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Multi-Temporal Assessment of Shoreline and Mapped Beach-Area Changes Along the Sanghumukham–Veli Coast, Thiruvananthapuram, Kerala, India, using Remote Sensing and GIS

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ABSTRACT

Coastal shorelines are highly dynamic geomorphic boundaries that respond to waves, tides, currents, wind, sediment transport, sea-level fluctuations and human interventions. Monitoring shoreline position and mapped beach extent is therefore important for documenting coastal evolution and supporting coastal management. The present study evaluates spatial changes along the Sanghumukham-Veli coastal stretch in Thiruvananthapuram, Kerala, southwest India, using multi-temporal Google Earth imagery and Geographic Information System (GIS) techniques. Shorelines for 2015 and 2025 were manually delineated using the visible land-water boundary as the shoreline proxy. Twenty-two fixed transects were established approximately perpendicular to the coast, producing 21 inter-transect segments. Beach width was examined along the transects, while the area enclosed between adjacent transects was calculated for each observation year. The total mapped inter-transect beach area decreased from 136.58 ha in 2015 to 133.82 ha in 2025, a net reduction of 2.76 ha (2.02%). Seventeen of the 21 inter-transect segments showed reduced mapped beach area, whereas four segments showed localized increases. The largest reductions occurred toward the Sanghumukham sector, while a localized accretionary sector occurred in the central portion of the study area. These results demonstrate pronounced spatial heterogeneity in mapped beach-area change. Because the analysis is based on a visible land-water boundary and mapped area rather than a tidal-datum shoreline, the observed area differences should not be interpreted directly as shoreline retreat rates. The study provides a spatial baseline for repeated monitoring. It highlights the need for future analyses that incorporate acquisition dates, tidal information, positional and digitization uncertainties, field observations, and standardized shoreline-change statistics such as NSM, EPR, and LRR.

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1. Introduction

The shoreline represents the dynamic interface between terrestrial and marine environments and is one of the most important linear geomorphic features of coastal regions (Boak and Turner, 2005; Mahapatra et al., 2013; Mukhopadhyay et al., 2012). Its position continuously changes in response to waves, tides, currents, sediment supply, wind activity, sea-level fluctuations and anthropogenic interventions. Consequently, coastal landscapes exhibit considerable spatial and temporal variability, with beaches, dunes, cliffs, spits and tidal inlets undergoing continuous morphological adjustment. Understanding these changes is essential for effective coastal management, particularly in densely populated and rapidly developing coastal regions.

Coastal zones support important ecological, economic and social activities, including fisheries,

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tourism, transportation and urban development. Increasing population pressure and infrastructure development can modify natural sediment transport processes and influence shoreline position. Beaches, which are predominantly composed of unconsolidated sediments ranging from fine sand to gravel, respond to the balance between sediment supply, erosion, transport and deposition. Wave-induced longshore currents are particularly important in redistributing sediment along sandy coastlines. Shoreline changes may occur over different temporal scales, ranging from seasonal fluctuations associated with tides, storms and monsoon conditions to longer-term changes related to sediment budgets, sea-level rise, tectonic processes and human interventions. Therefore, systematic monitoring at appropriate spatial and temporal scales is necessary to understand coastal dynamics.

Traditional shoreline surveys provide accurate local measurements but are often time-consuming and spatially limited. Remote sensing offers repeated observations over relatively large areas, while Geographic Information Systems (GIS) provide an effective environment for integrating, visualizing and quantitatively analysing spatial data. Satellite imagery has consequently become an important source for shoreline monitoring because of the spectral contrast between land and water. Multi-temporal satellite datasets, combined with GIS-based analysis, enable systematic extraction and comparison of shoreline positions across different periods. Recent studies have increasingly integrated Landsat and Sentinel-2 imagery with automated shoreline extraction, GIS-based statistical techniques, artificial intelligence and UAV observations for coastal monitoring. The uncertainty associated with satellite-derived shoreline positions may vary with coastal setting, underscoring the importance of accounting for positional accuracy when interpreting shoreline change.

Many scholars have used Landsat satellite data to identify and map shorelines using various image-processing approaches. For instance, specific investigations utilized density slicing to isolate coastal boundaries (Braud and Feng, 1998; Frazier and Page, 2000). Other researchers applied the Normalized Difference Vegetation Index (NDVI) to delineate waterlines (Ryu et al., 2002). Additionally, both supervised and unsupervised classification algorithms have been widely implemented to extract precise shoreline features (Guariglia et al., 2006; Ustun et al., 2004; Roy et al., 2018; Baig et al., 2020; Logesh et al., 2021). The Digital Shoreline Analysis System (DSAS) has become an established approach for quantitatively assessing shoreline change using multiple historical shoreline positions (Douglas and Crowell, 2000; Henderson et al., 2026; Paul et al., 2024; Megha et al., 2025). Earlier investigations established various approaches to calculating shoreline change rates, including end-point and regression-based methods (Kumaravel et al., 2013). Subsequent studies incorporated GIS-based transect analysis to quantify erosion and accretion. Recent applications demonstrate the usefulness of geospatial techniques for repeated shoreline measurements over large areas (Dhanil Dev et al., 2023; Himmelstoss et al., 2021; Henderson et al., 2026). The current USGS DSAS version 6.1, released in 2026, provides a standalone framework for shoreline or boundary-change analysis and includes statistical measures such as linear regression rates and associated uncertainty.

Along the Indian coast, remote-sensing-based investigations have documented substantial spatial variability in shoreline response. Kumar et al. (2010) investigated shoreline changes and spit morphology along the southern Karnataka coast, while Maiti and Bhattacharya (2009) applied remote sensing to shoreline-environment monitoring along the Paradip coast. More recent studies have increasingly adopted DSAS and multi-temporal satellite imagery for quantitative shoreline assessment. Giri et al. (2024) investigated shoreline dynamics along the Subarnarekha and Budhabalanga estuaries using DSAS, demonstrating its application for quantifying erosion and accretion. Rafi et al. (2024) similarly used multiple DSAS-derived statistics to evaluate shoreline alteration along the Jagatsinghpur coast. Sajay and Mitra (2025) assessed shoreline changes along the Kozhikode coast using multi-temporal Landsat imagery from 2000–2024 and DSAS-based Net Shoreline Movement (NSM), End Point Rate (EPR) and Linear Regression Rate (LRR) statistics. Recent investigations of the Central Kerala coast have further incorporated shoreline change with coastal slope, wave height, tidal range and landform characteristics to assess coastal vulnerability, highlighting the importance of integrating shoreline dynamics with other coastal-hazard indicators.

The Kerala coast is particularly susceptible to spatially variable shoreline changes due to the interaction between natural coastal processes and increasing anthropogenic pressures. Pradeep et al. (2022), using remote sensing, GIS, field observations and machine-learning approaches, documented significant shoreline changes along a 58-km section of the Kerala coast between Pozhiyoor and Anchuthengu. More recently, Jena et al. investigated long-term shoreline dynamics along the South Kerala coast using satellite imagery from 2000 to 2024 and identified Panchmukhi as one of the locations experiencing significant erosion. These findings emphasize the need for detailed local-scale monitoring of the Sanghumukham sector. Recent research on coastal protection measures in Kerala has also demonstrated the applicability of remote sensing and DSAS for evaluating shoreline response to coastal engineering interventions.

The combined influence of waves, tides, currents, winds and sediment availability governs shoreline and beach changes. Erosion occurs when sediment removal exceeds sediment supply, whereas accretion occurs when deposition exceeds erosion. Obliquely approaching waves can generate longshore currents that redistribute sediment along the coast, resulting in alternating erosional and depositional sectors. Shoreline migration may therefore occur either landward or seaward, depending on the prevailing sediment budget and hydrodynamic conditions. However, short-term or seasonal shoreline fluctuations should not necessarily be interpreted as permanent long-term trends. Multi-temporal remote sensing and GIS provide an effective means of documenting such spatial and temporal variability.

The present study aims to establish a GIS-based framework to document multi-temporal changes in shoreline position and mapped beach extent along the Sanghumukham-Veli coastal stretch of Thiruvananthapuram, Kerala, using imagery from 2015 and 2025. A consistent transect-based approach is used to compare the visible land-water boundary between the two observation years. Beach width is examined along individual transects, while changes in mapped area between adjacent transects are quantified to identify sectors showing relative reduction or increase in beach extent. The study, therefore, treats the visible land-water boundary as a proxy for the shoreline and the inter-transect polygon area as the principal quantitative indicator. The resulting geospatial database provides a baseline for continued coastal monitoring while recognizing the limitations associated with imagery timing, tidal stage, positional accuracy and manual digitization.

2. Study Area

The study area is located along the southwest coast of India in Thiruvananthapuram district, Kerala. It comprises approximately 5.1 km of coastline extending between Sanghumukham in the south and Veli in the north. The geographical coordinates of the area are approximately $8°31'0''$–$8°28'0''$N latitude and $76°53'0''$–$76°55'0''$E longitude (Fig. 1). Sanghumukham Beach is situated adjacent to Thiruvananthapuram International Airport and is an important recreational and cultural location. Veli is located between the Arabian Sea and Veli Lake and is an important tourism destination. The location of the study area within a heavily utilized coastal sector makes it particularly well-suited to investigating shoreline variability and the interaction between natural coastal processes and human activities.

The study area has a tropical coastal climate. The southwest monsoon generally extends from June to September, followed by the post-monsoon period, while February to May represents the pre-monsoon period. Seasonal variations in rainfall, wind and wave conditions can influence beach morphology and sediment redistribution. Consequently, the timing and tidal stage of imagery are important when interpreting a visible land-water boundary. The retained Google Earth records identify the observations by year (2015 and 2025), but the exact image acquisition dates and contemporaneous tidal stages were not consistently available for independent verification. This limitation is considered when interpreting the mapped differences. The Thiruvananthapuram coast is characterized by sandy beaches, coastal plains, barrier beaches/spits, pocket beaches and locally developed cliffs and promontories. The orientation of the wave approach relative to the shoreline influences the direction and magnitude of sediment transport. The Veli sector also contains tidal-inlet and backwater-related geomorphic features. Therefore, both marine processes and local geomorphology influence the coastal setting. Recent studies of Kerala have similarly emphasized the influence of coastal orientation, wave conditions, tides, coastal slope, sea-level change and coastal structures on shoreline variability.

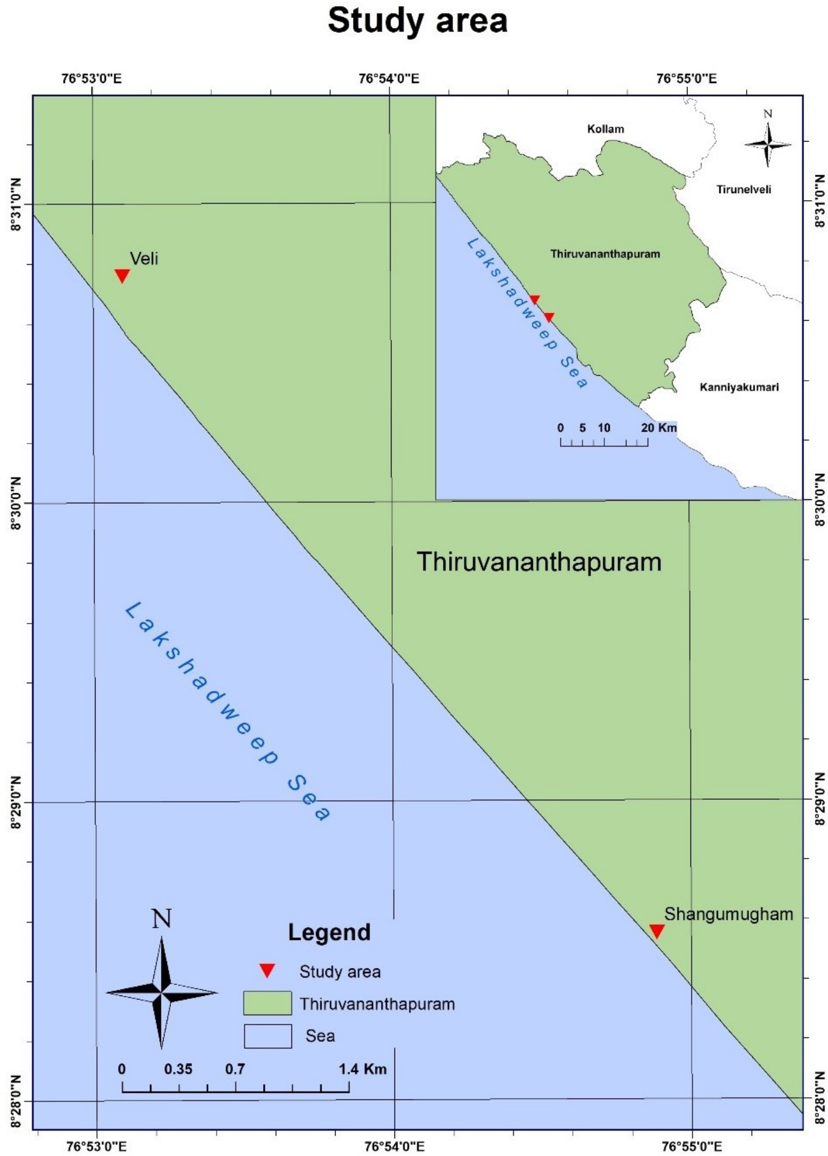

Fig. 1. Location of the study area.

3. Materials and Methods

3.1. Data and Materials

The present study was carried out to assess spatial variation in the shoreline proxy and mapped beach extent along the Sanghumukham-Veli coastal stretch using multi-temporal remote sensing and Geographic Information System (GIS) techniques. Google Earth imagery from 2015 and 2025 was used to delineate the visible land-water boundary and compare its spatial position between the two observation years. ASTER Global Digital Elevation Model (GDEM) data obtained from the United States Geological Survey (USGS) EarthExplorer were used as the elevation dataset for the study area. The Area of Interest (AOI) covering the selected coastal stretch was extracted and processed for further GIS analysis. The exact acquisition dates and tidal stages of the historical Google Earth scenes were not consistently available in the retained dataset and, therefore, could not be incorporated as tidal corrections.

3.2. Image Processing and GIS Analysis

The spatial datasets were processed using ArcGIS 10.2. The workflow included the extraction of the AOI, preparation of the geodatabase, definition of the coordinate reference system, re-projection where necessary, clipping and manual digitization of relevant spatial features. Shorelines for 2015 and 2025 were manually delineated from the corresponding Google Earth imagery using the identifiable visible land-water boundary as the shoreline proxy. This

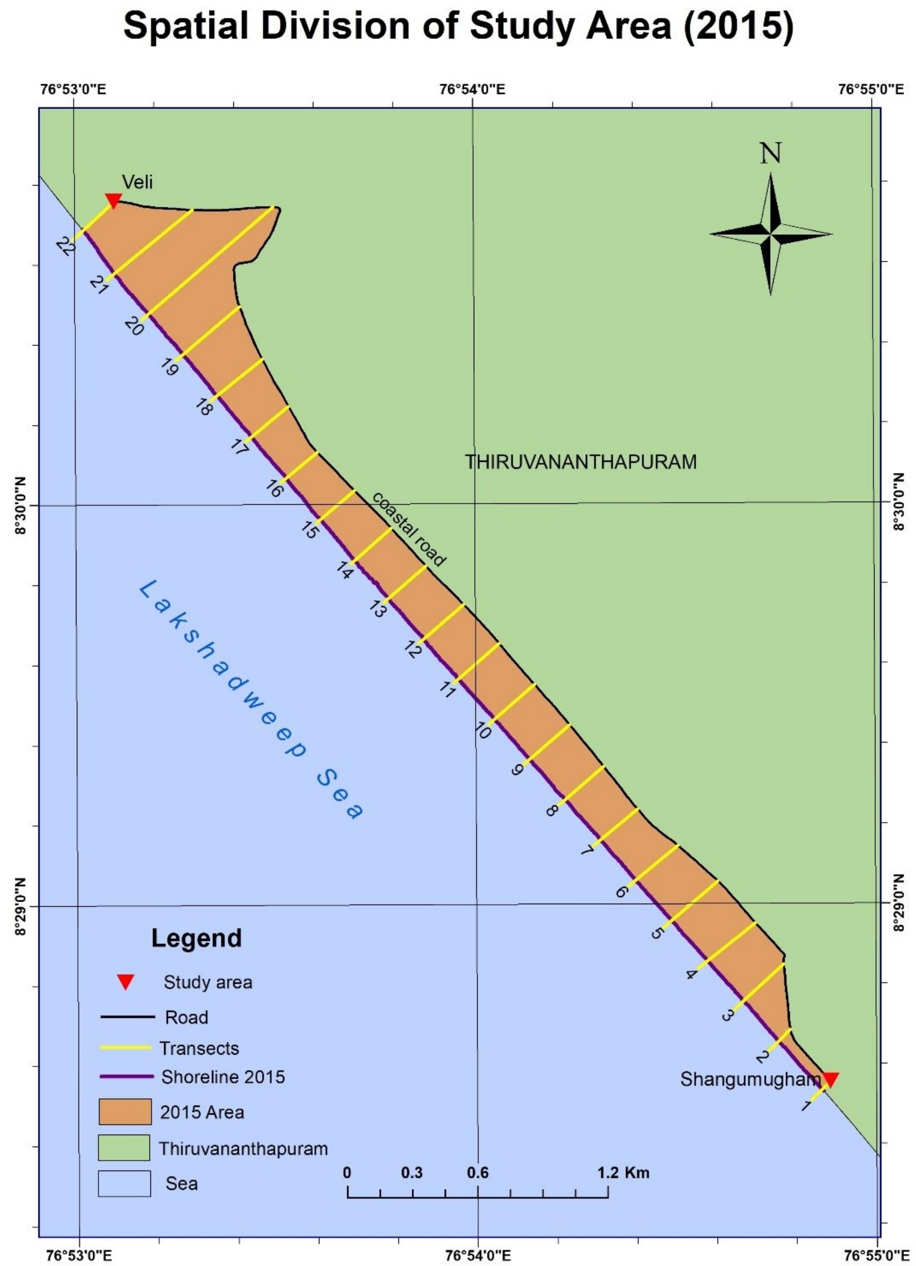

Fig. 2. Monitored spatial division of the area using transects, 2015.

proxy represents an instantaneous image-based waterline and is not a shoreline referenced to a specified tidal datum, such as mean high water. The digitized shorelines were incorporated into the GIS geodatabase and overlaid to identify spatial differences between the two observation years.

3.3. Transect-Based Shoreline Change Analysis

Shoreline-related change was evaluated using a fixed transect-based approach. Transects were constructed approximately perpendicular to the shoreline using the median of the coastal road as the common landward reference. Twenty-two transects (T1–T22) were established along the study stretch and extended from the road reference towards the tree line and subsequently to the shoreline (Figs. 2 and 3). The same transect positions were maintained for both 2015 and 2025 to ensure consistency in the comparison. The distinction between 22 transects and 21 inter-transect segments is important: the transects are the measurement lines, whereas each pair of adjacent transects defines one polygonal segment for area analysis.

The distance from the road reference to the tree line and from the road reference to the shoreline proxy was measured along each transect. Beach width was

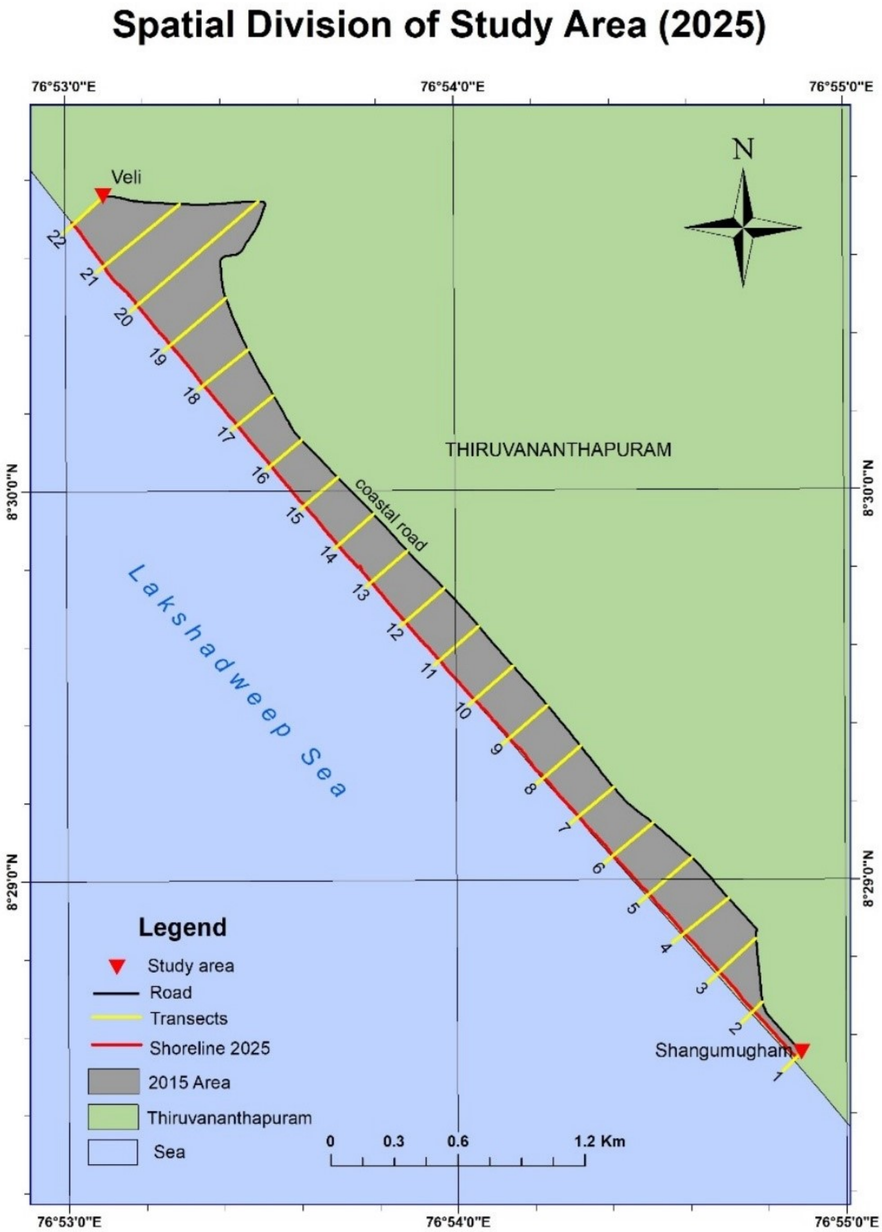

Fig. 3. Monitored spatial division of the area using transects, 2025.

estimated as the difference between these two distances:

$$BW = D_{TL} - D_{SL}$$

where BW represents beach width, DTL is the distance from the road reference to the tree line, and DSL is the distance from the road reference to the mapped shoreline proxy. The 2015 and 2025 measurements were compared to identify spatial variations in beach width and shoreline proxy position. Because the analysis did not maintain a formal uncertainty budget for each shoreline vertex, small differences should be interpreted with caution.

3.4. Inter-Transect Area Analysis

To assess spatial variation in the mapped beach area, the area between successive transects was calculated for both observation years. The study comprised 21 inter-transect segments (T1–T2 to T21–T22). The area of each segment was determined from the corresponding GIS polygons for 2015 and 2025. The change in area between the two years was calculated as:

$$\Delta A = A_{2025} - A_{2015}$$

Table 1. Changed beach area in hectares.

Transect segment	Area 2015 (ha)	Area 2025 (ha)	Change in area (ha) (2025–2015)	Interpretation
1→2	1.682088256	1.143063917	-0.539024339	Erosion
2→3	3.960878426	3.552308262	-0.408570164	Erosion
3→4	6.623196842	6.225254128	-0.397942714	Erosion
4→5	7.130689139	6.778352548	-0.35233659	Erosion
5→6	6.551344542	6.285883405	-0.265461137	Erosion
6→7	5.706653475	5.498916073	-0.207737402	Erosion
7→8	5.64812043	5.500335866	-0.147784564	Erosion
8→9	5.90956417	5.746701833	-0.162862337	Erosion
9→10	6.001148766	5.855593597	-0.145555169	Erosion
10→11	6.070495642	6.030814664	-0.039680978	Erosion
11→12	6.071722282	6.010368448	-0.061353834	Erosion
12→13	5.792315	5.751210078	-0.041104922	Erosion
13→14	5.329628152	5.270973615	-0.058654537	Erosion
14→15	5.242573173	5.237790536	-0.004782637	Erosion
15→16	4.861242366	4.892121735	0.030879369	Accretion
16→17	4.937511194	4.974619306	0.037108112	Accretion
17→18	5.975880842	6.007028157	0.031147315	Accretion
18→19	7.489074327	7.505243176	0.016168848	Accretion
19→20	14.30971284	14.27700004	-0.032712795	Erosion
20→21	13.10850173	13.10770233	-0.000799399	Erosion
21→22	8.181064667	8.169994787	-0.01106988	Erosion

where Δ A represents the change in mapped area, and A_{2015} and A_{2025} represent the corresponding areas for 2015 and 2025, respectively. Negative values indicate a reduction in mapped beach area, whereas positive values indicate an increase. These values are interpreted as changes in mapped beach extent rather than direct measurements of shoreline retreat or advance rates in m yr^{-1}.

The combination of multi-temporal shoreline digitization, fixed transect measurements and GIS-based inter-transect area analysis provided a consistent framework for assessing shoreline variability along the Sanghumukham-Veli coastal stretch during 2015–2025.

4. Results

4.1. Spatial and temporal variation in shoreline position

The multi-temporal shoreline-proxy maps for 2015 and 2025 show noticeable changes in the mapped land-water boundary configuration along the Sanghumukham-Veli coastal stretch. The comparison was carried out using the same 22-transect framework and the same 21 inter-transect polygonal units for both observation years. The quantitative analysis of the 21 inter-transect segments indicates that mapped beach-area changes were spatially heterogeneous during 2015–2025. Of the 21 segments analysed, 17 showed a reduction in mapped beach area, whereas 4 showed an increase. Thus, a reduction in mapped beach extent was the dominant spatial pattern, although localized increases occurred in the central portion of the coastal stretch.

The total mapped inter-transect beach area decreased from 136.58 ha in 2015 to 133.82 ha in 2025, representing a net reduction of approximately 2.76 ha, equivalent to about 2.02% of the 2015 mapped area over the 10 years. The mean area of an individual inter-transect segment decreased from 6.50 ha to 6.37 ha (Table 1).

The magnitude of change was not uniform along the coast. The largest reduction occurred in the 1→2 segment, where the mapped area decreased from 1.68 ha in 2015 to 1.14 ha in 2025, representing a loss of 0.54 ha. Other pronounced reductions occurred in segments 2→3 (0.409 ha), 3→4 (0.398 ha), 4→5 (0.352 ha), and 5→6 (0.265 ha) (Table 1). These segments are concentrated toward the Sanghumukham sector, indicating that this portion of the study area experienced the strongest reduction in mapped beach area during the observation period.

The magnitude of reduction progressively decreased through segments 6→7 to 14→15. The change in the 14→15 segment was relatively small, with a reduction of only 0.0048 ha. In contrast, positive changes were observed in four consecutive segments, 15→16, 16→17, 17→18 and 18→19. The largest positive change occurred in segment 16→17, with an increase of 0.0371 ha, followed by 17→18 (0.0311 ha), 15→16 (0.0309 ha) and 18→19 (0.0162 ha) (Table 1). This localized increase indicates

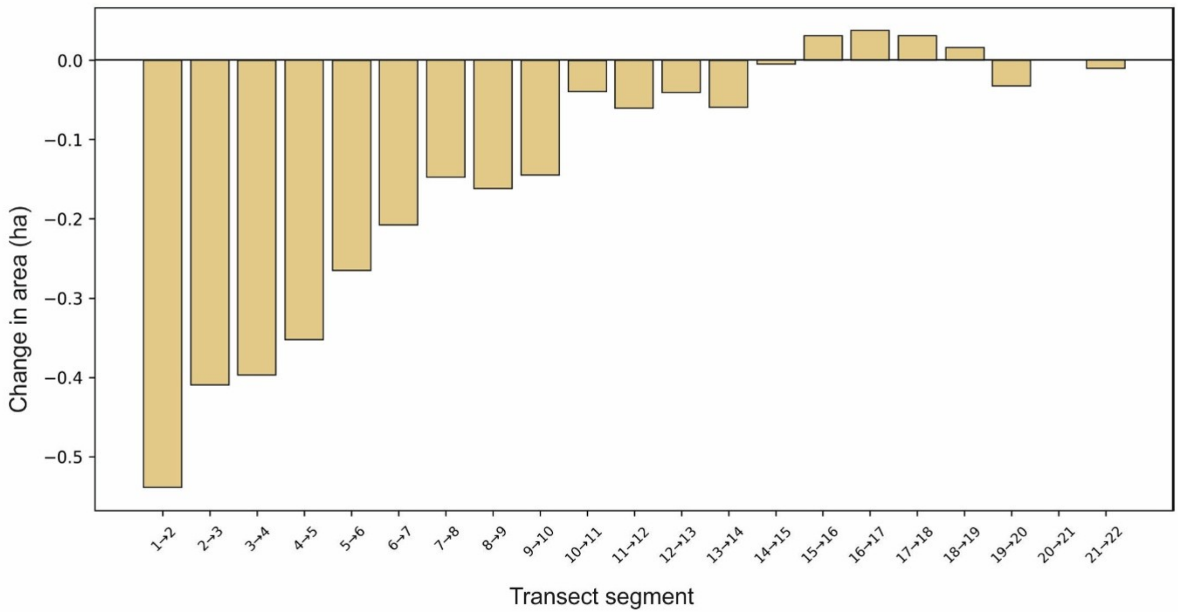

Fig. 4. Spatial variation in inter-transect beach area change along the Sanghumukham-Veli coastal stretch during 2015–2025..

an accretion-dominated sector within the middle-to-northern part of the study area.

Beyond this zone, the trend became negative again. The 19→20, 20→21 and 21→22 segments recorded reductions of 0.0327, 0.0008 and 0.0111 ha, respectively. Thus, the spatial pattern is characterized by relatively strong erosion toward the Sanghumukham sector, a localized zone of accretion in the central portion, followed by minor erosion toward the Veli sector.

4.2. Quantitative assessment of erosion and accretion

The total reduction in mapped area during 2015–2025 was approximately 2.76 ha, corresponding to an annualized mapped-area change of approximately 0.276 ha yr^{-1} over the ten-year interval. This value is an area-change metric and must not be interpreted as a shoreline-retreat rate in m yr^{-1}. Conventional shoreline-change rates such as Net Shoreline Movement (NSM), End Point Rate (EPR) and Linear Regression Rate (LRR) were not calculated because the retained results do not contain the complete point-to-point shoreline-position dataset required for a statistically consistent DSAS-style analysis. The magnitude of very small segment-level changes should therefore be interpreted with caution in light of image and digitization uncertainty.

The largest erosional change was concentrated in the southern portion of the study area. The first six inter-transect segments alone accounted for approximately 2.17 ha of area loss, indicating that a substantial proportion of the total observed reduction occurred in this sector (Fig. 4). Conversely, the four accretionary segments collectively gained approximately 0.115 ha, which compensated only partly for the erosion observed elsewhere (Table 1).

The results therefore demonstrate that the study coast cannot be considered uniformly erosional. Rather, it consists of alternating sectors of erosion and localized accretion, with the overall balance during 2015–2025 being negative.

5. Discussion

5.1. Spatial variability of shoreline change

The results demonstrate pronounced spatial heterogeneity in the mapped beach response along the Sanghumukham-Veli coastal stretch. Although the overall balance indicates a reduction in mapped beach area, the occurrence of both erosional and accretional sectors indicates that the observed pattern may involve alongshore redistribution of sediment as well as local changes in beach extent. The strongest reduction occurs toward the Sanghumukham end of the study area, while a localized increase occurs farther north. These are observations from the mapped dataset; they do not, by themselves, establish the underlying hydrodynamic mechanism.

The alongshore contrast is consistent with the behaviour expected in dynamic sandy coastal systems, where waves and currents can redistribute sediment between adjacent sectors. However, because wave, current, sediment-budget and tidal observations were not collected as part of the present analysis, the causes of the observed spatial pattern cannot be demonstrated directly from the dataset.

The spatially variable behaviour is also consistent with previous descriptions of coastal response being influenced by wave climate, coastal orientation, sediment availability, monsoon variability and anthropogenic interventions (Alexandrakis and Poulos, 2014). These factors are therefore considered plausible contributors rather than demonstrated causes in the present study.

5.2. Erosion-dominated southern sector (Sanghumukham)

The concentration of the largest mapped-area losses in segments 1→2 to 6→7 identifies the Sanghumukham sector as the portion with the greatest reduction in mapped beach extent during 2015–2025. Independent regional research has also identified Sanghumukham as an erosion-prone sector of the South Kerala coast. The agreement between the present local-scale mapping and broader regional observations supports the interpretation that this sector warrants continued monitoring. Nevertheless, the present dataset cannot establish a single causal mechanism. Wave approach, longshore sediment transport, seasonal sediment redistribution, coastal structures and other human interventions remain possible contributors that require independent observations for verification.

The agreement with regional studies should therefore be interpreted as spatial consistency rather than proof of causation. In particular, the present analysis is based on two observation years and an image-derived shoreline proxy, so seasonal variability and differences in tidal stage may contribute to the mapped change.

5.3. Localized accretionary sector

The positive changes recorded between segments 15→16 and 18→19 indicate a localized accretionary sector. The relatively small magnitude of these increases, compared with the losses in the southern segments, suggests that accretion is insufficient to offset the overall reduction in mapped beach area. Localized increases within an otherwise reduction-dominated coast may reflect redistribution of sediment alongshore, but this remains a hypothesis in the absence of sediment-transport measurements. Similar alternating patterns of erosion and accretion have been documented along the Kerala coast. The relatively small magnitude of the four positive changes, compared with the losses in the southern segments, indicates that the mapped gains compensate only partially for the overall reduction in mapped beach area.

5.4. Comparison with recent Kerala studies

The overall reduction in mapped beach extent observed in this study is consistent with recent regional assessments of the Kerala coast. Pradeep et al. (2022) reported that a large proportion of the 58-km coastal stretch between Pozhiyoor and Anchuthengu experienced erosion during 2006–2020. More recently, Shanmuga Priyaa et al. (2025) identified significant erosion at Shanghumugam and neighbouring beaches using long-term satellite observations. Studies farther north along the Kerala coast have likewise documented substantial erosion and localized accretion using multi-temporal satellite data and GIS/DSAS techniques. These comparisons provide regional context, but differences in datasets, shoreline proxies, observation periods and analytical methods mean that numerical rates from those studies should not be directly compared with the mapped-area changes reported here.

More recently, Sundar et al. (2024) analysed shoreline dynamics along the South Kerala coast over a long time period and identified significant erosion at Sanghumukham and neighbouring beaches. Studies farther north along the Kerala coast have similarly documented substantial erosion and localized accretion using multi-temporal satellite data and GIS/DSAS techniques. Thus, the present study contributes a more localized assessment of the Sanghumukham-Veli sector, demonstrating that regional erosional trends are expressed through considerable spatial variability at the local scale.

6. Conclusion

- The comparison of 2015 and 2025 Google Earth imagery indicates a predominantly reduction-dominated pattern in mapped beach extent along the Sanghumukham-Veli coastal stretch. Total mapped inter-transect beach area decreased from 136.58 ha to 133.82 ha, representing a net reduction of 2.76 ha (2.02%).

- Of the 21 inter-transect segments defined by the 22 fixed transects, 17 showed a reduction in mapped beach area, and four showed localized increases. The largest reductions occurred toward the Sanghumukham sector, whereas a localized increase occurred in the central portion of the study area.
- The spatially variable pattern demonstrates that the study coast is not uniformly erosional or accretional. The mapped changes are consistent with a heterogeneous coastal response, but the present dataset does not permit the observed patterns to be attributed conclusively to individual hydrodynamic or anthropogenic drivers.
- The GIS database provides a useful baseline for repeated local-scale monitoring. Because the principal metric is mapped inter-transect area rather than shoreline displacement rate, future work should incorporate additional observation dates, documented tidal conditions, quantified positional and digitization uncertainties, field observations, and complete shoreline-position datasets for NSM, EPR, and LRR analysis.

Credit statement

Indu G: Writing - Original draft, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization, Reviewing, and editing.

Declaration of competing interests

The author declares that she has no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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AI-decaration

No AI was used in generating any part of this manuscript.

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