International Journal of Engineering and Techniques - Volume 12 Issue 2, April 2026

RESEARCH ARTICLE OPEN ACCESS

Spatio-Temporal Analysis of Seasonal Vegetation Dynamics Using Sentinel-2 NDVI in the Mahaweli River Basin, Sri Lanka

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Abstract:

Vegetation dynamics are important indicators of environmental conditions, ecosystem health, and climatic variability. The study investigated the spatio-temporal variation of vegetation in the Mahaweli River Basin, Sri Lanka from 2016 to 2025. Normalized Difference Vegetation Index (NDVI) derived from satellite imagery is the core of the study. Seasonal NDVI analysis was conducted for both wet and dry seasons to evaluate vegetation conditions and long-term trends within the basin. The results revealed noticeable seasonal variations in vegetation cover, with the wet season recording slightly higher mean NDVI values compared to the dry season. Mean NDVI values ranged from 0.545 to 0.698 during the wet season and from 0.513 to 0.680 during the dry season. Statistical analysis showed that the dry season exhibited greater variability in vegetation conditions compared to the wet season. Trend analysis using linear regression, Theil–Sen slope estimation, and Mann–Kendall testing indicated positive NDVI trends during both seasons over the study period. The findings suggest gradual improvement in vegetation health and density within the Mahaweli River Basin from 2016 to 2025. Annual anomaly analysis also demonstrated temporal fluctuations associated with climatic and environmental variability while maintaining an overall increasing trend. The study highlights the effectiveness of remote sensing and GIS techniques for long-term vegetation monitoring and environmental assessment. The findings provide valuable information for watershed management, environmental monitoring, and sustainable land resource planning in Sri Lanka.

***Keywords* — NDVI, Vegetation Dynamics, Remote Sensing, GIS, Mahaweli River Basin, Spatio-temporal Analysis, Seasonal Variation, Trend Analysis**

I. INTRODUCTION

Vegetation is a cornerstone of ecosystem functionality which is playing a critical role in regulating climate, maintaining soil fertility, supporting biodiversity, and influencing hydrological cycles. Monitoring vegetation dynamics over time is essential for understanding environmental change, particularly in regions affected by climatic variability, land use transformation, and anthropogenic pressures [5],[9]. Traditional field-based surveys are limited in spatial coverage and temporal frequency. Hence, remote sensing has emerged as a reliable tool for large-scale, repetitive monitoring of vegetation patterns [1], [2].

Normalized Difference Vegetation Index (NDVI) is one of the most widely applied indicators for assessing vegetation health, density, and productivity [11]. NDVI is derived from the spectral reflectance difference between the red and near-infrared (NIR) bands. The bands correlate with chlorophyll activity and canopy vigor. Its widespread adoption in ecological studies,crop monitoring,and forest management [3],[7].

The launch of high-resolution satellite sensors has revolutionized vegetation monitoring as its capable of providing imagery with high spatial (10–20 m) and temporal resolution. This allows for detailed spatio-temporal analyses, enabling researchers to detect seasonal and inter-annual variations in vegetation at regional scales [4], [6]. Advanced time-series analysis approaches such as trend detection using Mann–Kendall tests, BFAST decomposition, and seasonal anomaly mapping, have been increasingly applied to NDVI datasets to quantify both short-term fluctuations and long-term changes in vegetation cover [8], [16].

In tropical monsoon climates such as Sri Lanka, vegetation dynamics are strongly influenced by seasonal rainfall and temperature patterns, with distinct wet and dry periods. Previous studies have shown that rainfall variability, combined with land use changes and irrigation practices, can significantly affect vegetation health, crop yields, and ecosystem resilience [13], [15]. Understanding these dynamics is crucial for sustainable land and water management, conservation planning, and climate adaptation strategies.

The Mahaweli River Basin is one of the largest river basins in Sri Lanka where particular interest due to its ecological, hydrological, and agricultural significance [9], [12]. Despite its importance, studies integrating high-resolution NDVI data for spatio-temporal analysis and seasonal trend detection remain limited. The t study aims to analyse NDVI-based vegetation dynamics in the Mahaweli River Basin over a 10-year period (2016–2025), focusing on dry and wet seasons.

The outcomes are provide insights into vegetation responses to climatic variability, land use changes, and human interventions that supports informed decision-making for natural resource management and sustainable development in the basin [6], [13].

II. STUDT AREA

The Mahaweli River Basin covers approximately 10,000 km² being the largest river basin in Sri Lanka. The basin extends from the central highlands to the north-eastern coastal plains [9], [10]. It lies roughly between 6°55′–8°55′ N latitude and 79°40′–81°55′ E longitude with the Mahaweli River flowing north-eastward into the Bay of Bengal [11]. The basin experiences a tropical monsoonal climate with distinct wet and dry seasons influenced by the Southwest and Northeast monsoons [13], [14]. The basin consists with diverse land use including forests, irrigated agricultural lands, grasslands, and settlements. The Mahaweli Development Program has transformed land use patterns through expanded irrigation and agricultural activities [12], [16]. Seasonal rainfall variability and the human-induced land changes has been affected vegetation growth and distribution, making this basin a suitable site for NDVI-based spatio-temporal analysis [6], [17].

III. DATA AND METHODOLOGY

3.1 Data Sources

The study utilized Sentinel-2 Level-2A surface reflectance data from the European Space Agency (ESA) Copernicus program. The data covers the Mahaweli River Basin from 2016 to 2025. Sentinel-2 offers 10–20 m spatial resolution and high revisit frequency, making it suitable for detailed vegetation monitoring. To ensure data quality, images with >10% cloud cover were excluded. Remaining images underwent cloud and shadow masking using the Scene Classification Layer (SCL), and topographic correction was applied using the C-correction method. The method adjusts reflectance values based on slope and solar angle to reduce terrain-induced errors in hilly areas.

3.2 Advanced NDVI Calculation

Vegetation dynamics were quantified using NDVI, calculated as:

$$NDVI = (\rho^{NIR} - \rho^{Red}) / (\rho^{NIR} + \rho^{Red})$$

Where ρ^{NIR} and ρ^{Red} are the surface reflectance values in the near-infrared and red regions respectively.

Level-2A surface reflectance and C-correction reduces atmospheric scattering and slope effects producing more accurate NDVI. Seasonal composites were generated by computing the median NDVI of all images per season mitigating residual cloud and sensor noise. To reduce soil brightness effects in sparse vegetation areas, SAVI was computed as:

$$SAVI = ((1 + L) * (\rho^{NIR} - \rho^{Red})) / (\rho^{NIR} + \rho^{Red} + L)$$

Where is a soil adjustment factor. SAVI was used alongside NDVI in low-vegetation areas to validate vegetation trends, increasing reliability.

3.3 Seasonal Classification

The study area was divided into wet and dry seasons based on Sri Lanka's monsoonal climate. Seasonal NDVI composites were derived using the median of images for wet (October–January) and Dry Season (May–September). The approach ensures representative vegetation conditions while reducing temporal noise.

3.4 Spatio-Temporal Analysis

Pixel-wise time series of NDVI were extracted for each season and seasonal averages were computed to quantify vegetation dynamics across the basin for spatio-temporal assessment.

3.5 NDVI Anomaly Detection

NDVI anomalies were calculated to detect deviations from normal vegetation patterns:

$$NDVIanom(x,y,t) = (NDVI(x,y,t) - \overline{NDVI}(x,y)) / \sigma NDVI(x,y)$$

Where:
$\overline{NDVI}(x,y)$ is the long-term mean NDVI at pixel (x,y) and $\sigma NDVI(x,y)$ is the standard deviation of NDVI at pixel (x,y)

This z-score approach standardizes anomalies, allowing for consistent detection across heterogeneous landscapes.

3.6 Trend Analysis

Vegetation trends were evaluated using both linear regression and non-parametric statistics. Seasonal NDVI trends were fitted as:

$$NDVI(t) = \beta 0 + \beta 1\, t + \epsilon$$

Where $\beta 1$ indicates the trend magnitude and direction.

A non-parametric method (Mann–Kendall Test) is used to assess trend significance. Sen's slope was computed to quantify the rate of change per year. Trend values were mapped spatially to visualize areas of increasing or decreasing vegetation, providing insight into local environmental changes.

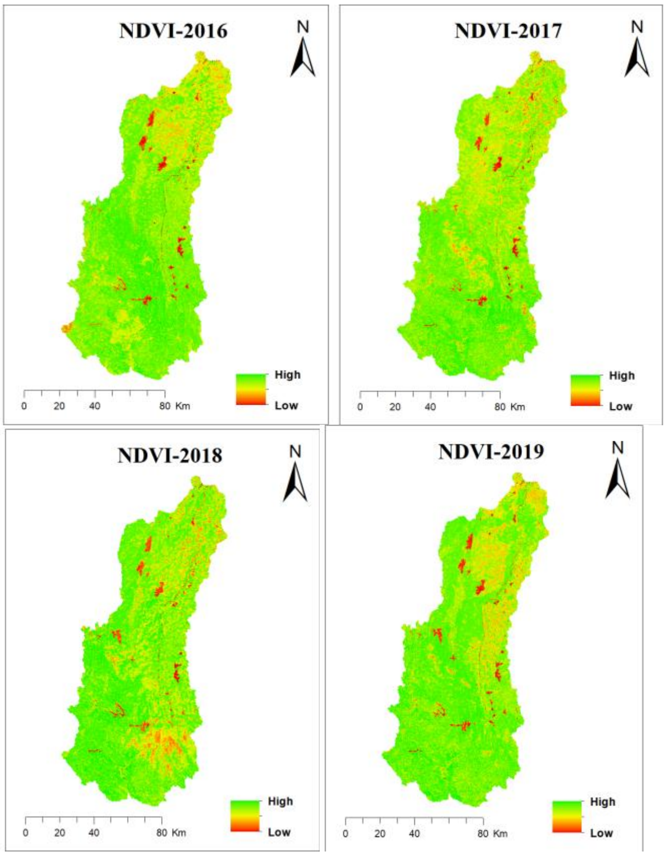
3.7 Statistical and Graphical Analysis

Descriptive statistics quantified vegetation conditions. Time series plots visualized inter-annual trends. Maps and plots were generated using Google Colab, which allowed rapid processing of multi-temporal datasets at high spatial resolution.

IV. RESULTS AND DISCUSSION

4.1 Seasonal NDVI Distribution (2016–2025)

The spatial distribution of NDVI across the Mahaweli River Basin demonstrates clear seasonal variability over the study period. During the wet season, NDVI values were generally higher for some years indicating dense vegetation cover (Fig.1). In contrast, dry season NDVI values were lower, reflecting reduced soil moisture and vegetation activity. High NDVI values in the upper catchment corresponded to dense forest cover, whereas the lower basin and plains showed moderate NDVI (Fig.2). The difference reflects agricultural landscapes and mixed vegetation. Seasonal mapping reveals that forested areas maintained relatively stable NDVI across years. Whereas agricultural regions exhibited pronounced seasonal variation due to cropping cycles and irrigation practices. The observed patterns confirm that vegetation growth is strongly influenced by seasonal precipitation, consistent with Sri Lanka's monsoonal climate. These results align with previous regional studies indicating higher vegetation activity during wet periods.



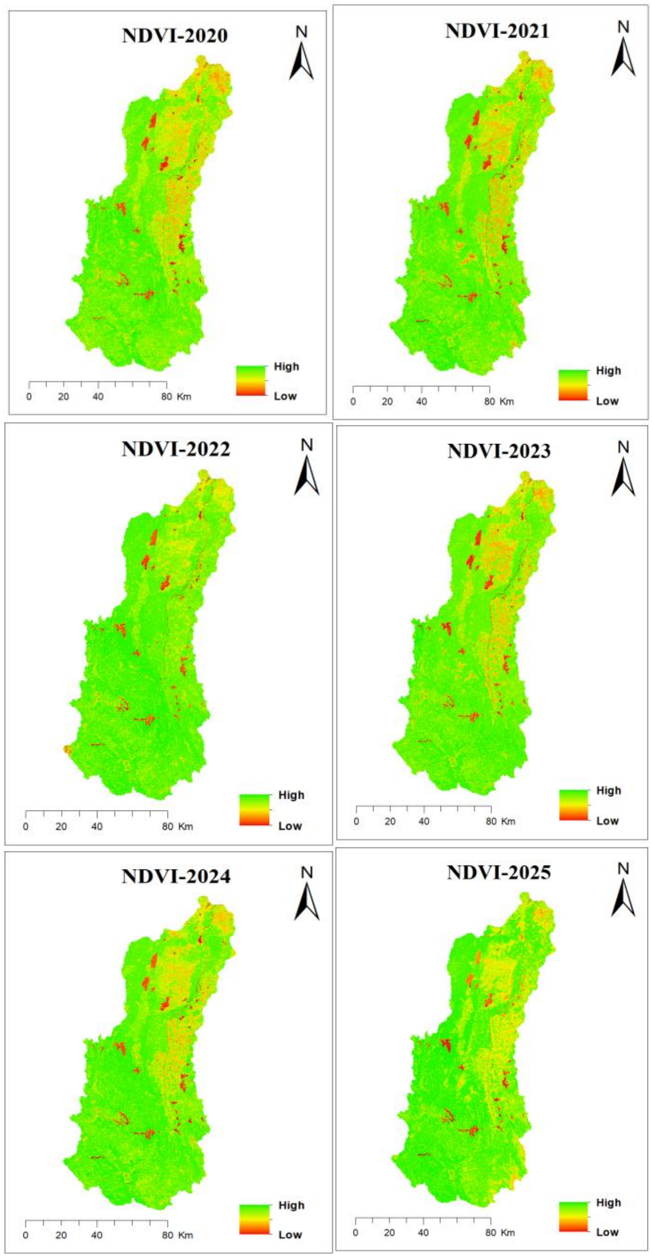
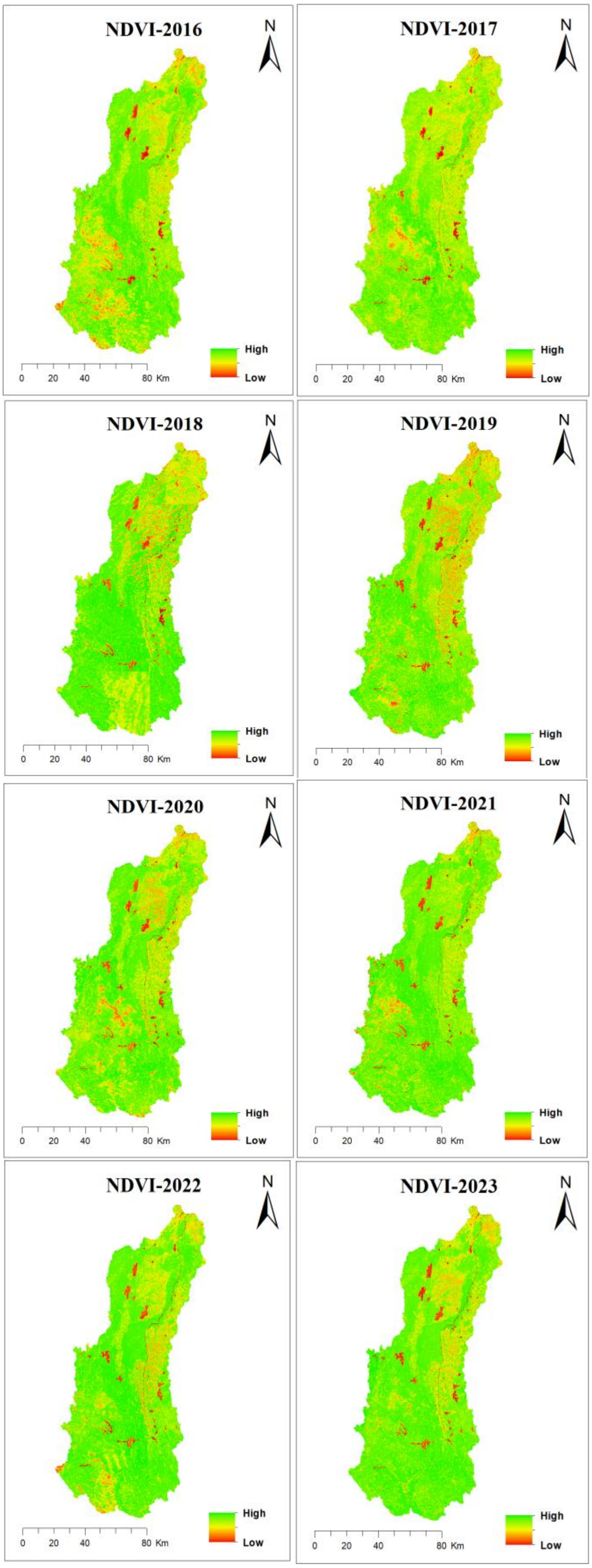


Fig. 1 NDVI Distribution from 2016 to 2025 in Wet Season



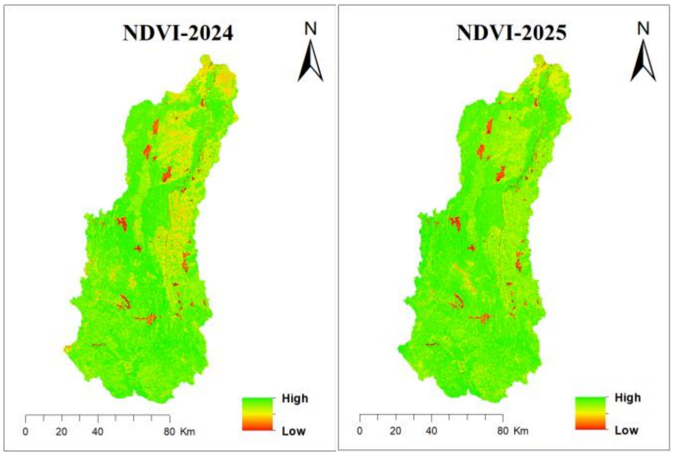


Fig. 1 NDVI Distribution from 2016 to 2025 in Dry Season

4.2 Seasonal NDVI Statistics

Statistical analysis of NDVI values from 2016–2025 provides insight into inter-annual variability (Table 1,Table 2).The coefficient of variation was higher during the dry season, reflecting greater heterogeneity in vegetation response under water-limited conditions. Maximum NDVI values were consistently observed in the central highlands while minimum values occurred in urbanized and semi-arid lowland areas. Seasonal statistical differences highlight the strong sensitivity of vegetation to rainfall and irrigation patterns. Regions with low NDVI during dry seasons could indicate vulnerability to drought or anthropogenic pressure.

TABLE I
MEAN NDVI FOR WET AND DRY SEASON

Year	Wet Season	Dry Season
2016	0.545	0.520
2017	0.557	0.513
2018	0.630	0.638
2019	0.632	0.602
2020	0.622	0.619
2021	0.639	0.664
2022	0.698	0.660
2023	0.658	0.658
2024	0.654	0.645
2025	0.625	0.680

TABLE II
NDVI STTISTICS FOR WET AND DRY SEASON

	Wet Season	Dry Season
Mean	0.626	0.620
Standard Deviation	0.043	0.056
Coefficient Variation	0.069	0.090

4.3 NDVI Time Series Analysis

Time series analysis over the 10-year period shows general stability in forested regions and moderate fluctuations in agricultural areas (Fig.3).Wet season NDVI exhibited slight upward trends in upper catchments. The Variation suggests improving vegetation density, possibly due to forest conservation efforts.

Dry season NDVI showed more pronounced fluctuations, reflecting variability in rainfall and cropping practices. The results demonstrate that integrating temporal decomposition methods provides more accurate detection of abrupt vegetation changes than simple year-to-year comparison.

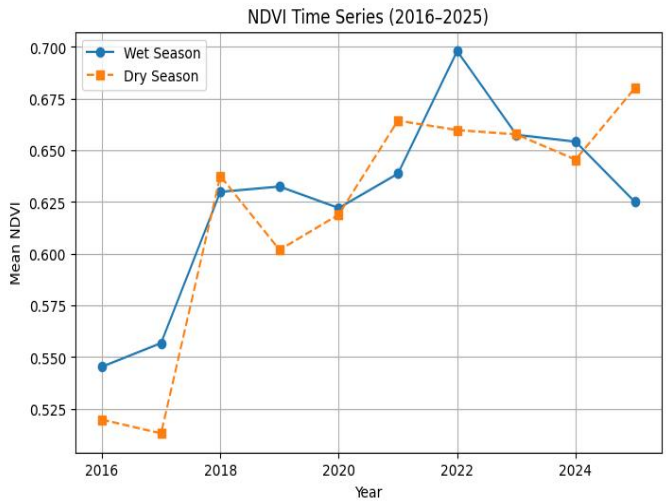


Fig. 3 NDVI variations from 2016 to 2025

4.4 NDVI Anomalies

NDVI anomalies were calculated using standardized z-scores for both seasons (Table 3). Spatial analysis showed that lowland agricultural areas were more sensitive to anomalies than forested regions, reflecting higher vulnerability to climatic variability.

TABLE III
NDVI ANOMALIES FOR WET AND DRY SEASON

Season	Theil–Sen Slope (NDVI/year)	Linear Trend Slope	Mann–Kendall Trend
Wet Season	0.00886	0.01061	Increasing
Dry Season	0.01396	0.01629	Increasing

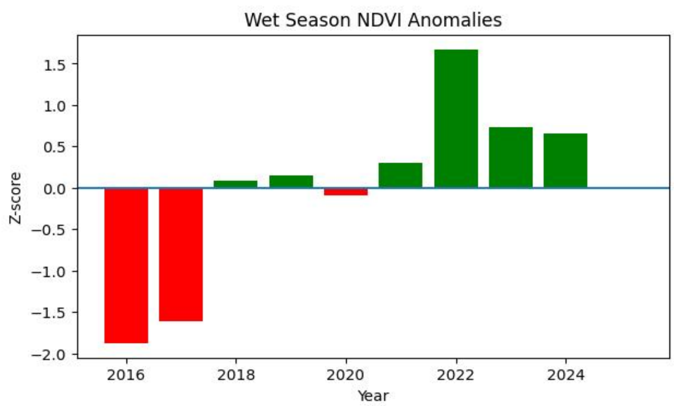


Fig. 4 NDVI anomalies variations for wet season

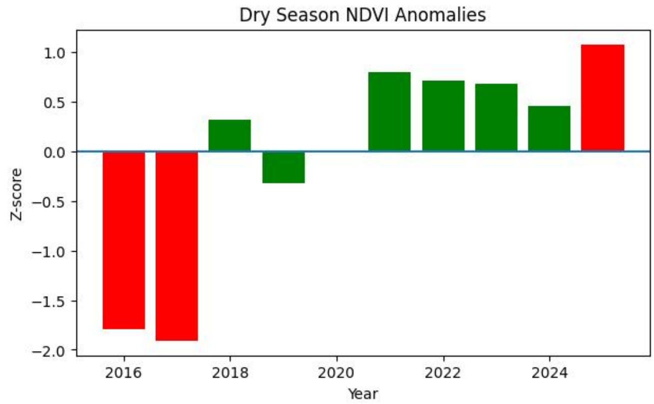


Fig. 5 NDVI anomalies variations for dry season

4.5 Vegetation Trend Analysis (2016–2025)

Long-term vegetation trends were evaluated using linear regression and Theil–Sen slope estimation. The results revealed positive NDVI trends during both wet and dry seasons across the study period (Fig.6, Fig.7). Wet season NDVI showed a gradual increase, indicating improving vegetation conditions and enhanced greenness within the basin. Similarly, dry season NDVI also demonstrated an increasing trend with a comparatively stronger rate of increase than the wet season.

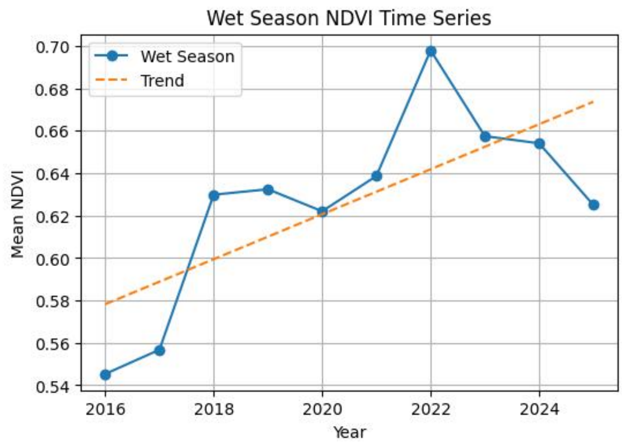


Fig. 6 NDVI variation for wet season

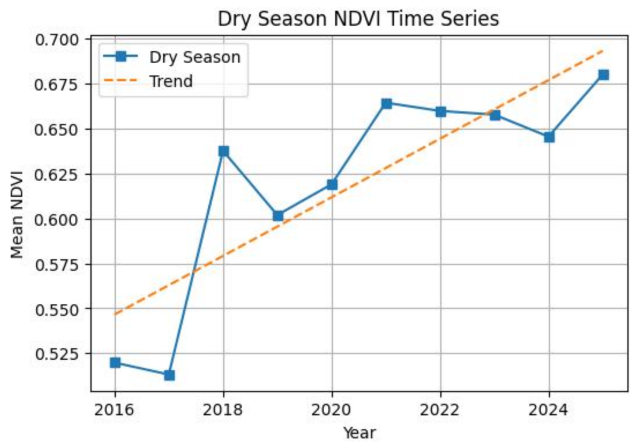


Fig. 7 NDVI variation for dry season

The Mann–Kendall test confirmed that trends were statistically significant in forested areas but not in lowland agricultural zones, highlighting spatial variability in long-term vegetation changes.

4.6 Discussion

The spatio-temporal analysis of NDVI from 2016 to 2025 revealed seasonal and inter-annual variations in vegetation conditions within the Mahaweli River Basin. The results indicate that both wet and dry seasons experienced an overall increasing trend in vegetation greenness during the study period. Mean NDVI values ranged from 0.545 to 0.698 for the wet season and from 0.513 to 0.680 for the dry season, indicating moderate to dense vegetation cover throughout the basin. The wet season recorded a slightly higher overall mean NDVI value compared to the dry season, confirming that vegetation conditions are generally more favourable during periods of higher rainfall. However, the difference between the two seasonal means is relatively small. The finding suggests that vegetation in the basin maintains considerable resilience even during drier periods. This behaviour may be associated with irrigation activities, perennial vegetation, and forest cover distributed across the basin. The temporal analysis showed that NDVI values gradually increased from 2016 onwards in both seasons. In the wet season, NDVI increased from 0.545 in 2016 to a peak value of 0.698 in 2022 before slightly declining afterward. Similarly, dry season NDVI increased from 0.520 in 2016 to 0.680 in 2025. The increase observed in the dry season is particularly significant because it indicates improving vegetation conditions despite seasonal water limitations. Expansion of irrigated agriculture and vegetation recovery in some areas may have contributed to this pattern. Statistical indicators further support these observations. The dry season exhibited a higher standard deviation and coefficient of variation compared to the wet season standard deviation and coefficient of variation. This indicates that vegetation conditions during the dry season were more variable and sensitive to environmental fluctuations such as rainfall variability, agricultural practices, and water availability. In contrast, the wet season showed relatively stable vegetation conditions across years due to consistent monsoonal rainfall. Trend analysis confirmed positive vegetation changes in both seasons. The Theil–Sen slope values of 0.00886 for the wet season and 0.01396 for the dry season demonstrate increasing NDVI trends over time. Similarly, the linear regression slopes also indicated positive trends, with stronger growth observed during the dry season. The Mann–Kendall trend analysis identified increasing trends in both seasons, suggesting that vegetation cover and health in the Mahaweli River Basin have generally improved during the study period. The anomaly analysis revealed temporal fluctuations associated with climatic variability and seasonal environmental conditions. Negative anomalies observed during some years indicate temporary reductions in vegetation greenness, possibly caused by lower rainfall or agricultural disturbances. These variations demonstrate the sensitivity of vegetation dynamics to hydro-climatic conditions within the basin.

V. CONCLUSION

The study assessed the spatio-temporal dynamics of vegetation in the Mahaweli River Basin from 2016 to 2025 using NDVI analysis derived from satellite imagery. The results revealed that vegetation conditions varied seasonally, with the wet season showing slightly higher NDVI values than the dry season.The trend analysis indicated an overall increase in NDVI values during both wet and dry seasons throughout the study period. The finding suggests gradual improvement in vegetation cover and health within the basin. The dry season exhibited comparatively higher variability, indicating greater sensitivity of vegetation to climatic conditions and water availability. The statistical and trend analyses confirmed positive long-term vegetation trends across the basin. The anomaly analysis also showed yearly fluctuations in vegetation conditions while maintaining an overall increasing trend. Thestudy demonstrates that remote sensing-based NDVI analysis is an effective approach for monitoring long-term vegetation dynamics and seasonal environmental changes in the Mahaweli River Basin. The findings can support environmental management, agricultural planning, and sustainable watershed management activities in Sri Lanka.

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