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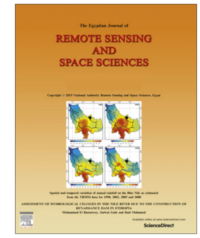

RESEARCH PAPER

Assessment of agricultural drought in Rajasthan (India) using remote sensing derived Vegetation Condition Index (VCI) and Standardized Precipitation Index (SPI)

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Rainfall Anomaly Index (RAI);
Yield Anomaly Index (YAI)

Abstract Owing to its severe effect on productivity of rain-fed crops and indirect effect on employment as well as per capita income, agricultural drought has become a prime concern worldwide. The occurrence of drought is mainly a climatic phenomenon which cannot be eliminated. However, its effects can be reduced if actual spatio-temporal information related to crop status is available to the decision makers. The present study attempts to assess the efficiency of remote sensing and GIS techniques for monitoring the spatio-temporal extent of agricultural drought. In the present study, NOAA-AVHRR NDVI data were used for monitoring agricultural drought through NDVI based Vegetation Condition Index. VCI was calculated for whole Rajasthan using the long term NDVI images which reveals the occurrence of drought related crop stress during the year 2002. The VCI values of normal (2003) and drought (2002) year were compared with meteorological based Standardized Precipitation Index (SPI), Rainfall Anomaly Index and Yield Anomaly Index and a good agreement was found among them. The correlation coefficient between VCI and yield of major rain-fed crops ($r > 0.75$) also supports the efficiency of this remote sensing derived index for assessing agricultural drought.

1. Introduction

Agricultural drought plays a major role in the economy of agrarian countries like India where more than 68% people are dependent upon agriculture. About 16% of India's total

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area is drought-prone and about 50 million people are annually affected by drought. The drought-prone areas of the country are mainly confined to western and peninsular India—mainly arid, semi-arid, and sub humid regions. The arid tract of western part of India is under threat of severe droughts due to paucity, abnormality of rainfall and severe climatic characteristics (Jain et al., 2010). In the year 2002–2003, India has faced one of the worst and exceptional drought episodes in terms of magnitude, spacing, dispersion and duration (Patel et al., 2012; Dutta et al., 2013). The occurrence of drought makes the land incapable of cultivation throughout the year and this situation renders harsh and inhospitable environmental condition for human being, livestock population and biomass potential and plant species (Siddiqui, 2004). So, there is an urgent need to make an effort to monitor and mitigate drought disaster with reference to span of time (Rathore, 2004). A well designed mitigation and preparedness plan can help the decision makers to reduce the effect of drought. In this context, monitoring of onset, duration, intensity and extent of drought has become important for managing the adverse impact of drought.

Although meteorological information from ground stations has good accuracy and is popular worldwide, the distribution and density of meteorological stations is insufficient for the spatial information detection required (Brown et al., 2008; Unganai and Kogan, 1998). The spatial extent of drought cannot be properly identified unless there is a good distribution of meteorological stations throughout the area. Even then requirement of time and cost for data preparation and chances of error may hinder the procedures of drought mitigation. In this context, drought monitoring through satellite based information has been popularly accepted in recent years for its low cost, synoptic view, repetition of data acquisition and reliability. In addition, the Normalized Difference Vegetation Index (NDVI) and Vegetation Condition Index (VCI) have been accepted globally for identifying agricultural drought in different regions with varying ecological conditions (Nicholson and Farrar, 1994; Kogan, 1995; Seiler et al., 2000; Wang et al., 2001; Anyamba et al., 2001; Ji and Peters, 2003). Satellite based Normalized Difference Vegetation Index (NDVI) is a useful tool for measuring and monitoring of environmental conditions such as crop condition simulation, yield estimation, land degradation, dryland studies etc. (Aboelghar et al., 2010; Kundu and Dutta, 2011; Barati et al., 2011; Mohamed et al., 2013; Kundu et al., 2014a, 2014b; Mondal et al., 2014). Unlike the meteorological based drought estimation, VCI provides satellite based near real time data with comparatively high spatial resolution (Quiring, 2009). It can estimate the status of vegetation according to the best and worst vegetation vigor over a particular period in different years that gives a more accurate result as compared to NDVI while monitoring drought at a regional scale (Bajgiran et al., 2008). The NOAA-AVHRR based VCI has been accepted widely for its suitability to assess several parameters of drought estimation, i.e., the emergence of drought, its duration, intensity and severity (Seiler et al., 1998; Domenikiotis et al., 2004; Quiring and Ganesh, 2010).

On the other hand, the Standardized Precipitation Index (SPI) is a very useful tool as well as an index to monitor meteorological drought which is exclusively based on precipitation data. According to McKee et al. (1993, 1995), SPI gives an easy and flexible way to monitor drought at a different scale (Table 2) ranging from near normal (−0.99) to extreme drought condition (< −2.0) and it has been recommended by various studies for its suitability to estimate meteorological drought at different time lag (Guttman, 1998; Patel et al., 2007; Kumar et al., 2009, 2012; Quiring and Ganesh, 2010; Poonia and Rao, 2012; Dutta et al., 2013; Zhang and Jia, 2013; Belayneh et al., 2014). The present study seeks to identify the onset and spatial extent of agricultural drought using geospatial techniques and assess the suitability of NOAA-AVHRR derived VCI to monitor the agricultural drought at regional scale. In order to compare the spatio-temporal extent of agricultural and meteorological drought, estimates of NOAA-AVHRR derived VCI were compared with Standardized Precipitation Index (SPI). Also, the Rainfall Anomaly Index (RAI) (Van Rooy, 1965; Barring and Hulme, 1991; Otun and Adewumi, 2009; Ganapuram et al., 2014) and crop Yield Anomaly Index (YAI) (Dutta et al., 2011) were calculated to show the deviation of rainfall and yield during normal and drought year as identified by long term satellite data. Further, the estimates of VCI were compared with yield of major rain-fed crops to observe the relationship between NOAA-AVHRR derived vegetation condition and actual yield of major crops.

2. Study area

Rajasthan is situated in the North-Western part of India and located between 23°30′ and 30°11′North latitudes and 69°29′ and 78°17′ East longitudes (Fig. 1). This is the largest state of India, it comprises 11% of the total geographical area of the country and consists of 32 districts, 41,353 villages and four major cities. One of oldest folded mountain chains of the world, the Aravalli is stretching from southwest to northeast of the state with a distance of more than 550 km. This mountain is playing a major role in the climatic as well as physiographic pattern of Rajasthan. The Arabian branch of Monsoon hits the Eastern slope of Aravalli and the Eastern part gets sufficient rainfall whereas the Western part remains dry. The South-Eastern part of Aravalli is characterized by humid climate, green vegetation and fertile soil whereas North-Western part has desert or semi desert condition. The Thar desert, located in the North-West of Rajasthan has a unique desert ecosystem. There is a vast diurnal variation in temperature during winter and summer season. The spatial pattern of precipitation shows a slow decrease in average annual rainfall from east to west part of the state which is mainly associated with the pattern of relief of this area. Stretching from southwest to northeast part of the state, the Aravalli Mountain plays a major role in the climatic pattern of Rajasthan. The Arabian branch of Monsoon hits the Eastern slope of Aravalli and the Eastern part gets sufficient rainfall whereas the Western part remains dry. As a consequence, the South-Eastern part of Aravalli is characterized by humid climate, green vegetation and fertile soil whereas North-Western part has desert or semi desert condition. There are two crop seasons in the study area, Kharif and Rabi. Kharif crops are dependent upon monsoonal rainfall for water and sown in June–July and harvested in the months of September and October, whereas Rabi crops are cultivated in winter season. They are sown in October–November and

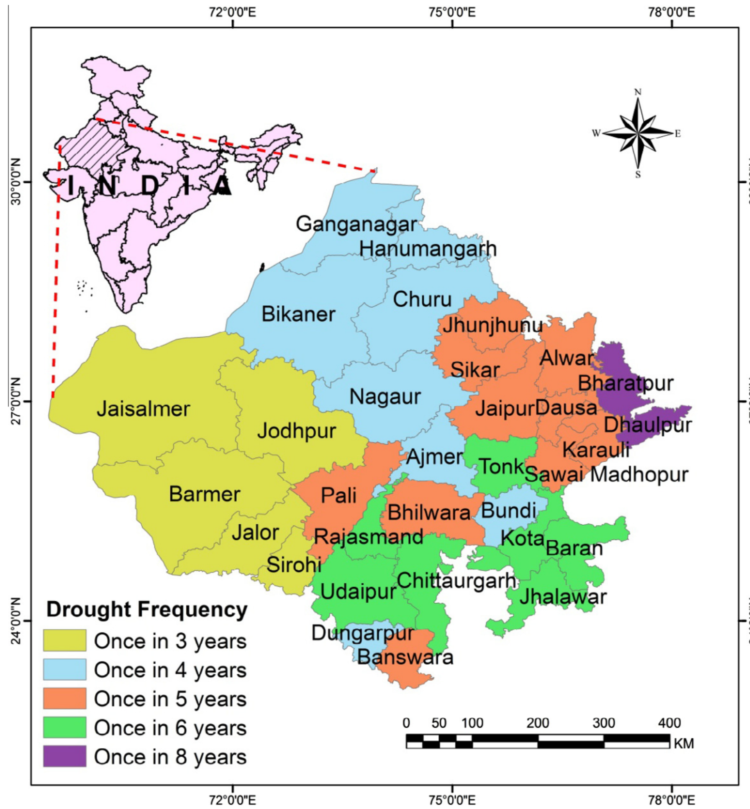

Figure 1 Study area.

harvested in the months of March–April. Drought is a very common phenomenon over here. According to the Disaster management and Relief Department, the Western part of Rajasthan experiences drought very frequently (once in 3–4 years) whereas most of the Eastern part of Rajasthan experiences drought once in 5–6 years (Fig. 1).

3. Materials and methods

In order to monitor the onset, duration and spatial extent of agricultural drought, long term NDVI has been used in the present study. This index is useful for estimation of biomass potential measuring leaf area index (LAI) and production pattern (Thenkabail et al., 2004). Over the years, NDVI has been successfully used by many researchers in different studies based on vegetation phenology, vegetation classification and mapping of continental land cover (Tucker et al., 1985; Tarpley et al., 1984). NDVI is suitable for monitoring drought, estimating healthy status of vegetation, crop growth conditions and crop yields (Kogan, 1987; Dabrowska-Zielinska et al., 2002; Singh et al., 2003). The basic concept of NDVI is based on the fact that internal mesophyll structure of healthy green leaves reflects Near-Infrared (NIR) radiation whereas the leaf chlorophyll and other pigments absorb a large proportion of the red visible (VIS) radiation. This function of internal leaf structure becomes reversed in case of unhealthy or water stressed vegetation.

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{VIS})/(\mathrm{NIR} + \mathrm{VIS}) \quad (1)$$

NDVI is calculated by the difference between reflectance in near infrared (NIR) and visible red (VIS) band of electromagnetic spectrum. The value of NDVI ranges between -1 and $+1$. It is found below 0.1 in the areas with barren rock, sand and snow cover whereas it may range from 0.6 to 0.8 in temperate and tropical rainforests. NDVI has been accepted as a popular index for monitoring agricultural drought (Son et al., 2012), estimating soil moisture (Xin et al., 2006; Chen et al., 2011) and vegetation condition (Singh et al., 2003). However, the utility of NDVI for studying vegetation and related issues may be constrained by several sources of error that usually occur due to atmospheric noise and many other reasons like satellite orbital drift, satellite change and sensor degradations (Kogan, 1995). Since weather related NDVI fluctuations cannot be detected easily, the ecological component must be separated from the impact of weather for estimating the actual condition of vegetation health. In this context, Kogan (1995) suggested Vegetation Condition Index for identifying drought related vegetation stress and measuring the intensity, time of onset, duration, dynamics and impacts of drought on overall vegetation condition.

NOAA-AVHRR based NDVI has been successfully used for global long term vegetation trends (Fensholt and Proud, 2012), categorization and quantification of vegetative drought (Rulinda et al., 2012) and estimating the drought vulnerability (Do and Kang, 2014; Vrieling et al., 2014). Long term (1984–2003) satellite data from NOAA-AVHRR GIMMS (Global Inventory Modeling and Mapping Studies) have been used in the present study to compute VCI for monitoring the agricultural drought. The AVHRR gives information through different channels which are sensitive to incoming solar radiation (light) in the visible (channel 1: 0.58–0.68 mm), near infrared (channel 2: 0.75–1.0 mm), mid-infrared (channel 3A: 1.58–1.64 mm), far infrared (channel 3B: 3.55–3.93 mm), thermal infrared (channel 4: 10.3–11.3 mm and channel 5: 11.5–12.5 mm) range (Quiring and Ganesh, 2010). The GIMMS NDVI dataset has 1.1 km of spatial resolution at nadir and they are corrected to eliminate the effect of volcanic aerosols, satellite drift, cloud cover and residual sensor degradation. The dataset consisting of fifteen day composite images of past 20 years (1984–2004) was stacked, converted from GEOTIFF format to image (.img) format and resized according to the boundary of study area. The resized stacked layers then re-projected into Alberts Equal Area Projection considering the WGS 84 datum. This projection was adopted to keep the original pixel size. In order to get the actual value of NDVI ranging from +1 to −1 scale, the re-projected images were rescaled using the scale factor 0.001.

3.1. Vegetation Condition Index (VCI)

The following VCI equation was applied on the final NDVI database:

$$\text{Vegetation Condition Index (VCI)} = (\text{NDVI}_j - \text{NDVI}_{\min})/(\text{NDVI}_{\max} - \text{NDVI}_{\min}) * 100 \quad (2)$$

Here, $\text{NDVI}_{\max}$ and $\text{NDVI}_{\min}$ represent maximum and minimum NDVI of each pixel calculated for each month and j represents the index of current month. VCI value is being measured in percentage ranging from 1 to 100. The range between 50% and 100% indicates above normal condition of vegetation whereas the values ranging from 50% to 35% indicate the drought condition and below 35% indicates severe drought condition (Kogan, 1995). This index normalizes NDVI and separates the long-term ecological signal from the short-term climate signal and in this sense it proves to be a better indicator for monitoring water stress condition as compared to NDVI (Kogan and Sullivan, 1993). The resulted images of Vegetation Condition Index (VCI) were classified on the basis of drought severity classification proposed by Kogan (1995).

3.2. Standardized Precipitation Index (SPI)

It was calculated using the following formula and classification scheme (Table 1) as proposed by Mckee et al. (1993). Long term monthly rainfall data (1983–2004) were collected from Meteorological Department of India and SPI was estimated to observe the spatio-temporal extent and intensity of meteorological drought event. The gamma distribution is normally defined as:

$$\text{g(x)} = \frac{x^{\alpha-1} \cdot e^{-\frac{\chi}{\beta}}}{\beta^{\alpha} \cdot \Gamma(\alpha)} \quad \text{for } x > 0 \quad (3)$$

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

3.3. Crop Yield Anomaly

It is a useful technique for identifying deviation of yield for a particular year from its long term trend. Crop statistics of major rainfed crops i.e., Maize, Sorghum and Pearl Millet (1984–2004) were collected from the website of Rajasthan Krishi. Yield anomalies of these crops were calculated using the following formula:

Table 1 SPI classification (McKee et al., 1993).

SPI value	Category	Probability (%)
>2.0	Extremely wet	2.3
1.5–1.99	Very wet	4.4
1.0–1.49	Moderately wet	9.2
−0.99 to 0.99	Near normal	68.2
−1.0 to −1.49	Moderately dry	9.2
−1.5 to −1.99	Very dry	4.4
<−2.0	Extremely dry	2.3

$$\text{YAI} = (Y - \mu)/\sigma \quad (4)$$

where,
YAI = Yield Anomaly Index
Y = Crop Yield
μ = Long term average yield
σ = Standard Deviation.

3.4. Rainfall Anomaly Index (RAI)

Among different indicators of drought monitoring, rainfall anomaly is the most effective and simple meteorological drought index. Average annual rainfall of Rajasthan was collected for a period of 22 years (1983–2004) and rainfall anomaly of each year was calculated using long term average rainfall of study area. The years with low rainfall values indicate negative departure from mean seasonal rainfall which is further denoted as drought years. The following formula was used for calculation of Rainfall Anomaly Index:

$$\text{RAI} = (R - \mu)/\sigma \quad (5)$$

where,
RAI = Rainfall Anomaly Index
R = Rainfall
μ = Long term average rainfall
σ = Standard Deviation

4. Results and discussion

4.1. NDVI and drought monitoring

Long term NDVI for different fortnights of rain-fed season (July–September) was used in the present study. Though NDVI has been used by many authors for studying drought, it has been recommended by a number of studies to use VCI rather using NDVI alone. The stacked NDVI layers were visualized to identify differences in vegetation health during drought and wet year (Fig. 2a and b). In order to assess the performance of NOAA-AVHRR derived NDVI, two consecutive years, 2002 and 2003 were chosen for their distinct NDVI characteristics. While visually comparing the NDVI of 2002 and 2003, a visible difference was observed between the eastern and western part of Rajasthan. The diversity in NDVI indicates spatial variation in vegetation health within the area. This kind of spatial variability has occurred mainly because of the uneven distribution of monsoonal rainfall which is significantly less in western part than the eastern part of the area.

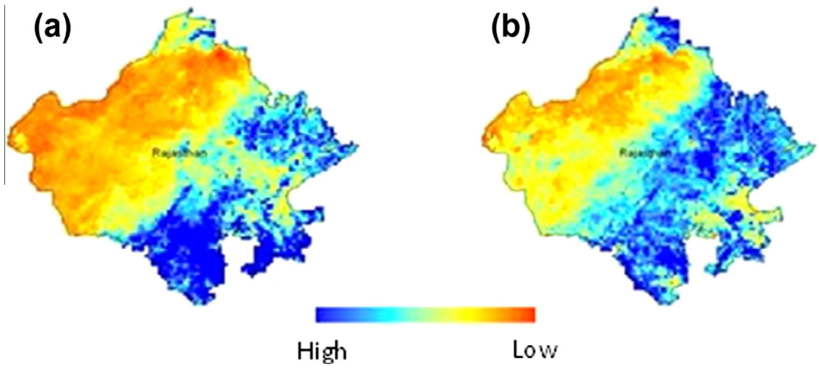

Figure 2 NDVI of August, 2002 (a) and 2003 (b).

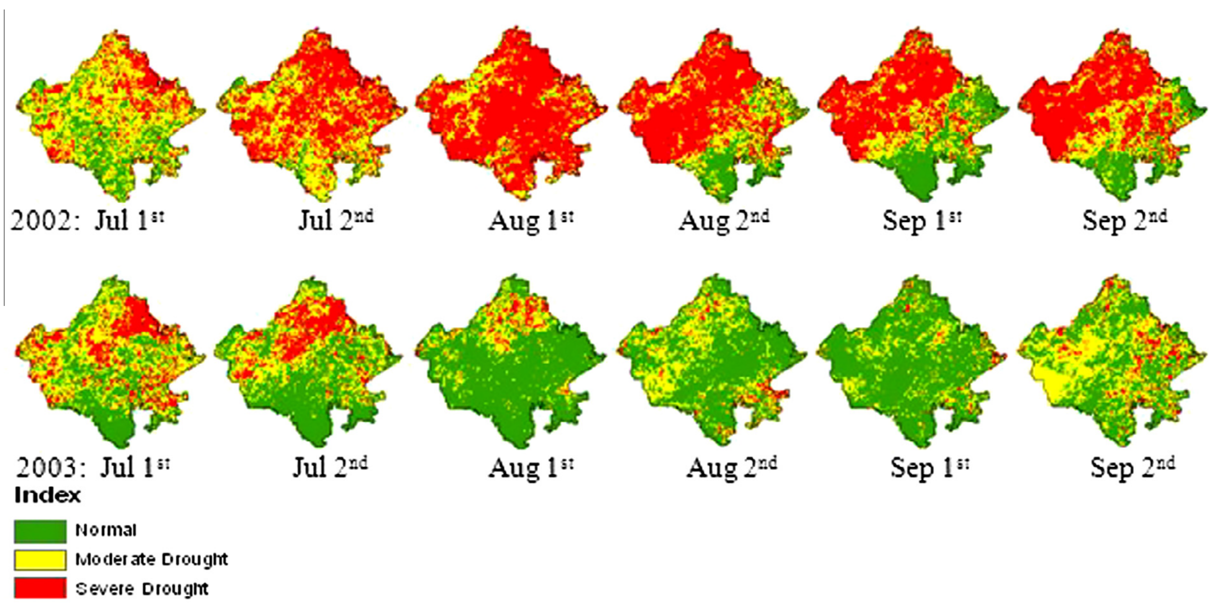

Figure 3 Spatio-temporal (fortnightly) pattern of Vegetation Condition Index for drought year (2002) and normal year (2003).

Also, the NDVI image of both the years shows considerable temporal variation within the study area. The NDVI of western part was found relatively less during both the years which can be explained by the presence of great Indian Thar Desert and the semi-arid climatic region surrounding it. However, the NDVI during the year 2002 was found far less than 2003 in most of the areas which indicates a vegetation stress condition during the peak Monsoon season.

4.2. Drought monitoring through VCI

In order to quantify drought from a long term observation from space, the NDVI derived drought index, VCI was used in the present study. Fig. 3 illustrates the vegetation condition for different fortnights of kharif crops for the year 2002 and 2003. It was found that severe drought condition prevailed during kharif season of the year 2002 over a large area of Rajasthan. The onset and extent of drought can be clearly observed from the VCI maps of consecutive fortnights of 2002. Acute water stress is evident all over the state during the 1st fortnight of August, 2002. From the 2nd fortnight of August 2002, the condition was quite improved over the eastern part. Rajasthan had experienced one of the worst droughts during this year and it was the fifth incessant drought in the state (Malik, 2014). Almost 40 million people and 50 million cattle were affected in 2002 drought alone. In spite of prevalence of drought condition over a large area of Rajasthan during this year, some areas of eastern Rajasthan had remained unaffected from water stress. These areas are characterized by humid and sub humid type of climate which helps to keep the area green even during the drought year. Spatial variation in vegetation health resulted from the uneven distribution of rainfall has a great influence in variation of agricultural yield of Rajasthan. Since the region receives monsoonal rainfall much higher than the western part even in drought year, it remains suitable for cultivation of Kharif crops. However, the vegetation condition was visibly stressed during the year 2002 than 2003. The vegetation health was found normal over a large area of Rajasthan during the year 2003. Even some part of the western Rajasthan was comparatively greener due to sufficient amount of rainfall in 2003.

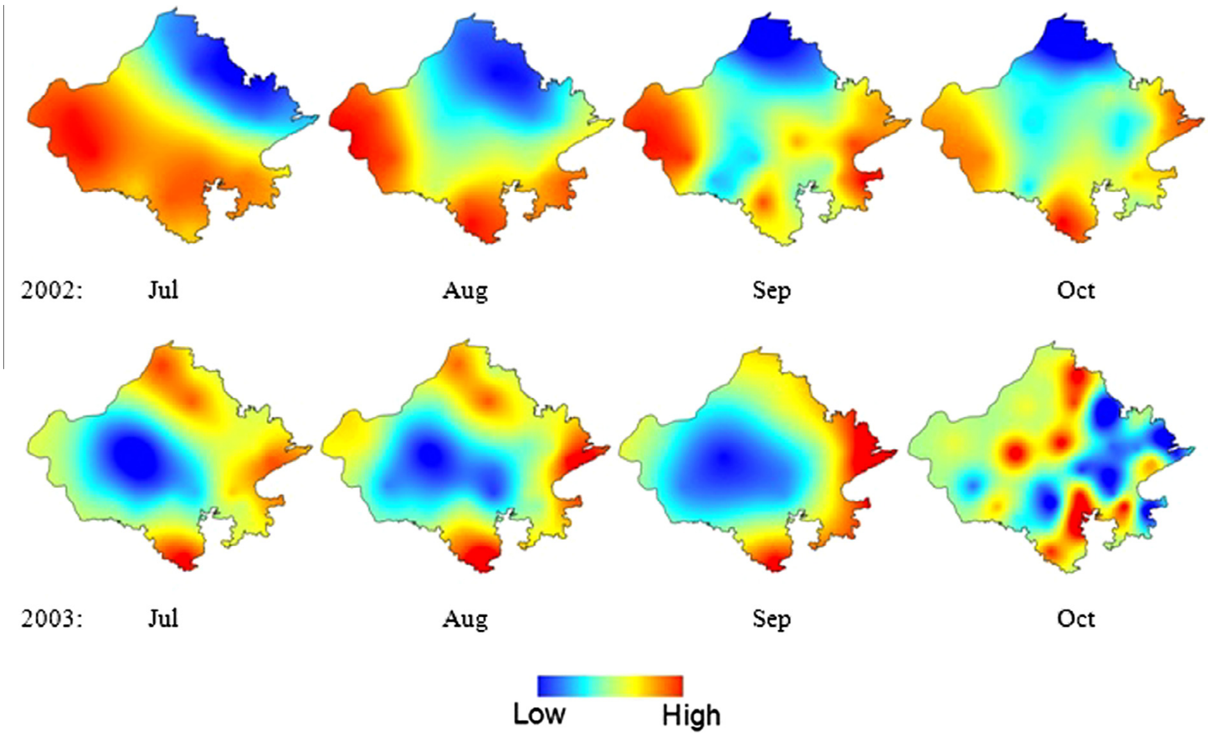

Figure 4 Standardized Precipitation Index (SPI) for drought year (2002) and normal year (2003).

4.3. Drought monitoring through SPI

The SPI is a very popular meteorological drought index which has been frequently used by decision makers for measuring and monitoring the intensity of meteorological drought events. Except these, SPI is useful for identifying spatio-temporal extent of long term historical droughts. In this study, this index was used to identify the incidence of meteorological drought, its intensity and spatio-temporal extent and thus comparing the results with agricultural drought index VCI. The spatio-temporal pattern of SPI shows that there was a prolonged dry condition prevailing during the monsoonal season of 2002 (Fig. 4). The SPI values ranged from −1.00 to −2.00 during the month of July and August (Table 2) indicating the presence of a moderately to extremely dry condition over the state.

4.4. VCI and SPI of July 2nd and August 1st Fortnight

In order to study the temporal variation of VCI, a drought year VCI sequence was compared with that of a wet year (Fig. 5). The average VCI value was found below 50 for all of the districts of Rajasthan during the drought year, among them maximum districts were having VCI value below 35 which indicates existence of a severe drought condition over the region, whereas, the vegetation condition of maximum districts of Rajasthan was above normal during 1st fortnight of August, 2003. The difference between VCI of drought year and normal year was highest in the 1st fortnight of August indicating the effect of varying monsoonal rainfall upon vegetation health.

While talking about agricultural drought, the whole scenario remains incomplete if we do not focus on meteorological conditions of the region. In order to study the highly variable nature of monsoonal rainfall, the SPI values of both the years were compared with each other (Fig. 6). The average SPI value of Rajasthan was found to be −1.40, −1.58 and −1.70 during July, August and September respectively and it was 0.67, 0.55 and 0.45 during the normal year (2003). It indicates the prevalence of moderately to very dry conditions over the region during 2002. The result of SPI agrees with the findings of satellite based drought index VCI which confirms the occurrence of drought during the rain-fed months of 2002.

4.5. Fortnightly pattern of VCI and SPI

The fortnightly pattern of VCI of two selected districts from different agro climatic regions is illustrated in the following graphs (Fig. 7). A distinct difference between VCI of drought year and normal year is clearly evident from the following graphs where average VCI of normal year was more than 40 throughout the kharif season and it was much less in drought year. It even reached below 20 in the semiarid district Ajmer during August, 2002 and during end of September to October, 2002 in Humid Banswara. As a whole, VCI values were much greater in the normal year 2003 than the drought year 2002 indicating prevalence of normal condition in 2003 and drought condition in the year 2002.

A significant difference in SPI of drought year (2002) and wet year (2003) can be observed from the fortnightly pattern of SPI (Fig. 8). The average SPI of Rajasthan was found more than 0.75 throughout the kharif season of 2003 whereas it was much less during the year 2002. The SPI value reached below −1.50 in the semiarid district Ajmer and humid Banswara during September, 2002. The results obtained from the fortnightly

Table 2 District wise SPI during drought (2002) and wet year (2003).

Sl. No.	Districts	Drought year (2002)			Wet year (2003)		
		SPI02_Jul	SPI02_Aug	SPI02_Sep	SPI03_Jul	SPI03_Aug	SPI03_Sep
1	Ajmer	−1.24	−1.47	−1.5	0.49	0.23	0.25
2	Alwar	−1.54	−1.54	−1.58	0.67	0.6	0.54
3	Banswara	−1.61	−1.5	−1.63	1.15	1.22	1.07
4	Baran	−1.27	−1.31	−1.33	0.86	0.77	0.51
5	Barmer	−1.14	−1.24	−1.37	0.48	0.19	0.15
6	Bharatpur	−1.3	−1.48	−1.48	0.73	0.77	0.67
7	Bhilwara	−1.24	−1.48	−1.72	0.33	0.06	0.04
8	Bikaner	−1.33	−1.65	−1.88	0.58	0.39	0.36
9	Bundi	−1.54	−1.9	−1.81	1.05	0.69	0.58
10	Chittaurgarh	−1.32	−1.52	−1.85	0.44	0.44	0.35
11	Churu	−1.78	−1.87	−2.04	1.07	0.95	0.75
12	Dausa	−1.71	−1.88	−1.58	0.54	0.34	0.06
13	Dhaulpur	−1.59	−1.61	−1.5	0.84	0.88	0.78
14	Dungarpur	−1.33	−1.29	−1.59	0.9	0.72	0.47
15	Hanumangarh	−1.28	−1.62	−2.35	0.5	0.35	0.58
16	Jaipur	−1.61	−1.81	−2.18	0.58	0.36	0.28
17	Jaisalmer	−1.21	−1.33	−1.77	0.58	0.66	0.18
18	Jalor	−1.44	−1.63	−1.4	0.65	0.47	0.6
19	Jhalawar	−1.44	−1.63	−1.97	0.68	0.61	0.39
20	Jhunjhunu	−1.6	−1.82	−1.65	0.67	0.6	0.47
21	Jodhpur	−1.39	−1.79	−1.96	−0.03	−0.02	0.52
22	Karauli	−1.42	−1.53	−1.88	1.01	1.01	0.02
23	Kota	−1.08	−1.32	−1.48	0.39	0.3	0.98
24	Nagaur	−1.25	−1.48	−1.49	0.53	0.42	0.29
25	Pali	−1.4	−1.64	−1.71	0.35	0.3	0.41
26	Rajsamand	−1.37	−1.6	−1.95	0.7	0.57	0.35
27	Sawai Madhopur	−1.21	−1.43	−1.61	0.84	0.71	0.46
28	Sikar	−1.44	−1.74	−1.39	0.81	0.69	0.52
29	Sirohi	−1.72	−1.87	−1.85	0.48	0.36	0.54
30	Sri Ganganagar	−1.56	−1.79	−1.92	1.04	0.89	0.41
31	Tonk	−1.31	−1.54	−1.59	0.76	0.52	0.24
32	Udaipur	−1.12	−1.29	−1.38	0.66	0.69	0.52

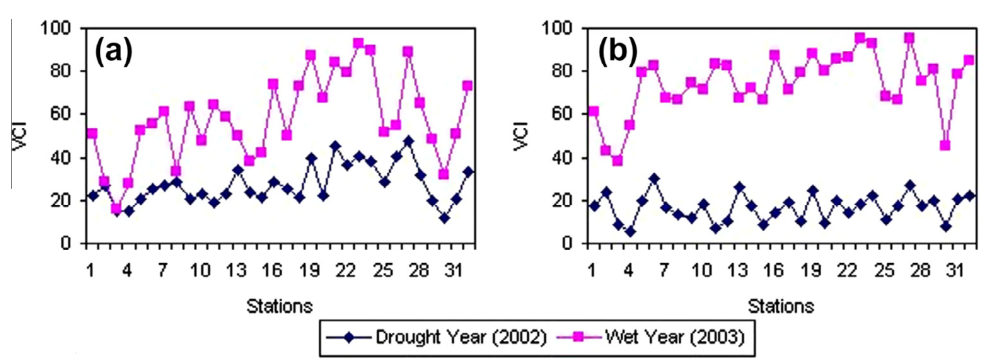

Figure 5 Comparison of drought and normal year VCI during July (a) and August (b) for different districts of Rajasthan.

pattern of SPI significantly coincide with the fortnightly pattern of VCI in both of districts.

4.6. Rainfall Anomaly Index (RAI)

Long term average annual rainfall of Rajasthan was analyzed for a period of 22 years (1983–2004) using the Rainfall Anomaly Index to identify the years with meteorological drought. It was found that the results from remote sensing based index VCI and meteorological drought index RAI are quite identical as both of the indexes are indicating occurrence of drought in 2002 and normal condition in the year 2003. It can be observed from the following figure (Fig. 9) that the year 2002 took the second highest position in rainfall deficit followed by the year 1987 which is a remarkable year for occurrence of a severe drought.

4.7. VCI and yield of major rain-fed crops

Agricultural drought has an inverse relation with the amount of precipitation received by an area and it influences the productivity of crops directly. In order to examine whether VCI based

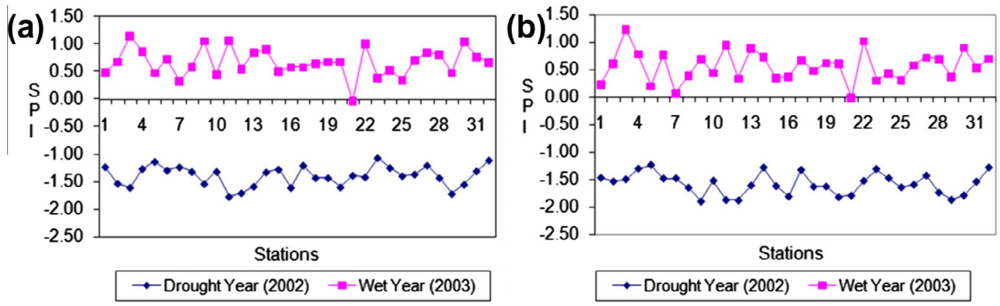

Figure 6 Comparison of drought and normal year SPI during July (a) and August (b) for different districts of Rajasthan.

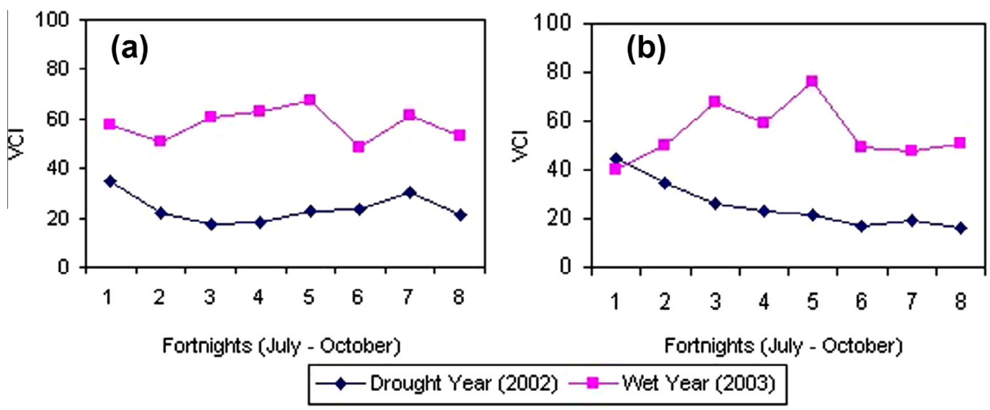

Figure 7 Fortnightly pattern of VCI in semiarid Ajmer (a) and humid Banswara (b).

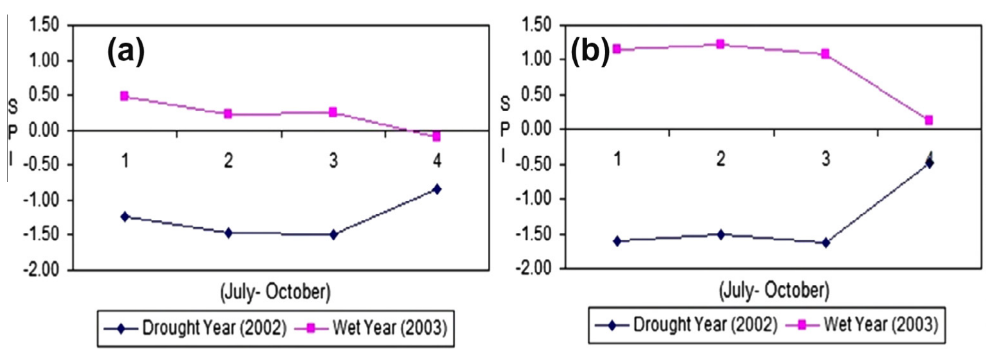

Figure 8 Monthly pattern of SPI in semiarid Ajmer (a) and humid Banswara (b).

agricultural drought has impact upon crop yield and how crop yield varies with drought and normal year, the yield of major kharif crops was analyzed for 2002 and 2003 respectively. It can be observed that crop yield of major kharif crop like sorghum was significantly less during the year 2002 and vis-à-vis during 2003 (Table. 3). In order to assess the validity of NOAA-AVHRR derived VCI estimates, the average VCI of rain-fed season was compared with yield of major rain-fed (kharif) crops which reveals that a good agreement exists between them (Fig. 10). It indicates that 57%, 64% and 61% of the variation in sorghum, pearl millet and maize yield respectively are accounted for by the vegetation condition of the districts. The correlation co-efficient (r) was found to be 0.75, 0.80 and 0.78 ($p = 0.05$) for sorghum, pearl millet and maize respectively which reveals that there is a strong positive correlation present between VCI and yield of major kharif crops. It confirms the fact that vegetation health during monsoonal season plays a significant role in crop yield of that season.

4.8. VCI and Yield Anomaly Index (YAI)

In order to compare the VCI with yield based drought index, YAI was calculated using the long term yield data (1984–2004) of major crops for the year 2002 and 2003. YAI of Sorghum and Maize of the year 2002 was compared with YAI of 2003 (Fig. 11) which shows that most of the districts are having positive YAI in 2003 whereas it was negative in the year, 2002. It can be observed that Jhalawar district has highest YAI (Sorghum) in 2003 and lowest YAI in 2002 among all districts of Rajasthan. As remote sensing based drought index VCI indicates occurrence of agricultural

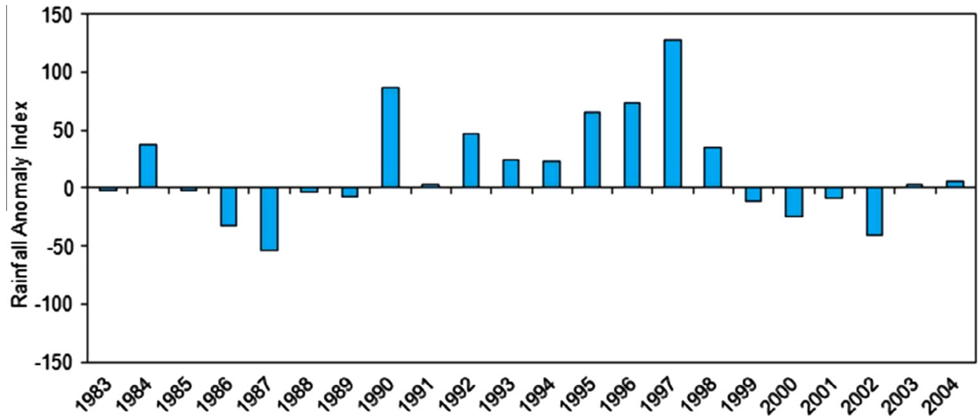

Figure 9 Rainfall anomaly of Rajasthan.

Table 3 District wise VCI and yield during drought (2002) and wet year (2003).

Districts	Drought year (2002)		Wet year (2003)		Districts	Drought year (2002)		Wet year (2003)	
	Average VCI	Sorghum yield (kg/ha)	Average VCI	Sorghum yield (kg/ha)		Average VCI	Sorghum yield (kg/ha)	Average VCI	Sorghum yield (kg/ha)
Ganganagar	18	143	61	717	Barmer	19	128	71	714
Bikaner	24	125	43	714	Jalor	10	128	79	714
Churu	8	200	38	667	Sirohi	25	232	88	1068
Jhunjhunu	5	105	55	667	Bhilwara	10	12	80	639
Alwar	20	151	79	520	Udaipur	20	528	85	334
Bharatpur	30	327	83	703	Chittaurgarh	14	450	86	411
Dhaulpur	17	131	68	713	Dungarpur	18	129	95	714
Sawai Madhopur	13	153	67	1293	Banswara	22	128	93	712
Jaipur	12	54	75	947	Bundi	11	71	68	1471
Sikar	19	125	72	714	Kota	18	720	67	920
Ajmer	7	38	83	583	Jhalawar	27	510	95	1985
Tonk	10	40	82	538	Baran	17	205	76	1115
Jaisalmer	26	100	67	714	Dausa	20	70	81	874
Jodhpur	17	272	72	758	Hanumangarh	8	143	46	706
Nagaur	9	134	66	449	Karauli	21	129	79	714
Pali	14	40	88	524	Rajsamand	22		85	1453

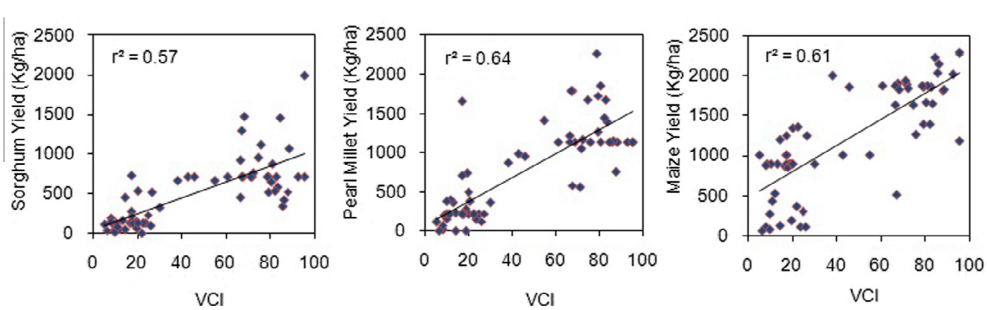

Figure 10 VCI vs yield of major rain fed crops.

drought during the year 2002, this outcome of YAI also supports the findings of our study. Failure of Monsoon in this state called upon severe drought during the year 2000 causing long term consequences of shortage of food, drinking water, fodder, and also employment opportunities. Almost all districts had suffered from acute diminution of ground water storage due to deficiency of rainfall during the period (UNDMT, 2002). Not only this state, India as a whole experienced about 21.5% deficit of rainfall during the year and it was below 56% especially in the month of July leading to a severe drought over most of the regions in the country (Bhat, 2006).

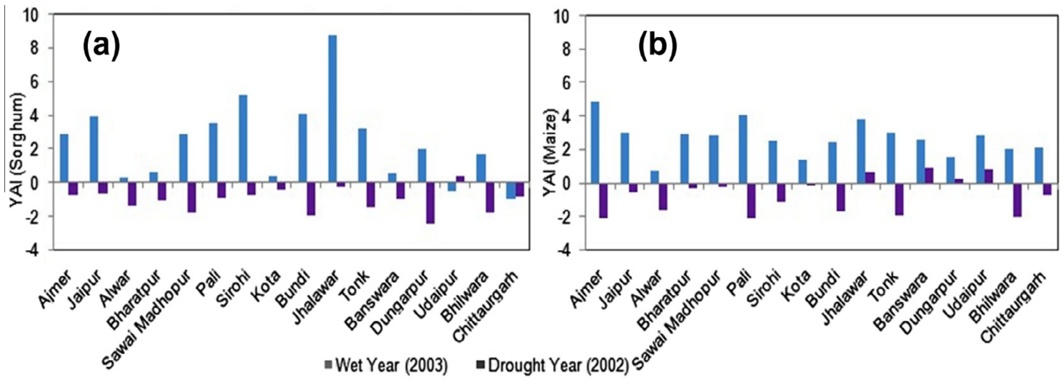

Figure 11 District wise yield anomaly of sorghum (a) and maize (b).

5. Conclusions

The present study attempts to identify the spatio-temporal extent of agricultural drought over Rajasthan using remote sensing based Vegetation Condition Index (VCI) and assesses the performance of VCI by comparing the estimates with meteorological drought indicator SPI, RAI and yield based index YAI. It was found that NOAA-AVHRR NDVI derived VCI estimates can be useful for monitoring onset, duration and spatio-temporal extent of agricultural drought. The VCI was found less than 35% over most of the areas of Rajasthan in 2002 indicating drought related stress during that year. While comparing the estimates of the meteorological based Standardized Precipitation Index (SPI), Rainfall Anomaly Index (RAI) and Yield Anomaly Index (YAI), the results were found identical with the outcome of VCI. In order to validate the VCI based estimates, the correlation between VCI and yield of major rain-fed crops was analyzed which indicates a strong positive correlation ($r \geqslant 0.75$) exists between them. It also proves and justifies the usefulness of remote sensing and GIS technique for identifying drought related stress in rain-fed crops. Unlike the meteorological data available from sparsely distributed meteorological stations, remote sensing based index VCI can be successfully used for delineating the spatio-temporal extent of agricultural drought.

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References

Aboelghar, M., Arafat, S., Saleh, A., Naeem, S., Shirbeny, M., Belal, A., 2010. Retrieving leaf area index from SPOT4 satellite data. Egypt. J. Remote Sens. Space Sci. 13, 121–127.

Anyamba, A., Tucker, C.J., Eastman, J.R., 2001. NDVI anomaly patterns over Africa during the 1997/98 ENSO warm event. Int. J. Remote Sens. 22, 1847–1859.

Bajgiran, P.R., Darvishsefatb, A.A., Khalilic, A., Makhdoum, M.F., 2008. Using AVHRR-based vegetation indices for drought monitoring in the Northwest of Iran. J. Arid. Environ. 72, 1086–1096.

Barati, S., Rayegani, B., Saati, M., Sharifi, A., Nasri, M., 2011. Comparison the accuracies of different spectral indices for estimation of vegetation cover fraction in sparse vegetated areas. Egypt. J. Remote Sens. Space. Sci. 14, 49–56.

Barring, L., Hulme, M., 1991. Filters and approximate confidence intervals for interpreting rainfall anomaly indices. J. Clim. 4, 837–847.

Belayneh, A., Adamowski, J., Khalil, B., Ozga-Zielinski, B., 2014. Long-term SPI drought forecasting in the Awash River Basin in Ethiopia using wavelet neural network and wavelet support vector regression models. J. Hydrol. 508, 418–429.

Bhat, G.S., 2006. The Indian drought of 2002—a sub-seasonal phenomenon? Q. J. R. Meteorolog. Soc. 132, 2583–2602.

Brown, J.F., Wardlow, B.D., Tadesse, T., Hayes, M.J., Reed, B.C., 2008. The Vegetation Drought Response Index (VegDRI): a new integrated approach for monitoring drought stress in vegetation. GISc. Remote Sens. 45, 16–46.

Chen, C.F., Son, N.T., Chang, L.Y., Chen, C.R., 2011. Monitoring of soil moisture variability in relation to rice cropping systems in the Vietnamese Mekong Delta using MODIS data. Appl. Geogr. 31, 463–475.

Dabrowska-Zielinska, K., Kogan, F.N., Ciolkoszs, A., Gruszczynska, M., Kowalik, W., 2002. Modelling of crop growth conditions and crop yield in Poland using AVHRR-based indices. Int. J. Remote Sens. 23, 1109–1123.

Do, N., Kang, S., 2014. Assessing drought vulnerability using soil moisture-based water use efficiency measurements obtained from multi-sensor satellite data in Northeast Asia dryland regions. J. Arid. Environ. 105, 22–32.

Domenikiotis, C., Spiliotopoulos, M., Tsiros, E., Dalezios, N.R., 2004. Early cotton yield assessment by the use of the NOAA/AVHRR derived drought Vegetation Condition Index in Greece. Int. J. Remote Sens. 25, 2807–2819.

Dutta, D., Patel, N.R., Kundu, A., 2011. Analyzing the performance of auto regressive integrated moving average (ARIMA) model for predicting agricultural productivity in eastern Rajasthan. Res. J. Agric. Sci. 2, 555–559.

Dutta, D., Kundu, A., Patel, N.R., 2013. Predicting agricultural drought in eastern Rajasthan of India using NDVI and standardized precipitation index. Geocarto. Int. 28, 192–209.

Fensholt, R., Proud, S.R., 2012. Evaluation of earth observation based global long term vegetation trends – comparing GIMMS and MODIS global NDVI time series. Remote Sens. Environ. 119, 131–147.

Ganapuram, S., Nagarajan, R., Sehkar, G.C., Balaji, V., 2014. Spatio-temporal analysis of droughts in the semi-arid Pedda Vagu and

Ookacheti Vagu watersheds, Mahabubnagar District, India. Arabian. J. Geosci. http://dx.doi.org/10.1007/s12517-014-1696-0.
Guttman, N.B., 1998. Comparing the Palmer drought index and the standardized precipitation index. J. Am. Water Res. Assoc. 34, 113–121.
Jain, S.K., Keshri, R., Goswami, A., Sarkar, A., 2010. Application of meteorological and vegetation indices for evaluation of drought impact: a case study for Rajasthan, India. Nat. Hazards 54, 643–656.
Ji, L., Peters, A.J., 2003. Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices. Remote Sens. Environ. 87, 85–98.
Kogan, F.N., 1987. Vegetation index for a real analysis of crop conditions. In: Proceedings of the 18th Conference on Agricultural and Forest Meteorology, AMS, W. Lafayette, Indiana, 15–18 September 1987, Indiana, USA, pp. 103–106.
Kogan, F.N., Sullivan, J., 1993. Development of a global drought watch system using NOAA/AVHRR data. Adv. Space Res. 13, 219–222.
Kogan, F.N., 1995. Application of vegetation index and brightness temperature for drought detection. Adv. Space Res. 15, 91–100.
Kumar, M.N., Murthy, C.S., Sesha Sai, M.V.R., Roy, P.S., 2009. On the use of Standardized Precipitation Index (SPI) for drought intensity assessment. Meteorol. Appl. 16, 381–389.
Kumar, M.N., Murthy, C.S., Sesha Sai, M.V.R., Roy, P.S., 2012. Spatiotemporal analysis of meteorological drought variability in the Indian region using standardized precipitation index. Meteorol. Appl. 19, 256–264.
Kundu, A., Dutta, D., 2011. Monitoring desertification risk through climate change and human interference using remote sensing and GIS techniques. Int. J. Geomat. Geosci. 2, 21–33.
Kundu, A., Dutta, D., Patel, N.R., Saha, S.K., Siddiqui, A.R., 2014a. Identifying the process of environmental changes of Churu district, Rajasthan (India) using remote sensing indices. Asian J. Geoinf. 14, 14–22.
Kundu, A., Patel, N.R., Saha, S.K., Dutta, D., 2014b. Monitoring the extent of desertification processes in western Rajasthan (India) using geo-information science. Arabian J. Geosci. http://dx.doi.org/10.1007/s12517-014-1645-y.
Malik, D., 2014. Without Rain, a Bleak Outlook, India Together, The News in Proportion, 29 March.
McKee, T.B., Doesken, N.J., Kliest, J., 1993. The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th Conference on Applied Climatology, Anaheim, CA, America. Meteorol. Soc. Boston, pp. 179–184.
McKee, T.B., Doesken, N.J., Kleist, J., 1995. Drought monitoring with multiple time scales. In: Proceedings of the 9th Conference on Applied Climatology, Dallas, TX, America. Meteorol. Soc. pp. 233–236.
Mohamed, E.S., Schutt, B., Belal, A., 2013. Assessment of environmental hazards in the northwestern coast-Egypt using RS and GIS. Egypt. J. Remote Sens. Space Sci. 16, 219–229.
Mondal, S., Jeganathan, C., Sinha, N.K., Rajan, H., Roy, T., Kumar, P., 2014. Extracting seasonal cropping patterns using multi-temporal vegetation indices from IRS LISS-III data in Muzaffarpur District of Bihar, India. Egypt. J. Remote Sens. Space Sci. 17, 123–134.
Nicholson, S.E., Farrar, T.J., 1994. The influence of soil type on the relationships between NDVI, rainfall, and soil moisture in semiarid Botswana: I. NDVI response to rainfall. Remote Sens. Environ. 50, 107–120.
Otun, J.A., Adewumi, J.K., 2009. Drought quantifications in semi-arid regions using precipitation effectiveness variables. In: 18th World IMACS/MODSIM Congress, 13–17 July 2009, Cairns, Australia.
Patel, N.R., Chopra, P., Dadhwal, V.K., 2007. Analyzing spatial patterns of meteorological drought using standardized precipitation index. Meteorol. Appl. 14, 329–336.
Patel, N.R., Parida, B.R., Venus, V., Saha, S.K., Dadhwal, V.K., 2012. Analysis of agricultural drought using vegetation temperature condition index (VTCI) from Terra/MODIS satellite data. Environ. Monit. Assess. 184, 7153–7163.
Poonia, S., Rao, A.S., 2012. Analysis of meteorological drought at arid Rajasthan using Standardized Precipitation Index. In: 92nd America. Meteorol. Soc. Annual. Meet. (January 22–26, 2012).
Quiring, S.M., 2009. Developing objective operational definitions for monitoring drought. J. Appl. Meteorol. Climatol. 48, 1217–1229.
Quiring, S.M., Ganseh, S., 2010. Evaluating the utility of the Vegetation Condition Index (VCI) for monitoring meteorological drought in Texas. Agric. For. Meteorol. 150, 330–339.
Rathore, M.S., 2004. State level analysis of drought policies and impacts in Rajasthan, India, Working paper 93, Drought Series, Paper 6, Int. Water. Manage. Inst.
Rulinda, C.M., Dilo, A., Bijker, W., Stein, A., 2012. Characterising and quantifying vegetative drought in East Africa using fuzzy modelling and NDVI data. J. Arid. Environ. 78, 169–178.
Seiler, R.A., Kogan, F., Sullivan, J., 1998. AVHRR-based vegetation and temperature condition indices for drought detection in Argentina. Adv. Space Res. 21, 481–484.
Seiler, R.A., Kogan, F., Wei, G., 2000. Monitoring weather impact and crop yield from NOAA AVHRR data in Argentina. Adv. Space Res. 26, 1177–1185.
Siddiqui, A.R., 2004. Regional Evaluation of Desertification Hazards in the Aridlands of Western Rajasthan (an unpublished Ph. D. thesis). AMU, Aligarh, Uttar Pradesh, India, pp. 221.
Singh, R.P., Roy, S., Kogan, F.N., 2003. Vegetation and temperature condition indices from NOAA AVHRR data for drought monitoring over India. Int. J. Remote Sens. 24, 4393–4402.
Son, N.T., Chen, C.F., Chen, C.R., Chang, L.Y., Minh, V.Q., 2012. Monitoring agricultural drought in the Lower Mekong Basin using MODIS NDVI and land surface temperature data. Int. J. Appl. Earth Obs. Geoinf. 18, 417–427.
Tarpley, J.D., Schnieder, S.R., Money, R.L., 1984. Global vegetation indices from NOAA-7 meteorological satellite. J. Clim. Appl. Meteorol. 23, 4491–4503.
Thenkabail, P.S., Gamage, M.S.D.N., Smakhtin, V.U., 2004. The use of remote sensing data for drought assessment and monitoring in Southwest Asia. Research report. 85, Int. Water. Manage. Inst. Colombo, Sri Lanka.
Tucker, C.J., Townshend, J.R.G., Goff, T.E., 1985. African land cover classification using satellite data. Science 227, 369–375.
UN Disaster Management Team, 2002. India: Situation report on Rajasthan drought 25 Dec 2002.
Unganai, L.S., Kogan, F.N., 1998. Southern Africa's recent droughts from space. Adv. Space Res. 21, 507–511.
Van Rooy, M.P., 1965. A rainfall anomaly index (RAI) independent of time and space. Notos 14, 43–48.
Vrieling, A., Meroni, M., Shee, A., Mudec, A.J., Woodard, J., (Kees) de Bie, C.A.J.M., Rembold, F., 2014. Historical extension of operational NDVI products for livestock insurance in Kenya. Int. J. Appl. Earth Obs. Geoinf. 28, 238–251.
Wang, J., Price, K.P., Rich, P.M., 2001. Spatial patterns of NDVI in response to precipitation and temperature in the central Great Plains. Int. J. Remote Sens. 22, 3827–3844.
Xin, F., Tian, G., Liu, Q., Chen, L., 2006. Combining vegetation index and remotely sensed temperature for estimation of soil moisture in China. Int. J. Remote Sens. 27, 2071–2075.
Zhang, A., Jia, G., 2013. Monitoring meteorological drought in semiarid regions using multi-sensor microwave remote sensing data. Remote Sens. Environ. 134, 12–23.