Sagari RR. India's Livestock Economy, Seminar 564, August; 2006.
22. Shah R, Bharadiya N, Manekar V. Drought index computation using standardized precipitation index (SPI) method for Surat District, Gujarat. Aquatic Procedia.2015; *4*, 1243-1249.
23. Thornthwaite CW. An approach toward a rational classification of climate. Geographical review. 1948; 38(1): 55-94.
24. Vicente-Serrano SM, Beguería S, Lopez-Moreno JI. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. Journal of climate. 2010; 23(7): 1696-1718.
25. Vicente-Serrano SM, Beguería S, Lorenzo-Lacruz J, Camarero JJ, López-Moreno JI , Azorin-Molina C, Sanchez-Lorenzo A. Performance of drought indices for ecological, agricultural, and hydrological applications. Earth Interactions. 2012;16(10): 1-27.
26. Vora A, Parikh D. Water management to combat drought. Sardar Patel Institute of Economic and Social Research.1996; 26(2): 33.
27. Wilhite DA, Glantz MH. Understanding: the drought phenomenon:The role of definitions. Water International.1985; 10(3): 111-120.
28. Zarei A, Asadi E, Ebrahimi A, jafary MM, Malekian A, Tahmoures M, alizadeh EE. Comparison of meteorological indices for spatio-tem-poral analysis of drought in Chahrmahal-Bakhtiyari province in Iran. Hrvatski meteoroloski casopis.2017; 52(52): 13-26.