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Seasonal drought assessment using the Normalized Difference Drought Index (NDDI) in Satara District of Western Maharashtra (2014-2023)

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Abstract

This study investigates the spatio-temporal variability of drought in Satara district of Western Maharashtra from 2014 to 2023 using the Normalized Difference Drought Index (NDDI), derived from Landsat-8 satellite data. Seasonal drought conditions were assessed for *rabi*, summer, and *kharif* seasons, along with drought-rainfall relationships. Results showed substantial seasonal variations, with summer consistently exhibiting the highest drought severity due to elevated temperatures and minimal precipitation. *Kharif* season showed the least drought impact as a consequence of monsoonal rainfall and improved vegetation cover. *Rabi* season displayed moderate drought stress influenced by limited residual soil moisture. The correlation analysis confirmed a strong negative relationship between rainfall and NDDI during *kharif* ($r = -0.70$), moderate during summer ($r = -0.56$), and weak during *rabi* ($r = -0.21$). Spatial analysis identified persistent drought hotspots in the eastern region of Satara, particularly Man, Khataav, Phaltan, and Khandala. The findings demonstrate the usefulness of NDDI as a remote-sensing-based agricultural drought monitoring tool and provide guidance for sustainable water resource planning and climate-smart agricultural management in drought-prone areas.

Keywords: NDDI, drought classification, Satara District, remote sensing, seasonal trends

Introduction

Drought is a significant detrimental climatic phenomenon for ecosystems and human society. Recent years have seen a sharp rise in worldwide drought episodes as a result of accelerated climate change. For the purposes of water management and drought mitigation, precise and reliable worldwide mapping and monitoring of drought severity is required. Regional drought assessment and mitigation initiatives should benefit from global products obtained from operational satellite remote sensing, particularly in regions of the world where alternative information sources are limited by inadequate infrastructure development and sparse measurement networks (Mu *et al.*, 2013) [8]. Agriculture forms the backbone of the Indian economy and is often the first sector to feel the effects of drought, owing to its heavy dependence on soil moisture reserves and water availability during various stages of crop growth. Planning to lessen the effects of drought would be made easier with an understanding and development of technologies for drought monitoring and prediction.

There are several methods for describing drought, however the use of drought indices is common (Tsakiris *et al.*, 2007) [10]. When comparing the different indices, Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI) and Normalized Difference Drought Index (NDDI) are better suited for tracking the characteristics of agricultural drought (Stancalie and Serban, 2014) [9].

The NDDI is thought to be more accurate than the NDVI or NDWI algorithms alone for identifying drought on agricultural land. It has a higher sensitivity level to drought due to computations from the NDVI and NDWI modifications (Dobri *et al.*, 2021) [5]. The main goal of the NDDI is to record the spatio-temporal pattern and severity of the drought by integrating

multiple indicators to investigate the phenomenon. As an indicator of drought conditions, the NDDI value ranges from -1 to 1, with higher values denoting a more severe drought. The NDVI is sensitive to vegetation, while the NDWI is sensitive to water resources and water content in leaves. The NDDI uses these two facts in their drought prediction. (Khampera *et al.*, 2018).

Satara district in western Maharashtra presents distinct agro-climatic contrasts, with high-rainfall areas in the west and drought-prone conditions toward the east. This spatial variability, together with seasonal cropping practices, makes it a suitable region for monitoring drought dynamics over time.

This study aims to conduct a spatio-temporal analysis of NDDI from 2014 to 2023 for Satara district, assessing seasonal variations (*rabi*, summer and *kharif*) and their relationship with rainfall. The results will highlight regions vulnerable to drought and provide useful information for sustainable agricultural planning and resource management in the district

Materials and Methods

Study area

Satara district lies in the western region of Maharashtra, extending between 17°05' to 18°11' N latitude and 73°33' to 74°54' E longitude as shown in the Fig-1. Rainfall distribution in the district shows a strong west-east gradient, with Mahabaleshwar in the western side receiving more than 6000 mm of annual rainfall, while eastern tahsils such as Man, Phaltan, Khandala, and Khatav receive only about 500 mm or even less (Barakade, 2012) [2]. The eastern region is therefore highly susceptible to drought conditions. As noted by Pravin and Hemalata (2020), among the 11 tahsils, Khandala, Phaltan, Man and Khatav experience severe drought and Koregaon shows partial drought influence.

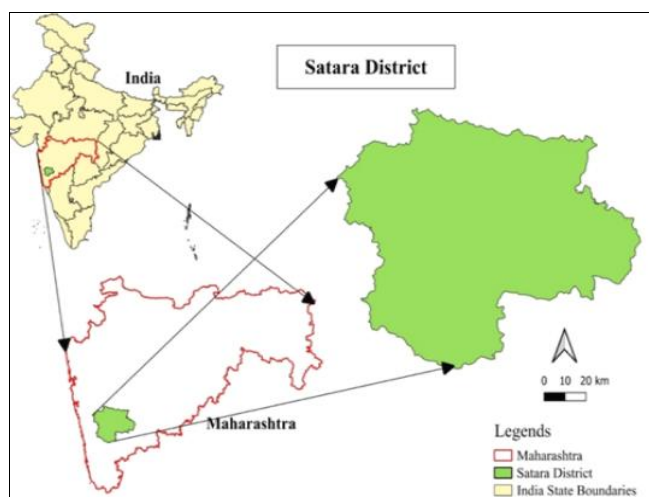


Fig 1: Location of study area-Satara District of Western Maharashtra

In this study, Landsat 8 Collection 2 Level 2 data, obtained from USGS Earth Explorer, for the period from 2014 to 2023 were used to find out NDVI and NDWI then NDDI by using the software QGIS.

Normalized Difference Drought Index

The Normalized Difference Drought Index algorithm is considered as more accurate for detecting drought on agricultural land compared to using the NDVI or NDWI algorithms individually. This is because it combines the results of the NDVI and the NDWI, which enhances its sensitivity to drought conditions (Dobri *et al.*, 2021) [5].

NDDI is the ratio of difference between NDVI and NDWI to the

sum of NDVI and NDWI bands, it expressed as:

$$\text{NDDI} = (\text{NDVI} - \text{NDWI}) / (\text{NDVI} + \text{NDWI})$$

Where, NDVI is calculated as $(\text{NIR} - \text{RED}) / (\text{NIR} + \text{RED})$ with NIR and RED indicating near-infrared and red reflectance, respectively (Deering, 1978) [4]. The NDWI is derived as $(\text{NIR} - \text{SWIR}) / (\text{NIR} + \text{SWIR})$, where NIR and SWIR are the reflectance in the near infrared and short wave infrared bands (Gao, 1996) [6].

NDDI is considered more sensitive to drought conditions than the NDVI and NDWI. A high NDDI value indicates drought, typically corresponding with low NDVI and NDWI values, reflecting reduced vegetation and moisture. Conversely, a low NDDI value suggests no drought or water scarcity, with NDVI and NDWI values being relatively high, indicating healthy vegetation and adequate water availability. The NDDI mainly divided into five classes (Artikanur and Setiawan (2022) [1], Herawati *et al.* (2024) [7]. These classes are given in the Table 1.

Table 1: Classification of NDDI

Class	NDDI Values
Very Low Severity	< -2.0
Low Severity	-2.0 to 0.7
Moderate Severity	0.7 to 1.25
High Severity	1.25 to 3.0
Very High Severity	>3.0

Results

Season-wise Temporal Analysis of Mean NDDI (2014-2023)

Seasonal analysis of mean NDDI from 2014 to 2023 was carried out to assess drought variability across *rabi*, summer and *kharif* seasons in Satara district which is presented in Table 2 and depicted in the Fig 2. NDDI reflects both vegetation health and moisture stress, and its seasonal trends help in identifying drought-prone

Table 2: Seasonal Variation in Mean NDDI for Satara District (2014-2023)

Year	Mean NDDI		
	<i>Rabi</i>	Summer	<i>Kharif</i>
2014	0.92	1.63	0.42
2015	0.90	1.08	0.43
2016	0.79	1.38	0.35
2017	0.58	1.21	0.38
2018	0.84	1.42	0.40
2019	0.90	1.90	0.32
2020	0.66	1.30	0.38
2021	0.73	1.50	0.32
2022	0.64	1.39	0.37
2023	0.69	1.30	0.39

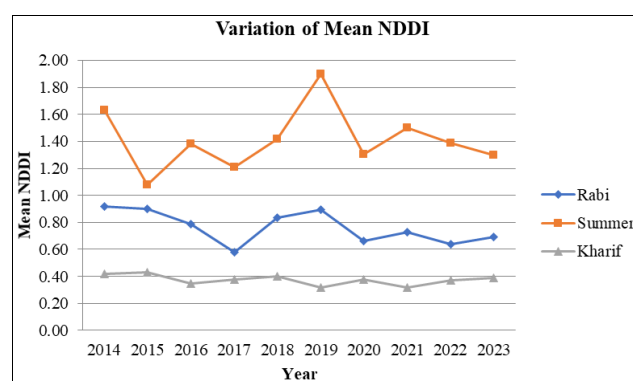


Fig 2: Variation of mean NDDI during *rabi*, summer and *kharif* for Satara District (2014-2023)

The *rabi* season NDDI values reveal a broad range, with the mean peaking at 0.92 in 2014 and dropping to its lowest at 0.58 in 2017. Both 2015 and 2019 recorded comparatively elevated levels (0.90), suggesting more intense dryness during those years. From 2020 onward, the values showed a gradual decline, falling between 0.64 and 0.73, which may reflect a shift toward slightly improved soil moisture or reduced drought intensity in the recent *rabi* seasons.

In the summer season, NDDI showed significantly high readings, peaking at 1.90 in 2019, followed by 1.63 in 2014. The lowest value appeared in 2015 (1.08), indicating slightly less drought intensity that year. Elevated values above 1.30 were also recorded in other years, including 2016, 2018, and 2021, reflecting a general tendency of increased dryness during this hot time.

Compared to the other two seasons, *kharif* values remained relatively low, with readings ranging from 0.32 (2019 and 2021) to 0.43 (2015). Slight increases were seen in 2014 (0.42) and 2023 (0.39), whereas years like 2016 and 2017 registered values closer to 0.35 and 0.38, respectively, suggesting mild to moderate drought conditions during the monsoon period.

Season-wise Spatial Assessment of NDVI Using Thematic Maps (2014-2023) for Satara District

Fig 3 to 5 represents the spatial variability of vegetation condition in Satara district evaluated using NDVI thematic maps across *rabi*, *kharif*, and summer seasons from 2014 to 2023.

Rabi

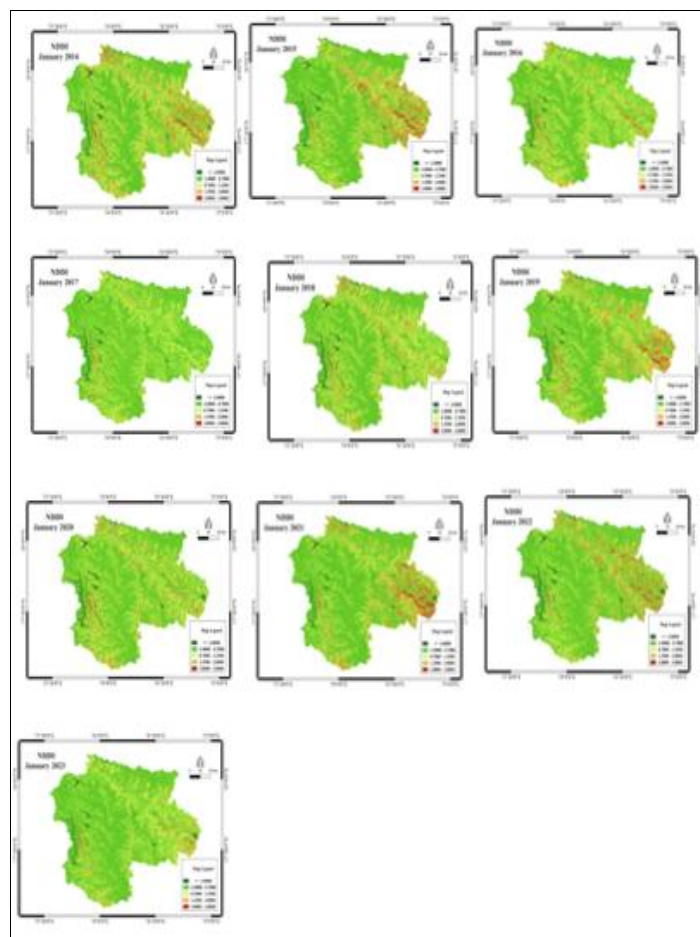


Fig 3: Seasonal NDVI map during *rabi* season for Satara District (2014-2023): January representation

Summer

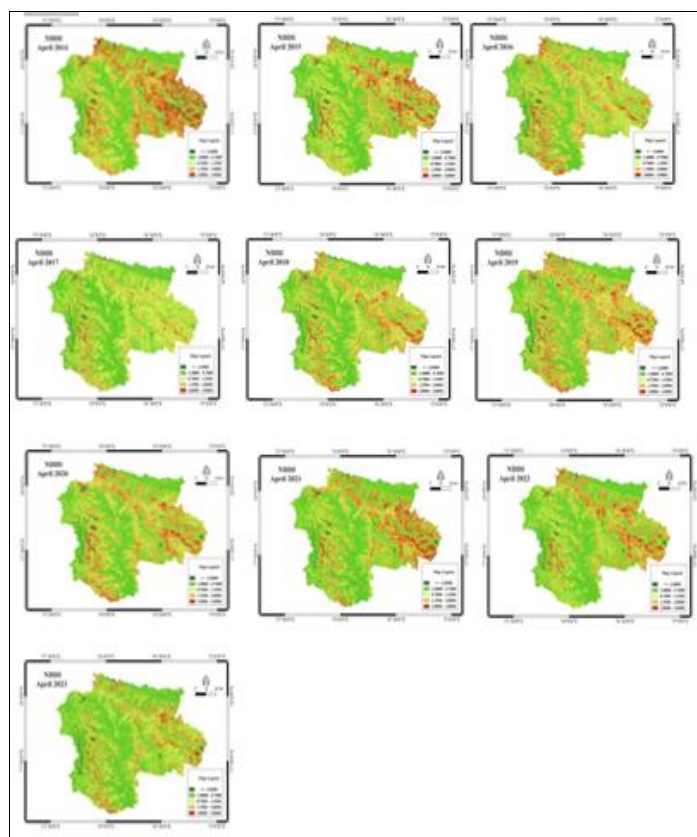


Fig 4: Seasonal NDVI map during summer season for Satara District (2014-2023): April representation

Kharif

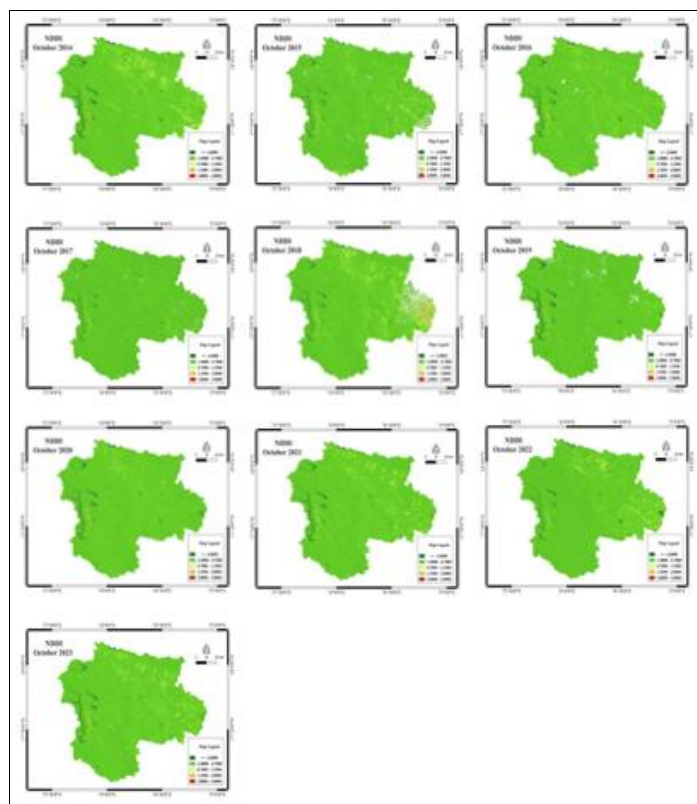


Fig 5: Seasonal NDVI map during *kharif* Season for Satara District (2014-2023): October representation

The Satara district's drought intensity varies both spatially and temporally, as seen by the examination of NDDI maps (Fig 3 to 5) during the three seasons. In 2014, comparatively more severe drought conditions throughout the *rabi* season, however most regions experienced less severe drought conditions in 2017.

Drought severity was significantly higher in the summer than it was in other seasons. During summer 2014 showed widespread drought-prone areas, whereas, 2023 exhibited comparatively lesser drought conditions. Because of the impact of monsoon rainfall, the district experienced very little drought during the *kharif* season. According to its increased rainfall and vegetation cover, 2019 had the least severe drought, whereas 2015 had the most severe during *kharif*.

The eastern Satara region continuously displayed decreased vegetation cover and increased drought severity according to the NDDI maps taken throughout all three seasons, highlighting its ecological sensitivity to seasonal and annual climatic fluctuations.

Seasonal Area-wise Drought Severity Classification Using NDDI in Satara District (2014-2023)

Rabi Season

The area-wise drought severity classification using NDVI during the *rabi* season (2014-2023) is presented in Table 3 and illustrated in Figure 6.

Table 3: Per Cent Area Classified Based on NDDI-Derived Drought Severity in Satara District during *Rabi* Season (2014-2023)

Year	Very Low Severity (%)	Low Severity (%)	Moderate Severity (%)	High Severity (%)	Very High Severity (%)	Total (%)
2014	0.52	53.19	19.76	22.47	4.06	100
2015	0.65	57.70	19.42	17.50	4.72	100
2016	1.57	52.75	26.37	17.64	1.67	100
2017	1.89	54.94	30.60	11.78	0.80	100
2018	1.51	53.30	22.95	20.41	1.82	100
2019	0.72	54.28	20.94	20.14	3.92	100
2020	1.98	54.44	22.00	19.64	1.93	100
2021	0.43	60.62	17.47	16.82	4.67	100
2022	2.37	57.25	20.29	15.91	4.17	100
2023	0.37	61.14	21.97	15.69	0.84	100

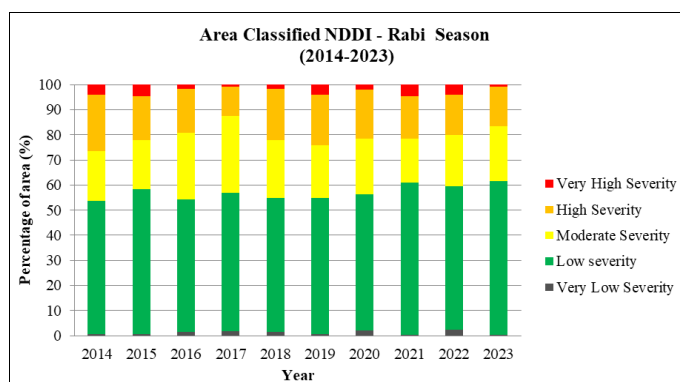


Fig 6: Percent area classified NDDI during *rabi* season for Satara District (2014-2023)

From the Table 3 and Figure 6, during the *rabi* season in Satara district, the NDDI reflected a consistent dominance of low drought severity areas over the ten-year period. The very low severity class consistently fewer than 2.5% of the area in all years, with the highest recorded in 2022 (2.37%) and the lowest in 2023 (0.37%). The proportion of area under low severity remained notably high each year, ranging from 52.75% (2016)

to 61.14% (2023), highlighting generally favourable moisture availability. The moderate severity class varied moderately across years, with a minimum of 17.47% in 2021 and peaking at 30.60% in 2017. High severity levels fluctuated between 11.78% (2017) and 22.47% (2014), while the very high severity category was relatively low, staying below 5% in most years and highest in 2021 (4.67%).

Summer Season

The area-wise drought severity classification using NDDI during the summer season (2014-2023) is presented in Table 4 and illustrated in Figure 7.

Table 4: Per Cent Area Classified Based on NDDI-Derived Drought Severity in Satara District during Summer Season (2014-2023)

Year	Very Low Severity (%)	Low Severity (%)	Moderate Severity (%)	High Severity (%)	Very High Severity (%)	Total (%)
2014	1.76	28.91	22.97	30.44	15.91	100
2015	1.13	34.43	27.39	26.83	10.21	100
2016	1.06	28.50	27.62	33.87	8.95	100
2017	0.94	36.01	30.15	29.03	3.87	100
2018	0.81	35.49	24.27	31.39	8.03	100
2019	1.37	28.57	24.44	33.63	11.99	100
2020	0.89	33.91	23.36	31.74	10.10	100
2021	0.43	60.62	17.47	16.82	4.67	100
2022	0.46	40.10	25.27	25.46	8.72	100
2023	0.37	61.14	21.97	15.69	0.84	100

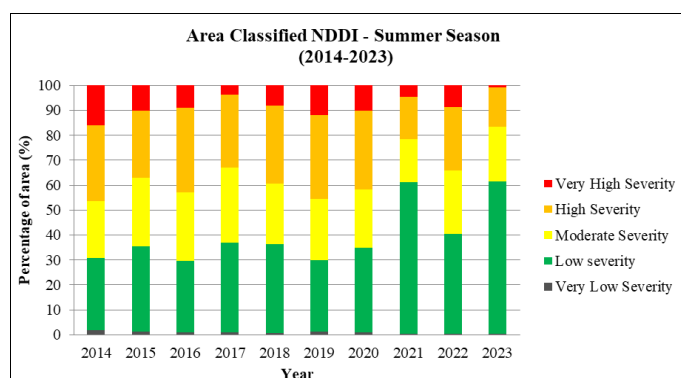


Fig 7: Percent area classified NDDI during summer season for Satara District (2014- 2023)

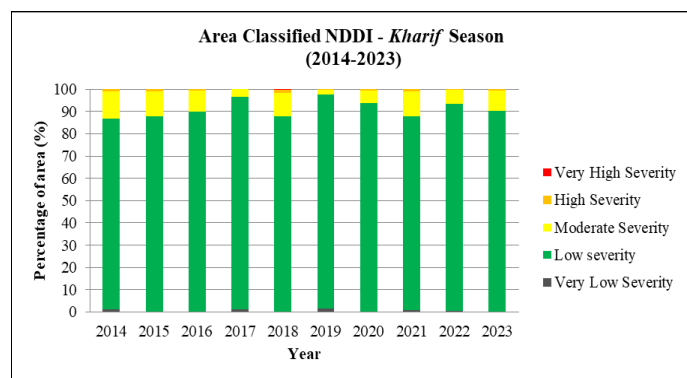
During the summer season, the Normalized Drought Difference Index (NDDI) revealed substantial variability in drought severity levels across the years in Satara district. Table 4 and Figure 7 shows that very low severity remained consistently minimal, below 2% in all years, with the highest being 1.76% in 2014. The area under low severity was comparatively larger in years like 2023 (61.14%), 2021 (60.62%), and 2017 (36.01%), indicating favourable moisture conditions. Moderate severity ranged between 17.47% (2021) and 30.15% (2017), while high severity showed significant peaks in 2014 (30.44%), 2016 (33.87%), and 2019 (33.63%). The very high severity class was highest in 2014 (15.91%), 2019 (11.99%), and 2015 (10.21%), reflecting years with intense drought conditions during the summer season. In contrast, 2023 recorded the least very high severity area (0.84%).

Kharif Season

The area-wise drought severity classification using NDVI during the *kharif* season (2014-2023) is presented in Table 5 and illustrated in Figure 8.

Table 5: Per Cent Area Classified Based on NDDI-Derived Drought Severity in Satara District during *Kharif* Season (2014-2023)

Year	Very Low Severity (%)	Low Severity (%)	Moderate Severity (%)	High Severity (%)	Very High Severity (%)	Total (%)
2014	1.12	85.82	11.98	1.00	0.08	100
2015	0.08	92.75	6.75	0.40	0.02	100
2016	0.19	89.75	9.40	0.62	0.04	100
2017	0.00	99.13	0.79	0.07	0.01	100
2018	0.04	87.77	10.39	1.63	0.16	100
2019	1.54	95.94	2.23	0.25	0.05	100
2020	0.10	93.72	5.71	0.42	0.05	100
2021	1.05	85.95	11.73	0.96	0.32	100
2022	0.40	93.10	6.17	0.31	0.03	100
2023	0.15	90.17	9.17	0.46	0.04	100

**Fig 8:** Percent area classified NDDI during *kharif* season for Satara District (2014-2023)

The NDDI-based drought severity classification during the *kharif* season (2014-2023) in Satara district presented in Table 5 and illustrated in Figure 8 clearly shows that low severity drought dominated throughout the decade. In all years, over 85% of the total area was classified under the low severity category, reaching a peak in 2017 with 99.13%, indicating extremely favourable moisture conditions during that year.

The moderate severity category remained minimal, with the highest value in 2014 (11.98%) and the lowest in 2017 (0.79%), showing limited moderate drought conditions. The high and very high severity classes together accounted for less than 2% of the area in most years, confirming the absence of critical drought stress during *kharif*. Additionally, the very low severity class fluctuated slightly across years, with a maximum of 1.54% (2019) and minimum values approaching zero in some years, like 2017.

The seasonal analysis of NDDI classification from 2014 to 2023 demonstrated distinct patterns of drought severity across *kharif*, *rabi*, and summer seasons in Satara district. *Kharif* season consistently experienced the least drought impact, with over 85% of the area falling under the low severity category in most years and negligible proportions under high or very high severity. This reflects favourable rainfall distribution during the monsoon, supporting healthy vegetation growth. In contrast, both *rabi* and summer seasons exhibited relatively higher drought severity, with notable shares of area under moderate to high severity categories.

Summer season showed the greatest drought intensity, with a larger area affected by high and very high severity, especially in 2016 and 2019, attributed to higher evapotranspiration demand and minimal rainfall. These results align with the findings of Davaagerel *et al* (2021)^[3] who reported highest drought severity in summer season. The overall trend emphasizes the dependence

of vegetation on monsoonal rainfall and the necessity of efficient water management during the drier seasons.

Table 6: Year-Wise Trends in NDDI and Rainfall during *Rabi*, Summer and *Kharif* Season for Satara District (2014-2023)

Year	<i>Rabi</i>		Summer		<i>Kharif</i>	
	Mean NDDI	Rainfall (mm)	Mean NDDI	Rainfall (mm)	Mean NDDI	Rainfall (mm)
2014	0.92	20.6	1.63	13.6	0.42	666.4
2015	0.90	1.9	1.08	69.6	0.43	317.2
2016	0.79	0.7	1.38	6.7	0.35	688.3
2017	0.58	0.0	1.21	25.7	0.38	984.2
2018	0.84	19.7	1.42	2.9	0.40	599.2
2019	0.90	37.7	1.90	11.4	0.32	1303.2
2020	0.66	12.8	1.30	39.6	0.38	940.0
2021	0.73	6.6	1.50	38.0	0.32	838.9
2022	0.64	156.6	1.39	60.6	0.37	812.9
2023	0.69	3.0	1.50	20.3	0.39	403.0

Table 7: Rainfall-NDDI correlation by season

Season	Correlation Coefficient (r)
<i>Rabi</i>	-0.21 (p=0.54)
Summer	0.56 (p=0.09)
<i>Kharif</i>	0.70 (p=0.02*)

Note: * $p < 0.1$, ** $p < 0.05$.

Rainfall and NDDI exhibited a negative association across all three seasons (Table 7), indicating that drought severity (higher NDDI) increases as rainfall decreases. The negative correlation between NDDI and rainfall across seasons concurs with Dobri *et al.* (2021)^[5], reinforcing the index's utility in drought monitoring. The strongest and statistically significant correlation was observed during *kharif* ($r = -0.70$, $p < 0.05$), highlighting the sensitivity of vegetation moisture stress to rainfall variability in the monsoon driven season. A moderate negative correlation during summer ($r = -0.56$, $p < 0.10$) indicates partial rainfall control on vegetation dryness when irrigation or residual soil moisture may buffer drought effects. Conversely, *rabi* showed a very weak and insignificant relationship ($r = -0.22$, $p > 0.10$), likely due to limited rainfall and agricultural dependence on irrigation during this season.

Summary

The study investigated the spatio-temporal drought patterns in Satara district of Western Maharashtra using the Normalized Difference Drought Index (NDDI) derived from Landsat-8 Collection 2 Level-2 data for a ten-year period (2014-2023). NDVI and NDWI were computed for each season (*rabi*, summer and *kharif*), and integrated to generate NDDI maps and seasonal drought severity classifications. The study also examined the relationship between NDDI and seasonal rainfall.

Season-wise temporal analysis revealed clear differences in drought intensity. Summer consistently exhibited the highest NDDI values, reflecting severe moisture stress due to high temperatures and minimal rainfall. *Rabi* season showed moderate drought intensity with considerable year-to-year variation, while *kharif* season exhibited the lowest NDDI values owing to monsoonal rainfall and favourable vegetation conditions.

Spatial analysis of NDDI maps indicated that eastern parts of Satara including Man, Khatav, Phaltan, and Khandala experienced persistent drought across years and seasons. In contrast, western regions near Mahabaleshwar consistently

showed lower drought severity because of higher rainfall and denser vegetation cover.

In *rabi*, 2014 recorded high drought intensity, whereas 2017 reflected better conditions. During summer, 2014 showed the most severe drought conditions, while 2023 demonstrated notable improvement. *kharif* seasons generally showed lower drought severity, with 2015 as a drier year and 2019 reflecting healthier vegetation cover.

Correlation analysis between rainfall and NDDI revealed a significant negative relationship during *kharif* ($r = -0.70$), indicating that rainfall strongly controls vegetation moisture conditions in this season. Summer showed moderate negative correlation ($r = -0.56$), while *rabi* exhibited weak association because most crops rely on irrigation rather than rainfall. Overall, the NDDI proved highly effective in identifying spatial and seasonal drought variability and highlighting drought-prone regions in Satara district.

Conclusion

The spatio-temporal evaluation of NDDI from 2014-2023 demonstrates clear seasonal drought dynamics in Satara district. Summer emerged as the most drought-prone period due to high temperatures and minimal rainfall, whereas *kharif* showed minimal drought stress due to reliable monsoon rainfall. *Rabi* season exhibited moderate drought severity with stable vegetation conditions supported by irrigation practices. Persistent drought hotspots in eastern tahsils highlight their heightened vulnerability and demand priority attention in future water resource planning. The significant negative relationship between *kharif* rainfall and NDDI highlights rainfall dependency of the region's agriculture. The analysis further reveals that NDDI is an effective indicator for assessing drought, as reflected by its strong negative correlation with rainfall, particularly during *kharif*. Overall, the findings emphasize the importance of continuous drought monitoring, strategic water management and targeted mitigation efforts to support sustainable agriculture in the drought sensitive regions of Satara district.

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