LONG TERM SHORELINE EVOLUTION OF SOUTHWESTERN COAST OF INDIA – ALAPPUZHA, KOLLAM AND THIRUVANANTHAPURAM

Dissertation report submitted for the partial fulfilment of the award of Master of Science Degree in Applied Geography and Geo-informatics

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DISSERTATION REPORT

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This is to certify that **Mr. Bevelio Philip Goes** student of M.Sc. 4th semester, Applied Geography and Geoinformatics, Central University of Karnataka has done through the dissertation work entitled **"LONG TERM SHORELINE EVOLUTION OF SOUTHWESTERN COAST OF INDIA – ALLAPPUZHA, KOLLAM AND THIRUVANANTHAPURAM** at National Centre for Earth Science Studies, Aakkulam, Kerala, in partial fulfilment of requirements for the award of degree in Master of Science in Applied Geography and Geoinformatics during the year 2022. This also declared that this project work has not been submitted to any other university for award of any degree or diploma.

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Abstract

The Southwest coast of India from Shertallai to Neyyattinkara is a region of high energy conditions thus being a very dynamic coastline. It has been observed that this sensitive region has experienced high urban growth, morphological alterations by anthropogenic events and an increasingly erratic climate. Effects of these phenomena direly affect the shoreline and result in receding coasts in several regions. To assess these effects, a shoreline analysis for the three southern districts of Kerala; Alappuzha, Kollam and Thiruvananthapuram are conducted in the given study. The shorelines are generated using the sophisticated python toolkit CoastSat and the rate of shoreline change is calculated using the DSAS extension tool within ArcGIS. Dataset for shoreline generation includes the Landsat Series (5, 7, 8) and Sentinel 2. To limit the effect of errors the positional uncertainty of shorelines is calculated and used as a parameter to obtain the Weighted Linear Regression (WLR). The results obtained are visualised for the entire coastal stretch as seven classes and the geographical correlation is conducted between the WLR and the hard structures that are dispersed along the coast. It is observed that due to the net northward longshore sediment transport, the region below groynes and ports are accreting and those in the north are erosion. Due to high wave activity and anthropogenic events geologically sensitive cliffs like Varkala are vulnerable. A total of 44% of the coastal stretch is under moderate to very high erosion and 31% and 25% of the total coast is stable and accreting. The disparity in accretion and erosion stretches created by the hard structures, mining and associated climatic factors are hampering the coastal equilibrium in southwest India.

CHAPTER 01
Introduction

1.1 Preface

A coast is defined as a transitional zone from land to sea with the shoreline demarcating the interface between these entities (ChenthamilSelvan, et al., 2014). It can be the vegetation line or berm crest or High Tide Line (HTL) or the landward limit in presence of hard structures like a seawall. Such a unique zone is characterised by unique climatological, morphological and ecological processes. The dynamic nature of the coastal zone is attributed to the interaction of the land features with the associated oceanographic phenomena like waves, tides, currents and storms. To safeguard the oncoming oceanic assails, the inland is generally shielded by natural barriers like sandunes, mangroves, barrier reefs and cliffs depending on the beach morphology.

The sediment transport regime along the coast is a result of coastal processes, which result in the formation of erosion and accretion zones. The coastal processes include developments like longshore current, river transport, and offshore transport. Naturally, the coast is sustained by a balanced equilibrium between sediment supply and sediment export from the system. The coastal front is characterised by headlands and bays and the inland plains are often dissected by waterbodies like rivers, creeks, estuaries and lagoons. These intertwined coastal features contribute to the coastal sediment supply through the process of deposition. When the sediment supply is reduced, the coastal erosion becomes predominant and the accretion reduces. Hence, a deficiency in this sediment supply and an increase in sediment export leads to erosion of the coastline. This drift results in a general receding coast which is a bane thus, creating a region of high vulnerability. The rate of coastal erosion is influenced by the degree of exposure to waves, tidal conditions, the intensity and frequency of storms, the bottom characteristics of the shore, and the anthropogenic activities within the region.

The coastal regions are great avenues of opportunities that have led to high population densities and huge economic activities. These zones have a unique ecosystem providing a plethora of opportunities to various walks of life. The coast constitutes only 1/10th of the total landmass but sustains more than 50% of the world's population (Yadav, et al., 2017). Such large-scale human intervention and exploitation can disturb the sensitive coastal equilibrium, thereby making it a vulnerable area. The degradation of this area is manifested by the erosive action of the shoreline. With the nascent stages of increasing anthropogenic interference like economic activities like mineral and sand mining, dredging, construction of hard structures for harbours and ports and unscientifically built hard structures for shoreline protection, an increase in the coastal erosional rates of some regions has been observed. In addition to these anthropogenic events is the effect of climate change-induced weather phenomena on the coast. The topical trend of storm intensification and wave action has significantly contributed to coastal degradation.

1.2 Literature Review

One of the major concerns among the current generation is the issue of climate change. The rise in the average temperature of the earth has led to initial signs of catastrophe; the major one being the melting of glaciers and ice caps which in turn causes sea-level rise. The first landmasses to bear the wrath of this phenomenon are the coasts. The rising sea levels along with the intensification of oceanic processes are increasing the vulnerability of the coastlines. The forefront coastal feature of the sea are the shorelines which are subject to coastal processes like tides, waves, longshore currents and winds. Hence it is essential to understand the shoreline dynamics involving an analysis of shoreline change. Such studies can provide an insight into the status of the liability of the coast.

1.2.1 Previous Studies

To assess the vulnerability of the coastal regions many shoreline analyses were conducted for various regions across the globe using a wide array of methods. Those methods and their respective outcomes are discussed in the following. For example, in 1994 in the region of Punta Uvero in Puerto Rico, a historical shoreline change rate was analysed using the DSMS/DSAS application by Thielert & Danfortht. This study was conducted to assess the accuracy of the DSMS tool in shoreline extraction. The Shoreline change rate using End Point Rate (EPR) for the stretch ranged from 0.58 m/y to -3.52 m/y. Similarly, a previous study was conducted for a 65 km section of the North Carolina Outer Banks (Dolan, et al., 1991). In this study three types of rates were calculated namely; EPR, Linear Regression Rate (LRR) and Jackknifing (JK). The EPR produced a result of 0.15 m/y whereas LRR and JK produced the rate of 0.01 m/y for the time-frame of 1940 to 1986. Using the open-source satellite images and the CoastSat Tool, shorelines from 1984 to 2019 were generated for the meso-macro tidal Truc Vert beach of southwest France. In this study, various sectors were analysed with results of −4.63 m/y at Cape Négade, +3.34 m/y at Cap Ferret and −8.38 m/y at La Salie (Castelle, et al., 2021).

In the Indian context, there have been several studies on coastline change in various sectors. Although for a 6100 km coastline, the studies conducted have great regional disparity and focused on certain regions. A shoreline study by Sreenivasulu, et al., in 2017 for the Tupilipalem Coast of Andhra Pradesh was conducted. The quantification was based on the areal distribution of Erosion and Accretion zones. The total net erosion was quantified at 0.316 Km^2 and 0.571 Km^2. Another similar study for the Karnataka coast was conducted by ChenthamilSelvan, et al., 2014 using Remote Sensing and GIS techniques. The shorelines were analysed from 1973 to 2006 using the DSAS tool by calculating the EPR and Weighted Linear Regression Rate (WLR). The entire coast was analysed for the coastal districts; Uttar Kannada, Udupi and Dakshina Kannada. Through this analysis, it was deduced that 30% of the coastline was erosive and observed in isolated pockets. In the Mangalore region, a shoreline study involved the coast from New Mangalore Port to Talapadi from north to south for three time-frame between 1967-2005. These beaches showed an initial accreting trend from 1967 to 2001 but displayed severe erosion from 2001 to 2005 (Kumar et. al, 2009).

Several studies were conducted along the Kerala coast. In 2021 an assessment of the shoreline change was conducted for the coast of the Kasargod district of Kerala. The shorelines were considered from 1968 to 2018 using EPR and LRR. Through this study, the effects of hard stabilisation were observed in which a seawall construction is resulting in an accretionary trend. Two river mouths were considered, with the Shiriya river mouth experiencing an erosion of 96% whereas the Thrikaripur river mouth experienced accretion of 61% (Vrinda et al., 2021). The Chavara coast within the Kollam district is a hotspot for coastal erosion due to persistent beach mining and unscientific hard stabilisation. Two types of studies for this region were conducted by the Coastal Processes Group of ESSO-National Centre for Earth Science Studies, Thiruvananthapuram. In 2016 a volumetric analysis to calculate the sediment flux using the CERC and Kamphuis formulae and the LITDRIFT module of LITPACK. The results showed that erosion occurs from October to January with a cumulative negative beach change thus making it dynamically unstable. In 2020, a shoreline evolution along this coast is deduced using the same numerical model; LITLINE module of LITPACK, A negative shoreline trend along with the mining sites of Vellanathuruthu, Ponmana and Kovilthottam are observed. The annual surf zone for northern longshore transport is calculated at 78,961 m3/y during the fair season and 15,560 m3/y for southern transport from June to July. A comprehensive long term shoreline evolution is conducted for the entire Kerala coast by Nair, et al., in 2018. Using the DSAS tool the LRR and EPR rates for the entire coast were calculated for shorelines from 1968 to 2014. The erosion accretion values were 59.5% and 28.6% respectively. Considering the net shoreline movement, the maximum percentage of total erosion lies within the 25m to 50m at 21.6%. In this study, maximum erosional rates were observed at Ponmana at -7.3 m/y using LRR statistics. Using the LRR, maximum accretion was observed at Kochi at the rate of 42 m/y. based on the study it was concluded that 50% of the beach was dynamically stable with seasonal erosion and accretion.

1.3 The Coastal State of Kerala

The Peninsula India is home to 9 states and 3 union territories within the maritime region. The western coast of India is characterised by steep slopes, promontories and submerged estuaries (Ahmad, 1972). The coast of Kerala is no different, comprising of a 590 kms of coastal stretch facing the Arabian Sea. From the 13 districts of Kerala a total of 9 districts are coastal namely- Kasaragod, Kannur, Kozhikode, Malappuram, Thrissur, Ernakulam, Alappuzha, Kollam and Thiruvananthapuram- in the order from north to south as shown in Figure 1. Located on the south-western coast of the Indian peninsula, Kerala is known for its scenic beauty and vast economic resources. The urbanised coast of Kerala possesses a high population density of 2363 persons/Km^2 (SAC, 2012). This is approximately 2.5 times the total population density of Kerala, thus emphasising the enormous stress on the coastal region.

This coast is a highly dissected region with 41 rivers exiting through specific inlets of the 48 that flow towards the sea. Among these inlets 20 are perennial and the remaining are seasonal (Nair, et al., 2018). Due to the swift flow and shorter course originating from the Western Ghats, these rivers are devoid of the deltaic mouth that most rivers in India possess. Unlike other coastal states, the coastal regions of Kerala are unique with backwater complexes. These are the dominant coastal waterbodies within the Kerala districts. The backwaters/lagoons are separated from the Arabian Sea by onshore sand bars and spit formation. This fairly straight coastline is also interjected by promontories that are composed of laterite or Precambrian crystalline rocks like Charnockites and Khondalites. The coast of Kerala possesses both erosional (Headlands and Cliffs) and depositional features (Bay Barriers, Barrier beaches and Spits) along the coast. The coast is tectonically stable with the coastal terrain being a result of tertiary denudation (Nair, et al., 2018). According to a study by MoEF, approximately 53% of the entire Kerala coastline is classified as artificial i.e., it is laid with hard structures and the remaining coast is eroding, accreting and stable at 10%, 29% and 8% respectively (Pavithran, et al., 2014).

The tropical region of Kerala is among the wettest states in India. The state is subjected to moderate-heavy rainfall during the months of June to September whose source is the south-west monsoon winds. This is majorly attributed to the massive orogenic belts of the Western Ghats and the Southern Granulite terrain that act as a blockade against the eastward movement of the south-west monsoonal winds. The state of Kerala was less prone to extreme weather phenomena until recent years with 8 cyclones affecting the region of Kerala in the span of five years. The name of the cyclones are Ockhi, Gaja, Vayu, Kyarr, Maha, Nisarga, Burevi, and Tauktae in chronological order of their occurrence. Current events of storm intensification are attributed to the broader spectrum of Global warming. This is creating the vulnerable coast of Kerala as a hotspot for disasters like cyclonic storms and their associated catastrophes like storm surges, torrential rainfall and flooding. Although the entire Kerala coast comes under microtidal classification, the coastal hydrodynamics is mainly influenced by wind activity, hence being a wave-dominated region with the high energy conditions observed increasing southwards. This southwards intensification of waves is attributed to the general increasing shelf gradient from north to south (Nair, et al., 2015).

The shoreline of the Kerala coast is subject to erosion due to the heavy rainfall, the recent events of increased storm frequencies, wave intensification, sea level rises, anthropogenic interference that drastically reduces the sediment supply and areas of mud deposits and the characteristic loose sandy beaches (Paul, et al., 2013).

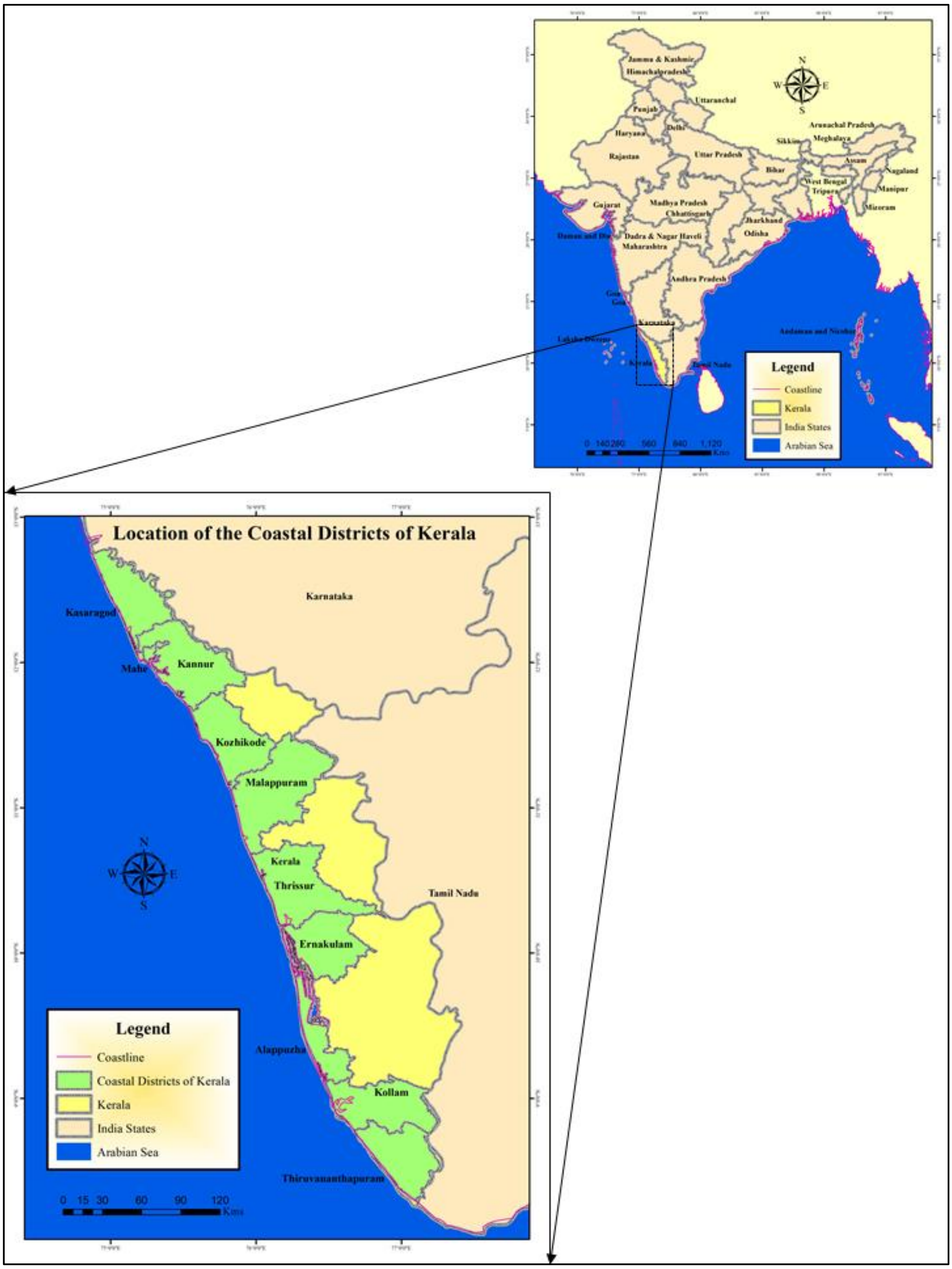

Figure 1: Location of the Coastal Districts of Kerala.

1.4 Study Area

The southernmost districts of Kerala include; *Thiruvananthapuram, Kollam and Alappuzha* from south to north. With the wave activity increasing southwards, the shores of Thiruvananthapuram, Kollam and Alappuzha are classified as High, Medium and Low energy regions respectively. The southern coast is renowned for its mineral-rich sandy beaches and prominent lagoons making this region an industrial as well as a touristic hotspot. The northern district; Alappuzha is renowned for its mudbank formations which remain an enigma for scientific research due to the lack of a well-established genesis. This district also houses a 17 km mining stretch from Valiyazhikkal to Thottappilly in its southern region. The central district; Kollam is a hotspot for mining activity located within the Chavara stretch of 22 kms. The coastal stretches of this district are also dispersed with numerous hard stabilisations. The southernmost district; Thiruvananthapuram which also hubs the capital of the Kerala state is a touristic hotspot with stretches of sandy beaches and a major seaport under construction. This region is characterised by numerous cliff formations of different rock types with the incompetent cliffs eroding at a higher rate. Such a morphologically diverse coastline within a stretch of 200 Kms makes it an ideal region for studying the shoreline dynamics.

The Kerala Districts lie within 77.267˚E, 9.892˚N and 77.267˚E, 8.293˚N coordinates with Alappuzha, Kollam and Thiruvananthapuram having coastal stretches of 82 kms, 47 kms and 71 kms respectively. The total geographical area of this region is approximately 5743.82 Km^2. The location at the tip of the Indian Peninsula makes it among the first regions to be susceptible to the effects of turbulences within the Indian ocean. Apart from the proximity to oceanic instabilities, the coast is also exposed to a higher degree of wave action due to the steeper shelf gradient than that of the northern coasts.

The sandy beaches are known for the mineralisation of the radioactive monazites, and high concentrations of Ilmenite, Sillimanite, Rutile and Zircon which are ores of Titanium, Aluminium and Zirconium. Some beaches of this coast are also famous for the enigmatic formation of mudbanks with recent observations of dwindling occurrences. Both Lateritic and rocky cliffs are dispersed along the coast. The lateritic rocks cap the incompetent bed that is vulnerable against the coastal charges. These cliffs undergo high erosion causing a high risk of slippage and cliff recession (Sajinkumar, et al., 2016). The entire coast of the study area is dispersed with hard stabilisations that were constructed either for shoreline protection or the construction of harbours. These factors highlight the need for a detailed coastline study of the southwestern coast of India.

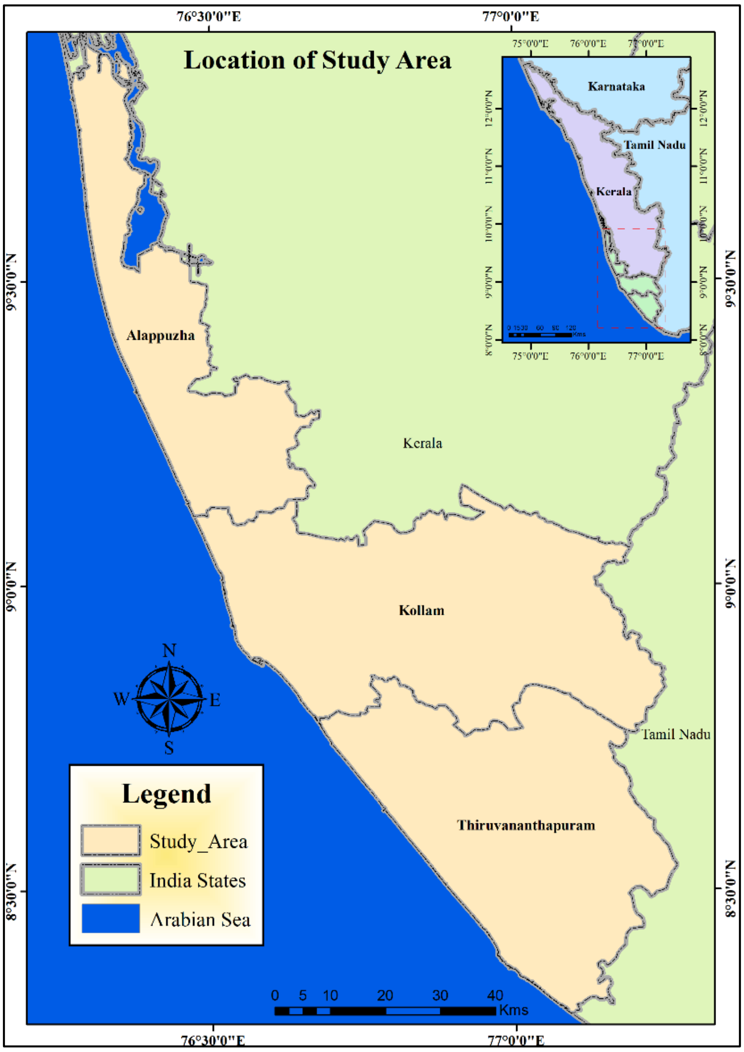

Figure 2: Location of Study Area.

1.5 Geomorphology of the Study Area

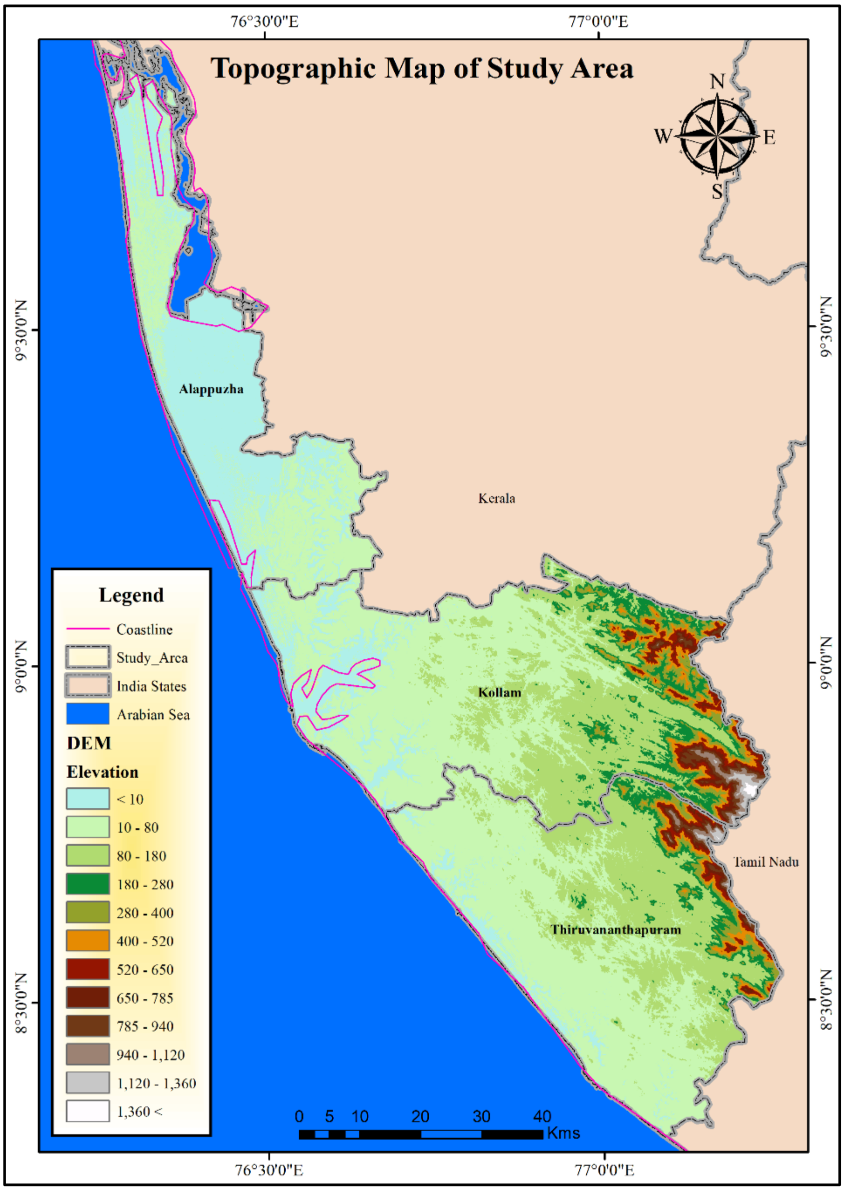

Figure 3: Topographic Map of the Study Area. (Data Courtesy: NASADEM)

The coastal front is characterised by headlands and bays and the inland plains are often dissected by waterbodies like rivers, creeks, estuaries and lagoons. These intertwined coastal features contribute to the coastal sediment budget through processes of erosion and deposition. The dominant waterbody within the Kerala districts is the famous backwaters/lagoons. Also, a unique formation observed is the mudbanks along the coast of Alappuzha forming a region of suspended sediments. Another unique and notable formation are the Placer deposits in the

Alappuzha and Kollam districts. A major headland is observed in the central region of the study area within the Kollam region.

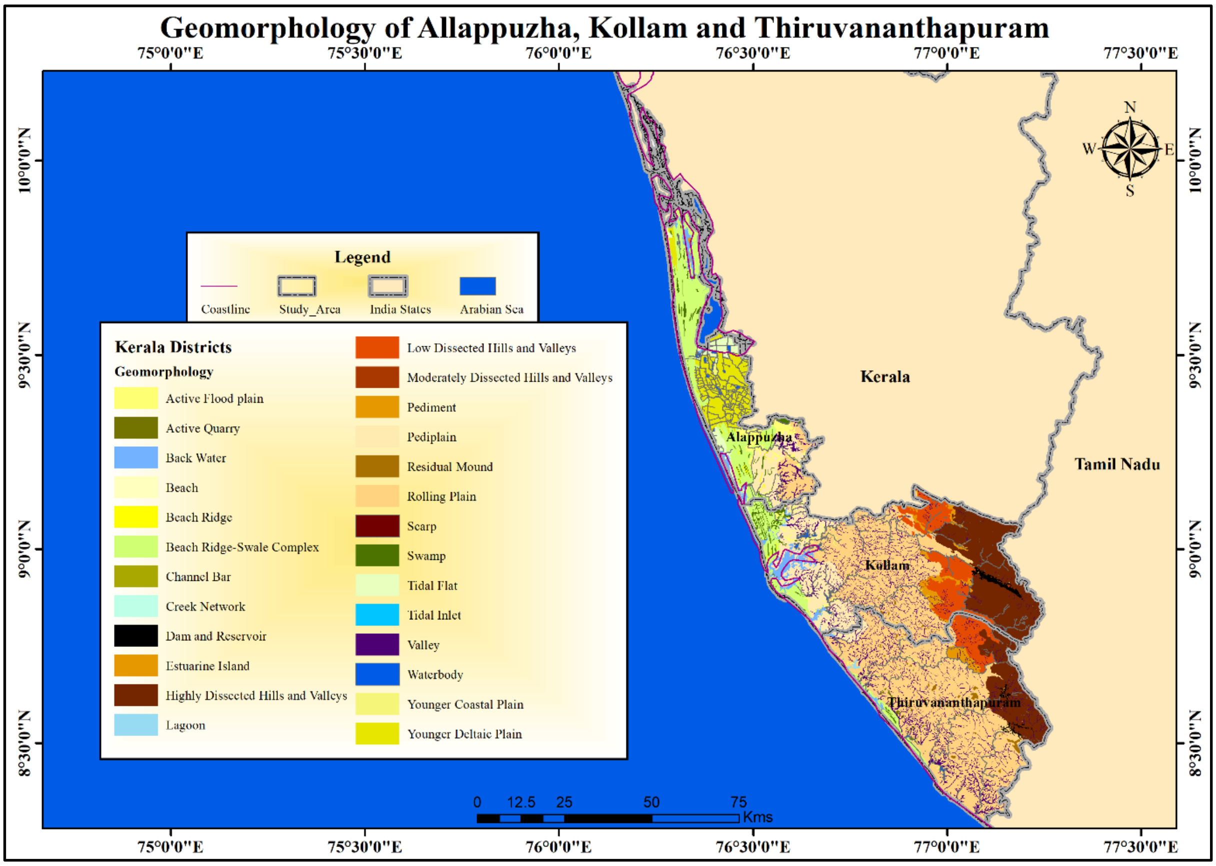

Figure 4: Geomorphological Map of the Study Area. (Data Courtesy: Bhukosh-GSI)

The north of Alappuzha depicts a spit formation and is the largest spit on the west coast of India (Nair, et al., 2018). The Alappuzha district having a very limited width tapering northwards is comprised mainly of coastal features like beaches, plains, swamps, swales, tidal flats, ridges and backwaters. The south-eastern extent is predominant of rolling plains and pediplains. The southern districts of Kollam and Thiruvananthapuram have similar geomorphic features owing to their wider geographical extent. The eastern fringes are dominated by the scarps, dissected hills and valleys of the southern granulite terrain. Check dams are also observed within this region. The central region is entirely a rolling plain with the coastal area being a swale and backwater complex along with sandy beaches.

1.6 Geology of the Study Area

Being a coastal region, the entire Alappuzha district is complex of sand and clay. A portion in the south-eastern area is sandstone, gneisses, schists and the acid to intermediate charnokites of the southern granulite terrain (SGT). As observed in the below map, the region of Kollam and Thiruvananthapuram possess charnokites, gneisses, schists, granulites, and lateritic formations on the eastern peripheries. The coastal edges are complexes similar to the northern Alappuzha with dispersed lateritic, gneissic and charnokites formations. The southern Kollam and the northern and southern limits of Thiruvananthapuram are outcropped by sandstone belonging to the Warkalli beds of the Ambalapuzha formation. These beds are characteristic of 2 ichnofossils; Skolithos linearis and Planolites beverleyensis and are a geologically important formation which capped in certain regions by laterite.

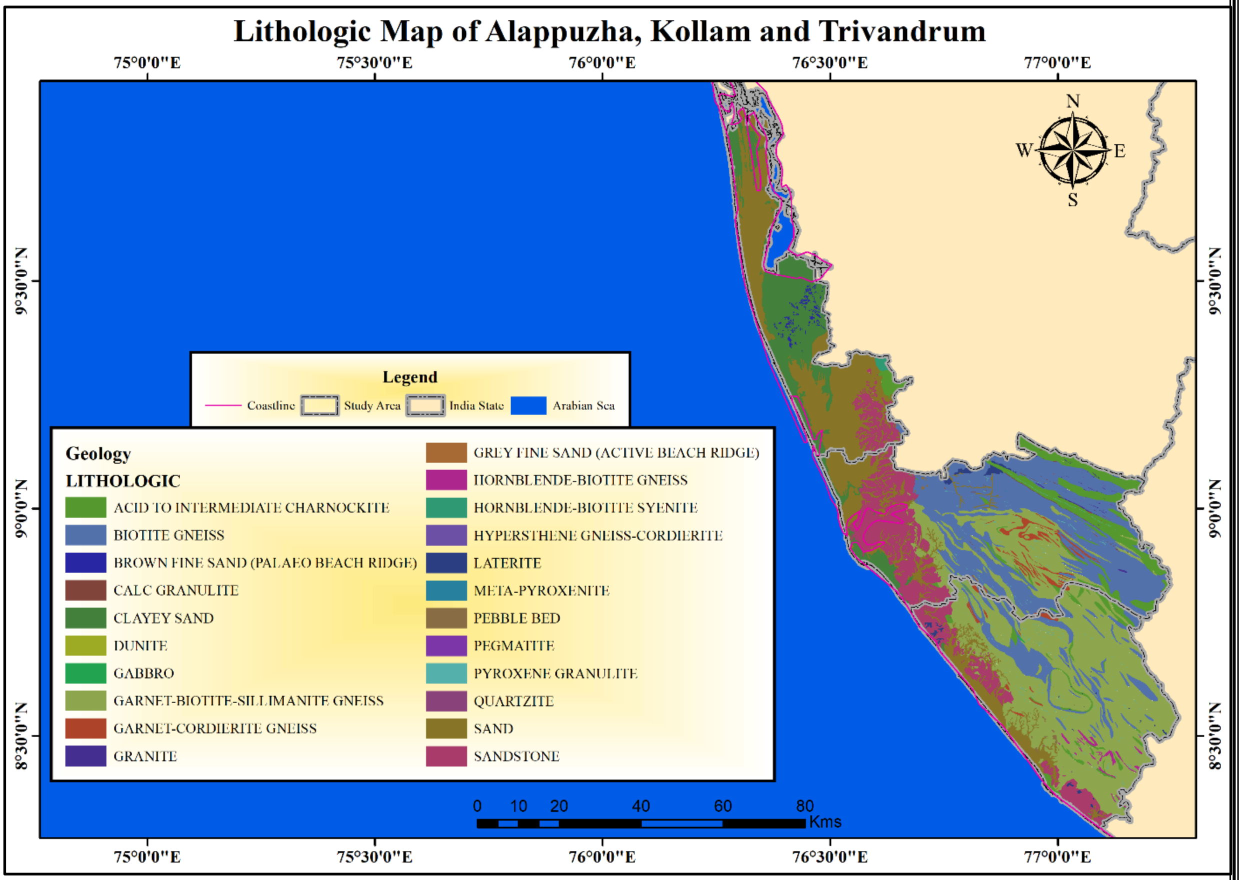

Figure 5: Geological Map of the Study Area. (Data Courtesy: Bhukosh-GSI)

1.7 Aims and Objectives

1.7.1 Aim

To evaluate the Long-term shoreline changes along the high energy part of the south-west coast of India.

1.7.2 Objectives

- Collection of time-series shorelines from 1988 to 2022 during the fair season
- Generating shorelines change rates for the southern part of south-west coast of India
- Correlating the anthropogenic events with the shoreline evolution
- Detection of shoreline change hotspots and comparing the results with previous studies
- To appraise the overall trend of shoreline change along the coast of the study area

Chapter 2
Methodology

The shoreline analysis involves a complex range of tools and analysis for the following:

- Extraction of shorelines
- Shoreline uncertainty calculation
- Shoreline change rate analysis
- Hotspot correlation with previous studies

2.1 Extraction of Shorelines

There are various modes of shoreline generation that include; manual digitizing of toposheets or satellite imagery, Sobel or other filtering techniques for edge detection, Otsu's thresholding technique using NDWI and image classification of satellite images. The manual digitizing method although with high accuracy is a time-consuming process whereas the other Photogrammetry and GIS techniques can speed up the process but have lower accuracy values. To tackle this dilemma a middle ground can be agreed upon where the extraction process is rapid and the RMSE values of the accuracy are better. The CoastSat tool is the best option for long-term shoreline generation which uses a combination of image classification and Otsu's thresholding technique.

The CoastSat tool is an open-source Python toolkit that enables extraction and analysis of the shoreline from the Landsat and Sentinel datasets via the Google Earth Engine (GEE) repository. It is developed by Kilian Vos, a research scholar from the University of New South Wales, Sydney. This toolkit broadly handles 4 functions namely;

1. *Retrieval of Satellite Images:* Through the GEE archive the time series Landsat Collections (5, 7 & 8) and Sentinel-2 datasets can be obtained for visualisation analysis and classification. The Optical (RGB), Near Infrared (NIR) and Thermal (SWIR1) bands are acquired as inputs for the analysis. Using the GEE processing the satellite

images can be clipped for the desired study area/region of interest as a polygon and rendered within the toolkit as .tif files.

2. *Digital Image Processing:*

    a) Image sharpening: The retrieved images are processed with pansharpening and cloudmasking for increasing the accuracy and spatial resolution.

    b) Image Classification: Using the Multilayer Perceptron in scikit-learn which is a form of neural network classification, the TIFF files undergo unsupervised image classification thus dividing into four classes; Water, White-Water, Sand and other land features. Using this the sand-water divide i.e., the wet-dry partition along the coast is delineated. This is considered as the limits of shoreline.

    c) Modified Normalized Difference Water Index (MNDWI): The MNDWI of the area is calculated using the below formula:

$$\text{MNDWI} = \frac{SWIR1 - Green}{SWIR1 + Green}$$

    This index ranges between -1 to 1 and is used for Sub-pixel resolution border segmentation.

3. *Extraction of the Shoreline:* The shoreline can be extracted either by creating a reference line manually or by using the default algorithm in CoastSat. By default, the classified image along with the MNDWI image, the shoreline is deduced. The border of the sand and water class and the subsequent Otsu's Threshold in the index demarcates the high tide line (Sand-Water interface) thus being considered as the shoreline of the study area. The shoreline is also generated for inland waterbodies, although these aren't considered for shoreline analysis via the transects. The shoreline

can be exported as a GeoJSON or a .shp file which can be used for further processing in GIS softwares.

4. *Shoreline Analysis:* From the time series created shoreline, transects are generated for shoreline analysis. The output graph depicting the shoreline change is generated.

The accuracy of the CoastSat tool for shoreline generation has an RMSE ranging from 7.3 to 12.7 m. The CoastSat tool requires installation of the Anaconda software, which is an open-source distribution of python. Step by step installation of Anaconda distribution and the associated environments for CoastSat is available on the GitHub repository of CoastSat.

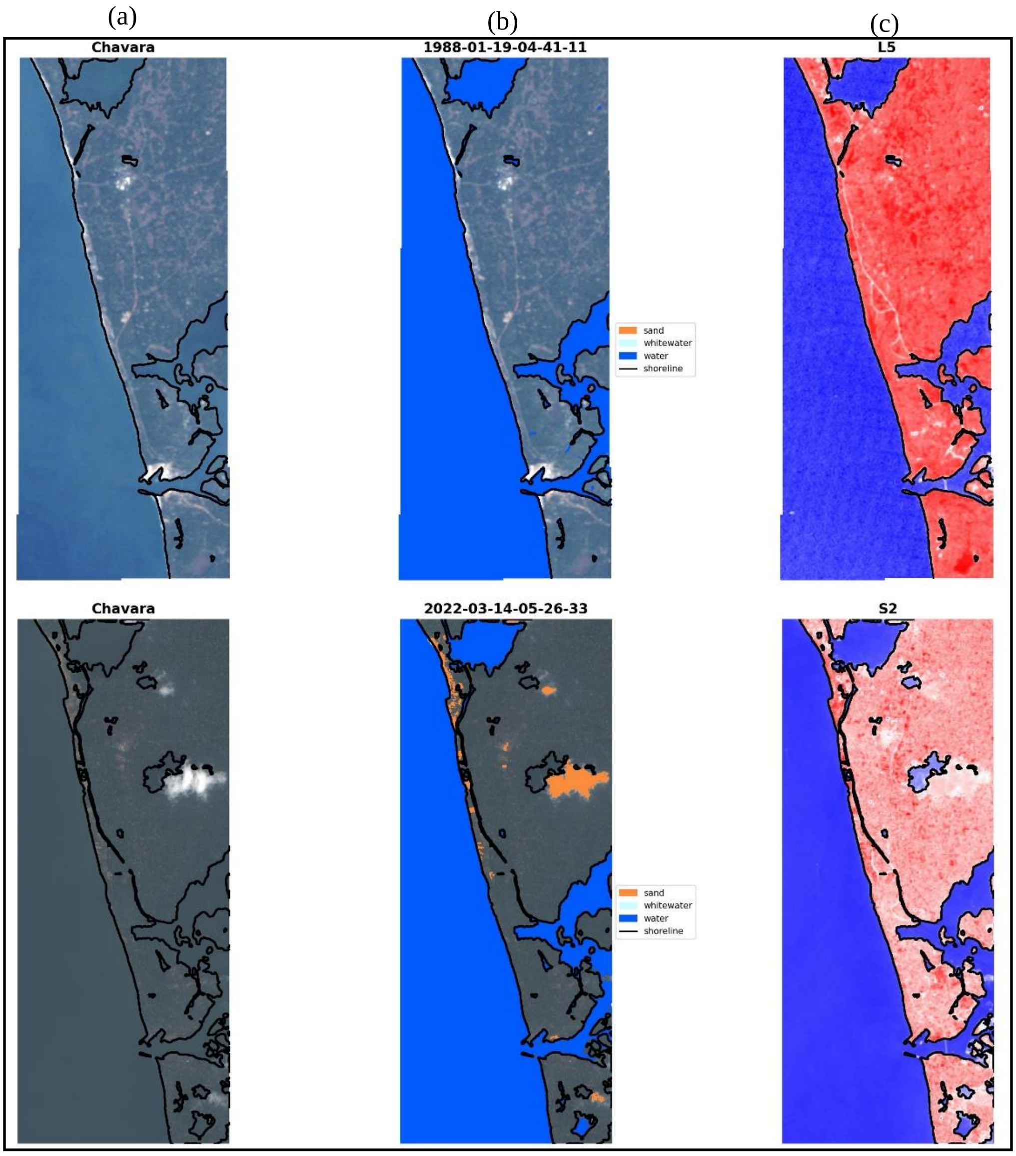

Figure 6: Generated Coastline for Chavara Stretch for 1988 and 2022. a.) raw satellite image. b.) Classified image into 3 classes; sand, whitewater and water. c.) MNDWI image.

(Image Courtesy: Landsat 5 and Sentinel 2)

Above is a demonstration of the CoastSat toolkit in Anaconda and its associated Jupyter Notebook. The demonstration is conducted on the southern part of Thiruvananthapuram for one month period. Due to processing limits it is recommended to subdivide the Area of Interest into less than 100 Km^2.

2.2 Shoreline Uncertainty Calculation

The shorelines generated from the given method have a very low RMSE for shoreline position accuracy. Although, the satellite images used as inputs for the tool are of varying resolutions ranging from 60-10 metres. Each satellite due to orthorectification errors has its characteristic Geo-Accuracy. Apart from this, Tidal variations are also present for various time scales resulting in the horizontal uncertainty of shorelines. Other errors include toposheet plotting error, digitising error and seasonal variation errors. This can result in errors within the positioning of the generated shorelines. To compensate for this error, uncertainty values for each coastline can be generated.

In the generated coastline, a geo-accuracy for each coastline is mentioned. Using this data along with the pixel resolution and the tidal fluctuations data, the uncertainty values are calculated using the following formula:

Eq. 01 ------ $$U = \pm\sqrt{(E_r^2 + E_p^2 + E_{td}^2)}$$ (Yadav, et al., 2017)

Where-

- E_r : Is the error due to Ortho rectification
- E_p : Is the pixel resolution of satellites
- E_{td} : Is the tidal fluctuation errors

The inputs for E_p and E_r are based on the resolution and geo-accuracy of respective satellites, the inputs for E_{td} are obtained from the data repositories of IOC - Sea Level Monitoring for data after 2013 and from the Permanent Service of Mean Sea Level (PSMSL) for tidal data before 2013. Both these data are acquired from the tidal gauges in Kochi. Uncertainties due to seasonal variation are not considered as only the fair season shoreline is considered for the given analysis. The maximum values are observed in the errors due to pixel resolution with a maximum value of 60 whereas the least error was observed in tidal fluctuations as the study area is a microtidal region.

2.3 Shoreline Change Rate Analysis

For calculation of the shoreline rates, the tool used for the present study is the Digital Shoreline Analysis System (DSAS) created by the United States Geological Survey (USGS), available as an extension to the ESRI ArcGIS software. This tool uses the measurement baseline method to calculate the shoreline change at user-specified intervals. The advantage of this tool is the ability to calculate the time series rate of change of shoreline, and evaluate and resolve the nature of shoreline dynamics and changing trends (Lima, et, al. 2021). For the present study, the DSAS version 5.1 is used as an extension for the ArcGIS 10.7. The list of statistical parameters that are processed using this software as part of this work are as follows:

- Net shoreline movement (NSM): As the name suggests, this parameter provides the shoreline movement considering the oldest and youngest shoreline only.
- End Point Rate (EPR): EPR uses the oldest and youngest shorelines as inputs for the calculation of the year rates. The net distance is divided by the time elapsed to obtain the result.
- Uncertainty of the end point rate (EPRunc): This is the uncertainty value for the EPR.
- Linear regression rate (LRR): Unlike the EPR, the LRR calculates the yearly rates using all the shorelines by means of the least square regression method. It is more reliable than the EPR as it takes into account the entire shorelines for calculation. The LRR is

basically the slope of the linear trend obtained from plotting the shoreline distances to time.

- Standard error of linear regression (LSE), Confidence interval of linear regression (LCI), and R-squared of linear regression (LR2): These parameters are the supplemental statistics for LRR.
- Weighted linear regression rate (WLR): Similar to LRR, the WLR calculates the shoreline change rate using all the shorelines as the input. The only difference is that the WLR also takes into account the shoreline position uncertainty values thus being a more robust statistical parameter than the LRR.
- Standard error of weighted linear regression (WSE), confidence interval of weighted linear regression (WCI), R-squared of weighted linear regression (WR2): These parameters are supplemental statistics to the WLR (Himmelstoss, et al., 2021).

Considering all these factors, in the given study the WLR statistic adopted for analysing the multi-dated shorelines.

2.4 Correlation of shoreline change hotspots with Previous Studies

Based on the computed shoreline change rates and the literature review from similar studies done earlier for the study area the trend of shoreline change is assessed.

CHAPTER 03
Results & Discussion

The coastline of southern Kerala is characteristic of its high economic value and unique geological and environmental phenomena. The provenance of Precambrian Khondalites and Charnokites along with the longshore sediment transport regime has favoured the localised deposition of heavy minerals and sand within the distinctive coastal morphological setting of lagoons and barrier beaches. If these resources are extracted for their economic value for a long-term extraction beyond their sustainable quantity, it can lead to a high erosive trend within the site. To tackle erosion, hard structures have been introduced as part of coastal protection. But often it is observed that these structures are not efficient due to a lack of site-specific scientific study thus further hampering coastal preservation. With vast anthropogenic activity, erosion along the coast is inevitable. The location of transects (Figure 7) for this study is selected based on the following factors;

1. Zones with high concentration of heavy minerals
2. Stretches having high prospects for sand and clay resources
3. Sectors that are highly eroding
4. Anthropogenic influence- presence of hard structures along the coast

The Alappuzha-Varkala sector is characteristic of high heavy mineral concentrations with general decreasing order of Ilmenite, Sillimanite, Rutile, Zircon and Monazite (MINERAL RESOURCES, 2022). In the district of Kollam, erosion hotspots are observed in the mining sites (Chavara stretch). The mineral-rich coast is divided into two stretches namely; the Chavara stretch extending from Neendakara to Kayamkulam of the Kollam coast and its northern contiguity- part of the Alappuzha stretch from Valiyazhikkal (Kayamkulam) to Thottappilly. The mining/eroding locations along the Alappuzha coast are Thrikunnapuzha and Arattupuzha and those of the Chavara coast are Vellanathuruthu, Ponmana, Kovilthottam and

Sakthikulangara (Sekhar et al., 2003; Prasad, et al., 2020; Nathan et al., 2014). The erosive effect is so intense that caving of shoreline by 120 -200 metres is observed at Kovilthottam and Vellanathuruthu (Prasad R., et al., 2016).

The availability of black sand along the coast of southern Kerala makes it ideal as construction material. The Alappuzha coast and certain blocks of Kollam coast are zones having potential for sand mining (Dinesh et al., 2014). The Veli-Shangumugam stretch of approximately 5 kms is known to possess glass sand deposits (Prabhakumar & Pradeep, 2014).

Mudbank locations are documented near the Alappuzha beach to Purakadu beach. The uniqueness of this feature is that the mudbank's sediment source is not well established due to its location being away from a river mouth. Various hypothesis explaining the mudbank formation are formulated but is not proven due to lack of evidence. Studies were conducted to estimate the erosive trend, demarcating the erosion hotspots and hard structures. Hard stabilisations along the coast are intended for shoreline protection. These may sometimes have an inverse outcome, thereby further hampering the shoreline. For example, groynes are very susceptible to the effects of longshore transport. The area south of the groyne will experience accretion and the north part will experience erosion for a northward's longshore current movement and vice versa. This creates a highly dynamic coast that is prone to beach rotation on account of changing longshore current directions. In the Alappuzha district, the coasts of Kottamkulangara and Purakadu Beach are a series of groynes and the coast near Kayamkulam Kayal is overlain by a seawall. These regions experience high shoreline changes (Ratheesh et al., 2021). The Kollam beach south of the Thangassery headland has a major breakwater and groyne constructed for coastal protection. The lateritic cliff capping the sandstone of the Warkalli beds at northern Thiruvananthapuram in Varkala is a famous tourist destination and is vulnerable to severe erosion and slippage. This is largely attributed to anthropogenic activity as well as the erosion caused by the perched aquifer within the cliff. Known for its Geological aesthetics- the Warkalli beds with embedded ichnofossils-, the Vision Varkala Infrastructure Development Corporation Ltd (VIVID) has applied for acknowledgement of the sedimentary geo-morphological structure as a Geo-Park to UNESCO. The Thazhampalli region is shielded by a seawall and the Valiathura-Panathura stretch is a coast with a series of seawalls and groynes. These two areas have observed high erosional trends. The Kovalam and Vizhinjam cliffs are of hard rock types under the erosive influence. Also, the recent construction of the Vizhinjam port may have effects on its northern or southern beaches.

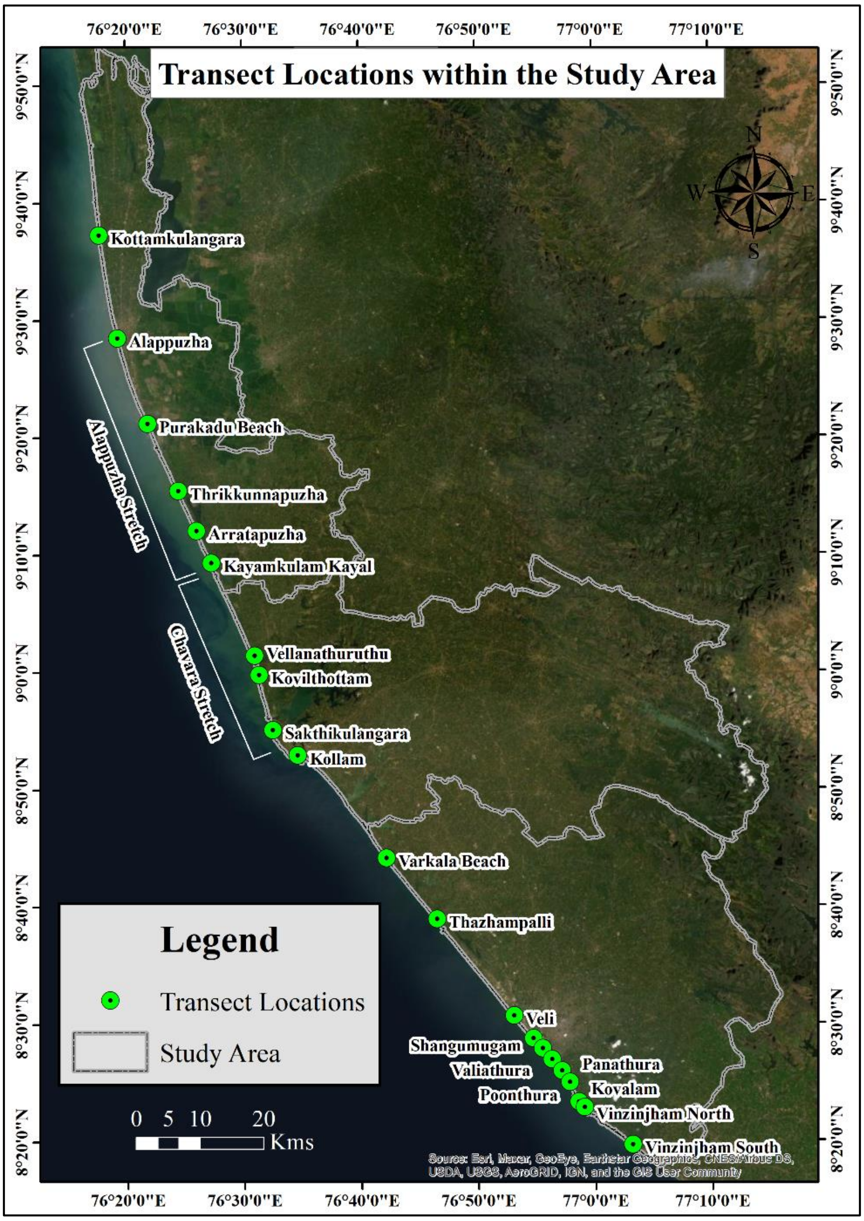

Figure 7: Shoreline Change Hotspot Locations along the Coastline of Study Area. (Basemap Courtesy: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)

3.1 Shoreline Positional Uncertainty Calculation

The generated shorelines have their respective uncertainties based on sensor origin and tidal variation. The Pixel Error (E_p) which is one of the parameters for shoreline position uncertainty is calculated by taking half its resolution as its value. The satellite sensors with their respective E_r are given in Table 1.

Table 1: The Sensors with respective Resolutions and calculated Pixel Errors.

Sensor	**Resolution**	**Pixel Error (E_p)**
Landsat 5	60m	30m
Landsat 7	30m	15m
Landsat 8	30m	15m
Sentinel 2	10m	5m

The Geo-accuracy parameter is computed within the CoastSat tool and is characteristic of each satellite image. These values range from 1 to 8.915 metres. The third parameter which is the tidal fluctuation is calculated using the range between the monthly tidal means/averages of each year considered for the shoreline analysis. In this study, only the tidal range within the fair season is considered.

Table 2: The Year wise calculated Tidal Range in metres.

Year	**Tidal Range (m)**
1988	0.090
1990	0.102
1991	0.070
1994	0.132
1997	0.067
2000	0.197
2001	0.102
2005	0.045
2013	0.129
2015	0.052
2020	0.065
2022	0.061

The difference between tidal means calculated is minuscule for southern Kerala with the average variation at 0.093 metres.

Using these three parameters within Equation 01, the shoreline positional uncertainty is calculated. An example of the calculation is given below using the parameters for shoreline dated 09/02/2010. This shoreline is obtained from the sensor; Landsat 7.

$$U = \pm\sqrt{(E_r^2 + E_p^2 + E_{td}^2}$$

$$U = \pm\sqrt{[(4.604)^2 + (15)^2 + (0.129)^2]}$$

$$U = \pm\sqrt{[21.2 + 225 + 0.016]}$$

$$U = \pm\sqrt{246.21}$$

$$U = \underline{\underline{\pm 15.7m}}$$

For the given shoreline, it indicates that its position may lie 15.7 metres in the landward direction or towards sea.

3.2 Shoreline Change Rates

Using the DSAS tool the shoreline change rates i.e., the WLR, LRR and EPR parameters for the entire coastline of the study area are calculated along pre-defined transects taken at 50 m intervals. The rates have more or less similar values with minimal deviation.

Table 3: Percentage of shoreline change classes for the Study Area at different Statistical Rates.

Shoreline Change Rates	**Erosion**	**Stable**	**Accretion**
WLR	44%	30%	26%
LRR	45%	29%	26%
EPR	40%	34%	26%

In the above table, the percentage of coastal stretch under accretion is the same (26%) whereas the eroding and stable stretches differ slightly. The maximum values obtained for WLR, LRR and EPR are 49.09, 27.32 and 42.36 m/y respectively and the minimum values are -6.97, -7.37 and -5.73 m/y respectively. The extreme erosional rates have a lower deviation than that of accretion with LRR displaying the highest value. For the accretion extremes, the maximum values are observed in WLR and the minimum in LRR. Figure 8 shows the graphical representation of the computed rates along the entire coastal stretch of the study area with the respective peaks and troughs defining the extreme values of erosion and accretion. From the figure it can be seen that there is minimal variation between the three rates. Since the WLR parameter considers the positional uncertainty in the statistical calculation, it is considered as the most robust and accurate among the three rates.

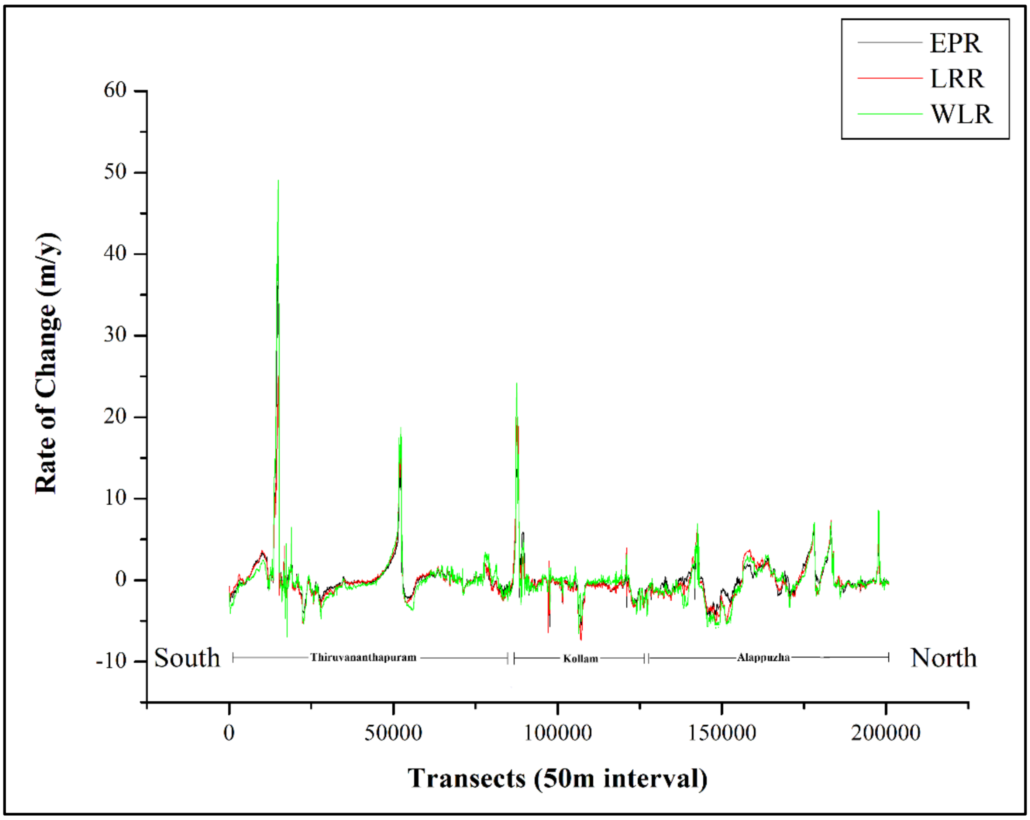

Figure 8: Graphical representation of Statistical Rates (EPR, LRR & WLR) during 1988 to 2022 along the Coast of the Study Area.

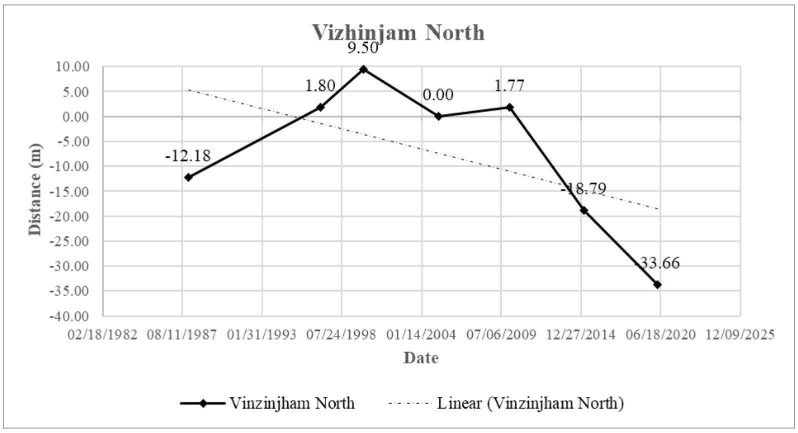

Figure 9: Time-Series Shoreline Pattern across the Northern regions of Vizhinjam harbour

A high accretionary zone with a maximum value of 49.09 m/y is observed at the Vizhinjam harbour. This is attributed to the construction activities being carried out along this stretch as part of port development. The sandy shore which existed before the commencement of port construction at Vizhinjam is being transformed into a port (port development currently in progress). Further north i.e., about 20km north of Vizhinjam port, there is another well marked accreting zone. It is the region to the south of the Muthalapozhi fishing harbour which shows a maximum accreting rate of 18.76 m/y. The next northward peak of 24.18 m/y is observed at the southern end of the breakwater structure located towards the south of the Thangassery headland. The prominent accreting areas further north are at Thottappilly, Kottamkulangara, Arthunkal and Kodumthuruth with rates of 6.92, 6.87, 7.16 and 8.49 m/y respectively.

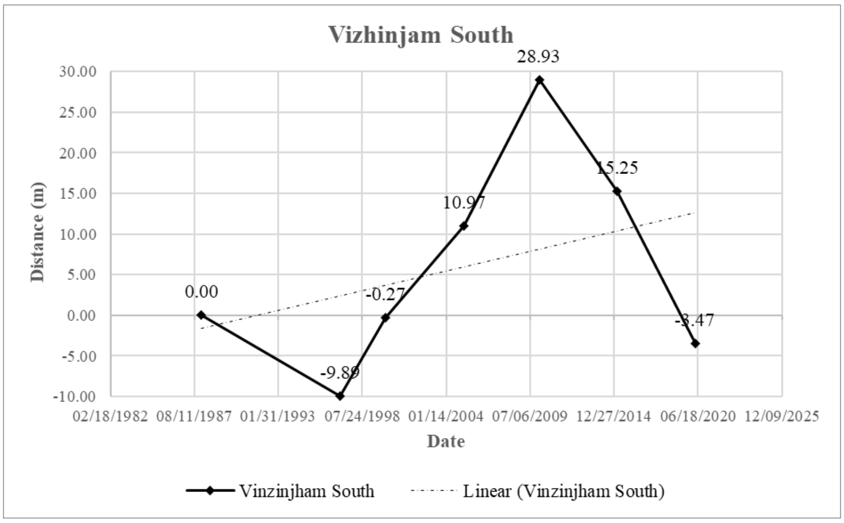

Figure 10: Time-Series Shoreline Pattern across Southern regions of Vizhinjam.

The mudbank region of Alappuzha is an accreting stretch with the maximum WLR being 3.1 m/y. The Varkala coastline is an accreting coastline with a maximum value of 1.84 m/y. The major source of sediment supply for this region is the eroding cliff whose maximum WLR value is -0.55 m/y.

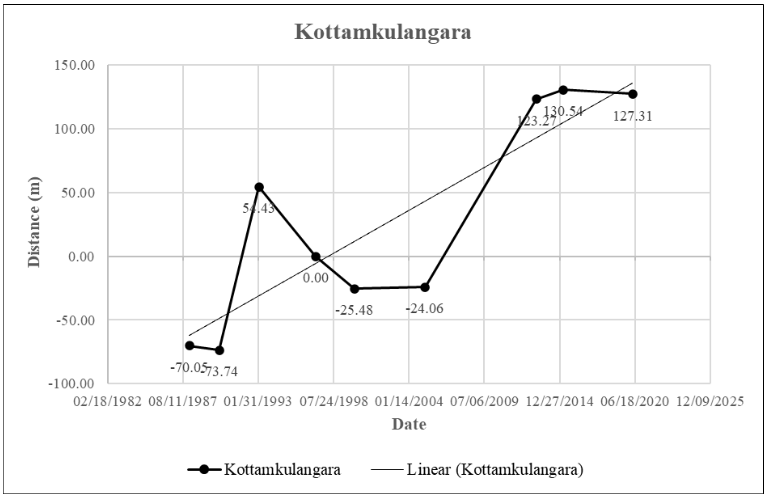

Figure 11: Time-Series Shoreline Pattern across Kottamkulangara

The Kollam beach south of the Thangassery headland that is located behind a breakwater and north of a constructed groyne is fairly stable with an average rate of 0.58 m/y. Although this beach consists of varying accretionary, stable and erosive transects.

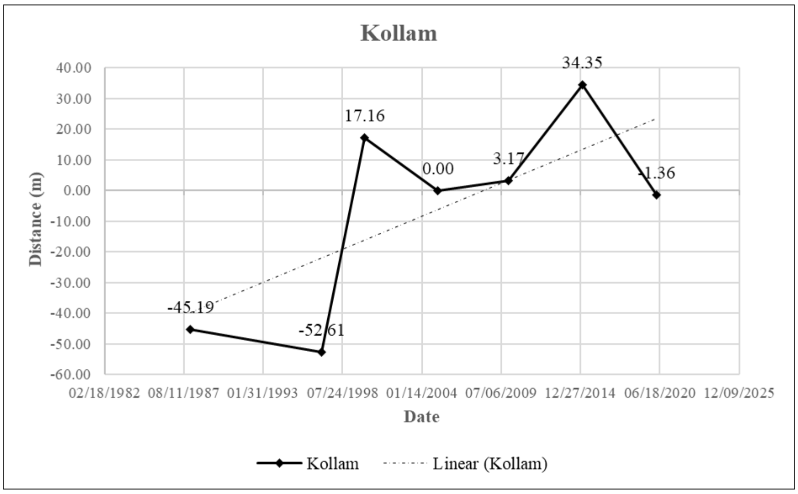

Figure 12: Time-Series Shoreline Pattern across Kollam beach.

The entire coast is dispersed with erosional extremes along its stretch. It is observed that the pocket beaches north of the Vizhinjam port are undergoing erosion within the moderate to severe erosion classes with a maximum erosive rate of one transect at Kovalam beach being -6.97 m/y. This rate is also the maximum rate within the entire study area. The region of Ponmana shows a maximum erosional rate of -6.56 m/y. The region Purakadu beach is a highly eroded stretch with 13.5 kms under erosion and a maximum erosion of -5.92 m/y observed at one transect.

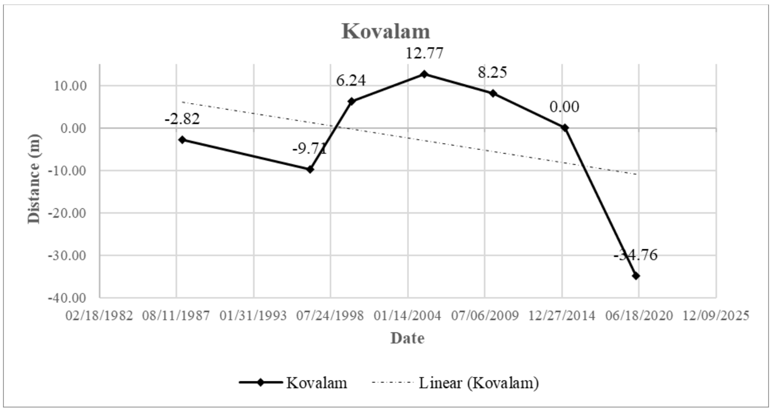

Figure 13: Time-Series Shoreline Pattern across Kovalam

The stretch from Veli to Panathura stretch is a highly erosive region. The 1 Km Veli Stretch is lie under the stable category. The maximum erosive rates for the following hotspot are as follows; -2, -4.79, -2.63, -3.2 and -0.71 m/y respectively for Shangumugam, Valiathura, Bhimapalli, Poonthura and Panathura.

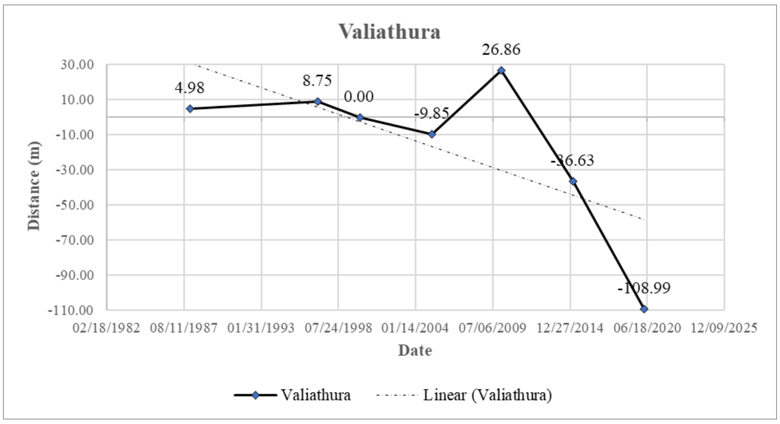

Figure 14: Time-Series Shoreline Pattern across Valiathura.

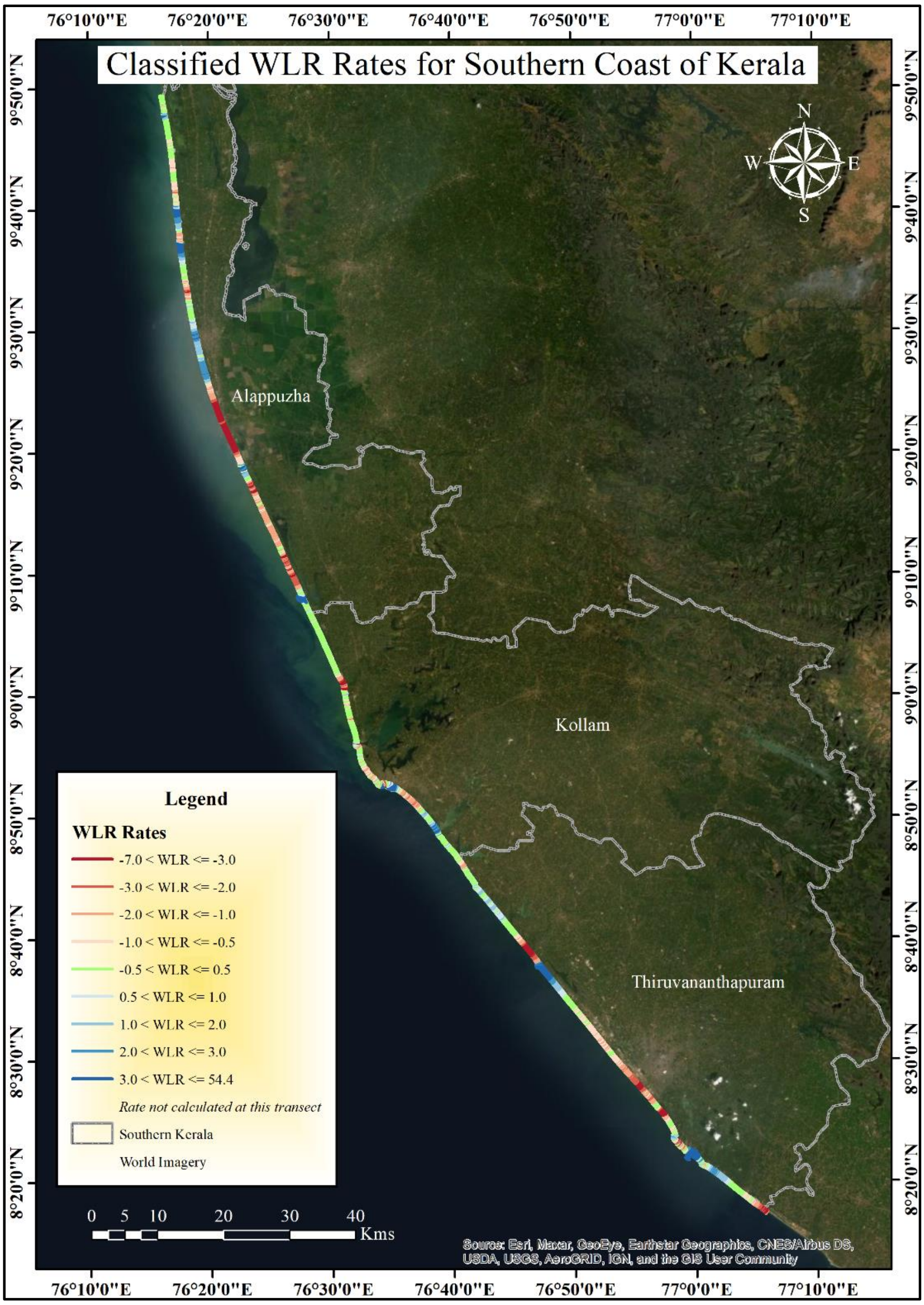

Figure 15: Computed WLR rates from 1988 to 2022 for entire Coast using DSAS. . (Basemap Courtesy: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)

Although the accretion peaks are comparably higher in value, they are for short stretches, unlike the erosional peaks which are spanned along larger stretches of the coast. Hence calculating the area of erosion is a better statistic for interpreting shoreline analysis. The formula for calculating the net areal change for each transect is given below;

$$N_a = \text{Length} * \text{Width}$$

$$N_a = (\text{Transect Interval}) * \text{NSM}$$

Where:

Transect interval = 50 m => 0.05 km

NSM = Net Shoreline Movement

By classifying the shoreline change rates a classwise areal erosion for each district can be obtained. The classes will be as displayed in the below table:

Table 4: Classified Shoreline Changes and respective values. (Nair, et al., 2018)

Classes	Values (m/year)
Very High Accretion	> 5
High Accretion	5 - 2.5
Moderate Accretion	2.5 - 0.5
Stable	0.5 - -0.5
Moderate Erosion	0.5 - 2.5
High Erosion	2.5 - 5
Very High Erosion	<-5

Of the three coastal stretches considered for the study (i.e., Thiruvananthapuram, Kollam and Alappuzha), the Alappuzha coast with a total length of 82 km is the longest. coast with a total length of 82 km, 42 km is under erosion, 18 km is stable and coast with a total length of 82 km is accreting.

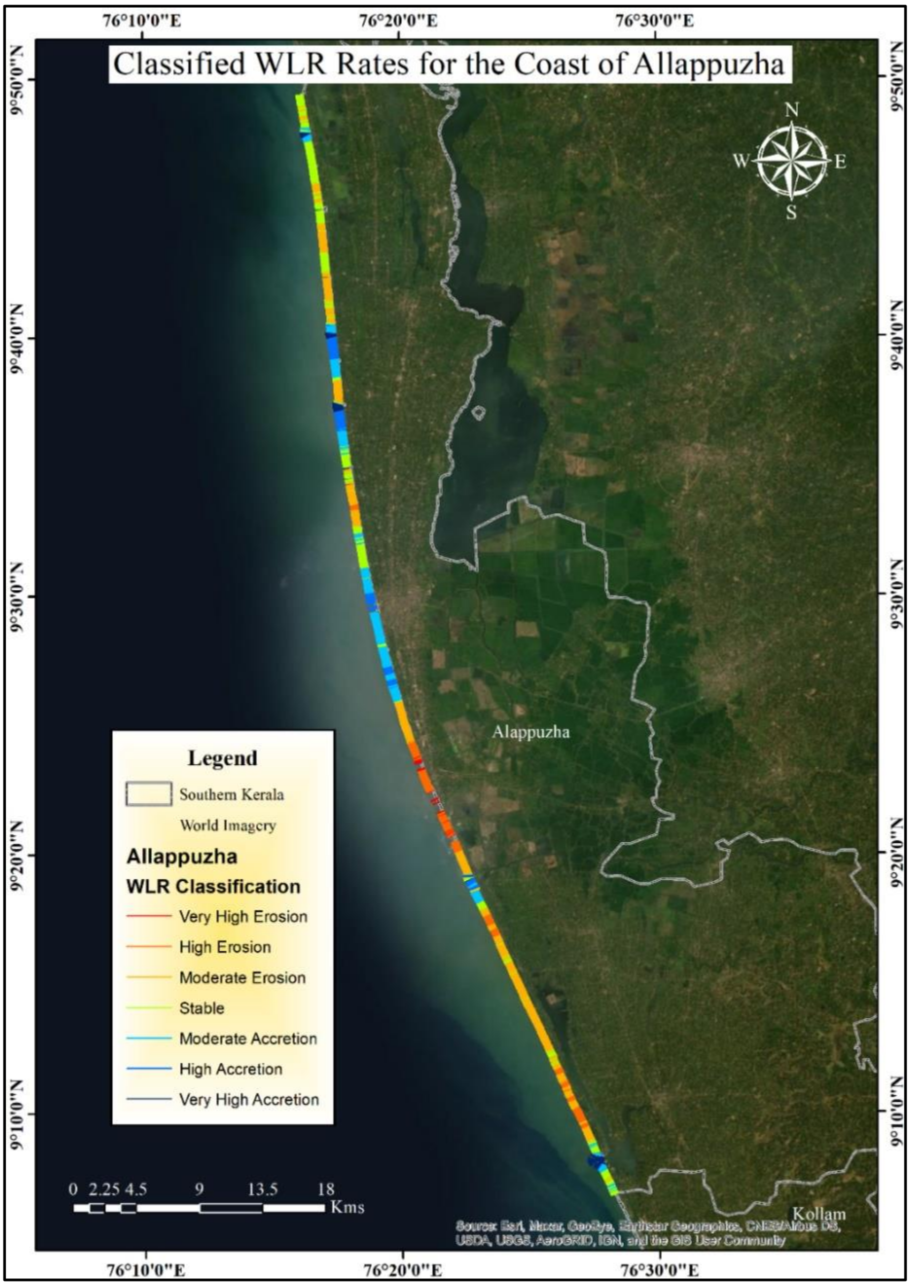

Figure 16: Classified WLR Map for Alappuzha. (Basemap Courtesy: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)

The coast is having a maximum percentage of areal change within the Very High Accretion zone which is 25.33% of total area. Net movement within the stable beach is least at 7% which corroborates with the observed stable beach status. Only 8.53% of the total area has a net change within the Very High Erosion class. Considerable erosion is seen with areal change percentages of 15.66% and 17% for High Erosion and Moderate Erosion respectively.

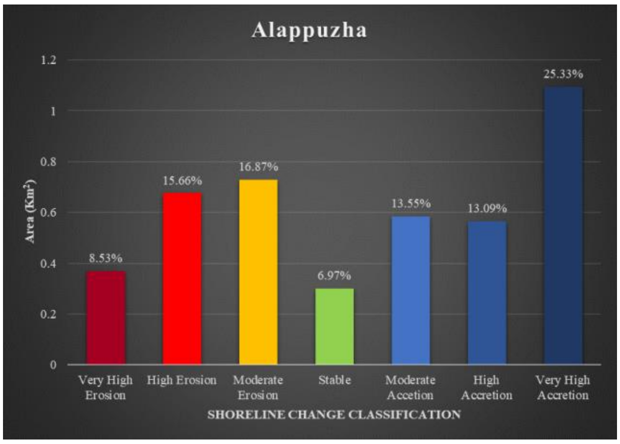

Figure 17: Bar Graph depicting the Classwise Areal Distribution Shoreline Change of Alappuzha.

The Kollam coast is the shortest stretch within the study area with a total length of approximately 47 m. Approximately 13 kms is an erosional stretch, 8 kms undergoes accretion and 25 kms of the coast is a stable beach. The stable stretch of the coast is mostly protected.

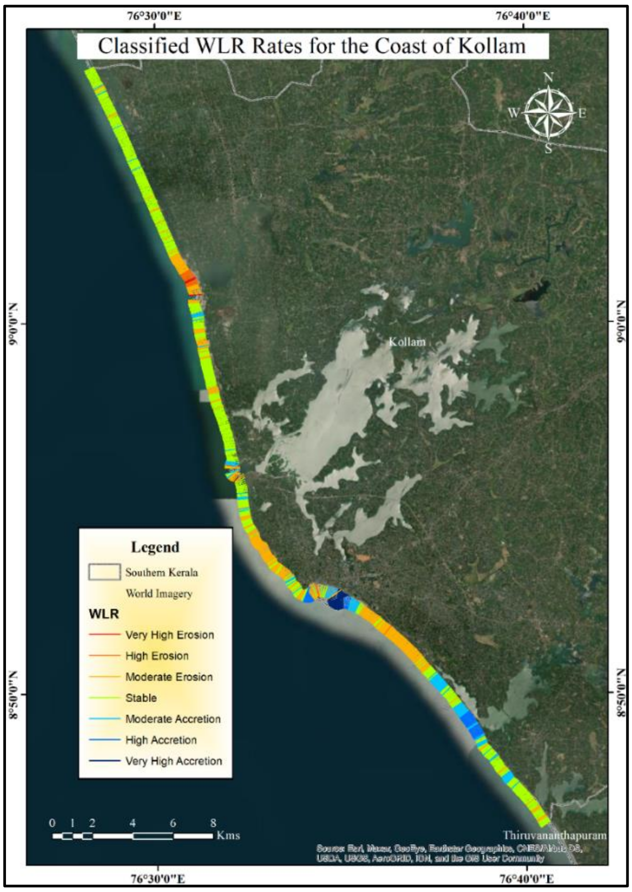

Figure 18: Classified WLR Map for Kollam. (Basemap Courtesy: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)

In this district, the maximum areal change is for the Moderate Erosion class which is 26% with followed by the Very High Accretion class at 25%. The least areal change is within the Very

High Erosion class at 3%. The stable region is at 23% which is attributed to its large coastal stretch which is protected.

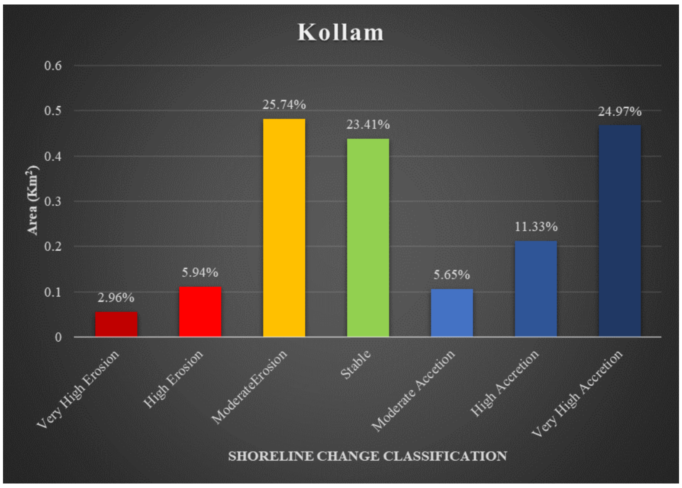

Figure 19: Bar Graph depicting the Classwise Areal Distribution Shoreline Change of Kollam.

The southernmost district; Thiruvananthapuram has a total coastal stretch of 71 kms. As per the study, almost half of the stretch (i.e., 32km) is eroding and the stable and accreting lengths are 18 km and 21 kms respectively.

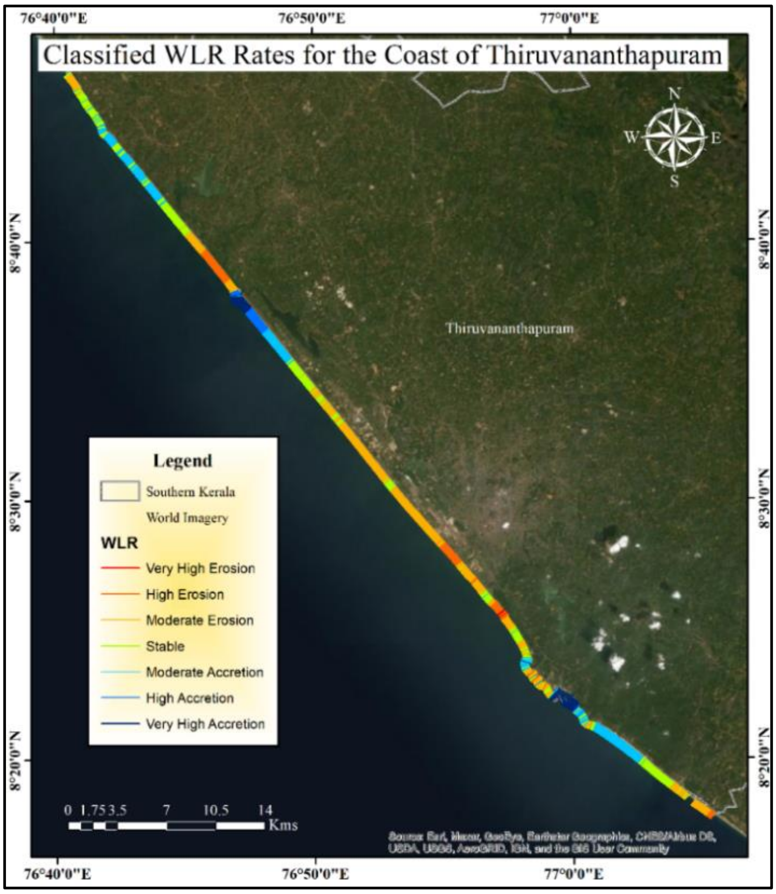

Figure 20: Classified WLR Map for Thiruvananthapuram. (Basemap Courtesy: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)

For the Thiruvananthapuram coast, the maximum net areal movement, falls under the class of Very High Accretion at 43% and the least is under Very High Erosion at 1%. Significant net movement is observed within the High and Moderate Erosion class.

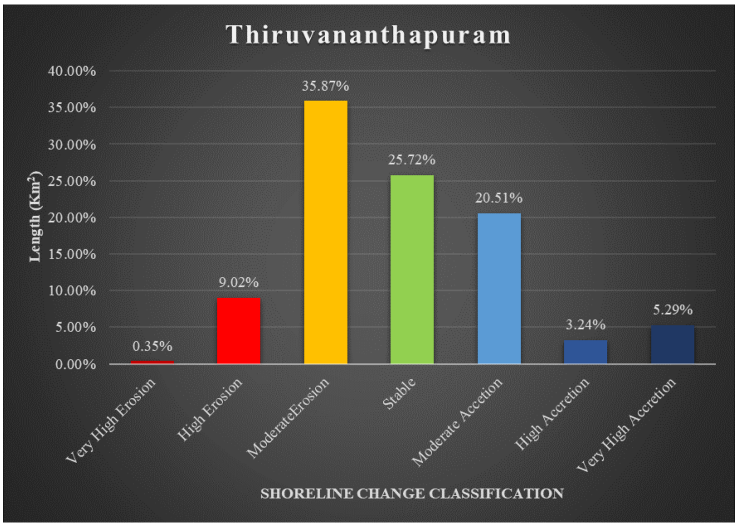

Figure 21: Bar Graph depicting the Classwise Areal Distribution Shoreline Change of Thiruvananthapuram.

Chapter 04
Conclusion

The coasts across the globe are gaining immense attention from the scientific community due to the ecological diversity, economic value and increasing vulnerability. Especially the coastal region of southwestern India has recently been under great scrutiny owing to the shifting trend of weather phenomena and the overall pattern of a receding shoreline. Using the CoastSat tool for shoreline generation is among the best methods for rapid coastal studies due to the low RMSE values. Although the positional uncertainty for shorelines generated before 2016 is very high i.e., > 15 m due to the coarser spatial resolution of the Landsat series. The shorelines before 1999 have a higher positional uncertainty of more than 30m owing to the Landsat 5 spatial resolution. The shorelines with the highest positional accuracy are obtained from the Sentinel 2 series having positional uncertainty values within the 5-6 m range. The WLR compensates for the shoreline uncertainty by incorporating the uncertainty values within its regression statistics. The lack of daily tidal data availability in this study is another limitation as tidal range could not be calculated and only calculation of the difference between the tidal means was possible to use as input within the positional uncertainty calculations.

High accretion zones are observed at Kottamkulangara, sandy beaches that are immediately south of Thangassery, Arthunkal and Kodamthuruth groynes and the Vizhinjam and Muthala Pozhi harbours. Extreme erosive rates are observed at the sandy beaches north of these features like Kovalam, Kayamkulam Kayal breakwater and the above-mentioned locations. This corroborates well with the previous study mentioning the net northward sediment transport in this region which is due to the northward direction of longshore current within the surf zone (Nair, et al., 2015). Sandy coasts with a series of groynes like Purrakkad, Kottamkulamgara north, Valiathura, Bhimpalli, Poonthura and the Chavara and Alappuzha stretches are highly erosive with observations of High to Very High erosion rates. The erosive regions of Chavara and Alappuzha are also mining sites where beach washing is conducted. The construction of the Vizhinjam harbour began in 2014-2015. The northern beaches including Kovalam have observed a sudden drastic increase from a fairly stable to a very high erosive beach. Seawall features although protecting its landward side, it blocks the sediment supply from inland to the beaches thus further hampering the nearby coastal dynamics. Another disadvantage is during extreme events of storm surges these walls can collapse causing a sudden flow of sediment, thus disturbing the coastal equilibrium.

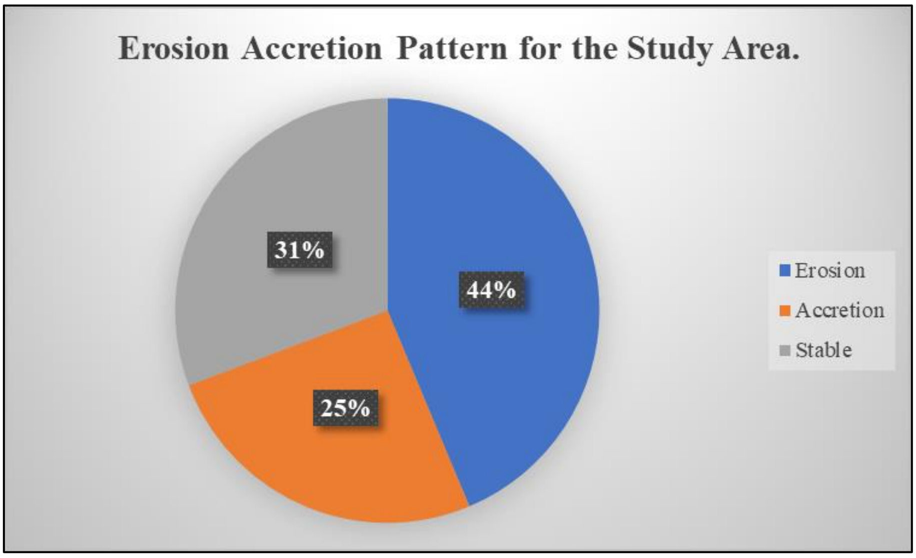

Figure 22: Pie-chart displaying total Erosion and Accretion Stretches for the Study Area

Such hard stabilisations on a coast with soft characteristics are a bane to natural coastal processes. The Shoreline Management Plan (SMP) by the National Institute of Ocean Technology (NIOT) uses a sensible approach to shoreline protection. It recommends the use of environmentally compatible soft solutions like sand bypassing, beach nourishment and offshore submerged dykes or reefs. These approaches have already been tested and have shown positive results along the coasts of Kadalur and Pondicherry which were eroding coasts, but have recently been accreting. Hence, similar approaches can be adopted for the high erosive region of the southwest coast of India.

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