ASSESSMENT OF COASTAL VULNERABILITY USING GIS AND AHP: A STUDY IN DIGHA-MANDARMANI COAST, WEST BENGAL

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DECLARATION

The Thesis titled "***Assessment of Coastal Vulnerability using GIS and AHP: A Study in Digha-Mandarmani Coast, West Bengal***" is prepared and submitted for the award of the degree of ***Master of Engineering in Civil Engineering*** course of ***Jadavpur University*** for the session of ***2022-2024***. I hereby declare that all of the work included in this thesis is original to me. The work mentioned in this thesis has not been submitted in part to support an application for a different degree or certificate from this university or any other. All sources of information and assistance used in the thesis have been properly credited.

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RECOMMENDATION CERTIFICATE

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Final Examination for Evaluation of thesis

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ABBREVIATIONS

AHP – Analytical Hierarchy Process
ASTER – Advanced Spaceborne Thermal Emission and Reflection Radiometer
CCS – Cloud Classification System
CHRS – Center for Hydrometeorology and Remote Sensing
CVI – Coastal Vulnerability Index
DEM – Digital Elevation Model
DSAS – Digital Shoreline Analysis System
ERS – European Remote Sensing
ESRI – Environmental Systems Research Institute
GIS – Geographic Information System
GPS – Global Positioning System
IDW – Inverse distance weighted interpolation
IMD – Indian Meteorological Department
INCOIS – Indian National Centre for Ocean Information Services
IPCC – Intergovernmental Panel on Climate Change
LULC – Land Cover and Land Use
MOES – Ministry of Earth Sciences
MVI – Meteorological Vulnerability Index
NASA – National Aeronautics and Space Administration
NOAA – National Oceanic and Atmospheric Administration
PMGSY – Pradhan Mantri Gram Sadak Yojana
PVI – Physical Vulnerability Index
RRI – River Research Institute
RS – Remote Sensing
RSMC – Regional Specialized Meteorological Centre
SRTM – Shuttle Radar Topography Mission
SVI – Socio-economic Vulnerability Index
USGS – United States Geological Survey

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1. Introduction

Coastal areas are diverse, active, and multi-functional systems, with many environmental and biological values, socio-economic happenings, and high biodiversity. Coastal areas can be severely affected by various processes and remains to be in hotspot, as these regions regularly inundate due to weather and climate influences and natural events such as tsunami, shoreline erosion and devastation due to calamities like cyclones.

Climate change refers to a change in the global climate pattern. Our planet has witnessed changes in the climatic pattern over the centuries. However, the changes that have occurred from the mid to the late 20th century are more apparent. Deforestation and burning of fossil fuels have caused an increase in carbon dioxide levels in the atmosphere resulting in an enhanced greenhouse effect, global warming and a change in climatic pattern. To name a few major changes, the world is currently facing increased temperature, unjustified droughts, unpredictable weather patterns, sudden rains and storms, and snowfall. and the weather is no longer predictable enough. Rainfall and storms have become more unpredictable and occur more frequently in India due to climate change. Most developing countries sufferers from immense challenges due to the climate extremes and especially for countries that have a highly dense population, limited resources, and dependence on non-renewable energies and sources, and have very little capacity to cope with these environmental threats.

Globally, Coastal areas, when compared to hinterland, are more vulnerable to natural hazards like tropical cyclones, storm surges and flooding as the area is directly exposed to the sea (Guleria, 2020). What actually makes these hazards turn into disasters, is the vulnerability of the people and their means of livelihood and the fragility of infrastructure. Though only 2% of the total land area around the world is coastal region, about 10% of world's population live in coastal areas (Neumann et al., 2015), as they offer access points for marine transport, tourism and other livelihood facilities like fishing. As a result of the climate change, the average surface temperature of earth increased by 1.1° C (Hansen et al., 2010) and polar ice is melting. Both the melting of polar ice (Dutton et al., 2015) and thermal expansion of ocean water (Wigley & Raper, 1987) accelerate the rise of sea level. Many metropolitan cities located near coastal areas have become unsustainable due to sea level rise and increasing storm surges (Jacob, 2015). Thus, assessment of vulnerability of coastal area is important to help stakeholders and policymakers for understanding the impacts of natural hazards and for identifying the vulnerable regions of a coastline to frame out mitigation measures and environmental management planning.

Geographic Information System (GIS) is helpful in the field of coastal vulnerability studies because it can be used to analyze and monitor the elevation and slope profile, periodical shoreline changes, geomorphology, land cover and land use and other factors and events like cyclonic storms and floods, which affects the vulnerability of coastal areas. All the hazard-related data with the help of GIS can be transferred into visual information as a map (Gillespie et al., 2007). Better forecasting of the discovery of disaster-prone regions as well as the regions of security measures can be achieved with the help of Remote Sensing and GIS (Matori et al., 2014). Moreover, Analytical Hierarchy Process (AHP) can be further used as a decision-making method for the determination of coastal vulnerability as it provides a better understanding of complex decisions by employing a pairwise comparison procedure between the affecting parameters and by ranking them according to their relative importance.

The purpose of the study is to assess the vulnerability of a coastline and represent it as a visual information or map using Remote Sensing datasets combined with GIS and AHP which will help disaster managers, policymakers and planners in disaster management and risk mitigation strategies. Further, it can be beneficial for the coastal community who are in some way or other suffering due to natural hazards.

2. Literature Review

2.1 Concept of Coastal Vulnerability

Coastal vulnerability is a concept that identifies people and places that are susceptible to disturbances resulting from coastal hazards. Hazards in the coastal environment, such as coastal storms and erosion, pose significant threats to coastal physical, economic, and social systems. The theory of vulnerability has been an evolving idea over the past few decades. Gornitz et al., 1994, proposed an index-based method considering six variables to assess the vulnerability of coastal areas (Fig 2.1). Later, several other studies modified the method and introduced new parameters like Land Use and Land Cover (Mohamed, 2020; Roy et al., 2023), Population Density (Furlan et al., 2021; Mullick et al., 2019) etc. Some other studies considered meteorological parameters like Precipitation, Dew Point, Wind Speed to assess the vulnerability of coastal area (Marzouk et al., 2021). Beside this index-based method, there are various approaches for determining the vulnerability of coastal areas. Some scholars considered many other parameters and modified this index-based method using analytical hierarchy process (Thirumurthy et al., 2022) and Artificial Neural Network (ANN) (Mandal et al., 2022).

	Ranking of coastal vulnerability index				
	Very low	Low	Moderate	High	Very high
VARIABLE	1	2	3	4	5
Geomorphology	Rocky, cliffed coasts Fiords Fiards	Medium cliffs Indented coasts	Low cliffs Glacial drift Alluvial plains	Cobble beaches Estuary Lagoon	Barrier beaches Sand Beaches Salt marsh Mud flats Deltas Mangrove Coral reefs
Coastal Slope (%)	> 1.9	1.3 – 1.9	0.9 – 1.3	0.6 –0.9	< .6
Relative sea-level change (mm/yr)	< -1.21	-1.21 – 0.1	0.1 – 1.24	1.24 –1.36	> 1.36
Shoreline erosion/ accretion (m/yr)	>2.0 Accretion	1.0 –2.0	-1.0 – +1.0 Stable	-1.1– -2.0	< - 2.0 Erosion
Mean tide range (m)	> 6.0	4.1 – 6.0	2.0 – 4.0	1.0 –1.9	< 1.0
Mean wave height (m)	<1.1	1.1 – 2.0	2.0 – 2.25	2.25 –2.60	>2.60

Fig 2.1: Ranking of coastal vulnerability index variable (Gornitz et al., 1994)

In many studies, parameters were classified into different categories and sub-indexes were calculated to determine the overall vulnerability index. De Serio et al., 2018 classified parameters into two groups: Physical and Socio-economic parameters and calculated Physical Vulnerability Index (PVI) and Socio-economic Vulnerability Index (SVI) to determine the Coastal Vulnerability Index. Some other researchers classified parameters into three groups: Exposure, Sensitivity and Adaptive Capacity to assess the vulnerability (Ghosh & Mistri, 2022). Some studies on coastal vulnerability assessment are described briefly in Table 1.

Table 1: Previous studies, parameters and methods for Assessment of Coastal Vulnerability

Author(s)& Year	Title	Study Area	Parameters Considered	Data Sources	Method for Calculating CVI
Vivien M. Gornitz 1990	Vulnerability of the East Coast, U.S.A. to Future Sea Level Rise	East Coast of U.S.A including parts of Cape Cod, Long Island and the New Jersey barrier beaches, the North Carolina Outer Banks, the southern Delmarva Peninsula, and Georgia-South Carolina	(1) Sea Level Rise (2) Mean Tide Range (3) Coastal Slope (4) Geomorphology (5) Shoreline Change (6) Mean Wave Height.	(1) USGS (2) Tide gauge data. (3) Coastal Erosion Information System.	Index Method
Vivien M. Gornitz, Richard C. Daniels, Tammy W. White and Kevin R. Birdwell, 1994	The Development of a Coastal Risk Assessment Database: Vulnerability to Sea-Level Rise in the U.S. Southeast	U.S. South-East Coast extending from the Virginia-North Carolina border to the Texas-Mexican border	(1) Elevation (2) Geology (3) Geomorphology (4) Sea Level Rise (5) Shoreline Change rate (6) Mean Tide range (7) Maximum Wave Height (8) Annual Tropical Storm Probability (9) Annual Hurricane Probability (10) Hurricane frequency intensity index (11) Mean forward velocity. (12) Annual mean number of extra tropical cyclone (13) Mean Hurricane Surge	(1) USGS (2) National Ocean Service, 1988 (3) Coastal Erosion Information System (4) U.S. Army Corps of Engineers (5) Tide Gauge data.	Index Method

D. C. Roy, T. Blaschke 2011	A Grid-Based Approach for Spatial Vulnerability Assessment to Flood: A Case Study on the Coastal Area of Bangladesh	Dacope, an upazila (sub-district) of Khulna district of Bangladesh.	(1) Sensitivity; Population and age, Livelihood and poverty, Health, Water and sanitation, Housing and shelter, Roads and other infrastructure, Land use/cover, Environment, Gender (2) Coping Capacity; Assets, Education and human resource capacity, Economic alternatives.	(1) Bangladesh Bureau of Statistics (BBS). (2) Bangladesh Local Government Engineering Department	Weighted overlay using AHP
Farida Duriyapong and Kanchana Nakhapakor 2011	Coastal vulnerability assessment: a case study of Samut Sakhon coastal zone	Samut Sakhon coastal zone, south-central Thailan	(1) Shoreline erosion rate (2) Slope (3) Mean tide range (4) Mean wave height (5) Population density (6) Land use (7) Cultural Heritage (8) Roads/Railway	(1) GISTDA (2) Royal Thai Survey Department, Land Development Dept. (3) Hydrographic Dept, Royal Thai Navy (4) Meteorological stations (5) Dept. of land development	Index Method using AHP
S. R. C. Reyes, A. C. Blanco; 2012	Assessment of Coastal Vulnerability to Sea Level Rise of Bolinao, Pangasinan using Remote Sensing and Geographic Information System	Bolinao, Pangasina	(1) Sea level anomaly (2) Tide Range (3) Coastal Topography. (4) Socioeconomic Variables.	(1) ERS-1, and ERS-2, (2) Envisat 1, (3) TOPEX/PO (4) SEIDON, (5) JASON-1 and JASON-2. (6) NAMRIA	Index method modified by AHP
Li Lin, Pgrni Pussella; 2017	Assessment of vulnerability for coastal erosion with GIS and AHP techniques case study: Southern coastline of Sri Lanka	South-western coastline of Sri Lanka	(1) Geomorphology (2) Sand dune width (3) Coastal slope (4) Rate of coastline erosion. (5) Average tidal range (6) Direction of tides (7) Mean wave height (8) Protection measures. (9) Adjacent land use.		Weighted overlay using AHP

Francesca De Serio, Elvira Armenio, Michele Mossa and Antonio Felice Petrillo; 2018	How to Define Priorities in Coastal Vulnerability Assessment	Apulian region facing the Adriatic Sea, included between the Gulf of Manfredonia and the city of Barletta	(1) Physical parameters; Coastal slope, coastline landform, significant wave height, shoreline change rate, sea-level rise, Tidal data, Coastal Elevation. (2) Socio-Economic Parameters; Population, Road networks, Land use and land cover.	(1) ECMWF model (2) Aerial photos (spatial), GPS measurements. (3) Literature review data	Index method modified by AHP
Rashmisikha Behera, Abhipsa Kar, Manas Ranjan Das, Prachi Prava Panda; 2019	GIS-based vulnerability mapping of the coastal stretch from Puri to Konark in Odisha using analytical hierarchy process	Puri, Bhadrak, Balasore, Ganjam, Jagatsinghpur and Kendrapara	(1) Social Parameters; Population, Infrastructure and heritage importance, (2) Geological Parameters; Soil type, shear strength of soil, (3) Physical Parameters; Shoreline change rate, Tidal Range, Coastal slope, Proximity to sea.	(1) Census Data (2) Data obtained from Hotel Association, Puri, and field survey (3) Google Earth Pro (4) Literature Review.	Modified AHP process
Md. Reaz Akter Mullick, A.H. Tanim, S M Samiul Islam; 2019	Coastal vulnerability analysis of Bangladesh coast using fuzzy logic based geospatial techniques	The coast of Bangladesh, located at the head of Bay of Bengal	(1) Coastal Characteristics; Coastal Slope, Elevation, Rate of Shoreline Changes. (2) Coastal Forcing; Sea Level Rise, Significant Sea level height, Cyclone track density (Cyclone intensity per year per 30 km radius), Mean Tidal Range. (3) Socioeconomic; Land-use, Population Density,	(1) Digital Bathymetry Data. (2) SRTM DEM (3) 40 years shoreline change rate from another paper. (4) SWAN model (5) JTWC (6) NOAA (7) Sentinel 2 Satellite image (8) BBS 2011	Index method modified by Fuzzy Logic

Mirela Barros Serafim, Eduardo Siegle, Alessandra Cristina Corsi, Jarbas Bonetti; 2019	Coastal vulnerability to wave impacts using a multi-criteria index: Santa Catarina (Brazil)	Southern Brazil, the coastline of the state of Santa Catarina	(1) susceptibility; Significant wave height, Potential longshore drift, Beach width, Elevation and Slope. (2) Adaptive Capacity; Urbanized area, Distance of developed area from the coastline, Number of residents, Income per capita		Index method with AHP
Soha A. Mohamed, 2020	Coastal vulnerability assessment using GIS-Based multicriteria analysis of Alexandria-northwestern Nile Delta, Egypt	Alexandria-northwestern Nile Delta, Egypt	(1) Land Cover (2) Backshore elevation (3) Shoreline composition/seabed type (4) Relative sea level change rate (5) Shoreline change rate (erosion, accretion or stable) (6) Tidal range (7) Average wave height (8) Shore protection structures (9) Beach type	(1) Topographic maps (2) ASTER (3) Landsat-8 OLI/TIRS (4) Coastal variables (Tabular data) provided by Coastal Research Institute in Alexandria.	Index Method by AHP
Muhammad Al-Amin Hoque, Biswajeet Pradhan, Naser Ahmed, Bayes Ahmed & Abdullah M. Alamri; 2021	Cyclone vulnerability assessment of the western coast of Bangladesh	Ganges tidal deltaic plain, which is known as western coastal zone, Bangladesh	(1) Physical; Elevation, Slope, Proximity to cyclone track and coastline, Land Cover and Land Use. (2) Social; Population density, Children, female, disabled and older population, wooden house, Literacy rate, Dependency on agriculture. (3) Mitigation Capacity; Distance to cyclone shelter and health care, Cyclone warning system, Road networks, Proximity to coastal vegetation, Embankments.	(1) USGS Earthexplorer (2) DigitalGlobe foundation (3) SOB (4) BBS (5) IBTrACS (6) LGED and Fieldwork	Fuzzy AHP Overlay

Mohamed Marzouk, Khalid Attia, Shimaa Azab; 2021	Assessment of Coastal Vulnerability to Climate Change Impacts using GIS and Remote Sensing: A Case Study of Al-Alamein New City	Al-Alamein New City, Egypt	(1) Meteorological Parameters; Surface Temperature, Precipitation, Sea Level Pressure, Dew Point, Wind Speed, Wind Direction, (2) Topographical Structure; Coastal Slope, Coastal Regional Elevation, (3) Engineering Geology; Composition of Earth Material. (4) Shoreline; Erosion or Accretion.	(1) NOAA's NCDC and open data portal. (2) DEM (3) Geologic Map (4) Satellite Imagery.	Equal weighted overlay of maps.
Sanzida Murshed, David J. Paull, Amy L. Griffin, Md Ashraful Islam; 2021	A parsimonious approach to mapping climate-change-related composite disaster risk at the local scale in coastal Bangladesh	Patharghata Upazila, Bangladesh	(1) Threat; Cyclone frequency, storm surge, sea level rise, shoreline change rate. (2) Sensitivity; Population Density, Land use and land cover. (3) Exposure; Geomorphology, slope, bathymetry.	(1) NOAA (2) Available literature and reports. (3) BWDB tide gauge. (4) USGS (5) Google Earth, LGED, BBS (6) Landsat OLI and TIRS (7) Field Data (8) SRTM DEM (9) GMRT	Disaster Risk Index mapping
Pintu Mandal, Arabinda Maiti, Sayantani Paul, Subhasis BhattacharyaSuman Paul; 2022	Mapping the multi-hazards risk index for coastal block of Sundarban, India using AHP and machine learning algorithms	Pathar Pratima CD Block of South 24 Parganas district of West Bengal, India	(1) Cyclonic storms (2) Storms and Tidal Surge (3) Embankment Breaching (4) accretion and erosion, (5) soil salinization (6) inundation.	(1) IMD (2) Central Water Commission, India (3) Irrigation and Waterways Department, WB (4) USGS	Index Method using ANN and AHP
Kasturi Mandal, Priyanka Dey; 2022	Coastal vulnerability analysis and RIDIT scoring of socio-economic vulnerability indicators – A case of Jagatsinghpur, Odisha.	Jagatsinghpur, Odisha.	(1) Shoreline change rate. (2) Barrier type. (3) Coastal slope (4) Signification wave height. (5) Shoreline exposure (6) Regional Elevation (7) Coastal geomorphology (8) Tidal surge height.	(1) LANDSAT MSS (2) LANDSAT TM (3) GEBCO (4) INCOIS (5) SRTM DEM (6) LISS IV (7) OSDMA (8) Google Earth Imagery.	Index Method

Soumen Ghosh, Biswaranjan Mistri; 2022	Analyzing the multi-hazard coastal vulnerability of Matla–Bidya inter-estuarine area of Indian Sundarbans using analytical hierarchy process and geospatial techniques	Matla–Bidya inter-estuarine area of Indian Sundarbans delta	(1) Exposure; Elevation, Slope, Drainage density, Proximity to coastline, Rainfall deviation, Cyclone track density, Storm surge height, Flood inundation risk. (2) Sensitivity; Population density, Household density, Poverty ratio, % of net shown area, % of people living in kutcha house. (3) Adaptive Capacity; Literacy rate, Workforce, Percentage of population living in pucca house, Percentage of people can access primary medical services, electricity, banking and internet.	(1) SRTM DEM data, 2015, (2) Landsat 8 OLI, 2020 (3) Google earth pro, (4) Irrigation and Waterways Directorate, Govt. Of West Bengal. (5) Cyclone eatlas-IMD (6) India-WRIS (Water Resource Information System) (7) Census of India 2011 (8) Human Development Report (2009 & 2010) (9) Field Survey 2020-21	Index Method modified by AHP
S. Thirumurthy,M. Jayanthi M. Samynathan M. Duraisamy, S. Kabiraj, N. Anbazhahan;2022	Multi-criteria coastal environmental vulnerability assessment using analytic hierarchy process-based uncertainty analysis integrated into GIS	Two densely populated coastal districts of India, namely Kancheepuram and Tiruvallur Districts of Tamil Nadu	(1) sea-level rise induced inundation. (2) coastal elevation. (3) coastal slope (4) extreme rainy days (5) historical shoreline change (6) tidal range (7) geomorphology	(1) SRTM DEM. (2) Indian Metrological Department rainfall data (2007–2016) (3) High-water lines from satellite images of 1973, 1988, 2003, and 2018	Index Method modified by AHP
Paramita Roy, Subodh Chandra Pal, Rabin Chakraborty, Indrajit Chowdhuri, Asish Saha, Manisa Shit; 2023	Effects of climate change and sea-level rise on coastal habitat: Vulnerability assessment, adaptation strategies and policy recommendations	India's coastline stretches between 7◦ and 24◦N latitude and 70◦ and 94◦E longitude, with the "Arabian Sea" to the west and the "Bay of Bengal" to the east.	(1) Geomorphology (2) Sea Level Change (3) Coastal Slope (4) Relative Sea Level Change (5) Mean Wave Height (6) Mean Tide Range (7) Shoreline Change Rate (8) Land Use and Human Activities (9) Population.	(1) Geological Survey of India (2) Toposheet, Landsat, Sentinel (3) National Hydrographic Office (4) PSMSL (5) NIOT JASON-1, Wintidex (6) Census of India	Index Method

2.2 Methods for determining CVI

2.2.1 Index Methods and Modifications

Gornitz et al., 1994 created the coastal vulnerability index (CVI) concept, considering the consequences of the rise in sea levels (particularly flood and erosion) using the following parameters: geomorphology, shoreline change frequency, the slope of the coast, rate of sea level, wave height, and range of tide (Fig 2.1). In recent years, there has been a substantial increase in vulnerability indices for specific coastal locations. Coastal indexes were created to group coastlines under homogeneous groups with comparable characteristics. These classifications can then aid the establishment. The Gornitz's formula was used for most vulnerability evaluations.

Later, the CVI assessment was improved by changing the availability and geographic location parameters. Composite vulnerability indices and multiple-scale coastal vulnerability indexes have resulted from the development of CVI assessment. Different subindices based on parameter features are used in a multiple scale CVI, which are then blended for overall CVI, considering both the socioeconomic vulnerability index (SVI) and physical vulnerability index (PVI). The PVI risk factors observed are coastal slope, geomorphology, elevation, coastline fluctuation, rising sea level, range of tide, the height of the wave, and SVI risk factors consisting of road network, tourism, land use and population. PVI and SVI are then calculated using the hierarchical analytical process (AHP), and the overall CVI is determined by the average of PVI and SVI (Rocha et al., 2023). AHP is a process involving multiple criteria in deciding which various variables are given a priority ranking(Bui et al., 2023). The factors, which are dependent on the physical properties of the area, are the initial stage in determining the CVI. These characteristics are quantified and ranked, with the most common being low, moderate, high, and very high. (Ghazali et al., 2018) investigated the northwest of Peninsular Malaysia coastal vulnerability by summing factors and assigned values to different factors. The authors looked at five parameters and assessed vulnerability by adding a parameter to the variables based on the parameter's relevance and the effect of sea-level rise, with the following results: geomorphology, the slope of the coast, coastline change, tide range, and wave height.

2.2.2 GIS and Dynamic Computer Models

In numerous analyses, coastal vulnerabilities are displayed using a GIS. The use of the square root of the output average has been combined with GIS approaches to evaluate the coastal vulnerability. Physical vulnerability is measured by the square root of the parameter's average, while social and environmental vulnerabilities are calculated using the normalized technique. In ArcGIS software, the three vulnerabilities are combined and visually shown as reported by Malaysia, Thailand, and Vietnam, in order to map the vulnerable coastlines. Climate change risk and the adaptation efforts simulator (simCLIM), community vulnerability assessment tool (CVAT), dynamic interactive vulnerability assessment (DIVA), and coastal and climate decision support systems (DSS) have been developed and publicly available (Ghoussein et al., 2018). The Digital Shoreline Assessment System (DSAS) has been widely used with ESRI ArcGIS 10 extension program to measure the rate of change of coastline. To diminish the risk of cyclones, the Ayeyarwady Delta coast of Myanmar has implemented integrated coastal zone management (ICZM), which then developed an expert decision support system (EDSS) for coastal cyclone and storm vulnerability (Win et al., 2020). In the monitoring and mapping of geo-hazards, satellite remote-sensing data combined with GIS provides an excellent alternative to traditional mapping methodologies. It is used to handle, gather, share, record, analyze, update, organize, and integrate spatial (geographic) information extracted from Global Positioning System (GPS), maps, and remote sensing. GIS allows mapping and transforming overall risks data into visual information(Anfuso et al., 2021). GIS is the most direct method for mapping any risk area closely. It is an important tool for expanding, developing, and testing vulnerability models that explicitly focus on area.

2.3. Parameters for the determination of CVI

2.3.1 Sea Level Rise

The Earth's average temperature has been steadily rising, resulting in the melting of polar ice caps and glaciers. This contributes to rising sea levels, leading to coastal erosion and the inundation of low-lying areas, threatening millions of people living in coastal regions. According to National Oceanic and Atmospheric Administration; NOAA's 2021 Annual Climate Report the combined land and ocean temperature has increased at an average rate of 0.14°F (0.08°C) per decade in total since 1880; however, the average rate of increase since 1981 has been more than twice as fast: 0.32°F (0.18°C) per decade as shown in Fig. 2.2.

According to NASA Antarctica is losing ice mass (melting) at an average rate of about 150 billion tons per year, and Greenland is losing about 270 billion tons per year due to global warming, adding to sea level rise at a rate of 3.4 millimeters (about 0.13 in) per year (Fig. 2.3). In general, the Sea Level Rise is caused due to two physical phenomena: One is due to thermal expansion of seawater, and the other is glacial melting. Impact of SLR affects other parameters such as shoreline change, geomorphology, land use, land cover and ground water flow. SLR not only results in the inundation of coastal areas, but also increases the vulnerability of coastal regions to flooding caused by storm surges and tsunamis.

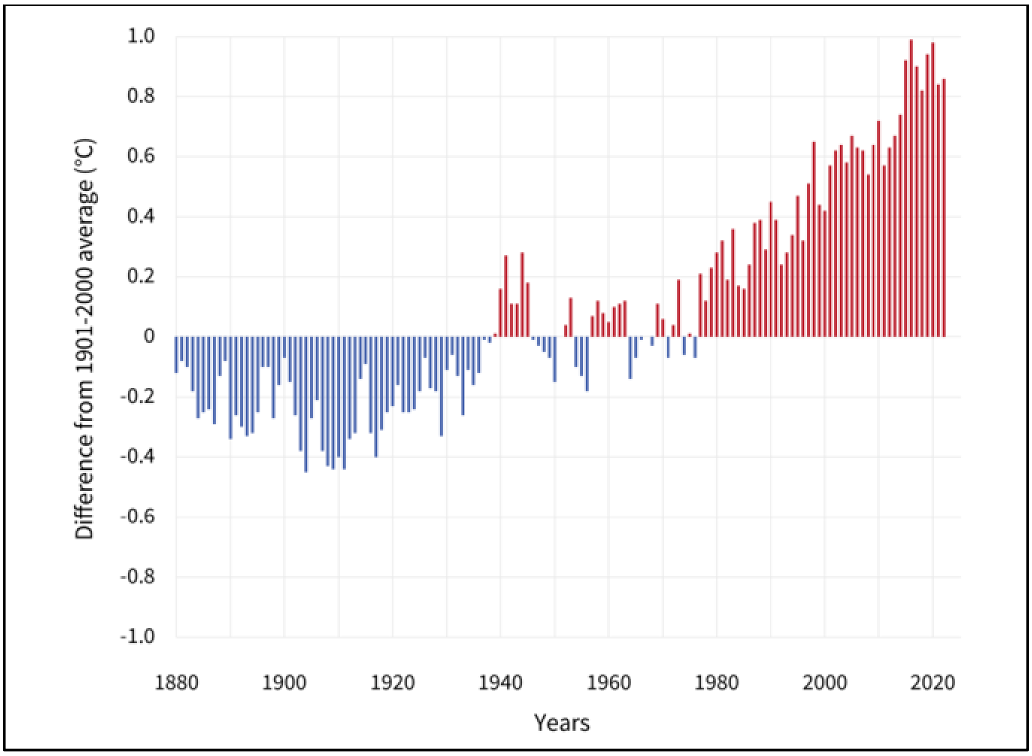

Fig 2.2: Difference between temperature of last two decades and average surface temperature (13.9°C) of the Earth(NOAA, 2021)

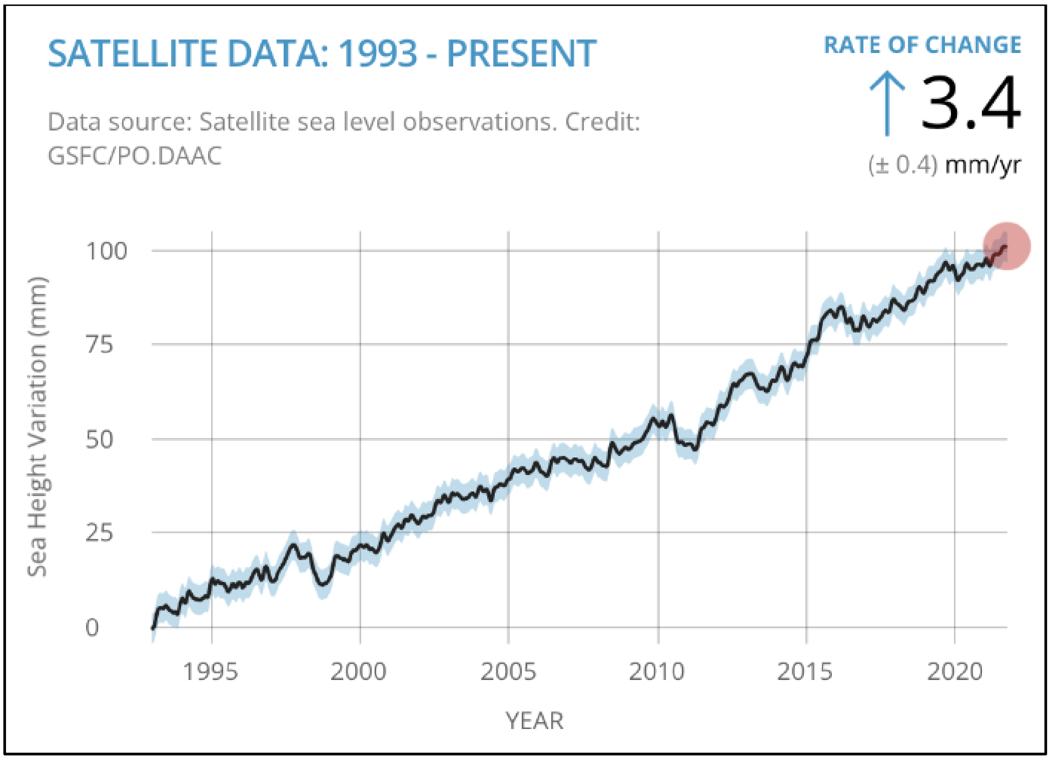

Fig 2.3: Sea level rise from 1993 to present (NASA)

2.3.2 Elevation of Coastal Area

It is the average elevation of any region above the mean sea-level. It is crucial to study this parameter in detail to determine and quantify the amount of land affected by future rising sea levels. Coastal locations that have low-lying elevations are considered to be very vulnerable, whereas coastal areas that have higher elevations are considered to be less vulnerable (Gornitz et al., 1994). The coastal elevation is relevant to use in assessing vulnerability because it could be used to (1) detect and measure the scope of land threatened by sea-level rise, (2) potentially predict land available for mangrove relocation, and (3) evaluate the effects of rising of sea level on community (Nidhinarangkoon & Ritphring, 2021). Since higher altitudes are more resistant to flooding caused by sea-level rise or storms, coastal regions with higher elevations are considered less vulnerable.

2.3.3 Geomorphology

Geomorphology is the scientific study of land formations and land shapes. The geomorphological structure of the coastal area is essential in evaluating the consequences of susceptibility. Different landforms and their material respond differently to natural hazards that occur along the coastal belt. Geomorphology has been considered as an important parameter in understanding the dynamic coast (Mujabar & Chandrasekar, 2012). Coastal areas with rocky or cliffed coasts are less vulnerable compared to sand beaches because sand beaches can erode quickly and provide less resistance to the natural forces of the open sea.

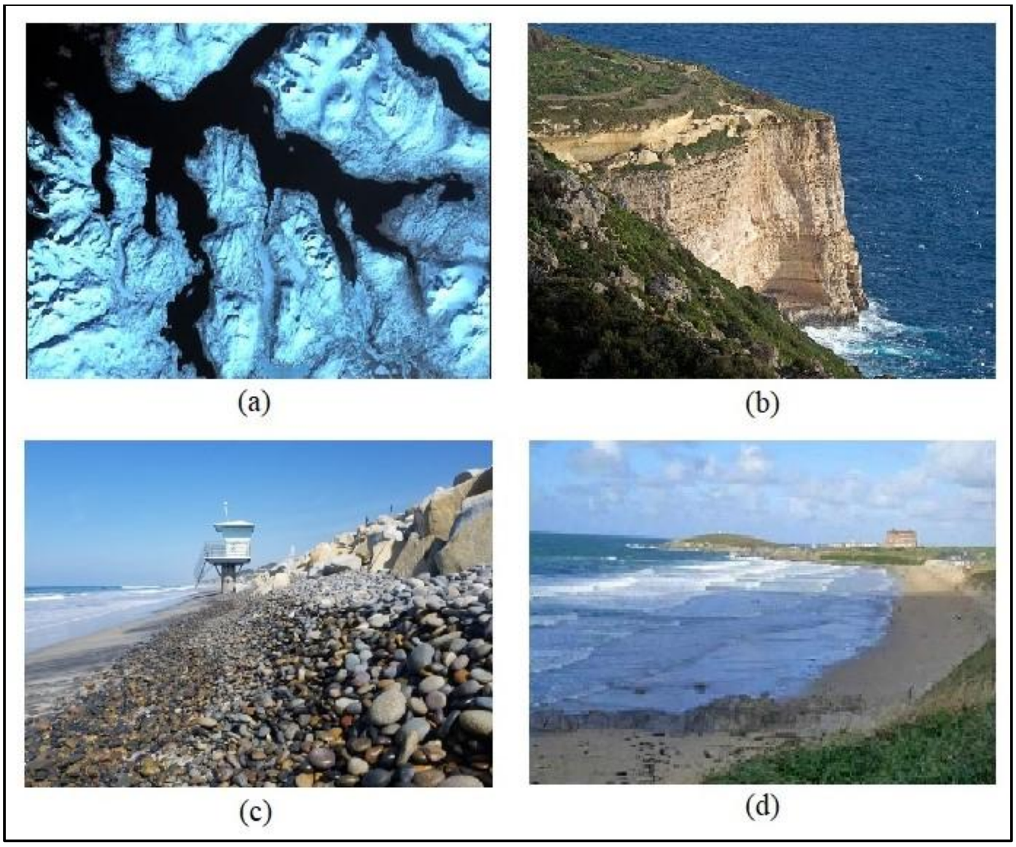

Fig 2.4: (a) Fjords (NASA Earth Observatory), (b) Cliffed Coast (Wikipedia),

(c) Cobble Beach (Coastal Processes Group), (d) Sand Beach (Britannica)

2.3.4 Shoreline Changes: Erosion and Accretion Patterns

Shoreline or coastal line is the boundary between land and sea and continuously change due to erosion, accretion, topography and tidal processes and sea-level changes. Shoreline change is a natural process, but additional shoreline changes occur when the perturbations are introduced by anthropogenic factors/activities such as construction of structures, ports, industries, aquaculture farming etc. in coastal waters. They occur in three-time evolutions, viz. seasonal, annual and decadal. Monitoring changes in shoreline helps to identify the nature and processes that caused these changes in any specific area, to assess the human impact and plan management strategies (Selvavinayagam, 2008). Accurate detection and frequent monitoring of shorelines are essential to understand land accretion and erosion activities along the coastline (Mujabar & Chandrasekar, 2013).

2.3.5 Tide Range

The height difference between high and low tide due to the moons and the sun’s gravitational pull, is referred to as the tidal range. The side of the Earth closest to the Moon experiences the Moon’s pull the strongest, and this causes the seas to rise, creating high tides. On the side facing away from the Moon, the rotational force of the Earth is stronger than the Moon’s gravitational pull. The rotational force causes water to pile up as the water tries to resist that force, so high tides form on this side, too. Elsewhere on the Earth, the ocean recedes, producing low tides. The gravitational attraction of the Sun also plays a small role in the formation of tides. Tides move around the Earth as bulges in the ocean. Most shorelines experience two high and two low tides within a twentyfour-hour period. From the standpoint of vulnerability, there is an evident tendency to categorize coastal regions with a higher tidal range as extremely susceptible, while coastal regions with a lower tidal range are deemed less susceptible.

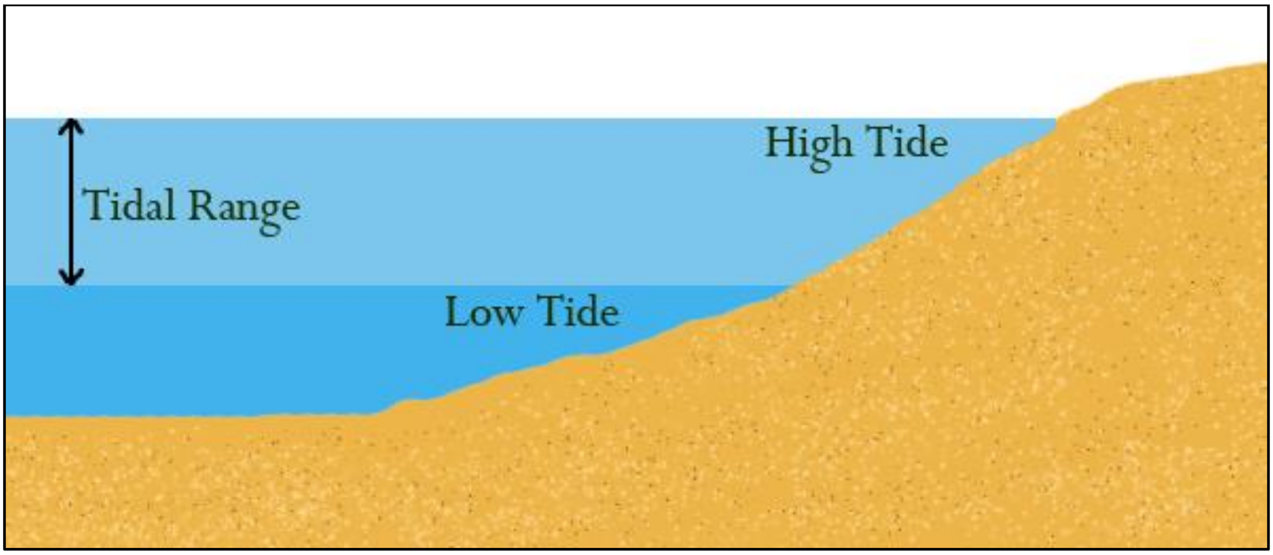

Fig 2.5: Tidal Range (Wikipedia)

2.3.6 Significant Wave Height

Significant Wave height is used here as an indicator of wave energy, which drives the coastal sediment budget. Wave energy increases as the square of the wave height; thus, the ability to mobilize and transport beach or coastal materials is a function of wave height (Gornitz et al., 1994). Increase in wave height results in land loss due to increased erosion and flooding along the coast. The higher the wave height, the more the region is vulnerable and vice-versa.

Intensification in futuristic wave climate can have direct implications on coastal infrastructure, thereby increasing the risk of damage and inundation. This increasing wave height gradually results in coastal flooding and erosion. Other aspects such as marine transportation and navigation, frequency of flooding and erosion along coastlines are also a matter of concern.

2.3.7 Coastal Slope

The slope is one of the deterministic characteristics of vulnerability inundation in coastal areas. Low sloping coastal regions retreat faster than steeper regions (Kaliraj et al., 2017). Hazards like inundation and flooding are mainly due to coastal slopes and urbanization. The lagoons and spits formation that affect always depend on the slope of the coastal area. The gentler slopes with more sediment, rock and soil material carrying into the ocean from landform coastal plains. The steeper the coast, the more prone to risks the coast. The sediment transport and soil erosion along the coast may cause the bathymetric affect more on the land surface. Thus, understanding and protecting the coastal slope is also important.

2.3.8 Saltwater Intrusion

Saltwater intrusion in coastal aquifers, as a natural process, is caused by a higher density and solute concentration of sea water and is exacerbated by extraction of fresh ground water in over pumped catchments (Kacimov et al., 2009). Ground water is essential as it is a main resource for drinking water, agriculture, inhabitants and even for industries. The most common reason for saltwater intrusion in coastal aquifers is intensive or uncontrolled groundwater extraction via water wells that depress the water table (J. Bear, 1999; J. J. Bear & Cheng, 2010). Beaches act as shield to control the saltwater to intrude into fresh ground water. Still the boundary of coastal aquifer depends on the amount of water flowing out of it and the balance between ground water and saltwater flow. This currently concerned sever issue needs to be addressed more by coastal management authorities to protect the ground water quality.

2.3.9 Land Use and Land Cover

Understanding the land use land cover is very much needed for coastal areas. Land use in a simplistic sense denotes the effective use of landscape, and land cover is how the land area is covered. In general, land cover refers to forests, vegetation, agriculture, water-land, etc.; land use refers to its development, usage, etc. Rapid increase in urban industries and population over the coast leading to the LULC change pattern makes the coast more vulnerable to floods, storm surges, inundation, etc. Large development of infrastructures, increasing population, waste dumping all comes under the land use pattern, which effectively disturbs biological system globally.

2.3.10 Population Density

Population density can be selected as one of the subindexes of socio-economic variables (Vittal Hegde & Radhakrishnan Reju, 2007). People in densely populated areas act to protect their properties from erosion. They are reluctant to abandon their properties and infrastructures that have been built up over many years. On the other hand, the areas where few people live may not suffer the same pressure or the same urge for protection. Thus, the coastal areas having high population density can be considered as more vulnerable than areas with low population density.

2.3.11 Transportation

Scientific studies predict that sea level rise will accelerate and, therefore, transportation infrastructure along the coast continues to be vulnerable to inundation (Koetse & Rietveld, 2009). Roads present near the coast may be flooded during extreme weather events causing disruption in transportation resulting difficulties in evacuation and making the coastal area and people living in that area more vulnerable.

2.3.12 Meteorological Parameters

Meteorological parameters are important factors for determining weather conditions and can indirectly affect the vulnerability of coastal areas. In tropical regions some meteorological parameters can reach extremes, indicating some common natural hazards like tropical cyclones. Tropical cyclones are associated with high winds and heavy rainfall. According to India Meteorological Department (IMD), the dangers associated with cyclonic storms are generally threefold, causing very heavy rains with floods, strong wind and storm surge. Surges are mostly unpredictable in terms of damage, so there has been a significant contribution given to observe its impact (Dube et al., 2009; Rao et al., 2010). More cyclones occur in the Bay of Bengal than the Arabian Sea, and the ratio is approximately 4:1. A storm surge is a rise in sea level that occurs during tropical cyclones. Cyclones and storm surges cause coastal flooding, leading to overtopping of coastal defenses and inundation of low-lying areas, but on the other hand, these cyclonic systems provide most of the annual rainfall essential for the agriculture and water resource management (Krishnakumar et al., 2006).

Shahapure et al., 2010 developed an integrated model using rainfall data which was applied to the runoff simulation of a coastal urban watershed in Navi Mumbai, in Maharashtra state of India to analyze the flooding in monsoon season along with the tidal influences. Rainfall intensity can be useful to identify the flood-hazard areas (Kourgialas & Karatzas, 2011).

As global temperatures increase, so does evaporation, which speeds up the hydrologic cycle. Increased evaporation can lead to more frequent and intense storms. Storm-affected areas may see more precipitation and are at a higher risk of flooding. Faster winds are associated with substantially more precipitation, explaining a small, but highly statistically significant fraction of daily rainfall variability (Back & Bretherton, 2005).

2.4 Integration of Geographic Information System (GIS) and Remote Sensing (RS) in Coastal Vulnerability Assessment

2.4.1 Introduction to GIS and RS

Geographic information system (GIS) is a computer-based technology developed by Environmental Systems Research Institute (ESRI), that allows digitization and graphical representation of geographical data for making efficient planning and decision. It captures, stores, manipulates, represents, and analyses spatial data. Different from other types of computerized systems such as spreadsheets, word processors and database management systems, GIS processes and manages spatial data. While word processors and spreadsheets are computer tools for dealing with text and numbers respectively, GIS handles maps, images and other types of spatial data with specific references to locations on the Earth's surface.

Remote sensing is the process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation at a distance; typically, from satellite or aircraft. GIS allows us to combine remote sensing data with other types of data, such as demographic, environmental, or topographic information, to gain a more complete understanding of a region.

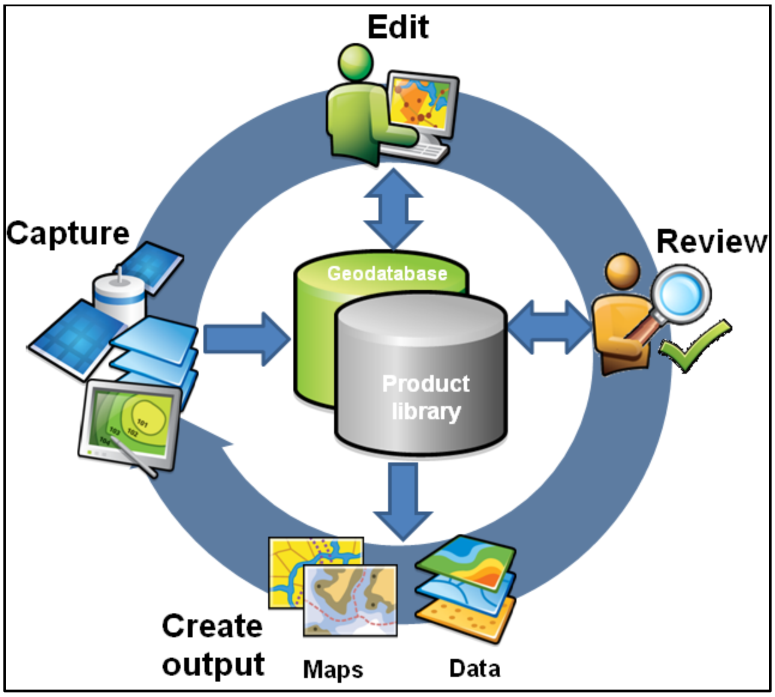

Fig 2.6: Step by step process of GIS (ArcGIS)

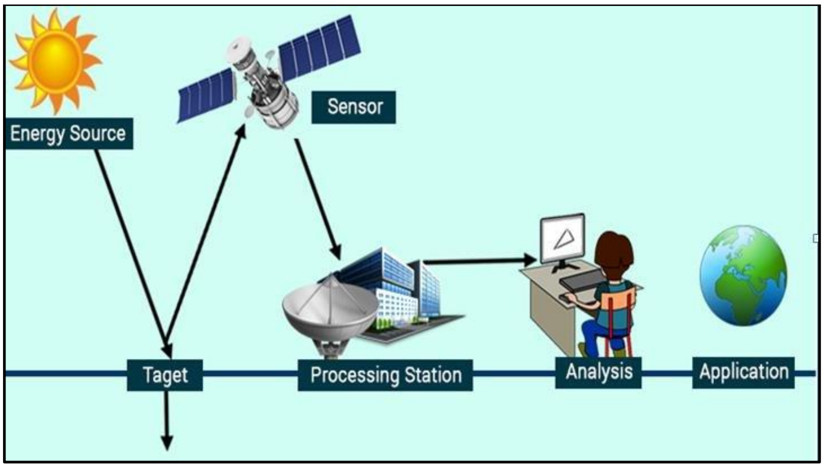

Fig 2.7: Remote Sensing Process (Singh et al. 2018)

2.4.2 Some Common Satellite Sensor data used for Coastal Vulnerability Studies

2.4.2.1 Shuttle Radar Topography Mission (SRTM) and Digital Elevation Model (DEM)

The Shuttle Radar Topography Mission (SRTM) payload flew aboard the Space Shuttle Endeavour during the STS-99 mission by NASA. SRTM collected topographic data over nearly 80% of Earth's land surfaces, creating the first-ever near-global dataset of land elevations. The SRTM payload consisted of two radar antennas, one located in the shuttle's payload bay and the other installed on the end of a 200-foot mast that extended from the payload bay. Each SRTM radar assembly contained two types of antenna panels: C-band and X-band. C-band radar data were used to create near-global topographic maps of Earth called Digital Elevation Models (DEMs).

2.4.2.2 Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is a Japanese remote sensing instrument onboard the Terra satellite launched by NASA in 1999. It has been collecting data since February 2000. ASTER provides high-resolution images of Earth in 14 different bands of the electromagnetic spectrum, ranging from visible to thermal infrared light. The resolution of images ranges between 15 and 90 meters. ASTER data is used to create detailed maps of surface temperature of land, emissivity, reflectance, and elevation.

2.4.2.3 Landsat Series

The Landsat program is the longest-running enterprise for acquisition of satellite imagery of Earth. It is a joint NASA / USGS program. On 23 July 1972, the Earth Resources Technology Satellite was launched. This was eventually renamed to Landsat 1 in 1975. The most recent, Landsat 9, was launched on 27 September 2021. The instruments on the Landsat satellites have acquired millions of images. The images, archived in the United States and at Landsat receiving stations around the world, are a unique resource for global change research and applications in agriculture, cartography, geology, forestry, regional planning, surveillance and education, and can be viewed through the U.S. Geological Survey (USGS) Earth Explorer website. Landsat 7 data has eight spectral bands with spatial resolutions ranging from 15 to 60 m; the temporal resolution is 16 days. Landsat images are usually divided into scenes for easy downloading. Each Landsat scene is about 115 miles long and 115 miles wide.

2.4.2.4 Sentinel Series

Sentinel-2 is an Earth observation mission from the Copernicus Program that acquires optical imagery at high spatial resolution (10 m to 60 m) over land and coastal waters. The mission's Sentinel-2A and Sentinel-2B satellites are to be joined in orbit in 2024 by a third, Sentinel-2C. The mission supports services and applications such as agricultural monitoring, emergencies management, land cover classification, and water quality. Sentinel-2 has been developed and is being operated by the European Space Agency. The satellites were manufactured by a consortium led by Airbus Defence and Space in Friedrichshafen, Germany.

2.4.2.5 Jason Series

The Jason-3 and Ocean Surface Topography Mission (OSTM)/Jason-2 satellites are the latest in a series of ocean altimeter missions to collect data on ocean circulation, sea level rise, and wave height observations. The data collected is used to inform climate monitoring, operational oceanography and seasonal forecasting. Jason-3 ensures the continued flow of high-quality altimetry data after Jason-2 is decommissioned. NCEI is the designated archive and public interface for OSTM/Jason-2 and Jason-3 data, providing access and visualization methods for the general public, expert members of the Ocean Surface Topography Science Team (OSTST), and members of the OSTM/Jason-2 and Jason-3 Science Working Teams.

2.4.3 Role of GIS and RS for Coastal Vulnerability Studies

GIS encourages the development and use of standards for coastal data definition, collection and storage, which promotes compatibility of data and processing techniques between projects and departments, as well as ensuring consistency of approach at any one site over time. Coasts all around the world are fast developing and firm management policies must be established. If any management of the shore is to be effective, it is necessary for the policies to be based on informed decision-making. This requires ready access to appropriate, reliable and timely data and information, in suitable form for the task at hand. Since much of this information and data is likely to have spatial components, one branch of information technology with apparent potential for contributing significantly to coastal management in a number of ways is GIS.

2.5 Analytical Hierarchy Process (AHP) and its application in Coastal Vulnerability Studies

The AHP method proposed by (Saaty, 1977), provides a better understanding of complex decisions by decomposing the problem into a hierarchical structure. AHP enables us to arrive at a scale of preference amongst the available alternatives by employing a pairwise comparison procedure between the decision elements and by ranking them according to their relative importance.

The limitation in index method studies is that the weights are deduced using an individual’s discretion, moreover socioeconomic factors are not taken into consideration. AHP can be used as an improvement to the traditional CVI studies as AHP-deduced weights provide better estimations. AHP has several advantages over these traditional methodologies:

1. It takes into consideration expert opinions when the data involved are inconsistent or insufficient. This has immense significance, especially in the case of mapping coastal vulnerability as the data is highly heterogeneous in terms of its scale, temporal resolution, etc. The ability of

AHP to integrate expert opinion as well as convert qualitative information to quantitative weights makes it very beneficial to coastal vulnerability studies.

2. The pair-wise comparison allows the prioritization of various parameters relative to each other. This is important in the case of regional studies, where one parameter may be more dominant in one region than the other. Also, it is always desirable to use logically derived weights in the case of ranking studies (e.g., AHP derived) rather than those allocated arbitrarily.

3. The test of consistency in the case of AHP helps to check the effectiveness of measurements and judgments, which provide a certain degree of reliability to the study in comparison with random weights.

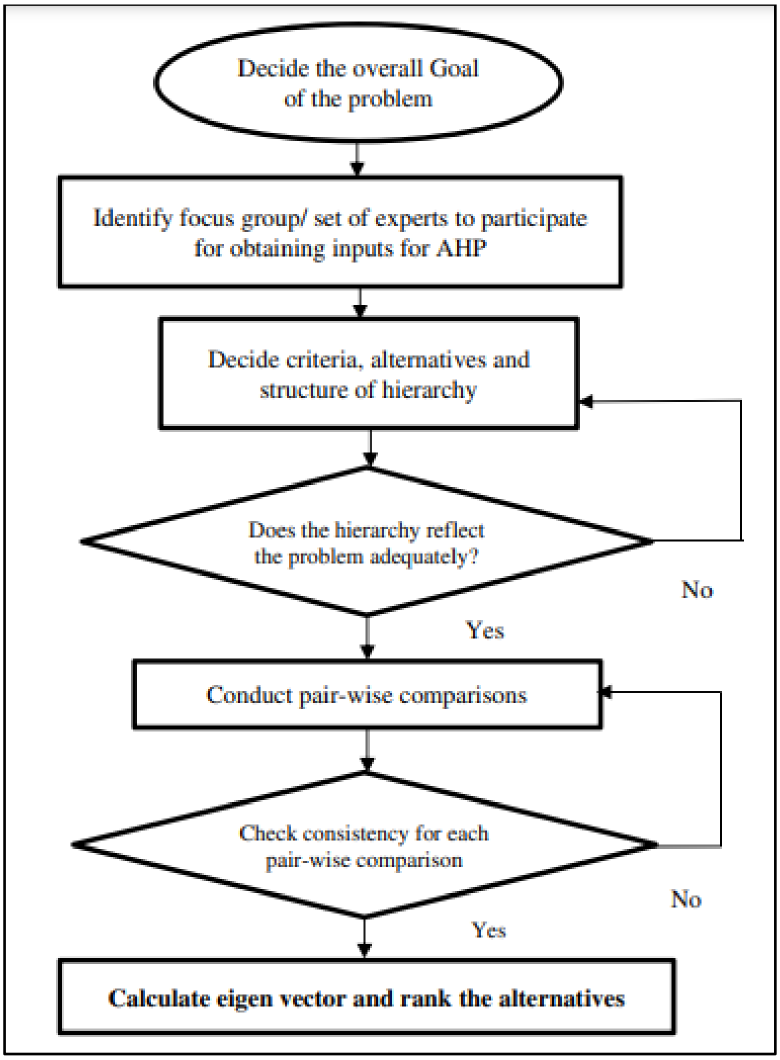

Fig 2.8: AHP Process (Thakkar, 2021)

AHP has been used as a decision-making tool in several studies relating to landslide hazard zonation, flood mapping and soil erosion hazard mapping (Phukon et al., 2012; Sinha et al., 2008). A recent study (Le Cozannet et al., 2013) dealing with AHP and coastal vulnerability discusses the advantages, disadvantages and uncertainties of this approach extensively.

2.6 Critical Review

Many research work is done on the assessment of coastal vulnerability for different coastal areas around the world considering various parameters and various methods. However, in West Bengal, specially, in Digha-Mandarmani coastline, only a few research works are carried out considering only few parameters. An assessment of vulnerability of Midnapur-Balasore coast was done considering only three parameters: shoreline change rate, land use and human activities and population density using traditional index-based method (Jana & Bhattacharya, 2013). Later, another study on assessment of coastal area of Digha-Junput was carried out using traditional index method by considering geomorphology, shoreline change rate, coastal slope, relative sea level change, mean wave height, mean tidal range, tsunami arrival height (Paul et al., 2020).

From the literature review, it can be stated that CVI can be affected by many parameters like sea level rise, elevation, slope, shoreline change, wave height, tidal range, geomorphology, coastal inundation, saltwater intrusion, land cover and land use, population density etc. Moreover, some meteorological parameters like rainfall, wind speed can be used to describe the vulnerability of coastal areas due to natural disasters like cyclones, floods etc. Thus, research work can be carried out to find out the CVI of Digh-Mandarmani coastline using GIS, RS and AHP, considering the above-mentioned parameters.

3. Objective and Scope of Work

3.1 Objective

The main objective is to assess the coastal vulnerability of a coastal stretch in West Bengal using GIS and Analytical Hierarchy Process; considering physical, meteorological and socio-economic parameters and representing their variations throughout the coastal stretch as visual information (maps) and producing coastal vulnerability map. This will help disaster managers, policymakers and planners in disaster management and risk mitigation strategies. Further, it can be beneficial for the coastal community who are in some way or other suffering due to natural hazards for ages.

3.2 Scope of Work

- Identification of physical, meteorological and socio-economical parameters, which are responsible for the vulnerability of the coastal area.
- Collection of data for physical, meteorological and socio-economical parameters and to produce sub-models using the collected data.
- Collection of experts' opinion using questionnaire survey.
- Reclassification of parameters into different risk classes.
- Calculation of the weightage of each parameter using AHP and experts' opinion.
- Producing models and maps which will be able to show variations of different parameters and vulnerability of areas throughout the coastal stretch.

4. Methodology

4.1 Study Area

The study area (Fig 4.1) is almost 22 km long coastline located at the East Coast of India and covering Digha, Shankarpur, Tajpur and Mandarmani; West Bengal (from West to East). The coastline of the study area is bounded by West Bengal-Odissa state border in the south-west direction and Pichaboni river estuary in the north-east direction and lies between 21° 36' 41''N to 21° 41' 21''N latitudes and 87° 29' 6''E to 87° 45' 21''E longitudes (Fig 4.1). The area comes under Ramnagar I and II blocks of Purba Medinipur District of West Bengal. The coastline consists of fine sand with low gradient and during monsoon the area is affected by strong longshore current from Bay of Bengal. The study area is a tourist hotspot offering many recreational activities and is still under development. Thus, it is important to assess the vulnerability of this area.

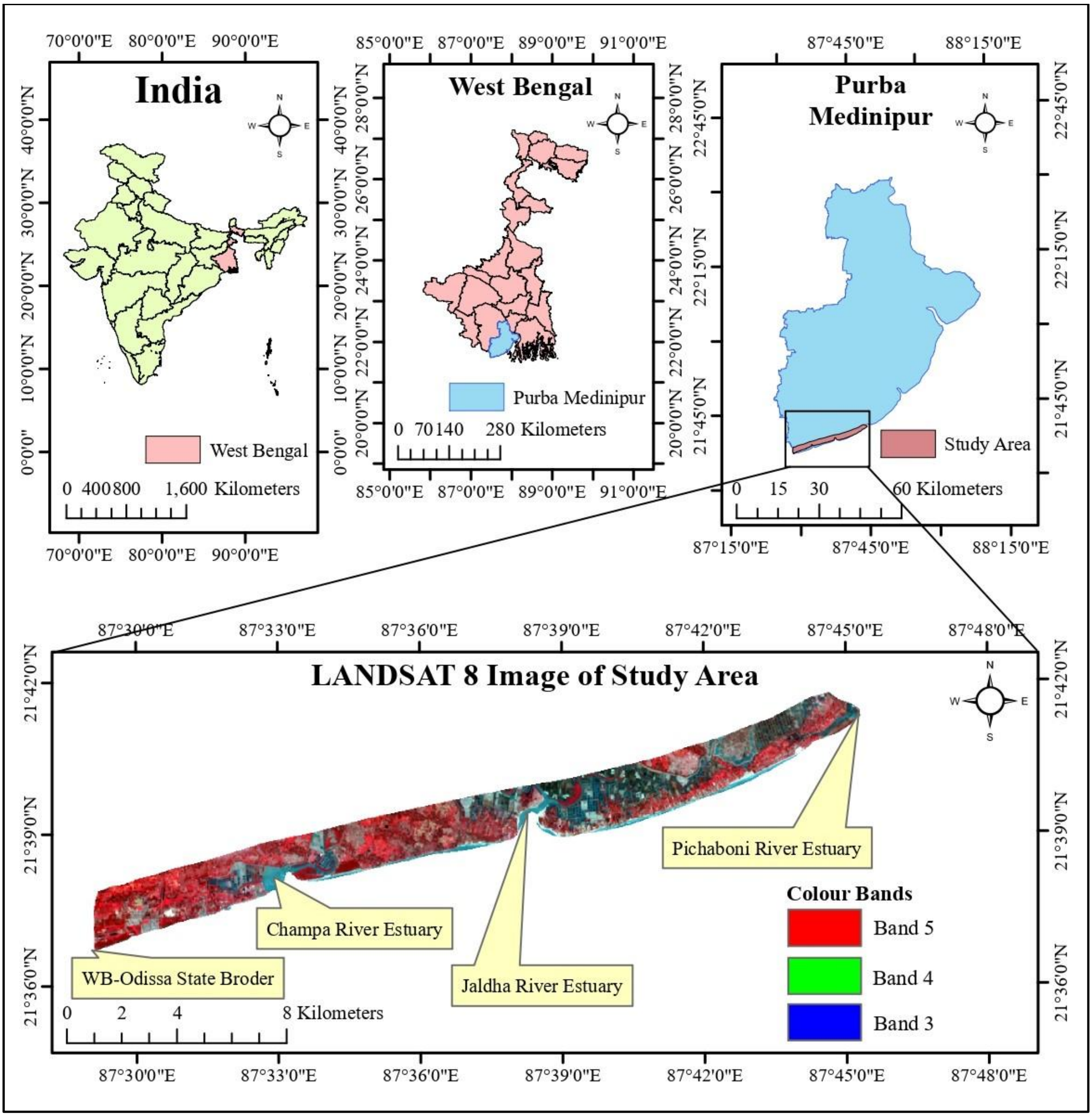

Fig 4.1: Location Map of Study Area

4.2 Selected Parameters

Based on the literature review, the parameters which are considered to determine the CVI of the study area, are classified as (Fig 4.2):

(1) Physical Parameters: Sea Level Rise (SLR), Elevation of the area (ELE), Coastal Slope (SLO), Geomorphology (GEO), Shoreline Change Rate (SCS), Mean Tide Range (MTR), Sea-surface Wave Height (SWH), Saltwater Intrusion (SI).

(2) Socio-Economic Parameters: Population Density (POP), Land Use and Land Cover (LULC), Transportation (TRP).

(3) Meteorological Parameters: Precipitation (PPT), Extreme Weather Events (EWE), Temperature (TMP), Wind Speed (WSD).

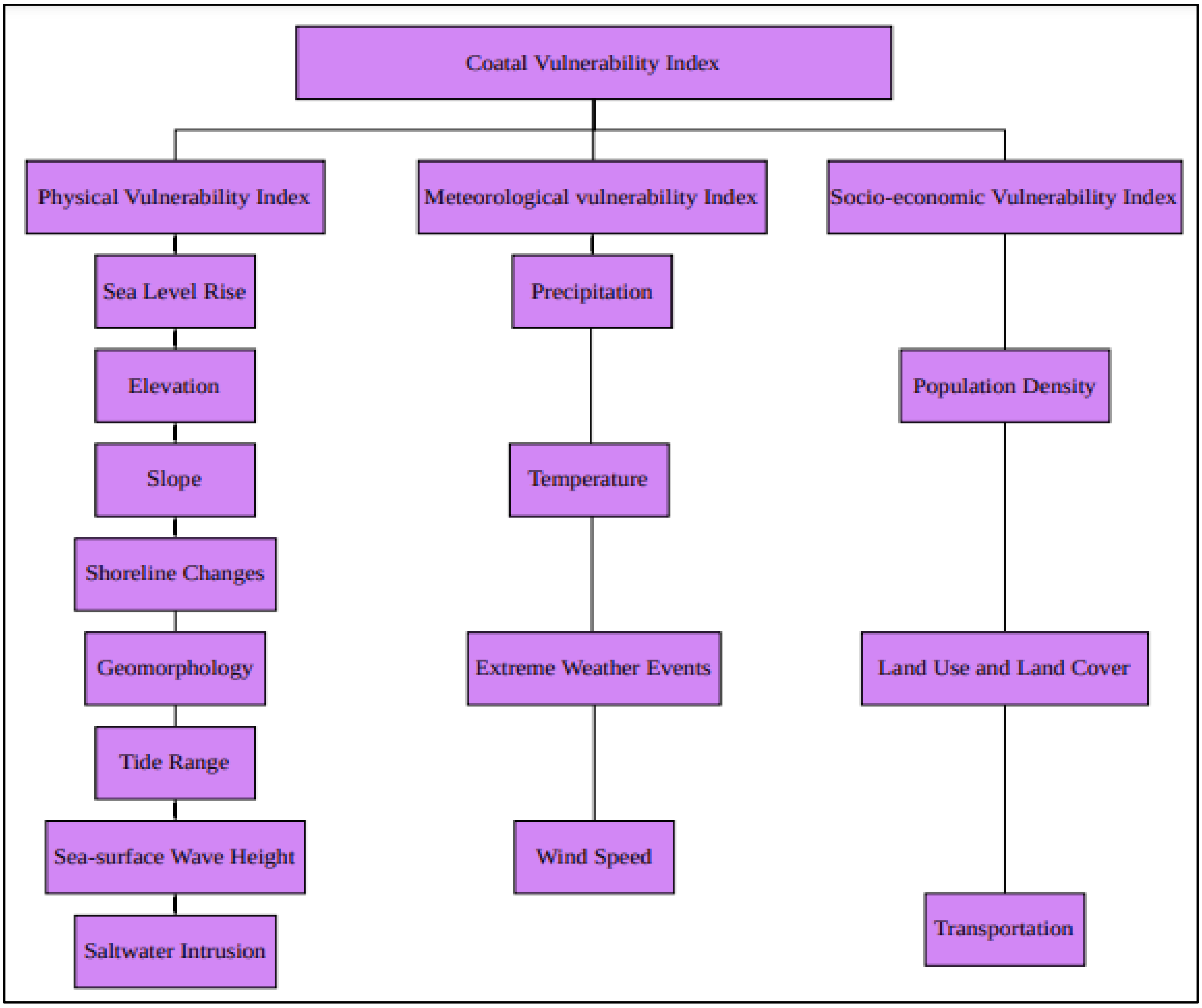

Fig 4.2: Parameters for determining CVI

4.3 Determination of CVI

The basic steps for determining CVI area discussed below and shown in Fig 4.3

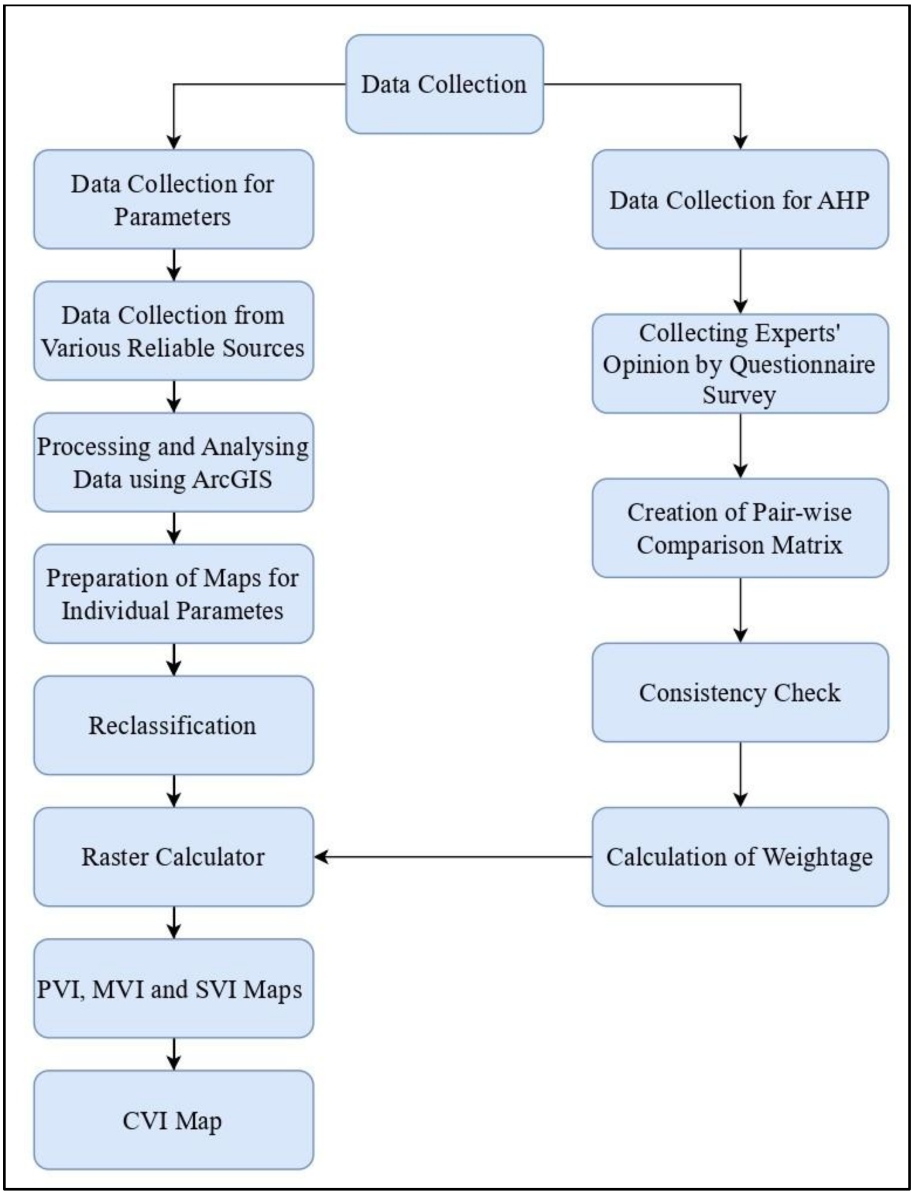

Fig 4.3: Steps for determining CVI

4.3.1 Data Collection

(a) Table 2: Data from various reliable sources

Parameter	Data Source	Time Period	Reference
Sea Level Rise (SLR)	Literature Review	1977 to 2012	(Sahoo et al., 2014)
Elevation (ELE)	Shuttle Radar Topography Mission (SRTM)		(Sankari et al., 2015; Zhang et al., 2019)
Coastal Slope (CS)	SRTM		(Kaliraj et al., 2017; McAdoo et al., 2007)
Shoreline Changes (SCS)	Landsat 8	2013, 2016, 2020, 2022, 2024	(Patel et al., 2021; A. Yadav et al., 2021)
Geomorphology (GEO)	Geological Survey of India (GSI) Bhukosh		(A. B. Yadav et al., 2022)

Tidal Range (MTR)	WX Tide	2015 to 2023	(A. B. Yadav et al., 2022)
Sea-Surface Wave Height (SWH)	Copernicus Marine Service	1993	(Benveniste et al., 2020)
Saltwater Intrusion (SI)	Literature Review		(Sarkar et al., 2021)
Land Use and Land Cover (LULC)	Sentinel 2	2023	(Karra et al., 2021)
Population Density (POP)	Census 2011 and Survey of India		(Rai & Nathawat, 2017)
Transportation Network (TRP)	Geosadak, PMGSY National GIS		(Sharma et al., 2024)
Rainfall (PPT)	PERSIANN CCS, Center for Hydrometeorology and Remote Sensing (CHRS)	2011 to 2021	(Ahmad et al., 2022; Nguyen et al., 2019)
Temperature (TMP)	WorldClim 2	1970 to 2000	(Fick & Hijmans, 2017)
Extreme Weather Events (EWE)	Literature Review, IMD		(SINGH, 2007)
Wind Speed (WSD)	Global Wind Atlas	2008 to 2017	(Davis et al., 2023)

(b) Collection of Data for AHP: Questionnaire Survey (Annexure A1 and A2) was carried out among Academic Personnel who has sufficient knowledge about Coastal Studies, Authors who previously researched on Coastal Vulnerability assessment and an ex-officer of West Bengal Disaster Management & Civil Defence Department who has work experience in coastal area of West Bengal. As there were too many parameters, so, instead of traditional ranking scale and method, experts were asked to rank parameters on a scale from 1 to 5 to keep the survey as short as possible for ease of handing and calculating, where, 1 means less importance and contribution to Coastal Vulnerability. Later the ranks were modified to a 1 to 9 scale while calculating weightage of each parameter.

4.3.2 Some Tools Used to Analyse Collected Data

(a) Band Composite and Mosaic tools

Band composite tool can create a raster dataset containing subset of the original raster dataset bands. This is useful to create a new raster dataset with a specific band combination and order. In general, band compositing refers to the process of combining spatially overlapping images into a single image based on an aggregation function while Mosaicking refers to the process of spatially assembling image datasets to produce a spatially continuous image. These tools were used to combine different bands of LANDSAT8 image into a single raster file.

(b) Raster Calculator

The Raster Calculator tool helps to create and execute a Map Algebra expression that will output a raster. It allows to use the layers and variables list to select the datasets and variables to use in the expression and calculate the value of each pixel of the output ratser. For this study it is used to calculate and create average values for some parameters.

(c) Digital Shoreline Analysis System (DSAS)

The Digital Shoreline Analysis System (DSAS) is a software extension for ArcGIS that allows for automated shoreline change calculations along the coast. The user must supply the shoreline data and the software helps the user create measurement locations (transects) and completes the shoreline change calculations at each location. This tool is used to calculate and represent the shoreline change rates of study area by creating transects at 100 meters spacing.

(d) Inverse distance weighted (IDW)

IDW interpolation method determines cell values using a linearly weighted combination of a set of sample points. The weight is a function of inverse distance. The surface being interpolated should be that of a locationally dependent variable. In this study, the variations of different meteorological parameters are estimated using IDW interpolation method.

4.3.3 Reclassification of Parameters into different Risk Classes

Parameters were reclassified into five risk classes based on literature review and some parameters, which vary regionally, were reclassified based on their lowest and highest values or conditions as shown in Table 3.

Table 3: Reclassification Parameters into Different Risk Classes

Parameter	Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)	Reference
SLR (mm/year)	<1.8	1.8 to 2.5	2.5 to 2.95	2.95 to 3.16	> 3.16	(Gornitz et al., 1994)
ELE (m)	≥ 30	21.1 to 30	10.1 to 20	5.1 to 10	0 to 5.0	(Gornitz et al., 1994)
GEO	Rocky, Cliffed Coasts	Medium Cliff intended Coasts	Low Cliffs, Glacial Drift, Salt Marsh, Coral Reefs, Mangroves	Pebble Beaches, Anthropogenic Terrain Estuary, Lagoons, Alluvial Plains	Barrier Beaches, Sand Beaches, Mud Flats, Deltas	(Gornitz et al., 1994)
SCS (mm/year)	> +2.0 (Accretion)	+1.0 to +2.0	–1.0 to +1.0 (Stable)	-1.1 to –2.0	< –2.0 (Erosion)	(Gornitz et al., 1994)
MTR (m)	< 1.0 (Microtidal)	1.0 to 1.9	2.0 to 4.0 (Mesotidal)	4.1 to 6.0	> 6.0 (Macrotidal)	(Gornitz et al., 1994)
SWH (m)	<0.37	0.37 to 0.38	0.38 to 0.39	0.39 to 0.40	>0.40	
SLO (Degree)	> 4.5	4.0 to 4.5	3.5 to 4.0	3.0 to 3.5	<3.5	(Paul et al., 2020)
SI (SMI)	<1 (Not Mixed)				>1 (Mixed)	(Sarkar et al., 2021)
LULC	Wetlands, Salt marshes, Open lands, River and Inlets mouths	Mangroves, Dunes, vegetations	Scattered villages, Agricultural lands, Saltpans	Jetties, Fisheries	Hotels, Tourist Spots, Industries, Buildings	(Jana & Bhattacharya, 2013)
POP (Person/sq km)	0 to 500	501 to 1000	1000 to 1500	1500 to 2000	>2500	(Jana & Bhattacharya, 2013)

TRP (Distance of a Road from Coastline in meters)	0 to 100	100 to 250	250 to 500	500 to 1000	<1000	
PPT (mm/year)	< 2129	2129 to 2137	2137 to 2145	2145 to 2153	> 2153	
TMP (°C)	< 26.50	26.51 to 26.54	26.54 to 26.57	26.57 to 26.60	> 26.60	
WSD (m/s)	< 3.3	3.3 to 3.67	3.67 to 4.05	4.05 to 4.41	> 4.41	
EWE (degree of proneness)	No proneness	Low	Moderate	High	Very High	RSMC, IMD Cyclone Hazard Climatology

4.3.4 Calculation of Weights of different parameters using AHP

Three separate comparison matrixes are made for physical, meteorological and socio-economic parameters. For each matrix the geometric mean (GM) is determined after pair-wise comparison of ranks of different parameters. In order to validate the results of the AHP, the consistency ratio (CR) is calculated using the formula,

$$CR = \frac{CI}{RI}$$

Where, CR = Consistency Ratio

CI = Consistency Index

RI = Random Consistency Index (Table 4)

It should be noted that consistency ratio lower than 0.10 verifies that the results of comparison are acceptable. The Consistency Index is calculated using the following expression;

$$CI = \frac{(\lambda max - n)}{n-1}$$

Where, λmax =Maximum Eigen value of pair-wise comparison matrix

n = Dimension of pair-wise comparison matrix

The weightage of each parameter is calculated by diving the geometric mean of that parameter with the total geometric mean of all parameters.

Table 4: RI Values for different size of matrix (Saaty, 1980)

Size of Matrix	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

4.3.5 Preparation of Vulnerability Map

The Physical, Meteorological and Socio-economic vulnerability indexes (PVI, MVI and SVI) of each pixel is determined by raster calculator tool using the formula (Mahapatra et al., 2014):

$$VI = \Sigma W_i X_i$$

Where, W_i = Weightage of a parameter, determined by AHP calculations (Annexure B).

X_i = Risk rating of that parameter (Table 3).

Three vulnerability maps; PVI, SVI and MVI are created using physical, socio-economical and meteorological parameters respectively. The final coastal vulnerability index (CVI) map is created by using the average of PVI, SVI and MVI.

5. Results and Discussions

5.1 Calculation of Weightage by AHP

Table 6: Comparison Matrix and Weightage of Physical parameters

Parameter	Ranks	SLR	ELE	SLO	SWH	MTR	SI	SCS	GEO	Mean (GM)	Wt. (%)
SLR	9	1	1.8	1.286	1	1.286	9	1.8	3	1.862	19.56
ELE	5	0.556	1	0.714	0.556	0.714	5	1	1.667	1.035	10.87
SLO	7	0.778	1.4	1	0.778	1	7	1.4	2.333	1.449	15.22
SWH	9	1	1.8	1.286	1	1.286	9	1.8	3	1.862	19.56
MTR	7	0.778	1.4	1	0.778	1	7	1.4	2.333	1.449	15.22
SI	1	0.111	0.2	0.143	0.111	0.143	1	0.2	0.333	0.207	2.17
SCS	5	0.556	1	0.714	0.556	0.714	5	1	1.667	1.035	10.87
GEO	3	0.333	0.6	0.429	0.333	0.429	3	0.6	1	0.621	6.52

Total Mean = 9.52

λmax =8.0003, n = 8, RI = 1.41

$$CI = \frac{\lambda max - n}{n-1}$$

$$= \frac{(8.0003-8)}{8-1} = 0.00004$$

$$CR = \frac{CI}{RI}$$

$$= \frac{0.00004}{1.41} = 0.00003$$

0.00003 < 0.1; Hence, the results are acceptable.

Table 7: Comparison Matrix and Weightage of Meteorological Parameters

Parameter	Ranks	PPT	EWE	TMP	WSD	Mean (GM)	Wt. (%)
PPT	9	1	1.8	9	1.286	2.136	40.91
EWE	7	0.778	1	5	1.4	1.661	31.81
TMP	1	0.111	0.2	1	0.143	0.237	4.54
WSD	5	0.556	0.714	7	1	1.187	22.74

Total Mean = 5.221

λmax =4.0857, n = 4, RI = 0.90

$$CI = \frac{\lambda max - n}{n - 1}$$

$$= \frac{(4.0857 - 4)}{4 - 1} = 0.0286$$

$$CR = \frac{CI}{RI}$$

$$= \frac{0.0286}{0,90} = 0.032$$

0.032 < 0.1; Hence, the results are acceptable.

Table 8: Comparison Matrix and Weightage of Socio-Economic Parameters

Parameter	Ranks	POP	LULC	TRP	Mean (GM)	Wt. (%)
POP	5	1	0.714	1.667	1.06	33.33
LULC	7	1.4	1	2.333	1.484	46.67
TRP	3	0.6	0.429	1	0.636	20

Total Mean = 3.18

λmax =3.0002, n = 3, RI = 0.58

$$CI = \frac{\lambda max - n}{n - 1}$$

$$= \frac{(3.0002 - 3)}{3 - 1} = 0.0001$$

$$CR = \frac{CI}{RI}$$

$$= \frac{0.0001}{0.58} = 0.00017$$

0.00017 < 0.1; Hence, the results are acceptable.

5.2 Physical Parameters and PVI

5.2.1 Sea Level Rise

From collected sea gauge data by RRI Digha, specially, during monsoon season, it was observed that sea level rise is occurring at a considerable rate about 5mm/ year since past three decades (Sahoo et al., 2014).

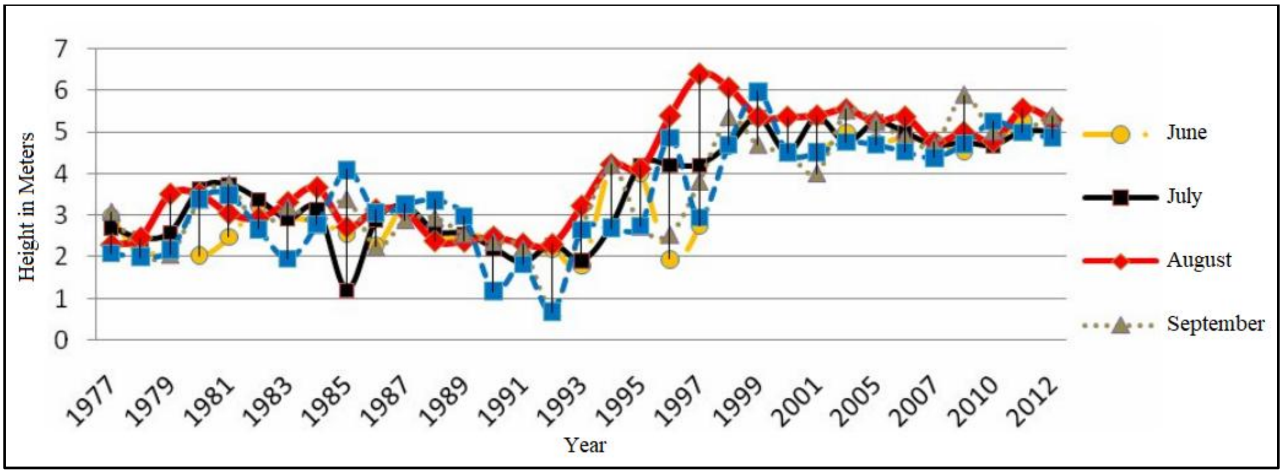

Fig 5.1: Variation of highest sea gauge during 1977-2012 (Sahoo et al., 2014)

5.2.2 Elevation

Most parts of the study area have an average elevation of 0 meter to 5 meter range. The Elevation data obtained from SRTM global 30m resolution data set shows that most parts of Digha, Shankarpur and Tajpur shows an average elevation in the range 5 to 10 meters, while some parts have elevation in the range 10 to 20 meters. On the other hand, the coastline of Mandarmani has an average elevation only in the range of 5 to 10 meters.

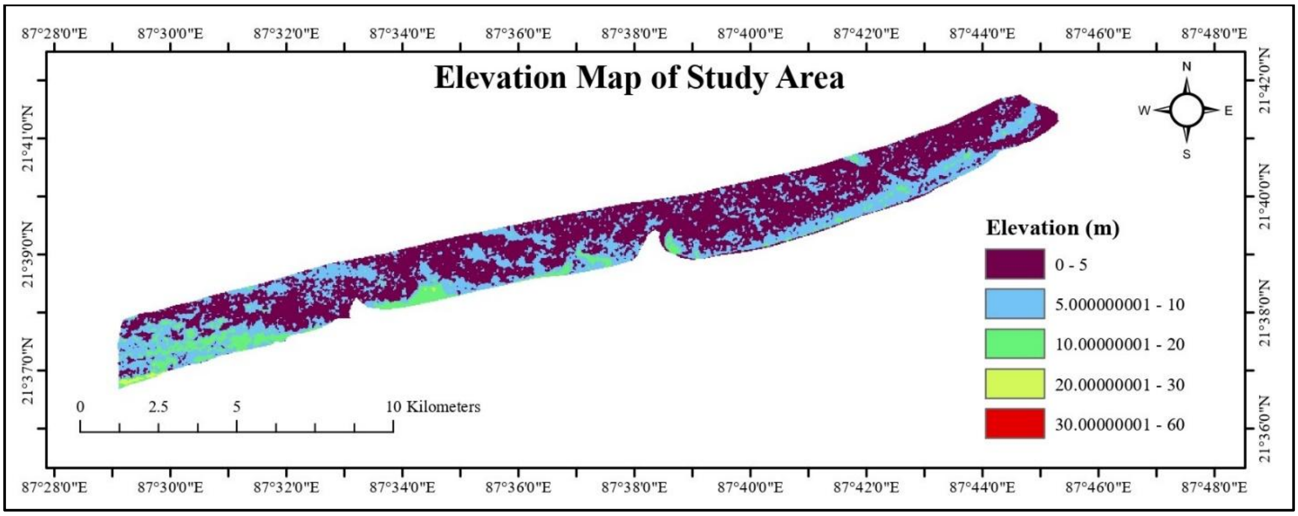

Fig 5.2: Elevation Map of Study Area

5.2.3 Coastal Slope

Data collected from the SRTM global 30 meters resolution datasets shows that the average slope of the study area is less than three degrees except some parts of the coastline which has a steeper slope; greater than 4.5 degrees.

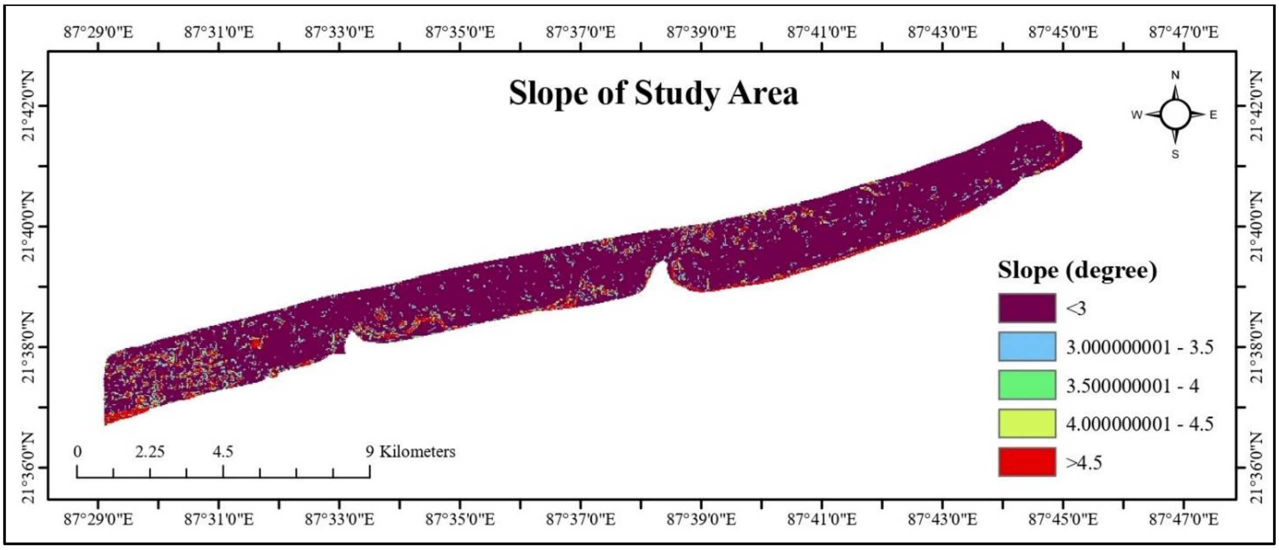

Fig 5.3: Slope of Study Area

5.2.4 Shoreline Changes: Erosion and Accretion Patterns

Shoreline change rates is calculated using Digital Shoreline Analysis System tool and Landsat images of different years by creating transects at a spacing of 100 meters. It shows most parts of Shankarpur and Tajpur coastline and some parts of Digha and Mandarmani coastline are going through severe erosion while some parts of the whole coastline are in the moderate erosion-accretion range.

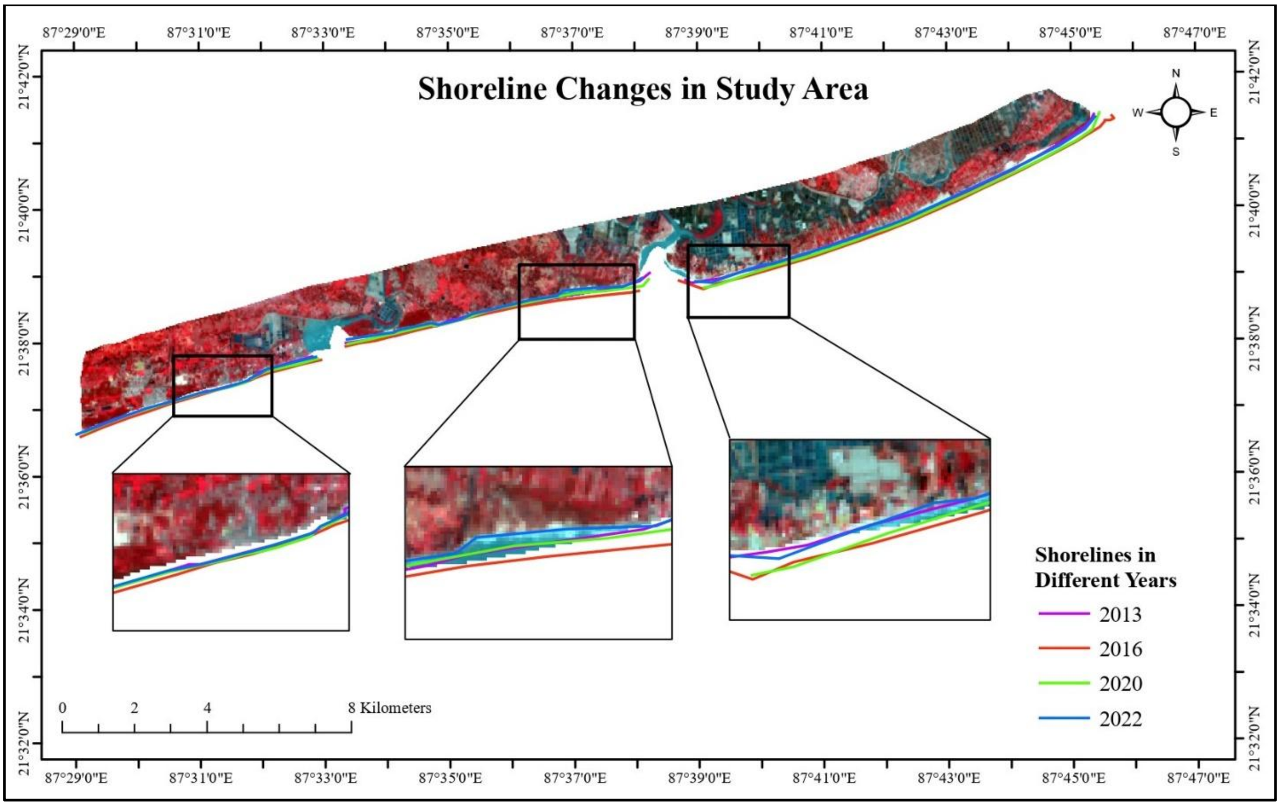

Fig 5.4: Shoreline changes in study area throughout different years

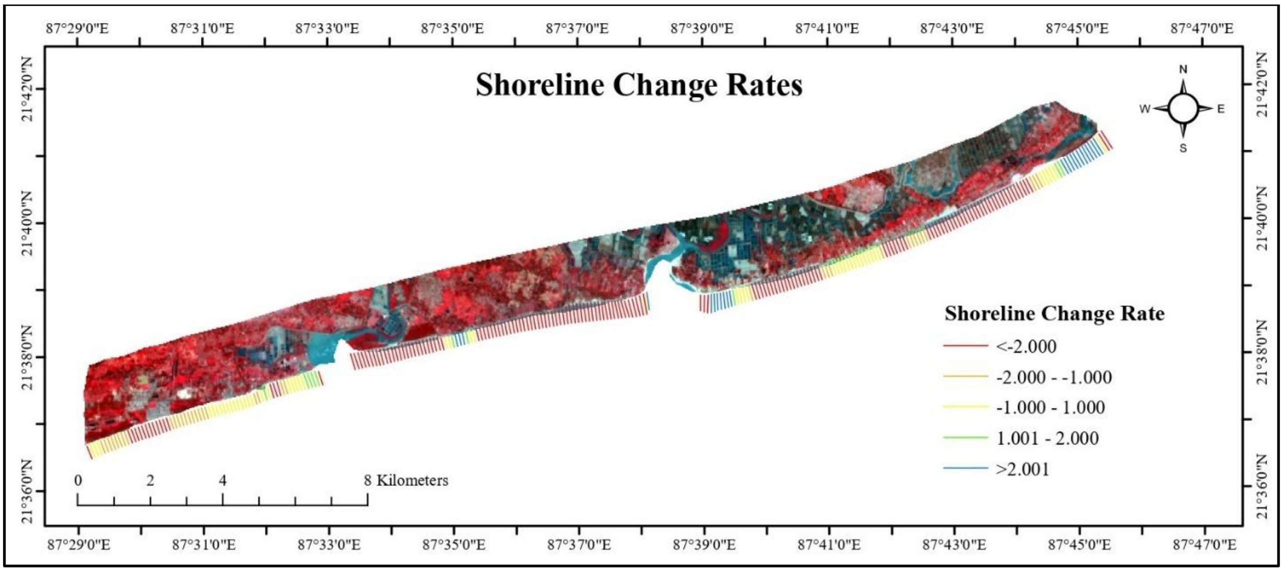

Fig 5.5: Shoreline Change Rate in Study Area

5.2.5 Geomorphology

Geomorphology data obtained from GSI Bhukosh datasets shows the study area is coastal plain; the coastline mainly consists of fine sand beaches with some parts shielded with black boulder stone barriers.

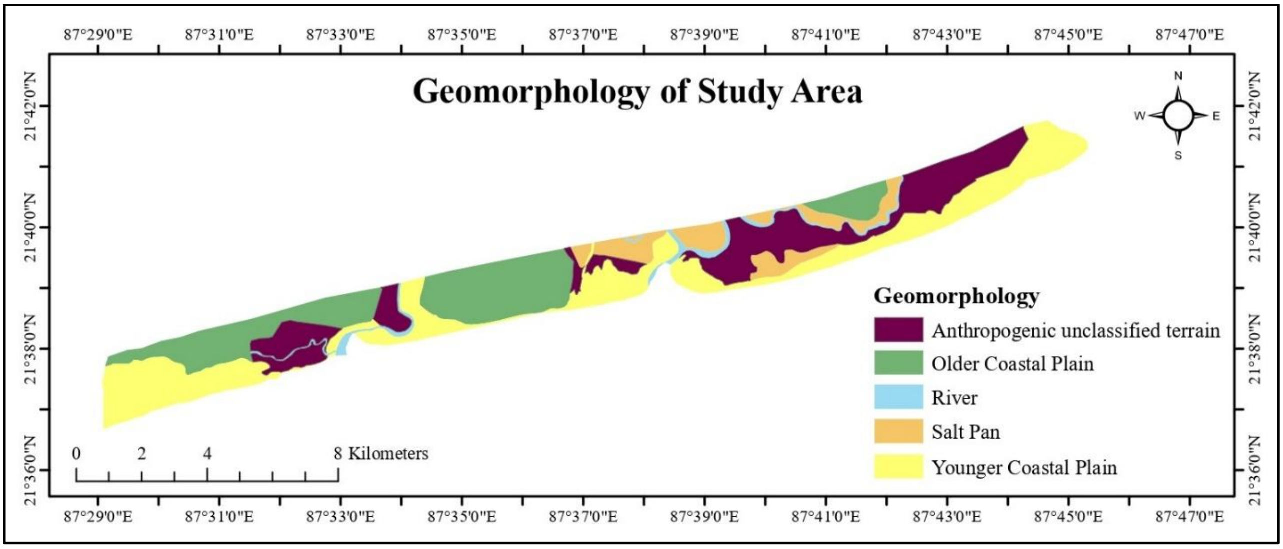

Fig 5.6: Geomorphology of Study Area

5.2.6 Mean Tide Range

Data collected from WX Tide for Sagar Island (the closest coastal station to study area) shows that the study area falls under meso-tidal range; 2 meters to 4 meters range. The average tidal range is calculated using previous 2 years data of high and how tide and the value of mean tide range is around 3.8 meters.

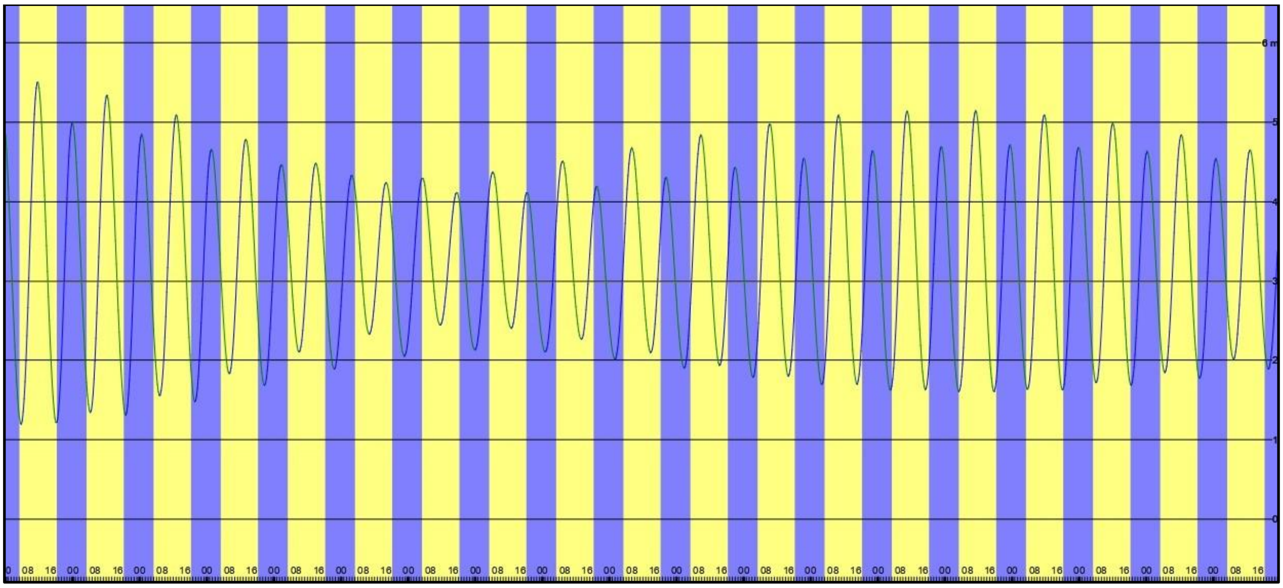

Fig 5.7: High and Low Tide heights in a span of 20 days using WX Tide

5.2.7 Sea Surface Wave Heights

Sea-surface wave heights are obtained from Copernicus Marine Service and later the influence of the waves on study area is estimated by IDW technique. Parts of Mandarmani has less wave height varying from 0.36 to 0.38 meters, while Digha and Shankarpur have an average wave height from 0.38 to 0.41 meters range.

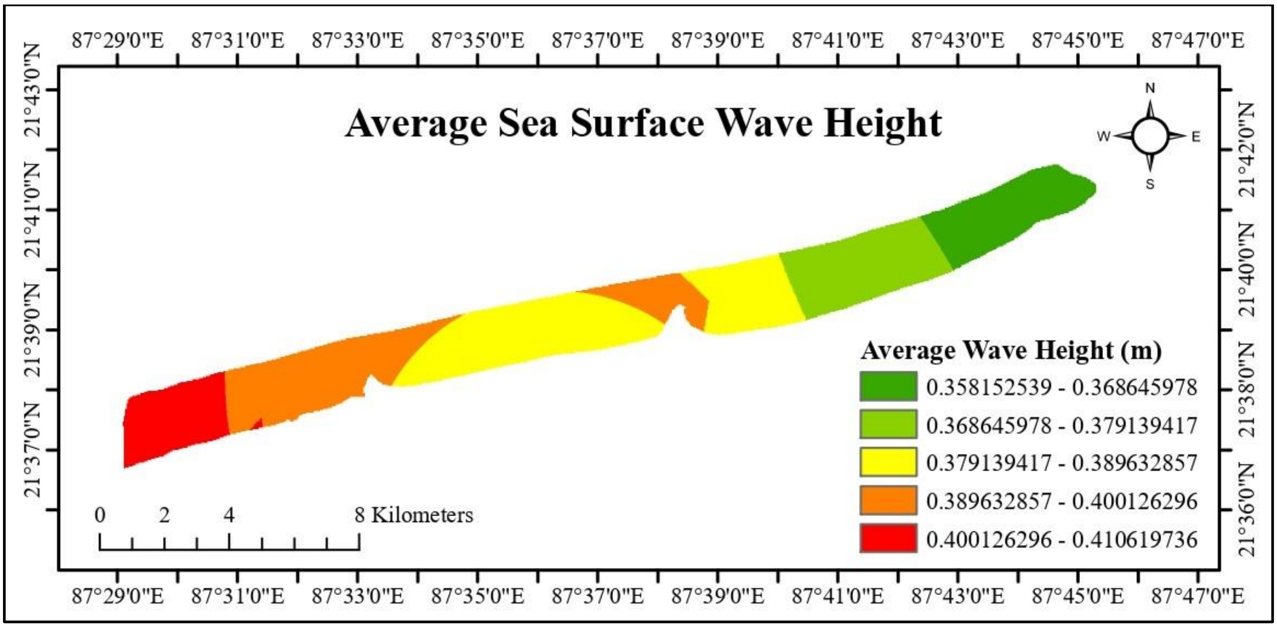

Fig 5.8: Sea-surface wave heights influencing the parts of Study Area

5.2.8 Saltwater Intrusion

In this study, the saltwater intrusion is determined by Sea-water Mixing Index (SMI) by considering Na^{+}, Mg^{2+}, Cl^{-} and SO_4^{2-}. Data obtained from (Sarkar et al., 2021), shows that the entire study area has SMI less than 1.

5.2.9 Physical Vulnerability Index (PVI)

The average PVI values along the coastline of Digha area are higher than the average PVI values of Mandarmani coastline.

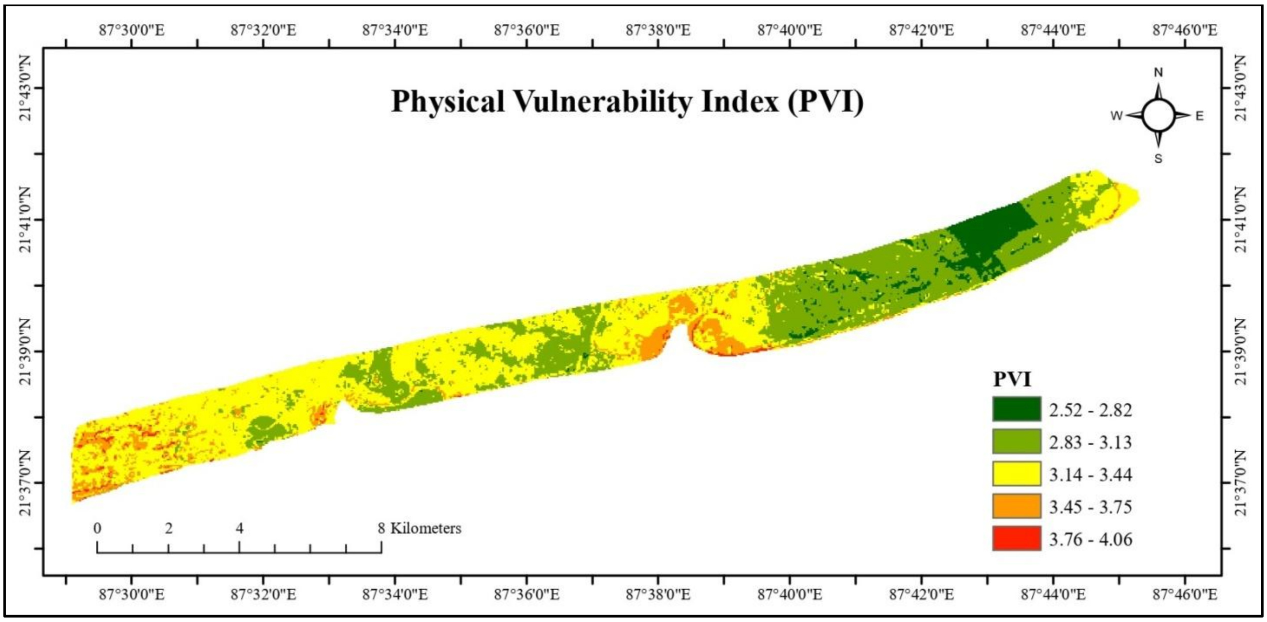

Fig 5.9: Physical Vulnerability Index of Study Area

5.3 Meteorological Parameters and MVI

5.3.1 Rainfall

Longterm rainfall trends over a period of 10 years (2011 to 2021) is estimated using PERSIANN CCS data from CHRS data portal with IDW interpolation technique. More average annual rainfall value can be seen in Mandarmani than Digha in last 10 years.

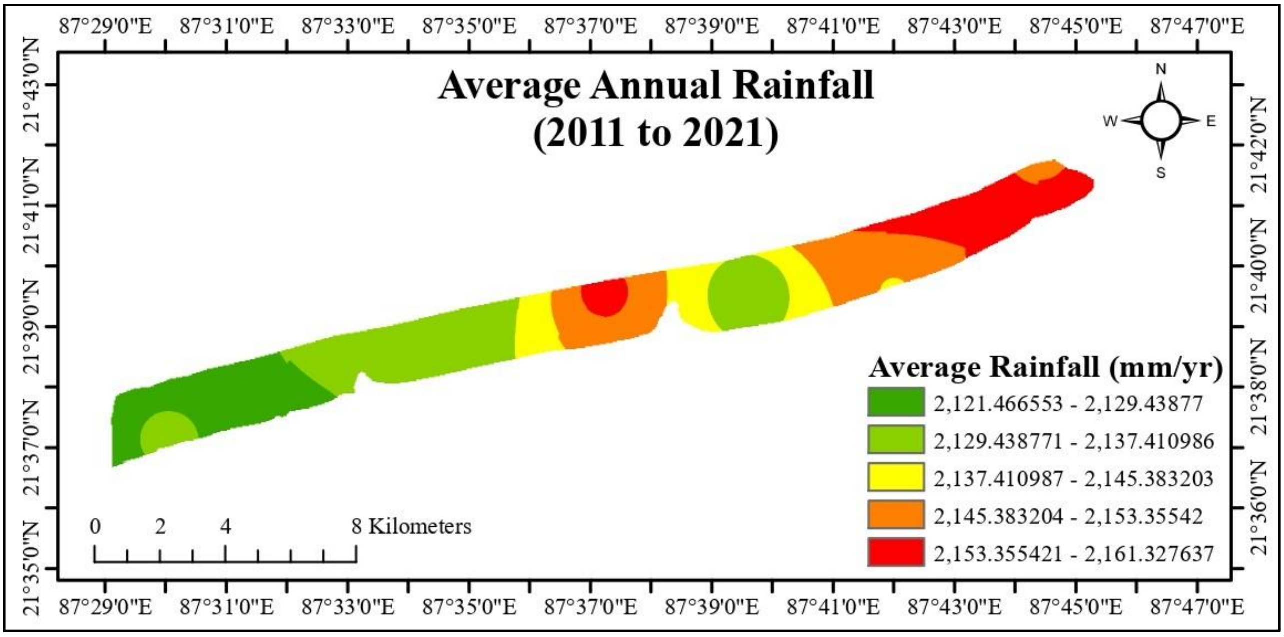

Fig 5.10: Rainfall trends in Study Area from 2011 to 2021

5.3.2 Temperature

Temperature is estimated from WorldClim2 data for a period of 1970 to 2000 using IDW interpolation. The average annual temperature of Mandarmani area is higher than the average annual temperature of Digha area.

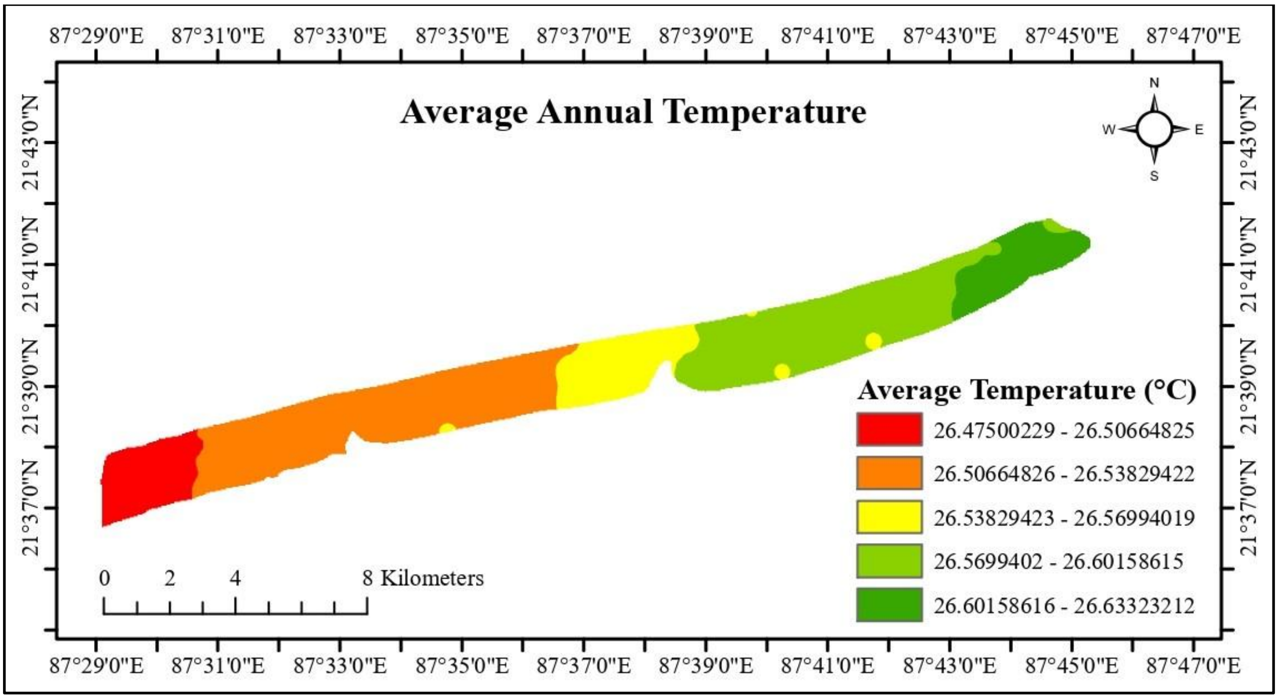

Fig 5.11: Average Annual Temperature Variation (1970 to 2000)

5.3.3 Wind Speed

Wind Speed is determined by Global wind atlas data for a period of 10 years (2008 to 2017). It can be seen that the average wind speed decreases with the distance from shoreline. However, the average wind speed along Mandarmani and Shankarpur-Tajpur coastline is much higher than the average wind speed along Digha coastline.

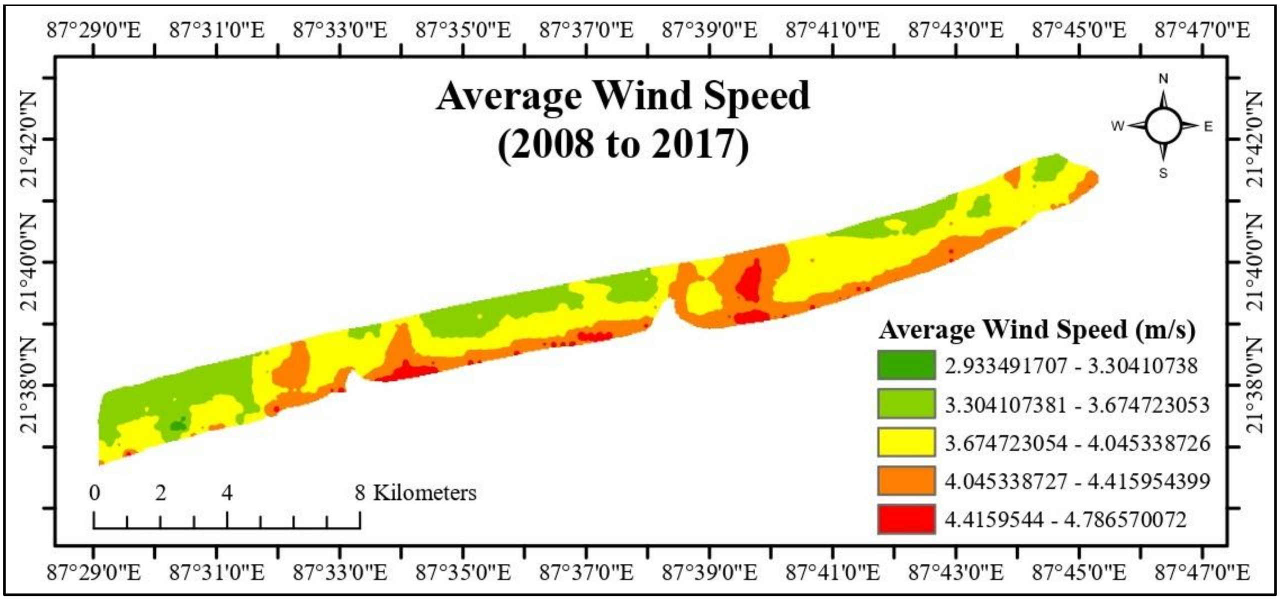

Fig 5.12: Average Annual Wind Speed in Study Area (from 2008 to 2017)

5.3.4 Extreme Weather Events

On an average 5-6 tropical cyclonic storms occur per year in the northern part of Bay of Bengal (Singh, 2007). A recent Cyclone Hazard Climatology report published by Regional Specialized Meteorological Centre (RSMC), Delhi, Indian Meteorological Department (IMD), Ministry of Earth Sciences (MOES), Government of India and World Meteorological Organization (WMO) in 2023, stated that Purba Medinipur District, where the study area is located, is a very high cyclone hazard prone districts of India based on frequency of total cyclones, total severe cyclones, actual/estimated maximum wind strength, probable maximum storm surge associated with the cyclones and daily probable maximum precipitation.

5.3.5 Meteorological Vulnerability Index (MVI)

The average MVI value of Mandarmani area is the highest and the average MVI values of Tajpur coastal area is higher than Digha and Shankarpur coastal area. This indicates that the coastline of Mandarmani is comparatively more prone to extreme weather conditions like cyclonic storms and storm surges.

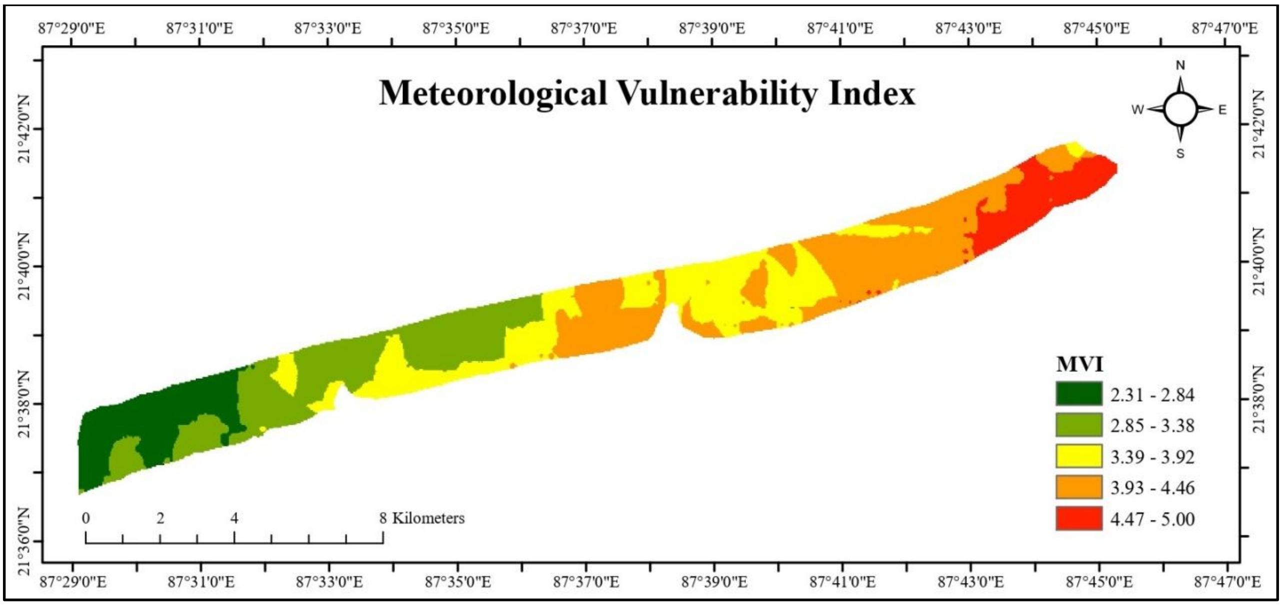

Fig 5.13: Meteorological Vulnerability Index of Study Area

5.4 Socio-economic Parameters and SVI

5.4.1 Population Density

The population data for each urban/rural area is collected from Census of India 2011 data and the digitized maps of those areas are taken from Survey of India. The population density is determined by dividing the population value by the area which is estimated by geometry calculation feature. The population density of Digha, specially, New Digha area is much higher than the population density of Mandarmani, which has an average population density in the range from 0 to 500 persons per square kilometers.

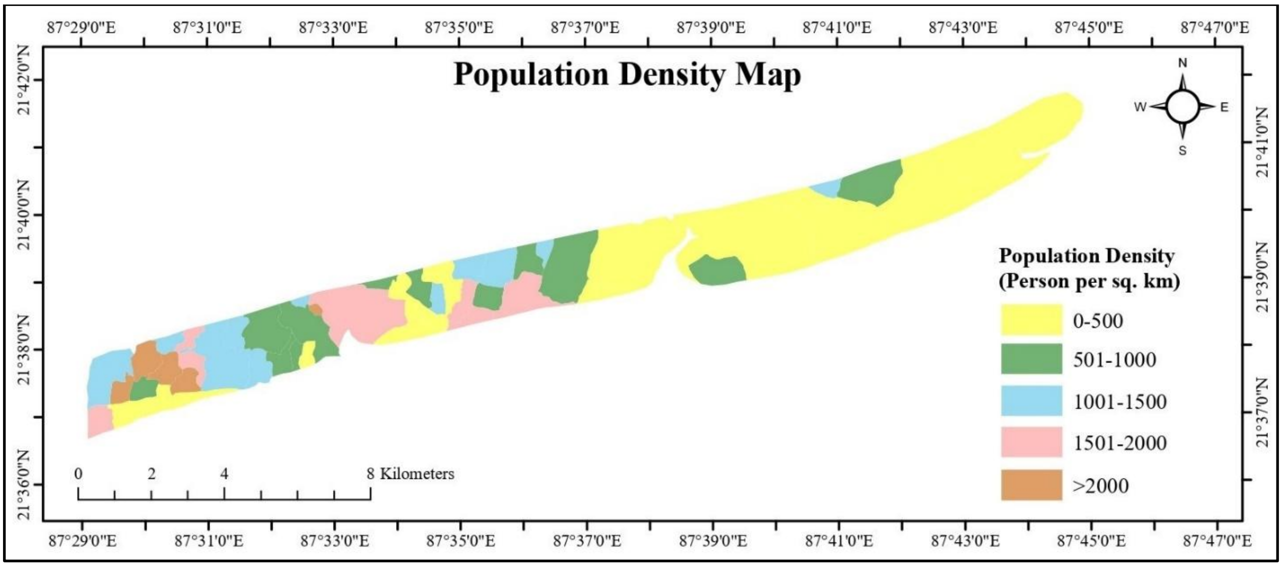

Fig 5.14: Population Density of Study Area

5.4.2 Transportation Network

The road network of study area is established from Geosadak, PMGSY National GIS data portal. Though the study area mostly contains rural roads network, a national highway NH116B is present in Digha. Also, a rural road is present within 100 meters of shoreline in Shankarpur-Tajpur coastline. The vulnerability of road network is estimated by the distance of the road from shoreline.

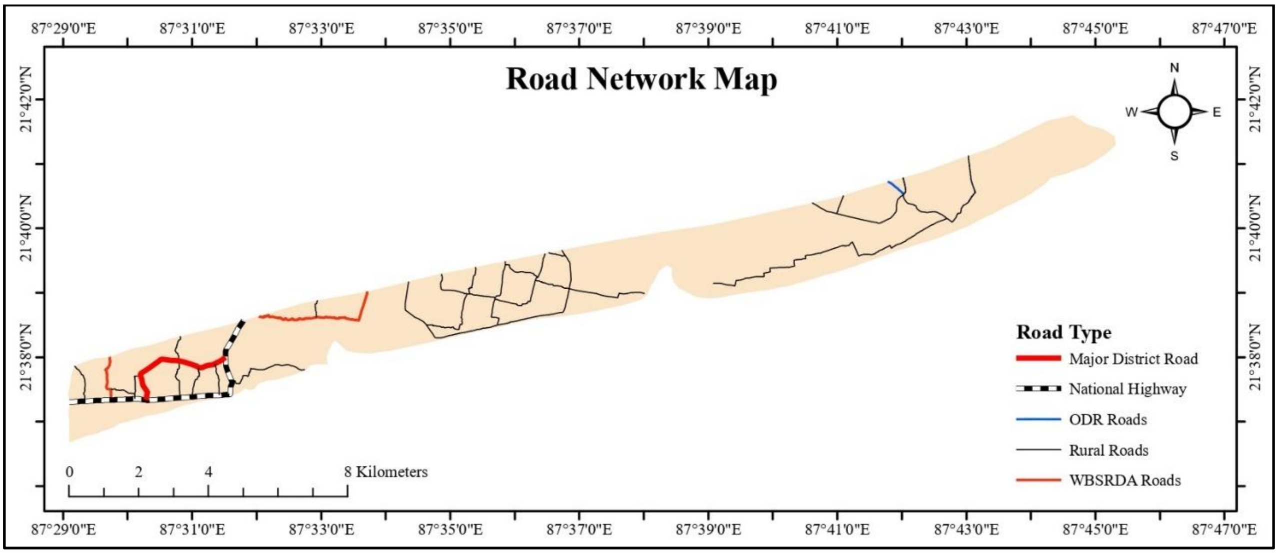

Fig 5.15: Road Network Map of Study Area

5.4.3 Land Cover and Land Use (LULC)

The LULC data is estimated using Sentinel 2 data. The study area is a tourist hotspot, hence, many house, hotels, markets, amusement parks and other man-made buildings can be seen along the coastline. Digha has more of these man-made structures compared to Shankarpur and Mandarmani. The study area is still under development process. For example, in recent years, Dheusagar Amusement Park was constructed along the coastline of New Digha and Biswa Bangla Park near the coastline of Old Digha.

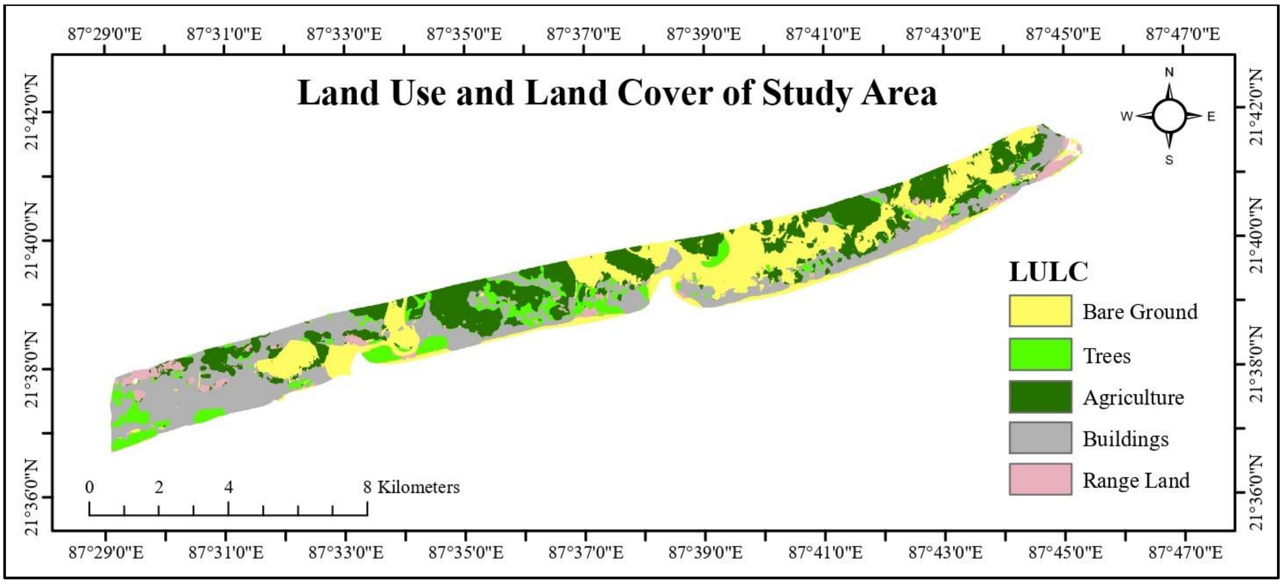

Fig 5.16: Land Use and Land Cover Pattern of Study Area

5.4.4 Socio-Economic Vulnerability (SVI)

The SVI is higher for Digha compared to Mandarmani coastline as there are more man-made structures and more people living in that area. They are more vulnerable to natural calamities.

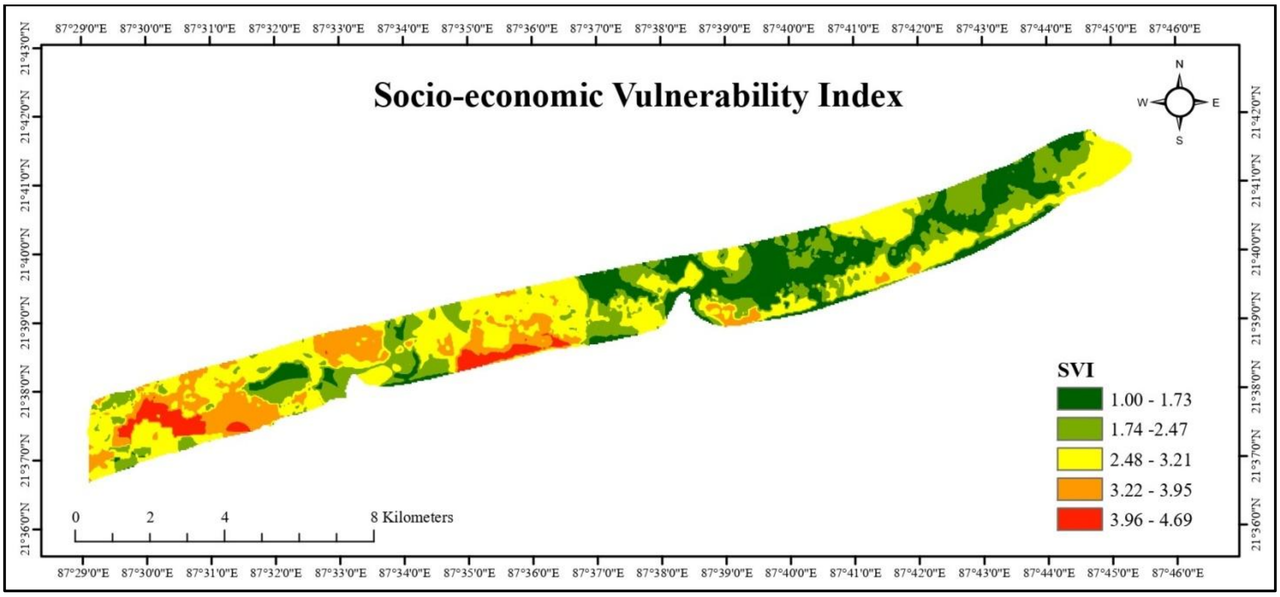

Fig 5.17: Socio-economic Vulnerability Index of study Area

5.5 Coastal Vulnerability Index (CVI)

The highest CVI values from 3.662 to 3.961 can be observed in few areas near Shankarpur-Tajpur coastline, whereas, most parts of the study area have an average CVI value between 3.062 to 3.361 and the lowest CVI values from 2.462 to 2.761 can be observed in some parts of Mandarmani and Digha, away from shoreline.

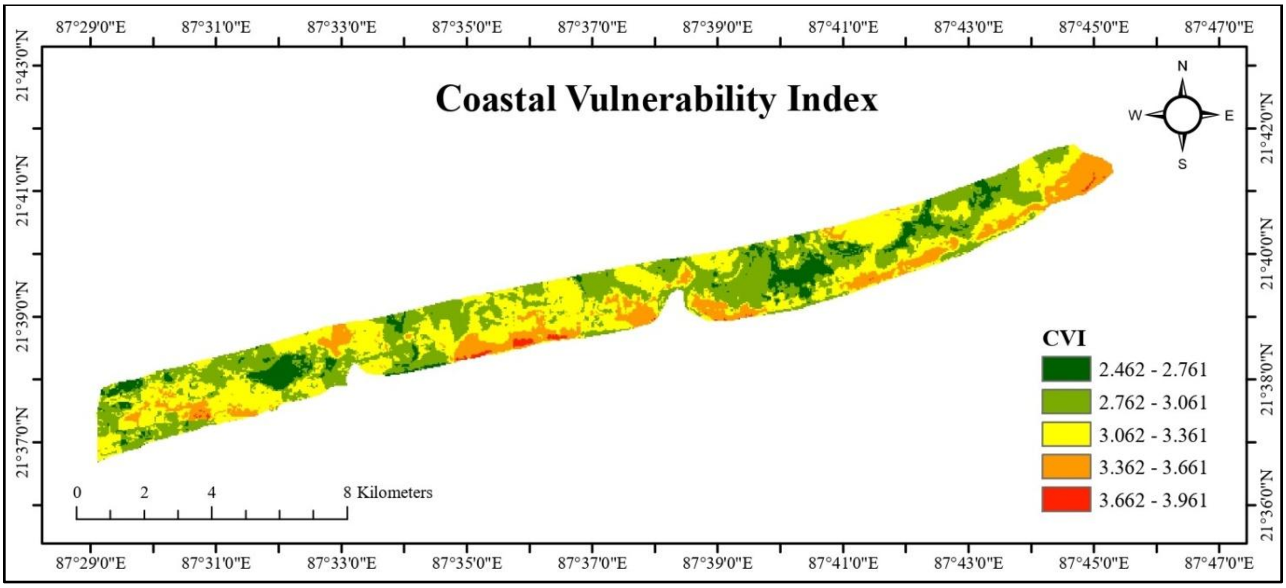

Fig 5.18: Coastal Vulnerability Index of Study Area

5.6 Classification of PVI, MVI, SVI and CVI values

Theoretically, the values of all these indexes may vary from 1 to 5, but these indexes are divided into 5 equal-ranged classes (Table 9) based on their maximum and minimum values to show the vulnerability of the study area more precisely.

Table 9: Classification of Vulnerability Indexes

Index	Very Low	Low	Moderate	High	Very High
PVI	2.52 to 2.82	2.83 to 3.13	3.14 to 3.44	3.45 to 3.75	3.76 to 4.06
MVI	2.31 to 2.84	2.85 to 3.38	3.39 to 3.92	3.93 to 4.46	4.47 to 5.00
SVI	1.00 to 1.73	1.74 to 2.47	2.48 to 3.21	3.22 to 3.95	3.96 to 4.69
CVI	2.462 to 2.761	2.762 to 3.061	3.062 to 3.361	3.362 to 3.661	3.661 to 3.961

6. Conclusion

It can be clearly seen from the results, that overall CVI values for coastline for Digha and Shankarpur-Tajpur are higher than the CVI values of Mandarmani coastline. The average shoreline erosion rate is less for Digha, Shankarpur-Tajpur coastline compared to Mandarmani coastline. But higher sea-surface wave height, presence of road network, more man-made structures near the coastline and higher population density contribute to the higher CVI values of the coastline of Digha and Shankarpur-Tajpur compared to Mandarmani coastline. Also, meteorological trends in study area shows that average MVI value for Mandarmani coastline is higher which indicates that the coastline of Mandarmani is more prone to natural calamities like cyclones and storm surges, compared to Digha coastline. However, higher CVI values for Digha coastline implies that during such an event, Digha will be in more hazardous condition due to higher population density, and presence of man-made structures (involvement of higher capital cost) which indicates more probability of damage or loss of property and livelihood; even loss of lives.

All the data used to determine CVI are secondary data, collected from various reliable sources, no direct field measurement is performed. Obtaining high resolution data and showing variations, specially, for meteorological parameters like temperature, for such small study area is quite challenging work. In most cases while mapping the variations of meteorological parameters, IDW interpolation method is used. Different parameter data are obtained for different time span. Also, the census data is a decade old, the present growth scenario of population is not taken into account, it may vary largely in some areas as the study area is still being developed.

Results of this study are essential for future coastal planning purposes and can be used to help decision makers enact appropriate adaptation measures to alleviate future change due to possible rise in sea-level and to take possible disaster management steps during natural calamities.

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Annexure A1

Questionnaire for Research Work

I, Gunjan Roy, a student of M.E. Civil Engineering, Jadavpur University, want your valuable opinion and suggestions about the parameters mentioned below for my research work on the vulnerability of coastal areas due to natural calamities.

1. Please rate the following parameters on a scale from 1 to 5, which make the coastal areas vulnerable to natural disasters. (1 means that the parameter is the least responsible and 5 means that the parameter is the most responsible for making coastal areas vulnerable. You can also give the same rating for two or more parameters)

Parameter	Your Rating
Sea Level Rise	
Elevation of the Coastal Area	
Coastal Slope	
Sea Surface Wave Height	
Mean Tide Range	
Saltwater Intrusion	
Shoreline Changes: Erosion and Accretion	
Geomorphology	

2. Please rate the following parameters on a scale from 1 to 5, which may cause flooding in coastal areas directly or indirectly. (1 means that the parameter is the least responsible and 5 means that the parameter is the most responsible for flooding. You can also give the same rating for two or more parameters)

Parameter	Your Rating
Precipitation	
Wind Speed and Direction	
Extreme Weather Events	
Temperature	

3. Please rate the following on a scale from 1 to 5, who (which) may be affected by the flooding directly or indirectly. (1 means the parameter is the least affected and 5 means the parameter is the most affected. You can also give the same rating for two or more parameters)

Parameter	Your Rating
Population Density	
Land Cover and Land Use	
Transportation	

Please write below if you would like to share any other information;

Name:

Designation:

Date:

Annexure A2

Questionnaire for Research Work

I am Gunjan Roy, a student of M.E. Civil Engineering, Jadavpur University. I want your valuable opinion and suggestions about the parameters mentioned below for my research work on the vulnerability of coastal areas due to natural calamities.

* Indicates required question

1. Please rate the following parameters on a scale from 1 to 5, which make the coastal areas vulnerable to natural disasters. (1 means that the parameter is the least responsible and 5 means that the parameter is the most responsible for making the coastal areas vulnerable) *

Mark only one oval per row.

	1	2	3	4	5
Sea Level Rise	◯	◯	◯	◯	◯
Elevation of the Coastal Area	◯	◯	◯	◯	◯
Coastal Slope	◯	◯	◯	◯	◯
Sea Surface Wave Heigh	◯	◯	◯	◯	◯
Mean Tide Range	◯	◯	◯	◯	◯
Saltwater Intrusion	◯	◯	◯	◯	◯
Shoreline Changes: Erosion and Accretion	◯	◯	◯	◯	◯
Geomorphology	◯	◯	◯	◯	◯

2. Please rate the following meteorological parameters on a scale from 1 to 5, which may cause flooding in coastal areas directly or indirectly. (1 means that the parameter is the least responsible and 5 means the parameter is the most responsible for flooding) *

Mark only one oval per row.

	1	2	3	4	5
Precipitation (Rainfall)	⬭	⬭	⬭	⬭	⬭
Extreme Weather Events	⬭	⬭	⬭	⬭	⬭
Temperature	⬭	⬭	⬭	⬭	⬭
Wind Speed and Direction	⬭	⬭	⬭	⬭	⬭

3. Please rate the following on a scale from 1 to 5, which may be affected by the flooding directly or indirectly. (1 means that the parameter is the least affected and 5 means the parameter is the most affected due to flooding) *

Mark only one oval per row.

	1	2	3	4	5
Population Density	⬭	⬭	⬭	⬭	⬭
Land Cover and Land Use	⬭	⬭	⬭	⬭	⬭
Transportation	⬭	⬭	⬭	⬭	⬭

Annexure B

Weightage of Parameters

Parameters	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Avg Wt. (%)
Physical Parameters								
SLR	17.31	12.07	14.06	15.52	15.52	19.56	18	16
ELE	17.31	8.61	10.94	15.52	12.07	10.87	14	12.76
SLO	9.614	8.61	10.94	8.62	8.62	15.22	10	10.23
SWH	9.614	12.07	14.06	15.52	12.07	19.56	10	13.27
MTR	9.614	12.07	14.06	12.07	8.62	15.22	10	11.66
SI	17.31	15.52	10.94	1.72	15.52	2.17	14	11.03
SCS	9.614	15.52	14.06	15.52	15.52	10.87	14	13.59
GEO	9.614	15.52	10.94	15.52	12.07	6.52	10	11.46
Meteorological Parameters								
PPT	37.49	21.88	21.88	15	32.15	40.91	26.92	28.034
EWE	29.18	28.12	28.12	45	32.15	31.81	34.62	32.714
TMP	20.84	21.88	21.88	15	10.72	4.54	19.23	16.298
WSD	12.49	28.12	28.12	25	24.98	22.74	19.23	22.954
Socioeconomic Parameters								
POP	36.85	36	33.33	33.33	30.44	33.33	39.12	34.63
LULC	26.3	36	33.33	33.33	30.44	46.67	39.12	35.03
TRP	36.85	28	33.33	33.33	39.12	20	21.76	30.34