Dynamic Changes in Coastal Geomorphology of Shiroda Coasts, using Remote Sensing and GIS: An Approach to Climate Change and Coastal Disaster Risk

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Abstract
The coastline is a unique land feature formed through the interaction between land and sea. It is essential to monitor and detect hotspots and observe spatial and temporal influences of climate change in the coastal environment. Coastal landform changes can be best studied through remote sensing data. This study examines the dynamic changes in the sand spit and associated coastal area of the Shiroda coasts of Sindhudurg district. The Normalized Difference Water Index (NDWI) was used to distinguish land and water and the area was calculated by reclassifying the NDWI index of all images with two classes- land surface of sand spit and water.

It was found that the spit area is decreasing seasonally at a dynamic rate. Additionally, geomorphic maps were prepared for the study area and showed disastrous changes in the coastal landforms. It is a need that coastal communities worldwide must address the challenges of coastal flooding and rising sea levels caused by climate change. Climate change is causing uneven rainfall distribution, storms and cyclones, leading to coastal erosion, flooding and landform damage. Additionally, it has a negative impact on the geomorphic features of coastlines.

Keywords: Climate Change, Coastal Disaster, Coastal Geomorphology, Coastal erosion, Geomorphic maps, Sandspit.

Introduction

In recent years, shorelines have been altered by construction and development. Due to these changes, there is now a greater need for reliable methods of including risk assessments coastal regions[24]. Besides this, repeated storms cause beach erosion and restoration efforts. Compared to a single intense storm, a cluster of storm events tends to worsen the erosion of beach and dune systems[14,57]. The higher wave energy is positively correlated with more intense sediment transport capability, producing more erosion[51].

Climate change is causing coastal erosion, flooding and damage to urban areas, negatively impacting socio-economic assets[48]. Communities located along coastlines across the globe need help in preparing for coastal flooding and rising sea levels linked to climate change[10].

Numerous scholars have contributed their research findings on a variety of topics including climate change, the impact of storms and cyclones on coastal environments, damage to coastlines, the vulnerability of coastal areas to climate change and disaster mitigation with strategic plans[25,27,32,40,49,52]. Remote Sensing (RS) and Geographic Information Systems (GIS) have allowed humans to observe changes on the Earth's surface using sensors. This technology, combined with freely available data like Landsat and Sentinel, has enormous potential in monitoring and detecting hot spots and observing spatial and temporal climatic changes. The application of geospatial technology has made it easier to determine the normalized difference between water index, moisture index and vegetation index, dramatically improving humans' ability to explore remote sensing data and obtain accurate results[3,53].

The use of remote sensing has several advantages over traditional methods for mapping land surface water (LSW). It is a cost-effective and dependable source of information that allows for frequent and consistent observations. The normalized difference water indices (NDWIs) which are calculated using various band combinations like green, near-infrared (NIR), or shortwave-infrared (SWIR), have also been shown to be effective in LSW mapping[33]. Regarding mapping water bodies, the NDWI is the most suitable tool. This is because water bodies tend to strongly absorb and reflect low radiation in the visible to infrared wavelength range[21,37,48]. Remote sensing data can provide insight into hydrological conditions using the Normalized Difference Water Index (NDWI) which is highly sensitive to variations[54].

The coastline is a distinctive land feature created by the interaction between the sea and land. The International Geographic Information Committee (IGDC) has recognized it as one of the 27 vital land surface features[55,60]. During the fieldwork, various erosional and depositional features were observed including beaches, sandbars, sand spits, dunes, cliffs and rocky platforms. Based on these observations, it has been decided to investigate the spatial and temporal patterns of geomorphological changes in coastal landscapes. The study focused on coastal landform processes and their interaction with sea waves, currents and beach materials. In this study, remote sensing and GIS techniques were used to analyze the coastal landforms of Shiroda.

The results for each class of geomorphological features of coasts are displayed in tables 2 and 3. Among all these landforms, typically, spits are found near the mouths of estuaries[46]. The coastal system is influenced by multiple factors such as river discharge, catchment of the river, geology, freshwater input, sediment from the river, waves, tides, currents and climatic conditions. Human activities like ports, aquaculture, construction and industries also impact the coastal geomorphology system. One of the most prominent coastal geomorphic systems is the spits which are formed due to the accumulation of sediments when alongshore drift reaches a headland. The sediments that make up spits, come from various sources including rivers and eroding bluffs. Changes in these sources can significantly affect spits and other coastal landforms.

Spits are particularly important in understanding the morphodynamics near the estuarine mouth and the coastal landscapes. The orientation of spits depends on the tidal flow, river/estuarine channel geometry and waves. This provides a good indication of the direction of the net littoral drift[2,19,26,29]. The use of remote sensing data has gained popularity in geomorphological investigations due to its increasing level of detail and accessibility which creates new opportunities[50].

Coastal erosion and Disastrous risk due to Climate change

It has been observed that coastal erosion rapidly changes the coastal landscape in the study region. Based on the evidence, the primary cause of coastal erosion is the rising sea level and the resulting environmental impacts[9]. A study on the basis of a tool called LIS Coast (Large scale Integrated Sea-level and Coastal Assessment Tool) created by the Joint Research Centre of the European Commission, revealed that a significant portion of the world's sandy coastline is currently experiencing erosion.[57,58] Almost half of the world's sandy beaches would disappear by the century's end if no steps are taken to reduce greenhouse gas (GHG) emissions[58]. The occurrence and severity of hurricanes, storm surges and floods increased due to the effects of global warming. Additionally, a rise in sea level contributes to changes in ocean dynamics and leads to the erosion of coastlines. These two phenomena are significant factors in coastal erosion[59].

Flooding occurs when cyclones hit the coast due to the highest water level. Storm surges, tides, wind waves, river discharge and rainfall influence this. Storm surges are the main factor that affects the height of the surge on the coast influenced by different characteristics of the cyclone[42]. Coastal flooding caused by storm surges, high tides and wind waves can devastate society. Researchers in one of their research have created potential flood maps for extreme water elevations along the north Maharashtra and Gujarat coast to prepare for such events. These maps were generated using climate change projections for tropical cyclones[42]. In the North Atlantic Basin, the authors have quantified the rates of cyclone impact, mangrove damage and resilience loss in their study region over twenty-five years of analysis[15].

In connection with the shoreline alteration, a study was conducted on the shoreline change at Ponnani Fishing Harbour (PFH) in Malappuram, India. Digital Shoreline Analysis System (DSAS) version 5.0 was used to estimate the changes. Results showed that the shoreline retreated by 285.9 m while accreting by 132.32 m at the Ponnani Harbour area over the last thirty years. The study also predicted that the shoreline at Ponnani and Puthuponnani beaches may experience further erosion of about 100 meters by 2030, with a potential increase in erosion rate that could erode another 140 m by 2040. Therefore, it is necessary to consider the Ponnani and Puthuponnani beach extents as high erosion risk zones based on the study's findings[12].

Evaluating coastal vulnerability has gained momentum due to the frequency and severity of tropical cyclones and the anticipated rise in sea levels giving ideas about vulnerability along the shoreline[44]. The level of vulnerability and risk resulting from coastal flooding are determined by factors such as coastal population density, topography and the presence of estuaries, deltas and nearby rivers in areas affected by cyclones[5,42].

Geomorphological Changes and Coastal hazard risk mitigation

Understanding the morphology of land surfaces is crucial for creating accurate geomorphological maps and utilizing GIS applications effectively. Similarities in land surface segmentation methods can be used to create a theoretical foundation for characterizing segments and their boundaries. Maximizing internal homogeneity and highlighting external differences are essential when defining landform units[38]. Geomorphology mapping has been greatly enhanced by introducing new technology such as GPS, satellite imagery, DEMs and GIS which provide highly detailed data[16,40].

Geomorphological maps are helpful tools for understanding the physical features of the Earth's surface. They offer an objective and complete description of landforms including their specific names, shape and symbols. These maps also provide spatial information regarding the dimensions, slope, curvature and relief of landforms and their origin and evolution of genetic agents and processes. Furthermore, they consider the effects of bedrock lithology and structure control, activity status, rate of genetic processes and the type of bedrock and near-surface deposits[16].

The process of geomorphological mapping is crucial in comprehending the processes that occur on the Earth's surface. It helps us understand geochronology, natural resources, natural hazards and landscape evolution. This involves dividing the terrain into conceptual spatial entities based on various criteria such as form, process, composition, structure, chronology, environmental system associations (land cover, soils, ecology) and the spatial topological relationships of surface features (landforms)[6]. New research has shown that advances in methodology have made it possible to reconstruct the geomorphology of past periods particularly relevant to climate change in the late 20th and 21st centuries.

As a result, scientists can now make connections between climatic variability and geomorphology, which will help predict future geomorphic changes and understand how geomorphic processes contribute to coastal changes and even contribute to predicting carbon flux and carbon cycle[30]. When evaluating coastal hazard and risk mitigation measures, it is essential to conduct a survey and map of both the emerged and submerged coastal areas. In order to obtain accurate and georeferenced spatial data, remote sensing techniques are the best option. By utilizing these techniques, a survey campaign can be conducted thoroughly and efficiently, simultaneously gathering all the required information[17].

Due to the rising number of disasters worldwide and global environmental changes such as climate change, adopting new strategies for reducing exposure and vulnerability becomes more crucial. Hazard mitigation is difficult as it competes with other development goals and affects various sectors. Disaster risk reduction is a critical policy objective requiring coordination, management and resources[1,8,18,23,28,45]. Coastal plains in Asia and the Pacific region, where many densely populated cities are located, are highly susceptible to severe natural disasters.

Geomorphic features in these areas play a crucial role in determining risk and vulnerability to such calamities. In the past few decades, rapid land-use changes have necessitated a shift in risk assessment methodologies, focusing on analyzing and evaluating the interaction between social structures and natural disasters[22]. This type of data, which shows changes over a decade, is helpful for disaster management. We utilized advanced techniques, various GIS-based layers and remote sensing data to create a geomorphic map that plays a crucial role in this attempted study.

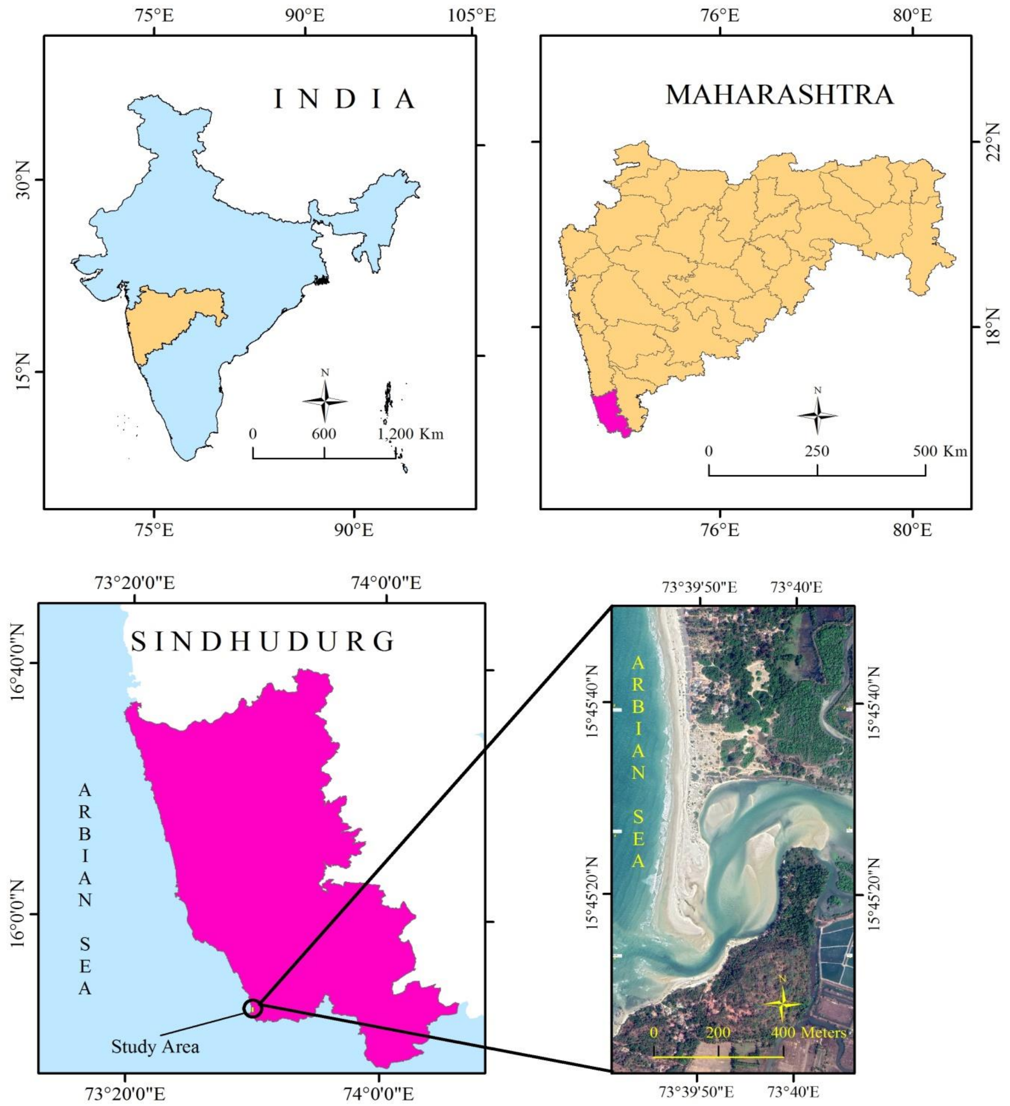

Figure 1: Location map of Study area

Study Area

The research site is situated on Shiroda Beach, near Khalchikar village in the Vengurla taluka of Maharashtra's Sindhudurg district (Fig. 1.) This area was chosen due to its clear demarcation on satellite images. The selected region spans approximately 1 square kilometer and ranges from 73° 38' 10" E to 73° 41' 20" E and 15° 44'05" N to 16 47'10" N. The climate in this area is hot and humid, with average temperatures ranging from 17°C to 35°C. The best weather conditions are typically experienced between November and February. Annual rainfall averages around 900 mm with the heaviest rain occurring between June and September during the monsoon season.

Material and Methods

The primary research methodology utilized involves using satellite images to identify coastal landforms and decadal variations. The first part of the study utilized Land Sat satellite data from 1973 to 2023[35]. This was done to gain insight into the long-term changes occurring in the spit and the coastal landforms. The Land Sat satellite system captured images in 1973, 1980, 1990, 2000, 2019 and 2023 and table 1 provides more detailed information on these images. The main focus of the research is also to map the spit using satellite imagery. The area of interest is approximately one sq. km and all satellite images have been analyzed. The objective is to understand the morphology of the spit using multi-temporal satellite images.

While not all morphological classes could be distinguished, we gained insight into the shifting of the spit. The Land Sat satellite data has been particularly helpful in understanding the spit's movements from 1973 to 2023. In 2006, 2019, 2021 and 2023, field data was collected through a spit survey using Total Station instruments and handheld GPS devices, resulting in over 1123 points. These data sets were used to create a Digital Elevation Model, allowing for tracking changes in the spit's position. Furthermore, cross-sectional profiles were computed to gain more insight into the spit's shifting patterns.

Normalized Difference Water Index (NDWI): The study of remote sensing applications finds water extraction a complex topic. This is due to existing water indices often misclassifying turbid water, small waterbodies and land features in shadow areas. To improve the accuracy of water body mapping using Landsat imagery, a new water index called the weighted normalized difference water index (WNDWI) was proposed. Spectral profiles and experiments were conducted to develop this index and reduce errors[20]. This effective tool for identifying open water features is the modified NDWI (MNDWI). Unlike the standard NDWI, the MNDWI can effectively reduce built-up land, vegetation and soil noise, providing more precise and accurate water information. With the NDWI, the extracted water area may be overestimated due to built-up land noise.

Therefore, the MNDWI is recommended for water regions with a background of built-up land areas. Remotely sensed imagery has long been used for water resources assessment and coastal management. Thematic information extraction techniques are often used to identify open water areas[4,56,61]. Traditional methods typically rely on aerial photographs and ground survey techniques when identifying open water features. Unfortunately, these approaches can be slow, costly and require skilled personnel. Fortunately, remote-sensing technology has emerged as a more efficient option for extracting water features and monitoring water-bodies changes. This technology leverages various data sources such as multi-/hyper-spectral image data, airborne lidar, microwave data and video images[7].

Methods such as the normalized difference water index (NDWI) and modified normalized difference water index (MNDWI) use spectral water indices which are calculated using one green-band image and one near-infrared (NIR) or shortwave infrared (SWIR) band image. These methods can extract water body information more accurately, quickly and comprehensively than general feature classification methods[33]. The FCC band combination requires the fusion of bands 4, 3 and 2, which must be saved in the ERDAS imagine format within ArcGIS.[31]

For the attempted study and to distinguish between water and land areas, the ERDAS Imagine's software utilized the Normalized Difference Water Index (NDWI) and the Modified Normalized Difference Water Index (MNDWI). The NDWI generated a range of -1 to +1 where values between 0 and +1 indicate water areas, while values between 0 and -1 represent land areas.

Table 1
Details of Land Sat Satellite Images

S.N.	Land Sat Satellite	Date	Path	Row	Resolutions
1	Land Sat 1 MSS	2 March 1973	P157	R49	60 m
2	Land Sat 3 MSS	6 April 1980	157	49	60 m
3	Land Sat 5 TM	3 April 1990	147	49	30 m
4	Land Sat 7 ETM	18 Feb 2000	147	49	30 m
5	Land Sat 7 ETM	10 April 2010	147	49	30 m
6	Land Sat 8	3 April 2019	147	49	30 m
7	Land Sat 9	8 April 2023	147	49	30 m

Table 2
Estimated values for Sand Spit and Land Part

Class / Year's	1973	1980	1990	2000	2010	2019	2023
Spit and Land Part	0.556	0.496	0.449	0.421	0.417	0.414	0.389
Sea Part	0.245	0.305	0.352	0.38	0.384	0.387	0.412
Total Area	0.801	0.801	0.801	0.801	0.801	0.801	0.801

Table 3
Comparison values for coastal landforms for the year: 2006, 2019 and 2023

		Year 2006		Year 2019		Year 2023	
S.N.	Name	Area in sq. Km.	Percentage	Area in sq. Km.	Percentage	Area in sq. Km.	Percentage
1	Beach	0.030	2.517	0.023	1.96	0.008	0.67
2	Berm	0.00	0.059	0.001	0.10	0.001	0.10
3	Built up	0.01	0.710	0.047	3.99	0.048	4.11
4	Bund	0.003	0.392	0.004	0.30	0.004	0.30
5	Curvilinear beach	0.02	1.350	0.014	1.15	0.016	1.38
6	Estuary	0.11	9.768	0.132	11.25	0.142	12.05
7	Groins	-	-	0.008	0.65	0.008	0.65
8	Mangroves	0.05	4.411	0.127	10.78	0.109	9.27
9	Mud-flats	0.01	0.489	0.004	0.36	0.019	1.59
10	Open land	0.20	16.991	0.097	8.26	0.115	9.71
11	Salt pan	0.03	2.249	0.033	2.81	0.033	2.80
12	Sand bar	0.12	9.974	0.074	6.34	0.056	4.79
13	Sand dunes	-	-	0.011	0.95	0.011	0.93
14	Sand spit	0.06	5.144	0.077	6.56	0.071	5.98
15	Sea	0.20	17.326	0.198	16.89	0.212	17.99
16	Tidal Inlet	0.01	1.098	0.011	0.93	0.011	0.93
17	Vegetation	0.32	27.238	0.313	26.63	0.309	26.17
18	Waterbody	0.00	0.283	0.001	0.07	0.001	0.06

The NDWI and MNDWI are calculated by differentiating between the band combinations of the Land Sat images, specifically by selecting the Infrared band, either near or middle. The NDWI was represented by the following equation:

$$NDWI = (Green - NIR) / (Green + NIR) \quad (1)$$

where green= reflected radiation and near-infrared (NIR) = reflected radiation.

The NDWI was applied to all of the Land Sat MSS images. For the Land Sat TM, ETM and OLI images, coastline extraction used the Modified Normalized Difference Water Index (MNDWI). The MNDWI is having following equation:

$$MNDWI = (Green - MIR) / (Green + MIR) \quad (2)$$

where green = reflected radiation between and mid-infrared (MIR) = emissive radiation.

The NDWI values were analyzed in ERDAS Imagine Software, a commonly used index by researchers to determine the difference between land and water[11]. Seven decadal images from 1973 to 2023 were used in ERDAS to enhance the edges between the land and water. The results were then processed in ArcGIS to reclassify the map and create a shape file for the water and land area. Table 2 displays the spit and land area, focusing on the spit's geomorphology. The Shiroda spit showed a significant change from 1973 to 2023, as seen in figures 2 and 3. Figure 4 displays detailed information regarding Land Sat 9 MSS imagery and NDWI for 2023, which was used to calculate a trend line of 0.85.

Based on the data in table 2, the trend line calculations indicate that the Spit land Part and Sea Part classes have R2 values above 0.85. The trend for the Spit land Part is decreasing which is connected to the Sea Part. Figure 5 displays the trend line values for both classes.

As part of the methodology, we utilized Google Earth images from 2006, 2010, 2021, 2022 and 2023 to detect changes in coastal land features and sandspit. In India, the LISS IV with a 5.8m resolution is the last option for this type of study. Therefore, using Google Earth images is the most appropriate option[36]. This database aims to track the shifting of the coastal spits and landforms. We downloaded the required Google Earth images yearly at equal eye altitude from Google Earth Pro. These images were combined using AutoCAD software to create a single image. Then, import the output image into ArcGIS for georeferencing and re-project it in UTM Zone 43 North, identified by WGS 1984. Figure 6 depicts the spit's movement from 2006 to 2023.

As a last part of the methodology, using Arc GIS, digitized details of various geomorphic features were found in Google Earth images from 2006, 2019 and 2023. The purpose of this study was to gain a better understanding of the characteristics of these features including any morphological changes or short-term alterations to coastal landscapes. After creating vectors, we calculated the area for each year individually. We analyzed all landform classes such as beaches, berm lines, built-up areas, bunds, curvilinear beaches, estuaries, groins, mangroves, mud flats, open land, salt pans, sand bars, sand dunes, sand spits, seas, tidal inlets, vegetation and water bodies. According to the study, the Shiroda coastal environment and surrounding regions are under considerable threat of climate change that may cause damage to the coastal landforms (Fig. 7).

Results and Discussion

Coastal erosion is a problem that affects the entire world. In areas with more storms and rising sea levels, coastal flooding and erosion impact worsen. This is especially true in places where the coast is already vulnerable[13]. Coastal erosion can be managed through two protective measures: structural and non-structural. Structural measures can be further classified into two types: hard and soft. Hard structures like seawalls, breakwaters, jetties, groins and offshore dikes offer protection against erosion. Soft structures include beach nourishment, artificial dunes, mangroves, rise grass planting and coastal shelter belts.

On the other hand, non-structural measures involve land-use controls, setting warning lines such as the coastal baseline and coastal construction control line to protect the coast from improper construction and prohibit unreasonable sand mining and reclamation[9].

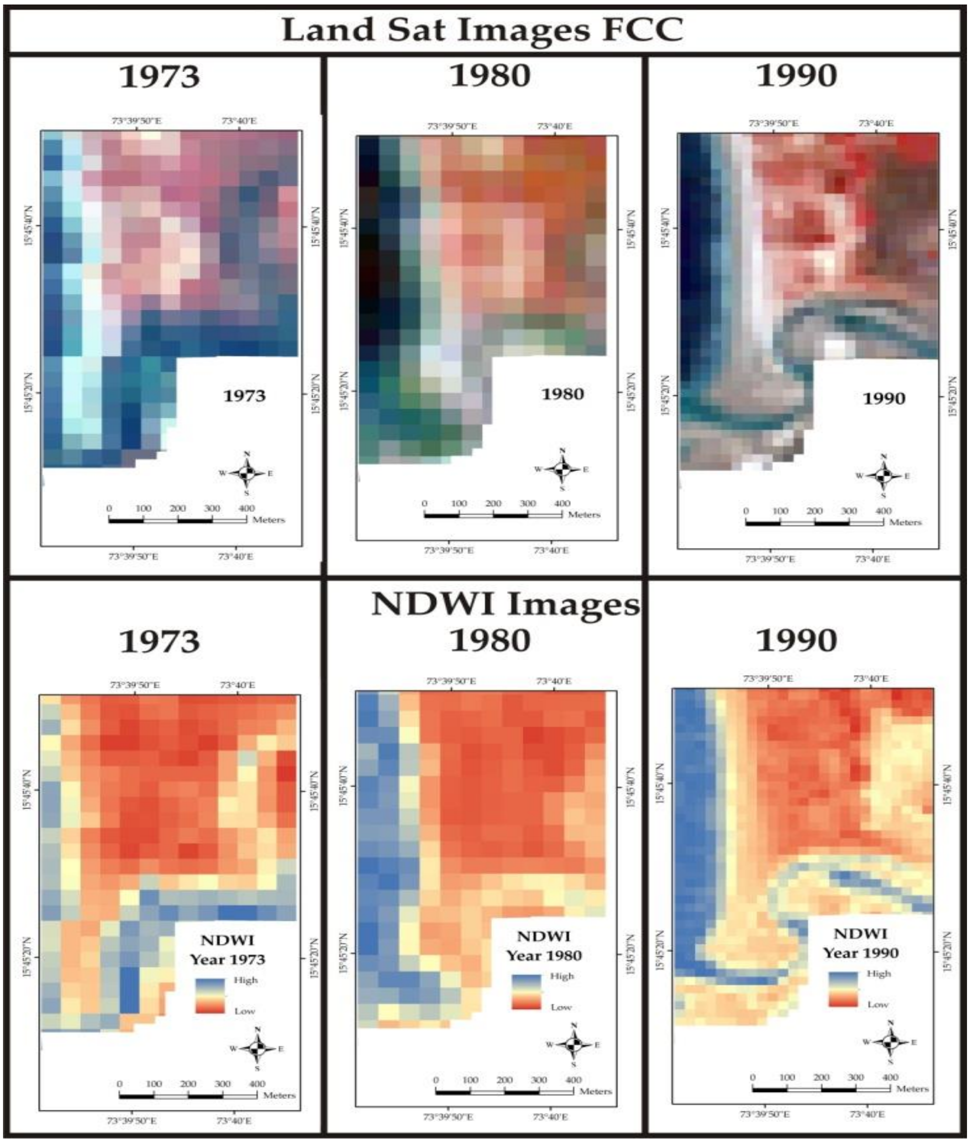

Figure 2: Land Sat Satellite Images and NDWI for the year 1973, 1980 and 1990

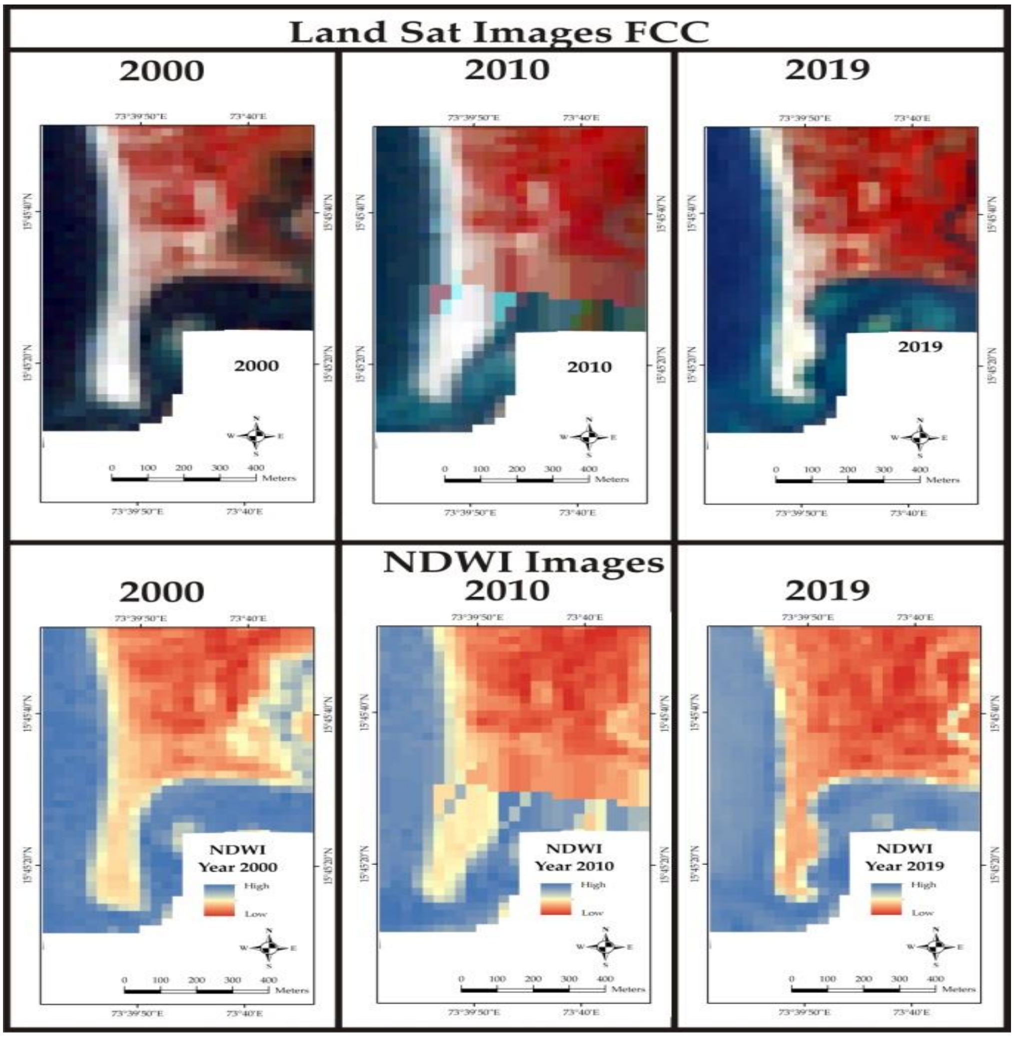

Figure 3: Land Sat Satellite Images and NDWI for the year 2000, 2010 and 2019

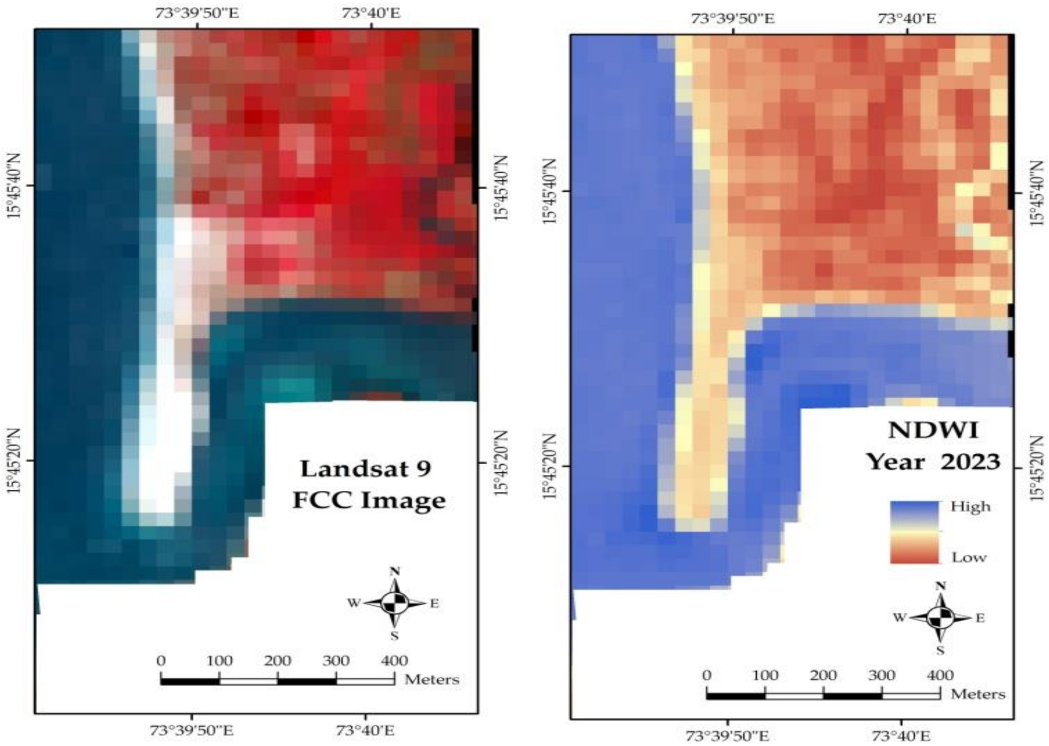

Figure 4: Land Sat Satellite Image and NDWI for the year 2023

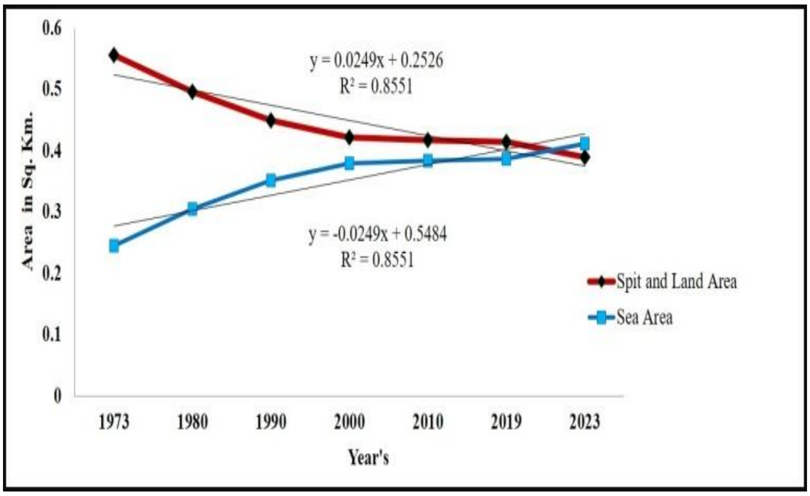

Figure 5: Trendline graphs: Sandspit and Sea water area

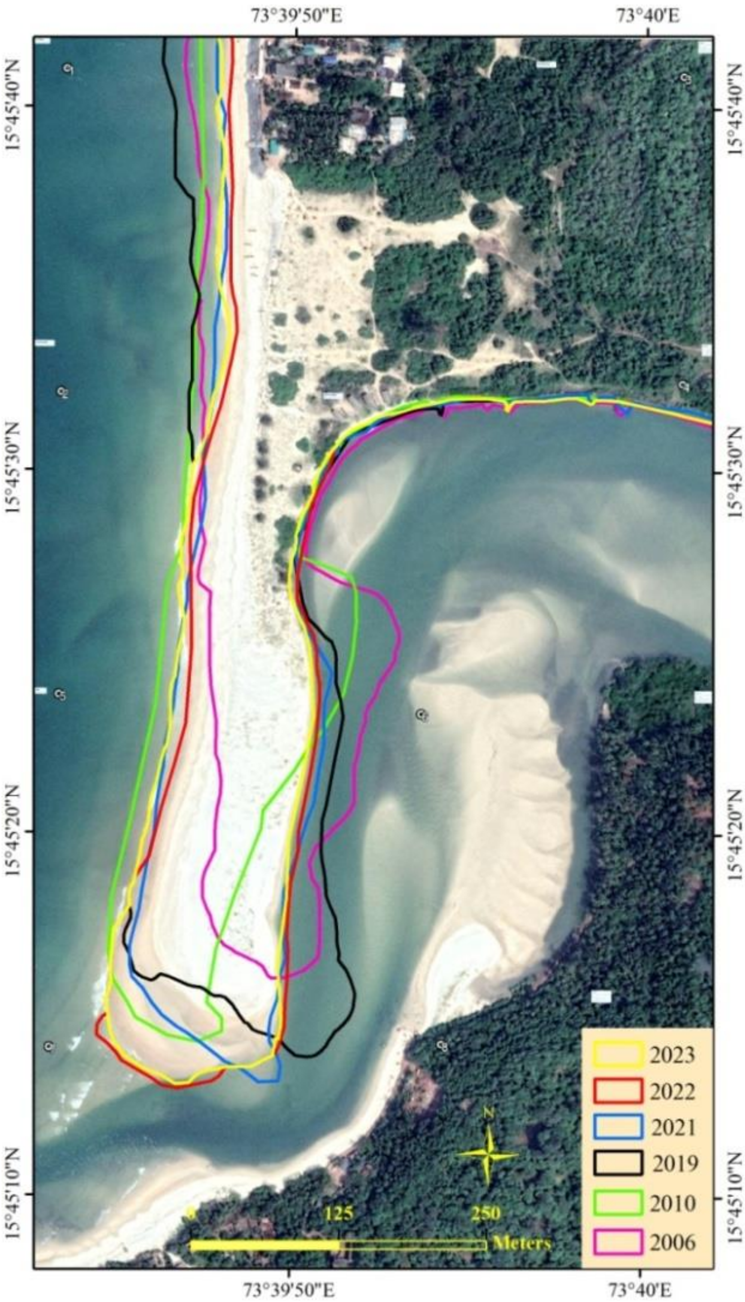

Figure 6: Year wise variations in Shiroda Sand Spit

Severe coastal storms can cause water levels to rise above the usual tide, leading to widespread flooding. The immediate consequences of such disasters include changes and the effects can be varied since they depend on the physical development of the coastal areas[34,42]. In some stormy weather situations, the forebeach can supply sand that helps the backbeach to grow. When the ocean water rises, waves may hit the berm crest and flood the backbeach. The sand that wears away from the berm crest and forebeach is transported across the backbeach by a shallow sheetwash created by wave runup. This sand subsequently settles at the base of the dunes due to the water level being much lower than the dune crests and the water flow rate decreases quickly as energy dissipates[39].

The impact of coastal disasters has accelerated due to the more frequent and intense cyclones, tidal impact and expected rising sea levels. In order to keep track of any damages to the coast, data is gathered from the shoreline regarding the condition of the landforms in the area. Storm surges can cause rivers, estuaries and creeks to carry inundation to low-lying inland areas, damaging valuable coastal environments. The attempted study has studied the decadal variations in coastal landforms in and around the Shiroda coasts. Detailed information about the morphology of coastal erosional and depositional landforms and their changes from 1973 to 2023 was obtained using satellite data.

Multi-spectral images and indices such as NDWI were particularly useful in calculating the land and sea area within the study area. The satellite data used for this study spanned from 1973's Land Sat 1 to 2023's Land Sat 9. The data from Google Earth for 2006, 2010, 2019, 2021, 2022 and 2023 indicated that the Shiroda spit's position was changing. The images demonstrate long-term changes. From 2006 to 2023, the spit shifted approximately 75.6 meters towards the west and 117.2 meters towards the south, indicating the combined effect of various factors such as climate, estuarine flow, sediment, sea waves, erosion and deposition.

In 2010, the spit had shifted entirely to the west side (Fig. 6, 7 and 8a). Between 2010 and 2023, the spit was eroded on the east side. In 2019, the spit area increased and shifted towards the east side, revealing short-term changes from 2019 to 2023 (Fig. 7). A sand spit is a collection of various sediments attached to land at one end and extending into the sea or estuary at the other. These formations protect mangrove swamps, mudflats, coastal communities and estuarine environments from cyclones, sea storms and waves. In Western Maharashtra, sand spits typically form at the mouths of estuaries and tidal inlets.

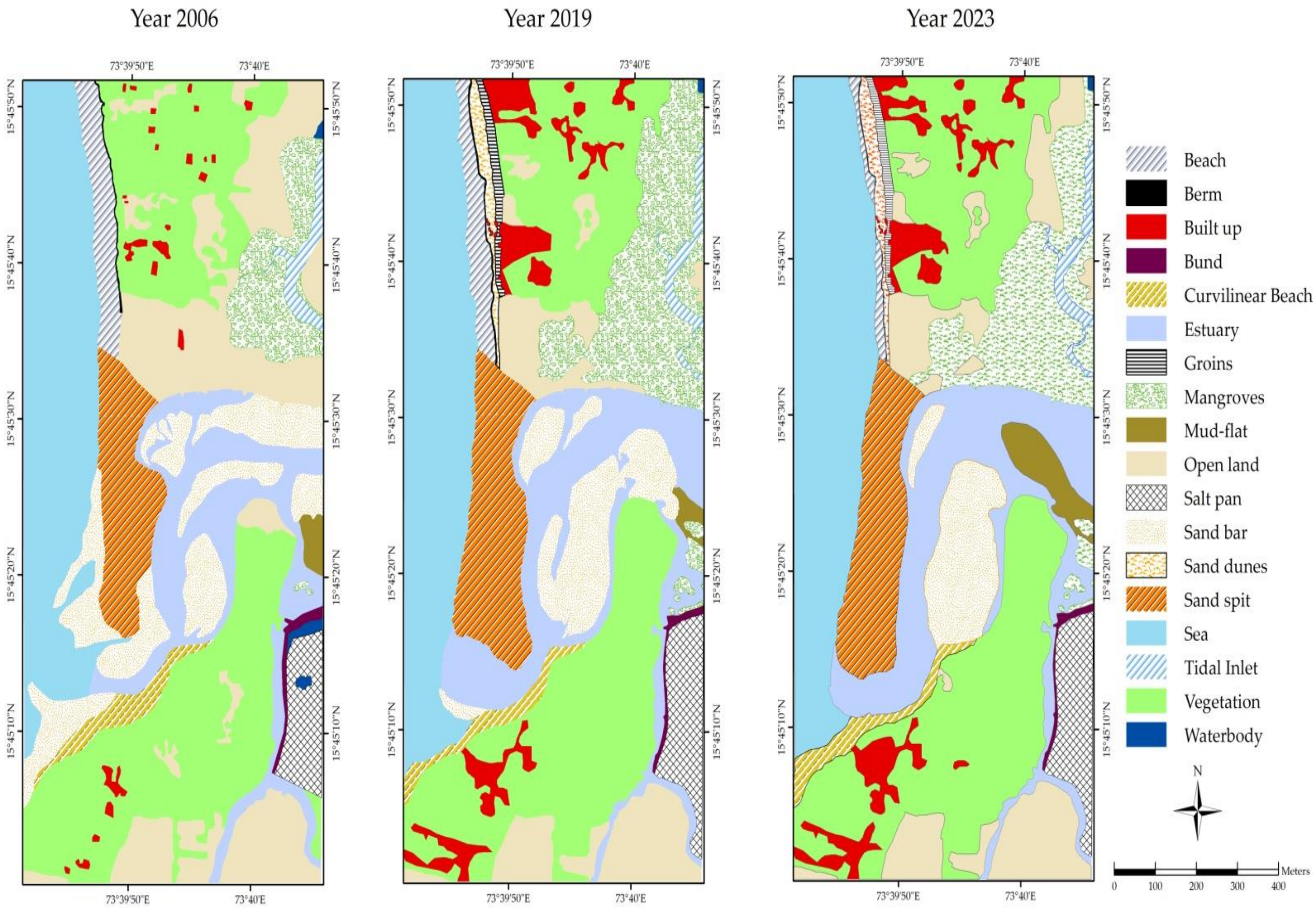

Figure 7: Geomorphic maps of coastal landforms of Shiroda Coasts for the year : 2006, 2019 and 2023

Figure 8: (a) Shiroda-Sand Spit; (b) Exposed Lateritic boulders on beach

It has been observed that the Geomorphic features of Shiroda Beach have changed in specific years namely 2006, 2019 and 2023. Over the years from 2006 to 2023, the beach has rapidly reduced in area and is now covered by Dunes, Groins and some parts of Settlements (Fig. 7). The Groins were not present in 2006 and were constructed by the Government to protect the coastline. Groins are man-made structures parallel to the coastline and essential in controlling the normal longshore movement of sand and minimizing shoreline erosion. They act as physical barriers across the active beach. When sand is trapped against the updrift side of the structure, it eventually creates a more extensive beach on the structure's "supply side."

The number of settlements in the study area has been on the rise. Between 2006 and 2023, there was a significant increase from 0.71 percent to 4.1 percent (Table 3). Meanwhile, sand bars in the estuarine part have undergone drastic changes. In 2006, they were present in many parts, but their presence decreased from 9.9 percent to 4.79 percent due to environmental impact. As for sand dunes, they were not observed in 2006 but were present in 2019 and 2023 accounting for approximately 0.95 percent in both years. Most of the coastal areas rely heavily on the ecosystem provided by mangroves. These plants play a vital role in safeguarding the land from environmental damage.

In the study area, mangroves accounted for 4.4% in 2006 and 9.27% in 2023. Various species, including birds, fish, crabs, shellfish and sea turtles, depend on mangrove habitats for survival. These habitats serve as nesting, breeding and birthing place for the diverse local fauna. For humans, mangroves are of great importance as they provide numerous benefits. The mudflats in this area exhibit topography ranging from centimeters to meters, created by mud bars, crab burrows and drainage creeks. The upper zone of the tidal flats consists of mud flats formed by settling suspended sediment that primarily consists of sortable silts due to depositional processes.

Between 2006 and 2023, mud flats in the study area increased by 0.49 and 1.59 percent respectively. The vegetation coverage in the study area has remained mostly the same, covering approximately 25 percent. However, the salt pan has been expanding over time. Overall, the area's geomorphology has changed between 2006 and 2023 (Fig. 8a and b).

Conclusion

Geomorphic maps were prepared for the study area, highlighting the concerning alterations in the coastal landforms due to climate change. Basically, geomorphological maps describe Earth's surface, including landform shape and spatial properties like dimensions, slope and relief. They also indicate the origin and evolution of landforms about genetic agents and processes and the status of those processes. The geomorphic maps of the attempted study show how coastal sediment characteristics interact with coastal processes and structures. They also indicate the type and deposits of sediments, reflecting climate change's disastrous impact.

The study found that the size of the spit is decreasing seasonally at a varying rate. The size, shape and characteristics of sand spits, sand bars and beaches are largely influenced by factors such as the type and availability of sand and sediments, wind speed and direction, sea waves and currents. In coastal Maharashtra, certain sand spits are particularly vulnerable to damage during cyclones and tsunamis. Additionally, erosion and deposition are ongoing processes in this region. To protect these valuable coastal landforms, it is essential to implement effective conservation practices.

Maharashtra's coastal areas are affected by both direct and indirect consequences of climate change. This includes increased extreme weather events like cyclones and storms, worsening the risks of erosion, flooding and coastal landscape changes in the region. It has been also noticed that the settlement and infrastructure in Shiroda are at greater risk of flooding from the Tiroda estuary in the mouth areas. The frequency of devastating effects increases in these locations and damages are escalating during storms, high floods, tides and cyclones. To identify potential sites of high erosion and help mitigate natural disasters, it is necessary to periodically assess the shifts and migration of sand spits and sand bars in the study area. This change detection study is crucial for protecting the area from further damage.

Coastal regions rely on erosional and depositional landforms to maintain a balanced ecosystem along the coastline. To improve the accuracy of geomorphic mapping, several factors and processes were examined. Local authorities and policymakers can use the resulting data to mitigate the risk of disasters in the study area. The methodology and results also offer new insights to mitigate potential catastrophic destructions, which can be applied to other coastal studies in India.

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