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RESEARCH ARTICLE

MULTI-SEASONAL ANALYSIS OF VEGETATION HEALTH AND SURFACE WATER AVAILABILITY IN LAKHIMPUR DISTRICT, ASSAM (2013-2023): AN NDVI AND NDWI-BASED SPATIO-TEMPORAL ANALYSIS

Sohail Ahamed[1], Nigar Alam Siddique[2] and Mu Einuddin[1]

1. Research Scholar, Department of Geography, AMU, Aligarh, India.
2. Professor, Department of Geography, AMU, Aligarh, 202002.

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Abstract

Understanding the relationship between vegetation health and surface water availability is crucial for sustainable land and water resource management. This study employs a spatio-temporal analysis of the Normalized Difference Vegetation Index (NDVI) and The Normalized Difference Water Index (NDWI) is a widely used remote sensing index for water body detection and monitoring trends in Lakhimpur District, Assam, covering the years 2013, 2016, 2019, and 2023 across pre-monsoon, monsoon, and post-monsoon seasons. Landsat 8 satellite images were processed in Google Earth Engine (GEE), Arc Map, and ensuring radiometric and geometric corrections for accuracy. The study finds a strong negative correlation (-0.988, p-value = 1.79×10^{-9}) between NDVI and NDWI, indicating that as vegetation cover increases, surface moisture availability declines. The results highlight increasing vegetation health over the decade but worsening water stress, particularly in monsoon and post-monsoon seasons. These findings emphasise the need for integrated land and water management strategies, including sustainable irrigation practices, afforestation with drought-resistant species, and climate adaptation measures. The study underscores the importance of continuous monitoring of vegetation and hydrological trends to mitigate environmental degradation and ensure ecological balance.

Introduction:-

Vegetation and water resources are critical components of the terrestrial ecosystem (Xue & Su, 2017), directly influencing biodiversity, climate resilience (Folke et al., 2010), and agricultural productivity (Smith & Boers, 2023). Remote sensing techniques have significantly enhanced our ability to monitor vegetation health (Kumar et al. (2023; Funk et al. (2015) and surface moisture dynamics over time (Smit & Ruessink, 2017). Among the widely used indices (Kumar et al., 2023), The Normalized Difference Vegetation Index (NDVI) (Huang et al., 2020) is a widely used metric for assessing vegetation health and productivity (Farias et al., 2023). serves as a proxy for vegetation density and productivity, whereas the Normalized Difference Water Index (NDWI) (Li et al., 2022) quantifies

Corresponding Author:-Sohail Ahamed
Address:-Research Scholar, Department of Geography, AMU, Aligarh, India.

surface water availability and moisture content(Taloor, Manhas, &Kothyari, 2021).Recent studies have shown that land-use changes, deforestation, agricultural expansion, and climatic variability contribute to variations in NDVI and NDWI (Huang et al., 2020; Werf et al., 2010; Batala et al., 2023; Shakarami et al., 2022). The Lakhimpur District of Assam, located in the northeastern part of India, is highly influenced by seasonal climatic patterns, experiencing intensive monsoon rainfall and fluctuating dry periods (Sathishkumar, Nirmolia, Bhattacharyya, &Patgiri, 2022).Understanding the relationship between vegetation growth and water stress in such a region is essential for sustainable land-use planning and water resource management (Yang et al., 2023).This study aims to analyze spatio-temporal (Yu, Yin, & Zhu, 2017)variations in NDVI and NDWI from 2013 to 2023 across pre-monsoon, monsoon, and post-monsoon seasons(Zeng et al. (2019); Bangar, Mishra, Jangid, & Rajput, 2021)in Lakhimpur District. By utilizing Landsat 8 satellite imagery (Vermote, Justice, Claverie, & Franch, 2016), Google Earth Engine (GEE) (Tamiminia et al., 2020), ArcMap (Issa, Qanazi, Natsheh, & Rashed, 2023), and QGIS (Muhammad et al., 2022),this research investigates trends in vegetation health and water availability. Furthermore, statistical analysis (Myers, J. L., Well, A. D., & Lorch Jr, R. F. (2013), including Pearson correlation and trend assessments, provides insights into the evolving vegetation-water interaction (Stackpoole et al., 2023; Garg et al., 2019).

Study Area:

Lakhimpur, named after Lakshmi, the goddess of prosperity, is an agricultural district in northeastern Assam, known for its fertile alluvial soil and abundant paddy cultivation (Basu, Bhadoria, & Mahapatra, 2023). It was declared a district in 1839 and reorganized multiple times, with Dhemaji separating in 1989. Once called Koliapani due to poor connectivity, transport improved with an aerodrome in 1954, ASTC bus services in 1957, and railways in 1963 (Stein et al., 2015). Covering 2,277 sq. km (2,257 sq. km rural, 20 sq. km urban), it has a population of 1,042,137, as per the 2011 Census). Located between 26°48'–27°53' N latitude and 93°42'–94°20' E longitude on the north bank of the Brahmaputra, it borders Arunachal Pradesh (north), Dhemaji (east), Majuli (south), and Biswanath District (west) (Raff et al., 2023)(Fig.1). The region faces challenges such as unpredictable weather patterns, soil degradation, and water scarcity, which can impact crop health and agricultural productivity (Bhattacharyya et al., 2023; Ingrao et al., 2023). Monitoring crop health and water availability is essential for mitigating these challenges and optimizing agricultural practices (Heong& Chen, 2023; Chaudhary et al., 2023).

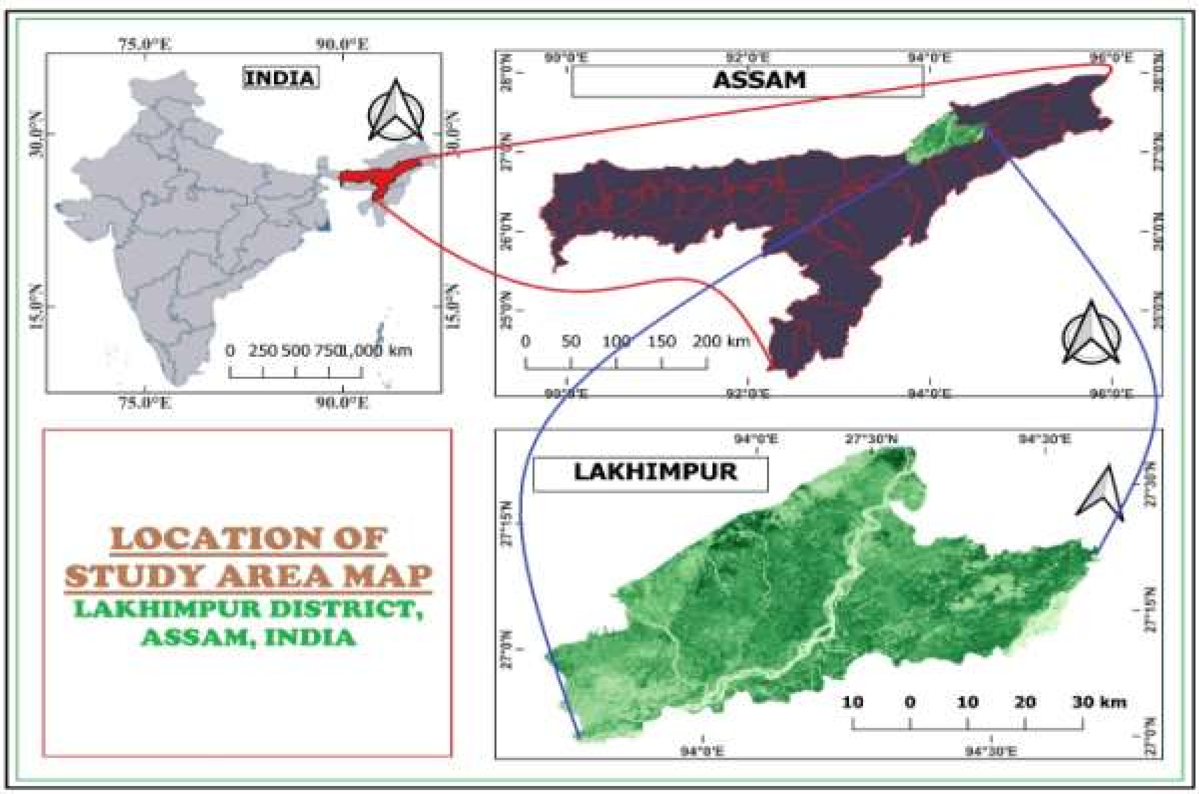

Fig 1: Locational Map of the Study area

Materials and Methods:-

Table1.0: Landsat 8 OLI Band Specifications

Satellite	Sensor	Data Source	Temporal Duration	Cloud Cover	Band Number	Band Name	Wavelength Range (µm)	Spatial Reso.(m)
Landsat 8	Operational Land Imager (OLI)	USGS	June 2013 - June 2023	≤ 5%	Band 3	Green	0.53 - 0.59	30
	Operational Land Imager (OLI)	USGS	June 2013 - June 2023	≤ 5%	Band 4	Red	0.64 - 0.67	30
	Operational Land Imager (OLI)	USGS	June 2013 - June 2023	≤ 5%	Band 5	Near-Infrared (NIR)	0.85 - 0.88	30

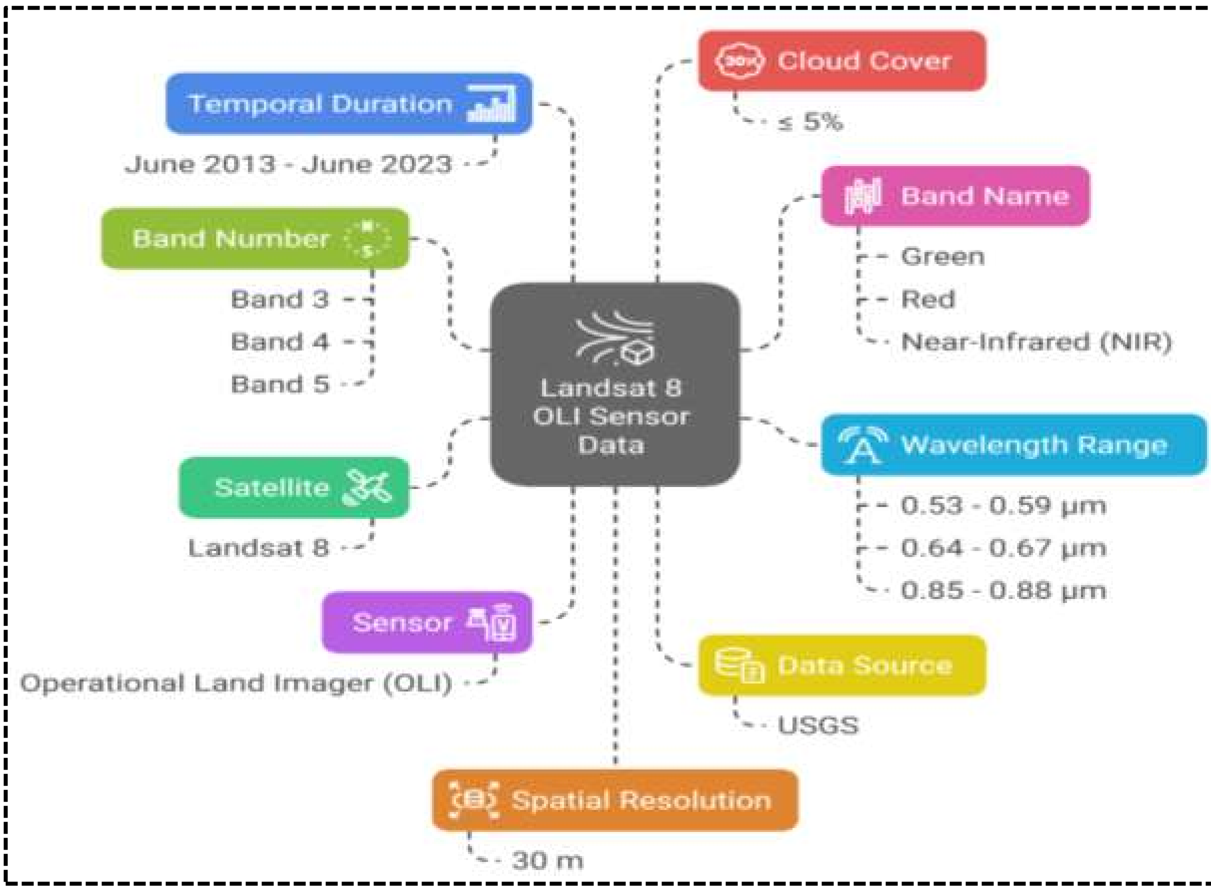

Fig
Flowchart showing the data specification

Method and Methodology:-

The study employs a seasonal spatio-temporal analysis of NDVI and NDWI in Lakhimpur District, Assam, covering the years 2013, 2016, 2019, and 2023 across the pre-monsoon, monsoon(Basu & Mondal, 2022), and post-monsoon seasons. To ensure comprehensive seasonal coverage, a total of 24 Landsat satellite images were acquired from Google Earth Engine (GEE)(Kolli, Opp, Karthe, & Groll, 2020).The images underwent radiometric corrections (applied in Google Earth Engine and QGIS) using the following formulas:TOA Reflectance Correction(Gorelick et al., 2017):

$$\text{TOA Reflectance} = \frac{M_L \times Q_{cal} + A_L}{cos(\theta)}$$

………… eq. (1)

where M_L is the radiance multiplicative scaling factor, Q_{cal} is the pixel digital number (DN), A_L is the radiance additive scaling factor, and θ is the solar zenith angle.The preprocessing steps included Dark Object Subtraction (DOS), which removes atmospheric scattering by subtracting the lowest reflectance values detected in non-reflective surfaces such as water bodies (Stathakis & Liakos, 2019), and cloud masking (GEE-based), which eliminates cloud-contaminated pixels using the Landsat QA band (Rassarandi&Adliani, 2023).Geometric corrections were performed to enhance data accuracy before further processing(Belfiglio, Luongo, & Mancini, 2022).Georeferencing was applied using the transformation equations:

$$x' = a_1 + a_2x + a_3y, \quad y' = b_1 + b_2x + b_3y$$

………… eq. (2)

Which aligns images using Ground Control Points (GCPs) to match real-world coordinates.The NDVI and NDWI indices were computed in GEE using the following formulas(Roark & Young, 2020):

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

………… eq. (3)

Where NIR (Near-Infrared Band) corresponds to Landsat 8 Band 5 and RED (Red Band) corresponds to Landsat 8 Band 4.

$$NDWI = \frac{(GREEN - NIR)}{(GREEN + NIR)}$$

………… eq. (4)

where GREEN (Green Band) corresponds to Landsat 8 Band 3 and NIR (Near-Infrared Band) corresponds to Landsat 8 Band 5.

The processed data was exported in GeoTIFF format for further analysis in ArcMap and QGIS, where spatial mapping and visualization were performed(Pratama, Gunawan, &Gultom, 2020).Python (Jupyter Notebook) was used for statistical analysis and trend detection.For trend analysis, the following linear equation was applied:

$$Y = mX + c$$

………… eq. (5)

where Y represents the NDVI or NDWI value, X represents the year (2013, 2016, 2019, 2023), m is the slope (rate of change), and c is the intercept.

The Pearson Correlation Coefficient was computed as follows:

$$r = \frac{\sum\left(X - \bar{X}\right)\left(Y - \bar{Y}\right)}{\sqrt{\sum\left(X - \bar{X}\right)^2}\sqrt{\sum\left(Y - \bar{Y}\right)^2}}$$

………… eq. (6)

where X represents NDVI values, Y represents NDWI values, $\bar{X}$ is the mean of NDVI, and $\bar{Y}$ is the mean of NDWI.Excel was used for data organization and tabulation. The Pearson correlation test ($r = -0.988, p$-value = 1.79×10^{-9}) confirmed a strong negative relationship between NDVI and NDWI, indicating increased vegetation cover but declining surface moisture. The findings were validated through comparative analysis with previous studies, leading to recommendations for sustainable land and water resource management in Lakhimpur District.

Results:-

The Results and Discussion of this study on Lakhimpur District, Assam (2013–2023), reveal a strong negative correlation (-0.988) between NDVI and NDWI, indicating that as vegetation cover increases, surface water availability declines. This trend suggests that expanding vegetation, likely driven by agricultural intensification or afforestation, is occurring under drier conditions. Seasonal variations across pre-monsoon, monsoon, and post-monsoon periods highlight the influence of land-use changes, climate variability, and shifting rainfall patterns on both vegetation health and water stress. The decline in NDWI values, especially in the post-monsoon season, points to higher evapotranspiration rates, groundwater depletion, or reduced surface water retention, which can impact agriculture, irrigation efficiency, and overall water resource sustainability. These changes raise concerns about long-term hydrological balance, as reduced surface moisture can affect soil conditions, alter wetland habitats, and disrupt local ecosystems. If these trends continue, increased competition for water resources is likely to arise, necessitating urgent and effective management strategies. The findings emphasise the need for sustainable land and water resource management, incorporating climate-resilient agricultural practices, efficient irrigation techniques, and conservation efforts to mitigate the adverse effects of declining water availability in Lakhimpur District.

Vegetation Health Assessment:
Pre-Monsoon NDVI form 2013-2023

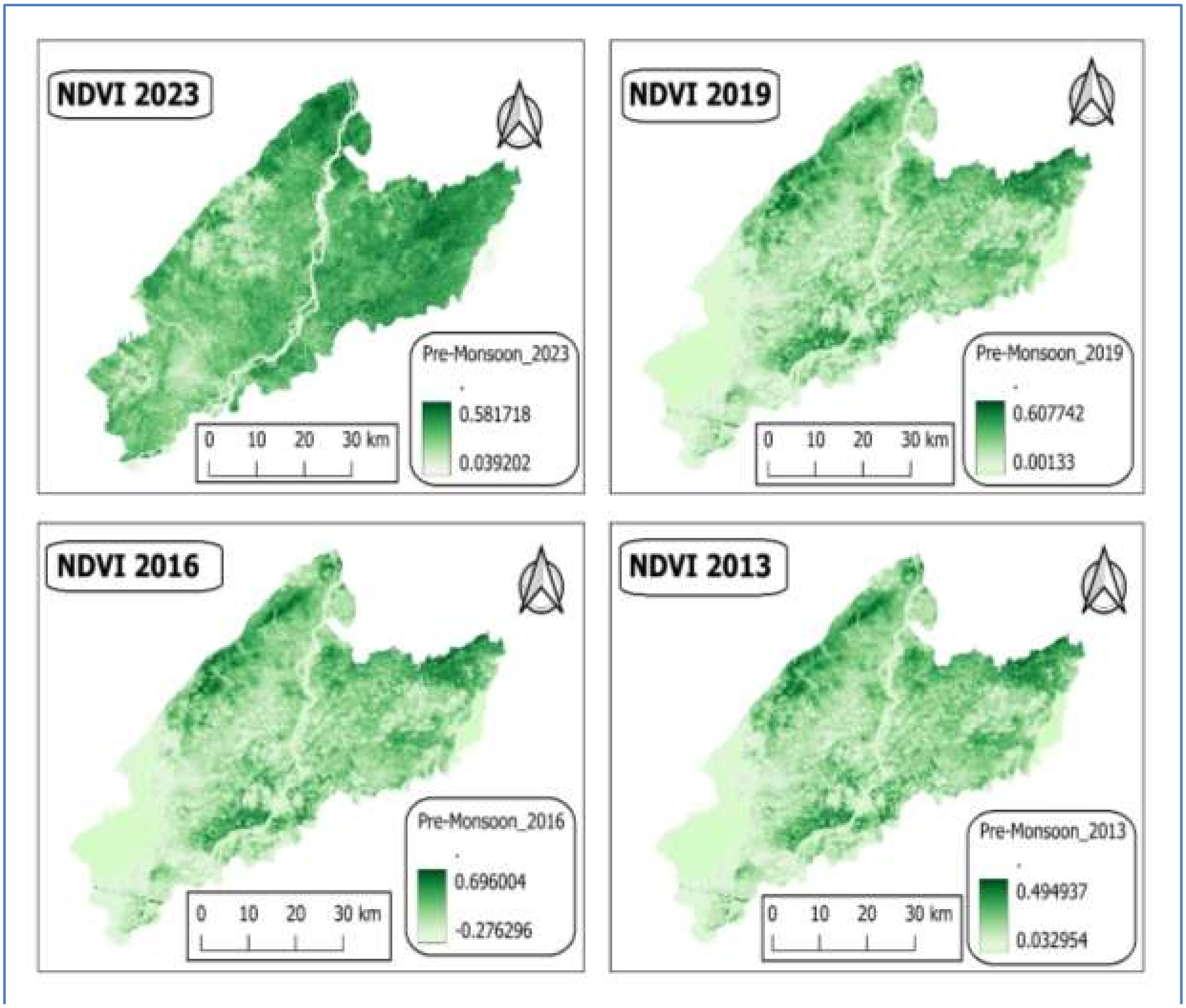

Figure 3: Pre- Monsoon_NDVI of Lakhimpur District during the years 2013, 2016, 2019 and 2023

Table 1: Pre-Monsoon NDVI for four seasons of Lakhimpur District
*Calculated by author from Raster Image

Season	Max_NDVI	Min_NDVI	Mean_NDVI	Standard_Deviation_NDVI
Pre-Monsoon 2013	0.6675	-0.251	0.1981	0.1011
Pre-Monsoon 2016	0.7901	-0.3956	0.3501	0.1321
Pre-Monsoon 2019	0.6531	-0.1655	0.2969	0.1111
Pre-Monsoon 2023	0.636	-0.213	0.3348	0.1167

The NDVI trends for the pre-monsoon seasons (2013–2023) indicate an overall improvement in vegetation health, with mean NDVI rising from 0.1981 in 2013 to 0.3348 in 2023. The highest maximum NDVI (0.7901) was recorded in 2016, followed by fluctuations in later years, suggesting variations in vegetation density, possibly due to climatic conditions or land-use changes. The minimum NDVI values show significant variability, with the lowest in 2016 (-0.3956), indicating barren land or urban expansion, while 2019 (-0.1655) and 2023 (-0.213) suggest some recovery. Standard deviation values reflect spatial heterogeneity, with the highest in 2016 (0.1321), implying a mix of healthy and degraded vegetation. The relatively stable NDVI in 2019 and 2023 indicates consistent vegetation cover, though slight declines in maximum NDVI suggest emerging stress factors. These fluctuations highlight the need for continuous monitoring to assess long-term environmental impacts and vegetation sustainability.

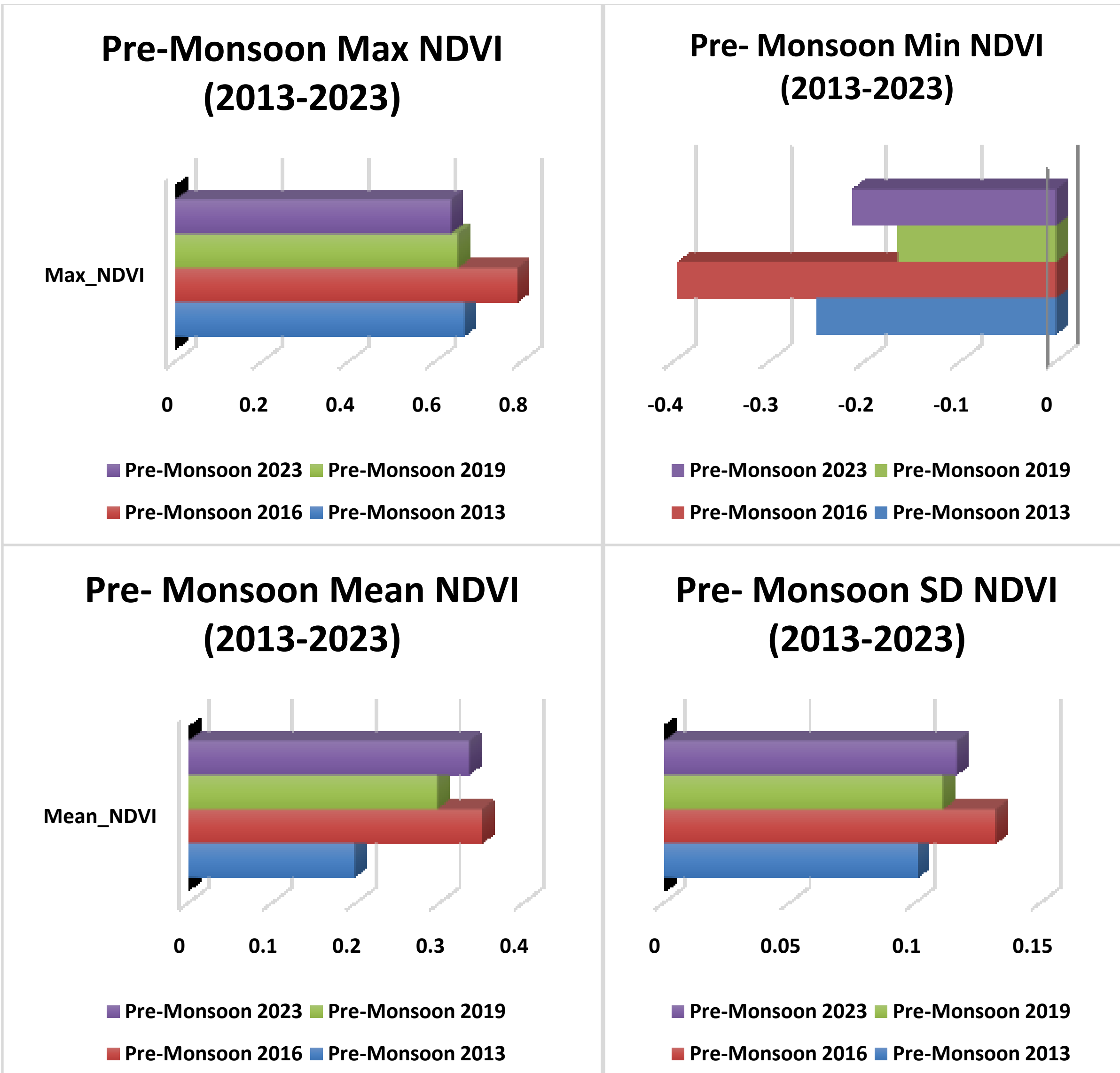

Fig:4 showing pre-monsoon NDVI

Monsoon NDVI form 2013-2023:

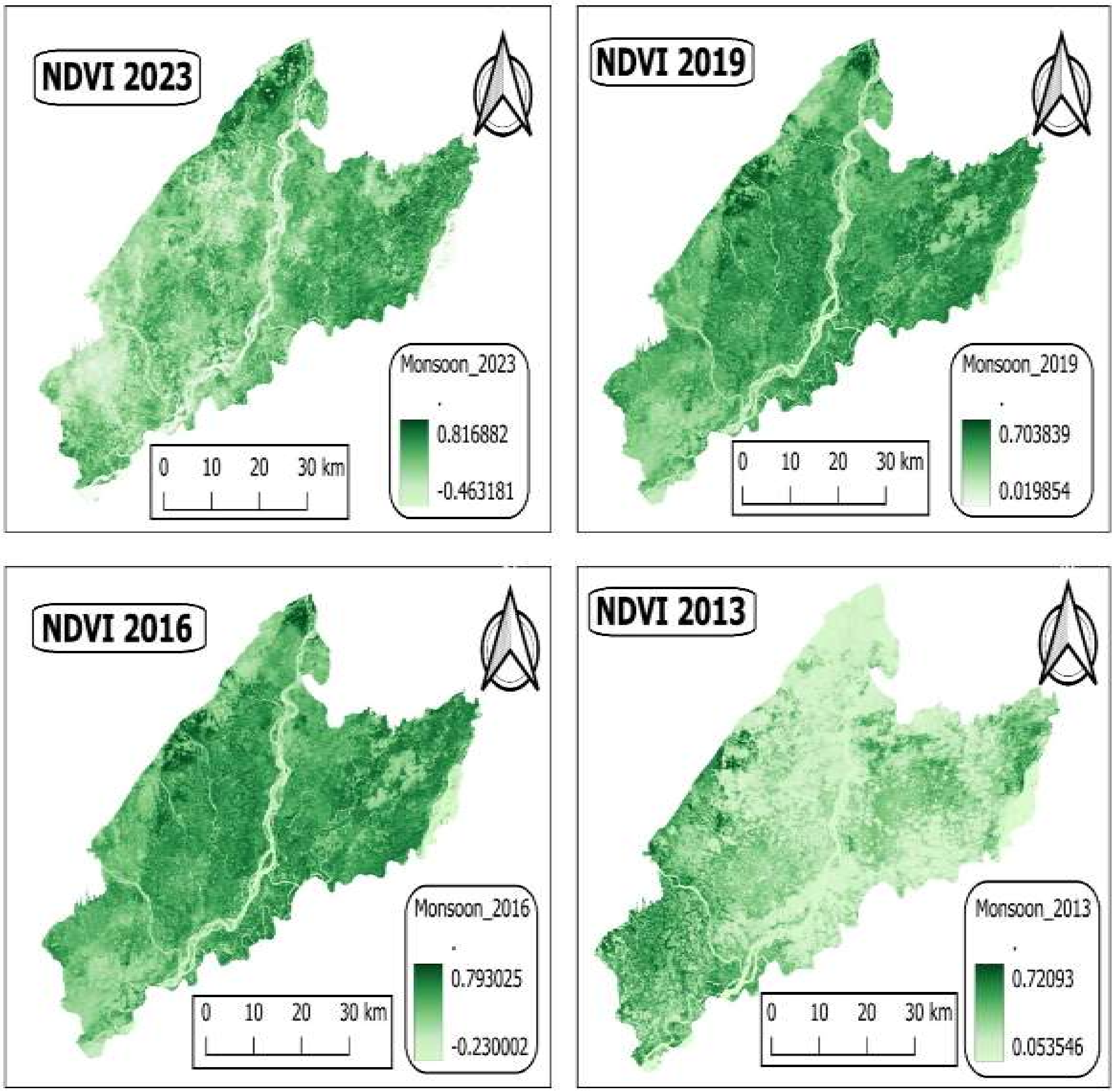

Fig.: 5: Monsoon_NDVI of Lakhimpur District during the years 2013, 2016, 2019 and 2023

Table 2: Monsoon NDVI for four seasons of Lakhimpur District

Season	Max_NDVI	Min_NDVI	Mean_NDVI	Standard_Deviation_NDVI
Monsoon 2013	0.8023	-0.3585	0.2856	0.1452
Monsoon 2016	0.8116	-0.4647	0.3984	0.1905
Monsoon 2019	0.7963	-0.2914	0.3508	0.1436
Monsoon 2023	0.8326	-0.515	0.4192	0.2416

***Calculated by author from Raster Image**

The NDVI trends for the monsoon seasons (2013–2023) show an overall improvement in vegetation health, with mean NDVI increasing from 0.2856 in 2013 to 0.4192 in 2023. The highest maximum NDVI (0.8326) in 2023 suggests dense vegetation, while the lowest minimum NDVI (-0.515) in the same year indicates areas of degradation or bare land. The peak mean NDVI in 2023 reflects enhanced vegetation growth, possibly due to favorable monsoon conditions. Standard deviation values, especially the highest in 2023 (0.2416), indicate increasing spatial variability in vegetation cover, suggesting a mix of healthy and degraded areas. The fluctuations in NDVI highlight the influence of climatic conditions and land-use changes, emphasizing the need for continuous monitoring of vegetation dynamics.

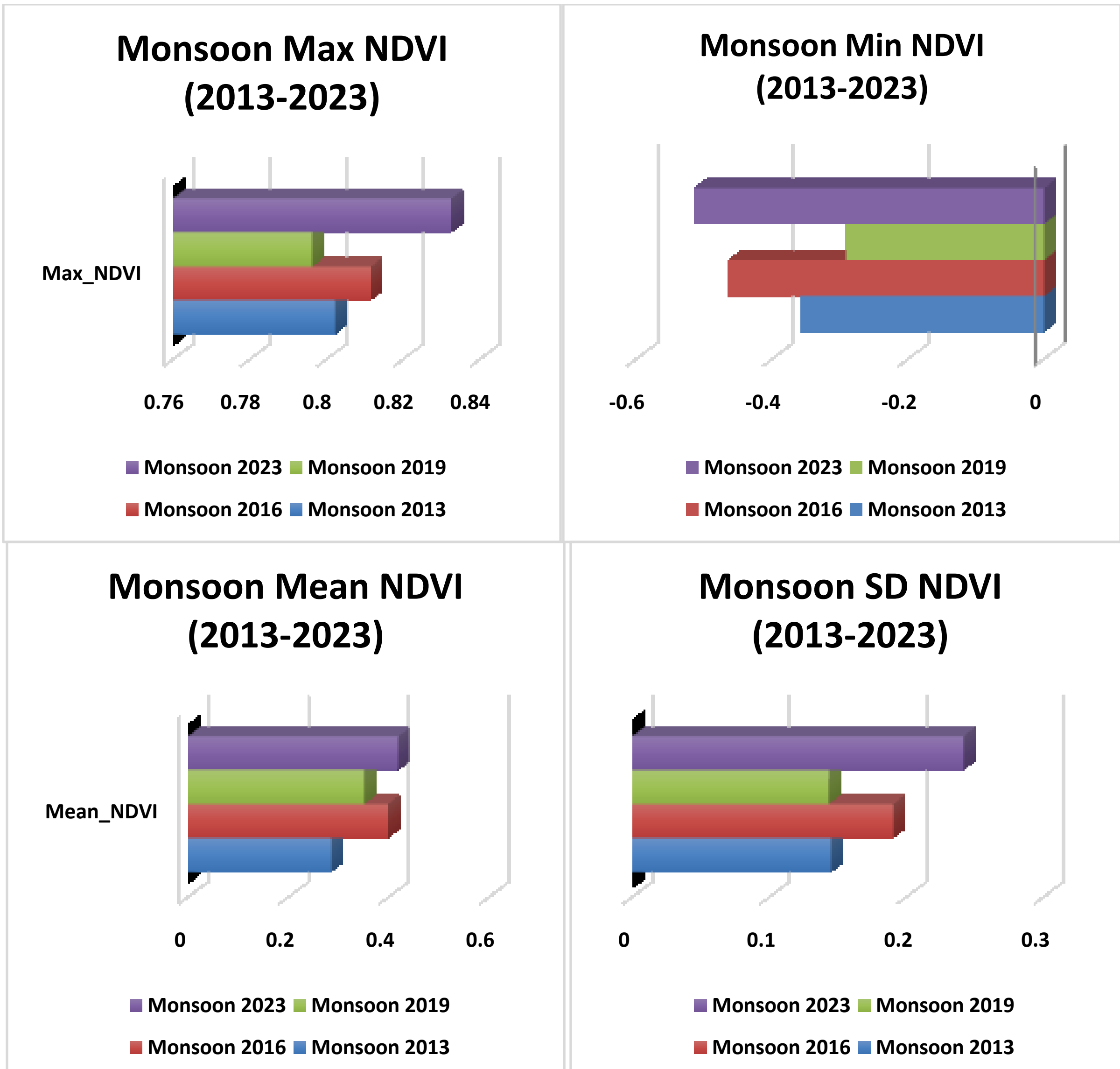

Fig:6 showing monsoon NDVI

Post-Monsoon NDVI form 2013-2023

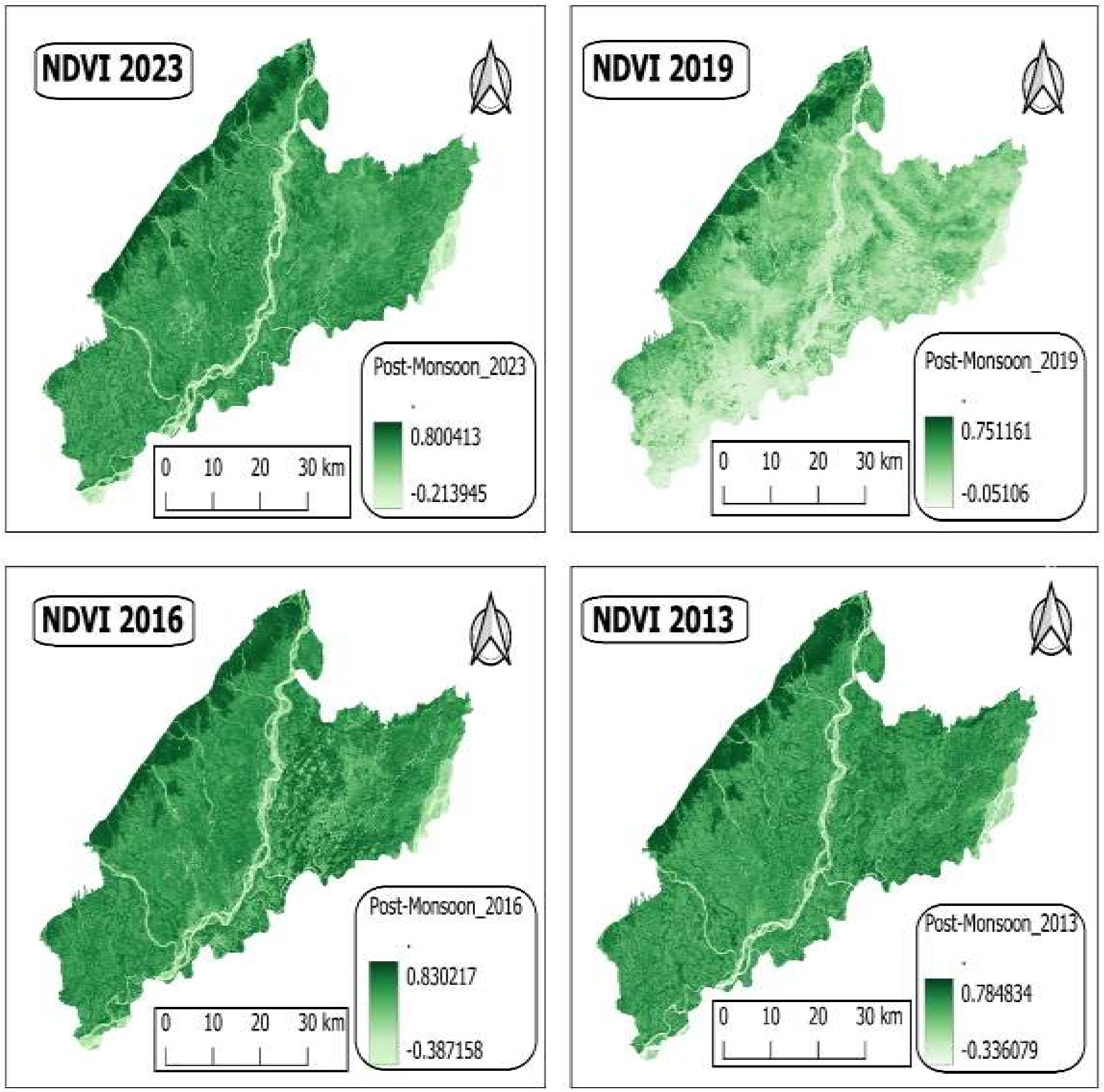

Figure 7: Post- Monsoon_NDVI of Lakhimpur District during the years 2013, 2016, 2019 and 2023

Table 3: Post-Monsoon NDVI for four seasons of Lakhimpur District

Season	Max_NDVI	Min_NDVI	Mean_NDVI	Standard_Deviation_NDVI
Post-Monsoon 2013	0.834	-0.552	0.4507	0.1875
Post-Monsoon 2016	0.84	-0.593	0.4765	0.2128
Post-Monsoon 2019	0.7873	-0.4401	0.3206	0.1546
Post-Monsoon 2023	0.8378	-0.4513	0.4833	0.1733

***Calculated by author from Raster Image**

The NDVI trends for the post-monsoon seasons (2013–2023) indicate overall vegetation stability with fluctuations in density. The mean NDVI increased from 0.4507 in 2013 to 0.4833 in 2023, reflecting improved vegetation health, particularly in recent years. Maximum NDVI remained relatively stable, peaking at 0.84 in 2016, suggesting consistently dense vegetation. However, minimum NDVI values fluctuated, with the lowest in 2016 (-0.593), indicating barren or degraded land, followed by a slight recovery in 2019 (-0.4401) and 2023 (-0.4513). Standard deviation values highlight variability, with 2016 (0.2128) showing the most heterogeneous vegetation cover, while 2019 (0.1546) indicates more uniformity. The increasing mean NDVI in 2023 suggests a positive trend in vegetation recovery, though continued monitoring is necessary to assess long-term sustainability.

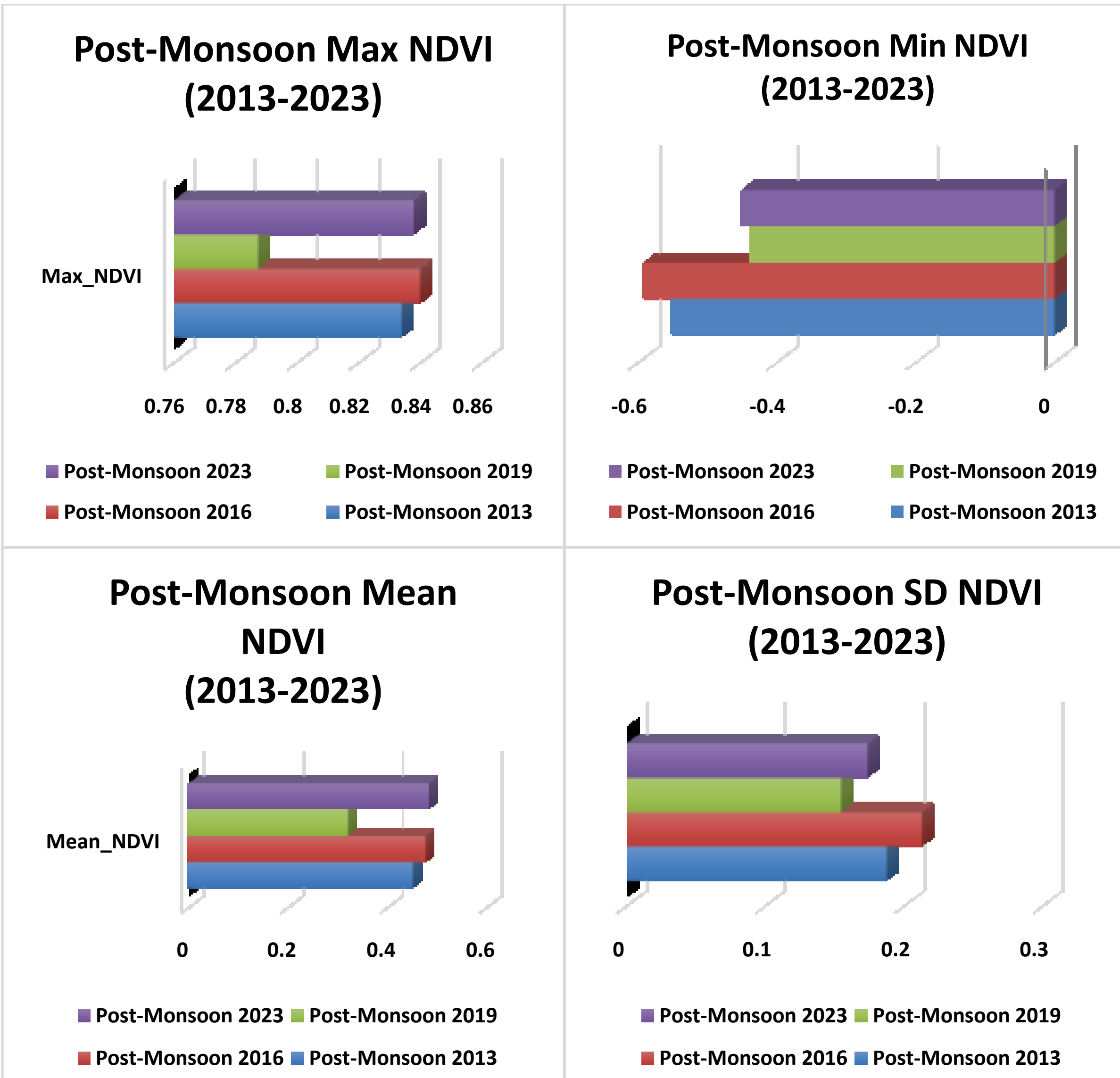

Fig:8 showing post-monsoon NDVI

Water Stress Detection:
Pre-Monsoon NDWI form 2013-2023

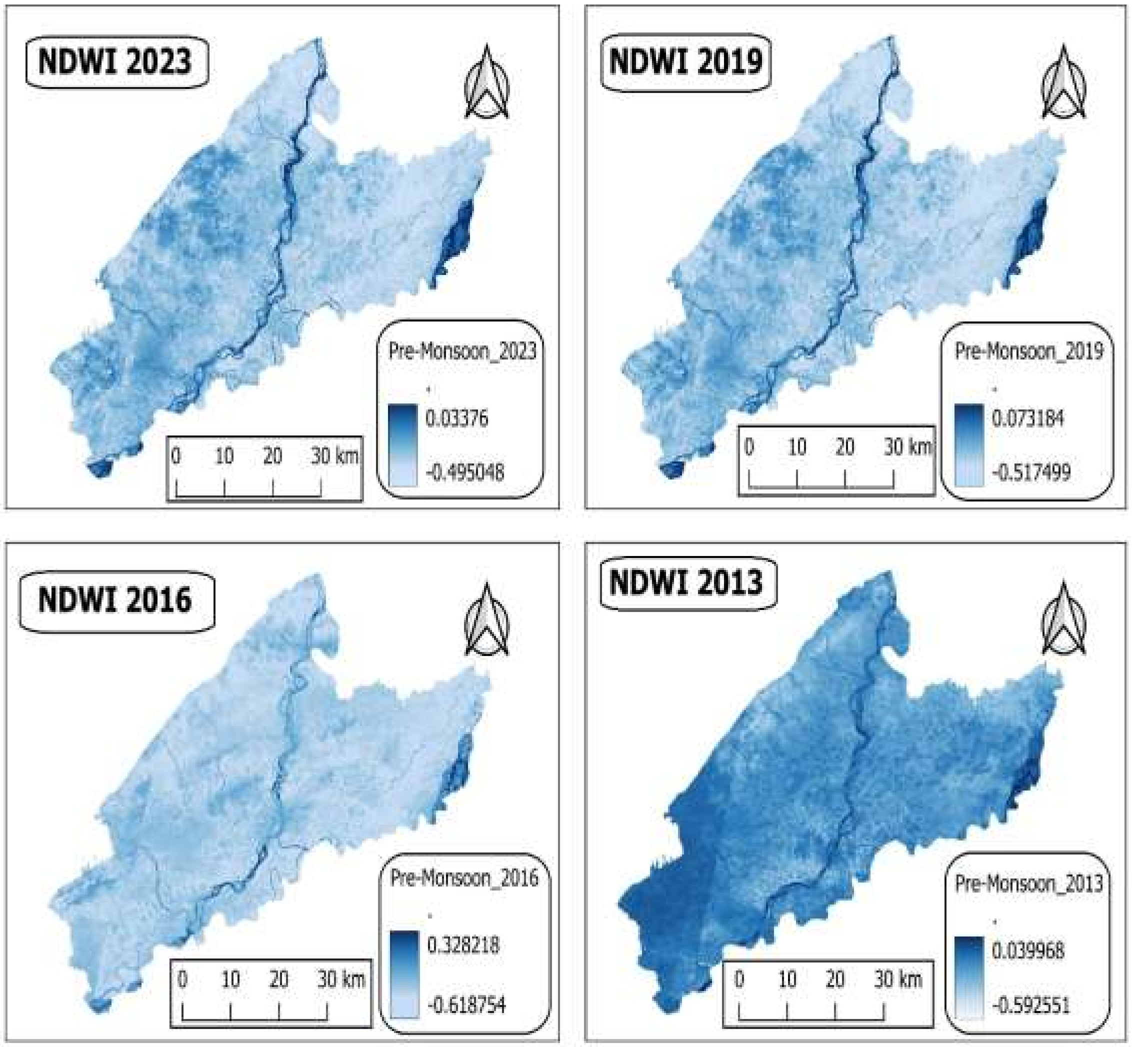

Figure 9: Pre- MonsoonNDWI of Lakhimpur District during the years 2013, 2016, 2019 and 2023

Table 4: Pre--Monsoon NDWI for four seasons of Lakhimpur District

Season	Max_NDWI	Min_NDWI	Mean_NDWI	Standard_Deviation _NDWI
Pre-Monsoon 2013	0.2402	-0.5926	-0.1793	0.0784
Pre-Monsoon 2016	0.4435	-0.6696	-0.2898	0.114
Pre-Monsoon 2019	0.2274	-0.5486	-0.2392	0.0947
Pre-Monsoon 2023	0.2684	-0.5484	-0.2786	0.0998

***Calculated by author from Raster Image**

The NDWI trends for the pre-monsoon seasons (2013–2023) indicate fluctuating water availability, with mean NDWI consistently negative, suggesting drier conditions. The lowest mean NDWI was recorded in 2016 (-0.2898), indicating the driest pre-monsoon period, while 2013 (-0.1793) had relatively higher moisture levels. Maximum NDWI values peaked in 2016 (0.4435) but remained lower in other years, reflecting localized water retention.

Minimum NDWI values show persistently negative trends, with the lowest in 2016 (-0.6696), hinting at significant water stress. Standard deviation values indicate variability, with 2016 (0.114) showing the highest fluctuation, suggesting uneven moisture distribution. The overall trend reflects pre-monsoon dryness, emphasizing the need for water resource management and conservation efforts.

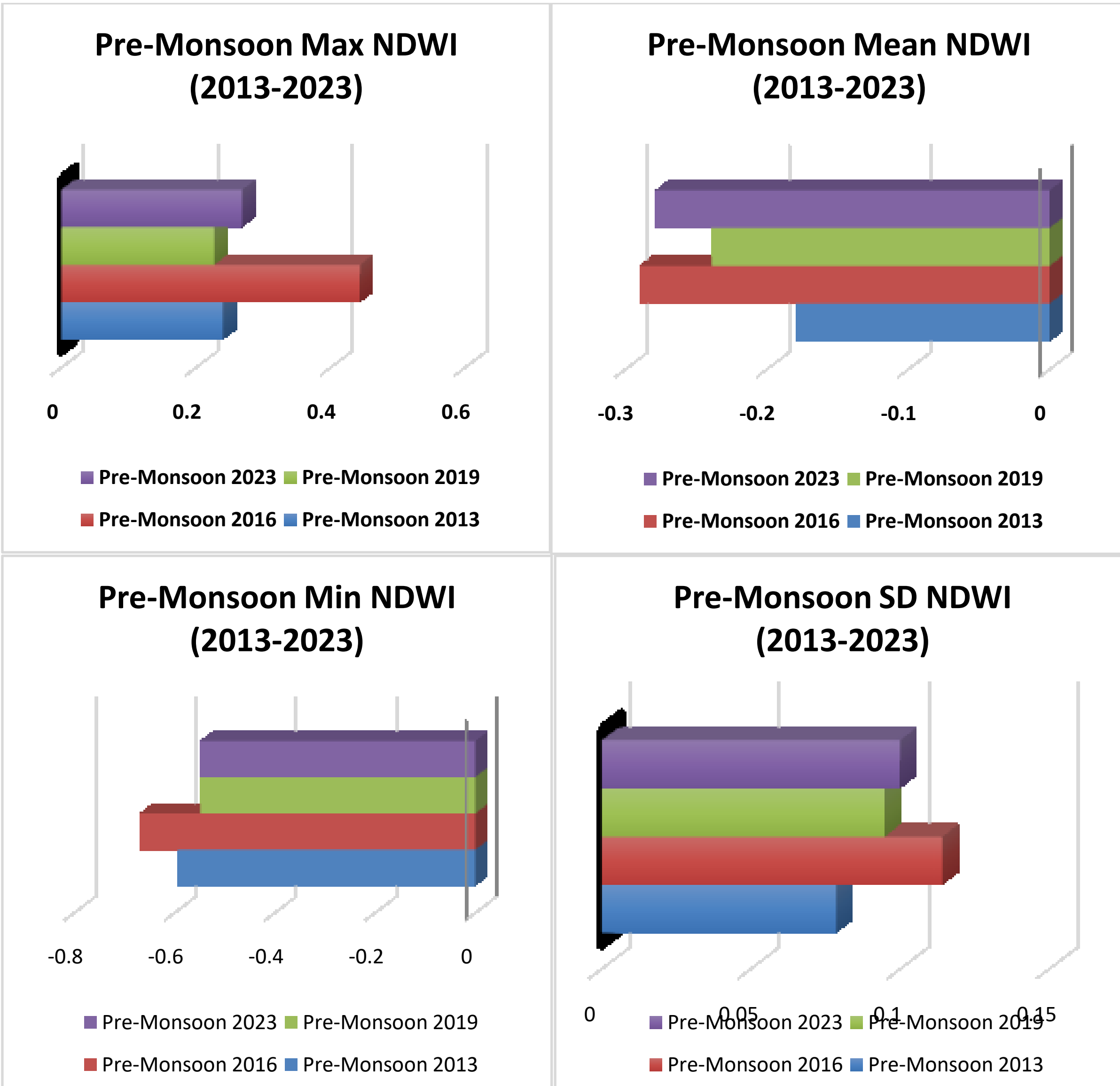

Fig:10 showing pre-monsoon NDWI

Monsoon NDWI form 2013-20:

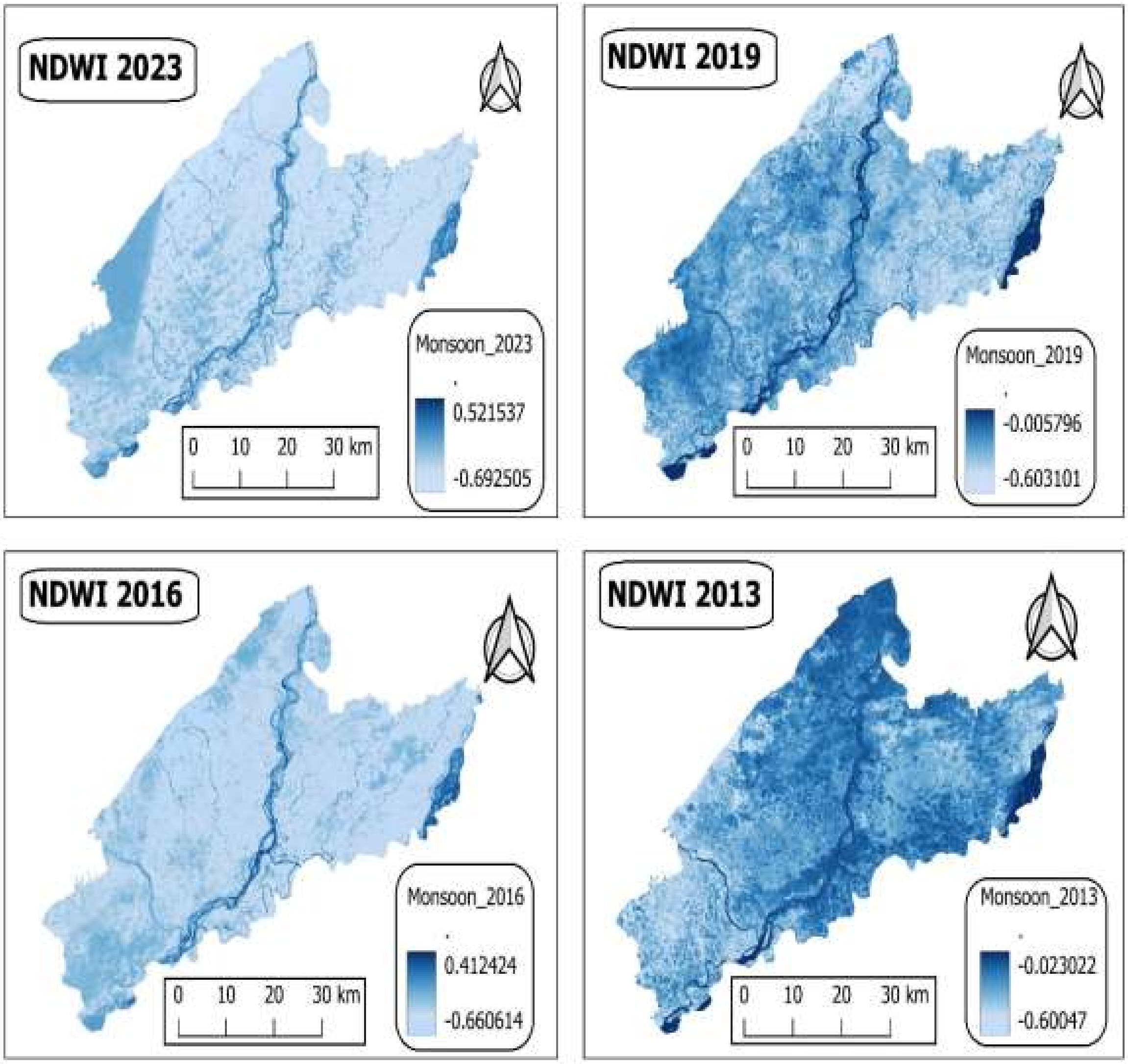

Figure 11: Monsoon_NDWI of Lakhimpur District during the years 2013, 2016, 2019 and 2023

Table 5: Monsoon NDWI for four seasons of Lakhimpur District

Season	Max_NDWI	Min_NDWI	Mean_NDWI	Standard_Deviation _NDWI
Monsoon 2013	0.3649	-0.6738	-0.2449	0.1192
Monsoon 2016	0.5138	-0.6908	-0.3232	0.1639
Monsoon 2019	0.3197	-0.6774	-0.291	0.1231
Monsoon 2023	0.563	-0.71	-0.3435	0.2071

***Calculated by author from Raster Image**

The NDWI trends for the monsoon seasons (2013–2023) indicate increasing dryness, with mean NDWI consistently negative, reflecting persistent water stress. The lowest mean NDWI was recorded in 2023 (-0.3435), suggesting a decline in surface moisture, while 2013 (-0.2449) had relatively better conditions. Maximum NDWI peaked in 2023 (0.563), indicating localized water presence, while minimum NDWI values remained highly negative, reaching -

0.71 in 2023, marking the most water-deficient period. Standard deviation increased over time, with 2023 (0.2071) showing the highest variability, suggesting uneven water distribution. The declining trend in mean NDWI highlights worsening monsoon-season moisture conditions, emphasizing the need for sustainable water management strategies.

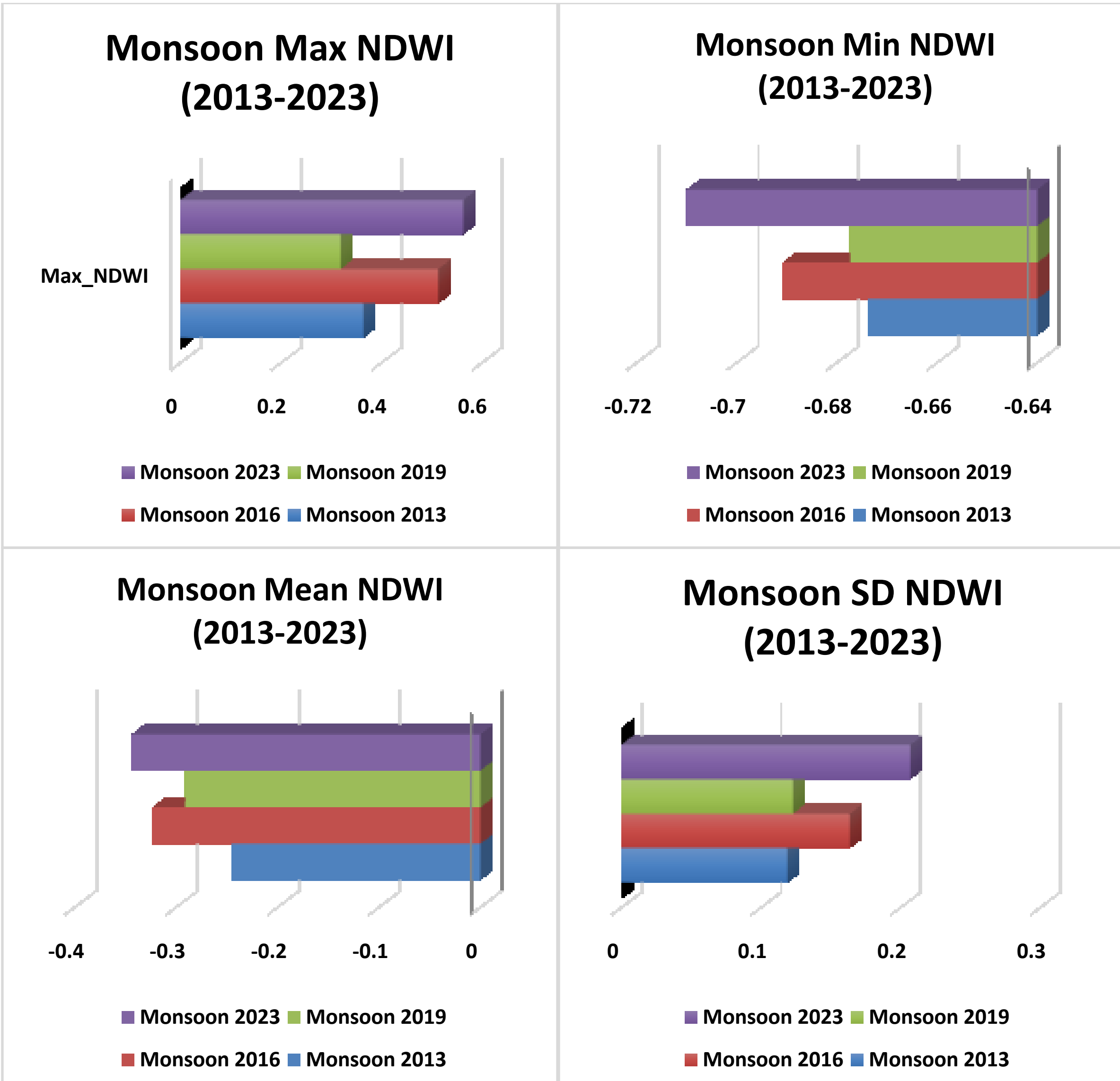

Fig:12 showing monsoon NDWI

Post-Monsoon NDWI form 2013-2023:

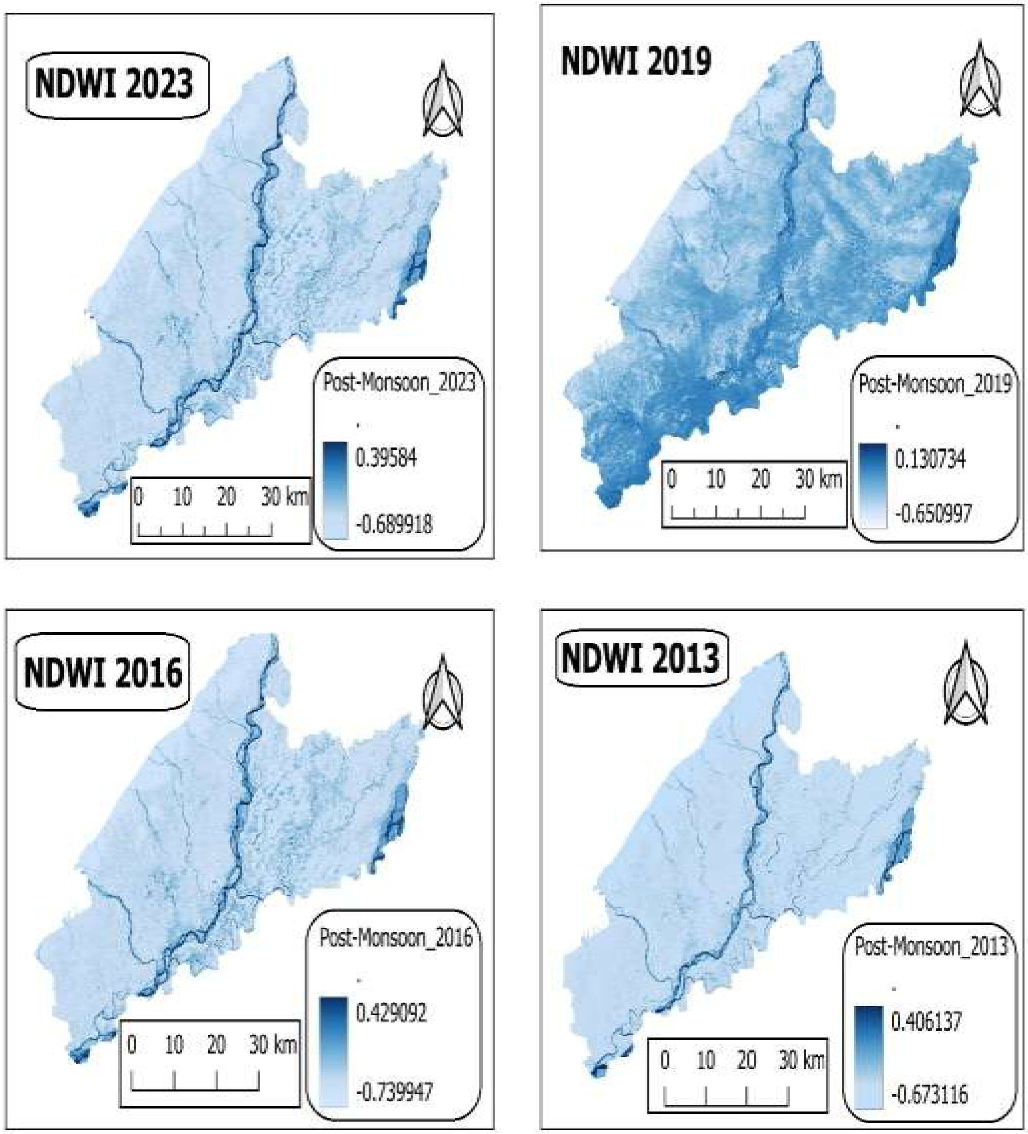

Figure 13: Post-Monsoon_NDWI of Lakhimpur District during the years 2013, 2016, 2019 and 2023

Table 6: Post-Monsoon NDWI for four seasons of Lakhimpur District

Season	Max_NDWI	Min_NDWI	Mean_NDWI	Standard_Deviation _NDWI
Post-Monsoon 2013	0.6567	-0.7224	-0.4014	0.1653
Post-Monsoon 2016	0.6084	-0.7399	-0.4105	0.1915
Post-Monsoon 2019	0.489	-0.6861	-0.2856	0.1298
Post-Monsoon2023	0.5508	-0.7329	-0.4156	0.1553

***Calculated by author from Raster Image**

The NDWI trends for the post-monsoon seasons (2013–2023) indicate persistent dryness, with mean NDWI consistently negative, highlighting ongoing water stress. The lowest mean NDWI was recorded in 2023 (-0.4156), reflecting deteriorating moisture conditions, while 2019 (-0.2856) showed a temporary improvement. Maximum NDWI values declined over time, with 2013 (0.6567) being the highest and 2019 (0.489) the lowest, suggesting reduced surface water availability. Minimum NDWI remained highly negative, with 2016 (-0.7399) marking the driest condition. The standard deviation peaked in 2016 (0.1915), indicating significant variability in moisture distribution. The overall trend suggests increasing post-monsoon dryness, underscoring the need for improved water conservation and management efforts.

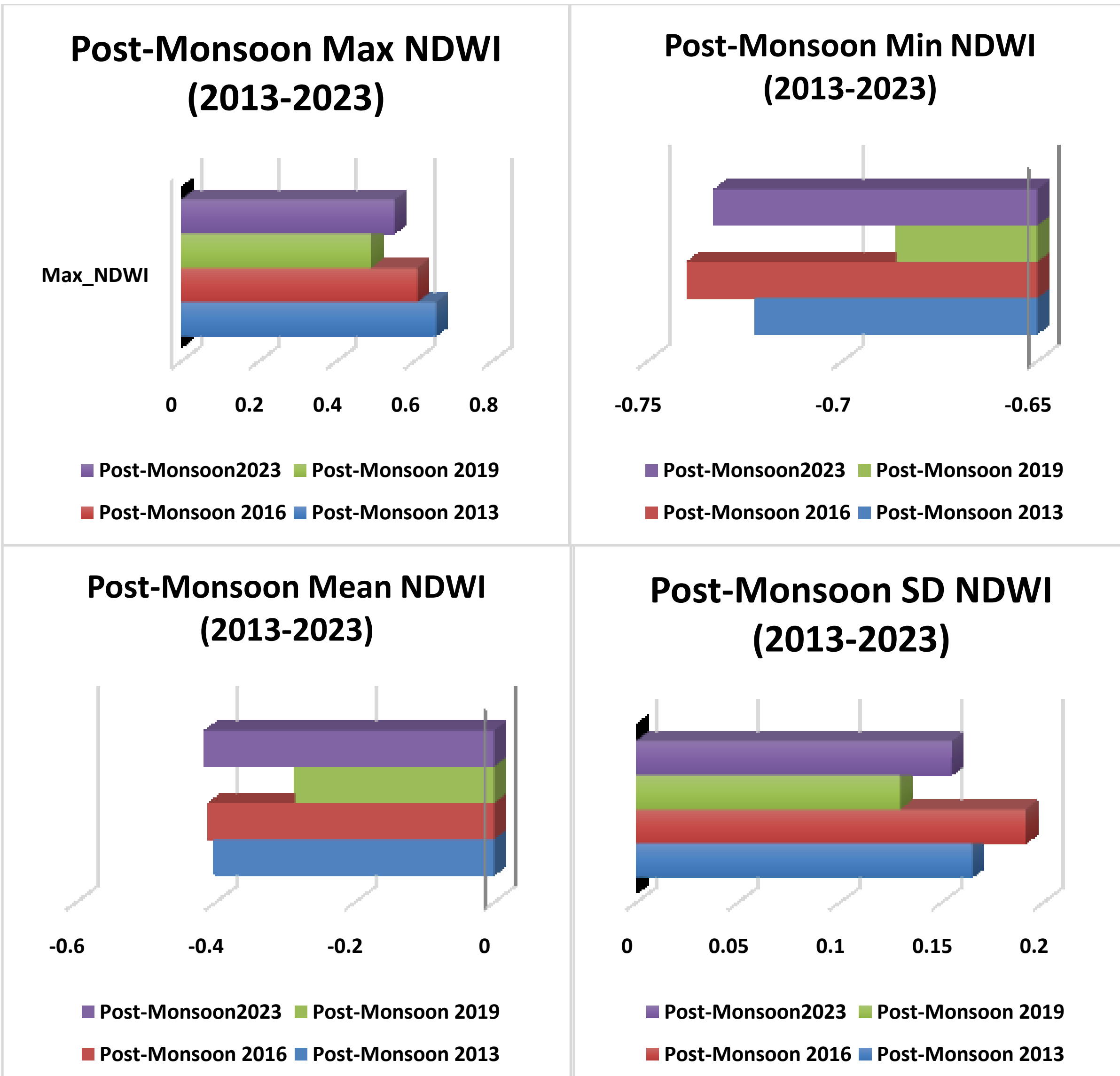

Fig:14 showing monsoon NDWI

Discussion:-

The multi-seasonal spatio-temporal analysis of vegetation health (NDVI) and water availability (NDWI) from 2013 to 2023 in Lakhimpur District, Assam, reveals a strong negative relationship between vegetation growth and surface water resources. The results indicate that while NDVI values have consistently increased across pre-monsoon, monsoon, and post-monsoon seasons, NDWI has shown a significant decline during the same period. This inverse relationship, supported by a Pearson correlation coefficient of –0.988, suggests that vegetation expansion is occurring under conditions of declining surface water availability.

Seasonal Patterns and Vegetation–Water Interactions:-

The seasonal analysis highlights distinct patterns in vegetation growth and water stress. NDVI values rose steadily during the monsoon and post-monsoon seasons, reflecting favorable climatic conditions, agricultural intensification, and possible afforestation efforts. Similar observations have been reported in other agricultural landscapes where monsoonal precipitation enhances vegetation vigor (Huang et al., 2020; Farias et al., 2023). Conversely, NDWI values consistently declined, even during the monsoon season, which typically replenishes water bodies. The declining NDWI suggests that increased evapotranspiration, reduced infiltration, and groundwater depletion are offsetting the benefits of rainfall, as also reported in studies on hydrological stress in South Asia (Shakarami et al., 2022; Batala et al., 2023).

Drivers of NDVI Increase and NDWI Decline:-

The rise in NDVI can be attributed to agricultural expansion, improved irrigation practices, and favorable climatic variability. However, the simultaneous decline in NDWI indicates that vegetation growth is heavily reliant on water withdrawals, especially from groundwater sources. This aligns with the findings of Stackpoole et al. (2023), who noted that vegetation gains in semi-humid regions often occur at the expense of declining hydrological resources. In Lakhimpur, intensive paddy cultivation and expansion of cropland may have increased water demand, thereby accelerating surface water depletion. Furthermore, changing rainfall patterns and the occurrence of erratic monsoons in Northeast India (Sathishkumar et al., 2022) likely exacerbate water scarcity, particularly during the pre-monsoon season.

Comparison with Earlier Studies:-

The observed trends are consistent with global evidence linking vegetation resilience to water availability (Smith & Boers, 2023; Yang et al., 2023). Similar negative correlations between NDVI and NDWI have been reported in other tropical and subtropical agricultural regions, where intensification of land use leads to moisture stress (Taloor et al., 2021; Sun et al., 2013). In the context of the Brahmaputra basin, studies highlight the dual challenge of maintaining agricultural productivity while conserving water resources (Raff et al., 2023). Our findings contribute to this discourse by demonstrating that Lakhimpur District faces a comparable vegetation–water trade-off that requires urgent policy attention.

Implications for Agriculture and Resource Management:

The increase in vegetation cover under conditions of reduced surface moisture poses sustainability concerns for agriculture and ecosystems in Lakhimpur. Declining NDWI values across all seasons suggest reduced soil moisture retention and shrinking surface water bodies, which could impact irrigation efficiency, groundwater recharge, and wetland ecosystems. Prolonged water stress, particularly during post-monsoon periods, may also threaten crop resilience and productivity. Effective management strategies are needed, including climate-resilient cropping patterns, micro-irrigation technologies, and conservation of natural wetlands.

Limitations and Future Directions:

Although NDVI and NDWI provide robust proxies for vegetation and water availability, they do not directly capture sub-surface moisture or groundwater fluctuations. Incorporating complementary datasets such as rainfall, soil moisture (SMAP), and evapotranspiration (MOD16) would improve future assessments. Furthermore, land use change mapping and socio-economic surveys could help disentangle the anthropogenic drivers of vegetation–water trade-offs. Future research should also evaluate adaptive water management strategies that balance agricultural intensification with ecological sustainability in Northeast India.

Seasonal trends of NDVI and NDWI from 2013 to 2023:

The trends highlight variations across pre-monsoon, monsoon, and post-monsoon periods. The analysis reveals a consistent increase in NDVI, indicating vegetation growth, while NDWI shows a declining trend, suggesting reduced surface moisture availability.

Table 7: Analysis of NDVI and NDWI Seasonal Trends (2013–2023)

YEAR	SEASON	MEAN_NDVI	MEAN_NDWI
2013	Pre-Monsoon	0.1981	-0.1793
2013	Monsoon	0.2856	-0.2449
2013	Post-Monsoon	0.4507	-0.4014
2016	Pre-Monsoon	0.3501	-0.2898
2016	Monsoon	0.3984	-0.3232

2016	Post-Monsoon	0.4765	-0.4105
2019	Pre-Monsoon	0.2969	-0.2392
2019	Monsoon	0.3508	-0.291
2019	Post-Monsoon	0.3206	-0.2856
2023	Pre-Monsoon	0.3348	-0.2786
2023	Monsoon	0.4192	-0.3435
2023	Post-Monsoon	0.4833	-0.4156

***Calculated by author from Raster Image**

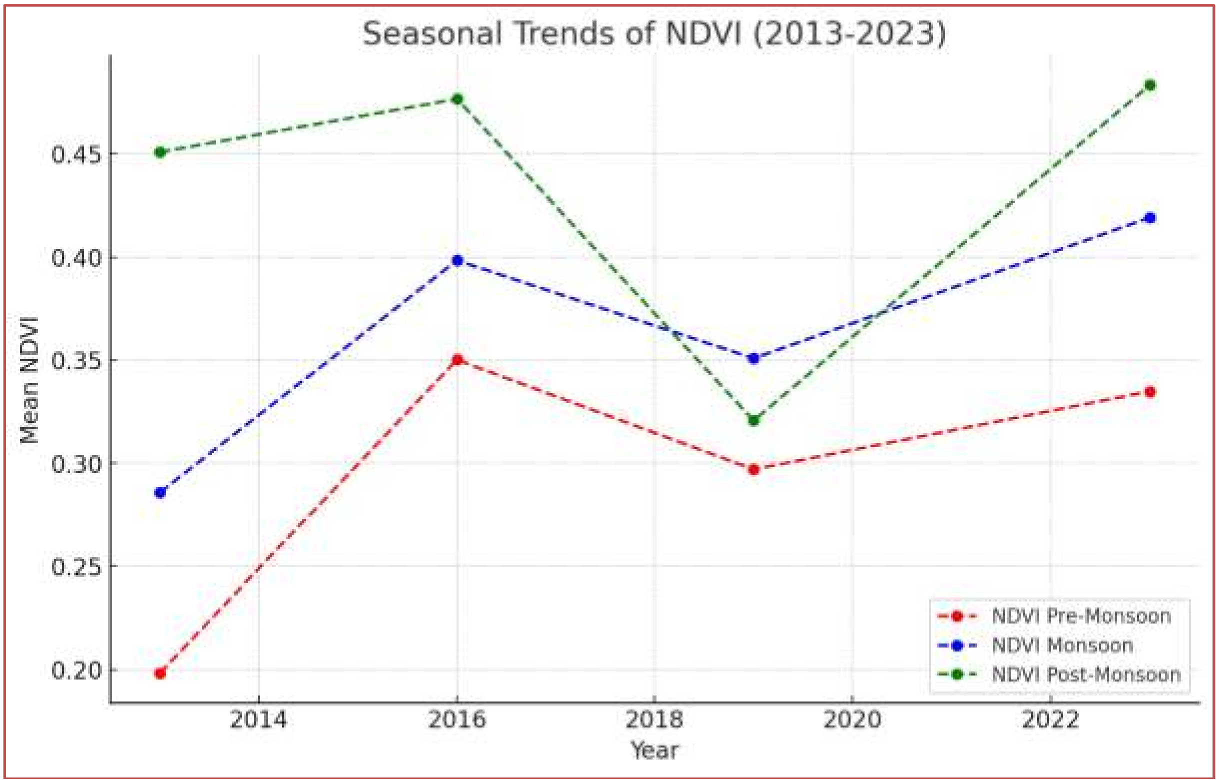

Fig 15: Showing seasonal trends of NDVI from 2013-2023

The analysis of NDVI and NDWI trends from 2013 to 2023 reveals a notable increase in vegetation cover alongside a progressive decline in surface water availability. NDVI values have consistently risen across all seasons, with the highest growth observed in the Post-Monsoon period, increasing from 0.4507 in 2013 to 0.4833 in 2023. This trend suggests enhanced vegetation productivity, likely driven by improved monsoonal rainfall, afforestation, or agricultural expansion. However, fluctuations in Pre-Monsoon NDVI, particularly the decline in 2019 (0.2969) before recovering in 2023 (0.3348), indicate potential water stress or land-use changes affecting early-season growth.

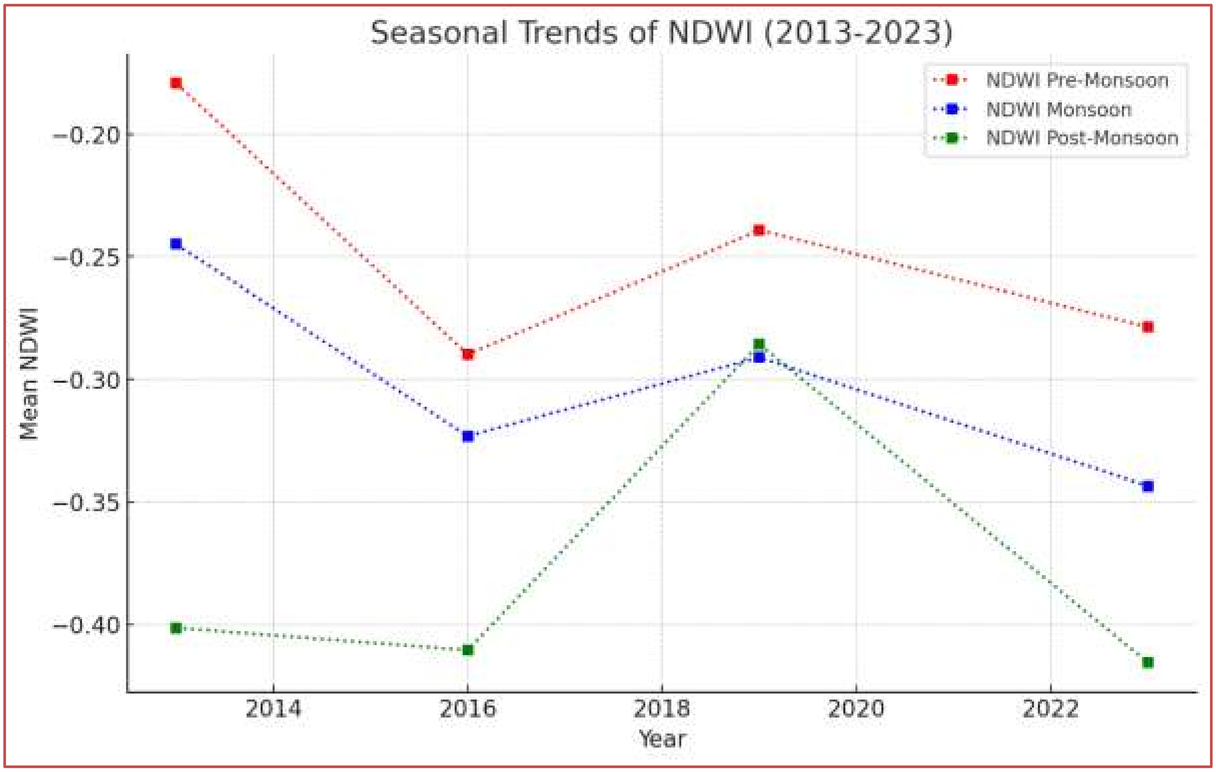

Fig 16: Showing seasonal trends of NDWI from 2013-2023

Conversely, NDWI has exhibited a consistent decline, indicating a reduction in surface water resources and increasing dryness. NDWI values have decreased across all seasons, with Monsoon NDWI dropping from -0.2449 in 2013 to -0.3435 in 2023, while Post-Monsoon NDWI declined from -0.4014 to -0.4156. This pattern suggests rising evapotranspiration, potential depletion of surface water bodies, and declining soil moisture availability. The Pre-Monsoon NDWI decline from -0.1793 in 2013 to -0.2786 in 2023 further highlights the early onset of dry conditions, likely linked to groundwater depletion or shifting rainfall patterns.

The inverse relationship between increasing NDVI and decreasing NDWI suggests that vegetation expansion is occurring under conditions of declining water availability, possibly driven by intensified irrigation, urbanization, or climate variability. These findings emphasize the need for sustainable water management strategies to balance vegetation growth with declining hydrological resources. Further research integrating soil moisture, rainfall variability, and land use change analysis is recommended to better understand the long-term implications of these trends.

Correlation Analysis Between NDVI and NDWI:

The Pearson correlation coefficient between NDVI and NDWI is -0.988, indicating a strong negative correlation. This suggests that as NDVI increases (improved vegetation health), NDWI decreases (reduced surface water availability and moisture content). The p-value (1.79×10^{-9}) confirms that this relationship is statistically significant.The major key findings of this study indicate that vegetation growth is occurring under drier conditions, possibly due to intensive irrigation, declining soil moisture, or shifting rainfall patterns. Seasonal water retention is decreasing, particularly in the post-monsoon periods, which suggests higher evapotranspiration rates or the depletion of surface water sources. The strong inverse relationship between NDVI and NDWI underscores the need for sustainable water management strategies to ensure that vegetation expansion does not come at the cost of hydrological decline.

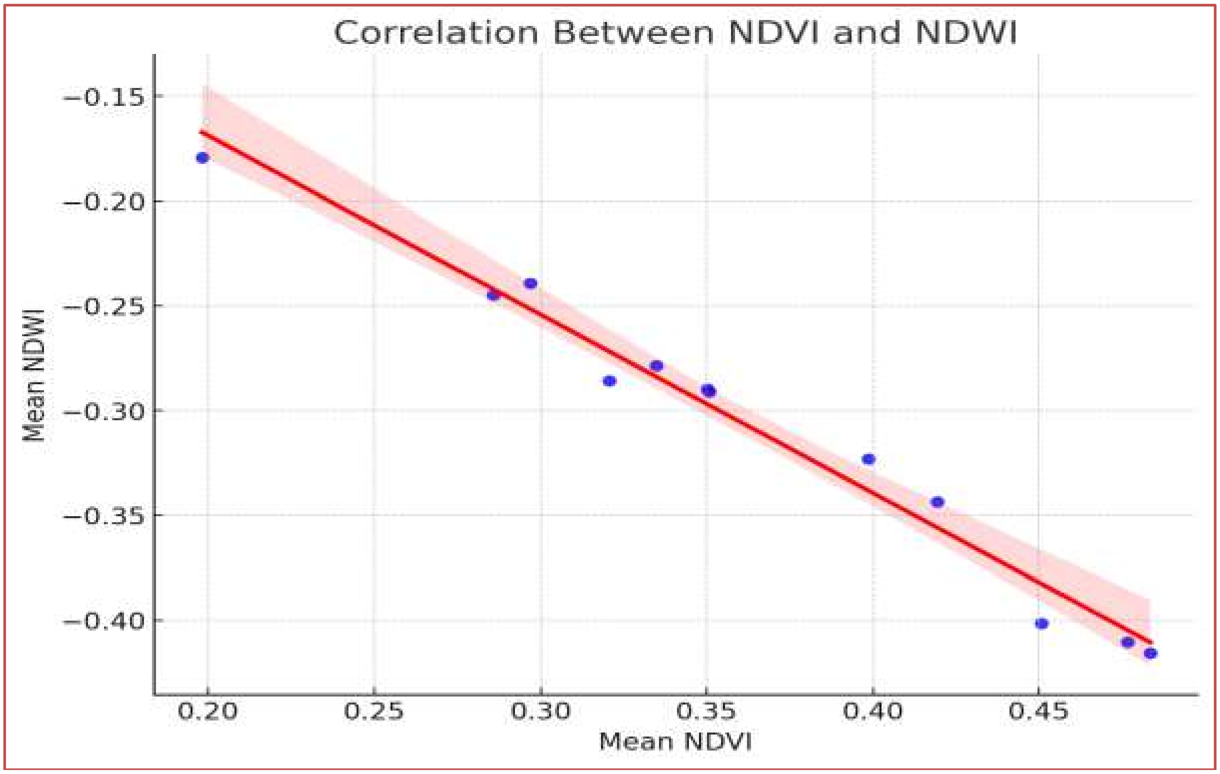

Fig:17 showing monsoon NDWI

Conclusion:-

The analysis of NDVI and NDWI trends from 2013 to 2023 reveals a clear trade-off between vegetation growth and water availability. NDVI shows a steady increase across all seasons, indicating improving vegetation health, while NDWI exhibits a consistent decline, highlighting worsening water stress. The strong negative correlation (-0.988, p-value = 1.79×10^{-9}) confirms that as vegetation expands, surface moisture decreases, possibly due to increased evapotranspiration, reduced open water bodies, or land-use changes.

These findings emphasize the need for balanced land and water resource management. While improving vegetation cover is beneficial for ecological sustainability, the declining NDWI trends suggest increasing hydrological stress. Effective water conservation strategies, afforestation with drought-resistant species, and sustainable urban planning are essential to mitigate the impact of decreasing surface moisture while ensuring long-term vegetation health. Continuous monitoring and adaptive policies are crucial to maintaining ecological balance and water security in the region.

Recommendations for Future Research:

Future research should integrate climate variables such as rainfall, temperature, and evapotranspiration to better understand the factors driving the inverse relationship between NDVI and NDWI. A long-term hydrological analysis is needed to assess the impact of declining NDWI on groundwater recharge, river flows, and wetland sustainability. Investigating the role of urbanization and land-use changes can help determine whether rapid expansion is exacerbating water stress despite increased vegetation cover. Advanced remote sensing and AI-based models can enhance the accuracy of NDVI and NDWI predictions for better decision-making. Comparative studies across different regions and climates can validate whether the observed trend is localized or part of a broader environmental shift. Additionally, research should focus on sustainable water resource management strategies, including efficient irrigation, rainwater harvesting, and afforestation with drought-resistant species. Finally, analyzing the socio-economic implications of NDWI decline on agriculture and livelihoods can help develop effective adaptation measures for affected communities.

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