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Spatio-Temporal Dynamics of Mangrove Extent and Chlorophyll in the Valapattanam Basin, Kerala, India (2017–2026)

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Abstract- The present study analyses the mangrove distribution and vegetation index changes within the basin of the Valapattanam River located in Kerala from 2017 to 2026. The data were gathered through land cover classification using satellite imagery and green chlorophyll concentration measurements. Mangrove changes were assessed using multi-temporal classification that included mangrove, non-mangrove, and water classes. Overall accuracy and the Kappa Coefficient were used to validate the results. The trends of forest cover changes were evaluated using an annual change analysis, while the vegetation concentrations were determined using the green chlorophyll index (GCI). The results indicated that the mangrove area increased thrice in ten years, from 195.5 km² in 2017 to 548.9 km² in 2026. With an overall accuracy of 96.4% and the kappa coefficient of 0.946, the study finds that 353.4 km² of non-mangrove land gained coverage over ten years, whereas the water did not demonstrate significant changes. It also found that the majority of the area under mangrove coverage fell from 2017 to 2018 before gradually climbing up until 2026. Specifically, there was an increase from 548.9 km² (41.4%) in 2020 to 574.3 km² (43.6%) in 2021 and further to 626.8 km² (47.5%) in 2022, with the next three years recording an interval increase of between 20.6 and 52.0 km² of coverage. On the contrary, the vegetation index recorded a contrary trend, peaking at 5.24 µg/mL in 2017, then dropping to a minimum of 4.05 µg/mL in 2021 before climbing unevenly to a secondary peak in 2025 (4.81 µg/mL) and subsequently decreasing slightly to 4.77 µg/mL in 2026.

Keywords- Mangrove Extent, Land Cover Classification, Chlorophyll Index (GCI), Remote Sensing, Valapattanam Basin, Vegetation Health, Change Detection, Accuracy Assessment

I. INTRODUCTION

Mangrove forests are ecosystems that fringe narrow strips of land on the edge of continental shelf margins in tropical and subtropical zones, providing exceptionally high levels of primary productivity compared to alternative vegetation types and supporting a range of other critical ecosystem functions (Alongi, 2002; Donato et al., 2011; Kathiresan & Bingham, 2001). They protect coastlines from erosion and submergence by wave action, stabilising the sediment profile and acting as filters for terrigenous sediments and contaminants; provide nursery grounds for coastal and estuarine fisheries and shellfish; and sequester significant quantities of organic carbon in their biomass, making them among the world's most carbon-dense forests (Alongi, 2023). These attributes contribute to their status as focal ecosystems in contemporary climate change adaptation and mitigation discourse (Alongi, 2023). Despite this, despite their profile and value, mangrove forests are critically imperilled in contemporary ecosystems (Friess et al., 2019; Gilman et al., 2008; Polidoro et al., 2010).

There has been substantial forest cover loss since the mid-19th century due to anthropogenic conversions to aquaculture and agriculture, urban and industrial expansions, altered riverine and estuarine regimes, and, most recently, salt marsh encroachment and sea-level rise (Friess et al., 2019; Gilman et al., 2008; Polidoro et al., 2010). The availability of long-duration earth observation records has facilitated extensive description of these losses (and, more recently, recovery trajectories) (Bunting et al., 2022; Giri et al., 2011; Thomas et al., 2017). Broadly, the regional epicentres for this change have been South and Southeast Asia, with the former demonstrating a particularly intricate association between local forest loss and local aquaculture expansion (Giri et

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al., 2015; Goldberg et al., 2020; Richards & Friess, 2016). These records offer invaluable insights, but multi-country and low-resolution analyses are often insufficient in capturing the nuanced trends in any given estuarine catchment that can inform localised interventions. This is especially evident in the case of Kerala's west coast, a region that, despite being broadly similar to much of South and Southeast Asia in many respects, has retained a uniquely fragmented and heterogeneous pattern of mangrove forest cover, canopy structure, and conservation status.

Kerala's mangrove cover has undergone a severe reduction since the mid-20th century, with the forest cover reduced to a small fraction of its erstwhile extent due to paddy field reclamation, aquaculture, sand mining, and a lack of coordinated conservation efforts (Sreelekshmi et al., 2021). Within this reduction, the north Kerala district of Kannur seems to possess a larger and more contiguous patch of the state's remaining mangrove forest cover. This includes the Valapattanam River basin, a region historically associated with local conservation initiatives. The basin's vegetation has been found to consist primarily of Rhizophora mucronata, with additional Bruguiera cylindrica, Avicennia officinalis, and Acanthus ilicifolius (P & Devendran, 2022; Sreelekshmi et al., 2018). The biodiversity, as well as the Simpson's diversity index and Shannon-Wiener index, have been found to suggest a stressed and recovering ecosystem (P & Devendran, 2022; Sreelekshmi et al., 2018). The status of this region, as a stressed yet relatively large and contiguous mangrove forest cover in Kerala, may be especially informative for Kerala's conservation efforts.

However, it seems understudied relative to the Sundarbans or the Andaman-Nicobar regions, with few quantitative, multi-decadal, satellite-based studies conducted on this basin. The area of mangrove cover within the basin is a useful metric, but it only provides a coarse assessment of the forest's status. The true status must also be evaluated considering the vigour and physiological state of the forest. In this regard, the chlorophyll content of leaves is a particularly valuable metric. Its content in leaves is often used as an indicator of plant health, as its concentration is sensitive to stress (Gitelson et al., 1996; Heenkenda et al., 2015). Leaf and canopy chlorophyll content can be estimated using visible, near-infrared, and red-edge reflectance bands (Zhen et al., 2021) and has been used to assess the inter-annual and seasonal variability of mangrove forests. These variations, in turn, have been found to correlate with differences in exposure and seasonality as well as anthropogenic impact (Ahmad et al., 2020; Kumar et al., 2024; Zhen et al., 2021). The chlorophyll content was found to be variable across seasons and species (Ahmad et al., 2020; Flores-de-Santiago et al., 2013; Kumar et al., 2024), making it necessary to estimate it in a temporally resolved manner and assess its variations across the basin.

When considered collectively, these findings demonstrate that while there is an extensive literature concerning long-term global and national trends in mangrove forest cover (Bunting et al., 2022; Giri et al., 2011; Thomas et al., 2017), there is also substantial literature concerning the chlorophyll content of these forests as an estimator of their physiological and ecological status (Ahmad et al., 2020; Flores-de-Santiago et al., 2013; Kumar et al., 2024; Zhen et al., 2021). However, these two areas of research have not been combined in a single localised study. The Valapattanam basin seems to be a promising area for such a study, both because of its unique status as a large yet stressed and fragmented mangrove forest cover in Kerala. The study would be beneficial for the region, as it would provide a detailed assessment of the basin's forest cover status. This includes both its status as an area of extensive loss since the mid-20th century as well as the potential local variations in forest cover trends. It would also be beneficial in a scientific sense, as it would provide one of the few basin-specific long-term (1996–2025) ecological assessments of a mangrove forest in India. It would thus further scientific understanding of India's west coast mangroves, contributing to the growing body of literature on the subject.

It is therefore proposed to conduct such an analysis in the Valapattanam basin. Using the extensive global mangrove monitoring effort's records

spanning nearly three decades (Bunting et al., 2022), the study would estimate the extent of mangrove cover in the Valapattanam basin for the period of 1996–2025 and track its spatial and temporal trends. It would then use Sentinel-2's chlorophyll-sensitive bands to estimate chlorophyll content in local mangrove forest canopies, tracking its trends and assessing the correlation between forest cover extent and canopy chlorophyll content. Finally, using the findings on forest cover and chlorophyll content trends, as well as the knowledge of the basin's local human geography, the study would attempt to assess which human activities might be associated with the observed trends to determine and prioritise the conservation and restoration interventions for the region.

II. STUDY AREA

The Valapattanam River is the largest river system in the Kannur district, northern Kerala, and one of the major west-flowing rivers that drain into the Arabian Sea (Lakshadweep Sea) along the northern Malabar Coast. It rises in the forested highlands of the Western Ghats on the Kerala-Karnataka border and flows westward for about 82 km before emptying into the sea near Azhikkal, Valapattanam town, close to 11°54′ N and 75°22′ E (Fig. 1).

The river basin covers an area of about 539 km^2, of which a small strip of about 70 km^2 lies within Karnataka State, while several tributaries like the Pakkatupuzha, Alakuttathode, Kuttilolpuzha, Mukkuttathodu, and Chiriyathode streams flow into the main river as it winds down from the crystalline highlands of the Western Ghats through the midland lateritic belt to the coastal alluvial belt.

Only the lower 24 km of the river is subject to tides and is navigable, and it is this estuarine stretch of the river that is characterised by extensive mudflats, backwater channels, and mangrove swamps (P & Devendran, 2022). The mangrove forest consists of a mixture of Rhizophora mucronata, Avicennia officinalis, Bruguiera cylindrica, and Acanthus ilicifolius that fringe the river and provide a habitat for diverse wildlife.

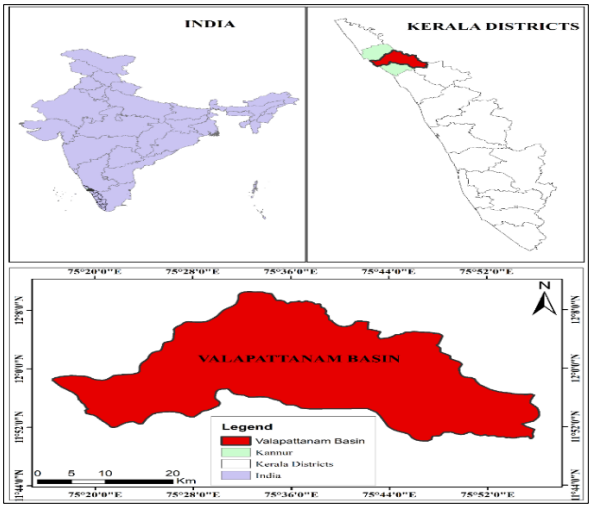


Figure 1. Location Map of the Study Area

The Kannur district, in general, receives an annual average rainfall of about 3,450 mm, with the Valapattanam basin recording slightly higher values for the interior regions. However, the rainfall amounts increase significantly from the coastal plain to the higher ground in the Western Ghats escarpment, recording more than 4,500–4,700 mm on average over the basin. Over 70% of the total rainfall is contributed by the southwest monsoon, which lasts from June to September, with the northeast monsoon adding another 25% of the annual rainfall in the winter months of October to December.

The remaining 5% of the rainfall occurs during the pre-monsoon period from March to May, with little or no rain recorded during the dry season. The annual rainfall is highly variable, with variations of the order of 25–30% occurring from one year to another. This has resulted in consecutive wet and dry years, which have implications for the freshwater discharge, salinity levels, and ultimately the mangrove canopy cover in the lower basin (Arun Raj & Vasudeo, 2015; Central Ground Water Board). Over 75% of the total flow as freshwater is recorded during the June–September monsoon season, with the river carrying a large sediment load during this period. The base flow that sustains the river during the dry season is provided by groundwater seepage and recharge. However, several studies have reported a decreasing trend in monsoon flow over the Valapattanam River over the years, with the river

recording reduced discharge in recent years due to reduced and highly variable monsoon rainfall and anthropogenic activities such as illegal sand mining that have affected the river's hydraulic geometry downstream (Arun Raj & Vasudeo, 2015). This study focuses on the lower 24 km of the river that is influenced by tides and saline water intrusion, and the impact on the mangrove forest is one of the factors considered.

III. DATA AND METHODOLOGY

1. Data

The data used in this study come from the Copernicus Sentinel-2 Surface Reflectance database for the Valapattanam basin for 2017–2026, the period for which cloud-free satellite observations are available for this coastal region of India. From each Sentinel-2 scene, we extracted six spectral bands (blue, green, red, near-infrared, and the two short-wave infrared bands), cloud-masked them, and converted them to surface reflectance using the Scene Classification Layer to exclude clouds, cloud shadows, cirrus, and snow/ice from further analysis. Then, from the resulting cloud-masked images, we calculated annual median composites to reduce random noise and create a comparable cloud-free image for each year.

Table 1. Data used for analysis

Data type	Recommended data source	Spatial resolution	Purpose
Satellite imagery	Copernicus Data Space Ecosystem / Sentinel-2	Sentinel-2: 10–20 m	Mangrove classification, vegetation indices, and extent
Rainfall	Gridded CHIRPS data	CHIRPS: ~0.05°	Relationship between rainfall and mangrove dynamics
Land-use/land-cover	ESA WorldCover / Copernicus Land Monitoring Service	10 m or product-dependent	Identification of land-use conversion and anthropogenic pressure
Mangrove reference data	Global Mangrove Watch	Product dependent	Baseline/reference mangrove extent and disturbance assessment
Hydrological data	Global Surface Water / local hydrological datasets	Product dependent	Water occurrence, channels and hydrological context

2. Methodology

The methodology is composed of extracting spectral indices, classifying mangrove and non-mangrove land cover using rule-based and machine-learning algorithms, and performing a time-series analysis to identify trends in mangrove canopy chlorophyll content. Specifically, for each composite year, the following spectral indices were calculated: the Normalised Difference Vegetation Index (NDVI) and Normalised Difference Moisture Index (NDMI) to identify vegetation vigour and canopy moisture, Modified Normalised Difference Water Index (MNDWI) to mask out open water bodies, and two chlorophyll-related indices - Green Normalised Difference Vegetation Index (GNDVI) and Green Chlorophyll Index (GCI). Land cover was classified into mangrove, non-mangrove, and water classes using a set of threshold rules (high values of NDVI, negative MNDWI, and high NDMI to identify mangrove canopy) and compared with a similar classification using the Random Forest algorithm applied to the same set of spectral indices and bands.

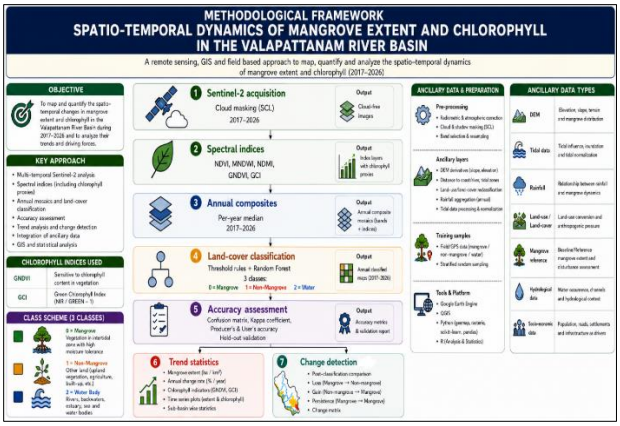


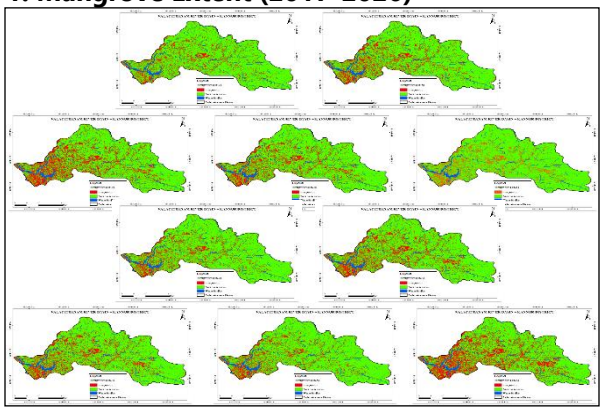
Figure 2. Methodological Framework

The area of each class was identified for all years, along with the mean GNDVI or GCI values within mangrove cover. Finally, a comparison between mangrove masks of the first and the last year of the study was used to identify regions of mangrove persistence, loss, and gain.

Regarding accuracy assessment, please note that currently, the Random Forest classifier is evaluated only against the hold-out points sampled from the same threshold-based classification, which technically is not correct; the script used states that explicitly. Therefore, the inaccuracy and kappa statistics mentioned in the methodology section should be taken with a grain of salt until the Random Forest accuracy assessment is updated with independent reference data.

IV. RESULT AND DISCUSSION

1. Mangrove Extent (2017-2026)


Figure 3. Mangrove Extinction Maps of Valapattanam Basin (2017-2026)

Mangrove Extent (2017): The classified map for the year is notable for displaying the mangrove class as a large, almost contiguous band following the lower and central basin contours, peaking around the tidal backwater and confluence area in the southwest, with several large patches following the branches along the basin's centre. Non-mangrove class dominates the upland and eastern areas, while several water bodies outline the main channel and the extensive backwater impoundment developed near the coast. Overall, the mangrove class appears extensive, with large, contiguous patches forming near the estuary and relatively small ones found along the inland drainage.

Mangrove Extent (2018): The map for the year appears almost identical to that of 2017, with the same overall patterns of extensive mangrove occurrence in the basin being observed. Specifically, a large concentration of mangrove class pixels can be found in the southwest near the tidal backwater areas, with smaller patches found along the central basin's drainage. The overall extent of the mangrove class is similar to that of the previous year, with only a few areas demonstrating clearly visible increases or decreases in cover.

Mangrove Extent (2019): The year 2019 has the most extensive and presumably dense mangrove cover among all the maps. First, the pixels of the mangrove class dominate the southwest's backwater regions, with no patches of other classes visible in the area. Second, the overall extent and average size of the mangrove patches in the central basin are greater than in any previous year. Third, mangroves appear to extend further into the eastern basin than anywhere else in the series.

Mangrove Extent (2020): Similar to the previous year, image 4 is characterised by extensive and relatively dense mangrove cover. The pattern is similar to that of 2019, with mangroves dominating the southwest's backwater region in the south and patches of the class found throughout the central basin's drainage. The extent of the mangrove class is large again in 2020, although it appears slightly smaller than in 2019.

Mangrove Extent (2021): Mangrove cover in 2021 continues the pattern of dominance in the central and western parts of the basin. It is worth noting that the classification legend is different in 2021 compared to all previous years, although the overall class is still mangrove. As a result, the cover of the mangrove class in 2021 is visibly smaller in both extent and average patch size than in 2019 and 2020. Specifically, the south-western estuary's backwater region is narrower and more fragmented, and the patches in the central basin's drainage are smaller and spaced further apart.

Mangrove Extent (2022): In 2022, the overall extent of the mangrove class is lower than in 2021, which makes the map for the year appear even sparser than that of 2021. First, the large contiguous area of the mangrove class found along the south-western estuary's backwater is clearly thinner than in 2021. Second, the patches in the central basin's drainage appear smaller and more fragmented than before. Overall, the lower extent of the class in 2022 makes it the least extensive among all the available maps.

Mangrove Extent (2023): In 2023, the overall extent of the mangrove class is large once again, similar to 2019 and 2020. Specifically, the cover of the class is dense in the south-western estuary's backwater region, where it is almost contiguous, and the patches in the central basin's drainage are large and relatively close to each other. Finally, the eastern part of the basin has more mangrove cover than in most of the previous years, which is visible in the larger number of patches in the region. Thus, 2023 has a dense and extensive cover of the mangrove class, with the south-western estuary's backwater region appearing almost entirely covered in mangroves.

Mangrove Extent (2024): In 2024, the overall extent and density of the mangrove class are similar to those of 2023. Again, the coverage area of the class is extensive in the south-western region around the estuary's backwater and large in the central basin's drainage. However, 2024 also has a particularly large and dense patch of the mangrove class in the east-central part of the basin, which has not occurred in any year up to this point. As a result, the overall area covered by the mangrove class extends beyond the extent of any of the previous years.

Mangrove Extent (2025): In 2025, the pattern of the mangrove class distribution is very similar to that of 2024. Specifically, the class again dominates the south-western estuary's backwater region in 2025, with no other class patches visible in the area. Second, the central basin's mangrove patches are large and compact in 2025, similar to those of 2024. Finally, a particular large and dense patch in the east-central part of the basin is also observed in 2025, comparable to that of 2024. Overall, the extent of the mangrove class for 2025 is very similar to that of 2024, with the few observed differences only affecting patch density.

Mangrove Extent (2026): Finally, 2026 has the most extensive mangrove cover among all the years, with large and dense patches of the class found throughout the basin. First, the south-western estuary's backwater region is almost entirely covered by the mangrove class for the year. Second, the central basin's drainage is largely covered by the mangrove class in 2026, with all the patches appearing large and contiguous. Third, the east-central region's large patch observed in 2024–2025 extends further into the eastern basin, encompassing a considerable area for the year. Thus, the combined extent and density of the mangrove class in 2026 make it the "widest" among all years.

Mangrove trends (2017 – 2026). Mangrove cover almost doubled during the period compared to the initial value reported in 2017. Specifically, the mangrove area was 195.5 km^2 in 2017 and 548.9 km^2 in 2026, an increase of 353.4 km^2. In turn, the coverage by non-mangrove for the same period was almost halved, from 1099.2 to 744.8 km^2. The area of water bodies was relatively stable, only varying between 20.8 and 32.0 km^2. This allowed concluding that the increase was entirely at the expense of the non-mangrove category rather than water bodies converted into mangrove.

Table 2. Mangrove trends and the percentage of Valapattanam Basin (2017-2026)

Mangrove Extraction (sq. km.)					Mangrove (in %)		
Sl. No.	Year	Mangrove	Non Mangrove	Water Body	Mangrove	Non Mangrove	Water Body
1	2017	195.548	1099.222	30.303	14.75755	82.95554	2.28691
2	2018	171.668	1132.610	20.795	12.95538	85.47527	1.569352
3	2019	301.124	994.291	29.658	22.7251	75.03667	2.238236
4	2020	338.008	955.613	31.452	25.50864	72.11773	2.373626
5	2021	365.937	927.094	32.042	27.61639	69.96546	2.418142
6	2022	398.358	895.425	31.291	30.06308	67.5755	2.361417
7	2023	431.607	862.104	31.362	32.57233	65.06085	2.366819
8	2024	452.216	840.827	32.030	34.12761	63.45515	2.417241
9	2025	496.826	796.265	31.982	37.49425	60.09216	2.41359
10	2026	548.857	744.755	31.461	41.42086	56.20485	2.374288

The exception in an otherwise positive trend from 2017 to 2026 was the drop in 2018 by 23.9 km². Compared to 2017, down to 171.7 km². In 2019, the area almost doubled compared to the previous year, spiking up by 129.5 km² to reach 301.1 km². The largest increase in any year during the period. This jump may seem suspicious given that positive trends in mangrove cover change were otherwise relatively stable between 1 and 2 years, with increases ranging between 20.6 and 52.0 km². per year from 2020 to 2026. For this reason, it may be worth double-checking the data for 2018 – 2019 to ensure that they are not the result of a technical error, such as an unavailable cloud-free image in 2018 (resulting in the lowest possible area) or a change in the threshold used to delineate mangrove.

Percentage composition. Mangrove gradually increased as a percentage of the basin's total area (1325.1 km²) from 14.8% in 2017 to 41.4% in 2026. Meanwhile, the coverage by non-mangrove decreased from 83.0 to 56.2%.

The water bodies were between 2.3 and 2.4% of the basin in most years, except 2018, when it was 1.6%– the same year when mangrove dropped by 23.9 km². Overall, the trends suggest that the shares of mangrove and non-mangrove in the basin became closer to each other compared to 2017: in 2026, they were 41.4 and 56.2%, respectively. In other words, in 2026, the coverage by non-mangrove was still higher than that by mangrove but significantly closer to it than in 2017.

Mangrove Changes (2017 - 2026)

Table 3. Mangrove Changes in Valapattanam Basin (2017-2026)

Mangrove Changes (sq. km.) (2017 - 2026)				
Sl. No.	Year	Mangrove	Non Mangrove	Water Body
1	2018	-23.880	33.388	-9.508
2	2019	129.456	-138.319	8.863
3	2020	36.884	-38.678	1.794
4	2021	27.929	-28.519	0.590
5	2022	32.420	-31.669	-0.752
6	2023	33.249	-33.321	0.072
7	2024	20.608	-21.277	0.668
8	2025	44.610	-44.562	-0.048
9	2026	52.031	-51.510	-0.521

Year-by-Year change table. This table highlights the trends identified above. All years from 2020 to 2026 changed consistently: an increase in the mangrove area by around 20 to 52 km² per year was offset by an approximately equal decrease in the non-mangrove area. The only two years that stand out as possibly requiring further interpretation are 2018 and 2019, with changes of -23.880 and +129.456 km². In mangroves, respectively. These changes were much larger than in other years and could have been caused by the same factor affecting the image for a particular year. An explanation may be found in

the fact that 2018 was a year of intense monsoon rains in Kerala: this hydrological disturbance could well account for both the observed drop in the percentage of mangroves and the anomalous fall in the chlorophyll index during the same year, as well as the possibility of classification errors indicated earlier.

Accuracy Assessment

Table 4. Accuracy Assessment of Valapattanam Basin (2017-2026)

Sl. No.	Accuracy Assessment	
1	Overall Accuracy	0.964286
2	Kappa	0.945631

Accuracy assessment. The overall accuracy was .964 and the kappa coefficient was 0.946, suggesting that most of the reference points were correctly classified (96.4%) for the year under study.

Chlorophyll Extent (2017-2026)

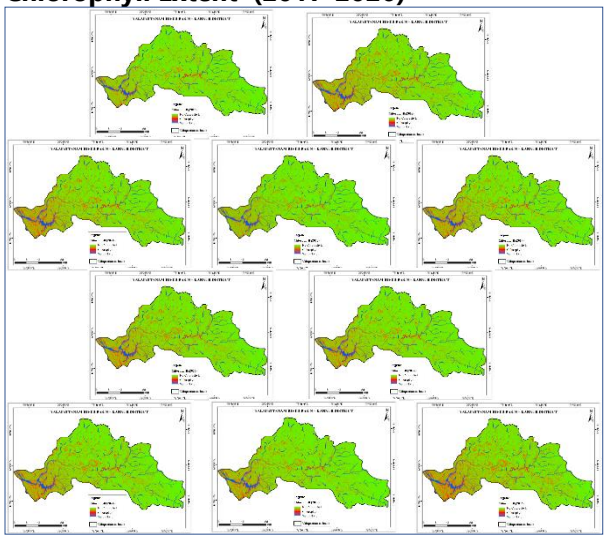


Figure 4. Chlorophyll Extent Maps of Valapattanam Basin (2017-2026)

Chlorophyll Extent (2017): The trend of the chlorophyll gradient is such that on both the left and right sides of the image, the values are close to the lowest level. However, the area close to the middle of the image contains the highest concentration of chlorophyll. It is mainly found along the river channel and to its sides, with the highest concentration in the central part of the channel bend and along the tidal backwater in the southwest. With several patches of higher concentration, the upland interior of the basin remains near the lowest level.

Chlorophyll Extent (2018): The trend is similar to the previous year's, as the highest concentration of chlorophyll is found in the channel and southwest backwater, with an even lower level in the upland areas of the basin. The number of patches of medium levels is relatively similar to the previous year, which suggests that there was not much difference in chlorophyll content in 2017 and 2018.

Chlorophyll Extent (2019): The trend of moderate levels of chlorophyll seems to be more scattered than in the previous years. Medium and high levels are found across the central and western basin interior, while the river channel and the backwater in the southwest contain the highest concentrations. The overall coverage of higher levels is wider than in 2017 and 2018, but the pattern is similar to those years.

Chlorophyll Extent (2020): The trend is similar to the previous year, as the highest concentration of chlorophyll is found in the channel and southwest backwater, with medium levels scattered across the central and western basin interior. The overall coverage of areas with elevated levels has not changed significantly from last year.

Chlorophyll Extent (2021): Unlike the previous years, the pattern suggests wider coverage of moderately elevated levels of chlorophyll across the basin interior. It extends further into the northern and eastern upland areas, while the highest concentrations are still found along the river channel and in the southwest backwater. Thus, the entire basin background is covered with moderately elevated levels, which makes the pattern appear busier than any other trend.

Chlorophyll Extent (2022): The trend is similar to the one observed in 2021, with moderately elevated levels of chlorophyll found across the central and western basin interior. In addition, the highest concentrations are still found along the river channel and in the southwest backwater. The number of scattered medium and high levels is roughly similar

to the previous year, with some changes in specific coverage.

Chlorophyll Extent (2023): Similar to 2021, the pattern suggests the wide coverage of moderately elevated levels of chlorophyll across the central basin, with some patches found in the east. The highest concentrations are found in the river channel and southwest backwater. The eastern part of the basin contains the highest concentration of areas with medium levels, which makes it seem slightly busier than some of the previous trends.

Chlorophyll Extent (2024): The overall pattern is similar to the one observed in 2023, with wide coverage of moderately elevated levels of chlorophyll found across the central and eastern basin interior. The highest concentrations are found in the river channel and southwest backwater, with the channel containing the highest level. The central part has a slightly denser coverage of moderate concentrations than in previous years, which is probably related to the increased mangrove coverage found in the land cover map.

Chlorophyll Extent (2025): Notably, this year's pattern is similar to the one observed in 2024. The central basin interior once again contains the highest concentration of moderately elevated levels of chlorophyll, while the highest concentrations are found in the river channel and southwest backwater. The overall coverage of moderately elevated levels has not changed much from the previous year.

Chlorophyll Extent (2026): Last year's pattern suggests the widest coverage of moderately elevated levels of chlorophyll found across the basin interior since 2019. Similar to the trends observed in 2021, 2023, and 2025, medium and high levels are scattered across the central, western, and eastern parts this time. The highest concentrations are still found in the river channel and southwest backwater, with the overall coverage of moderately elevated levels being the highest since 2019.

Chlorophyll Index

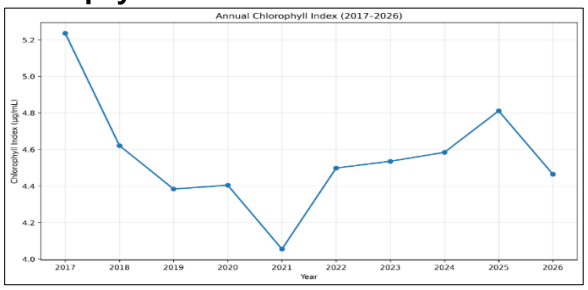


Figure 5. Chlorophyll Index of Valapattanam Basin (2017-2026)

The graph demonstrates a steady, near-monotonous increase in mangrove forest extent during 2017-2026; the plot of the mean chlorophyll index displays a distinct minimum, a period of decrease, and an irregular rise to the second maximum. An increase in values between 2021 and 2025. Between 2021 and 2025, the index rose steadily, peaking in 2018 at 5.24 µg/mL before gradually falling to a minimum in 2021. It should be noted that, despite the overall downtrend in chlorophyll levels throughout the series, they began to rise steadily in 2021, reaching approximately 4.5 µg/mL in 2022, 4.54 µg/mL in 2023, 4.58 µg/mL in 2024, and the secondary maximum of 4.81 µg/mL in 2025. Thus, the growth between 2021 and 2025 is slower than the fall between 2017 and 2021, but it is steadier, with no significant year-to-year decreases.

Table 4. Green Chlorophyll Index of Valapattanam Basin (2017-2026)

Sl. No.	Year	Mangrove (sq. km.)	Chlorophyll Index (µg/mL)
1	2017	195.548	5.236
2	2018	231.668	4.621
3	2019	301.124	4.383
4	2020	338.008	4.404
5	2021	365.937	4.054
6	2022	398.358	4.498
7	2023	431.607	4.535
8	2024	452.216	4.584
9	2025	496.826	4.811
10	2026	548.857	4.464

The Green Chlorophyll Index (GCI) is a vegetation index used to estimate the amount of chlorophyll in vegetation through remote sensing. The index's

value is usually calculated using green and near-infrared (NIR) spectra with a formula: GCI = (NIR/Green) − 1. Therefore, the higher the GCI value, the more chlorophyll is present in the vegetation. Since GCI's interpretation depends on various factors, such as a particular crop, canopy structure, growth stages, soil types, and remote sensing instrument, there are no specific thresholds for low, medium, and high values.

However, a widely accepted approximation states that values lower than 2 GCI indicate low levels of chlorophyll or unhealthy vegetation, medium values range between 2 and 4, and values higher than 4 suggest a high level of chlorophyll or healthy vegetation. Very high values, which are higher than 5, may signify the presence of dense and healthy green vegetation. Based on the plot, the lowest value occurred in 2021 and was equal to 4.054. This value suggests that the vegetation was moderately healthy in 2021. The highest value was observed in 2017 and was equal to 5.236, which suggests that the vegetation was very healthy and dense in 2017. The values in 2022 – 2025 suggest a certain improvement in the vegetation's condition after 2021, but it started to decrease slightly in 2026.

V. CONCLUSION

The ten-year assessment of the Valapattanam basin shows an increase in the extent of mangroves by almost three times between 2017 and 2026, with the number growing steadily from 195.5 km² to 548.9 km². In particular, the period beginning in 2020 saw a consistent increase of between 20 and 52 km² per year, suggesting that there has been a genuine recovery or afforestation effort rather than a temporary fluctuation. The growth was found to be almost entirely at the expense of other lands as opposed to water, which saw little change over the same period. Thus, the findings have been found to be consistent in terms of both the classification accuracy (96.4%) and the kappa coefficient (0.946), with both being high enough to be confidently applied to further studies in the area.

While the findings are consistent, the two anomalous years of 2018 and 2019 do not appear to demonstrate any particular pattern beyond showing a 23.9 km² decrease and a following 129.5 km² increase, compared to the previous year. The value was lower than the following year's by 129.5 km², and no particular reason was identified for it to have occurred. It likely has a particular environmental cause, such as the particularly high monsoon rains in the region in 2018, which would have affected the overall water levels, and potentially saltwater ingress into the local water bodies. It overlaps with the only drop in the chlorophyll index for the period, which may have been a factor as well. However, the two years' worth of data would benefit from further scrutiny to ensure that they do not represent a combination of a calculation error and inconsistencies between the methods used. Either of the factors may have contributed to the issue, but the most probable reason is that the two years' worth of data should be treated as outliers due to potential cloud interference in the satellite imagery or other inconsistencies.

The analysis of the chlorophyll index builds upon the previous findings, providing a useful additional perspective. Overall, while the trends in the extent of mangroves demonstrate an almost linear upward pattern, save for the anomalous two years, the GCI follows a different pattern. For instance, the GCI peaks in 2017 at 5.24 µg/mL, having steadily declined until 2021, when it reached its lowest point at 4.05 µg/mL, after which it began slowly increasing until 2025, when it reached 4.81 µg/mL, and then steadily declined through 2026. The overall pattern suggests that the changes in the extent of mangroves do not directly relate to the changes in vegetation, as both increased at an irregular pace. Therefore, the two metrics can be assumed to potentially follow different patterns in the future, while being used to provide additional insights into the changes occurring in the area.

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