



Spatiotemporal Assessment of Agricultural Drought in Maharashtra, India Using Remote Sensing-Based Vegetation Indices and Climatic Variables (2001–2023)

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ABSTRACT

Agricultural drought is a major environmental hazard affecting crop production, water resources, and ecosystem sustainability, particularly in monsoon-dependent regions. Maharashtra frequently experiences drought due to rainfall variability and increasing temperature. This study assessed the spatiotemporal characteristics of agricultural drought across Maharashtra during 2001–2023 using satellite-derived vegetation indices and climatic variables. Seasonal Normalized Difference Vegetation Index (NDVI), rainfall, and land surface temperature were used to derive the Vegetation Condition Index (VCI), Temperature Condition Index (TCI), and Vegetation Health Index (VHI). Time-series analysis, the Mann–Kendall trend test, correlation, and multiple regression analyses were applied to evaluate vegetation dynamics and climatic influences, while a Composite Drought Vulnerability Index (DVI) identified drought-prone districts. Results revealed considerable spatial and temporal variability in drought conditions. Rainfall showed high inter-annual variability, whereas temperature exhibited an increasing trend that intensified vegetation stress. The integrated use of satellite-derived vegetation indices and climatic variables provides an effective framework for long-term drought monitoring, vulnerability assessment, and sustainable agricultural planning in Maharashtra.

Keywords: Agricultural drought; NDVI; VCI; TCI; VHI; Remote sensing; Maharashtra.

1. Introduction

Agricultural drought is one of the most significant natural hazards affecting crop production, water availability, and ecosystem sustainability. Unlike meteorological drought, agricultural drought reflects the combined effects of rainfall deficiency, high temperature, and vegetation stress, directly influencing agricultural productivity. With increasing climate variability and rising temperatures, the frequency and severity of drought events have increased, highlighting the need for reliable drought monitoring systems. Maharashtra is one of the most drought-prone states in India because of its dependence on monsoon rainfall and diverse climatic conditions. While the Western Ghats receive abundant rainfall, the central and eastern districts frequently experience rainfall deficits, prolonged dry spells, and increasing thermal stress. These conditions result in substantial spatial and temporal variability in agricultural drought, making continuous drought assessment essential for sustainable agricultural and water resource management.

Satellite remote sensing has become an effective approach for drought monitoring because it provides consistent observations of vegetation conditions over large areas. The Normalized Difference Vegetation Index (NDVI) is widely used to monitor vegetation greenness, whereas the Vegetation Condition Index (VCI), Temperature Condition Index (TCI), and Vegetation Health Index (VHI) improve drought assessment by integrating vegetation response with moisture and temperature stress. These indices provide reliable information on drought severity and vegetation health at different spatial and temporal scales. In addition to vegetation indices, statistical techniques such as time-series analysis, the Mann–Kendall trend test, correlation analysis, and multiple regression improve the understanding of long-term drought behaviour and the influence of climatic variables on vegetation. Integrating these approaches enables the identification of drought trends, climatic controls, and vulnerable regions, thereby supporting more effective drought monitoring and management.

This study integrates satellite-derived vegetation indices with rainfall and temperature data to assess agricultural drought across Maharashtra during 2001–2023. State- and district-level analyses were performed to evaluate drought severity, vegetation dynamics, climatic relationships, and drought vulnerability, providing scientific information for drought mitigation and sustainable agricultural planning.

Objectives

1. To assess the spatiotemporal characteristics of agricultural drought in Maharashtra using satellite-derived vegetation indices (NDVI, VCI, TCI, and VHI) during 2001–2023.
2. To analyze the influence of rainfall and temperature on vegetation dynamics using trend, correlation, and regression analyses.

- To identify drought-prone districts using a Composite Drought Vulnerability Index (DVI) for improved drought monitoring and management.

2. Materials and Methods

2.1 Study Area

The study was conducted in Maharashtra, India, located between 15°36'–22°06' N latitude and 72°36'–80°54' E longitude, covering an area of approximately 307,713 km². Maharashtra is the second-largest state in India and exhibits diverse climatic and physiographic conditions. The state comprises 36 districts, ranging from the high-rainfall Western Ghats and Konkan coastal region to the semi-arid plateau of central and eastern Maharashtra. The climate is predominantly tropical monsoon, Annual rainfall varies considerably across the state, ranging from less than 600 mm in rain-shadow regions to more than 4000 mm along the Western Ghats.

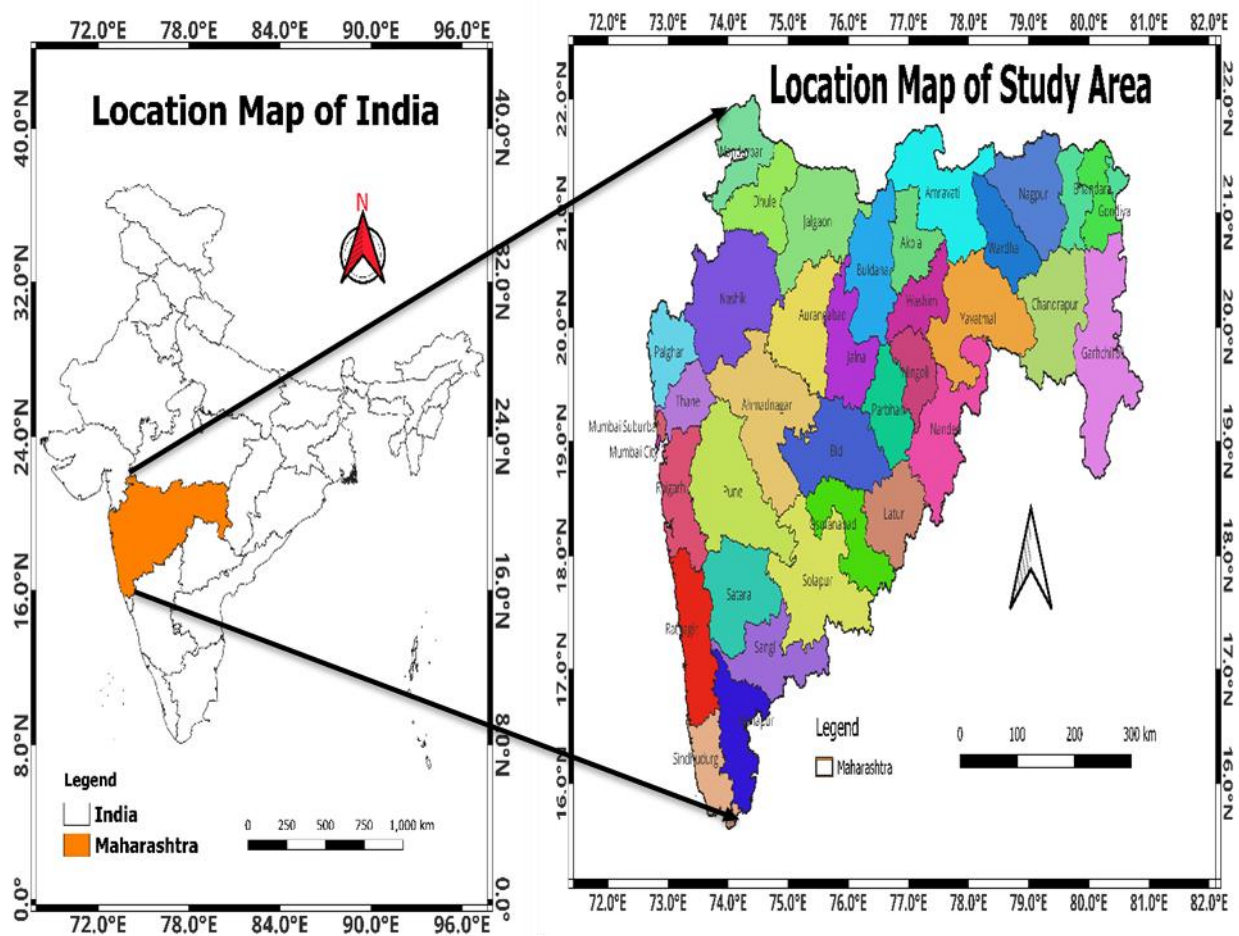


Figure 1. Location Map Study Area

2.2 Data Sources

The study integrated satellite-derived vegetation data with climatic datasets for the period 2001–2023. The datasets used are summarized in Table 1.

Table 1. Datasets used in the study

Dataset	Source	Spatial Resolution	Temporal Resolution	Purpose
NDVI	MODIS	250 m	Seasonal	Vegetation monitoring
Land Surface Temperature	MODIS	1 km	Seasonal	TCI calculation
Rainfall	IMD	District/Gridded	Seasonal	Climate analysis
District Boundary	Survey of India	Vector	Static	District-level analysis

2.3 Data Pre-processing

Satellite datasets were downloaded, mosaicked where required, and clipped to the Maharashtra boundary. Cloud-contaminated observations were removed using quality control procedures, and seasonal composite datasets were prepared for each year. Climatic datasets were checked for missing observations and organized into a consistent temporal database. All datasets were projected to a common coordinate system and resampled where necessary to maintain spatial consistency during analysis.

2.4 Vegetation Indices

2.4.1 Normalized Difference Vegetation Index (NDVI)

NDVI was used to evaluate vegetation greenness and photosynthetic activity throughout the study period. It was calculated using the near-infrared (NIR) and red spectral bands as

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

Higher NDVI values indicate healthier vegetation, whereas lower values represent sparse vegetation or drought-affected conditions.

2.4.2 Vegetation Condition Index (VCI)

VCI was calculated to minimize seasonal effects by comparing current NDVI with its historical minimum and maximum values.

$$VCI = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \times 100$$

VCI values below 40 indicate vegetation stress associated with drought conditions.

2.4.3 Temperature Condition Index (TCI)

TCI was derived from land surface temperature to quantify temperature-induced vegetation stress. Higher TCI values indicate favorable thermal conditions, whereas lower values indicate greater heat stress.

$$TCI = \frac{LST_{max} - LST}{LST_{max} - LST_{min}} \times 100$$

2.4.4 Vegetation Health Index (VHI)

The Vegetation Health Index integrates vegetation and temperature conditions to assess overall agricultural drought severity.

$$VHI = 0.5(VCI) + 0.5(TCI)$$

Based on VHI values, drought severity was classified into:

VHI Range	Drought Class
< 10	Extreme drought
10–20	Severe drought
20–30	Moderate drought
30–40	Mild drought
> 40	No drought

2.5 Time-Series Analysis

Seasonal NDVI, rainfall, and temperature datasets for 2001–2023 were analyzed to examine temporal variability in vegetation and climatic conditions across Maharashtra. Time-series plots were generated to identify fluctuations associated with drought and favorable monsoon years.

2.6 Trend Analysis

Long-term trends in NDVI, rainfall, temperature, VCI, TCI, and VHI were evaluated using the Mann–Kendall (MK) non-parametric trend test, which is suitable for environmental time-series data without requiring normal distribution. Trend significance was assessed at the 5% significance level ($p < 0.05$).

2.7 Correlation Analysis

Pearson's correlation analysis was performed to evaluate relationships among NDVI, rainfall, and temperature. Correlation coefficients were used to determine the direction and strength of climatic influences on vegetation dynamics.

2.8 Multiple Regression Analysis

Multiple linear regression analysis was conducted to quantify the combined influence of rainfall and temperature on vegetation conditions.

The regression model was expressed as

$$NDVI = \beta_0 + \beta_1(Rainfall) + \beta_2(Temperature) + \epsilon$$

where: β_0 = intercept

β_1 = rainfall coefficient

β_2 = temperature coefficient

ϵ = random error

Regression coefficients and their statistical significance were used to identify the dominant climatic factor affecting vegetation.

2.9 District-Level Drought Assessment

District-wise seasonal NDVI, VCI, TCI, and VHI values were computed to evaluate spatial variability in agricultural drought. The proportion of years with VCI values below 40 was calculated to estimate drought frequency for each district. The results were presented through thematic maps and statistical summaries to identify persistent drought-prone districts.

2.10 Composite Drought Vulnerability Index (DVI)

A Composite Drought Vulnerability Index (DVI) was developed by integrating long-term vegetation condition, rainfall anomaly frequency, and temperature-related stress indicators. The index was used to classify districts according to their relative drought vulnerability. Higher DVI values indicated greater susceptibility to recurrent agricultural drought, while lower values represented comparatively resilient districts.

2.11 Statistical Software

All statistical analyses, including descriptive statistics, time-series analysis, correlation analysis, regression analysis, and Mann–Kendall trend analysis, were performed using RStudio. Spatial data processing, map generation, and visualization were carried out using Geographic Information System (GIS) and remote sensing techniques.

3. Results and Discussion

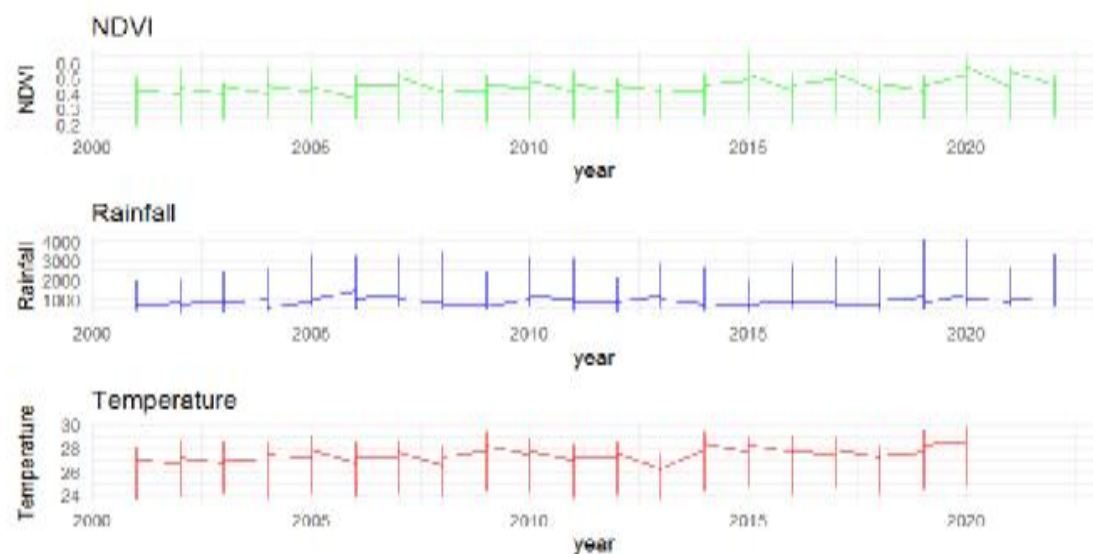
3.1 Spatiotemporal Variability of Vegetation and Climatic Conditions

The seasonal analysis of vegetation and climatic variables from 2001 to 2023 revealed substantial year-to-year variability across Maharashtra. Variations in NDVI, rainfall, and temperature reflected the combined effects of changing monsoon conditions and increasing thermal stress on vegetation. NDVI generally declined during drought years and improved in years with favourable rainfall, indicating that vegetation productivity is strongly influenced by climatic variability. Rainfall fluctuated considerably throughout the study period without showing a significant long-term trend ($p = 0.163$). In contrast, temperature exhibited a gradual increasing trend, suggesting that warming conditions have become an important factor affecting vegetation health. Mann–Kendall analysis further showed significant trends for NDVI ($p = 0.0149$), NDVI anomaly ($p = 0.0125$), VCI ($p = 0.0179$), and TCI ($p = 0.0058$), while VHI ($p = 0.1834$) did not show a significant long-term trend. These findings indicate that vegetation condition has changed significantly over time despite the absence of a significant rainfall trend.

Table 2. Mann–Kendall trend test results for state-level drought variables.

Variable	MK_p_value
Rainfall	0.162984
NDVI	0.014961
NDVI_Anomaly	0.012482
VCI	0.017864
TCI	0.00582
VHI	0.183447

The combined analysis suggests that rainfall variability remains the primary trigger of drought, whereas rising temperature intensifies vegetation stress by increasing evapotranspiration and reducing soil moisture availability. This highlights the importance of integrating vegetation indices with climatic variables for more effective agricultural drought monitoring and assessment in Maharashtra.

**Figure 2. Seasonal variability of NDVI, rainfall, and temperature**

3.2 Agricultural Drought Assessment Using Vegetation Indices

The Vegetation Condition Index (VCI), Temperature Condition Index (TCI), and Vegetation Health Index (VHI) effectively captured the spatial and temporal variability of agricultural drought across Maharashtra. The VCI heatmap showed noticeable differences in vegetation condition among districts and years, indicating that drought intensity varied with changing climatic conditions. Several districts repeatedly recorded VCI values below the drought threshold, reflecting persistent vegetation stress, while favourable monsoon years showed temporary improvements in vegetation health. VHI-based drought assessment revealed significant year-to-year variation in drought severity. Years such as 2009, 2014, 2015, and 2019 recorded larger areas under severe and extreme drought, whereas 2013 and 2017 were dominated by no-drought conditions, indicating favourable rainfall and vegetation recovery.

Table 3. Year-wise area (km²) under different drought severity classes in Maharashtra

Value	Pixel Count	Area (km ²)	Year	Class
3	50119	11679.24	2001	Moderate
4	316461	73744.98	2001	Mild
5	958336	223321.30	2001	No drought
2	135	31.45908	2002	Severe
3	13347	3110.254	2002	Moderate

Value	Pixel Count	Area (km ²)	Year	Class
4	118261	27558.39	2002	Mild
5	1193179	278046.80	2002	No drought
1	179	41.71241	2003	Extreme
2	17985	4191.049	2003	Severe
3	147174	34295.99	2003	Moderate
4	278060	64796.38	2003	Mild
5	881504	205417.10	2003	No drought
2	475	110.68940	2004	Severe
3	39206	9136.183	2004	Moderate
4	141512	32976.57	2004	Mild
5	1143742	266526.50	2004	No drought
1	5	1.165151	2005	Extreme
2	24836	5787.539	2005	Severe
3	169652	39534.04	2005	Moderate
4	337183	78573.83	2005	Mild
5	793247	184850.50	2005	No drought
3	9478	2208.660	2006	Moderate
4	127012	29597.63	2006	Mild
5	1188429	276939.90	2006	No drought
2	63	14.68090	2007	Severe
3	16751	3903.489	2007	Moderate
4	126469	29471.1	2007	Mild
5	1181645	275359	2007	No drought
3	84375	19661.93	2008	Moderate
4	256732	59826.32	2008	Mild
5	983813	229258.2	2008	No drought
1	14880	3467.49	2009	Extreme
2	125973	29355.52	2009	Severe
3	351385	81883.33	2009	Moderate
4	402662	93832.42	2009	Mild
5	430023	100208.4	2009	No drought
2	4057	945.4036	2010	Severe
3	52017	12121.53	2010	Moderate
4	217560	50698.06	2010	Mild
5	1051301	244984.9	2010	No drought
3	2719	633.6092	2011	Moderate

Value	Pixel Count	Area (km ²)	Year	Class
4	87513	20393.17	2011	Mild
5	1234682	287718.2	2011	No drought
1	1070	249.3423	2012	Extreme
2	57966	13507.83	2012	Severe
3	150046	34965.25	2012	Moderate
4	321532	74926.67	2012	Mild
5	794348	185107.1	2012	No drought
5	132492	308746.9	2013	No drought
1	50036	11659.9	2014	Extreme
2	188618	43953.7	2014	Severe
3	314722	73339.74	2014	Moderate
4	299785	69858.97	2014	Mild
5	471767	109936	2014	No drought
1	48322	11260.49	2015	Extreme
2	100981	23531.63	2015	Severe
3	180486	42058.69	2015	Moderate
4	246212	57374.84	2015	Mild
5	748906	174517.7	2015	No drought
2	23615	5503.009	2016	Severe
3	187604	43717.4	2016	Moderate
4	380702	88715.07	2016	Mild
5	732992	170809.3	2016	No drought
2	2510	584.9059	2017	Severe
3	28552	6653.479	2017	Moderate
4	150094	34976.44	2017	Mild
5	1143770	266533	2017	No drought
2	951	221.6117	2018	Severe
3	26129	6088.847	2018	Moderate
4	165432	38550.66	2018	Mild
5	1132413	263886.5	2018	No drought
1	58459	13622.71	2019	Extreme
2	136463	38091.82	2019	Severe
3	311644	72622.47	2019	Moderate
4	377968	88077.97	2019	Mild
5	413381	96330.27	2019	No drought
1	5584	1301.241	2020	Extreme

Value	Pixel Count	Area (km ²)	Year	Class
2	28752	6700.085	2020	Severe
3	93353	21754.07	2020	Moderate
4	189148	44077.2	2020	Mild
5	1008081	234913.3	2020	No drought

The VHI drought severity map showed that central and eastern Maharashtra were more affected by mild to moderate drought, while the Western Ghats and coastal districts experienced relatively lower drought severity because of better moisture availability and favourable climatic conditions. Overall, the combined use of VCI, TCI, and VHI provided a comprehensive assessment of agricultural drought by integrating vegetation response with rainfall and temperature, making these indices more reliable than rainfall alone for drought monitoring.

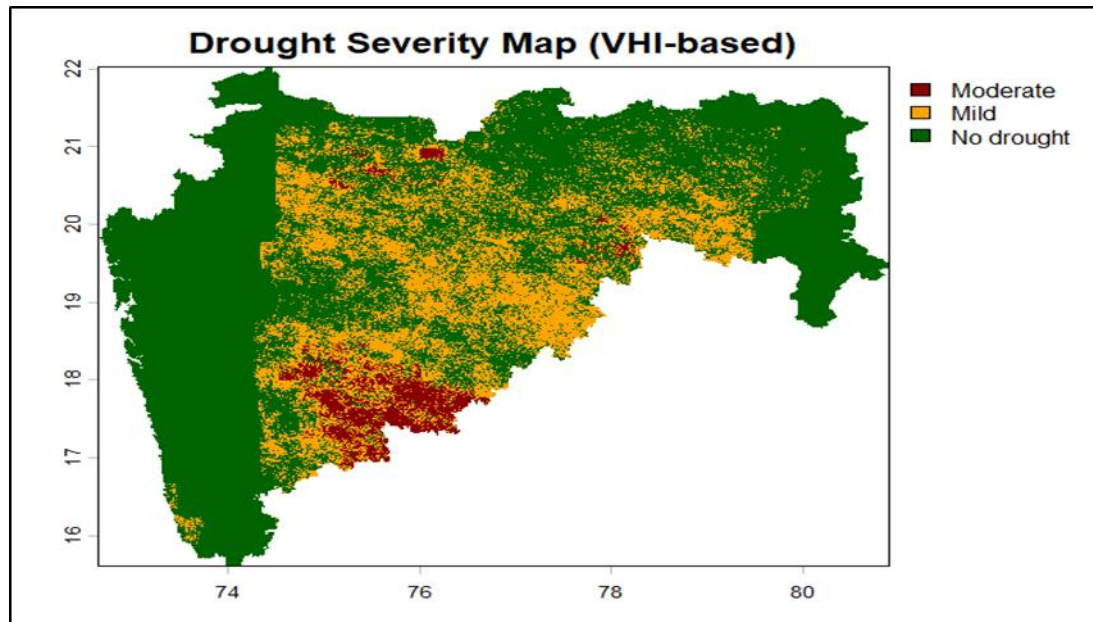


Figure 3. Drought severity map (VHI-based)

3.3 District-wise Drought Frequency

District-wise drought frequency analysis showed clear spatial differences in agricultural drought across Maharashtra. Based on VCI values below 40, Dhule and Wardha recorded the highest drought frequency (0.77), indicating frequent vegetation stress during the study period. Buldana, Hingoli, Washim, and Yavatmal also experienced high drought frequency (around 0.73), reflecting their greater vulnerability to recurring drought. Districts such as Ahmednagar, Aurangabad, Bid, Nashik, Jalgaon, Akola, Amravati, and Nandurbar showed moderate drought frequency, while Satara (0.14), Sangli (0.23), Solapur (0.23), Pune (0.27), and Mumbai Suburban (0.27) recorded the lowest drought frequency. The relatively low drought occurrence in these districts is likely associated with favourable rainfall, better water availability, and influence of Western Ghats and coastal climate.

Table 4. District-wise drought frequency (proportion of drought years, 2001–2023)

District_Name	Drought_Frequency	District_name	Drought_Frequency
Ahmednagar	0.590909091	Hingoli	0.727272727
Akola	0.681818182	Jalgaon	0.681818182
Amravati	0.681818182	Jalna	0.681818182
Aurangabad	0.636363636	Kolhapur	0.454545455
Bhandara	0.545454545	Latur	0.5
Bid	0.636363636	Mumbai Suburban	0.272727273
Buldana	0.727272727	Mumbai city	0.454545455
Chandrapur	0.545454545	Nagpur	0.5

District_Name	Drought_Frequency	District_name	Drought_Frequency
Dhule	0.772727273	Nanded	0.409090909
Garhchiroli	0.545454545	Sangli	0.227272727
Gondiya	0.545454545	Satara	0.136363636
Nandurbar	0.681818182	Sindhudurg	0.409090909
Nashik	0.636363636	Solapur	0.227272727
Osmanabad	0.454545455	Thane	0.409090909
Parbhani	0.545454545	Wardha	0.772727273
Pune	0.272727273	Washim	0.727272727
Raigarh	0.318181818	Yavatmal	0.727272727
Ratnagiri	0.363636364		

3.4 Climatic Controls on Vegetation Dynamics

The influence of climatic variables on vegetation was evaluated using correlation and multiple regression analyses. The results showed a weak relationship between NDVI and rainfall, indicating that rainfall alone could not fully explain vegetation changes across Maharashtra. In contrast, temperature exhibited a stronger relationship with NDVI, suggesting that thermal conditions played a greater role in vegetation dynamics. Regression analysis showed that rainfall had no significant effect on NDVI ($p = 0.478$), whereas temperature had a highly significant positive influence ($p < 0.001$). Similarly, the correlation analysis indicated a negligible relationship between NDVI and rainfall ($r = -0.0248$) and a moderate positive correlation between NDVI and temperature ($r = 0.4231$). The analysis further showed that favourable rainfall generally improved vegetation conditions, while increasing temperature.

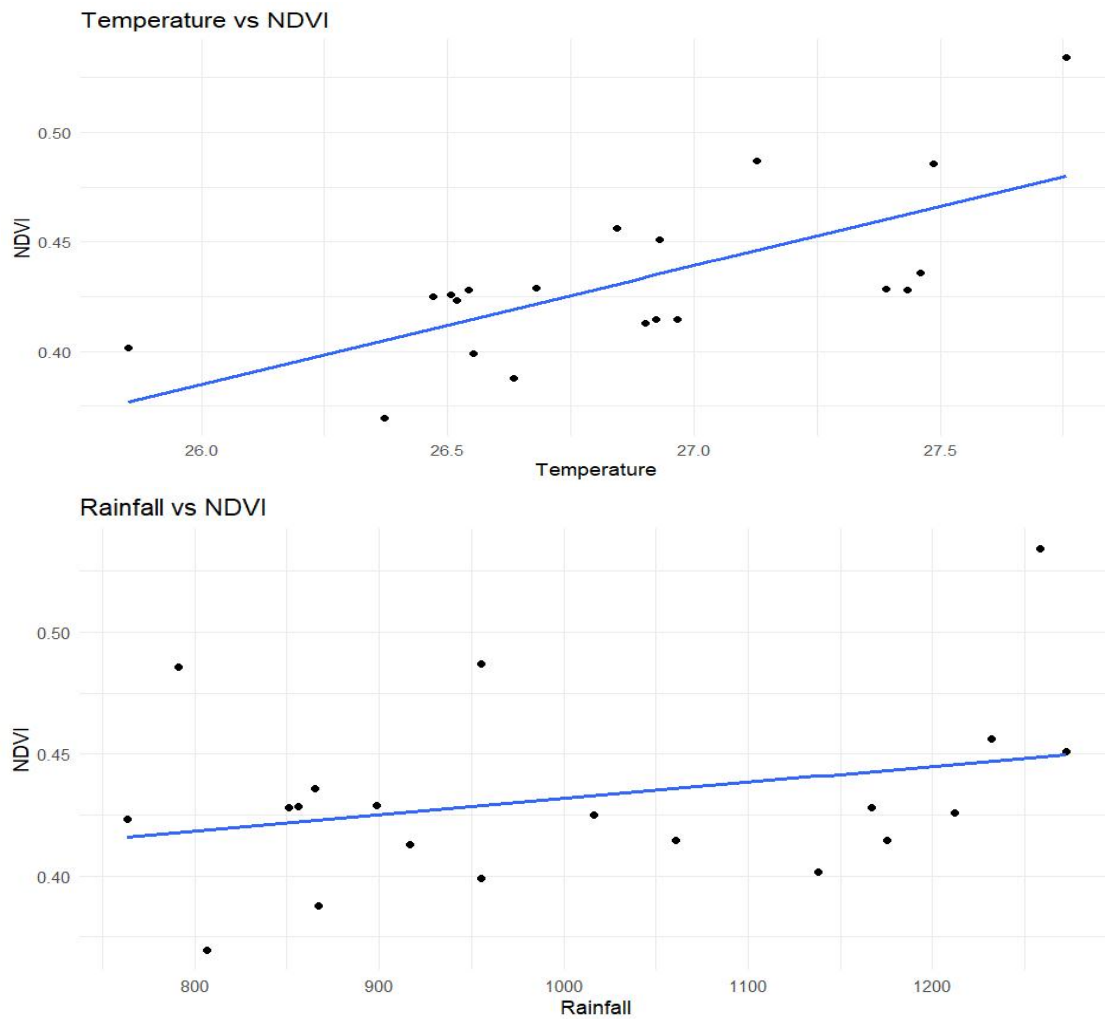


Figure 4. NDVI, rainfall and temperature at the district level.

3.5 Composite Drought Vulnerability Index

The Composite Drought Vulnerability Index (DVI) was used to identify districts with high agricultural drought vulnerability by integrating vegetation condition, rainfall anomalies, and temperature stress. The DVI map showed that Buldana, Latur, Akola, Wardha, Jalna, Hingoli, Washim, and Yavatmal were the most drought-prone districts, indicating persistent vegetation stress and recurring climatic extremes. In contrast, the western and coastal districts exhibited lower DVI values, reflecting more favourable climatic conditions and lower drought vulnerability. The consistency between DVI, drought frequency, and vegetation condition highlights the usefulness of the index for identifying vulnerable areas and supporting drought management and agricultural planning.

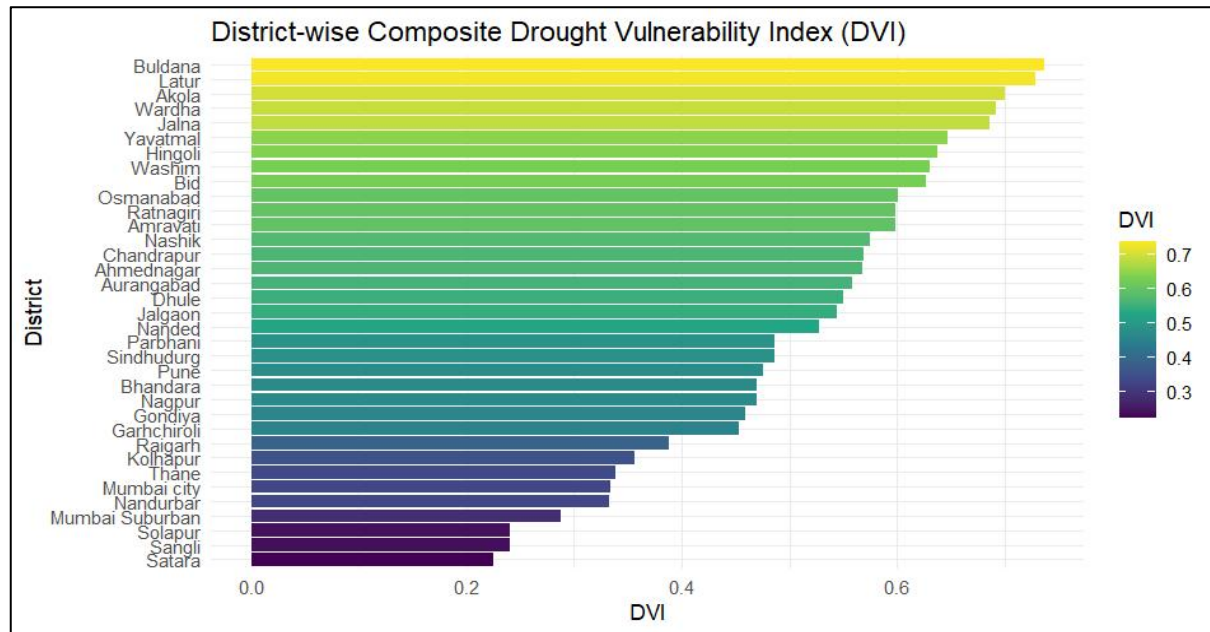


Figure 5. District-wise Composite Drought Vulnerability Index (DVI)

3.6 Integrated Discussion

The findings indicate that agricultural drought in Maharashtra is influenced by the combined effects of rainfall variability and increasing temperature. Although rainfall remains the primary factor triggering drought, the analyses showed that rising temperature has become a major driver of vegetation stress. Trend analysis revealed no significant long-term change in rainfall, whereas significant trends were observed in NDVI, VCI, and TCI, indicating increasing sensitivity of vegetation to thermal stress. District-level assessment further showed that interior districts were more vulnerable to drought, while western coastal districts experienced lower drought frequency and healthier vegetation. The strong agreement among drought frequency, VCI, VHI, and the Composite Drought Vulnerability Index (DVI) confirms the reliability of the identified drought-prone regions. Moreover, correlation and regression analyses demonstrated that temperature had a stronger influence on vegetation dynamics than rainfall. These results highlight the importance of integrating satellite-derived vegetation indices with climatic variables to improve long-term drought monitoring, agricultural planning, and climate-resilient resource management across Maharashtra.

4. Conclusion

This study assessed the spatiotemporal characteristics of agricultural drought across Maharashtra during 2001–2023 using satellite-derived vegetation indices and climatic variables. The results revealed considerable variability in drought conditions across both time and space. Rainfall showed high inter-annual variability without a significant long-term trend, whereas temperature exhibited a consistent increasing trend, indicating the growing influence of thermal stress on vegetation. Vegetation indices (NDVI, VCI, TCI, and VHI) effectively captured drought severity and highlighted reduced vegetation health during major drought years. District-level analysis showed that Dhule, Wardha, Buldana, Hingoli, Washim, and Yavatmal were among the most drought-prone districts, while Satara, Sangli, and Solapur experienced comparatively lower drought frequency. Correlation and regression analyses further demonstrated that temperature had a stronger influence on vegetation dynamics than rainfall, suggesting that rising temperatures are intensifying agricultural drought conditions. The Composite Drought Vulnerability Index (DVI) successfully identified vulnerable districts by integrating vegetation condition, rainfall anomalies, and temperature stress, providing a comprehensive assessment of drought risk. Overall, the study demonstrates that integrating satellite-based vegetation indices with statistical analyses offers a reliable framework for long-term agricultural drought monitoring. The findings can support drought preparedness, agricultural planning, and climate-resilient water resource management in Maharashtra and other regions with similar climatic conditions.

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