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Meteorological drought mitigation for combating climate change: a case study of southern Sindh, Pakistan

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K E Y W O R D S

Drought Analysis

Drought Indices

Potential Evapotranspiration (PET), SPI

SPEI

Hargreaves

Southern Sindh

A B S T R A C T

A meteorological drought study is performed using monthly time scale data from three separate locations in southern Sindh, Pakistan. Rainfall and temperature have been used to identify the drought. These data were transformed into drought indices known as the standardized precipitation evapotranspiration index (SPEI) and standardized precipitation index (SPI), which were derived using (the Hargreaves equation). In this study, two indices are compared for three separate meteorological stations Chhor, Mithi, and Badin where most socioeconomic livelihoods depend heavily on water. The SPEI is produced through a simple water balance combining precipitation and temperature, in distinction to the SPI, it just considers precipitation. In conclusion, our study showed that both indices were capable of detecting droughts that fluctuated in time across the reference period of 2004–2021. SPI and SPEI's direction of change was similar, however the impact on the drought condition varied. SPEI discovered more droughts with longer durations and greater with 13 moderate droughts at SPEI-3 for Chhor and Badin Station while Mithi indicated 8 moderate droughts during 2004-2021 and SPI-3 indicated 4 moderates for Chhor, Mithi and Badin indicated 6 moderate drought. Conversely, SPEI discovered more moderate-level droughts than SPI, however they were of shorter length and less frequent occurrence than the severe to moderate droughts. The findings imply that drought characteristics are significantly influenced by temperature variability.

1. Introduction

The world's most serious natural disaster is known as drought. Having an impact on crop production and economic growth, drought is becoming more regular and severe as the surface environment changes with increasing temperatures. Drought is defined as a lack of water that lasts for a long time and has a physical effect that lasts until the water content insufficiency is resolved [1-4]. Even though the occurrence has been studied on a global basis, Sometimes, its local or even regional factors remain overlooked. Drought evaluation is essential at the regional scale to develop climate change mitigation and adaptation strategies in that area. Drought is divided into five main classifications based on the characteristic used to define it: agricultural drought, hydrological drought, ecological drought, meteorological drought, and socio-economic drought [5,6]. Whenever meteorological drought affects any region, it is followed by hydrological and agricultural drought. This research study's main focus is on the lack of precipitation and temperature increase that occurred before the meteorological drought. The World Meteorological Organization (WMO) recommends these two basic drought scales which are the SPI and the SPEI [7], the SPI index recommended by McKee et al., and Vicente-Serrano et al. established the SPEI in 1993 [8, 9]. The valuable index SPI is used for mapping and identifying the drought [10]. Because SPI is deterministic, it has an advantage over other drought indices in terms of risk and decision analysis. When the SPI and SPEI approaches were compared [11], the SPEI method was shown to be more accurate.

When compared to the Percent of Normal (PN) approach, [12] discovered that the SPI method is more appropriate and trustworthy for analysing drought features, with a moderately high correlation coefficient. The input parameters for SPEI are surface evapotranspiration and precipitation, while precipitation is used for SPI computation [13-15]. Because of the rise in surface temperature, potential evapotranspiration (PET) is increasing, resulting in water scarcity in the basin [16]. On a temporal scale, SPEI was more responsive to drought assessment than SPI because SPEI's conditional probability is larger than SPI's. The SPEI and SPI are used in current research and can be combined to study drought features. Drought intensity, duration, and severity are some of the key drought characteristics that have been used to assess drought events. The SPI was used to evaluate drought by analysing two drought characteristics: duration and intensity [17]. A 6-month timeline SPI was used for drought evaluation, monitoring, and forecast. SPI is used to examine the unique and temporal aspects of meteorological dryness over a 12-month period [18].

Because of increase in dryness and declines in normal and wet occurrences, droughts typically have negative SPI values, and several drought indices have been employed to characterize and distinguish the pattern of rainfall change and drought conditions [19, 20]. In some situations, droughts may continue for several years, resulting in total devastation of agriculture and water supplies of the concerned area [21]. The beginning and ending points of drought are very difficult to assess. A drought may persist for uneven periods. It can persist for some time, or it can last for just a few months [22]. However, it may remain in place for a long period, until the climatic factors return to their normal place of action. Like many countries of the world, Pakistan also experiences such droughty years mostly in the Eastern side of Sindh which is covered by the desert of Thar. The primary aim of the research is to determine the SPI and SPEI time series for various timeframes because the methodology for doing so relies on the moving sum of the rainfall series. The area of research is considered for the following reasons.

(A)The area of Tharparkar lies in a very underdeveloped parts of Pakistan, therefore, no research had ever been conducted for the analysis of droughts.

(B)The people of this region of Sindh are extremely poor and they are thoroughly dependent upon their agriculture, so it is highly significant for us to analyse the drought in this arid region.

(C) The region of Tharparkar had been subject to severe droughty conditions in the 1980s. The possibility of those droughts existed for a longer time. However, the severity of 1990s droughts was for a shorter period. As this region is subject to frequent short-term droughts it is highly necessary for the researcher to conduct a thorough investigation in the said region, preserving some water for use and early warning before the drought comes, with the aid of the government, so that they can be prepared to face the drought period in order to protect the present and future of the people in that area, as well as agriculture, animal lives, and their own lives. This study's primary goal is to provide early drought warnings to residents in specific areas, and animal lives and agriculture growth in the area of study and researcher will submit this detail to "Pakistan Meteorological Department (PMD)", to take some good effort in this area for people lives and for agriculture and animals and this is a case study, and since the same work has not yet been done on the data which was used in this study, that is the key emphasis of this study.

2. Materials and Methods

2.1 Study Area

The Thar Desert, which runs along Pakistan's border with India, dominates rural Sindh Province. Tharparkar District, one of Sindh's twenty-nine districts, is located in-side this region as shown in (Fig.1). The most impoverished and isolated district is Tharparkar. Drought impacts on Tharparkar District's resources, services, and facili-ties due to climate change. Drought's historical and contemporary impact on Tharparkar District, as well as local climate and weather trends, economic conditions, and broader ramifications for Pakistan's development, are all examined in this study.

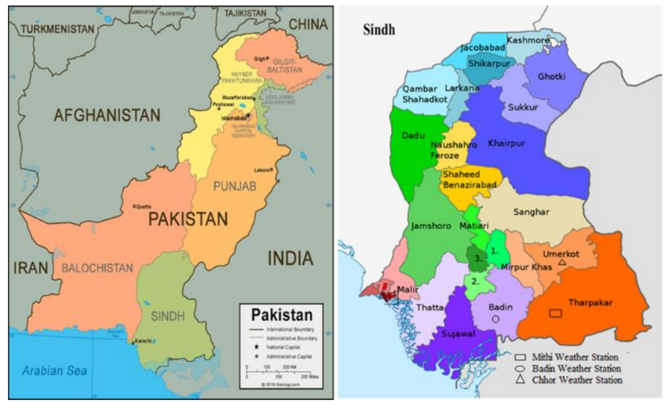
Deforestation, loss of biodiversity, air pollution, access to clean water to drink, and the effects of a changing climate are just a few of the environmental difficulties Pakistan faces because of population expansion and overpopulation [23]. Communities that rely on Pakistan's natural resources are especially at risk.

The climate is hot, arid, and prone to drought and the rainfall is less than 200 millimetres per year [24]. Extremes characterize the Thar Desert. It is very hot during the day and chilly at night in the summer. The days are warm, and the nights are frigid in the winter. The sandy ground heats up during the day but cools off at night.

The Tharparkar desert covers around 19,638 km², or roughly 20% of Sindh's total land area. The Tharparkar is one of the primary deserts of the Sindh. The summer season, which extends from May to October, and the wet season, which extends from November to April, were its only two distinct seasons. It also lacks a natural irrigation system. In winter, everyday temperatures range from 13 to 20 ^{0}C, while the summer range is from 21 to 30 ^{0}C. It relies on monsoon rains to support agriculture, pastured animals, and the numerous little communities dotting the rough landscape. The rainy season in Pakistan and Tharparkar District is known as the monsoon. Agriculture is at a crossroads, with ramifications for the industry, drinking water supplies, energy generation, and human health. It typically lasts from June through September during the summer monsoon season, Tharparkar District has around 60% of its yearly rainfall. During the monsoon, the months of July and August recorded 75% of the precipitation [25]. There are seasons when the Thar Desert receives almost no rain, sometimes for years at a time. This was true between 1999 and 2001, and again between 2014 (PMD) [26].

Temperatures and precipitation in Tharparkar district are directly linked to agricultural production and other important aspects of everyday life, such as water access and potability. Changes in these trends, as well as forecasting future trends, are critical for the district, as well as the country because agriculture is so important to both the local and national economies. Crop failure, caused by severe temperatures and unexpected rainfall patterns, has a long-term impact on people from all walks of life. Farmers rely on their crops for both food and revenue, so any changes in temperature or rainfall are doubly crucial to watch.

Mithi, a town in the Thar Desert, provides context with temperature and precipitation data. Rising average temperatures and increased evaporation and evapotranspiration rates, which result in higher amounts of atmospheric water vapor and changes in seasonal rainfall patterns, are the most generally considered markers of climate change. This is demonstrated by Mithi's situation.



(a) (b)

Fig. 1. (a) Pakistan map and (b) Sindh province, map according to the district [27]

2.2 Climate data

This study employed data from the Chhor, Mithi, and Badin weather stations of the PMD because there aren't many networks for measuring rainfall (PMD, 1947). The data set consists of maximum, minimum temperature, and precipitation variables of monthly time series. The base period of data is 2004 -2021 is used to calculate using ground station data and direct estimate through interpolation (as a function of elevation, longitude and latitude) [28], To adjust for data inhomogeneity at every station, the station compared with reference time-series data from near ground observation stations. The Geographical locations of the chosen meteorological stations are listed below in table 1.

Table 1

Several locations for weather stations and the data's base year

Selected Region	Latitude	Longitude	Record year
Mithi ws	24.740 DD	69.800 DD	2004-2021
Badin ws	24.656 DD	68.837 DD	2004-2021
Chhor ws	25.513 DD	69.784 DD	2004-2021

ws = Weather Station, DD= decimal degrees

Data from Karachi PMD has been collected and used in this research. Mithi weather station lies in Tharparkar region, Badin weather station in Badin Region and Chhor weather station lies in Umerkot region all stations mentioned in Fig..1 and I received different parameters like Precipitation, Maximum temperature, Minimum temperature, and more details also mentioned in Table.1. There are many other techniques to calculate the PET but we have selected a temperature-based empirical technique the Hargreaves equation. Hargreaves published the equation for PET estimate in 1975.

$$PET = 0.135 R_s (T_{mean} + 17.8) \quad (1)$$

Where R_s denotes worldwide solar radiation at the surface (mm/day) and T_{mean} denotes the average temperature (^{0}C). i.e has the minimum plus maximum.

Because R_s were not readily available, Hargreaves decided that R_s could be calculated using extra-terrestrial radiation (R_a) and the proportion of probable sunshine after analysing climate data and reviewing the literature (S). Finally, the predictive form was proposed by Hargreaves and Samani (1982):

$$R_s = K_{RS}(R_a)(TR^{0.50}) \quad (2)$$

TR is the daily temperature range in Celsius degrees (TR =Tmax -Tmin; where Tmax is the mean daily highest temperature and Tmin is the mean daily minimum temperature), and K_{RS} is an empirical coefficient fitted to R_s/R_a versus TR data.

Hargreaves et al. (1985) utilizing K_{RS} =0.16 (a number derived from meteorological data from the Senegal River Basin) and merging the two preceding equations, the following equation was created:

$$PET = 0.0022 R_a (T_{mean} + 17.8) TR^{0.50} \quad (3)$$

However, Hargreaves and Samani (1985) suggested that the coefficient be increased to account for peak demand months, resulting in the so-called Hargreaves equation of 1985:

$$PET = 0.0023. R_a. (T_{mean} + 17.8). TR^{0.50} \quad (4)$$

The method's significance stems from its simplicity, dependability, little data requirements, availability of computing, and low aridity influence from meteorological stations.

Whereas $T^0R = T_{max} - T_{min}$ (mean maximum minus mean minimum temperatures in ^{0}C); $T^0{}_{mean} is \frac{(T_{max} - T_{min})}{2}$; PET and R_a = same units of equivalent water evaporation; R_a= extraterrestrial radiation [29-31].

2.3. SPI and SPEI drought indices

A comparison of the SPI and SPEI was done to discover whether potential evapotranspiration influenced the drought index. Between 2004 and 2021, different time scales were used for the analysis. Meteorological, agricultural, and hydrological droughts are shown by different time periods (1, 3-6, and 12 months), respectively. We used the SPEI package of the R program package, SPI and SPEI were created a free statistical computing and graphics environment that provides a number of options for computing SPI and SPEI, and the SPEI is more appropriate for drought monitoring for agricultural purposes than the SPI. [32-34].

2.3.1 Standardized Precipitation Index (SPI)

The SPI [35] calculates the precipitation deficit over a range of timescales (1, 3, 6, 9, 12, and 24 months). It is determined as follows: It is based on the cumulative gamma distribution of some precipitation occurring at the observation post:

$$G(x) = \frac{1}{\beta_{pro}^{\alpha pro} \Gamma(\alpha_{pro})} \int_0^x y^{\alpha pro - 1.} e^{\frac{y}{\beta pro}} dy \quad (5)$$

Where

$$\alpha_{pro} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right),$$

$$A = ln(x_{sr}) - \frac{\sum_{i=1}^{n} \quad ln(x_i)}{n}$$

$$\beta_{pro} = \frac{x_{sr}}{\alpha_{pro}}$$

and x_{sr}= mean precipitation amount; n= precipitation measurement number; x_i= precipitation quantity in a sequence of data. When x equals 0, the cumulative probability is as follows:

$$H(x) = q + (1 - q) G(x,) \quad (6)$$

where q is the likelihood that the amount of precipitation will be zero.

Table 2

SPI and SPEI drought classification by [9].

Drought class/Category	SPI value
Extremely wet	SPI and $SPEI \geq 2.0$
Very wet	$1.5 \leq SPI$ and $SPEI < 2.0$
Moderately wet	$1.0 \leq SPI$ and $SPEI < 1.5$
Near normal	$-1.0 \leq SPI$ and $SPEI < 1.0$
Moderate drought	$-1.5 \leq SPI$ and $SPEI < -1.0$
Severe drought	$-2.0 \leq SPI$ and $SPEI < -1.5$
Extreme drought	SPI and $SPEI < -2.0$

$$SPI = \begin{cases} -\left(t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right), & 0 < H(x) \leq 0.5 \\ +\left(t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right), & 0.5 < H(x) \leq 1.0 \end{cases} \tag{7}$$

$$t = \begin{cases} \sqrt{\ln \frac{1}{(H(x))^2}}, & 0 < H(x) \leq 0.5 \\ \sqrt{\ln \frac{1}{(1 - H(x))^2}}, & 0.5 < H(x) \leq 1.0 \end{cases} \tag{8}$$

and C_0=2.515517, C_1=0.82853, C_2=0.010328, d_1=1.432788, d_2=0.189269, d_3=0.001308 For both dry and wet SPI, McKee et al. (1995) divided the SPI into three categories: moderate, severe, and extreme. In this study, meteorological conditions and the impacts of drought on available water supplies were tracked for 3, 6, 9, 12, and 24 months [23-31]. Due to its ability to be calculated over several reference periods and to account for the different response times of typical hydrological parameters to rainfall, SPI equation 7 is frequently used to evaluate drought. The SPI now serves as a global drought indicator. The index has an advantage over other methods of measuring drought in that it can describe the incidence of droughts with little assistance and over a range of time periods. In addition to measuring the severity of a drought or the amount of rainfall, it can be used to develop drought/flood contingency plans. The SPI is one of the main parts of strategic planning because it enables the medium- and long-term choices that must be made in order to effectively handle prospective drought conditions.

The fundamental benefit of SPI is the ability to compare regional droughts, whereas one of the disadvantages of standardized indices is that the severity of a drought event is only indicated in relative terms. Another drawback of the SPI is that only precipitation is considered as an input variable, whereas other meteorological variables and factors important in assessing drought that are considered in the computation of other indices are ignored.

2.3.2. Standardized Precipitation Evapotranspiration

The parameters for potential evapotranspiration and precipitation determined by (Vi-cente-Serrano, S. M., et, al, 2010) are the major components of the SPEI. For the purpose of estimating SPEI, the variations between the precipitation (P_i) and potential evapotranspiration (PET_i) throughout month i (D_i) were computed and averaged at various time scales (D_k).

$$D_i = P_i - PET_i \tag{9}$$

$$D^k = \sum_{i=0}^{k-1} P_{n-i} - PET_{n-i} \tag{10}$$

where n is the computation month and k is the number of months or the interest time scale. The probability density function of a three-parameter log-logistic distribution is utilized to consider the negative values of Dk in the next stage, which is based on the L-moment process (since this method is the most robust and easy approach [36].

$$f(x) = \frac{\lambda}{k}\left(\frac{x-\mu}{k}\right)^{\lambda-1}\left[\left(1 + \frac{x-\mu}{k}\right)^{\lambda}\right]^{-2} \tag{11}$$

Where

$$\lambda = \frac{2w_1 - w_0}{6w_1 - w_0 - 6w_2}$$

$$k = \frac{(w_0 - 2w_1)^{\lambda}}{\Gamma\left(1 + \frac{1}{\lambda}\right)\Gamma\left(1 - \frac{1}{\lambda}\right)}$$

$$\mu = w_0 - k\Gamma\left(1 + \frac{1}{\lambda}\right)\Gamma\left(1 - \frac{1}{\lambda}\right)$$

$$w_l = \frac{1}{n}\sum_{i=1}^{n} x_i \left(1 - \frac{i-0.35}{n}\right)^l, l = 0,1,2,$$

where f for density, k, λ, and μ are scale, shape, and origin parameters for D_k values in the range ($\lambda > D_k < \infty$); w_l $(l = 0, 1, 2, \ldots)$ is the order of probability weighted moments (for example w_l is probability weighted moments for order l); xi is the ordered random sample ($x_1 < x_2 \ldots < x_n$) of D_k; and n is the sample size.

The cumulative distribution function of the D_k series, according to the log-logistic distribution [9], is as follows:

$$F(x) = \left[\left(1 + \frac{k}{x-\mu}\right)^{\lambda}\right]^{-1} \tag{12}$$

Finally, the resulting $F(x)$ values are translated into matching Z-standardized normal values to calculate SPEI. Table 2 lists the classification of drought severity based on SPEI [28].

2.4. Drought Identification

Both the SPI and SPEI scales are used to characterize droughts (McKee et al., 1993). Because both indexes are calculated using the same concepts, the SPI scale is employed. The SPI/SPEI index scale as follows: extreme drought ≤ -2, severe drought lies in $-2 \leq SPI, SPEI < -1.5$ and moderate drought $-1.5 \leq SPI, SPEI < -1$ It's worth noting that drought ends when the SPI/SPEI approaches 0 and turns positive. In this study, the length of the drought is determined by how many months it lasted, while the intensity of the indicators reflects the severity of the drought. The Pearson correlation coefficient, r, is used to analyse whether the SPI and SPEI depict the same pattern (regardless of magnitude). It shows how well the two indexes are statistically related to one another. At a 95% and 90% confidence level, this coefficient determines if the indices have a linear connection. The relationship coefficient (R) is a value between +1 and -1, where +1 indicates a perfect positive relationship, 0 indicates there is no relation, and -1 indicates a perfect negative relationship. The magnitude of the correlation indicates the relationship's intensity, with a R value of 0.5 indicating a strong association (Taylor, 1990). The following formula is used to determine R:

$$R_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 (y_i - \bar{y})^2}} \quad (13)$$

Where n is the number of observations, and x and y are the SPI and SPEI values, respectively, for this research [30].

3. Simulation and Results

The SPEIs and SPIs for the various sub-basins were created and displayed monthly in Fig. 2-3 and yearly in Fig. 4-6 to show the temporal fluctuation of drought in the southern Sindh on various time scales (3, 6, 9 and 12 months). In general, and throughout each sub-basins, both in-dices show the same pattern of variation for all period, but the length and severity of the drought vary. Due to the region's significant natural climatic change, which is typical of the southern Sindh region, drought variability possibly connected to it. And their time scales pattern also demonstrated in Fig. 7-9 Moreover, the frequency of occurrence of droughts is no significant association is found between residuals in Fig.10-12 and the normally distributed Normal Q-Q plot of residuals for the SPEI and SPI at variable time scales have been characterized, a meteorological drought takes a quicker time (at most 3 month) to develop due to prevailing water scarcity, resulting in extreme variability of droughts. A meteorological drought, whereas the other, requires a extensive time of water shortage accumulation or reduction of reservoir water storage. As a result, meteorological droughts (3-month time scale) are the most common, followed by agricultural droughts (3–6-month time range) and finally hydrological droughts (12-month time scale). The drought, on the other hand, lasts longer and has a greater magnitude at longer timescales. Given that most crops require up to 6 months to fully develop, a water shortage lasting at least 3 months during the producing season will negatively influence negative influence on crop production, leading to agricultural drought. Because drought changes over time, it's reasonable to in-fer that prolonged drought on longer timescales is the consequence of the cumulative impacts of antecedent water scarcity, it might be made worse by determined and ongoing periods of drought. A change in seasonal rainfall patterns that prevents rainfall and affects activities that depend on the beginning of a rainy season can also cause a drought.

There were obvious discrepancies in certain years and across timelines between SPI and the SPEI. In SPEI, droughts lasted longer; the length of the drought lengthens as the number of droughts in the annually time series increases. SPEI and SPI categorize conditions as drought when water evaporation rises as a result of a increase in temperature.

In the Fig. 2, there are three stations Mithi, Badin and Chhor's drought index is calculated are shown in green colour for Badin, Yellow for Mithi and orange colour for Chhor station. And in the x-axis shows the years and y-axis indicates the index values. The drought is observed to occur from June to November for all stations, Mithi station shown moderate drought in the month of June, July and August, Badin stations shows moderate drought in July and august and severe in September and October, Chhor station shows moderate drought in June and July and severe in August in 2014.

Three distinct stations are marked in various colours like orange for Chhor, Yellow for Mithi and green for Badin station in Fig. 3. And in the x-axis shows the years and y-axis indicates the index values. The drought is observed to occur from May to November for all stations, Mithi station shown moderate drought in the month of June August and in September, and severe in the months of April and May, Badin stations shows moderate drought in June, July and August and severe in April, May and December, Chhor station shows moderate drought in April, May, June July and August.

Fig. 4-6 presents SPEI and SPI drought condition plots for the Chhor, Mithi and Badin Station over various time scales from 2004 to 2021. The x-axis shows number of years and Y-axis shows moderately index SPEI and SPI. The red colour signifies a drought, while the blue colour signifies no drought.

Fig. 7-9 display the SPEI and SPI time series plots for the Chhor, Mithi, and Badin Stations for various time scales from 2004 to 2021. The x-axis shows number of years and Y-axis shows moderately index SPEI and SPI. There are many droughts that occur in this region, as is evident from the time series plot above, and some of them are especially clear from the graph for the periods of 2005 to 2006, 2014 to 2016, and 2019 to 2020, which have more drought. It is also observed for all the stations that there is high rain during the periods 2006 to 2007 and 2011 to 2012, so less drought occurs during those times.

SPEI and SPI at the Chhor, Mithi, and Badin Station Fig. 10–12 display normal distribution graphs for various time scales from 2004 to 2021. And it is noticed across all available stations. For all stations, SPEI is more normally distributed than SPI, while shorter time scales like 3 and 6 months indicate a more normal distribution than 9 and 12 months.

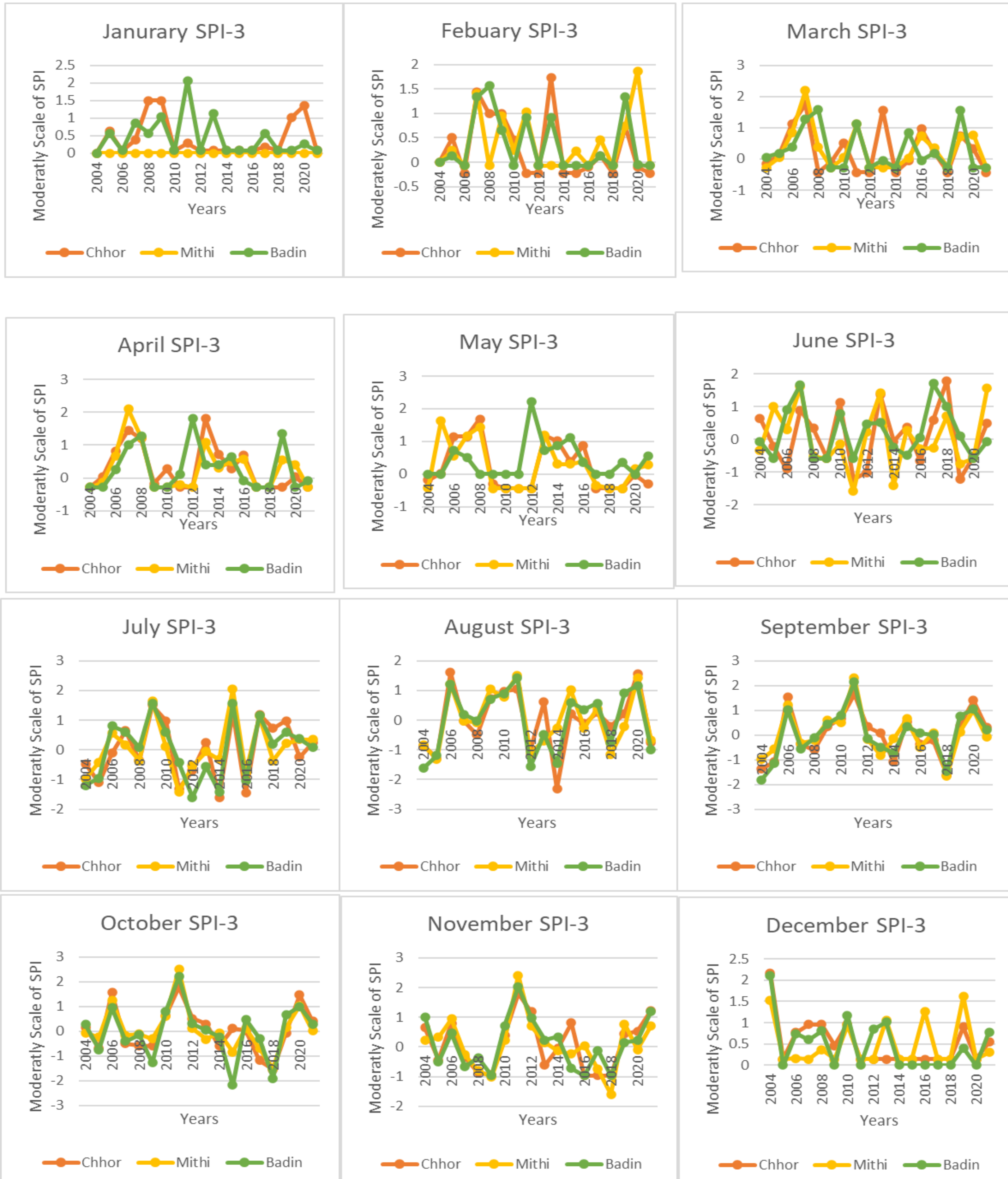


Fig. 2. Monthly drought conditions at the SPI index for Chhor, Mithi, and Badin stations from January 2004 to December 2021.

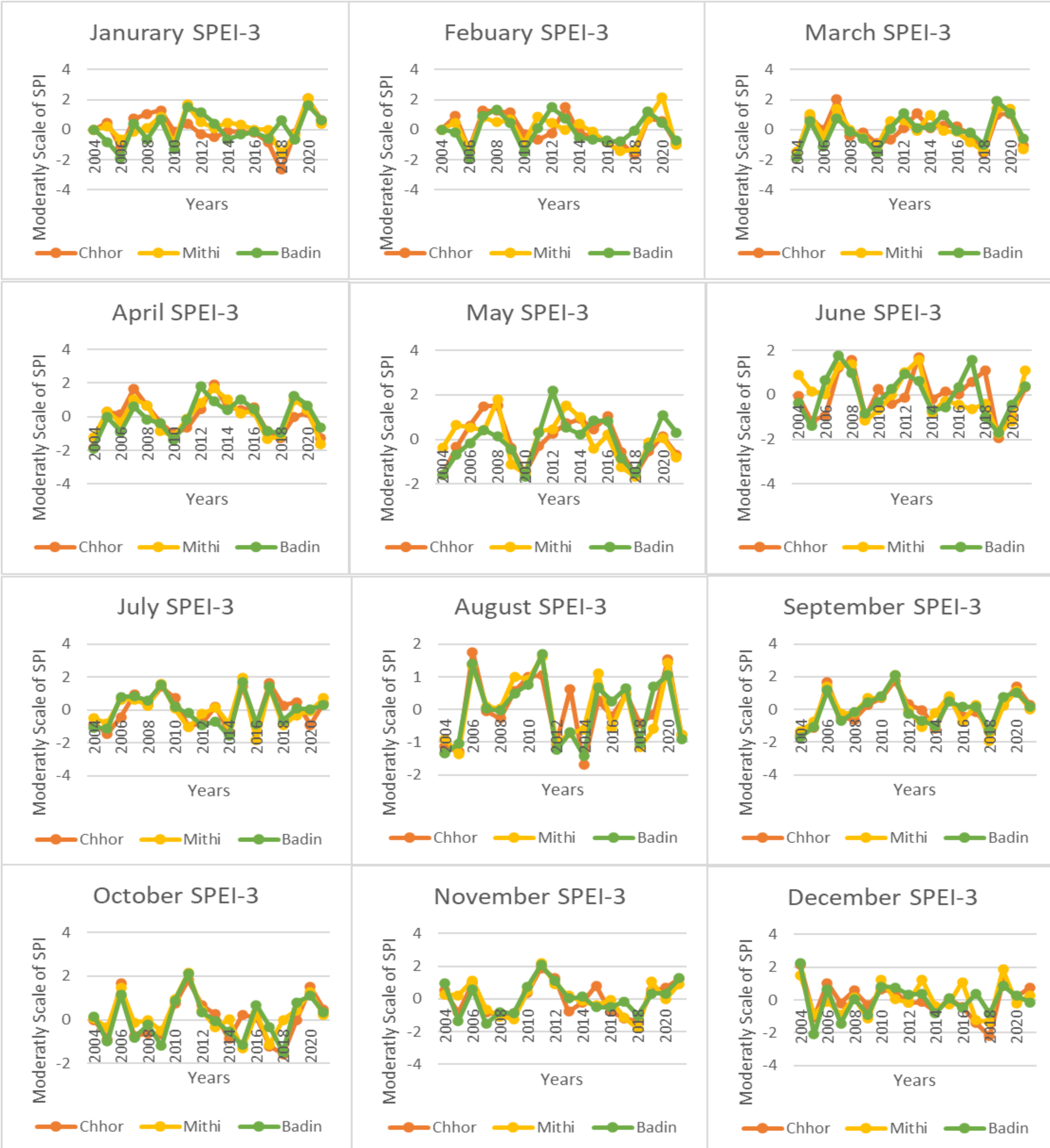
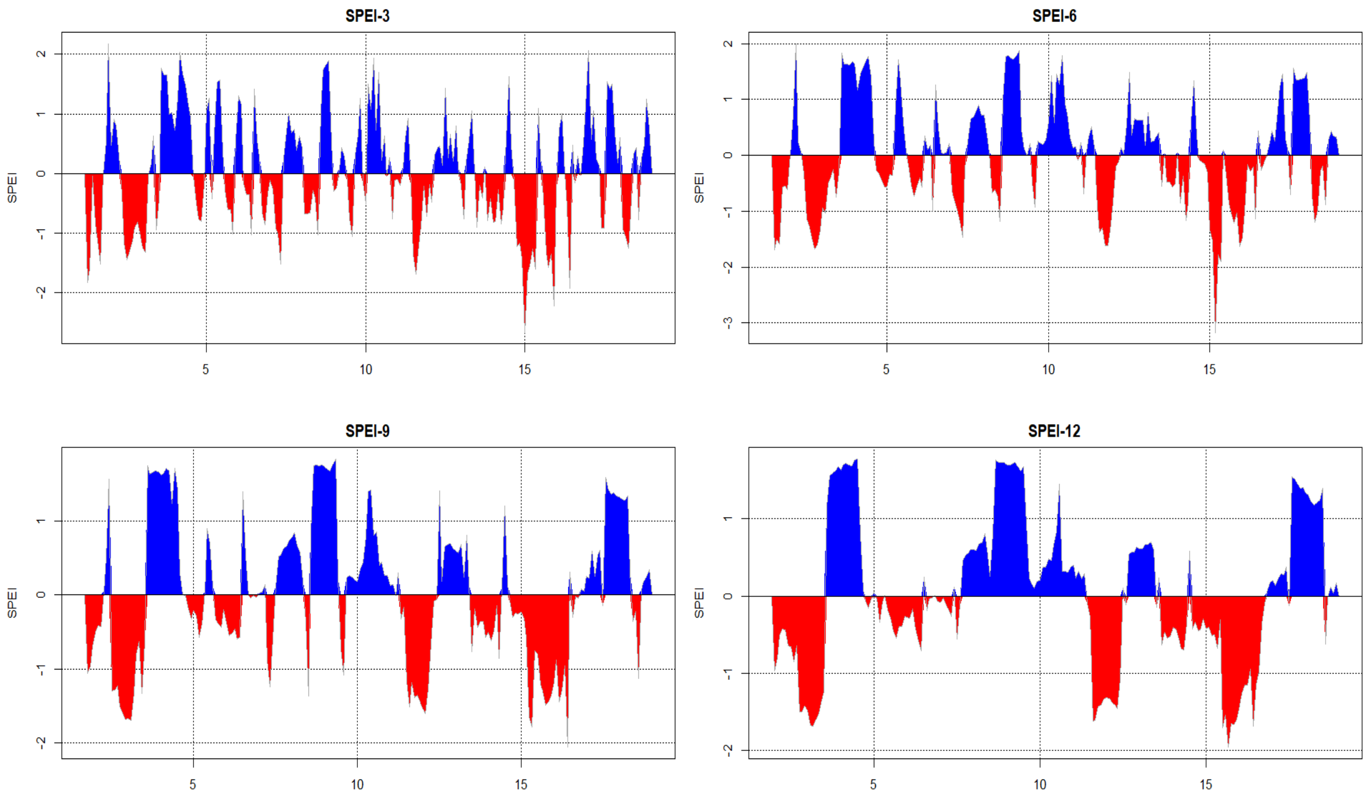


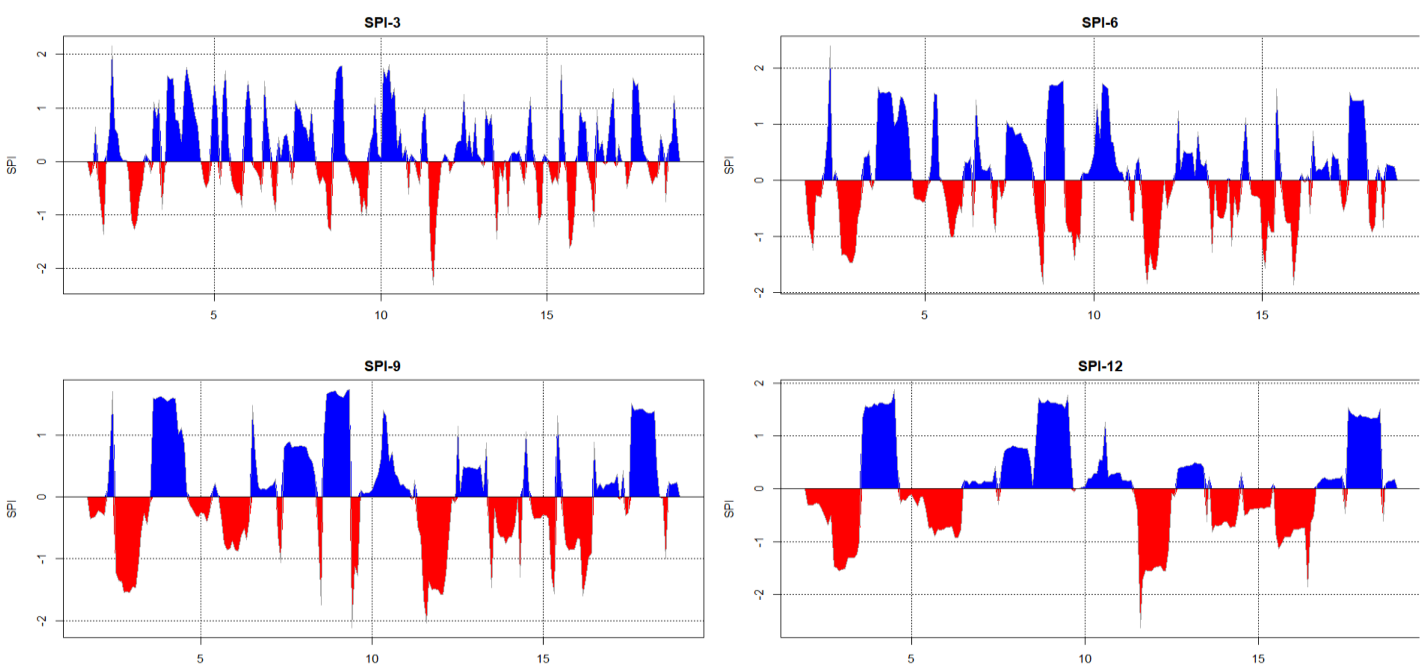
Fig. 3. Monthly drought conditions at the SPEI index for Chhor, Mithi, and Badin Stations from January 2004 to December 2021.

Chhor SPEI



(a)

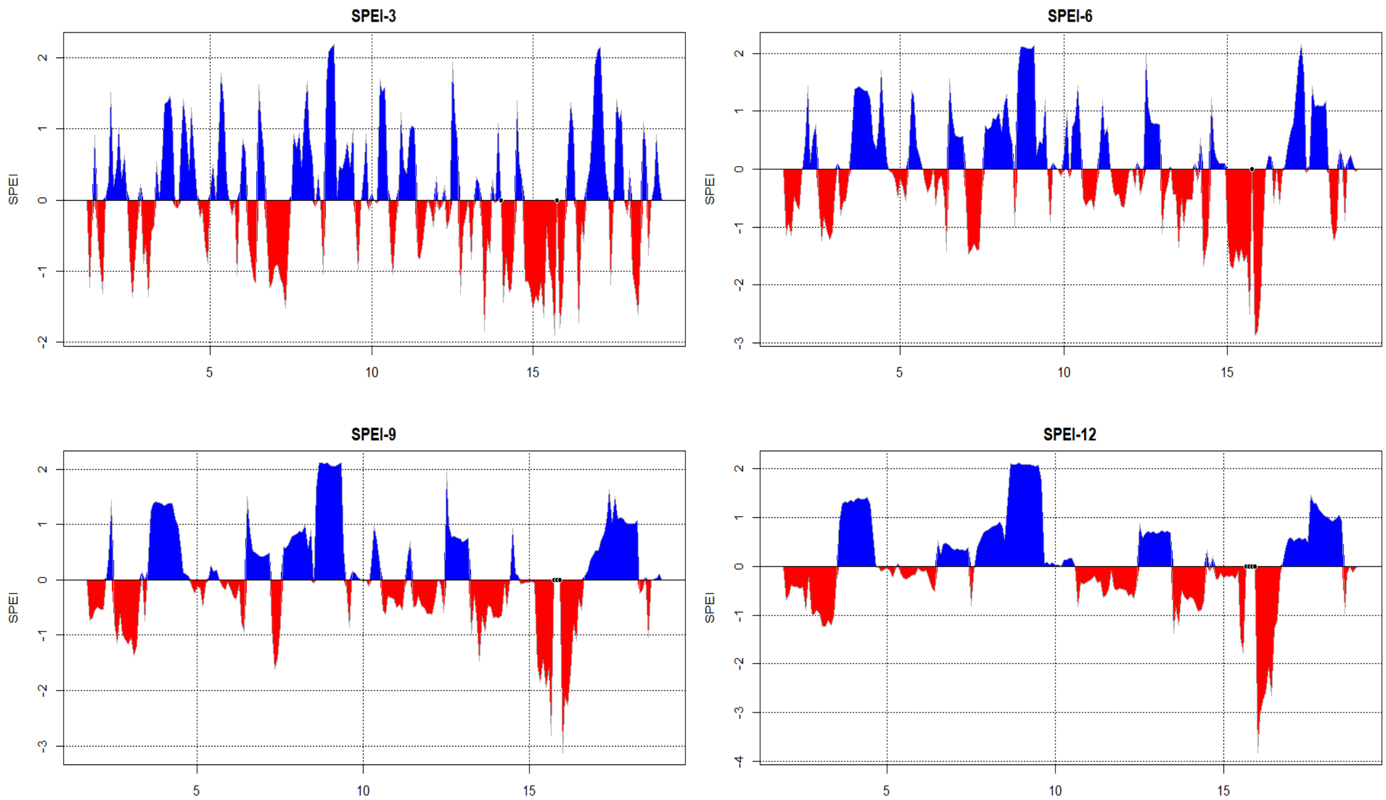
Chhor SPI



(b)

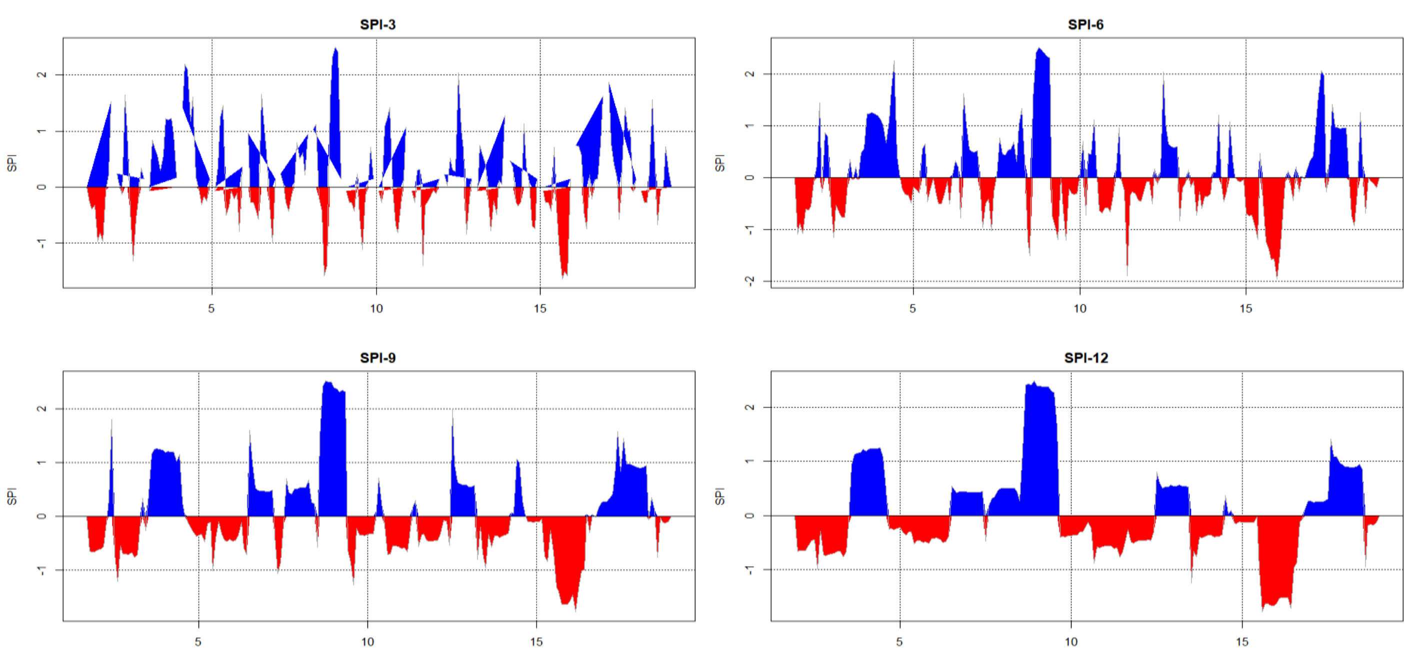
Fig.4. (a) SPEI drought condition (b) SPI drought condition, at different times periods of Chhor station from 2004 to 2021

Mithi SPEI



(a)

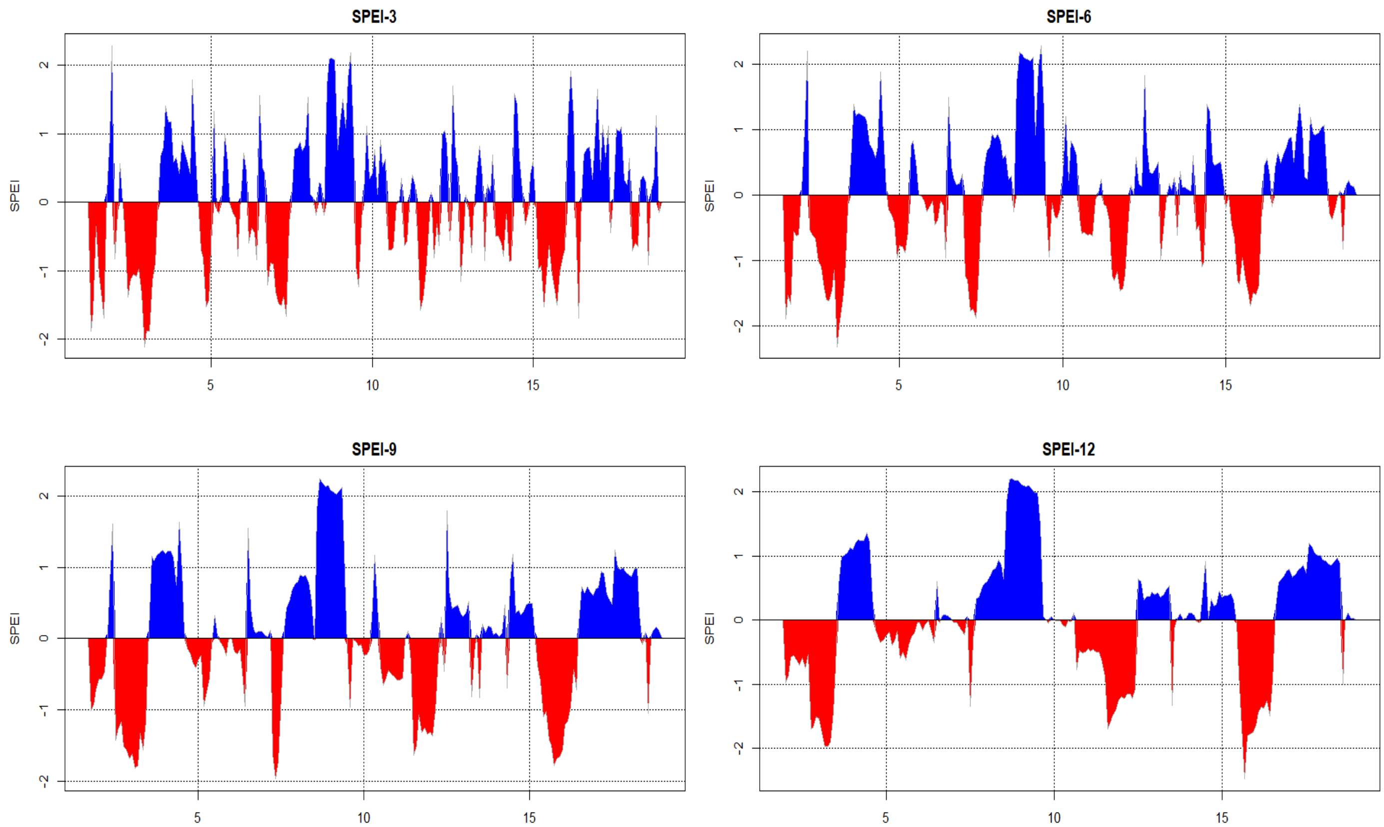
Mithi SPI



(b)

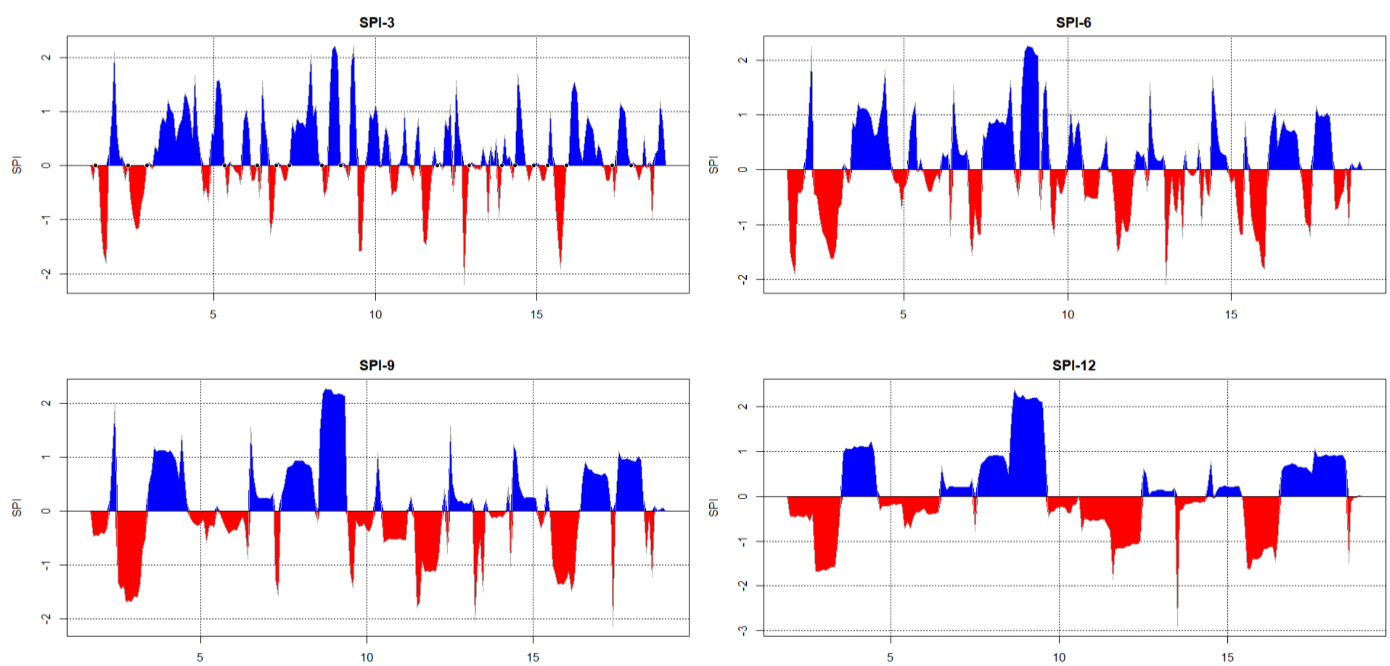
Fig. 5. (a) SPEI drought condition (b) SPI drought condition, at different times periods of Mithi Station from 2004 to 2021 [37]

Badin SPEI



(a)

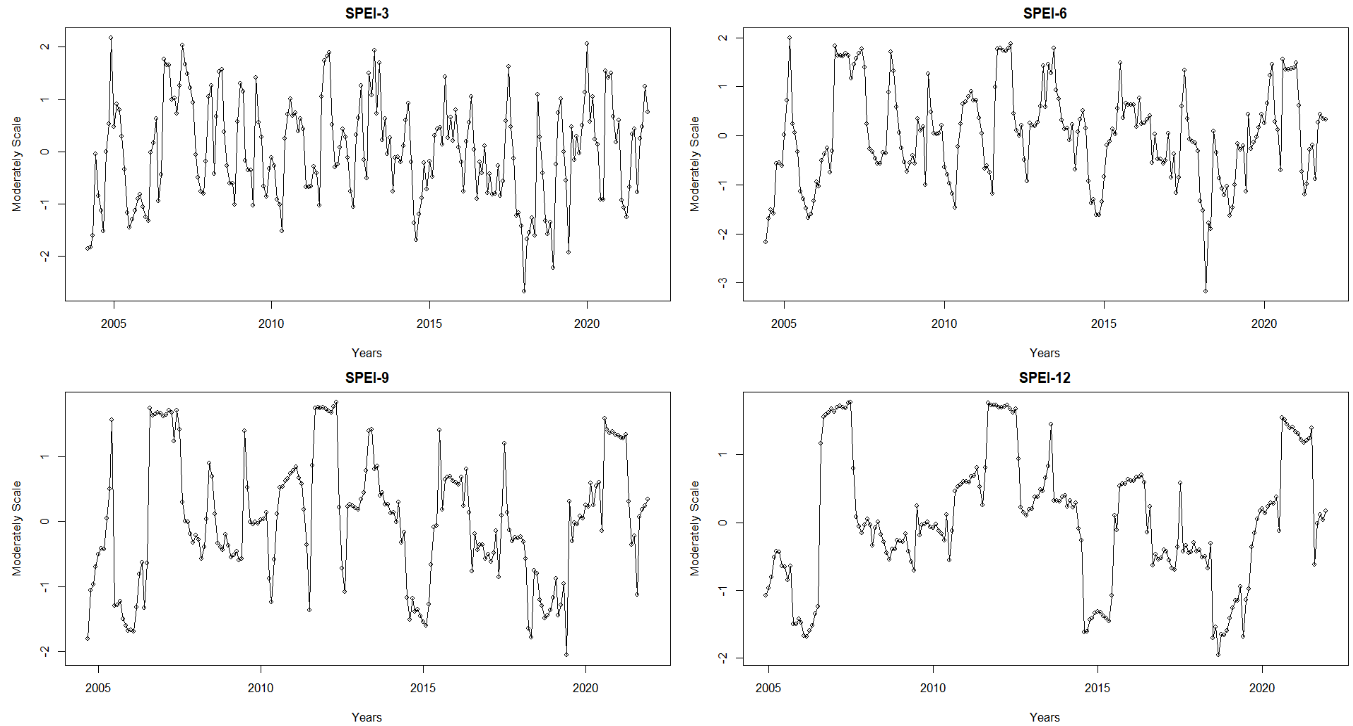
Badin SPI



(b)

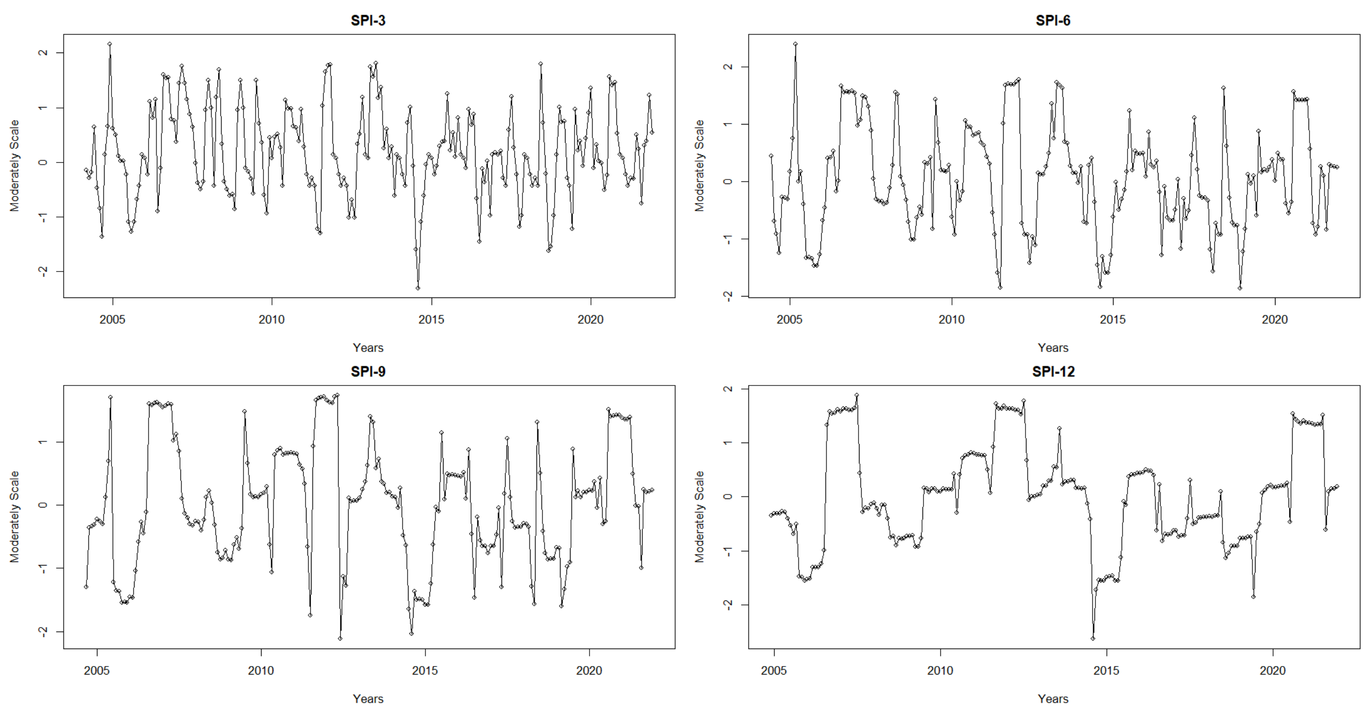
Fig. 6. (a) SPEI drought condition (b) SPI drought condition, at different times periods of Badin Station from 2004 to 2021

Chhor SPEI



(a)

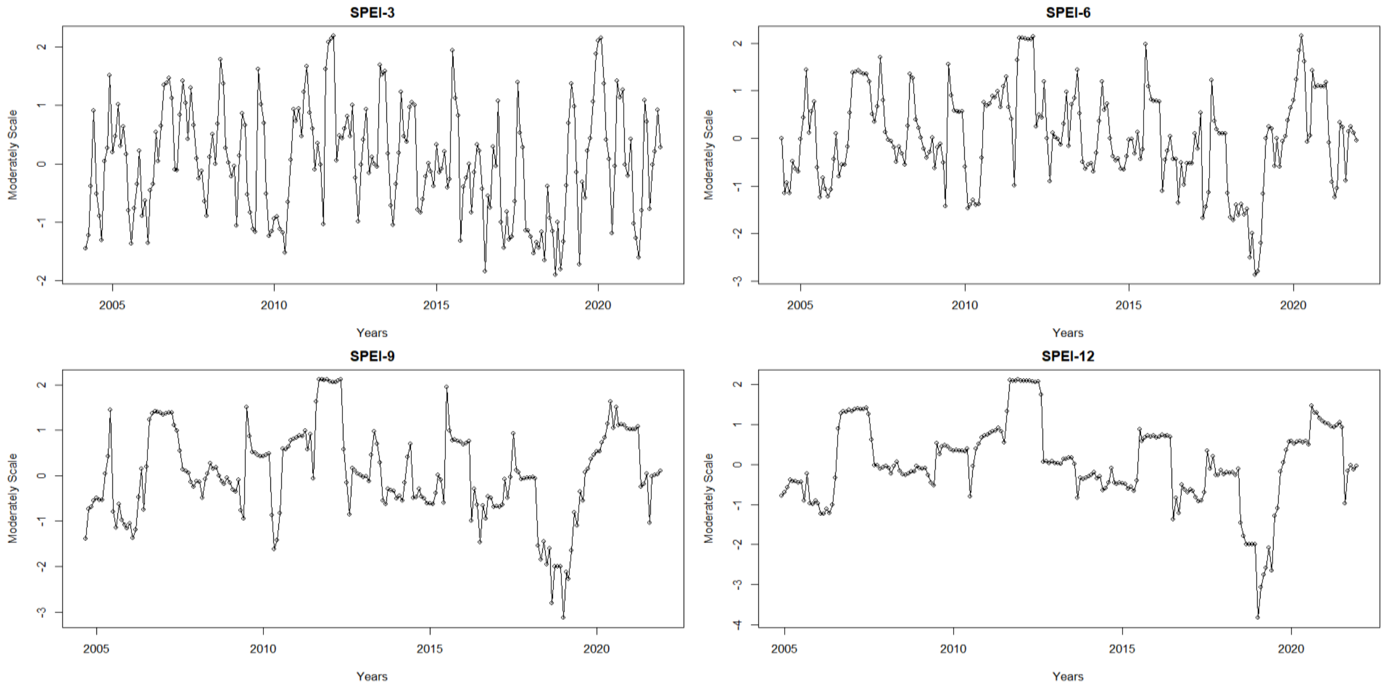
Chhor SPI



(b)

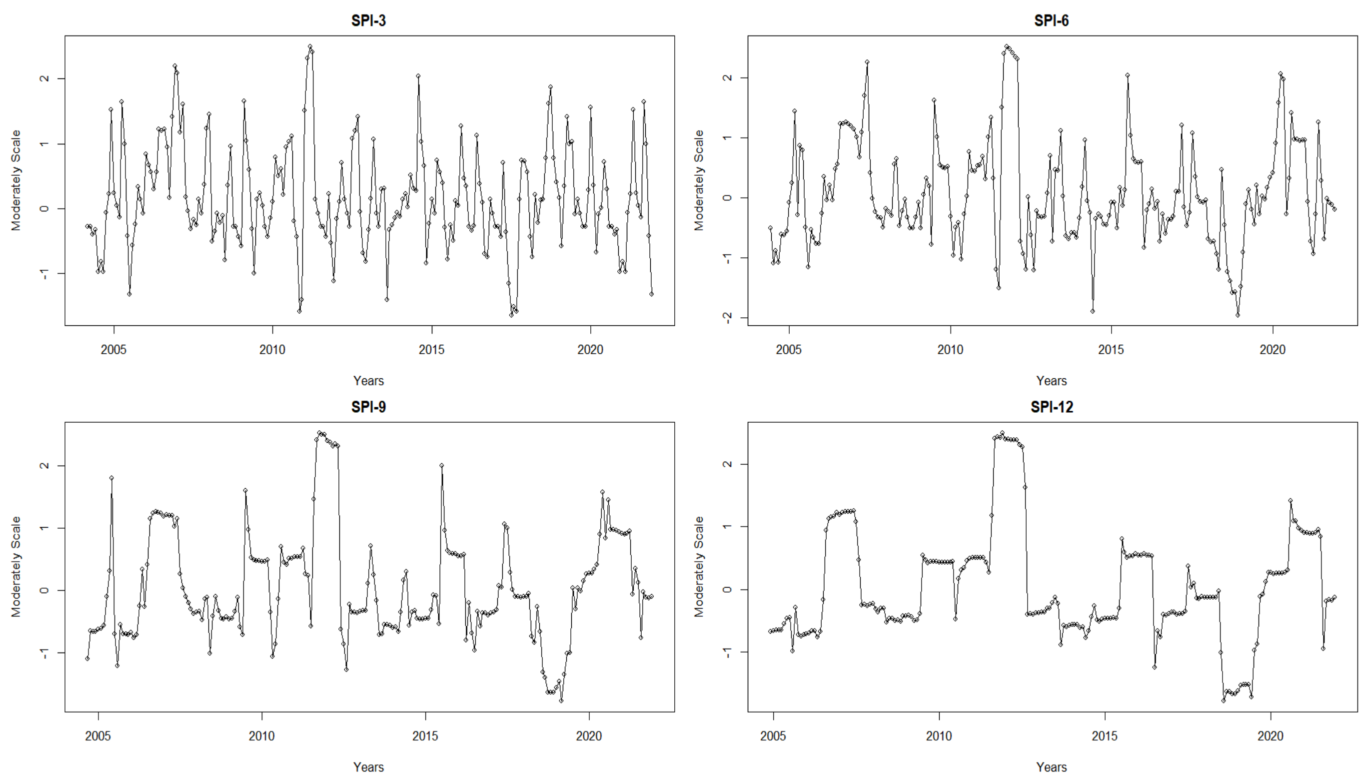
Fig. 7. (a) SPEI time series (b) SPI time series graph, at different time scales of Chhor Station from 2004 to 2021

Mithi SPEI



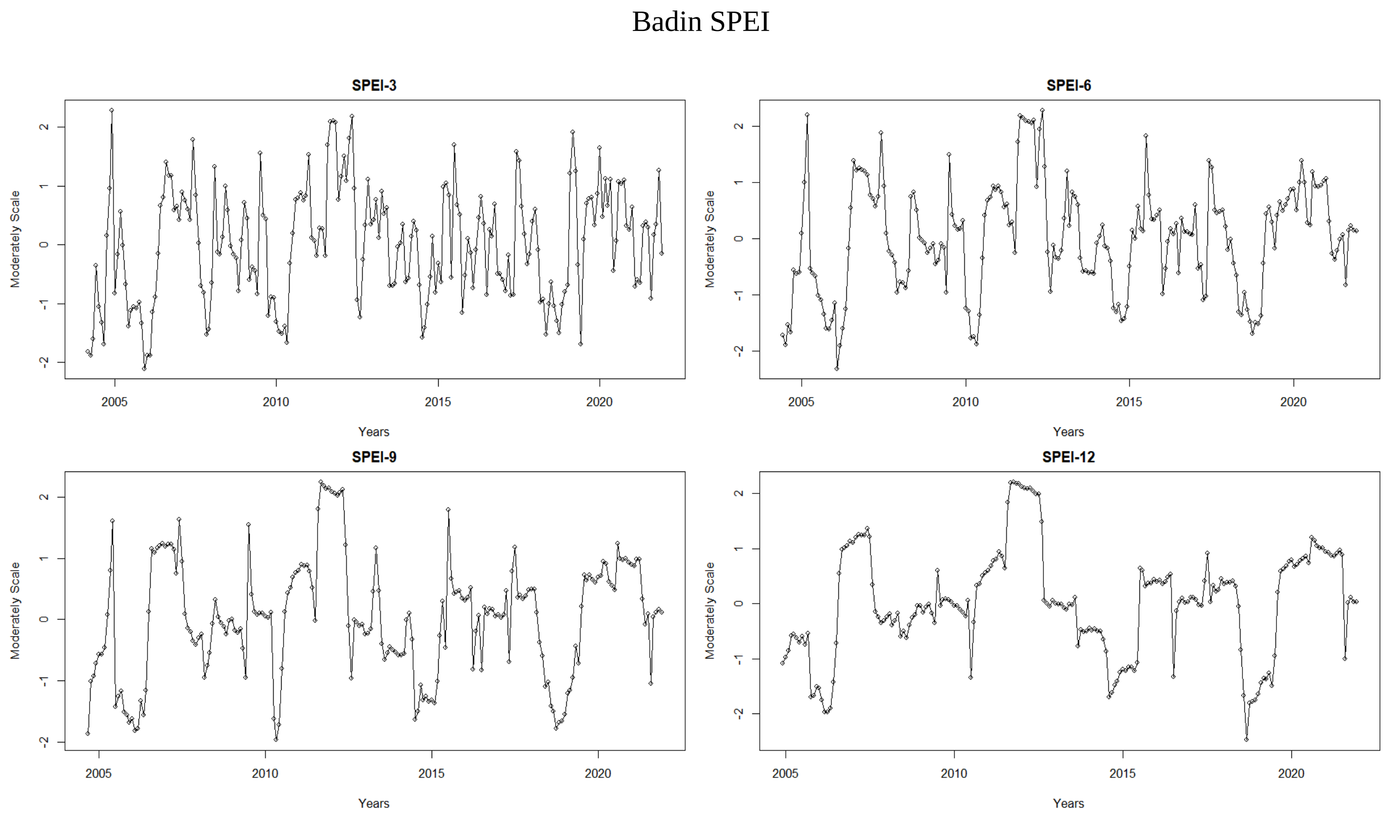
(a)

Mithi SPI

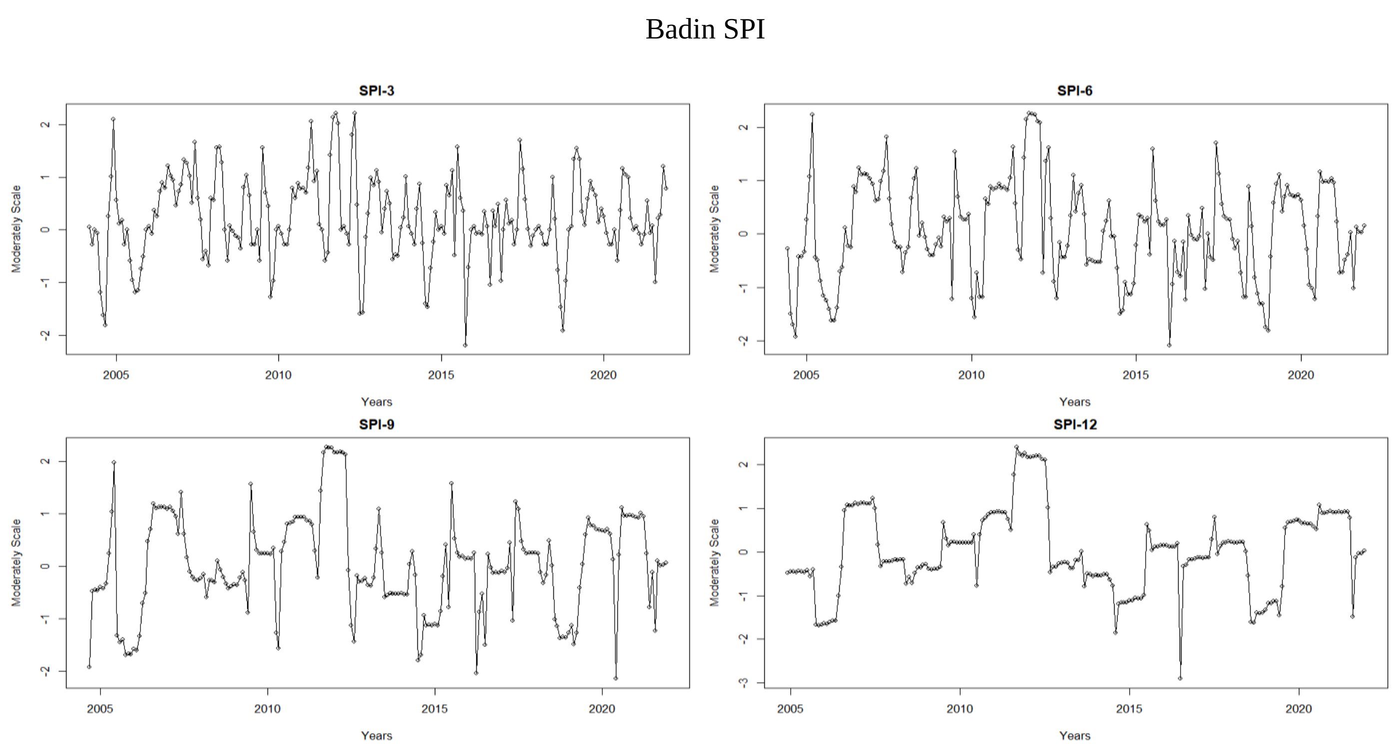


(b)

Fig. 8. (a) SPEI time series (b) SPI time series graph, at different time scales of Mithi Station from 2004 to 2021



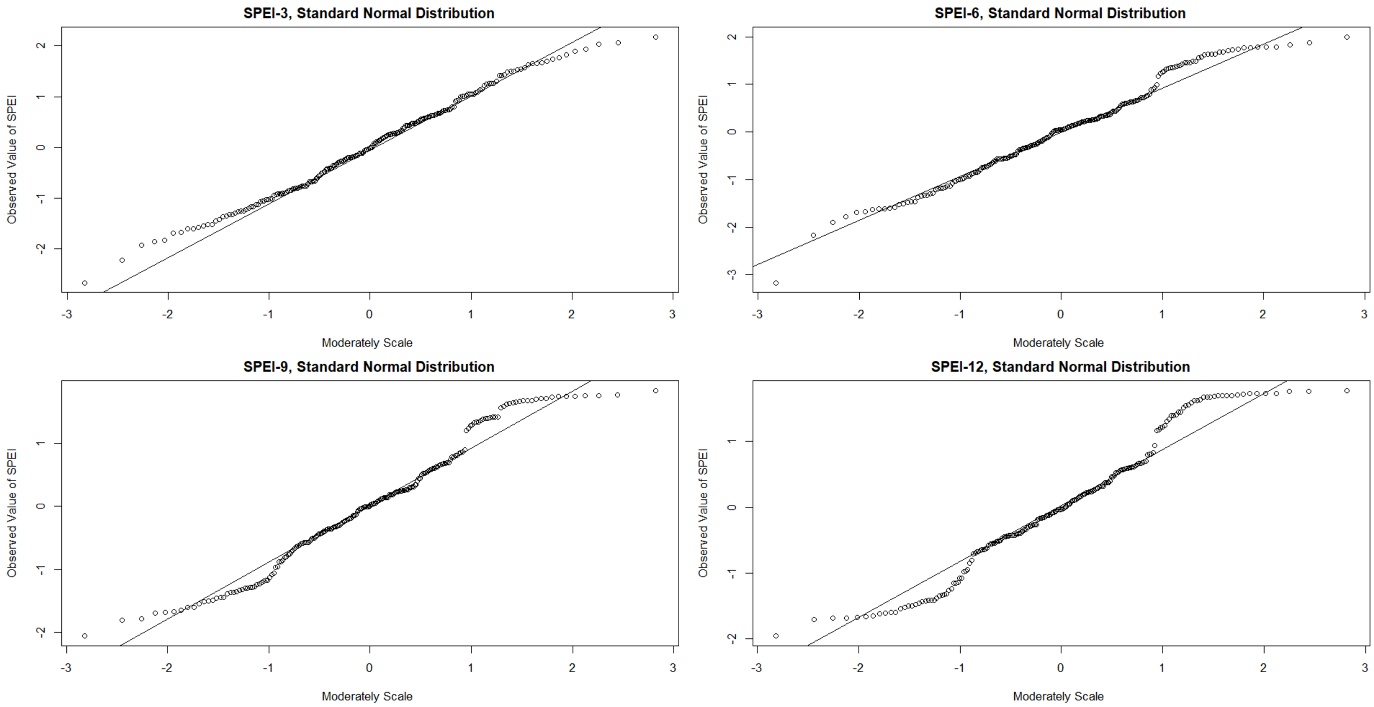
(a)



(b)

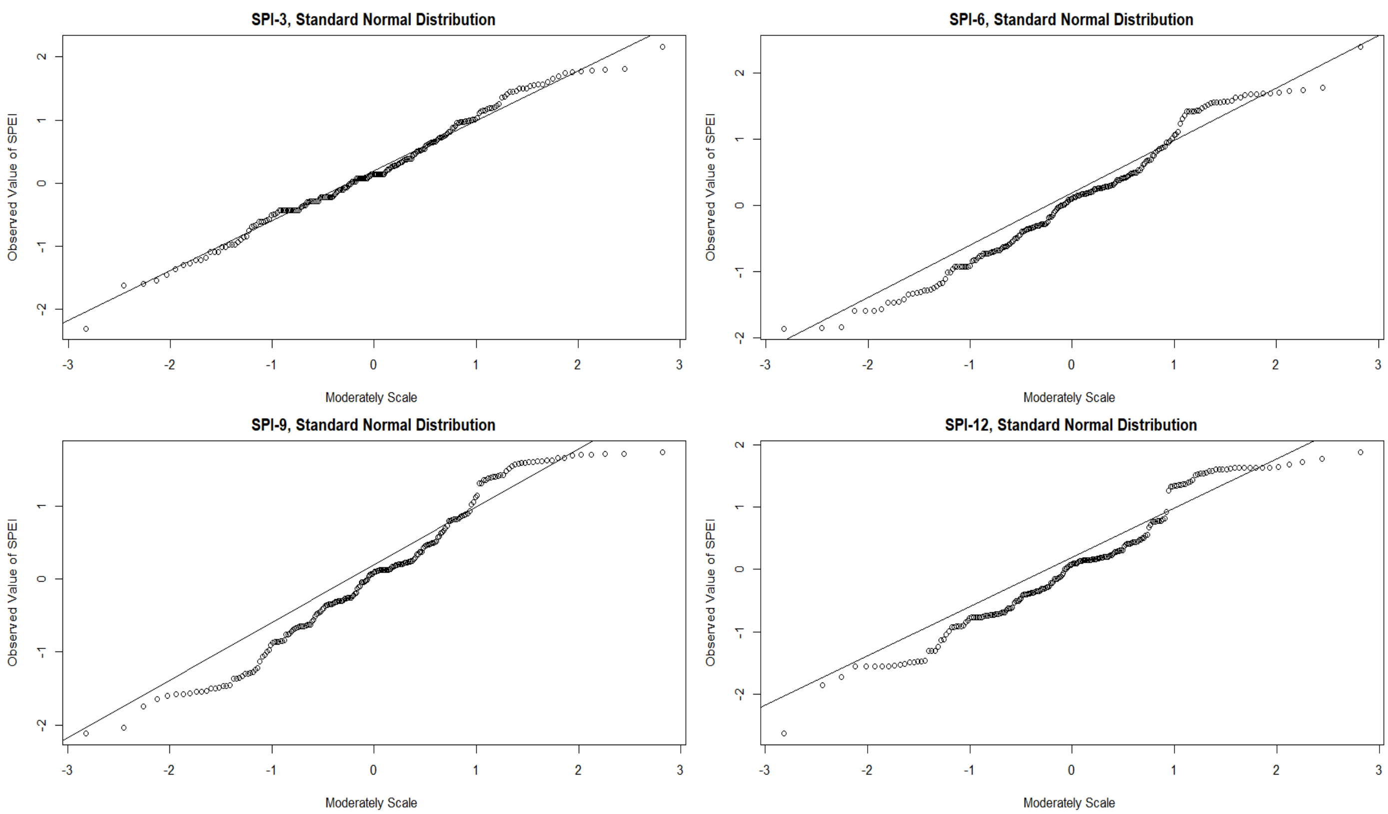
Fig. 9. (a) SPEI time series (b) SPI time series graph, at different time scales of Badin Station from 2004 to 2021

Chhor SPEI



(a)

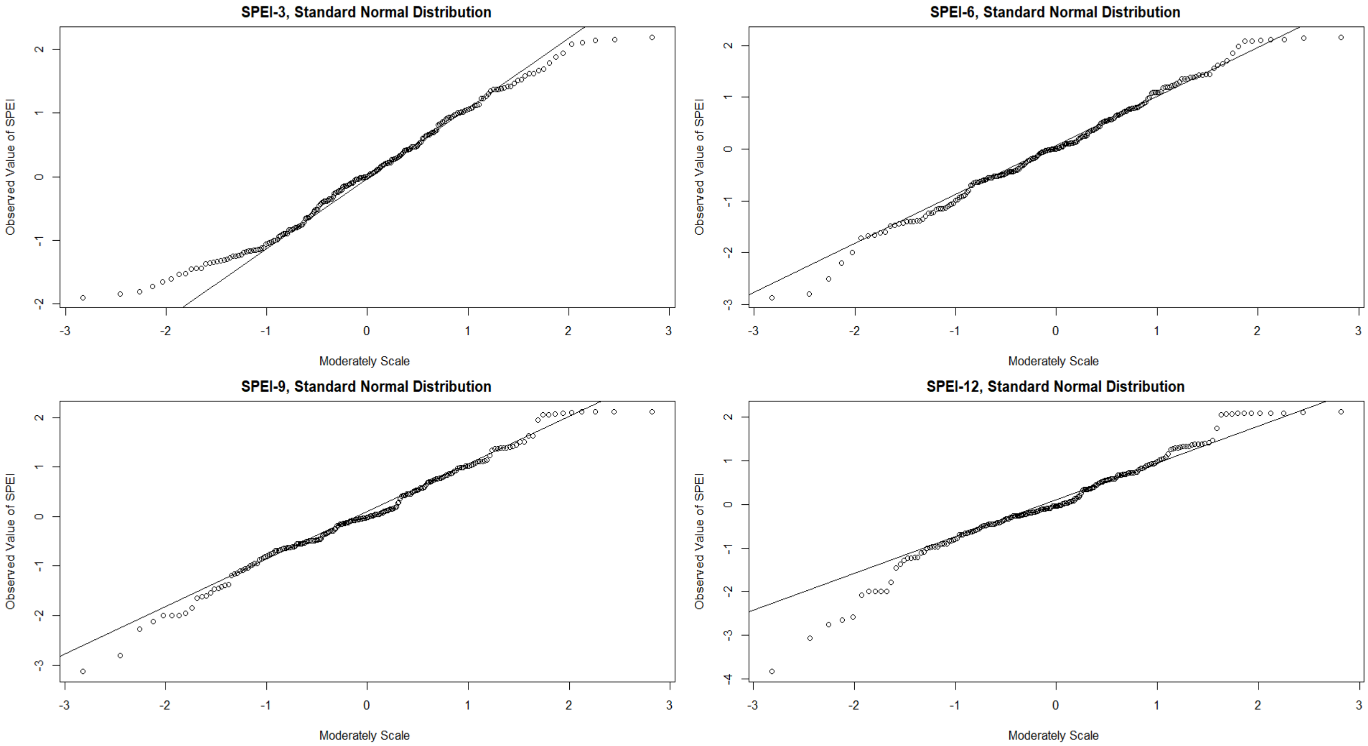
Chhor SPI



(b)

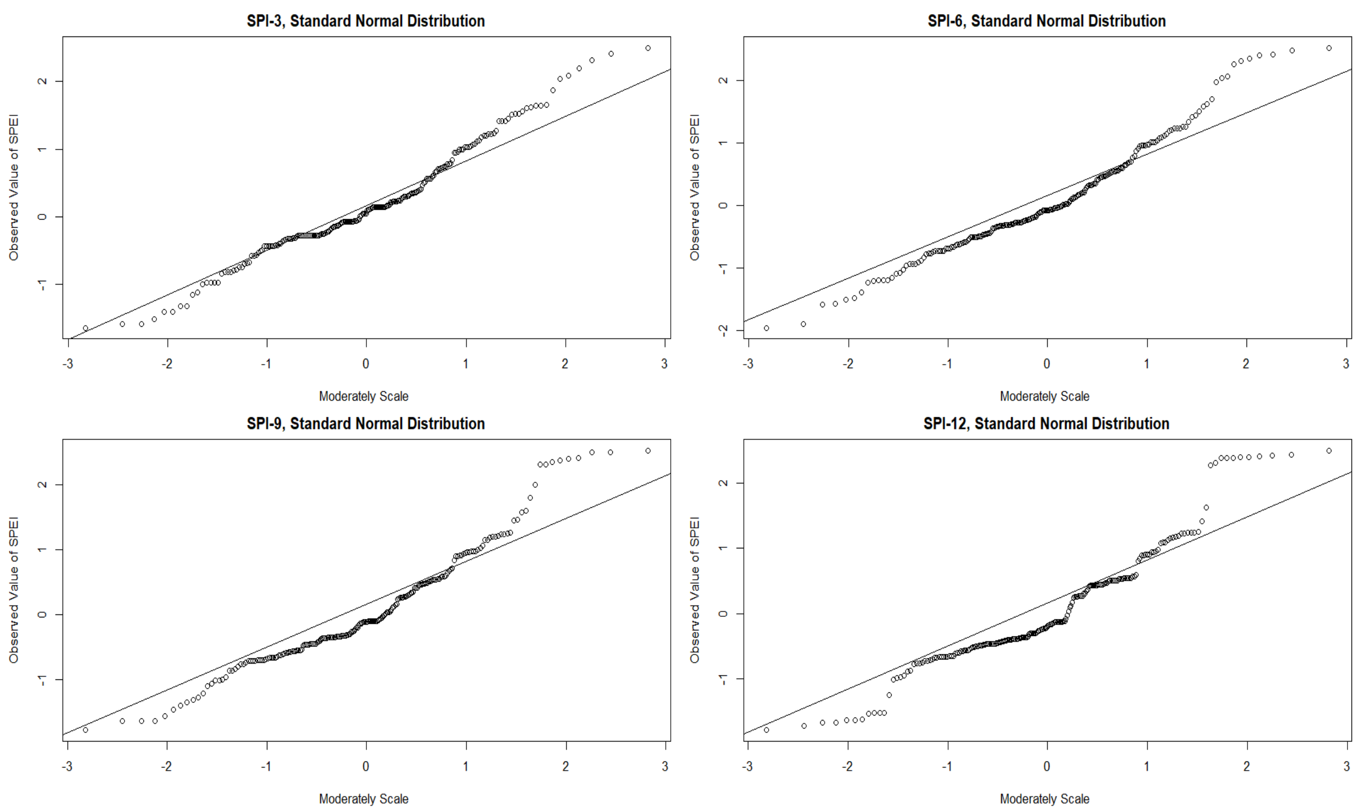
Fig. 10. (a) SPEI Normal Q-Q plot (b) SPI Normal Q-Q plot, at different time scales of Chhor Station from 2004 to 2021

Mithi SPEI



(a)

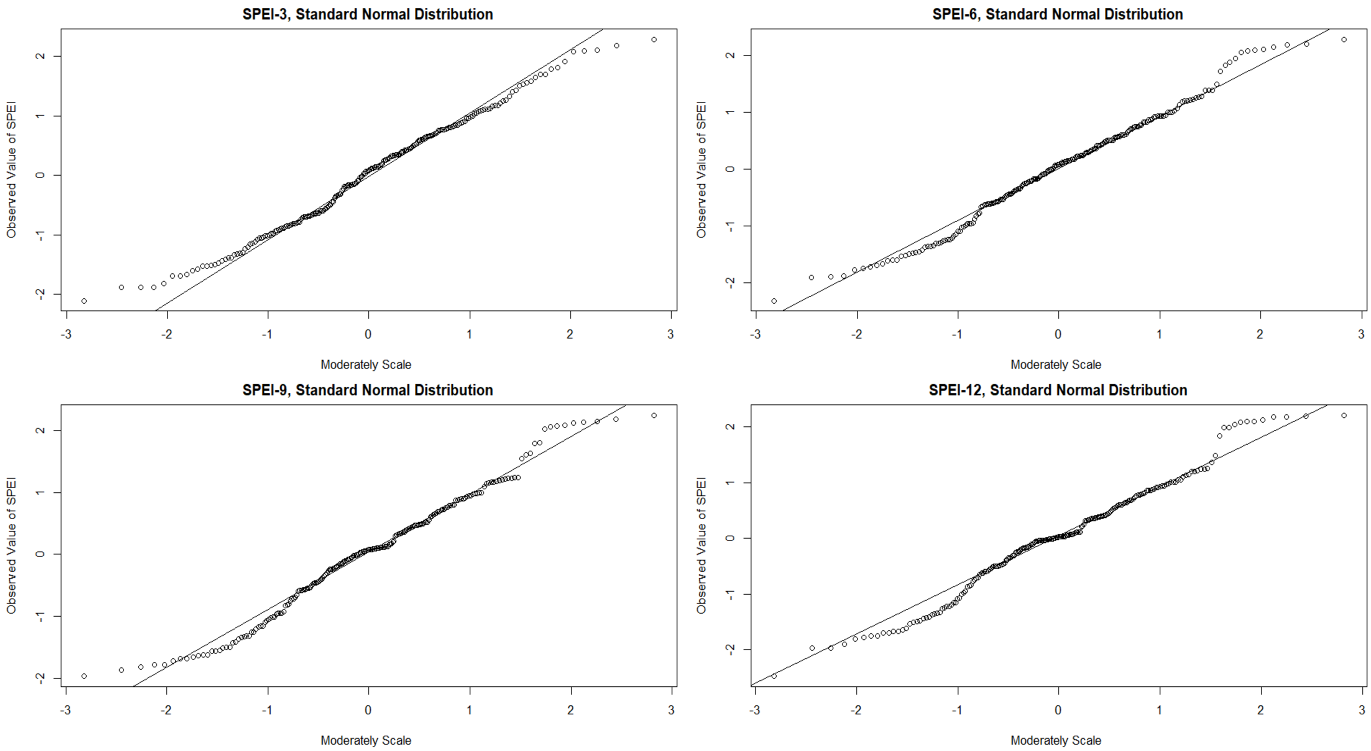
Mithi SPI



(b)

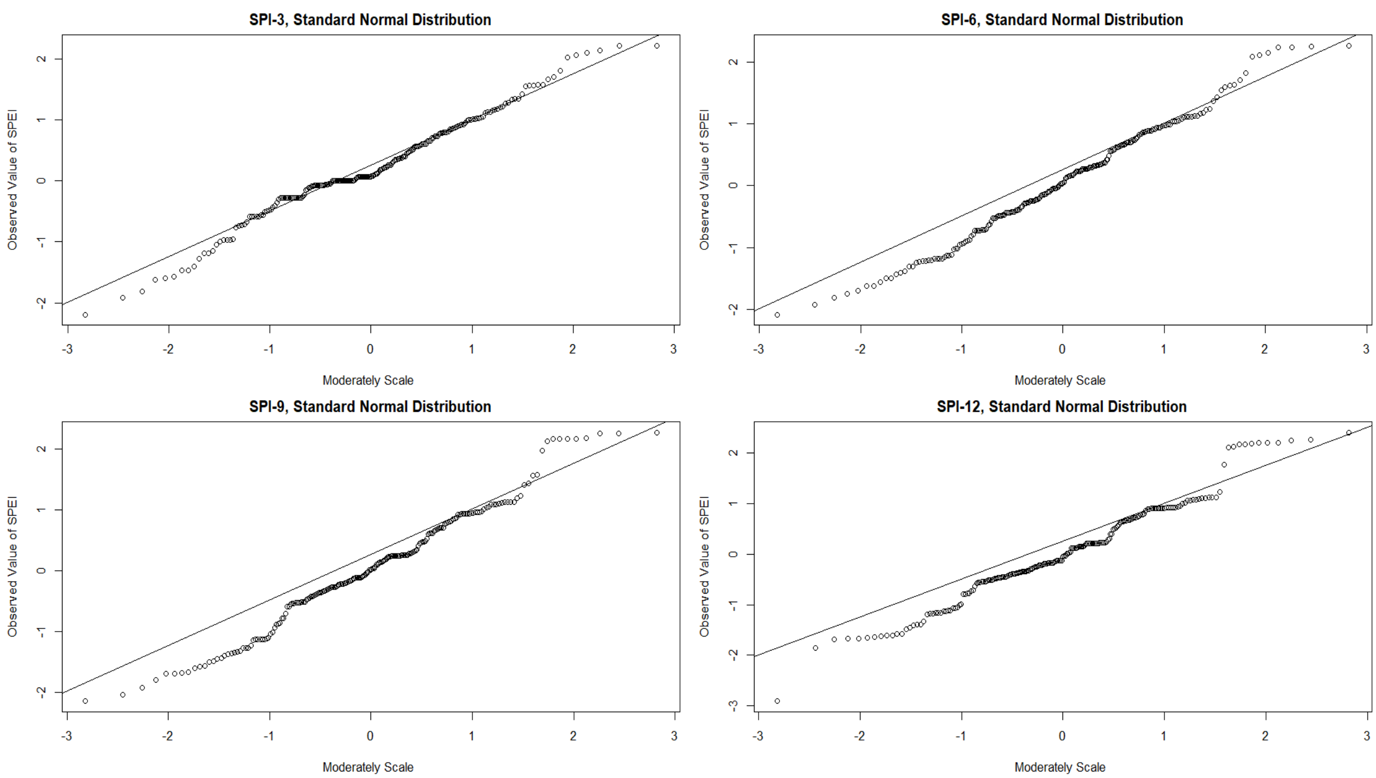
Fig. 11. (a) SPEI Normal Q-Q plot (b) SPI Normal Q-Q plot, at different time scales of Mithi Station from 2004 to 2021

Badin SPEI



(a)

Badin SPI



(b)

Fig. 12. (a) SPEI Normal Q-Q plot (b) SPI Normal Q-Q plot, at different time scales of Badin Station from 2004 to 2021

Table 3

Month-by-month drought for Chhor Station

Chhor Station SPEI and SPI different Time Scale drought categories														
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	$\sum$
	Sev	1											1	2
SPEI-3	Mod	1	1	2	1	3	1		1	1	1		1	13
	Ext	1											1	2
	Sev								1					1
SPI-3	Mod							1	1	1	1			4
	Ext								1					1
	Sev			1			1							2
SPEI-6	Mod		1	1	1	1	1	1	1	1	2	2	1	13
	Ext			1			1							2
	Sever													0
SPI-6	Mod		1				1	1	1		1	1	1	7
	Ext													0
	Sev						1							1
SPEI-9	Mod	2	2		1	1	1		1	1	1	1	1	12
	Ext						1							1
	Sev						1		1					2
SPI-9	Mod	1	1	1		1	1	2	1		1	1	1	11
	Ext						1		1					2
	Sev													0
SPEI-12	Mod	0	1	1	1	1	1	1	2	2	1	1	1	13
	Ext													0
	Sev								1					1
SPI-12	Mod	1	1		1	1	1		1	1	1	1	2	11
	Ext								1					1
	$\sum$	7	8	7	5	8	13	6	15	7	9	7	10	102

Mod = Moderate, Ext = Extreme, Sev = sever, Jan= January, Feb = February, Mar = March, Apr =April, , Aug = August, Sep = September, Oct = October, Nov = November, Dec = December, $\sum$ = Sum

Table 4

Month-by-month drought for Mithi Station

Mithi Station SPEI and SPI different Time Scale drought categories														
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	∑
SPEI-3	Sev													
	Mod	1			1	2	1	1		1		1		8
	Ext													
SPI-3	Sev													
	Mod						1			1	1	1		4
	Ext													
SPEI-6	Sev	1								1		1	1	4
	Mod	1	1	1	1	1		1		1		1	1	9
	Ext	1								1		1	1	4
SPI-6	Sev													0
	Mod						1	1			1	1	1	5
	Ext													0
SPEI-9	Sev	1	1	1						1				4
	Mod	1	1	1	2	2		1	1	1				10
	Ext	1	1	1						1				4
SPI-9	Sev													0
	Mod	1		1							1	1	1	5
	Ext													0
SPEI-12	Sev	1	1	1	1	1	1							6
	Mod	1	1	1	1	1	1		1					7
	Ext	1	1	1	1	1	1							6
SPI-12	Sev							1						1
	Mod	1	1	1	1	1	1		1	1	1	1	1	11
	Ext													0
	∑	12	8	9	8	9	7	4	3	9	4	8	6	87

Mod = Moderate, Ext = Extreme, Sev = sever, Jan= January, Feb = February, Mar = March, Apr =April, , Aug = August, Sep = September, Oct = October, Nov = November, Dec = December, ∑ = Sum

Table 5

Month-by-month drought for Badin Station

Badin Station SPEI and SPI different Time Scale drought categories														
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	∑
	Sev												1	1
SPEI-3	Mod	1	1	2	1	3	1	1		1	1	1	1	14
	Ext												1	1
	Sev										1			1
SPI-3	Mod							1	2	1	2			6
	Ext										1			1
	Sev		1											1
SPEI-6	Mod		1	2	2	1	1	1	1	1	2	1	1	14
	Ext		1											1
	Sev	1												1
SPI-6	Mod	2	1						1	1	1	1	1	8
	Ext	1												1
	Sev													0
SPEI-9	Mod	2	1	1	1	2	1	1	1	2	2	2	2	18
	Ext													0
	Sev				1		1							2
SPI-9	Mod	1	1		1	1	1	2	1	1	1	1	1	12
	Ext				1		1							2
	Sev									1				1
SPEI-12	Mod	2	1	1	1	1			2	2	2	2	2	16
	Ext									1				1
	Sev							1						1
SPI-12	Mod	1	1	1	1	1		1	2	1	1	1	1	12
	Ext							1						1
	∑	11	9	7	9	9	6	9	10	12	14	9	11	116

Mod = Moderate, Ext = Extreme, Sev = sever, Jan= January, Feb = February, Mar = March, Apr =April, , Aug = August, Sep = September, Oct = October, Nov = November, Dec = December, ∑ = Sum

Tables 3-5 summarize the main characteristics of the drought for the selected station for each month from 2004 to 2021. The last column on the right side of each table and the end of the last row of each table display the total number of droughts.

Table 6

The correlation coefficient for the Chhor station on various time scales

Monthly wise	Coefficient of Correlation r	Confidence interval at 90%		Confidence interval at 95%	
SPEI-3 & SPI-3	0.828	0.789	0.861	0.781	0.866
SPEI-6 & SPI-6	0.868	0.837	0.894	0.831	0.898
SPEI-9 & SPI-9	0.921	0.902	0.937	0.898	0.939
SPEI-12& SPI-12	0.961	0.951	0.969	0.949	0.971

Table 7

The correlation coefficient for the Mithi station on various time scales

Monthly wise	Coefficient of Correlation r	Confidence interval at 90%		Confidence interval at 95%	
SPEI-3 and SPI-3	-0.026	-0.138	0.086	-0.159	0.108
SPEI-6 and SPI-6	0.861	0.828	0.888	0.822	0.892
SPEI-9 and SPI-9	0.925	0.906	0.940	0.903	0.943
SPEI-12 and SPI-12	0.942	0.927	0.953	0.924	0.956

Table 8

The correlation coefficient for the Badin station on various time scales

Monthly wise	Coefficient of Correlation r	Confidence interval at 90%		Confidence interval at 95%	
SPEI-3 and SPI-3	0.735	0.679	0.783	0.667	0.791
SPEI-6 and SPI-6	0.868	0.785	0.858	0.777	0.864
SPEI-9 and SPI-9	0.904	0.881	0.923	0.875	0.926
SPEI-12 and SPI-12	0.965	0.956	0.972	0.954	0.973

Tables 6–8 present descriptions of the correlation coefficients between SPEI and SPI with 90% and 95% confidence intervals for the stations in Chhor, Mithi, and Badin. The SPI and SPEI have a statistically significant positive correlation, as shown by the stations' R-values, which are all greater than 0.5.

4. Conclusion, Limitation and Future Recommendation

This study investigated on the efficiency of SPI and SPEI to identify droughts. SPI is a measure based on rainfall, but SPEI includes temperature as well. The various timescales indicated different types of droughts, and both indices were able to separate them as well as their temporal variability. During the study's 2004–2021, time frame, SPEI saw more severe and moderate droughts than SPI. The SPEI experienced droughts that were larger and more prolonged, although not being immediately apparent. This is brought on by temperature-related increase in potential evapotranspiration, which raise the evaporation water needs and cause a water shortage. When temperature and precipitation were considered, SPEI found more severe droughts than SPI. According to research by SPI and SPEI, precipitation and temperature are the main factors that contribute to drought. The findings indicate that SPEI and SPI exhibit lesser correlation across shorter time scales, indicating that the indices are able to identify incongruous frequencies. Stronger correlations are found over longer time periods, are when it is most important to take evapotranspiration into consideration.

Unfortunately, Southern Pakistan, the area of this study's focus for the Tharparkar region of Pakistan, only has one meteorological station, which is located at Mithi and was installed in 2004. The oldest station in Pakistan is located in Badin. However, we chose the period for comparison of the results by which we obtained data from the stations, so this is a limitation of our study.

In terms of drought, the link between climate change and the water resources now available in Tharparkar is really pressing. Therefore, avoiding the expected drought conditions in the Tharparkar region is crucial and should be considered as an important future study. Unfortunately, our study was limited by the fact that there is only one weather station in Tharparkar, Province Sindh, Pakistan, and that station is in Mithi. This research can then be extended in the future with new models and more data.

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5. References

[1] J. J. Bruwer, "Drought policy in the Republic of South Africa", Drought Assessment, Management, and Planning: Theory and Case Studies, Springer, Boston, MA, pp. 199-212, 1993.

[2] D. A. Wilhite, "A methodology for drought preparedness", Natural Hazards, 13(3), 229-252, 1996.

[3] A. K. Mishra, and V. P. Singh, "A review of drought concepts", Journal of Hydrology 391, no. 1–2, 202–16, 2010. doi:10.1016/j.jhydrol.2010.07.012.

[4] M. Pedro-Monzonís, A. Solera, J. Ferrer, T. Estrela, and J. Paredes-Arquiola, "A review of water scarcity and drought indexes in water resources planning and management", Journal of Hydrology, 527, 482-493, 2015.

[5] W. Wang, M. W. Ertsen, M. D. Svoboda, and M. Hafeez, "Propagation of drought: from meteorological drought to agricultural and hydrological drought", Advances in Meteorology, 2016.

[6] A. Zargar, R. Sadiq, B. Naser, and F. I. Khan, "A review of drought indices", Environmental Reviews, 19(NA), 333-349, 2011.

[7] J. Zeng, J. Li, X. Lu, Z. Wei, W. Shangguan, S. Zhang, and S. Zhang, "Assessment of global meteorological, hydrological and agricultural drought under future warming based on CMIP6", Atmospheric and Oceanic Science Letters, 15(1), 100143, 2022.

[8] T. B. McKee, N.J. Doesken, and J. Kleist, "The relationship of drought frequency and duration to time scales", Eighth Conference on Applied Climatology, 17-22 January 1993, Anaheim, California, 22:1571–92. Anaheim, CA, USA, 2002.

[9] V. Serrano, M. Sergio, S. Beguería, and I. Juan, L. Moreno, "A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index", Journal of Climate 23, no. 7, 1696–1718, 2010. doi:10.1175/2009JCLI2909.1.

[10] J. H. Stagge, L. M. Tallaksen, L. Gudmundsson, A. F. Van Loon, and K. Stahl, "Candidate distributions for climatological drought indices (SPI and SPEI)", International Journal of Climatology, 35(13), 4027-4040, 2015.

[11] T. Homdee, K. Pongput, and S. Kanae, «A comparative performance analysis of three standardized climatic drought indices in the Chi River basin, Thailand", Agriculture and Natural Resources, 50(3), 211-219, 2016.

[12 D. Harisuseno, "Meteorological drought and its relationship with Southern Oscillation Index (SOI)", Civil engineering journal, 6(10), 1864-1875, 2020.

[13] Z. M. M. Sein, X. Zhi, F. K. Ogou, I. K. Nooni, K. T. Lim Kam Sian, and G. T. Gnitou, "Spatio-temporal analysis of drought variability in myanmar based on the standardized precipitation evapotranspiration index (SPEI) and its impact on crop production", Agronomy, 11(9), 1691, 2021.

[14] T. B. McKee, N. J. Doesken, and J. Kleist, "The relationship of drought frequency and duration to time scales", Eighth Conference on Applied Climatology, 17-22 January 1993, Anaheim, California, 22:1571–92. Anaheim, CA, USA, 2002.

[15] A. T. Ogunrinde, D. A. Olasehinde, and Y. Olotu, "Assessing the sensitivity of standardized precipitation evapotranspiration index to three potential evapotranspiration models in Nigeria", Scientific African, 8, e00431, 2020.

[16] D. Himayoun, and T. Roshni, "Spatio-temporal variation of drought characteristics, water resource availability and the relation of drought with large scale climate indices: a case study of Jhelum Basin, India", Quaternary International

525, 140–50, 2019. doi:10.1016/j.quaint.2019.07.018.

[17] A. Mokhtar, M. Jalali, H. He, N. Al-Ansari, A. Elbeltagi, K. Alsafadi, and J. Rodrigo-Comino, “Estimation of SPEI meteorological drought using machine learning algorithms. IEEE Access, 9, 65503-65523, 2021.

[18] A. Ghozat, A. Sharafati, and S. A. Hosseini, “Satellite-based monitoring of meteorological drought over different regions of Iran: Application of the CHIRPS precipitation product”, Environmental Science and Pollution Research, 29(24), 36115-36132, 2022.

[19] U. Kumar, S. Singh, J. K. Bisht, and L. Kant, “Use of meteorological data for identification of agricultural drought in Kumaon region of Uttarakhand”, Journal of Earth System Science, 130(3), 1-13, 2021.

[20] R. Niaz, M. M. Almazah, F. S. Al-Duais, N. Iqbal, D. M. Khan, and I. Hussain, “Spatiotemporal analysis of meteorological drought variability in a homogeneous region using standardized drought indices”, Geomatics, Natural Hazards and Risk, 13(1), 1457-1481, 2022.

[21] J. W. Lee, E. M. Hong, J. U. Kim, W. J. Jang, C. G. Jung, and S. J. Kim, “Evaluation of agricultural drought in South Korea using socio-economic drought information”, International Journal of Disaster Risk Reduction, 74, 102936, 2022.

[22] A. K. Mishra, and V. P. Singh, “A review of drought concepts”, Journal of Hydrology 391, no. 1–2, 202–16, 2010. doi:10.1016/j.jhydrol.2010.07.012.

[23] Z. M. M. Sein, X. Zhi, F. K. Ogou, I. K. Nooni, K. T. Lim Kam Sian, and G. T. Gnitou, “Spatio-temporal analysis of drought variability in myanmar based on the standardized precipitation evapotranspiration index (SPEI) and its impact on crop production”, Agronomy, 11(9), 1691, 2021.

[24] L. Shahzad, A. Yasin, “Analyzing resilience and food insecurity of drought prone communities of tharparkar desert”, Available online: https://www.researchsquare.com/article/rs-472894/v1 (accessed on 21 September 2021).

[25] M. H. Memon, N. Aamir, N. Ahmed, “Climate change and drought: impact of food insecurity on gender based vulnerability in district Tharparkar”, Pak. Dev. Rev. 57, 307–321, 2018.

[26] [Online] (Accessed on 21 September 2021) Pakistan Meteorological Department. PMD. Karachi. 1947. https://www.pmd.gov.pk/en/

[27] [Online] (Accessed on 12-December-2022) https://en.wikipedia.org/wiki/List_of_districts in_Sindh#/media/File:Pakistan_Sindh_districts _map.svg

[28] I. P. D. J. Harris, P. D. Jones, T. J. Osborn, and D. H. Lister, “Updated high-resolution grids of monthly climatic observations–the CRU TS3. 10 Dataset”, International journal of climatology, 34(3), 623-642, 2010.

[29] G. H. Hargreaves, and R. G. Allen, “History and evaluation of Hargreaves evapotranspiration equation”, Journal of irrigation and drainage engineering, 129(1), 53-63, 2003.

[30] S. Tirivarombo, D. Osupile, and P. Eliasson, “Drought monitoring and analysis: standardised precipitation evapotranspiration index (SPEI) and standardised precipitation index (SPI)”, Physics and Chemistry of the Earth, Parts A/B/C, 106, 1-10, 2018.

[31] H. Vangelis, D. Tigkas, and G. Tsakiris, “The effect of PET method on reconnaissance drought index (RDI) calculation”, Journal of Arid Environments, 88, 130-140, 2013.

[32] S. Beguería, S. M. Vicente-Serrano, F. Reig, and B. Latorre, “Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring”, International journal of climatology, 34(10), 3001-3023, 2014.

[33] B. Bera, P. K. Shit, N. Sengupta, S. Saha, and S. Bhattacharjee, “Trends and variability of drought in the extended part of Chhota Nagpur plateau (Singbhum Protocontinent), India applying SPI and SPEI indices”, Environmental Challenges, 5, 100310, 2021.

[34] L. Labudová, M. Labuda, and J. Takáč, “Comparison of SPI and SPEI applicability for drought impact assessment on crop production in the Danubian Lowland and the East Slovakian Lowland”, Theoretical and applied climatology, 128(1), 491-506, 2017.

[35] T. B. McKee, N.J. Doesken, and J. Kleist, “The relationship of drought frequency and duration to time scales”, Eighth Conference on Applied Climatology, 17-22 January 1993, Anaheim, California, 22:1571–92. Anaheim, CA, USA, 2002.

[36] A. R. Zarei, M. R. Mahmoudi, and A. Shabani, “Using the fuzzy clustering and principle component analysis for assessing the impact of potential evapotranspiration calculation method on the modified RDI index”, Water Resources Management, 35(11), 3679-3702, 2021.

[37] P. Kumar, S. F. Shah, M. A. Uqaili, L. Kumar, and R. F. Zafar, "Forecasting of drought: a case study of water-stressed region of Pakistan", Atmosphere 12, no. 10, 1248, 2021.

