MAUSAM, **74**, 4 (October 2023), 973-988

MAUSAM

DOI : https://doi.org/10.54302/mausam.v74i4.6040
Homepage: https://mausamjournal.imd.gov.in/index.php/MAUSAM

UDC No. 551577.38 (540.65)

Drought analysis in southern region of Tamil Nadu using meteorological and remote sensing indices

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(*Received 13 October 2022, Accepted 24 January 2023*)

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सार — **सूखा एक प्राकृतिक घटना है जो किसी क्षेत्र में अपेक्षित मात्रा की तुलना में अपर्याप्त वर्षा के कारण होता है, जो लंबे समय तक जारी रहने पर अंततः विभिन्न मानवीय गतिविधियों को बनाए रखने के लिए पानी की कमी का कारण बनता है। एक महीने का मानकीकृत वर्षा सूचकांक (SPI) से पता चला कि दक्षिणी क्षेत्र में मध्यम सूखे की स्थिति का अत्यधिक खतरा है। SPI के ऋतुनिष्ठ विश्लेषण से पता चला कि इस क्षेत्र को पूर्वोत्तरमॉनसून (NEM) ऋतु की तुलना में दक्षिणपश्चिमी मॉनसून (SWM) के दौरान अधिक सूखे की घटनाओं का सामना करना पड़ा। थूथुकुडी, डिंडीगुल, पुदुक्कोट्टई और विरुधुनगर में ऋतुनिष्ठ और वार्षिक पैमाने पर सूखे की अधिक घटनाएं देखी गईं। पूर्वोत्तर मॉनसून 2016, 2017 और 2018 के दौरान सामान्यीकृत अंतर वनस्पति सूचकांक (NDVI) से पता चला कि दक्षिणी जिलों में कुल क्षेत्र का 80 प्रतिशत से अधिक क्षेत्र सूखे की चपेट में था। NDVI विश्लेषण से पता चला है कि थूथुकुडी, रामनाथपुरम, पुदुक्कोट्टई, शिवगंगई और विरुधुनगर जिले सूखे के प्रति अत्यधिक संवेदनशील हैं। पूर्वोत्तर मॉनसून 2016, 2017 और 2018 के दौरान सामान्यीकृत अंतर जल सूचकांक (NDWI) विश्लेषण ने इन तीन वर्षों के दौरान 90 प्रतिशत से अधिक क्षेत्र में सूखे की स्थिति के साथ अधिक सूखे की स्थिति को देखा गया। NDVI और NDWI विश्लेषण से पता चला कि तमिलनाडु का दक्षिणी क्षेत्र मध्यम और गंभीर सूखे के प्रति सबसे अधिक संवेदनशील था। एनडीवीआई और एनडीडब्ल्यूआई और 3-, 6-, 9- और 12-महीने के मानकीकृत वर्षा सूचकांकों की तुलना से पता चला कि तीनों सूचकांक एक-दूसरे के साथ काफी सटीक हैं और इसलिए सूखे के विश्लेषण में उपयोगी हैं। हालाँकि, केवल एक सूखा सूचकांक सूखे की स्थानिक और कालिक सीमा को स्पष्ट रूप से परिभाषित नहीं कर सकता है। इस प्रकार, मौसम विज्ञान और दूर संवेदी सूचकांकों के संयोजन ने सूखे की स्थानिक-कालिक सीमा के बारे में एक विस्तृत विचार दिया है।**

ABSTRACT. Drought is a natural phenomenon caused due to inadequate rainfall over a region as compared to the expected amount, which when sustained over an extended period of time, eventually leads to shortage of water to sustain various human activities. One-month Standardized Precipitation Index (SPI) showed that the southern zone is highly prone to moderate drought conditions. The seasonal analysis of SPI showed that the region faced more drought instances during the South West Monsoon (SWM) compared with North East Monsoon (NEM) season. Thoothukudi, Dindigul, Pudukkottai and Virudhunagar showed the high occurrences of drought at seasonal and annual scale. Normalized Difference Vegetation Index (NDVI) during the NEM 2016, 2017 and 2018 showed that more than 80 per cent of the total area in the southern districts was under drought stress. NDVI analysis showed that Thoothukudi, Ramanathapuram, Pudukkottai, Sivagangai and Virudhunagar districts are highly vulnerable to drought. Normalized Difference Water Index (NDWI) analysis during the NEM 2016, 2017 and 2018 showed high drought stresses with more than 90 per cent of the area showing drought stress during these three years. NDVI and NDWI analysis showed that the southern region of Tamil Nadu was most vulnerable to Moderate and Severe droughts. The comparison of NDVI and NDWI and 3-, 6-, 9- and 12-month SPI showed that the three indices are fairly accurate with each other and hence are useful in the analysis of drought. However, just a single drought index cannot clearly define accurately the spatial and temporal extent of drought. Thus, a combination of meteorological and remote sensing indices gave a detailed idea about the spatio-temporal extent of drought.

Key words – Drought, SPI, NDVI, NDWI, Tamil Nadu.

1. Introduction

Drought is a natural phenomenon caused due to inadequate rainfall over a region in comparison to the expected amount, which when sustained over a longer period of time, eventually leads to shortage of water to sustain various human activities. Drought occurs as a result of the inadequate and irregular rainfall distribution and the intensity and the spatial coverage is impacted by various factors including the agroclimatic properties of the area, the cropping system used and the cropped area, the surface and ground water system conditions also plays an important role in the incidence of drought events (Wilhite, 2000a). Several states of India have fallen victims to these recurrent, long-term drought events leaving a marked disastrous aftermath on the various resources including the water resources, our ecosystems and also hampers various socioeconomic developments (Glantz, 1994).

Over the last few decades, India has faced frequent and severe droughts once in every three years (Mishra *et al.*, 2016) and the frequency and the intensity is expected to increase over the next few decades especially between 2020 to 2050 (Kulkarni *et al.*, 2016). The all-India drought that occurred in 2002 was one of the worst that the country has faced. The event saw a rainfall deficit of 22 percent which affected around 300 million people (Samra, 2004). In 2016, another all-India drought struck and affected over 330 million people caused due to the monsoon failures during the previous two years (Choudhary, 2016). Accordingly, in 2016-17, the state of Tamil Nadu faced one of the worst drought events in 140 years with a rainfall deficit of 82 percent, one of the lowest in India and eventually this caused the government to announce drought which causes several disturbances within the state (Kedia, 2017). The government of Manipur was forced to declare drought in 2019 when the state saw a rainfall deficit of 50 percent and a 60 percent deficit in the water reservoirs, seriously affecting over 90,000 hectares of agricultural land within 70 Blocks. The crop failure was estimated to be around 33 to 50 percent (Sarojkumar Sharma, 2019).

Drought is further classified into different categories: (*i*) Meteorological Drought (*ii*) Hydrological Drought (*iii*) Agricultural Drought and (*iv*) Socio-Economic Drought (Wilhite and Glantz, 1985). Agricultural drought is the condition where the soil moisture content is depleted to the point where crops vegetation cannot further flourish and is closely marked with the increased canopy temperature of the crops (Alshaikh, 2015). It is practically impossible to avoid drought events. However, when they do happen, the extreme effects can be alleviated through advanced and continuous assessment and monitoring (Agnew and Warren, 1996; Le Houérou, 1996; Smakhtin and Hughes, 2007). Drought intensity and frequency are becoming more common as a consequence of climate change (Jentsch and Beierkuhnlein, 2008). Drought can exacerbate already-suffering economic losses. Drought is expected to become more frequent and severe as a result of climate change, posing a threat to agriculture (IPCC, 2007; Mir *et al.*, 2012). Drought has a direct impact on agriculture due to high dependence of agriculture on weather and atmospheric physical conditions.

The agricultural sector is usually the first to be affected by drought with the rapid decrease of soil moisture content and this process is further accelerated with the influence of high temperatures and heavy winds (Wilhite, 2000a). This raises the necessity to improve the assessment and monitoring of drought conditions particularly in the most vulnerable regions in order to reduce the losses. Thus, it is highly crucial to have a thorough knowledge and understanding of drought aspects as well as the development of an effective approach to monitor drought events through a combination of various factors including the climatology, soil factors and the water supply factors (Wilhite, 2000b; Kim *et al.*, 2009; Vengateswari *et al.*, 2019).

The state of Tamil Nadu which lies in the southernmost part of the Indian subcontinent receives the majority of its rainfall during the North East Monsoon (NEM) season and is heavily rain shadowed during the South West Monsoon (SWM) season. The climatology of the state has been characterized as Semi-Arid to Arid regions (Nathan, 1998). This makes the state more vulnerable to droughts at varying extent and intensity. Particularly, the southern region is exposed to drought conditions especially during the North East Monsoon Seasons (Ramaraj *et al.*, 2015; Kokilavani *et al.*, 2021).

Several drought indices have been formulated by researchers to accurately describe the climatic conditions of several areas of the world so as to describe accurately, the extent of drought and to assess the risks over several regions routinely (Smakhtin and Hughes, 2007). several studies have been used in India using the precipitation-based indices like Percent Normal Precipitation (PNP), Standardized Precipitation Index(SPI), Enhanced Drought Index (EDI) and Palmer Drought Severity Index (PDSI) (Mishra and Desai, 2005; Pai *et al.*, 2011; Vengateswari *et al.*, 2019; Kokilavani *et al.*, 2021). The Standardized Precipitation Index (SPI) has been recommended by World Meteorological Organization (WMO) as the standard meteorological drought index (Hayes *et al.*, 2011).

Satellite remote sensing technology advancements have made it convenient to regularly monitor crop health and conditions across wide areas. Remote sensing and Geographic Information System (GIS) play a crucial role in agricultural drought diagnosis, assessment, and management since they offer current information at various spatial and temporal scales, which is difficult and time-consuming to obtain using conventional methods like Field Survey and questionnaire sampling (Thenkabail and Gamage, 2004; Murad and Islam, 2011; Wardlow *et al.*, 2012). Numerous scientists have regarded the vegetation index as one of the crucial variables for mapping agricultural fields, forecasting weather effects, calculating biomass, crop output, assessing drought conditions, and assessing the strength of the vegetation (Tucker *et al.*, 1982; Justice *et al.*, 1985; Hielkema *et al.*, 1986; Dabrowska-Zielinska *et al.*, 2002; Narasimhan and Srinivasan, 2005; Chakraborty and Sehgal, 2010; Kumar and Srinivasan, 2016).

It is believed that the Normalized Difference Water Index (NDWI) will provide more accurate information regarding the condition of vegetation or crops turgidity and health. It is based on the Shortwave Infrared (SWIR) band, which can detect moisture levels in both crop canopy and soil. The soil backdrop is prominent at the start of the growing season, making SWIR responsive to moisture content in the top 1-2 cm. SWIR develops sensitivity to foliar moisture content as the crop grows. A higher NDWI value indicates a wetter surface and *vice versa*.

Another often used indicator in studies based on analyses of the categorization, phenology and land use of vegetation is the Normalized Difference Vegetation Index (NDVI) (Tarpley *et al.*, 1984; Tucker *et al.*, 1985). NDVI is a frequently used attribute to assess drought, examine vegetation health, and estimate production (Kogan, 1987; Dabrowska-Zielinska *et al.*, 2002; Singh *et al.*, 2003). The difference between reflectance in the Near Infrared (NIR) and red wavelength bands of the electromagnetic spectrum is used to compute the NDVI.

Thus, with all this knowledge in perspective, a study was conducted in Agro-Climate Research Centre, Tamil Nadu Agricultural University, Coimbatore to assess the frequency and intensity of drought events in the Southern Region of Tamil Nadu with the objectives delineating drought using various meteorological and remote sensing indices and to compare the results from both satellite and observed inferences.

2. Materials and methodology

2.1. *Study area*

The study area is geographically located between 8° 9’ and 10° 50’ North Latitude and 77° 10’ and 79° 25’ East Longitude. The area extends from the high mountain regions in the west up to the coastal regions in the East. The area consists of the following districts, *viz.*, Dindigul, Madurai, Pudukkottai, Sivagangai, Tenkasi, Theni, Thoothukudi, Tirunelveli, Ramanathapuram and Virudhunagar. The study area map is depicted in Fig. 1. The elevation varies from the 100m above the mean sea level at the eastern coast and up to 2000m in the hilly region of western. This region of Tamil Nadu lies under the rain shadow region because of the Western Ghats. The maximum average annual temperature is 32 °C, rising to 41 °C in the summer. The minimum mean annual temperature is 23 °C and it lowers to around 14 °C in the winter. The climate is classified as tropical monsoon. The mean annual rainfall in the region is about 857 mm in 43 rainy days, of which 400mm is received during Northeast monsoon season. The region receives the majority of its rainfall during the NEM. The soil of this region includes coastal alluvium, black, red sandy soil and deep red soil.

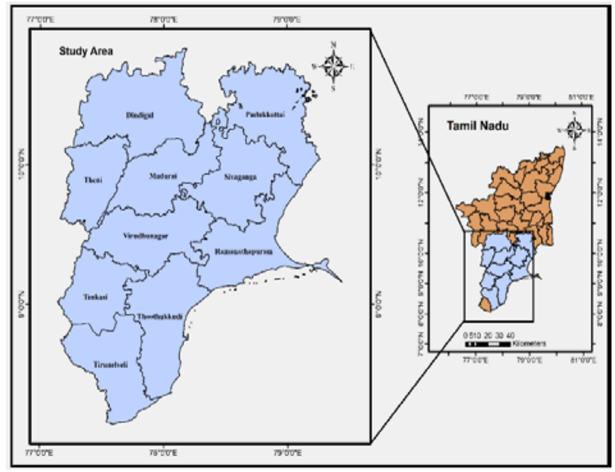

Fig. 1. Study area map

The total geographical area of the southern region of Tamil Nadu is about 41387.9 sq km or 41,38,790 ha. The total area under cultivation is 16,60,250 hectares which amounts to about 45 percent of the total area. Out of the total area under cultivation, the total irrigated area is around 7,22,166 hectares which is around 44 percent of the total area. The southern region covers the rivers of Vaigai, Sitrar, Thamraparani, Numbiar, Pachaiyar, Kludar, Arjunar, Kodumudiyaar, Manimuthar and Periyar. The patterns of irrigation are well irrigation, canal irrigation and irrigation by dams and lakes. The major crops grown in the region include rice, cotton, millets, sugarcane, sunflower, coriander and bengal gram. Sorghum, cotton and sunflower are cultivated as rainfed crops during Northeast monsoon season.

2.2. *Rainfall data*

The 30 years (1991-2020) district-wise historical rainfall data was collected from the respective research stations under Tamil Nadu Agricultural University located within the study area, *viz.*, Madurai, Thirunelveli, Thoothukudi, Virudhunagar, Pudukkottai, Dindigul and Theni. In addition to this, data was also collected from India Meteorological Department (IMD), Pune for those districts (Ramanathapuram, Tenkasi and Sivagangai) where the historical datasets could not be obtained. The study was focused mainly on the NEM Season, since this season have a profound impact on drought in most parts of Tamil Nadu.

2.3. *Drought assessment*

Rainfall is the primary driver of meteorological drought. The rainfall data for a period of 30 years from 1991 to 2020 was collected from various Research Centres under Tamil Nadu Agricultural University, Coimbatore. These rainfall data were used to calculate various drought indices. The study was conducted with the aim of addressing the use of SPI to be a competent drought index as compared with rainfall deviation and to study the spatial and temporal extent of drought using these indices.

2.3.1. *Standardised Precipitation Index (SPI)*

Standardized Precipitation Index (SPI) was formulated by McKee *et al.*, 1993. SPI values are dimensionless and are calculated by fitting a Gamma distribution function to rainfall measurements at different time scales. SPI over various time scales, such as 1- or 3-month SPI of a certain month, reflects variance in precipitation totals for that month and the preceding two months, respectively. As a result, SPI values are reported in standard deviations, with a positive number indicating above-average precipitation and a negative value indicating below-average precipitation. It is important to remember that when evaluating the SPI data, the "wetness" or "dryness" is measured relative to historical averages instead of the absolute sum of precipitation for the given region. 3-month SPI was used to analyse drought in this case. However, in order to assess the performance of SPI with that of remote sensing based vegetative indices (Normalized Difference Vegetation Index and Normalized Difference Water Index), SPI was calculated for the time scales of 1-, 3-, 6-, 9- and 12-month time scales.

The SPI, which measures the total variation of precipitation during a certain period of time from the climatological mean, is then normalised using the standard deviation of precipitation during the same period determined using data for the entire duration.

$$\text{SPI} = \frac{a - A}{\text{SD}} \qquad (1)$$

where,

SPI = Standardized Precipitation Index,

a = rainfall during the current period

A = Historical average of precipitation

SD = Standard Deviation of rainfall during the given duration.

SPI with a positive number indicates above-average precipitation and a negative value indicates below-average precipitation. According to SPI, drought occurs when the SPI value for a region in a particular time is less than or equal to -1. Accordingly, drought terminates when the SPI value becomes greater than 0, *i.e.*, positive value.

For the analysis of drought using SPI, daily rainfall data were arranged into monthly average throughout the study period and SPI was calculated for each station for a period of 30 years (1991 to 2020). The SPI was calculated based on equation (1) and the classification of the resultant values was done based on Table 1. The computation of SPI for various time scales was achieved using SPEI Package of R studio. The spatial extent of SPI over the study area was represented on a GIS by interpolating the SPI values using Inverse Distance Weighted (IDW) method.

TABLE 1

Classification of Standard Precipitation Index (SPI) values and the corresponding drought intensities (McKee *et al*., 1993)

SPI Value	Intensity
≥ 2.00	Extremely wet
1.99 to 1.50	Very Wet
1.49 to 1.00	Moderately Wet
-0.99 to 0.99	Near Normal
-1 to -1.49	Moderate drought
-1.50 to -1.99	Severe drought
≤ -2.00	Extreme drought

2.4. *Satellite data*

Earth Explorer offers Landsat 8-9 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS) Collection 2

TABLE 2

Classification of NDVI (Berhan *et al.*, 2011)

NDVI	Class
<0	Extreme drought
0 - 0.2	Severe Dry
0.2 - 0.4	Moderate Dry
0.4 - 0.6	Good Condition
>0.6	Very Good Condition

TABLE 3

Classification of NDWI (Gulacsi and Kovacs, 2015)

NDWI	Class
<0	Very Strong Drought
0 – 0.2	Strong Drought
0.2 – 0.4	Moderate Drought
0.3 – 0.6	Good Condition
>0.6	Very Good Condition

Level-2 Science Products (L2SP) from the U.S. Geological Survey (USGS). The Landsat collection 2, level 2 products offer atmospherically corrected data which includes the Surface reflectance and land surface temperature data from the Landsat 8 OLI/TIRS sensors. Since the Northeast Monsoon season have a major influence on drought in Tamil Nadu, the main emphasis was given on this season. As such, the Landsat 8 OLI/TIRS data with cloud cover less than 10 percent was downloaded from USGS Earth Explorer Website (https://earthexplorer.usgs.gov). Landsat 8 satellite was available at 30m spatial resolution and data was downloaded at a monthly interval for the months of October, November and December of 2016, 2017 and 2018.

2.4.1. *Normalised Difference Vegetation Index (NDVI)*

In order to comprehend vegetation density and evaluate changes in plant health, the Landsat Normalized Difference Vegetation Index (NDVI) is developed to evaluate vegetation greenness. The NDVI is calculated using the following formula given by Rouse *et al.*, 1973:

$$NDVI = \frac{(NIR - R)}{(NIR + R)} \tag{2}$$

where,

NIR = Near Infrared Band and

R = Red Band.

NIR corresponds to Band 5 of Landsat 8 and red, band 4. Thus, the equation for Landsat was derived as:

$$NDVI = \frac{(Band5 - Band4)}{(Band5 + Band4)} \tag{3}$$

The NDVI measures vegetation by calculating the difference between near-infrared (NIR), which vegetation strongly reflects, and red light, which vegetation absorbs or has a low reflectance. NDVI values vary from +1 to -1, with +1 often denoting lush, leafy vegetation and -1 typically denoting aquatic bodies. The classification as given by Berhan *et al.*, 2011 is given on Table 2.

2.4.2. *Normalised Difference Water Index (NDWI)*

Normalised Difference Water Index (NDWI) is widely used to assess drought and water stress conditions owing to its sensitivity to the moisture content. It is derived from the Near Infrared (Rajeevan *et al.*, 2006) and Short-Wave Infrared (SWIR) channels. The sensitivity of SWIR to the moisture content in the crop leaves as well as to the open water sources and soil moisture makes it feasible to use as change detection studies. Early in the growing season, the bare soil surface predominates, making SWIR sensitive to the top 1-2 cm of soil moisture content. SWIR is increasingly sensitive to leaf moisture content as the crop grows. SWIR band only offers data on surface moisture. Hence, NDWI can be used in addition to NDVI to assess drought (Gao, 1996). NDWI was calculated as follows:

$$NDWI = \frac{\rho(NIR - SWIR)}{\rho(NIR + SWIR)} \tag{4}$$

SWIR due to its sensitivity to moisture which results from the high absorptivity of light in this wavelength by water makes it convenient to detect vegetation moisture content and the spongy mesophyll cells in the plant canopy. Due to the fact that NIR reflectance is mostly driven by the internal structure and dry matter content of the leaf rather than the water content, NIR is employed in NDWI as well as NDVI. By eliminating the variations induced by the internal structure of the leaf and its dry matter content, the use of combined NIR and SWIR improved the accuracy of determining the moisture content of plants.

The NDWI value is dimensionless and it ranges from -1 to +1 based on the type and cover of vegetation. High

TABLE 4

Number of drought years based on 1-month SPI Values (1991-2020)

Drought	Dindigul	Madurai	Pudukkottai	Ramanathapuram	Sivagangai	Tenkasi	Theni	Thoothukudi	Tirunelveli	Virudhunagar
Moderate Drought										
Annual	17	13	15	14	16	15	16	17	15	22
SWM	10	10	11	7	6	4	13	9	6	8
NEM	8	3	7	6	9	7	6	4	8	12
Severe Drought										
Annual	7	8	11	11	8	9	10	11	13	10
SWM	3	3	8	4	2	3	6	4	6	3
NEM	5	2	4	5	4	6	5	2	5	6
Extreme Drought										
Annual	5	8	6	1	6	2	5	3	1	2
SWM	2	2	3	1	4	0	1	0	3	2
NEM	3	7	4	0	3	2	2	1	3	0

TABLE 5

Annual and Seasonal 1-month SPI Ranges (1991-2020)

District	Annual		South West Monsoon		North East Monsoon	
	Max	Min	Max	Min	Max	Min
Dindigul	2.5	-2.7	2.5	-2.7	2.4	-2.5
Madurai	2.8	-2.6	2.8	-2.4	1.9	-2.6
Pudukkottai	2.6	-3.3	2.6	-3.3	1.9	-2.5
Ramanathapuram	2.6	-2	2.4	-2	2.2	-1.9
Sivagangai	2.6	-2.4	2.6	-2.3	1.8	-2.4
Tenkasi	2.7	-2.7	2.7	-1.8	2	-2.7
Theni	2.4	-2.5	2.3	-2.3	2.6	-2.3
Thoothukudi	2.6	-2.3	2.6	-1.5	2.3	-2.4
Tirunelveli	2.7	-2.4	2.4	-2.2	1.9	-2.5
Virudhunagar	2.6	-2.3	2.6	-2.3	2.2	-1.8

vegetation moisture content and cover are associated with a higher NDWI results. Poor NDWI values indicate low vegetation moisture content and cover in terms of vegetation. NDWI value decreases during times of water stress. NDWI classification based on the classification done by Gulácsi and Kovács, 2015 is given in Table 3. Landsat 8 images of Band 4 (NIR) and Band 5 (SWIR) for the southern zone of Tamil Nadu was generated for the NEM season of 2016, 2017 and 2018.

2.5. *Comparison of Remote sensing-based indices and meteorological indices*

Comparative assessment of drought indices was done to evaluate the performance of each index in drought analysis. Meteorological index - Standardized Precipitation Index (SPI) at various time scales, *viz*., 1-, 3, 6-, 9- and 12-month time scale was compared with Normalized Difference Vegetation Index (NDVI) and

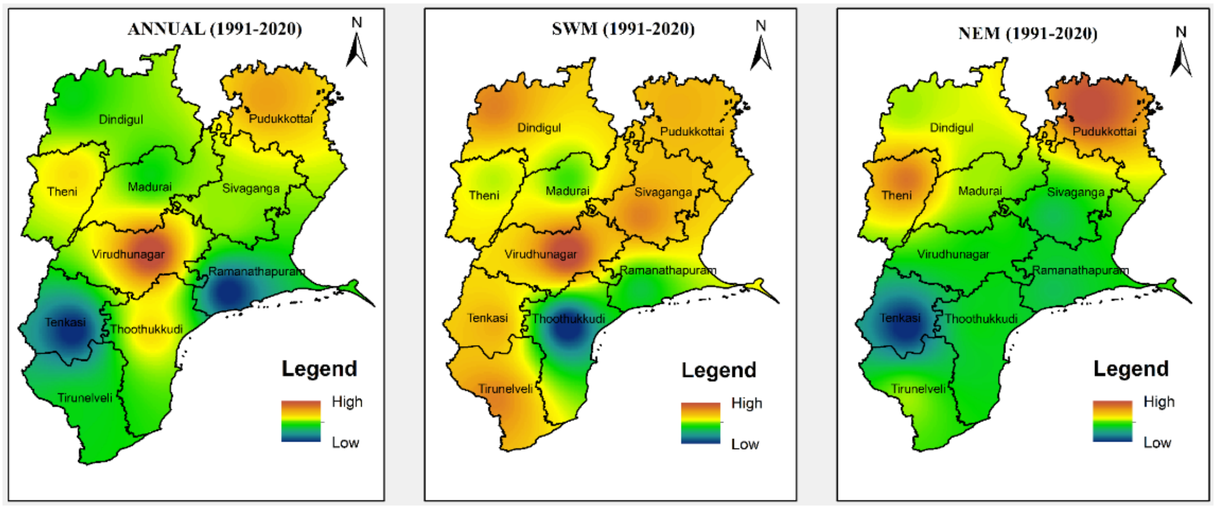

Fig. 2. Number of drought events based on 1-month SPI (1991-2020)

TABLE 6

Percentage area of drought during NEM 2016 based on NDVI

District	Extreme Dry	Severe Dry	Moderate Dry	Good Condition	Very Good Condition
Dindigul	0.3	22.9	50.2	25.9	0.8
Madurai	0.3	18.2	61.3	19.9	0.4
Pudukkottai	4.3	18.5	52.8	19.9	4.4
Ramanathapuram	1.5	35.8	55.1	7.4	0.2
Sivagangai	6.7	63.6	26.5	2.6	0.6
Tenkasi	1.0	39.0	51.7	8.2	0.1
Theni	0.5	40.9	45.3	13.2	0.2
Thoothukudi	8.2	20.6	40.6	22.3	8.3
Tirunelveli	3.7	32.3	50.6	10.0	3.5
Virudhunagar	0.4	40.7	52.2	6.6	0.1

TABLE 7

Percentage area of drought during NEM 2017 based on NDVI

District	Extreme Dry	Severe Dry	Moderate Dry	Good Condition	Very Good Condition
Dindigul	2.2	15.1	45.3	35.6	1.8
Madurai	0.6	8.6	48.2	40.8	1.8
Pudukkottai	1.3	21.9	59.0	17.4	0.3
Ramanathapuram	10.3	50.1	32.5	4.7	2.3
Sivagangai	1.0	29.5	52.9	16.5	0.2
Tenkasi	7.0	19.4	46.4	19.3	7.9
Theni	2.6	13.6	43.0	36.9	4.0
Thoothukudi	6.7	36.9	51.8	4.5	0.1
Tirunelveli	7.1	33.4	35.9	18.9	4.7
Virudhunagar	1.5	20.4	58.9	18.4	0.8

TABLE 8

Percentage area of drought during NEM 2018 based on NDVI

District	Extreme Dry	Severe Dry	Moderate Dry	Good Condition	Very Good Condition
Ramanathapuram	13.1	40.1	36.1	8.0	2.7
Madurai	7.3	36.2	37.2	18.6	0.7
Pudukkottai	3.2	31.9	45.4	19.1	0.4
Theni	8.0	25.8	42.9	21.1	2.2
Tenkasi	1.2	25.1	49.6	23.5	0.5
Virudhunagar	0.9	24.6	48.4	25.4	0.8
Thoothukudi	2.8	19.4	48.2	28.7	0.9
Dindigul	7.3	15.6	39.3	36.1	1.6
Tirunelveli	5.8	15.4	40.3	32.4	6.2
Sivagangai	9.6	18.3	32.6	31.5	8.0

Normalized Difference Water Index (NDWI) to study their feasibility in monitoring drought over the southern region of Tamil Nadu.

3. Results and discussions

3.1. *Drought analysis based on Standardized Precipitation Index*

The details of the analysis of drought in the southern region based on SPI values and the annual and seasonal ranges of SPI and the spatial map of drought frequency is given on Tables 4 and 5 and Fig. 2. respectively. The spatial and temporal extent of meteorological drought in the southern region of Tamil Nadu was analysed using Standardized Precipitation Index (SPI) at 1-month time scale. The assessment results indicated that the southern region was prone to moderate drought conditions. Virudhunagar, Thoothukudi and Dindigul observed the highest occurrence of drought at an annual basis. On a seasonal scale, Dindigul, Madurai, Pudukkottai, Theni and Virudhunagar observed a high occurrence of drought. Theother districts, *viz.*, Dindigul, Sivagangai, Madurai and Virudhunagar also observed a high frequency of drought. Similar results have also been made by Nathan, 1998.

The frequency of severe drought was highest in Thoothukudi, Pudukkottai and Ramanathapuram while the other districts observed a relatively low frequency. The frequency of extreme drought events was the least among all the drought classes. In both the seasonal and yearly comparisons, the region demonstrated a substantial fluctuation in both severe wet and dry periods.

Overall, the analysis of 1-month SPI over the southern region of Tamil Nadu indicated that the region is

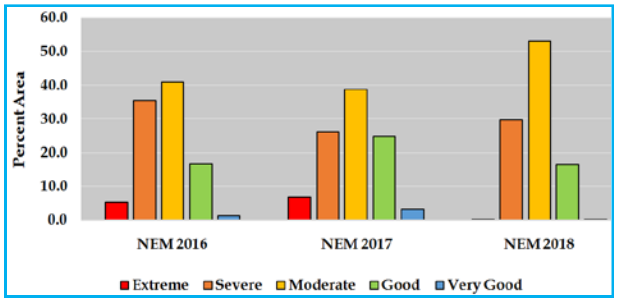

Fig. 3. Percentage Area of different drought classes based on NDVI - NEM 2016, 2017, 2018

more vulnerable to moderate droughts especially in the districts of Virudhunagar, Pudukkottai, Dindigul and Thoothukudi. The region also shows a spatial variation in terms of distribution and variability of rainfall. Similar results have been observed by Ramaraj *et al.*, 2017 and Sathyamoorthy *et al.*, 2020. The analysis of drought from the historical data on a seasonal scale indicated that there was a higher occurrence of drought during the SWM season as compared to NEM season. This could be due to the fact that since the region is heavily rain shadowed during the SWM season, the region receives scanty rainfall during the SWM. Similar findings have also been made by Vengateswari *et al.*, 2019.

The vulnerability of the region to drought during the NEM season could arise from the negative relationship of rainfall in the coaster regions of India especially Tamil Nadu region with the La Niña conditions and a negative phase of the Indian Ocean Dipole (IOD), resulting in a lower sea surface temperature thereby suppressing the landward movement of moisture from the Bay of Bengal to the coastal regions of Tamil Nadu (Mishra *et al.*, 2021).

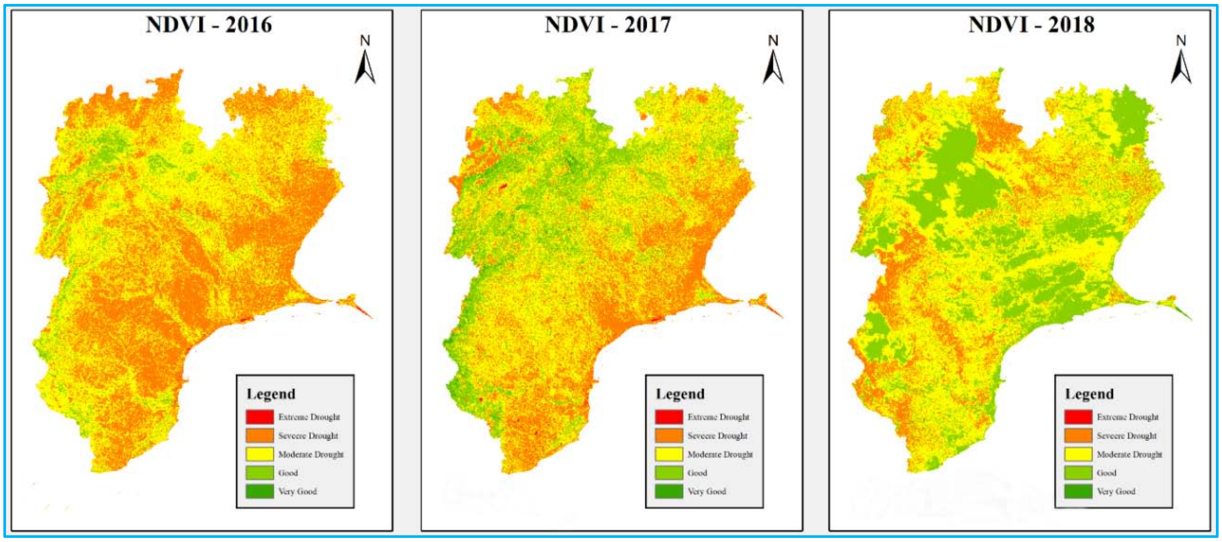

Fig. 4. Spatial Drought Distribution Map of NDVI during NEM 2016, 2017 and 2018

3.2. *Drought Analysis using NDVI*

The spatial extent of drought during the NEM seasons of 2016 to 2018 was assessed through the LANDSAT 8 derived NDVI indicated that during the NEM season of 2016, majority of the area shows stress condition, more particularly, the area under moderate and severe drought was prominent in the southern region of Tamil Nadu. The spatial extent of drought based on NDVI during the NEM of 2016, 2017 and 2018 is given on Figs.3 and 4 and Tables 6-8. Hence, it could be stated that the southern region of Tamil Nadu was under severe agricultural drought risk during the NEM season of 2016. This goes in agreement with the statements made by Mishra *et al.*, 2021 which stated that the NEM season of 2016 in the state of Tamil Nadu was the driest year in the 140 years' history of the state. Since the rainfall received during the NEM corresponding to the months of October to December (around 51% of the total rainfall received annually) were highly critical for the region, any deviation or fluctuations from the normal could seriously cripple the region in terms of agricultural productivity (Nathan, 1998).

The district wise analysis further indicated that about 90 percent of the area in the districts, *viz.*, Sivagangai, Virudhunagar, Ramanathapuram and Tenkasi were affected by moderate to severe drought. This goes on to show that these districts in particular, are more vulnerable to drought and that the spatial coverage of Severe drought was the highest in Sivagangai with 63.6 percent of the total area under drought. In the other districts, the spatial coverage of drought was varied from 69 to 84 percent. Hence, an inference could be made that during the NEM season of 2016, the southern districts were under a prominent risk of agricultural drought. This could be so due to increased dry spells during the period induced by the weakened NEM season over the region as a result of the La Niña phase of the ENSO and a negative phase of the IOD (Pothapakula *et al.*, 2020, Mishra *et al*., 2021).

During the NEM Season of 2017, the spatial extent of drought decreased compared to the same season in 2016. The drought stressed region covered 71 percent of the total area which indicated that the region was exposed to a moderate risk of agricultural drought during NEM of 2017. The district wise analysis indicated that Thoothukudi, Ramanathapuram, Pudukkottai, Sivagangai and Virudhunagar districts were highly vulnerable to drought conditions. The districts are most prone to moderate droughts during the NEM of 2017. Similar results have been made by Latha, 2021.

During the NEM season in 2018, the drought stressed area under the southern region of Tamil Nadu increased compared to that of 2017. Similarly, this region observed the highest area under moderate drought which occupied 83.3 percent of the total area. However, the district wise analysis indicated that compared with 2016, the drought affected area under the region was not as high as that of 2016. Nevertheless, all the districts indicated a considerable extent of drought area. Among the districts, Ramanathapuram had the highest area at 89.3 percent. Ramanathapuram, Pudukkottai and Madurai are had maximum drought area where the drought area across each district crossed 80 percent. The rest of the districts

TABLE 9

Percentage area under drought during NEM 2016 based on NDWI

District	Extreme Dry	Severe Dry	Moderate Dry	Good Condition	Very Good Condition
Dindigul	15.5	47.6	35.0	1.6	0.2
Madurai	9.5	64.5	24.7	1.1	0.3
Pudukkottai	17.2	65.6	15.9	1.0	0.3
Ramanathapuram	2.6	11.7	75.2	7.8	2.7
Sivagangai	24.9	62.8	11.4	0.7	0.3
Tenkasi	18.6	48.5	20.2	6.4	6.2
Theni	8.7	50.3	36.6	3.5	0.9
Thoothukudi	2.5	81.8	14.9	0.5	0.3
Tirunelveli	5.4	59.4	28.0	3.7	3.6
Virudhunagar	11.3	74.2	13.6	0.6	0.3

TABLE 10

Percentage area under drought during NEM 2017 based on NDWI

District	Extreme Dry	Severe Dry	Moderate Dry	Good Condition	Very Good Condition
Dindigul	1.4	37.2	57.9	3.2	0.2
Madurai	3.6	49.8	44.0	2.3	0.3
Pudukkottai	5.2	53.8	38.2	2.5	0.3
Ramanathapuram	2.7	14.9	68.0	11.5	2.9
Sivagangai	20.9	56.7	21.0	1.0	0.3
Tenkasi	12.5	49.1	25.0	7.1	6.3
Theni	4.7	47.1	43.8	3.5	0.9
Thoothukudi	11.7	72.9	14.0	1.0	0.4
Tirunelveli	19.6	45.1	27.0	4.6	3.6
Virudhunagar	6.8	63.5	28.2	1.2	0.3

observed moderate level of threat to droughts with the spatial coverage ranging from 60 to 80 percent of the total area.

Overall, the area under stressed conditions during the NEM of 2016 to 2018 was relatively high. Particularly, the NEM of 2016 and 2018 indicated signs of high risk of agricultural drought while NEM of 2017 observed signs of moderate risk. The southern region of Tamil Nadu is mostly frequently exposed to Moderate and comparatively lesser frequent to severe droughts. Hence, during the three years studied, there exists a certain variation of drought risks which could be brought upon due to the annual change in land cover mainly influenced by the variation of wet and dry periods (Fang and Wang, 2001). The lower NDVI values throughout the cropping season might imply that sowing timing is dependent on the monsoon, which further alters the NDVI value during this season (Sahoo *et al.*, 2015).

3.3. *Drought analysis using NDWI*

The spatial extent of agricultural drought in the southern region of Tamil Nadu was assessed with the Normalized Difference Water Index (NDWI) which uses the Near Infra-Red (Rajeevan *et al.* 2006) and Short-Wave

TABLE 11

Percentage area under drought during NEM 2018 based on NDWI

District	Extreme Dry	Severe Dry	Moderate Dry	Good Condition	Very Good Condition
Dindigul	1.1	18.7	67.3	12.7	0.2
Madurai	0.3	7.6	82.2	9.6	0.2
Pudukkottai	0.6	24.4	70.6	4.1	0.3
Ramanathapuram	3.7	15.6	73.3	4.8	2.6
Sivagangai	2.2	44.8	51.8	1.0	0.3
Tenkasi	6.3	20.6	54.4	12.5	6.2
Theni	3.0	23.3	66.3	6.5	1.0
Thoothukudi	0.9	30.0	67.1	1.7	0.3
Tirunelveli	4.2	32.1	53.6	6.5	3.6
Virudhunagar	0.3	32.3	66.7	0.4	0.3

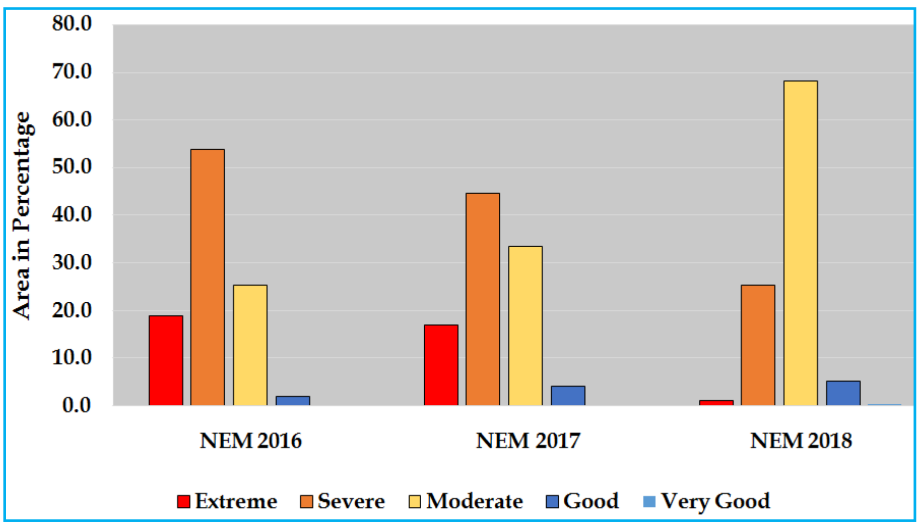

Fig. 5. Percentage Area under drought based on NDWI – NEM – 2016, 2017, 2018

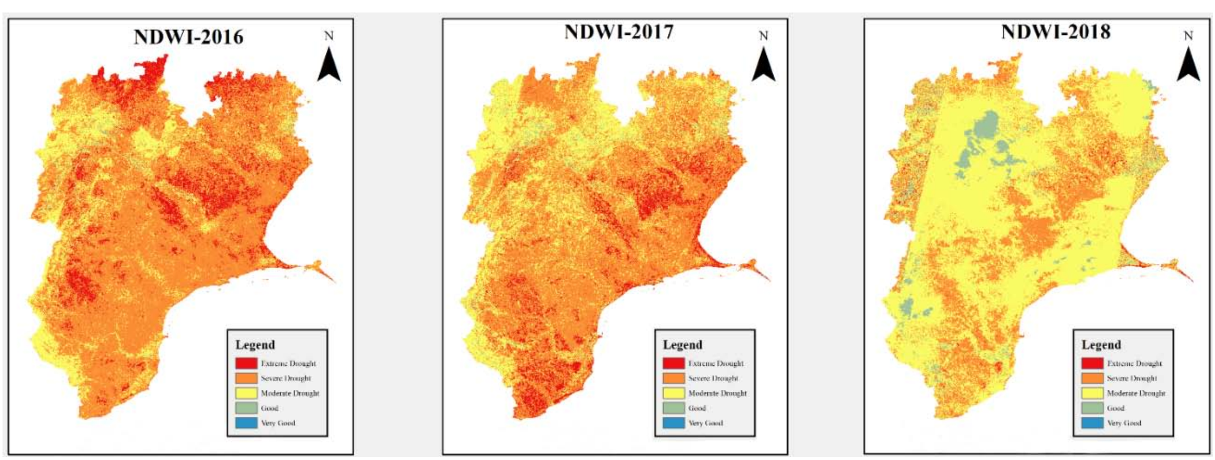

Fig. 6. Spatial Drought Distribution Map of NDWI during NEM 2016, 2017 and 2018

TABLE 12

Correlation between NDVI and SPI

Parameter	Correlation Coefficient	R^2
NDVI - SPI_1	0.35	0.12*
NDVI - SPI_3	0.37	0.14*
NDVI - SPI_6	0.51	0.26**
NDVI - SPI_9	0.47	0.22**
NDVI - SPI_{12}	0.51	0.26**

TABLE 13

Correlation between NDWI and SPI

Parameter	Correlation Coefficient	R^2
NDWI-SPI_1	0.29	0.08*
NDWI-SPI_3	0.52	0.27**
NDWI-SPI_6	0.55	0.3**
NDWI-SPI_9	0.51	0.26**
NDWI-SPI_{12}	0.53	0.28**

* - Significant at 5 percent level of significance
** - Significant at 1 percent level of significance

Infrared (SWIR) bands to detect the changes in the open water bodies and the liquid water content in the plant canopies. The spatial extent of drought during the NEM 2016, 2017 and 2018 based on NDWI is given in Figs. 5 and 6 and Tables 9 to 11. Kumaraperumal *et al.*, 2021 concluded that the NDWI because of the sensitivity of SWIR to moisture fluctuations, is more sensitive in monitoring drought than NDVI.

The assessment of drought in the southern region of Tamil Nadu using NDWI indicated that the entire zone observed drought stress conditions covering more than 90 percent of the area under drought stress conditions. The region was most prone to Moderate and Severe drought stresses during the NEM Season of 2016. Further analysis upon the districts indicated that all the districts are under drought risks with more than 90 percent area under drought stress. Sivagangai, Thoothukudi and Virudhunagar observed the largest area under drought stress and hence are highly vulnerable to drought during the NEM 2016. Nevertheless, all the other districts also observed a severe and moderate drought during this season. Similar studies in the analysis of drought in Tamil Nadu has also shown similar results (Mishra *et al.*, 2019; Kumaraperumal *et al.*, 2021; Latha, 2021). The poor vegetation index during this region may be due to the failure of NEM season and the early withdrawal of SWM in 2016. This led to the decline in the soil moisture content and hence, ultimately drastically increases drought stress condition. Furthermore, the drought in 2016 was associated to the fluctuation of the sea surface temperature, ENSO and negative phase of the IOD (Mishra *et al.*, 2021).

The assessment of the NEM season of 2017 and 2018 also observed a considerable area under drought area at 95 and 94 percent, respectively. The region was most vulnerable to moderate and severe drought. The district wise analysis in both the NEM of 2017 and 2018 indicated that the districts of Sivagangai, Thoothukudi and Virudhunagar are highly prone to moderate and severe drought conditions. Similar inferences have been reported by (Latha, 2021). The region observed a larger area under drought stress condition during the NEM of 2017 and 2018. Possible reasons may be due to the shortage of rainfall and extended dry spells which ultimately affected the crop health and condition (Barron *et al.*, 2010).

The occurrence of maximum area under drought condition during the study period may be due to the prolonged dry spell or rainfall deficits over the region and thereby causing a condition of an extended period of enhanced drought intensity and hence, impacting the crop health and conditions (Shumba O, 1999). It was also discovered that the value range of NDWI during the NEM of 2016 - 2018 was lower than that of NDVI, which may be ascribed to the fact that vegetation indices are known to be associated with changes in temperature and precipitation. However, precipitation was more prominent than temperature in determining crop condition (Zhang *et al.*, 2007).

3.5. *Comparison of meteorological and remote sensing indices*

One of the essential aspects of drought monitoring that gives a better understanding of the dynamics of vegetation condition is the response of meteorological factors. Pearson's correlation coefficient was used to compare remotely sensed index values to 1-, 3-, 6-, 9- and 12-month SPI during the major cropping season of the region which covered the months of October, November and December of 2016 to 2018. The remotely sensed index and SPI data were spatially connected by constructing 500 fishnet points from which the values are retrieved. The coefficient range conveyed relevant data on the performance of vegetation cover and the impact of rainfall (Kumaraperumal *et al.*, 2021).

The Pearson correlation coefficients between the NDVI and SPI at different time scales indicated that the NDVI correlated well with the 6-, 9- and 12-month SPI of which, the 6 and 9-month SPI observed the highest correlation coefficient (Tables 11 to 12). Several studies have also established a significant relationship between NDVI and SPI (Nicholson and Farrar, 1994; Wang *et al.*, 2001). The higher correlation of multi month SPI with that of NDVI and NDWI because of the fact that precipitation has no profound immediate influence on vegetation vitality. In most situations, rainfall during one month will have little effect on vegetation during that particular month, but the impact is observable over longer time periods (Ji and Peters, 2003).

The Pearson correlation coefficient established with the NDWI and SPI at varying time scale also observed that the NDWI had a strong correlation with 3, 6, 9 and 12-month SPI. The 6-month SPI observed the highest correlation coefficient during the study. Compared with NDVI, the NDWI observed a higher correlation with the SPI at 3-, 6-, 9- and 12-month timescales. This may be due to the sensitivity of the use of Short-Wave Infrared (SWIR) band in NDWI which gave a quick response to moisture changes in the plant canopy and are less influenced by the atmospheric scattering and thus, is more efficient in assessing drought as compared with NDVI (Agha Kouchak *et al.*, 2015). Similar inferences have also been observed by different studies regarding the correlation of SPI with NDWI (Kumaraperumal *et al.*, 2021). However, the correlation between the monthly SPI and NDWI was lower than that of NDVI. This may be due to the fact that the influence of rainfall over a month may not have profound effects on the vegetation health conditions over that month. However, the influence of rainfall on crops could be observed over a longer period of time (Ji and Peters, 2003).

The comparison of NDVI and NDWI with 3-, 6-, 9- and 12-month SPI observed that the three indices are fairly correlated with each other and hence are useful in the analysis of drought. Using a single drought index whether meteorological and satellite-based index, cannot determine the spatial and temporal extent of drought of varying degrees. Using a meteorological index to define drought may have complications regarding the spatial distribution of drought due to the limited availability of observed data. Similarly, using a single remote sensing index to define drought could give biased results as several factors could decrease the vegetation indices like pest and diseases infestations, stages of crop, etc. Moreover, the use of meteorological indices such as SPI at one month time scale and Moisture Adequacy Index at a weekly time scale allows the analysis of Short-Term Drought events. However, the effects of droughts over a longer period of time and the spatial extent can be thoroughly studied with the help of multispectral remote sensing indices. On the other hand, SPI over a longer time scale was highly correlated with multispectral remote sensing derived vegetative indices. Remote sensing derived vegetation indices can give idea about the influences of drought over a longer time period which can be useful for annual and perennial crops and in the analysis of forest vegetation. Thus, a combination of meteorological and remote sensing indices gave a detailed idea about the spatio-temporal extent of drought (WMO, 1975; Shaw and Krishnamurthy, 2009; Mishra and Singh, 2010).

4. Conclusion

To conclude, the analysis of drought over the Southern Region of Tamil Nadu revealed that the area was most vulnerable to drought during the NEM Season. The SPI analysis indicated that the region is mostly prone to moderate drought. NDVI and NDWI analysis during the NEM of 2016, 2017 and 2018 observed a high vulnerability of the southern districts to moderate and severe droughts. From the analysis, it was clear that Ramanathapuram, Thoothukudi, Tirunelveli and Pudukkottai districts are the most prone to drought. The comparison of NDVI and NDWI with SPI indicated that the three indices are fairly accurate with each other and hence are useful in the analysis of drought. However, just a single drought index cannot clearly define accurately the spatial and temporal extent of drought. The use of satellite images alone may not detect the short-term droughts or dry spells over a region as such events may have a profound effect on the crop production. Moreover, the vegetative indices may be affected by various other factors like pest and diseases, resulting in a lower index value. On the other hand, meteorological data may not be easily accessible to the potential users. Moreover, the limited availability of observed meteorological data may add to the complications in analysing the spatial extent of drought events. Thus, a combination of meteorological and remote sensing indices gave a detailed idea about the spatio-temporal extent of drought.

Author Statement

The authors stated that there are no competing interests and the work was accomplished in collaboration among all the authors. All the authors read and approved the final manuscript.

Disclaimer : The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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