Vegetation response to rainfall as monitored by NOAA–AVHRR

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Rainfall is an important meteorological parameter, which influences the type of vegetation in a region. The relationship between rainfall and vegetation is well established but it varies from region to region. Normalized Difference Vegetation Index (NDVI) is a simple index to monitor vegetation which can be derived from satellite data. Use of NDVI is well established in assessing the vigour and productivity of the vegetation. In this study an attempt has been made to find the relation between rainfall and NDVI in a few districts of Andhra Pradesh, India. The mean of maximum NDVI from 1989 to 1998 is correlated with seasonal normal rainfall. The NDVI lag to the monthly rainfall and reason for the lag based on land use of the districts was investigated. Districts were classified based on their NDVI profile and coefficient of variation of NDVI and finally the first three-month cumulative southwest monsoon rainfall effect on the seasonal cumulative NDVI of the district was correlated. The result shows that there is a high degree of correlation ($r = 0.81$) between the mean of maximum NDVI with the normal rainfall. The NDVI lags rainfall by two months in most of the districts and the initial three months rainfall correlates well with the seasonal cumulative NDVI.

Keywords: Monsoon, Normalized Difference Vegetation Index, rainfall, remote sensing.

INDIA is predominantly an agriculture-dependent nation and the southwest monsoon plays an important role in its economy. Onset of the monsoon and its progress command all agricultural operations from sowing of crops till harvest. Under rainfed agriculture, the phenology of the crop is greatly influenced by its antecedent rainfall. Though the total amount of rainfall received during the season is normal for the country, some parts of India are affected by drought due to uneven distribution of rainfall both spatially and temporally. In this context it is imperative to study the rainfall variation and its effect on vegetation. An attempt has been made in this study using remote sensing data to find the effect of seasonal rainfall on vegetation.

Remote sensing studies of vegetation normally use specific wavelengths selected to provide information about the vegetation present in the area from which the radiance data emanate[1]. The differential reflection of green vegetation in the visible and near infrared portions of the spectrum provides an innovative method for monitoring vegetation from space[2]. The Normalized Difference Vegetation Index (NDVI) is commonly used in this context[3,4]. This index is derived from Advanced Very High Resolution Radiometer (AVHRR) data from NOAA 9 to NOAA 14 polar orbiting satellite and is defined as

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

where R and NIR are the reflectance in the visible (0.58 to 0.68 μm) and near infrared (0.725 to 1.1 μm) channels respectively[2]. NDVI correlates well with variables such as green leaf biomass, leaf area index (LAI), total dry matter accumulation and annual net primary production[5–7].

Thus NDVI has become the primary tool for description of vegetation changes and interpretation of the impact of environmental phenomena[8]. NDVI is also effectively used for monitoring rainfall and drought, estimating net primary production (NPP) of vegetation and crop yields, detecting weather impacts and other events important for agriculture, ecology and economics[4,8,9]. The relation between rainfall and NDVI in southern parts of Africa was studied and results show that monthly NDVI follows monthly rainfall with a lag of one to two months and is best correlated with the bimonthly antecedent rainfall[10]. In a similar study in East Africa, NDVI and rainfall associations are analysed for ten vegetation formations. The study found that there is a strong similarity in both temporal and spatial patterns of the NDVI with rainfall[2].

Most of the above studies were carried out in the African continent where the rainfall pattern is different from the monsoon rainfall that exists in Andhra Pradesh (AP) (study area), India. Secondly the vegetation formation that exists in the districts of AP is different from that of Africa. In this study an attempt was made to find out the relation between the vegetation response to rainfall through NDVI for the study area and the applicability of this study is also discussed.

Data used and methodology

This study was carried out as part of a national operational project called the National Agricultural Drought

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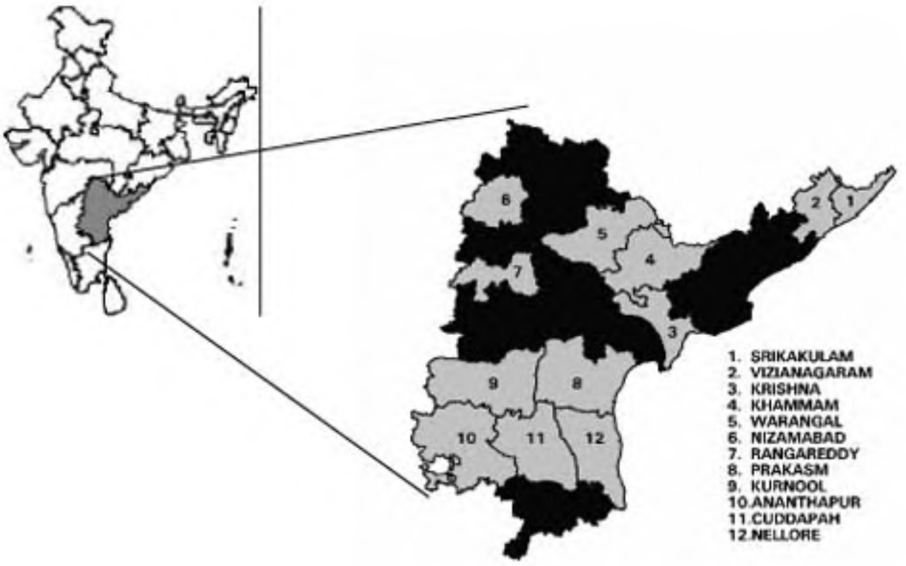

Figure 1. Location map of the study area.

Assessment and Monitoring System (NADAMS). The aim of the project was to provide space-based input on the prevalence, persistence and severity of drought to the administrators and decision-making authorities for drought management. The basic unit of drought management in India is a district for which the District Collector is the authority for relief management. Most of the data generated and available from this project have the district as a unit. Hence, this study has considered the district as its unit instead of agro-ecological zones or meteorological subdivisions.

Study area

The study area chosen consists of twelve districts of AP (Figure 1). AP is divided into three meteorological subdivisions. Districts were chosen in such a way that all three sub-divisions were represented.

The districts chosen for the study are:

Costal Andhra:	Srikakulam, Vizianagaram, Krishna, Prakasam and Nellore
Telangana region:	Rangareddy, Warangal, Khammam and Nizamabad
Raylaseema region:	Ananthapur, Cuddapah and Kurnool.

Secondly, the twelve districts were chosen taking into consideration their diverse land use. The land use for these districts and the type of vegetation such as percentage forest area, net crop sown area and net irrigated area are given in Table 1. The forest area in these districts ranges from 7.54 to 47.67%, net sown area from 26.07 to as high as 54.62% and irrigated area from 7.58 to 37.40% of the geographical area. Among the above districts, one with the least area under vegetation is Nellore (70.36%) and maximum vegetated area is Warangal (91.34%). Thirdly, the districts were chosen such that they fall under low rainfall to high rainfall zone.

Satellite data

The NOAA (National Oceanic and Atmospheric Administration) satellite, AVHRR (Advanced Very High Resolution Radiometer) Sensor's Local Area Coverage (LAC) data acquired daily at National Remote Sensing Agency (NRSA) earth station near Hyderabad, India have been used in this study. The 1.1 km NOAA–AVHRR data during the kharif season (June to October) from 1989 to 1998 has been used. The years 1991 and 1994 are not considered due to the aerosol effect of the Mt. Pinotobu volcanic eruption and non-availability of data respectively. Monthly NDVI generated as part of the NADAMS project at NRSA, Department of Space, Govt of India have been used. The brief methodology of the satellite data processing is given in Figure 2.

Rainfall

The district average rainfall data from India Meteorological Department (IMD) were used in this study. Monthly district-wise average rainfall data for all the districts under study from 1989 to 1998 were used.

Land-use statistics

The land-use statistics of all the districts was collected from Directorate of Economics and Statistics, Govern-

Table1. Percentage of different land use in the districts

District	Non-vegetated area (%)	Vegetated area (%)	Forest area (%)	Net sown area (%)	Net irrigated area (%)
Ananthapur	17.49	82.52	10.29	51.38	7.58
Cuddapah	26.65	73.34	32.87	25.30	10.27
Khammam	12.76	87.25	47.67	29.40	12.46
Krishna	22.63	76.70	7.54	55.39	37.40
Kurnool	11.36	88.64	18.08	51.09	10.17
Nellore	29.54	70.36	18.86	23.98	20.67
Nizamabad	16.67	83.32	21.53	32.05	19.72
Prakasam	17.49	82.50	25.82	34.30	11.49
Rangareddy	16.04	83.96	9.70	39.71	9.96
Srikakulam	23.51	76.50	12.08	55.71	31.16
Vizianagaram	24.22	75.78	17.76	51.86	23.17
Warangal	8.63	91.34	28.91	34.01	23.45

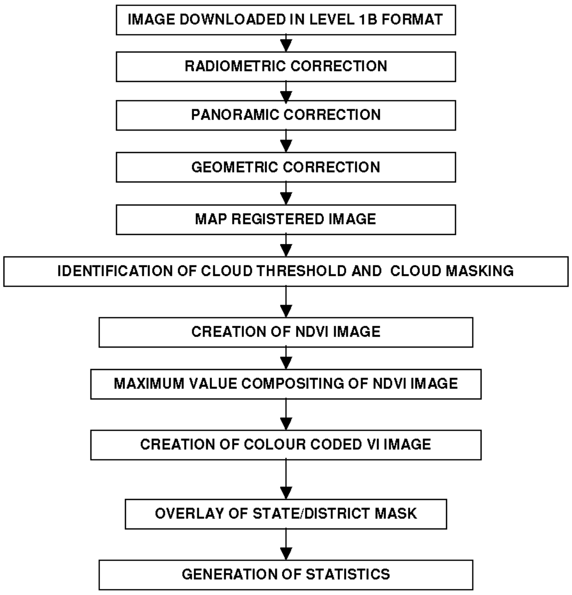

Figure 2. NOAA–AVHRR data processing methodology.

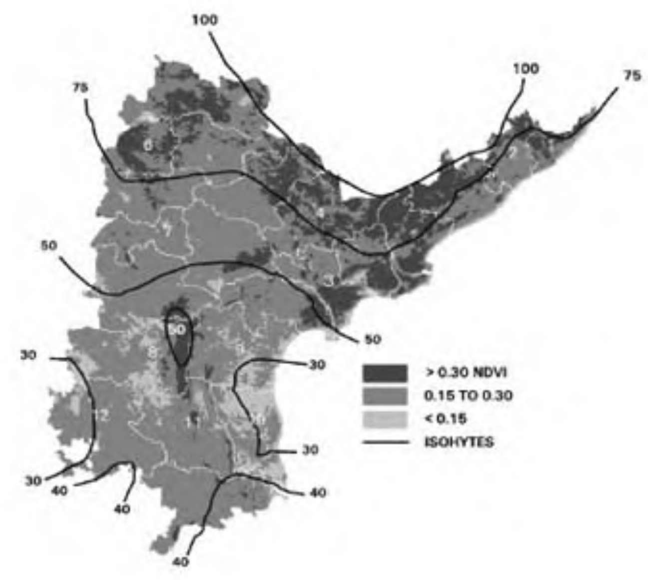

Figure 3. Mean of maximum NDVI (1989–98) of Andhra Pradesh overlaid with isohyets.

ment of AP. The percentage of land use under different categories for all the districts is given in Table 1.

Results and discussion

Relation between seasonal maximum value composite NDVI and rainfall

Davenport and Nicholson[2] used the integrated NDVI to relate rainfall with NDVI. To derive the NDVI–rainfall relation, Kogan[8] suggested the use of a normalization of NDVI values relative to the absolute maximum and the absolute minimum of NDVI. Richard and Poccard[10] used the raw annual mean to investigate the NDVI–rainfall relation. In this study the maximum NDVI during the month has been used to relate rainfall.

The southwest monsoon (June to September) contributes 68.5% of the annual rainfall in AP. Figure 3 shows that the northern parts of the State receive maximum rainfall up to 100 cm and it decreases gradually towards the south, which receives around 30 cm of rainfall. It can be seen from the mean of maximum NDVI during the monsoon period (June to October) from 1989 to 1998, that the region of maximum NDVI occurs in the region of maximum rainfall. There is a marked similarity between the spatial association of the seasonal rainfall and NDVI. The southwestern parts of the State, which receive the least rainfall of 30 cm, have low NDVI ranging from 0.05 to 0.2. The north and the northeastern parts which receive 100 cm rainfall, have high NDVI (> 0.3). The forest area, which receives rainfall of 50 cm, also has high NDVI. The seasonal mean of maximum NDVI corresponds well to rainfall with the linear correlation of 0.81, which is significant at 90% level and confirms the strong association between rainfall and density of the vegetation in the respective zones.

Classification of districts based on NDVI and its coefficient of variation

In the analysis of the relationship of NDVI with rainfall, it is found that low NDVI occurs in low rainfall regions and high NDVI occurs in high rainfall regions. In order to classify the districts based on the range of NDVI and its variations, the monthly average NDVI and its coefficient of variation from 1989 to 1998 is analysed. Figure 4 shows a plot of the average NDVI profile (1989–98) and Figure 5 shows plot of the monthly coefficient of variation of NDVI of the study districts. Warangal, Nizamabad, Srikakulam, Vizianagaram and Khammam have relatively high NDVI profile (Figure 4 *a*) throughout the season. The minimum NDVI at the start of the season is above 0.1 and goes beyond 0.25 at its peak vegetation. All these districts lie in the northern part of the State, which receives seasonal annual rainfall of 750 to 1000 mm. The coefficient of variation (Figure 5 *a*) profile of the above districts shows high variation during June and July and less variation during October. This is due to the fact that these districts are highly vegetated, having considerable forest area (> 10%). Hence the high NDVI at the start of the season is subject to fluctuation due to the variation in the onset of monsoon during the initial months. As the season progresses, the vegetation gets stabilized and becomes insensitive to small fluctuations in rainfall.

Districts with low NDVI profile (Figure 4 *b*) like Ananthpur, Prakasam and Nellore fall in the low rainfall zone of 300 to 400 mm. All these districts are in the southern part of the State. These districts have predominant areas under

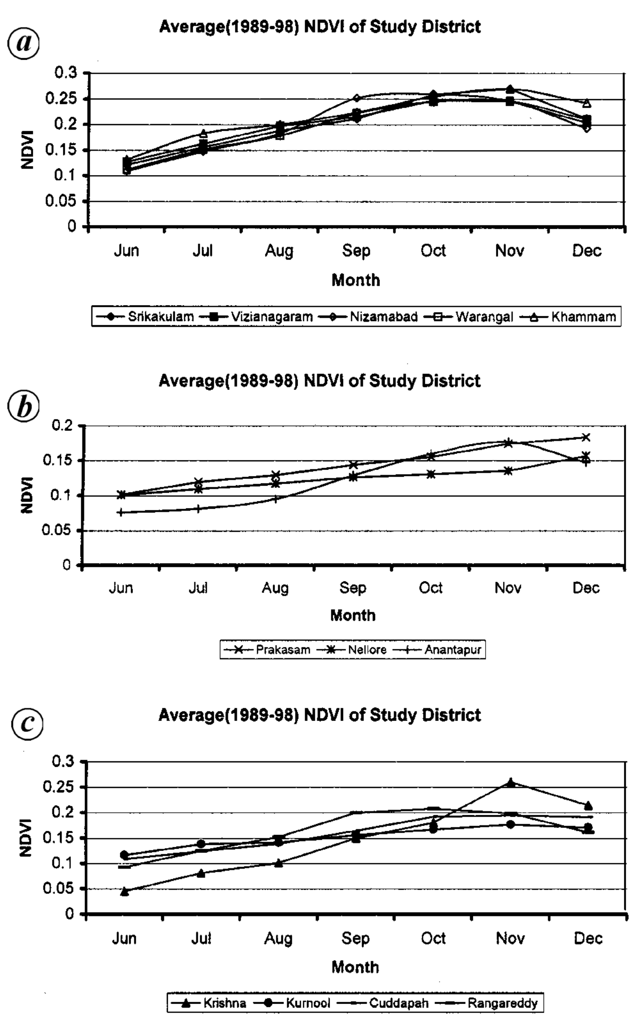

Figure 4. Average NDVI profile (1989–98) of the study districts.

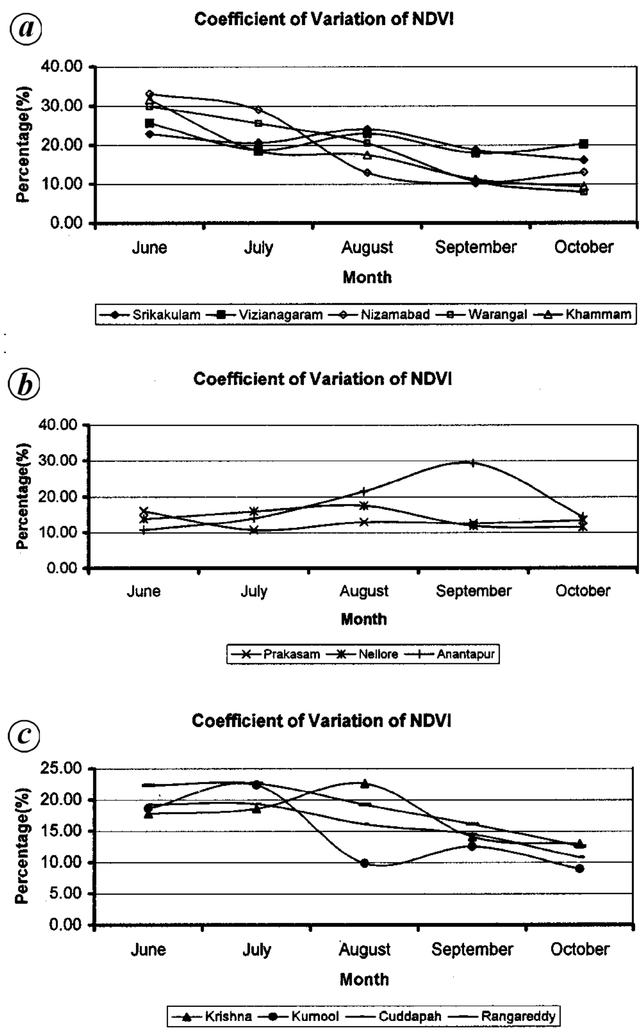

Figure 5. Coefficient of variation of NDVI of the study districts.

rainfed agriculture. Unlike the high NDVI districts, C_v (Figure 5 *b*) is almost uniformly low throughout the season except Ananthapur district which shows high C_v during September. Since there is no vegetation at the start of the season, there is no fluctuation of NDVI due to variation in the onset of monsoon or the amount of rainfall received. Hence C_v is low during the start of the season and stable throughout the season. All the other districts, namely Krishna, Cuddapah, Kurnool and Rangareddy have moderate NDVI profiles (Figure 4 *c*) which lie between the profiles of the above two groups of districts (i.e. districts with high and low NDVI profiles). The coefficient of variation of monthly NDVI (Figure 5 *c*) for these districts also lies between the high and low NDVI districts (i.e. below 25% at the start of the season and below 15% towards the end of the season). All these districts lie in the rainfall zone of around 500 mm. Here again, because of high percentage of vegetated area in the districts, there is high C_v at the start of the season which then reduces later in the season. Table 2 gives the classification of districts based on NDVI and its coefficient of variation.

NDVI lag over rainfall

The general phenology of the vegetation, which is translated as NDVI, closely resembles the seasonal cycle of rainfall of the region. The response of NDVI to rainfall has a lag, which is confirmed by Justice *et al.*[11]. Monthly NDVI follows monthly rainfall with a lag of one to two months and is best correlated with the bimonthly antecedent rainfall[12].

The districts under study have varying proportions of vegetated and non-vegetated areas. Different classes of vegetated area are forest and agricultural areas. Non-vegetated area includes barren land and land put to non-agriculture use. The average NDVI response from the districts will be influenced by land use and the cropping pattern of the districts under study.

The average monthly rainfall and monthly and cumulative monthly rainfall were calculated. The single-month rainfall was correlated with the monthly average NDVI for the same month (0), one-month lag NDVI (1) and two-month lag NDVI (2). In order to find the cumulative effect or rainfall over NDVI, the two-month (0 + 1, 1 + 2) and three-month (0 + 1 + 2) cumulative rainfall was correlated with the same month and with one-month lag.

Table 3 gives the correlation coefficient of the district with different time lag as discussed above. The correlation coefficient, which is significant at 90% significance level, is bold. It can be observed that in Kurnool, Nizamabad, Vizianagaram, Rangareddy and Warangal, NDVI with two-month lag has the maximum correlation. Such a relation was also observed by Richard and Poccard[10], who concluded that monthly NDVI data follow monthly rainfall data with a lag of one to two months and are best correlated with the bimonthly antecedent rainfall. Davenport and Nicholson[2] also reported that the best association

Table 2. Classification of districts based on NDVI and coefficient of variation (C_v)

Seasonal peak NDVI	Max C_v during the season	District
High NDVI (> 0.25)	High C_v (> 25%)	Srikakulam, Vizianagaram, Nizamabad, Warangal, Khammam
Moderate NDVI (0.2–0.25)	Moderate C_v (15–25%)	Prakasam, Nellore and Ananthapur
Low NDVI (< 0.2)	Low C_v (<15%)	Krishna, Kurnool, Cuddapah and Rangareddy

Table 3. Correlation between monthly NDVI and rainfall at various time lags

	Time lag					
	0	1	2	0 + 1	1 + 2	0 + 1 + 2
	n = 36	*n* = 36	*n* = 36	*n* = 27	*n* = 27	*n* = 18
District	0.00	1.00	2.00	0 + 1	1 + 2	0 + 1 + 2
Ananthapur	0.30	0.35	0.43	0.42	0.50	**0.63**
Cuddapah	0.28	0.54	0.56	0.66	**0.75**	0.58
Khammam	0.34	0.15	0.26	0.25	0.11	–0.11
Krishna	0.27	0.34	0.35	0.29	**0.41**	0.15
Kurnool	0.34	0.02	**0.41**	0.15	0.11	0.17
Nellore	–0.09	0.15	0.03	–0.12	–0.03	–0.15
Nizamabad	–0.20	–0.07	**0.40**	–0.07	0.00	0.05
Prakasam	0.39	0.42	0.50	0.37	**0.59**	0.51
Rangareddy	0.05	0.13	**0.57**	0.06	0.32	0.20
Srikakulam	–0.08	0.04	0.22	–0.01	0.05	0.11
Vizianagaram	0.26	0.31	**0.45**	0.37	0.39	0.37
Warangal	–0.20	–0.08	**0.47**	–0.07	0.04	0.17

Figures in bold indicate significant at $P = 0.1$

on a monthly scale is generally between NDVI and two previous months indicating lagged response. Four out of the total 12 districts have the highest correlation with multi-month cumulative rainfall. Cuddapah, Krishna and Prakasam have the highest correlation with 1 + 2 cumulative monthly rainfall and Ananthapur district has highest correlation with 0 + 1 + 2 cumulative monthly rainfall. All the district correlation coefficients at two-month lag are significant at 90% confidence level, except Nellore and Srikakulam. In the following section we shall discuss sets of districts based on the strength of correlation coefficient. Table 4 shows the districts with different lagged NDVI responses to rainfall.

Districts having strong correlation (> 0.5)

It can be observed from the table that the districts of Ananthpur (0.63), Cuddapah (0.75), Prakasam (0.59) and Rangareddy (0.57) districts have the high correlation coefficients (> 0.5). The vegetated area of all these districts is over 80%, except Cuddapah (74%). All these four districts fall in the low rainfall zone of the State (300–400 mm). Another common feature is that all these districts have net irrigated area less than 12% of the total vegetated area. Since irrigated areas have their own vegetation/NDVI cycle, which usually does not match with the rainfall-induced vegetation cycle, the less irrigated areas in these districts lead to better correlation of NDVI with rainfall.

Districts having moderate correlation (> 0.4 and < 0.5)

The correlation coefficients of Warangal (0.47), Vizianagaram (0.45), Nizamabad (0.40), Kurnool (0.41) and Krishna (0.41) all have a two-month lag, except Krishna district, which has 1 + 2 cumulative monthly rainfall correlation. All these districts have vegetated area above 75% of its geographical area. The percentage of net irrigated area of these districts is Warangal (23%), Vizianagaram (23%), Nizamabad (20%), Kurnool (10%) and Krishna (37%). These districts also have considerable forest area with Warangal (29%), Vizianagaram (18%), Nizamabad (22%), Kurnool (18%) and Krishna (8%). These two predominant vegetation features have diverse NDVI cycles. The forest vegetation responds to the rainfall events, while the irrigated area NDVI does not always respond to the rainfall. This gives a mixed response to the rainfall and hence the moderate correlation coefficient (> 0.4 and < 0.5) can only be attributed to the high percentage of both irrigated and forested area in all the above districts.

Table 4. Districts showing different lagged NDVI response to rainfall

Time lag (months)	District
2	Kurnool, Nizamabad, Vizianagaram, Rangareddy and Warangal
1 + 2	Cuddapah, Krishna and Prakasam
0 + 1 + 2	Ananthapur

Districts having poor correlation (<0.4)

Srikakulam ($r = 0.22$) has 41% of area under net irrigation and its total vegetation area is 76%. The low correlation is thus attributed to high percentage of net irrigated area (31%), which tends to offset the response of NDVI.

Nellore, which is in the southeastern part of AP, receives more rainfall during the northeast monsoon (October to December; 60%) than the southwest monsoon (June to September; 31%). Its vegetated area is the least at 70% of its geographical area. Most of the agricultural activity is carried out only during the northeast monsoon season (October to February). Further, C_v of rainfall during the southwest monsoon is high at 40.17%. Hence the correlation of NDVI with the southwest monsoon rainfall is poor.

Khammam has a coefficient of 0.26 at 90% confidence level. It has 86% of its geographical area under vegetation, of which 47% is under forest and only 17% under rainfed crops. Hence, majority of the vegetated area is dense forest where the change of NDVI is not so rapid as in the case of the semi-arid region in response to rainfall.

Relation between total seasonal rainfall and seasonal cumulative NDVI

The cumulative NDVI is directly proportional to the accumulated biomass. The cumulative NDVI can be directly correlated to the yield. The effect of the first three months rainfall during the monsoon on cumulative NDVI is crucial to the cumulative NDVI-based biomass estimation or yield estimation. The total rainfall from June to August and the total seasonal rainfall (June to September) were correlated with the cumulative NDVI of the season for all the study years. Table 5 shows the correlation coefficients. It can be observed from Table 5 that correlation of three-month rainfall (June to August) with seasonal cumulative NDVI is high when compared with the seasonal rainfall and seasonal cumulative NDVI. All the districts have a fair correlation ranging from 0.44 to 0.82 in the three-month rainfall and 0.44 to 0.72 in the seasonal rainfall. Only Rangareddy district has poor correlation under both circumstances. In general, the correlation decreases when cumulative NDVI is related to seasonal rainfall. This indirectly indicates that the first three months rainfall is crucial in achieving the normal cumulative NDVI, and monitoring the first three months rainfall is important in giving the yield forecast for the season.

Table 5. Correlation between seasonal integrated NDVI and rainfall ($n = 9$)

District	June to August	June to October
Ananthpur	0.82	0.66
Cuddapah	0.72	0.72
Khammam	0.80	0.50
Krishna	0.67	0.44
Kurnool	0.44	0.19
Nellore	0.56	0.51
Nizamabad	0.58	0.48
Prakasam	0.76	0.47
Rangareddy	0.18	0.14
Srikakulam	0.63	0.46
Vizianagaram	0.69	0.56
Warangal	0.62	0.62

Application of the study

Drought is a period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance and carries connotations of a moisture deficiency with respect to man's usage of water[12]. There are several indices to identify the beginning, end, spatial extent and severity of a drought. The most commonly used space-based index to describe drought is the NDVI. Hence this study has focused on the NDVI and its responses to rainfall. The study confirmed the relation between the density of vegetation and the amount of rainfall in the study area even under the monsoon type of rainfall, which is only four months in a year.

This study classified the districts based on level of NDVI and its coefficient of variation. The first two months of the kharif season is critical for the success of the season as crop emergence takes place during this period and it depends on the onset of the monsoon. Warangal, Nizamabad, Srikakulam, Vizianagaram and Khammam, which have high NDVI profiles have high C_v during June and July. This implies that the anomalous low or high values of NDVI during this part of the season are normal for these districts. On the contrary, Ananthapur, Prakasam and Nellore, which fall under the low rainfall zone with low NDVI profile have low C_v throughout the season. In these districts, anomalous variation at the start of the season, particularly negative deviation should be viewed critically for the success of the crop. Hence, during the early season drought assessment, variations in NDVI in the districts falling under the high rainfall zone with high C_v do not cause concern, while negative variation in the NDVI in the districts falling under the low rainfall zone with low C_v may lead to drought conditions.

The lagged response of NDVI to rainfall is a known fact but the period of lag varies from place to place depending upon the type of vegetation. In this study the districts were classified based on the lagged response to rainfall and this lagged response was attributed to the proportion of vegetated area under forest, irrigated area and rainfed area. The lagged response of NDVI to rainfall helps in forewarning of the vegetation condition, particularly in low NDVI cases, when a district suffers from water stress for two continuous fortnights. Depending on the lagged response of the district to rainfall, the forewarning could be issued on the condition of the crops.

The seasonal cumulative NDVI can be correlated to the yield and if a strong relation is established, it can be used to forecast the yield. The performance of the cumulative NDVI is dependent on the seasonal rainfall. This study shows that the first three months (June to August) rainfall has better correlation with the seasonal cumulative NDVI than the total seasonal rainfall. This implies that based on the performance of the first three months rainfall, one can predict the cumulative NDVI, which in turn can be used to forecast the yield.

Conclusion

The vegetation response to rainfall has been studied from different angles using the NOAA–AVHRR data. From the analysis of the rainfall and the NDVI data, it can be observed that maximum NDVI occurred in the region which received maximum rainfall and vice versa. The mean of maximum NDVI and the corresponding rainfall in the region have a linear correlation of 0.81, which is significant at 90% level. This confirms the strong association between rainfall and density of the vegetation in the respective zones.

Based on the analysis of NDVI profiles and the corresponding C_v the districts could be classified as those with high NDVI profile with high C_v at the start of the season, namely Srikakulam, Vizianagaram, Nizamabad, Warangal and Khamman and districts with low NDVI profile with low C_v throughout the season like Prakasam, Nellore and Ananthpur. Districts which fall between high and low NDVI and C_v profiles are those of Krishna, Kurnool, Cuddapah and Rangareddy. With reference to the lagged response of district NDVI to rainfall; Kurnool, Nizamabad, Ranga Reddy, Vizianagaram and Warangal have a two-month lag response to rainfall. Cuddapah, Krishna and Prakasam have the highest correlation with two-month (1 + 2) cumulative monthly rainfall and Ananthapur has highest correlation with (0 + 1 + 2) cumulative monthly rainfall. The district average NDVI of Khammam, Nellore and Srikakulam did not show significant lagged response to rainfall. The June to August cumulative rainfall and the total season cumulative rainfall were correlated with seasonal cumulative NDVI. The June to August rainfall shows higher correlation with cumulative NDVI than the seasonal rainfall. Hence the initial three month (June to August) rainfall is important for the normal development of the seasonal NDVI. This study has brought out clearly the lagged relation of NDVI with rainfall and how this relation can be used in drought-monitoring and assessment.

However, the strength of the relation and the duration of the lag vary from place to place depending on the land use. Hence further detailed studies have to be taken up for each agro-climatic region of the country to obtain the NDVI lagged relation with rainfall.

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