Drought Analysis Using the Standardized Precipitation Evapotranspiration Index (SPEI) at Different Time Scales in an Arid Region

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Abstract-Drought causes insufficient soil moisture and crop water balance damage. One of the most commonly used indicators in drought monitoring is the Standardized Precipitation Evapotranspiration Index (SPEI). In this study, the performance of the SPEI at 1-, 3-, 6-, 9-, and 12-month timescales was compared and analyzed from temporal and spatial variations at 12 meteorological stations in the Barmer arid region from 1979 to 2013. To determine the significance of drought characteristic trends, the modified Mann-Kendall (M-K) test is used. The results revealed that as the timescale increased, the temporal variations in the SPEI became more consistent. The M-K test revealed that the SPEI showed decreasing trends at 1 and 3 months, but increasing trends at 6, 9, and 12 months. The findings of this study are instructive and practical for drought assessment, risk management, and decision-making.

Keywords-drought; SPEI; Mann-Kendall; arid region; meteorology

I. INTRODUCTION

Drought has had devastating effects on the ecology in a global scale during the recent decades. Severe drought, particularly in arid and semiarid areas, poses a long-term danger to human livelihoods. Climate change, on the other hand, will become more common in the twenty-first century [1-2]. The severity of drought is determined by its duration, frequency, intensity, and the geographical distribution of rainfall, as well as the water requirements of humans, animals, crops, and the vegetative cover of the region. Drought features are difficult to define and analyze because of their complexity and intensity [3-5]. Drought is divided into four categories based on its impact: meteorological drought, agricultural drought, hydrological drought, and socioeconomic drought [6-8]. Drought can reduce crop production and threaten the socioeconomic sustainability of communities [9]. Furthermore, dry weather during a drought can cause forest fires, which are another major environmental issue [10]. Since India is an agrarian society and agriculture engages 68% of the population, analysis and forecasting of agricultural drought are more important than for other types of drought. The arid region of western India is threatened by severe droughts due to water scarcity, irregular rainfall, and severe climatic conditions [11]. Drought cannot be avoided, but it can be mitigated with forethought and planning. As a result, many studies have been conducted to provide an objective and quantitative assessment of drought severity. Drought indices are widely used to measure drought impacts [12]. They are proxies based on climate data that are assumed to adequately describe the degree of drought hazard. Over 150 drought indices have been developed and are widely used in drought assessment, monitoring, and forecasting [13]. The Standardized Precipitation Index (SPI) developed in [14] is a precipitation-based drought index that, unlike other indices, requires precipitation as an input. It is widely used due to its data minimalism. The SPEI [13], is a modified form of SPI that involves monthly climatic water balance (difference between precipitation and potential evapotranspiration) as input parameters.

The objective of this paper is to show the spatial and temporal variation of meteorological drought using SPEI at different time scales over the Barmer district from 1979 to 2013. The modified M-K test is used to determine the significance of drought characteristic trends.

II. MATERIALS AND METHODS

A. The Study Area

The study area is the Barmer district in western Rajasthan, India. This district covers an area of 28,387km^2. The district of Barmer is the third largest in Rajasthan and the fifth largest in India, and is known for its vegetation. It lies between 24°58' and 26°32'N and 70°05' and 72°52'E. The district is located in the western part of the state and is part of the Thar Desert. Because of the arid Thar Desert and the sandy soil, temperature varies greatly throughout the year. During summer the temperature rises to 46-51°C, whereas, during winter, it drops to 0°C. The Barmer district is primarily a desert, with an annual rainfall of 277mm. The district experiences frequent drought. Because of rapid urbanization and poor management, the

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district is also dealing with recent flood problems. With agriculture and cattle rearing being the only means of livelihood of the residents, persistent drought forces them to migrate to other parts of the state.

B. Data Collection

Daily and monthly weather data for the Barmer district were downloaded from global weather data [15] for 12 weather stations in western Rajasthan from 1979 to 2013.

C. Standardized Recipitation Evapotranspiration Index

SPEI [13], is derived from SPI and calculates the monthly climatic water balance using precipitation and potential evapotranspiration (*PET*) as input parameters.

$$D = P - PET \quad (1)$$

where *D* is a simple aggregation of water shortages or excesses over time, *P* is precipitation in mm, and *PET* is the potential evapotranspiration in mm. *PET* is calculated using the Penman-Monteith (PM) equation [16].

TABLE I. SPEI DROUGHT CATEGORY CLASSIFICATION

Drought class	SPEI
No-drought	Greater than -0.5
Mild	-0.5 to -0.99
Moderate	-1 to -1.49
Severe	-1.50 to -1.99
Extreme	Less than -2

On various time scales, the *D* values can be summarized:

$$D_n^k = \sum_{i=0}^{k=1} (P_{n-i} - PET_{n-1}), \;\; n \geq k \quad (2)$$

where *k* is the monthly time scale and *n* is the number of calculations.

The difference in water balance is normalized as a log-logistic probability distribution to estimate the value of SPEI. The probability density function is expressed by:

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left[1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]^{-2} \quad (3)$$

where *α*, *β*, and *γ* are scale, shape, and origin parameters respectively. As a result, the probability distribution function can be written as:

$$F(x) = \left[1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1} \quad (4)$$

SPEI can be calculated using the standardized values of *F*(*x*) given in [17]:

$$\text{SPEI} = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} \quad (5)$$

where $W = \sqrt{-2lnP}$ for $P \leq 0.5$. *P* is the probability of exceeding a determined *D* value, *P* =1-*F*(*x*). If *P* > 0.5, then *P* is replaced by 1 - *P* and the sign of the resultant SPEI is reversed. The constants are $C_0 =$ 2.515517, C_1 = 0.802853, $C_2 =$ 0.010328, d_1 = 1.432788, d_2 = 0.189269, and $d_3 =$ 0.001308.

SPEI can be classified mainly in 5 classes [14], as shown in Table I.

D. The Modified Mann–Kendall Test

To auto-correlate data, the modified M-K trend test is used [17-19], which is recommended by the World Meteorological Organization for analysing meteorological and hydrological variables. Under the no trend null hypothesis, the original M-K statistic value *Z* has a standard normal distribution with a mean of 0 and a variance of 1. After introducing a correcting factor n_1^s in *Z*, the modified M-K statistic Z^* can be estimated by the following equations:

$$Z^* = \frac{Z}{\sqrt{n_1^s}} \quad (6)$$

$$n_1^s = \begin{cases} 1 + \frac{2}{n_1}\sum_{jj=1}^{n_1-1}(n_1 - 1)\, jj & for\ jj > 1 \\ 1 + 2\frac{r_1^{n_1+1} - n_1 r_1^2 + (n_1-1)\, r_1^2}{n_1(r_1-1)^2} & for\ jj = 1 \end{cases} \quad (7)$$

where r_{jj} is a sample's self-correlation coefficient, and *jj* is lag. Significant change is observed, if |Z| or |Z*| ≥ 1.96 and *β* (confidence) value 0.05. The significant change is increasing in magnitude, if Z or Z^* are positive, else the magnitude is decreasing if *Z* or Z^* is negative.

The SPEI drought indices at various time scales are used to assess drought in arid regions. The main advantage of using SPEI over the commonly used SPI in determining drought is that SPEI takes into account both precipitation and *PET*. As a result, in comparison to the SPI, the SPEI captures the primary impact of rising temperatures on water demand. The M-K statistical test is used to determine whether a set of data values is increasing or decreasing over time, and whether the trend in either direction is statistically significant.

III. Results and Discussion

Figure 1 shows the temporal variation in monthly precipitation from 1979 to 2013. The monthly variation shows that the wet period lasts from July to September, and the dry period from November to January. In Barmer, the monthly precipitation ranges from 0 to 330mm. The variation of monthly PET is shown in Figure 2. PET value varies from 80 to 270mm.

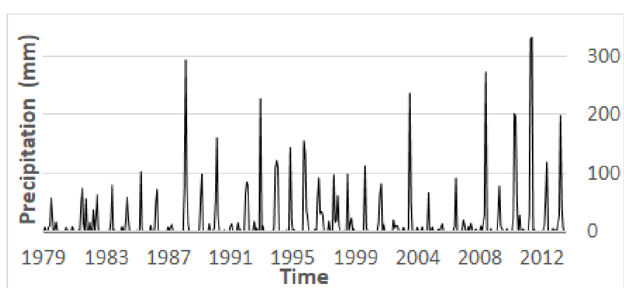

Fig. 1. Temporal variation of precipitation from 1979 to 2013.

A. Temporal Variation of SPEI

The monthly SPEI is calculated at 5 time scales (1, 3, 6, 9, and 12 months) from 1979 to 2013 (Figure 3). There are significant differences in the sensitivity of SPEI values at different time scales, with the smaller time scale indicating more obvious wet and dry changes. SPEI and SPI can produce better results with a time lag of more than one month and a minimum of 30 years of data. The intensity of the drought increased as the timescale increased. It has also been observed that a continuous mild drought leads to a severe drought. At 1 and 3 months, the SPEI value generally indicates meteorological drought, while at 6 and 9 months, it indicates agricultural drought. Droughts of severe intensity occurred in 1986, 1987, 2002, 2004, 2006, and 2009.

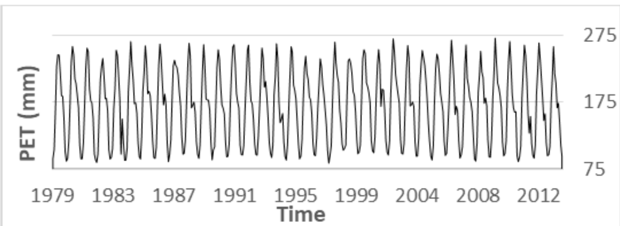

Fig. 2. Temporal variation of PET from 1979 to 2013.

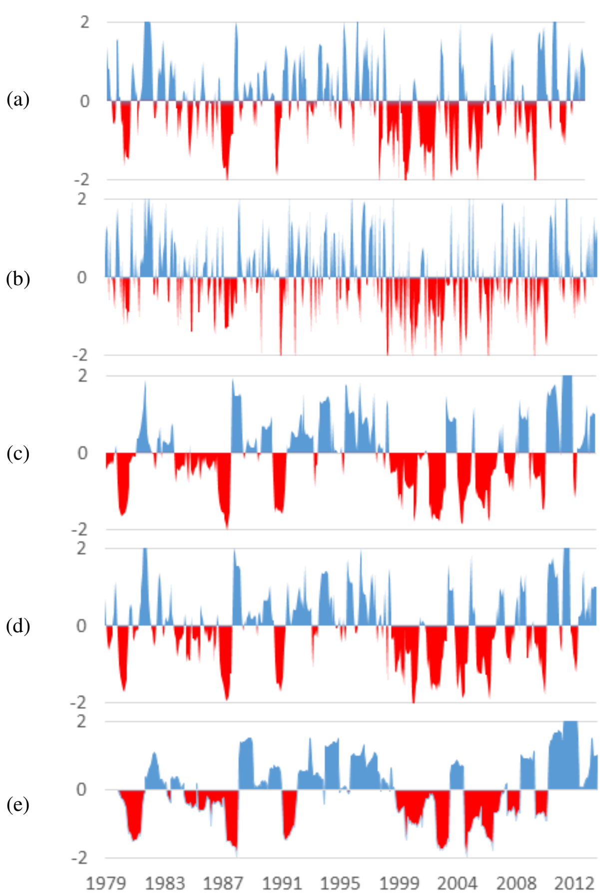

Fig. 3. SPEI at (a) 1-, (b) 3-, (c) 6-, (d) 9-, (e) 12-month time scale.

B. *Trends of Drought Characteristics*

The trends of SPEI at various time lags, obtained using the modified M-K method, and the Sen's slopes for the years 1979–2013 are shown in Table II. SPEI showed decreasing trends at 1 and 3 months, but increasing trends at 6, 9, and 12 month time scales. Only the SPEI at 12 months found significant trends, while the SPEI at other time scales showed insignificant trends. SPEI has a low Sen's slope (-0.01) at 1 month, indicating a clear downward trend, and zero at the other time scales.

TABLE II. M-K TEST FOR SPEI

Parameters	Z	Trends and significance	Sen's slope
SPEI1	-1.46	Insignificant decrease	-0.01
SPEI3	-1.1	Insignificant decrease	0
SPEI6	0.47	Insignificant increase	0
SPEI9	1.59	Insignificant increase	0
SPEI12	2.29	Significant increase	0

C. *Spatial Variations in SPEI*

For the spatial interpolation of drought characteristics, the Inverse Distance Weighted (IDW) interpolation method has been used. A severe drought was observed in 2002, followed by a period of good precipitation in 2003. As a result, we analyse the spatial distribution of drought in 2002 and 2003. The spatial distribution of the SPEI at 6-month time scale in Barmer for the drought (2002) and wet (2003) year is shown in Figure 4 during the wet months of the year (July to September). Throughout the region, high drought intensity was observed during the drought year and reflected in very poor vegetative conditions. During the wet year, wetness is observed in the starting of the monsoon and as monsoon passes, the degree of wetness decreases rapidly due to the high temperature variation and Thar Desert. As long as the SPEI values are high during the wet year of 2003, they improve plant conditions.

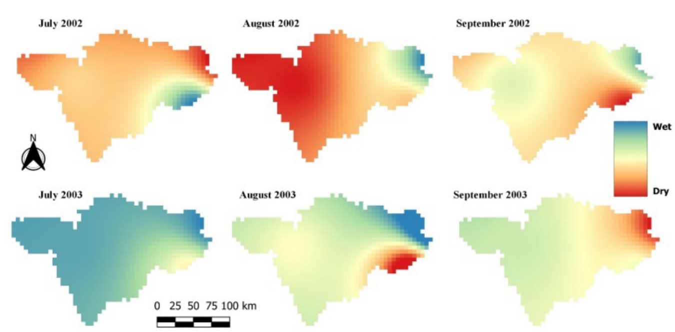

Fig. 4. Spatial distribution of drought indices for the drought year 2002 and the wet year 2003.

D. *Comparison of SPEI Drought with the Observed Drought*

The SPEI drought classification on a 12-month time scale is compared to the observed drought data from 1979 to 2005. The observed data are taken from the Central Arid Zone Research Institute, Jodhpur. The predicted by SPEI and observed number of drought years is shown in Figure 5. The drought year 1991 predicted by SPEI as moderate drought while observed showed it was severe drought year.

The SPEI drought index is one of most recently developed drought indices. Drought in the arid district of western Rajasthan is assessed using the SPEI drought indices at various time scales. Because the district has experienced frequent droughts due to climate change, it has become necessary to assess the droughts over time in order to reduce their impact. Crop yield loss occurs during drought years. Drought assessment helps in reducing the impact of agricultural droughts by effectively managing available water resources. Drought knowledge, both spatial and temporal, reduces risks, so the IDW interpolation method was used to show its spatial variation, which indicated that whenever there is a drought, the western region of Barmer is adversely affected.

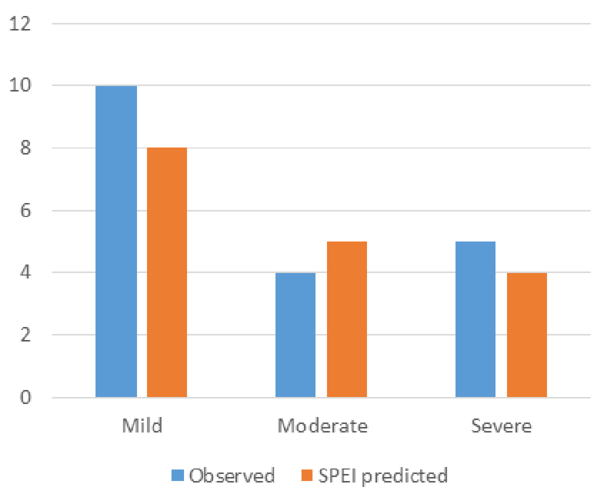

Fig. 5. Comparison of predicted and observed drought.

IV. CONCLUSION

In this paper, SPEI was used at different time scales to calculate the drought in Rajasthan's arid Barmer district, from 1979 to 2013. The index fluctuated the most on the shortest timescale. The fluctuations in the SPEI tended to be gradual over the longest timescale. As a result, the SPEI-reflected drought may be consistent over long timescales. Throughout the region, the spatial distribution showed a high level of drought intensity during the drought year. SPEI showed decreasing trends at 1 and 3 months, but increasing trends at 6, 9, and 12 month time scales. From 1979 to 2005, the annual SPEI showed 17 drought years out of the 19 totally observed drought years. SPEI can be used to estimate drought in arid regions at different time scales.

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