

**EXPLORING VULNERABILITY TO COASTAL
EROSION AND LOCAL COMMUNITY
ADAPTATION IN CHATTOGRAM,
BANGLADESH**



By

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CERTIFICATION

The thesis report titled “Exploring Vulnerability to Coastal Erosion and Local Community Adaptation in Chattogram, Bangladesh” submitted by Md. Kamrul Islam, Student ID. No. 21MURP002P, Session: 2021-2022 has been accepted as satisfactory in partial fulfilment of the requirements for the degree of Master of Urban and Regional Planning by Course and Thesis on 21st May, 2025.

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Dedication

Dedicated to my loving son, Ifan and my family

List of Publications

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- Publication 1: Islam, M. K., Jahan, I., & Azad, A. (2025). *Spatial Assessment of Coastal Erosion Vulnerability: Natural and Anthropogenic Factors in Chattogram, Bangladesh*. Natural Hazards Research. <https://doi.org/https://doi.org/10.1016/j.nhres.2025.05.001>.
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This is to certify that Md. Kamrul Islam has carried out this research work under my/our supervision, and that he has fulfilled the relevant Academic Ordinance of the Chittagong University of Engineering and Technology, so that he is qualified to submit the following Thesis in the application for the degree of MASTER of URBAN AND REGIONAL PLANNING BY COURSE AND THESIS. Furthermore, the Thesis complies with the PLAGIARISM and ACADEMIC INTEGRITY regulation of CUET.

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Abstract

Due to the dynamic system, coastal areas are prone to multiple types of hazards. The location of Bangladesh's coast is more dynamic and considered to be one of the most vulnerable in the world because every year different natural disaster causes a large number of casualties and damage. In the context of the sea levels rise and other coastal hazards, it is important to assess the coast's vulnerability to erosion hazards to take the required precautions to protect people and property. A location-specific index for assessing vulnerability has very rarely been developed by combining socioeconomic variables with physical variables. The main goal of this thesis is to comprehensively assess Chattogram's coastal erosion vulnerability, quantifying the extent of erosion and understanding the adaptive strategies employed by local communities to inform resilient and sustainable coastal management. In this study, Coastal Erosion Vulnerability Index (CEVI) was quantified for the Chattogram coast with the extensive use of geospatial technologies. The CEVI was estimated using fifteen coastal Erosion vulnerability assessment factors which include seven physical factors- Elevation, Slope, Geomorphology, Soil texture, Proximity to the coastline, Coastal vegetation, Soil Permeability and eight socio-economic factors Population Density, Land Use and Land Cover (LULC), Dependent Population, Tourist spots, Road Network, Literacy Rate, Proximity to health facilities, Physical Settlement. For the calculation of the weightage of each factor, the Principle Component Analysis (PCA) method was used for this study. Physical vulnerability, driven by proximity to the coastline and soil texture, plays a dominant role, contributing 78.23% to overall vulnerability. Socio-economic vulnerability, influenced by factors like road buffer and literacy rate, contributes 21.77%. The most vulnerable

areas encompass Sitakunda, Banshkhali, and Mirsharai upazilas, which require urgent interventions; in contrast, regions like Khulshi and Bayejid Bostami show low vulnerability. The model is highly accurate, with an AUC of 0.909, offering reliable predictions for disaster preparedness and mitigation efforts. The Weighted Average Index (WAI) from household surveys measured coastal erosion impacts, while an Adaptation Strategy Index (ASI) and an Entropy-based method evaluated adaptation strategies to establish overall adaptive capacity. Findings reveal severe erosion in several unions, with rates as high as -79.87 m/year, largely influenced by sand extraction, mangrove deforestation, and ship-breaking activities. Conversely, some areas exhibit sediment build-up due to hydrodynamic forces. Results indicate that communities face persistent risks from erosion, exacerbated by inadequate management, high water velocity, storm surges, and cyclonic disturbances. This study emphasizes updated coastal policies, ecosystem-based adaptation, and integrating traditional and scientific knowledge for erosion control, guiding sustainable management in the Chattogram coast and similar regions.

বিমূর্ত

বাংলাদেশের উপকূলীয় অঞ্চল একটি গতিশীল প্রাকৃতিক ব্যবস্থা হওয়ায় বিভিন্ন ধরনের বিপদ প্রবণ। এর মধ্যে চট্টগ্রাম উপকূলীয় অঞ্চল অত্যন্ত ঝুঁকিপূর্ণ হিসেবে বিবেচিত হয়, কারণ প্রতি বছর বিভিন্ন প্রাকৃতিক দুর্যোগে ব্যাপক প্রাণহানি ও ক্ষয়ক্ষতি ঘটে। সমুদ্রপৃষ্ঠের উচ্চতা বৃদ্ধি এবং অন্যান্য উপকূলীয় বিপদের প্রেক্ষাপটে, উপকূলীয় ক্ষয়জনিত ঝুঁকি মূল্যায়ন করা অত্যন্ত গুরুত্বপূর্ণ, যাতে মানুষ ও সম্পদ রক্ষার জন্য প্রয়োজনীয় পদক্ষেপ গ্রহণ করা যায়। এই প্রবন্ধের প্রধান উদ্দেশ্য হলো চট্টগ্রাম উপকূলের ক্ষয়জনিত ঝুঁকি সামগ্রিকভাবে মূল্যায়ন করা, ক্ষয়ের মাত্রা পরিমাপ করা এবং স্থানীয় জনগণের অভিযোজন কৌশল বোঝা, যাতে টেকসই ও সহনশীল উপকূল ব্যবস্থাপনা নিশ্চিত করা যায়। এই গবেষণায় ‘কোস্টাল ইরোশন ভালনারেবিলিটি ইনডেক্স (CEVI)’ নির্ধারণ করা হয়েছে ভূ-স্থানিক প্রযুক্তি ব্যবহারের মাধ্যমে। এই সূচক হিসাব করার জন্য ১৫টি উপকূলীয় ক্ষয়জনিত ঝুঁকি মূল্যায়ন উপাদান ব্যবহৃত হয়েছে, যার মধ্যে রয়েছে ৭টি ভৌত উপাদান: উচ্চতা, ঢাল, ভূ-আকৃতি, মৃত্তিকা গঠন, উপকূলের নিকটবর্তীতা, উপকূলীয় উদ্ভিদ এবং মৃত্তিকার পানি শোষণ ক্ষমতা; এবং ৮টি সমাজিক-অর্থনৈতিক উপাদান: জনসংখ্যার ঘনত্ব, ভূমি ব্যবহার ও আচ্ছাদন (LULC), নির্ভরশীল জনগোষ্ঠী, পর্যটন কেন্দ্র, সড়ক নেটওয়ার্ক, সাক্ষরতার হার, স্বাস্থ্যসেবার নিকটবর্তীতা এবং ভৌত বসতি। প্রতিটি উপাদানের ওজন নির্ধারণের জন্য Principal Component Analysis (PCA) পদ্ধতি ব্যবহৃত হয়েছে। গবেষণায় দেখা যায়, উপকূল থেকে দূরত্ব ও মৃত্তিকার গঠনভিত্তিক ভৌত ঝুঁকিই প্রধান, যা মোট ঝুঁকির ৭৮.২৩% এর জন্য দায়ী। অপরদিকে, সড়ক সংযোগ এবং সাক্ষরতার হার নির্ভর সমাজ-অর্থনৈতিক ঝুঁকির অবদান ২১.৭৭%। সবচেয়ে ঝুঁকিপূর্ণ এলাকা হিসেবে চিহ্নিত হয়েছে সীতাকুণ্ড, বাঁশখালী ও মীরসরাই উপজেলা, যেগুলোতে জরুরি হস্তক্ষেপ প্রয়োজন। অন্যদিকে, খুলশী ও বায়েজিদ বোস্তামী অঞ্চল অপেক্ষাকৃত কম ঝুঁকিপূর্ণ। গবেষণায় ব্যবহৃত মডেলটি অত্যন্ত নির্ভরযোগ্য, যার AUC মান ০.৯০৯, যা দুর্যোগ প্রস্তুতি ও প্রশমন কার্যক্রমের জন্য যথার্থ পূর্বাভাস প্রদান করে। উপকূলীয় ক্ষয়ের প্রভাব নির্ণয়ের জন্য গৃহস্থালি জরিপের মাধ্যমে Weighted Average Index এবং অভিযোজন কৌশল পরিমাপের জন্য Adaptation Strategy Index ও Entropy ভিত্তিক পদ্ধতি ব্যবহার করা হয়েছে। ফলাফল অনুযায়ী, বিভিন্ন ইউনিয়নে মারাত্মক ক্ষয় পরিলক্ষিত হয়েছে, যেখানে সর্বোচ্চ ক্ষয়ের হার বছর প্রতি-৭৯.৮৭ মিটার। এই ক্ষয়ের পেছনে বালু উত্তোলন, ম্যানগ্রোভ বন নিধন এবং জাহাজ ভাঙা শিল্প অন্যতম কারণ। বিপরীতে, কিছু অঞ্চলে জলপ্রবাহের প্রভাবে পলি সঞ্চয় লক্ষ্য করা গেছে। গবেষণায় আরও দেখা গেছে যে, মানব সম্প্রদায়গুলো ধারাবাহিকভাবে ক্ষয়ের ঝুঁকির মুখোমুখি, যা অপরিণামদায়ক ব্যবস্থাপনা, উচ্চ পানি প্রবাহ, জলোচ্ছ্বাস ও ঘূর্ণিঝড় দ্বারা আরও তীব্র হচ্ছে। এই গবেষণা কঠোর উপকূলীয় নীতি গ্রহণ, প্রকৃতিনির্ভর অভিযোজন এবং ঐতিহ্যবাহী ও বৈজ্ঞানিক জ্ঞান একত্রে ব্যবহার করে ক্ষয় নিয়ন্ত্রণের উপর গুরুত্বারোপ করে, যা চট্টগ্রামসহ অনুরূপ অঞ্চলের টেকসই ব্যবস্থাপনাকে সহায়তা করবে।

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Nomenclature

Acronyms and Abbreviations

AHP = Analytic Hierarchy Process

AC = Adaptive Capacity

ACI = Adaptive Capacity Index

ASI = Adaptive Strategy Index

AUC = Area Under the Curve

BBS = Bangladesh Bureau of Statistics

BDP = Bangladesh Delta plan

CEVI = Coastal Erosion Vulnerability Index

CVI = Coastal Vulnerability Index

CI = Capacity Index

CZP = Coastal Zone Policy

CDS = Coastal Development Strategy

CARDP = Coastal Area Resources Development Plan

DSAS = Digital Shoreline Analysis System

EBA = Ecosystem-Based approaches

EPR = End Point Rate

ESBN = Estuarine Set Bag Net

ESCAP = Economic and Social Commission for Asia and the Pacific

FAO = Food and Agriculture Organization

GIS = Geographic Information System

HM = Hybrid Model

HSC = Higher Secondary School Certificate

IPCC = Intergovernmental Panel on Climate Change

ICZM = Integrated Coastal Zone Management

IMTA = Integrated Multi-Trophic Aquaculture

KMO = Kaiser-Meyer-Olkin

MCDM = Multiple Criteria Decision-Making

MNDWI = Modified Normalized Difference Water Index

NGOs = Non-Government Organizations

NDWI = Normalized Difference Water Index

OLI = Operational Land Imager

PCA = Principal Component Analysis

PVI = Physical Vulnerability Index

ROC = Receiver Operating Characteristic

RMSE = Root Mean Square Error

SVI = Socio-economic Vulnerability Index

SLR = Sea Level Rise

SSC = Secondary School Certificate

SCE = Shoreline Change Envelope

LST = Land Surface Temperature

LULC = Land Use and Land Cover

LRR = Linear Regression Rate

LGED = Local Government Engineering Department

TOPSIS = Technique for Order Preference by Similarity to Ideal Solution

WAI = Weighted Average Index

Chapter 1: INTRODUCTION

In this chapter, the focus of the research topic is explained while situating the study within context by describing the background and presenting the problem that is at hand and needs to be solved. At this point, it also clarifies the importance of the study, why it is being undertaken, and how it fits within the scope of other related studies. Moreover, this chapter lists the main hypotheses and questions of the study alongside its goals, objectives, and the delimitations of the research. In highlighting the research gaps, this introductory chapter provides an outline to the reader, guiding them through the sequence and rationale of the study.

1.1 BACKGROUND OF THE STUDY

Coasts, the dynamic interface between land and water [1], Supports a significant portion of the global population [2] and are undergoing rapid environmental changes due to natural and anthropogenic influences [3]. Rising sea levels, tectonic activity, natural disasters, coastal inundation, erosion-accretion processes, and human interventions contribute to shoreline modifications [4]. Intensified storms and altered sediment transport further exacerbate these changes, leading to increased flooding, particularly in urbanized coastal regions [5], [6]. Currently, over 75% of the world's shorelines experience erosion [7], with climate change expected to intensify these impacts [8]. Coastal zones, home to over 40% of the global population, host diverse ecosystems that provide essential services [9]. Effective management strategies demand comprehensive assessments of coastline dynamics to mitigate risks and ensure sustainable coastal development [3].

Coastal erosion has emerged as a critical issue due to the high population density in coastal regions, where extensive development activities take place, including industrial operations, increased transportation, and growing tourism [10], [11]. Coastlines are one of the most dynamic systems influenced by meteorological-oceanographic, morphologic, and socioeconomic dynamics [12]. Approximately 20% of the world's population (1.4 billion) live within 25 km, and 40% (2.8 billion) reside within 100 km of the coastline [13], while coastal erosion may affect people at different levels based on the location and socio-economic situations. Coastal environments consist of marine, freshwater, and terrestrial habitats that support a wide range of Indigenous fauna, as well as vegetation with a high biological diversity [14]. Coastal areas around the globe are being subjected to major threats of infrastructure development, urbanization and coastal development, overfishing, pollution, and climate change, while it is vital to ensure proper preservation of the coastal zone for the sustainability of coastal environments [15].

Furthermore, coastal erosion is a significant issue influenced by severe weather events and sea level rise, leaving coastal communities more susceptible to natural disaster [16]. Bangladesh with its large low-lying coastal areas, is particularly more susceptible to natural disasters, while country's coastal zone covers 47,211 sq. km, representing a third of its total land area with about 35 million people (28% of the population)[17]. On the other hand, the coastal area of Bangladesh experiences different forms of natural hazards such as cyclones, storm surges, floods, and coastal erosion every year which cause a lot of damage to both properties and the environment and loss of lives [18].

Coastal environmental modification due to natural and human activities has become a global concern, necessitating a comprehensive understanding of coastline dynamics. In Bangladesh, a significant portion of coastal islands lies

within the central coastal zone, particularly in the Meghna estuary, which is experiencing rapid geomorphological changes [19]. Furthermore, shoreline change is driven by external forces, internal variables, and human interventions [20]. Here, internal factors include nearshore currents, tidal inundation, and sediment shifts, while external forces encompass tsunamis, storm surges, and coastal floods [7], [21]. Additionally, human activities such as dredging, infrastructure development, and deforestation further influence coastal dynamics, contributing to landward migration in many regions [22].

Coastal erosion has become a critical issue worldwide, with global coastlines retreating at rates ranging from 0.01 to 10 m per year, while alluvial deltas experience even more severe changes [23]. Around 70% of the global coastal population severely affected by coastal hazards resides in the Asian region, including Bangladesh [24]. The coastal region of Bangladesh, with a 710 km shoreline, covers approximately one-third of the country's land area and is home to about 37 million people, accounting for 25% of the total population [25]. A study conducted on Kutubdia Island of Bangladesh by Islam et al. (2023) showed that, between 1980 and 2021, the island lost 9.2439 sq. km, with erosion rates of -4.125 m/yr (End Point Rate or EPR) and -4.647 m/yr (Linear Regression Rate or LRR). Also, landward movement was most severe in the north, while the east remained stable.

Adaptation enhances sustainable shoreline management by mitigating social, economic, and environmental risks [27]. It must be dynamic and integrated into national policies to address evolving climate challenges [28]. In France, adaptation measures like beach renourishment and floodproofing could reduce Sea Level Rise (SLR)-induced displacement by up to 36% by 2080 [29]. West Africa prioritizes integrated coastal management and engineering interventions to enhance resilience [30]. Flexible, community-focused strategies

are crucial alongside hard infrastructure [27]. In Bangladesh, cyclone shelters, polder reinforcement, mangrove restoration, and early warning systems have protected over 400,000 people from tidal flooding and storm surges [31].

Moreover, Bangladesh is one of the most disaster-prone countries in the world due to its geographical location and exposure to various climate-induced hazards [32]. The coastal regions of Bangladesh are particularly vulnerable, experiencing recurrent hazards such as coastal erosion, tropical cyclones, and floods, which collectively lead to significant loss of life, damage to infrastructure, and environmental degradation [28], [33], [34]. Coastal erosion is a major concern, with the Chattogram coast experiencing an average erosion rate of 36 meters per year and the Cox's Bazar coast facing an even higher rate of 51 meters per year [35]. Chattogram (Previously known as Chittagong), a commercial city in Bangladesh, faces severe challenges related to coastal erosion, while surface runoff, exacerbated by rising sea levels and increased human activities, intensifies the erosion problem [36]. Local communities particularly fishermen and farmers are mostly susceptible to the impacts of coastal erosion. Studies conducted by Ganguli et al., (2018) and Sarwar & Woodroffe, (2013) indicate that over 1000 hectares of land are lost annually, forcing households to relocate and leading to the destruction of many infrastructures. In addition, the loss of mangroves which serve as a natural barrier, compounded the coastline's susceptibility to storm surges and flooding. Efforts such as embankment construction and mangrove rehabilitation have been initiated to combat this issue [37], [39]. Although lack of funding and community engagement are hindering the proper implementation of necessary steps, local authorities are encouraged to adopt measures to promote community resilience [40]. The enhancement of education and awareness can empower residents to participate collectively in protecting their coastal resources. On the other hand, collaborative and

innovative approaches should be implemented to combat emerging threats due to changing patterns of climatic variables in coastal regions. In that case, both immediate needs and long-term sustainability should be concentrated to develop the resilience and capacity of coastal communities from current to future generations [41].

Preserving the coastal zone is vital for maintaining the sustainability of coastal environments. Coastlines are one of the most dynamic systems influenced by meteorological-oceanographic, morphologic, and socioeconomic dynamics [12]. Approximately 20% (1409 million) of the world's population live within 25 km, and 40% (2818 million) reside within 100 km of the coastline [13]. Coastal environments consist of marine, freshwater, and terrestrial habitats that support a wide range of Indigenous fauna, as well as vegetation with a high biological diversity [14]. Coastal areas around the globe are being subjected to major threats of infrastructure development, urbanization and coastal development, overfishing, pollution, and climate change [15].

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Chattogram, a commercial city in Bangladesh, faces severe challenges related to coastal erosion. Surface runoff, exacerbated by rising sea levels and increased human activities, intensifies the erosion problem[36]. Erosion impacts

on local community particularly those who depend on fishing and agriculture. Research indicates that over 1000 hectares of land are lost annually, forcing households to relocate and leading to the destruction of many infrastructures [37], [38]. In addition, the loss of mangroves which serve as a natural barrier, compounded the coastline's susceptibility to storm surges and flooding. Efforts such as embankment construction and mangrove rehabilitation have been initiated to combat this issue[37], [39]. However, these measures typically meet resistance due to a lack of funding and inadequate community involvement. Local authorities are encouraged to adopt measures that promote sustainability while promoting resilience[40]. Education and awareness campaigns can empower residents to participate in protecting their coastal resources. As climate change continues threaten to coastal zones, stakeholders must collaborate on innovative solutions that address both immediate needs and long-term sustainability, ensuring the resilience of coastal communities for future generations[41].

1.2 CONTEXT OF THE STUDY

Vulnerability assessment, as a key tool in climate risk evaluation [42], is defined by the IPCC as the degree to which systems are susceptible to and unable to cope with adverse climate impacts, based on sensitivity, exposure, and adaptive capacity [192]; the Sixth Assessment Report deepens this framework by highlighting the role of structural inequalities, governance, and socio-political contexts that shape differentiated vulnerabilities and adaptive capacities across communities [193]. Spatial vulnerability assessments, particularly in coastal zones, assist in formulating and implementing mitigation measures [43], while Sudha Rani et al., (2015a) identified vulnerability assessment as a participatory, simulation-model, or indicator-based approach. Additionally, geospatial indicator-based methods measure the intensity of communities to hazards of

natural hazards about their vulnerabilities [44]. Some of the previous Multiple Criteria Decision-Making (MCDM) methods for coastal erosion vulnerability are the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and Fuzzy Logic which all have several constraints e.g., subjective weight assignments, difficulty in dealing with uncertainty [45]. Principle Component Analysis (PCA) is useful in this context as it reduces dimensionality from potentially hundreds of features while preserving variance, enhancing the credibility and interpretability of key factors that may explain coastal erosion [46]. Also, it has been proven that PCA increases the reliability of assessments on vulnerability because important variables related to regional coastal management strategies are identified for MCDM methods [45], [47]. PCA was chosen over methods like AHP or TOPSIS for its objective, data-driven approach and ability to reduce dimensionality while preserving key patterns [48]. By identifying and removing redundant variables, PCA enhances reliability and interpretability, making it ideal for developing the Coastal Erosion Vulnerability Index (CEVI) index in complex, dynamic settings like the Chattogram coast [49]. The (CEVI) assesses the erosion risk of coastal areas like Chattogram by combining physical factors (coastal slope, soil/geology, land use) with socio-economic indicators (population density, infrastructure exposure). Through weighted scoring, it generates a composite score to guide targeted interventions and adaptive planning. These models could also easily incorporate real-time data, which enables dynamic assessments based on changing conditions and emerging threats that would increase the resilience of coastal communities. Additionally, stakeholder involvement in such models can also help to ensure that they account for local knowledge and priorities resulting in more community engagement and ownership of coastal management efforts [50]. In doing so, the potential synergy between top-down and bottom-up approaches

is strengthened in this collaborative endeavour that ultimately empowers communities while significantly enhancing the transparency of these decision-making processes imperative for building trust levels among all stakeholders thereby ensuring perpetuity coastal management strategies.

Furthermore, enhancing spatial analytical tools such as those under remote sensing and Geographic Information System (GIS) technology could provide increased accuracy in monitoring and assessment of coastal ecosystems than normal. The use of these technologies can aid in the collection of real-time data that could lead to more timely actions taken from early detection alerts (i.e., environmental changes, potential hazards), and translate into a more flexible management practice when subjected to various climate change pressures [51]. In addition, promoting collaborations between local governments, Non-Government Organizations (NGOs,) and science organizations can increase shared resources and put in place long-term goals for managing multifaceted issues that coastal regions are challenged with. Such an approach includes not only empowering the communities but also promoting the ownership of such resources which gives rise to restoring practices that are both ecologically sound and economically viable. Such partnerships can also foster the inclusion of the communities by ensuring the people affected the most by coastal issues can participate in any decisions made.

1.3 RESEARCH QUESTIONS, AIM AND OBJECTIVES

The thesis aim is to answer three important research questions to achieve its research objectives for understanding the investigated subject matter.

1. What is the spatial distribution of erosion vulnerability along the Chattogram coastline, and how can it be mapped effectively?

2. How does coastal erosion affect the livelihoods of local communities in Chattogram, particularly those dependent on fisheries and agriculture?
3. How are local communities in Chattogram currently adapting to mitigate the impacts of coastal erosion?

The main aim of this thesis is to comprehensively assess Chattogram's coastal erosion vulnerability, quantifying the extent of erosion and understanding the adaptive strategies employed by local communities to inform resilient and sustainable coastal management.

To achieve this goal, three specific objectives were formulated.

1. To assess coastal erosion vulnerability integrating physical and socio-economic criteria and identify vulnerable areas within the Chattogram coastline using geospatial techniques.
2. To explore how coastal erosion impacts community dynamics, cultural practices, and traditional livelihoods in Chattogram District.
3. To identify the various strategies employed by local communities to adapt to coastal erosion.

1.4 SIGNIFICANCE AND SCOPE

A coastline consists of interconnected physical systems shaped by offshore and onshore processes. Coastal erosion, a key process, gradually wears away shoreline materials through forces like waves, tides, and currents. Erosion arises from natural and human factors over time, defined as the sea's encroachment on land beyond the temporary effects of weather and storms [52], [53]. Bangladesh's geographical location and complex climate challenges have made it one of the world's most disaster-prone countries [54]. Each year, the country's coastal regions face multiple hazards, including coastal erosion, tropical cyclones, and

flooding, all contributing to significant loss of life, property damage, and environmental degradation [55], [56]. The erosion rate along the coast near Chattogram reaches 36 meters per year, while the Cox's Bazar coast has experienced an erosion rate of 51 meters per year [57]. Additionally, in the case of integrating geospatial techniques with socioeconomic criteria, ensuring a distinct research contribution, a study conducted by Waqas, M., et al. 2023 [58] stated that the integration of geospatial techniques with socio-economic data enhances rainfall forecasting by capturing both physical and human factors, leading to more accurate predictions and informed decision-making in vulnerable areas like Thailand. Also, Hlaing, P. T., et al. 2024 [59] described that by combining spatial data (e.g., Digital Elevation Models, land use, soil properties) with model-driven analysis (SWAT) and machine learning techniques (Random Forest, Artificial Neural Networks, Support Vector Machine), the study enhances runoff prediction accuracy. This fusion addresses data scarcity and regional variability, marking a distinct contribution to hydrological modeling in complex environments like Thailand's Tha Chin River Basin. Additionally, Waqas, M., et al. 2024 [60] focuses on improving drought prediction using hybrid AI models but does not explicitly integrate geospatial techniques with socioeconomic criteria as a distinct research contribution.

Furthermore, recent studies emphasize that climate-induced sea-level rise, coupled with changes in land use and upstream hydrological alterations, is intensifying erosion in the eastern coast of Bangladesh, particularly in Chattogram [61], [62]. These compounded impacts are transforming previously moderate-risk areas into high-risk erosion zones. Chattogram's expanding urban footprint, unplanned coastal development, and sand mining have exacerbated shoreline retreat and sediment imbalance [63]. With projections indicating a sea level rise of up to 0.89 meters by 2100 under high-emission scenarios [64], erosion

will not only displace communities but also increase salinity intrusion, reduce agricultural productivity, and threaten regional food security. Moreover, geospatial vulnerability assessments have become crucial in identifying spatial heterogeneity in erosion impacts, integrating terrain, land use, population density, and socioeconomic sensitivity to guide localized adaptation [65], [66]. Moreover, Bangladesh is anticipated to endure severe impacts from climate change, which will exacerbate coastal erosion across its coastal districts, posing further threats to the local economy and environment [67], [68]. Unlike earlier works that mainly focused on physical exposure or historic shoreline change, this study incorporates both natural and anthropogenic drivers in a composite vulnerability index, offering a more nuanced understanding of risk dynamics.

The impacts of climate change, particularly sea level rise, are expected to intensify coastal erosion and changes of shoreline further, exacerbating socio-economic vulnerabilities and environmental risks in these regions [69]. Effective adaptation is crucial to mitigating the adverse impacts of shoreline changes on livelihoods, agriculture, and the coastal environment of Bangladesh [70]. While scientific and indigenous knowledge informs adaptive measures, various barriers, including resource constraints and policy gaps, hinder sustainable adaptation. Addressing these challenges requires a comprehensive understanding of shoreline dynamics and integrated adaptation and mitigation strategies. Several studies have been conducted on hazard coastal vulnerability assessment [71], coastal erosion [72], and migration and adaptation [73] in Chattogram. Additionally, a study was conducted on shoreline change and its impacts on Kutubdia Island [26]. To ensure sustainable coastal management practices, it is crucial to understand the shoreline change rate in the Chattogram coastal area including exploration of adaptation and mitigation practices. In light of these challenges, this study is conducted to assess coastal erosion vulnerability

by integrating physical and socio-economic criteria and identifying vulnerable areas within the Chattogram coastline using geospatial techniques. Also, this study incorporated the exploration of adaptation and mitigation strategies that address the vulnerabilities of communities, enhance resilience, and promote sustainable coastal management practices. The findings of this study will help policymakers, urban planners, disaster managers, and politicians develop disaster resilience policies and frameworks to make the coastline more resilient to hazards.

1.5 THESIS OUTLINE

This thesis consists of six chapters with the intent to analyze the susceptibility of the Chattogram coastal region to erosion and evaluate possible adaptation methods in a systematic manner. In **Chapter 1** the context and background of the study are presented alongside its significance, objectives, and scope; thus, explaining the coastal dynamics of the region. **Chapter 2** presents a review of relevant literature, covering theoretical frameworks, previous research on shoreline change, coastal erosion, vulnerability assessment methods, and gaps that this study aims to address. The study area and research methodology are described in **Chapter 3** through a presentation of the location as well as the data sources and analytical techniques which include EPR (End Point Rate) and LRR (Linear Regression Rate) together with GIS-based spatial analysis. The analysis of vulnerability is the primary focus of **Chapter 4** that contains area-based assessments of various Upazilas/Unions and rate-based evaluations of the change in positions of the shoreline over time; displaying the patterns of erosion and deposition through space and time. The socio-economic and environmental impacts of coastal erosion and the evaluation of the existing and proposed adaptation strategies that give most attention to community resilience and governance at the local level are examined in **Chapter 5** alongside sustainable

coastal management interventions. Lastly, the main findings, policy advice, and suggestions for further research are presented in **Chapter 6** which draws the conclusion of the study.

Chapter 2: LITERATURE REVIEW

This chapter's purpose involves presenting an extensive analysis of scholarly and research materials that address the investigated subject matter. The review analyzes existing research discoveries to develop the foundation for the present investigation. The chapter recognizes current deficits in knowledge and displays the main arguments while presenting the theoretical structures that shape this investigation. Through this chapter, the study demonstrates its relevance and originality while building a foundation for the research questions and methodology structure.

2.1 GENERAL DESCRIPTION OF COASTAL EROSION

2.1.1 Definition and Importance

Coastal erosion is characterized by the removal of sand and sediment from beaches and shorelines, resulting in permanent alterations to the coastal morphology [74]. It is driven by multiple factors, including wave action, sea-level rise, and human modifications such as dam construction and coastal development [75]. Erosion significantly disrupts ecosystems, thereby affecting biodiversity and habitat stability, particularly in environmentally sensitive areas such as coral reefs and mangrove forests [76]. Over 100 million people live within one meter of sea level, making them vulnerable to displacement and economic loss due to erosion and flooding [77]. Unlike immediate disasters, the effects of coastal erosion accumulate over time, necessitating proactive management and adaptation strategies [74].

2.1.2 Global Significance

Coastal erosion is a major global problem that impacts ecosystems, communities, and economies. Recent articles show that the causes of coastal

erosion are complex, including both man-made factors and climate change as well as natural phenomena. The global perspective on coastal erosion reveals alarming trends, with substantial land loss and sediment dynamics that warrant attention. Globally, more than 32 years have passed since erosion has appeared on about 28,000 km² of land and this is mainly due to human activity driver [78]. From 1990 to 2017, the coastal erosion led to significant land loss across India, In Andhra Pradesh: 65% and 69% of the coast was eroded, in Kerala [79]. Shoreline change, storm surge and sea-level rise are the primary risk factors and shoreline change is the most significant among them [80]. Erosion rates exhibit significant variation based on geological composition, with rocky coasts contributing substantially to sediment budgets. Coastal erosion not only poses a threat to land but also alters sediment transport, thereby affecting marine ecosystems and coastal environments resilience [80]. The interplay of natural and anthropogenic factors complicates mitigation efforts, necessitating integrated management strategies. Conversely, while coastal erosion poses significant risks, it also contributes to sediment supply in marine environments, highlighting a complex relationship between erosion and ecological dynamics. Understanding this duality is crucial for effective coastal management.

2.2 CHARACTERISTICS OF CHATTOGRAM COASTAL AREA

The Chattogram coastal area exhibits a complex interplay of environmental challenges and economic opportunities, significantly influenced by urbanization, climate change, and pollution. This region is characterized by its diverse ecosystems, including beaches, mangroves, and fisheries, which are vital for local livelihoods and biodiversity. The subsequent sections delineate key characteristics of the Chattogram coastal area.

2.2.1 Microplastic Pollution

A study identified a total of 452 microplastics in water samples collected from four beaches. The Kattoli Beach showed the maximum concentration of 29% of the total reported microplastics. The fibers contributed to 53% of the total microplastics, being the most common type at Anowara Beach. Both beaches were found to contain mostly fragments, making up 65% of all found items at Patenga Beach [81].

2.2.2 Urban Heat and Land Use Changes

The process of urbanization has much been responsible for remarkable rise in land surface temperature (LST). The built-up areas are projected to increase 45% to 60% by 2040, indicating immediate action for sustainable urban planning and climate mitigation strategies [82]. With a disturbance in vegetation, the LST tends to rise, thereby intensifying the heatwave impact during the summertime in cities. The reported relationship suggests the need for sustainable green space management to alleviate urban heat impacts [83].

2.2.3 Fisheries and Economic Impact

The fisheries resources of the Mirsharai coastal area are substantial, with capture fisheries providing 63 kg/ha and pond aquaculture 1656 kg/ha, although fish farmers already face severe challenges to their economic sustainability due to climate change and highly variable markets [84]. The fisheries within the Chattogram coastline area of Bangladesh have both positive and negative consequences. The ESN (Estuarine Set Bag Net) fishery in Kumira, Chattogram contributes over 18,713 TK a month to local fishermen's income with an average catch of 16.6 kg per boat per day [194]. It is one of the most important income sources for small-scale fishermen. Cumulative earnings are substantial, with shrimp farming being a dominant exporting industry and emphasizing the generation of revenue as well as employment in the coastal regions of Bangladesh

[195]. On the flip side, Bangladesh's mangroves and coastal ecosystems, along with agricultural prospects for peasants, are adversely affected due to the sheer magnitude of shrimp farming [195]. The economic cost of shrimp farming is claimed to be around USD 13.66 per acre a year. Alongside this, unregulated harvesting of baby shrimp leads to obliteration of other aquatic life with larvae mortality rates ranging from 98-99% for every handful of baby shrimp available [196].

2.2.4 Waterlogging Risks

Rainfall-induced waterlogging represents a significant risk to the urban landscape of Chattogram, affecting an estimated 8.42% of the urban area. Among this, approximately 3.03% is classified as highly vulnerable, underscoring the necessity for comprehensive strategies to address and mitigate the impacts of waterlogging on urban infrastructure and public health [85]. In contrast, while these challenges are pressing, the coastal area also holds potential for sustainable development through improved management practices and community engagement in environmental conservation.

2.3 DRIVERS OF COASTAL EROSION

Coastal erosion is a dynamic and complex process arising from wave action, tidal currents, and storm surges that remove shoreline sediments and cause coastal land loss naturally. Chattogram, Bangladesh, is serving as an example of low-lying coastal regions where this phenomenon is particularly pronounced since natural and also human-induced factors strengthen erosion. Natural drivers include sea-level rise and increased cyclone frequency and intensity, alongside riverine sediment transport changes. Anthropogenic influences can further exacerbate the problem in cases where they involve unplanned coastal development, sand mining, and destruction of mangrove forests. These forces

can reshape the coastline and also pose real threats to the livelihoods and housing and infrastructure for local communities.

2.3.1 Natural Drivers of Coastal Erosion

Coastal erosion is caused by a natural phenomenon but accelerating human activity, with a profound impact on coastal ecosystems and communities. Shoreline retreat is attributed to the combined influence of natural causes such as wave action, storm surges, sea level rise and sediment transport dynamics. An understanding of these drivers, and therefore what coastal management can do through change, is the crucial for effective coastal management.

Wave Action and Storm Surges: Storm surges essentially cause relativization of shores since here waves and performances might have made contributions to the destruction of shores during the monsoon season when currents intensify [86].

Sea Level Rise: Sea level also advances erosion even further due to the fact that water merges and floods the coastal region thus making frequent occurrences of floods [87].

Sediment Transport: Other factors that have great impacts on status of the beaches include longshore currents and sediment supply from rivers. Interference with these processes may therefore result to considerable erosion [74].

Tectonic Activity: Changes in the Earth's crust can bring shifts in the shape and size of coastlines affecting the degree of erosion caused by subsidence or uplift [79].

Conversely, while natural factors are significant, anthropogenic influences such as urban development and coastal infrastructure often exacerbate erosion,

highlighting the need for integrated management strategies that consider both natural and human-induced factors [88].

2.3.2 Anthropogenic Drivers of Coastal Erosion

Coastal erosion is significantly driven by anthropogenic activities, which have been identified as the primary contributors to changes in the coastal morphology. Among these, the construction of coastal structures, urban development, and alterations to sediment transport processes are at the top of the list. The following sections deal in detail with the key anthropogenic drivers of coastal erosion.

Coastal Development and Urbanization: Rapid urban growth blocks natural sediment flow, with shoreline retreat becoming more pronounced, especially in densely populated regions such as North Africa [88]. Although the coastal defense structures are aimed at eradicating erosion, they produce opposite results due to disruption in sediment and consequently leading to local erosion hotspots.

Sediment Supply Disruption: Dam construction and river channel modifications are human activities that significantly reduce the supply of sediment to the coast hence causing erosion [78]. In places such as West Bengal, the construction of seawalls has increment wave energy and for that reason erosion at their bases, thus revealing the shadow side of coastal engineering. The latter has left adverse effects on the same environment it sought to protect [86].

Climate Change Interactions: Anthropogenic interactions with climate change result in rising sea levels and more frequent storm incidences hence escalating the rates at which erosion takes place on the coastline [89]. Though major drivers of coastal erosion, anthropogenic factors cannot be isolated from the consideration of natural influences, such as extreme weather events and

geological processes, in shaping the dynamics of a coast. Such an understanding of how these factors interplay is a prerequisite for effective coastal management strategies.

2.4 VULNERABILITY TO COASTAL EROSION

Worldwide coastal stability and sustainability face considerable danger from erosion especially in the developing nation of Bangladesh. The combination of environmental elements and socio-economic conditions and infrastructural components produces the coastal erosion risks which affect Chattogram.

2.4.1 Concept of Vulnerability

Vulnerability reflects the susceptibility of individuals or groups to harm, influenced by various factors such as social context, personal characteristics, and systemic structures. Vulnerability in coastal management illustrates the complexities of defining vulnerable communities and environments, emphasizing the need for comprehensive assessments that consider social relationships and environmental dynamics [90]. In legal contexts, vulnerability serves to protect individuals unable to advocate for themselves, such as minors in medical situations [91]. Vulnerability is characterized by feelings of uncertainty, unpredictability, and irreversibility, which can lead to both protective behaviors and passive suffering [92].

2.4.2 Vulnerability Assessments of coastal erosion

Coastal vulnerability assessments provide a base for comprehending and minimizing risks in the coastal environment. Different approaches have been developed to assess these vulnerabilities with the incorporation of environmental, socio-economic, and geomatics' factors. The following sections outline major approaches and findings of recent studies. A grid-based risk assessment model was developed by including 14 indicators to assess coastal

exposure and socio-ecological environments, specifically in metropolitan areas like Shanghai and Sydney [93]. A hybrid model utilizing Bayesian networks and hydrodynamic simulations was utilized to assess the vulnerability of Konyaalt Beach due to any storms and sediment transport [94]. An econometric model for forecasting economic losses resulting from coastal erosion in Liaoning, China is presented. This econometric model divides the region into high, moderate, and low-risk areas. It predicted significant reductions in associated losses by 2025 [95]. Vulnerability assessments in Morocco's Agadir Bay revealed that 92% of the coastline is experiencing erosion, emphasizing the need for targeted conservation strategies [96]. Effective management strategies, including adaptive infrastructure and Ecosystem-Based Approaches, are essential for enhancing coastal resilience against erosion and climate change impacts [97][94]. While these assessments provide valuable insights for coastal management, they also highlight the need for continuous monitoring and adaptation to evolving environmental conditions.

2.4.3 Frameworks for Assessing Coastal Erosion Vulnerability

Coastal erosion vulnerability assessment frameworks are important steps toward understanding and managing the risks related to climate change and human-induced actions. There have been several techniques developed to use the hybrid of technology and ecological aspects to make a full evaluation. The following section extracts from recent studies some of the frameworks.

Hybrid Models and Bayesian Networks: The Hybrid Model (HM) Bayes factors are also coupled with hydrodynamic modeling in evaluating coastal vulnerability with due attention to environmental parameters such as wind and waves [94]. It lays more emphasis on the risks related to storm impacts and erosion against the background of adaptive infrastructure development and continuous monitoring.

Geomatics and GIS Approaches: Geomatics science, more specifically GIS and remote sensing, was used to develop the Coastal Vulnerability Index (CVI) for Agadir Bay in Morocco over 46 years, which showed major erosion trend patterns [96]. The Digital Shoreline Analysis System (DSAS) was applied to study shoreline changes, an essential input required for coastal management.

Multi-Scenario Analytical Frameworks: In Apulia, Italy, a multi-tier system that integrates remote sensing, GIS, and Bayesian Networks is applied to assess the vulnerability of coastal erosion under different climate change scenarios [98]. This will enable the evaluation of management measures, such as Nature-Based Solutions, that can be used to alleviate erosion impacts.

Vulnerability Index Utilization: The vulnerability indices classify coastal zones according to their geological and physical characteristics, as presented in the case of the Cherating to Pekan coast [97]. Such zonation ensures that specific zones requiring targeted management can be identified.

Multi-Hazard Frameworks: The application of a multi-hazard approach to vulnerability across multiple coastal hazards reveals great exposure in densely populated areas, as is the case with Macao [99]. This serves as a true reflection of the significance of natural habitats in vulnerability reduction and informs adaptive strategies. While these frameworks provide valuable insights for coastal management, challenges remain in data availability and the need for continuous adaptation to evolving environmental conditions.

2.5 ADAPTATION STRATEGIES TO COASTAL EROSION

Strategies to address coastal erosion serve as critical tools to combat shoreline retreat effects that harm both communities and their environments as well as infrastructure systems. Both structural and non-structural adaptation

measures are implemented in Chattogram to combat the increasing coastal erosion problem.

2.5.1 Engineering-Based Adaptations

Engineering adaptations to coastal erosion vulnerability must therefore be a composite of traditional and modern approaches. The study brings out different strategies comprising hard engineering solutions and nature-based engineering to offer a recommendation for the matter regarding climate change impacts on coastal areas. To ensure, herewith, an increased level of resilience to threatened coastal communities against aspects such as increasing levels of high-water visibility.

Traditional Hard Engineering Solutions: Sea walls, as well as groins, are structures that are used commonly, to protect coastlines. Their effectiveness, especially under adverse weather conditions, has been a subject of debate [100]. Hard-engineered structures have lessened erosion in Ghana, though at the same time negatively impacting local fishing communities due to insufficient consultation [101].

Nature-Based Engineering Approaches: New designs that imitate landscaping, by coincidence can increase sediment entrapment as well as biodiversity, are some of the results of the studies done near the Iberian Peninsula [102]. Approaches that support nature-based systems may ensure sustainable protection with the least ecological disruption involved [103].

2.5.2 Ecosystem-Based Approaches

Ecosystem-Based Approaches (EbA) promotes the incorporation of Ecosystem-Based Approaches into the mainstream of climate change policies and programs at all levels. Such methodologies were found to be more effective than

traditional hard engineering. The section below provides the major adaptation strategies as revealed by recent studies.

Integrated Multitrophic Aquaculture: The adoption of integrated multitrophic aquaculture (IMTA) could be perceived to enhance the resilience of coastal ecosystems due to diversified production and improved health of the ecosystem [104]. The system, therefore, boosts the efficient use of different species at various trophic levels as climate change continues exerting its pressure on aquaculture systems.

Nature-Based Solutions: The program on mangrove restoration presents such an initiative wherein these trees will act as natural barriers against erosion, offering improved sediment retention and stability to the coastline[105][106]. Combining nature-based solutions with traditional engineering can optimize coastal protection, as seen in various case studies across different regions [107].

Stakeholder Engagement and Living Labs: Utilizing living labs fosters stakeholder engagement, allowing for real-time testing of EbA strategies and adaptation measures [108]. Engaging local communities ensures that adaptation strategies align with socio-economic needs, enhancing their effectiveness and sustainability [107]. While Ecosystem-Based Approaches offer promising solutions, challenges remain in their implementation, particularly regarding long-term effectiveness and the need for comprehensive research to evaluate their performance under varying climate scenarios.

2.5.3 Community-Based and Policy Approaches

Coastal erosion is a major threat to communities around the world, highlighting the need for successful adaptations both at the community level and in terms of policy. This information is essential to minimizing climate change

risks and improving strategies for sustainable coastal management. The key adaptation strategies identified in the literature are presented below.

Community-Based Approaches: Public participation for a local coastal management vision in Ovar, Portugal. Participatory events with local stakeholders drove a common vision of the way forward for this study site, illustrating how decision-making needs to be run by citizens [109]. Livelihood diversification is a strategy that has been adopted by coastal communities in Indonesia to reduce their vulnerability towards erosion and climate change impacts [110]. To promote resilience, it is also crucial to increase awareness at the community level about coastal risks and how to adapt to them [110].

Policy Approaches: Managed relocation in Australia has been conceptualized as a vital change of policy, aimed at relocating communities from high-risk coastal settings by the Sendai Framework for Disaster Risk Reduction [111]. Effective coastal management requires integrating national risk hierarchies into local planning, ensuring that policies are responsive to evolving environmental conditions [111]. Identifying and ensuring diverse funding sources is critical to enabling coastal policy transition and the effective implementation of sustainable adaptation options [112]. While these strategies highlight proactive measures, there is a counterpoint regarding the resistance from communities to policy changes, particularly when it involves relocation or realignment, which can lead to social and political challenges [112].

2.5.4 Review of Global Adaptive Strategies to Coastal Erosion

Coastal erosion is a major global concern, with different regions employing adaptive responses appropriate to the specific weight of natural and socio-economic conditions. These include everything from structural measures to community-level approaches, which illustrates the spectrum of challenges posed

by climate change and anthropogenic influences. Here are some notable adaptive strategies used by different regions to mitigate coastal erosion.

Structural Defences: In Peninsular Malaysia, the government has implemented various coastal defense systems, including 55 structures along the Terengganu coastline, to mitigate erosion exacerbated by monsoonal winds [113]. In Java, Indonesia, mangrove forests are developed along the coasts to prevent wave erosion and enhance sediment deposition because they function as a natural breakwater [105].

Indigenous and Community-Based Approaches: In south-eastern Ghana, historical buildings used to have alternations of rooted sand fillings and reinforced structures above the ground. Recent developments, however, introduced hard flood protection schemes which can be detrimental to the local economy, suggesting the necessity of using soft engineering approaches [114]. The INCCA project in the Portugal context encourages the participation of stakeholders in the design of coastal types of adaptation strategies to achieve a common goal towards better management of threatened coasts [109].

Economic Considerations: A study focusing on Portugal points out the costs related to different adaptation strategies. It shows that a mix of defense and accommodation measures could be costly and hence highlights economic assessment as important in the decision-making process [115]. While their suggestions for adaptive strategies help to manage coastal erosion problems, there is still conflict on the appropriate ratio of structural measures to restoration of non-engineered ecosystems which would offer a better and sustainable outcome in the longer term.

2.6 POLICIES AND PROGRAMS RELATED TO COASTAL EROSION IN BANGLADESH

Bangladesh has adopted multiple policies and strategies regarding coastal erosion, particularly the Coastal Zone Policy (CZP) of 2005, which outlines guidelines on coastal development, and the Coastal Development Strategy (CDS) is formulated in 2006, which focuses on selected areas, concerns, and opportunities [192]. These policies strive to sustain the protection of the coastal belt, diminish vulnerabilities, and promote sustainable development in the coastal region. The CZP aims at stimulating economic activities and development alongside meeting fundamental requirements such as diminishing vulnerabilities and equitable distribution of resources [192]. The Coastal Development Strategy (CDS) is a targeted approach, focused on delineated areas and disadvantaged populations, where the ICZM program from 2006-2010 aimed at operationalizing and institutionalizing integrated coastal zone management approaches in Bangladesh [197]. As part of the Bangladesh Delta Plan (BDP) 2100, coastal erosion is listed as one of the critical issues. The plan focuses on protecting coastal areas from the rising sea levels, increasing river flows, and erosion from seasonal typhoons. In BDP, there is also a focus on the development of an integrated water resources development and management system that includes flood moderation, salinity intrusion management, and other protective measures to ensure the delta region's sustainability and social equity [198]. The UN/ESCAP-GoB Coastal Environment Management Plan for Bangladesh (1987) is also the first attempt to address Bangladesh's coastal erosion and environmental problems [199]. Along with the Bangladesh National Conservation Strategy (1987) and the Coastal Area Resources Development Plan (CARDP, 1988), these plans tried to manage the coastal zone of Bangladesh. Capacity building, afforestation, environmental flow evaluation, establishing databases were some of the as well as waste management were also parts of the

initiatives. The CARDP focused on coastal resource management, which was an attempt to enhance the overall coastal management, tackle coastal resource erosion, and increase the overall benefits for coastal people. Its strategy revolved around sustainable development for the coastal areas in an effort to counterbalance managed resource use on the coastal regions and the natural disasters like coastal erosion [200].

2.7 GAPS IN LITERATURE AND FUTURE RESEARCH DIRECTIONS

There is a growing consensus in recent studies that there are underlying deficiencies in the coastal erosion studies as well as in the literature on adaptation strategies. Coastal areas are threatened by climate change impacts like sea-level rise and the most intense storms [116]. Even though there have been improvements in assessing coastal erosion, further enhancements in uncertainty sampling and estimated time series data are required [116]. As it would now appear, climate change has not been the focus of studies on Indonesia's coastal vulnerability works since 2015 [117]. The economic vulnerability aspect is often not considered in the assessments due to the difficulties associated with its collection [118]. Studies emphasize the need for improved implementation of adaptation policies [119] and better understanding of coastal processes driving erosion [116]. Key research gaps include geographical imbalances in study areas, limited sectoral integration, and insufficient economic focus [119]. There's a pressing need to incorporate projected time series of coastal drivers into erosion models and adequately sample uncertainties associated with climate change scenarios [116]. Economic challenges in coastal adaptation include funding uncertainties, limitations in traditional cost-benefit analyses, and underestimated future risks [120]. Future research should focus on implementation phases of adaptation policies, address geographical imbalances, integrate multiple sectors, and improve contextualization within coastal governance frameworks [119].

Additionally, there's a need for more regional-scale studies and increased focus on the economic and financial aspects of coastal adaptation [119]. Additionally, the impacts of coastal development activities and existing erosion mitigation measures are poorly understood, necessitating thorough reviews of current management practices [121]. Addressing these gaps is crucial for enhancing the resilience of coastal social-ecological systems.

Chapter 3: METHODOLOGY

This chapter describes the study's methods of research design and methodology. It explains how the data was collected, analysed, and interpreted to answer the research questions and achieve the goals stated earlier in the document. The chapter starts with a study area description and information on the general strategy for conducting the research, and explains the reason the research strategy was chosen. This is followed by an explanation of the techniques used for data collection, sampling, and analysis.

3.1 STUDY AREA PROFILE

This section offers a comprehensive description of the geographic, social, and economic features of the study area. It is important to know the profile of the study area so as to contextualize and apply the findings of research. The description encompasses location, population, facilities, economic activities, and particularities relevant to the subject of investigation.

3.1.1 General Description

Chattogram is a major port city and the second-largest city in Bangladesh, situated on the country's south-eastern coast and serves as a vital economic and commercial hub. This City is also known for the main urban center of the country, which is a major port city on the Bay of Bengal [122], [123]. This study is conducted on four Upazilas (Mirsharal, Sitakhunda, Anwara, and Banshkhali) and the Chattogram metropolitan area (Figure 1), while the total area of the studied coastal region is 2,228 Sq. km. and the population is 9.2 million [124]. The 377 km-long coast boasts a diverse range of soil types, including tidal muds, estuarine deposits, and submerged beach and dune sands, and its economy is primarily driven by four key industries: fish farming, sea fishing, salt cultivation, and tourism [125]. A neighbourhood in southern Chattogram known for its

Petagna Beach, a popular destination along the coastline. An island situated near Chattogram in the Bay of Bengal is known for its coastal communities and vulnerability to natural disasters [126].

3.1.2 Geographical Location

The Chattogram coast of south-eastern Bangladesh has a dynamic geomorphology and considerable ecological resources. It extends about 245 km to the Bay of Bengal, comprising sandy beaches, estuarine ecosystems, and an intricate network of rivers. The coastline lies as a north-south orientation, bordered by hills on one side and influenced by the confluence of two major rivers: the Karnaphuli and Matamuhuri. [127], [128].

3.1.3 Coastal Geography and Vulnerability

The area contains various ecosystems, such as mangroves, salt marshes, and coral reefs which are important for biodiversity [127], [128]. The region is also at a high risk of natural calamities like floods and cyclones, with large areas being extremely vulnerable [129]. here are some records of monitoring that make mention of erosion and accretion, with differential rates affecting the landmass alteration over time [130]. The coastal area of Chattogram, on the other hand, is rich in resources and biological viability but is being challenged with industrial expansion and pollution impact that's worsening the area's sustainability and strength towards natural calamities.

Chattogram is highly vulnerable due to natural processes, human activities, and climate change, while the vulnerability of the coastline may vary, and certain areas could be more prone to erosion [131]. The interior coastal regions of Chattogram range in elevation from 6 to 12 meters, with the eastern hilly areas exceeding 12 meters. In contrast, offshore bathymetry shows depths from 0 to -1096 meters, while nearshore areas range from 0 to -44 meters [132]. Chattogram's

coast experienced more erosion than accretion, though accretion rates were higher. Maximum erosion reached 36.5 m/yr, while accretion peaked at 63.4 m/yr, with net area changes of 12.6 km² lost to erosion and 17.1 km² gained through accretion [133]. Also, a geospatial analysis conducted by Amin, S. B. 2021[134] of the Chattogram coast found that over the past 24 years, 70.02% of coastal transects in Chattogram showed accretion, while 29.07% experienced erosion. Also, the southern zones, Patenga and Anwara were identified as erosion hotspots, with maximum shoreline retreats of 35.1 m and 39.6 m, respectively, driven by urban expansion, sediment disruption, and wave action. Chattogram's coastal region is economically vital, hosting the country's busiest seaport and contributing significantly to trade and industrial activities [135].

3.1.4 Demographic and Socioeconomic Profile

The demographic and socio-economic profile of the Chattogram coastal region reveals the complex interaction of community structures. The region is characterized by a predominantly young population, with significant reliance on coastal resources for livelihood. The population in coastal villages like Kumira and Kattoli showed a shift from younger age groups (20-30 years) in 2005 to a more mature demographic (30-40 years) by 2018 [136]. Economic activities are primarily centered around fishing, agriculture, and small businesses. In Mirsarai, fishing yielded the highest income (BDT 359,035.3) compared to agriculture (BDT 231,900) [137]. A significant portion of the population lives in kaccha houses (93%), indicating low housing quality and economic vulnerability [137]. Educational attainment is low, with many respondents lacking formal education. However, there was a noted increase in secondary education holders in 2018 [136]. . economic activity and educational success Health indicators shows improvement. Including increased access to medical services and the transition to modern health care [138], [139].

3.1.5 Environmental and Ecological Aspects

The Chattogram coastal region faces major environmental and ecological challenges. due to pollution and habitat degradation, breaking activities have led to high levels of toxic metals in the water. with lead and chromium concentrations exceeding permissible limits [140]. The heavy metal pollution index is an important indicator of water quality. This poses a risk to the ecosystem and human health. Urban development hurts mangrove forest plants. This is important for protecting coastlines and biodiversity [141]. A correlation was found between increased surface temperature and decreased vegetation. Emphasizing the ecological consequences of habitat loss.

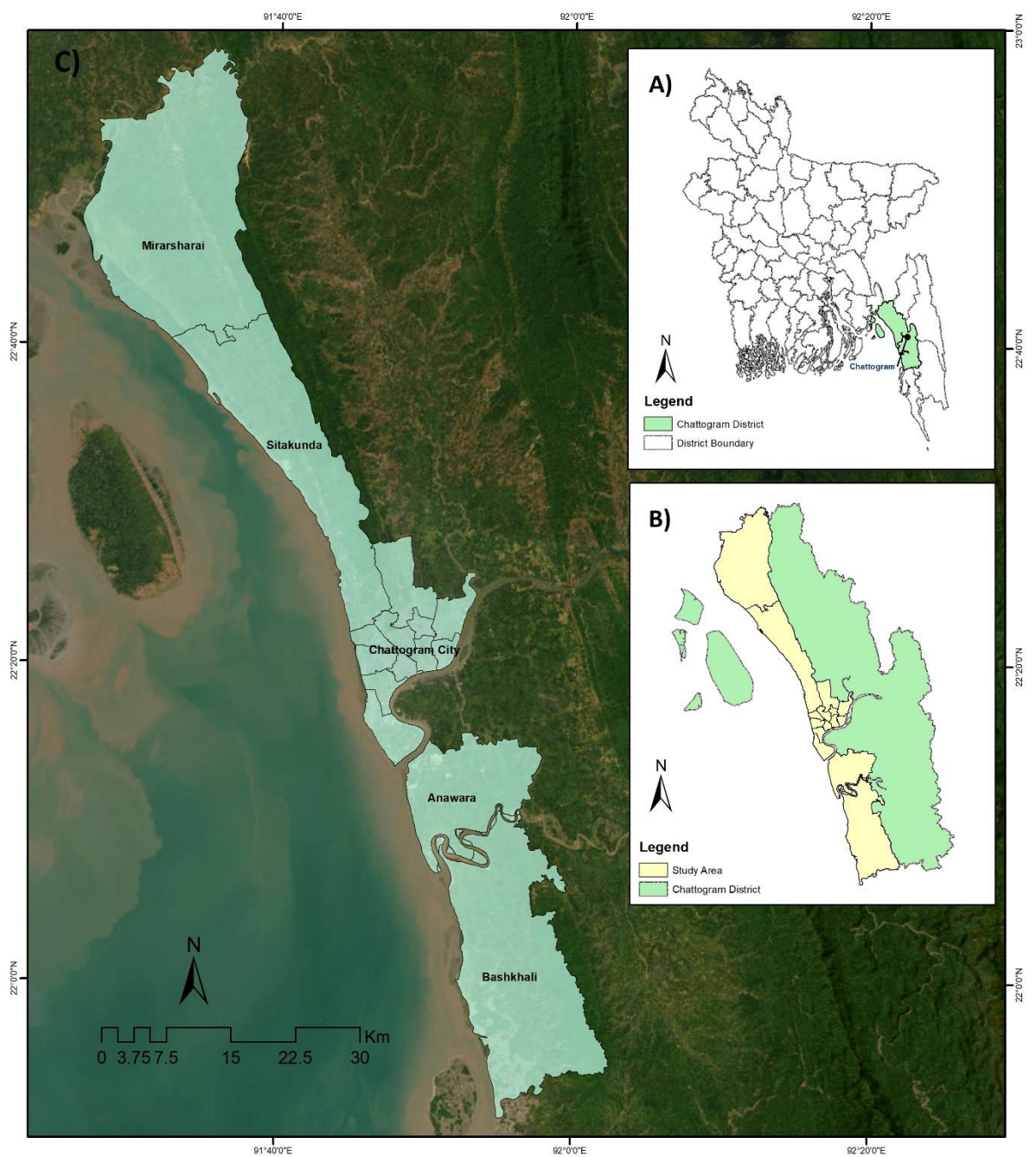


Fig. 3.1 Locality of the Study Area (A) Bangladesh, (B) Chattogram district, and (C) Study area

3.2 METHODS

This chapter describes the methodology of the study. A flow chart depicting the main steps relating to carrying out the study is shown in Figure 3.2.

3.2.1 Literature Review

To understand the concept and methods of assessing Chattogram's coastal erosion vulnerability, quantifying the extent of erosion, and understanding the adaptive strategies employed by local communities to inform resilient and sustainable coastal management, many papers and documents have been collected. In this regard, various journal papers, reports, conference papers, and dissertations have been reviewed. Outline the research design are quantitative or qualitative.

3.2.2 Statement of the problem

Coastal erosion poses a significant threat to the Chattogram coastline, impacting not only the physical landscape but also the socioeconomic conditions of local communities. Despite existing studies on coastal erosion, there is a lack of comprehensive assessments that integrate both physical and socioeconomic criteria to identify vulnerable areas and understand their nuanced effects on community dynamics and livelihoods. Addressing this gap is essential for developing effective adaptation strategies, as local communities face increasing challenges from erosion, necessitating a thorough exploration of their resilience and adaptive practices.

3.2.3 Formulation of goal and Objectives

Before introducing a study on a detailed basis, it is necessary to take a preliminary idea and knowledge about the study. The literature review has been carried out for background study and conceptual development which is a great help for a better understanding of the work and approaches. Furthermore, its

conceptualization is needed to formulate the aim and to proceed towards the efficient achievement of the objectives. The aim of this research is formulated based on the problem statement, and to achieve the aim of this research, the relevant two objectives are selected, which are mentioned in Section 1.3 of Chapter 1.

3.2.4 Calculation of Coastal Erosion Vulnerability Index (CEVI)

This section describes the calculation process of erosion vulnerability assessment within the study area and details the verification methods used for the results. An assessment of erosion vulnerability combines data from natural factors alongside anthropogenic factors. The parameters went through processing via [e.g., GIS-based tools, empirical models, or statistical techniques] to create an erosion vulnerability map.

Remote sensing and ArcGIS software were used to create the spatial layers of the chosen criterion utilizing GIS and remote sensing techniques. The coastal Erosion vulnerability index illustrates the degree of exposure of coastal areas to the impacts of physical and socio-economic factors. The approach of the CEVI in this study can be expressed by the Equation (1) as follows;

$$CEVI = W_1PVI + W_2SVI \quad (3.1)$$

where W1 and W2 are the weightage of PVI and SVI. PVI is the Physical Vulnerability Index and SVI is the Socio-economical Vulnerability Index, given by;

$$PVI = (X_1W_1 + X_2W_2 + X_3W_3 + \dots + X_{10}W_{10}) \quad (3.2)$$

$$SVI = (X_{11}W_{11} + X_{12}W_{12} + X_{13}W_{13} + \dots + X_{16}W_{16}) \quad (3.3)$$

In the above equations (2) and (3), Wn is the weight value of each variable derived by using PCA and Xn is the vulnerability score of each variable [142], [143].

The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy along with Bartlett's Test of Sphericity were employed to confirm data suitability for factor analysis and evaluate the weighting methods applied in preparing Physical Vulnerability Index (PVI) and Social Vulnerability Index (SVI). The KMO statistic provides a measure of common variance among variables and suitable factor analysis requires values that approach 1.0. Bartlett's Test of Sphericity showed that the correlation matrix displayed significant differences from an identity matrix to demonstrate sufficient variable correlations. The analysis produced satisfactory results which confirmed factor analysis as an appropriate method for deriving variable weights to calculate PVI and SVI.

CEVI is a systematic approach to quantifying vulnerability through the integration of physical and socio-economic factors, ensuring a holistic assessment of coastal vulnerability. By employing weighted indices derived from PCA, CEVI effectively highlights the most significant vulnerabilities, guiding targeted interventions and sustainable coastal management practices [144].

3.2.4.1 Data required for vulnerability assessment

Fifteen criteria under two vulnerability indices: (i) Physical and (ii) Socioeconomic, were considered to assess coastal erosion vulnerability. The criteria are chosen based on their applicability to coastal vulnerability and data accessibility. Seven criteria were selected for assessing the physical vulnerability of coastal erosion (Fig. 3.2 to 3.8). The selected criteria are Elevation, Slope, Geomorphology, Soil Texture, Soil Permeability, Proximity to the coastline, and Coastal Vegetation [145], [146]. In addition, the eight criteria for socio-economic vulnerability mapping in the assessment of coastal erosion are as follows: Population density, Dependent population, Tourist spots, Land Use/Land Cover (LULC), Road network, Distance to Healthcare, and Literacy rate (Fig. 3.9 to 3.16). Qualitative data, such as population density, dependent population, literacy rate,

and tourist spots were obtained based on the smallest administrative boundary (Union). The data used in the study was aggregated from multiple data sources comprising both national as well as international organizations considering existing literature, and data availability. The data type and other relevant information about each criterion are presented in Table 3.2.

3.2.4.2 Accuracy Assessment of Land Use and Land Cover (LULC) Data

The confusion matrix classification results reveal a strong accuracy level with 84% of pixels matching the reference data correctly (Table 3.1). The Kappa Coefficient of 0.80 demonstrates substantial agreement between classification results and reference data while accounting for chance agreement. The model demonstrates reliable performance, which is reflected in its positive performance indicators.

Table 3.1. Accuracy assessment (Confusion matrix) of LULC Classification

		Referenced Data					Producer Accuracy (%)
		Water bodies	Vegetation	Crop land	Built Area	Bare ground	
Classified Data	Water bodies	27	0	0	0	0	100
	Vegetation	0	30	4	1	0	85.71
	Crop land	1	0	23	3	2	79.31
	Built Area	0	0	0	22	4	84.62
	Bare ground	2	0	3	4	24	72.73
User Accuracy (%)		90	100	76.67	73.33	80	
Overall Accuracy (%)		84					
Kappa Coefficient		0.80					

The User Accuracy showed that most categories had strong performance metrics and particularly Vegetation achieved perfect accuracy at 100% while Waterbodies reached 90%. The Built Area classification shows 73% User Accuracy which indicates that 23% of the pixels labeled as built-up areas represent different land types especially Bare Ground which appears to be

commonly mistaken for built-up areas. On the other hand, the Producer Accuracy, which indicates how well the classification captures all actual instances of a class, also shows solid performance for most classes: Waterbodies achieve perfect detection along with high classification accuracy for vegetation and built areas, yet Bare ground and cropland exhibit some missed area identification errors.

The classification model achieves strong overall performance and dependable results especially in identifying vegetation and waterbodies. The model currently fails to differentiate built-up areas from other land cover classes effectively with bare ground being the main issue and thus requires improvements in either feature selection methods or more training data to enhance recognition of built environment spectral features.

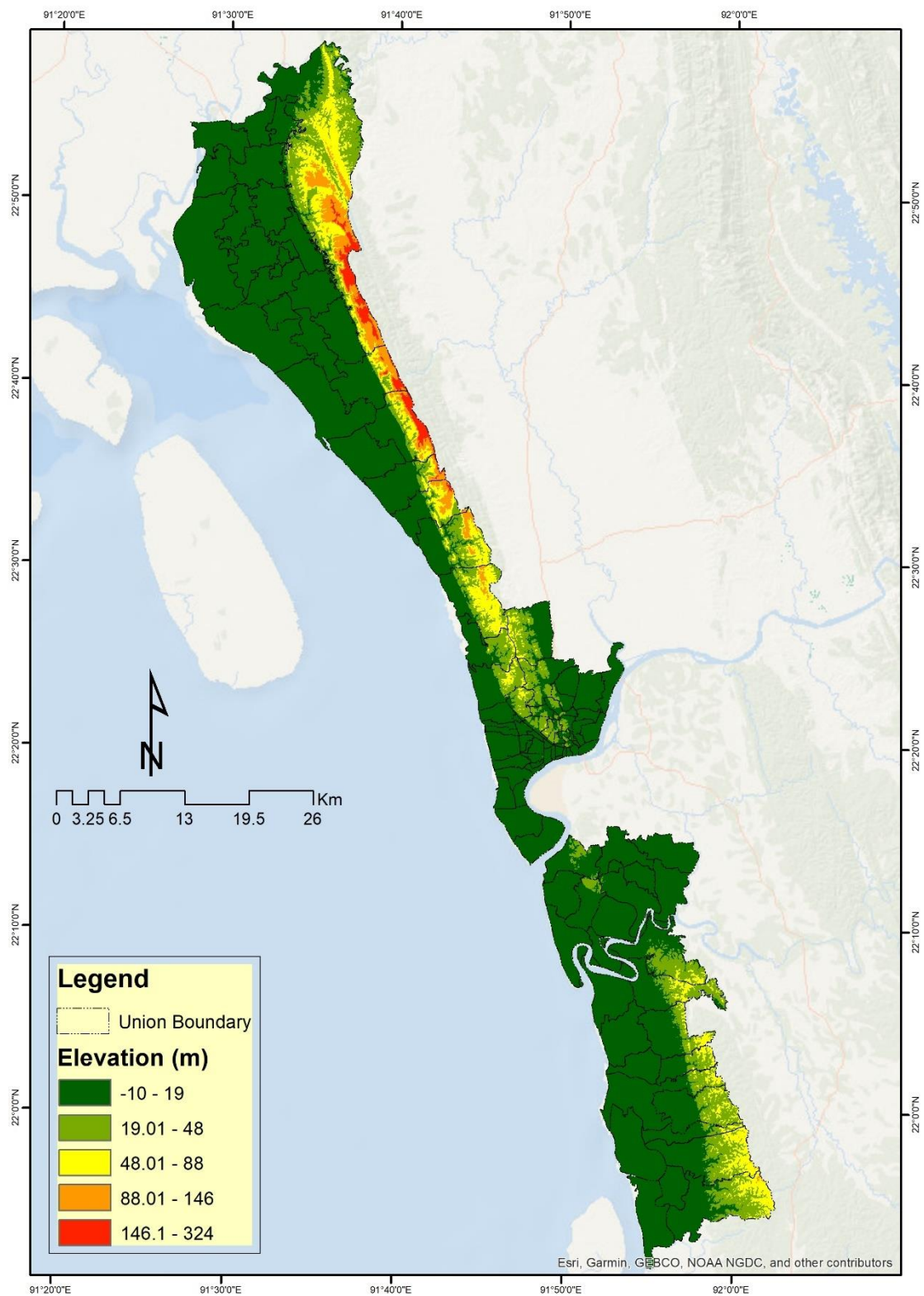


Fig. 3.2 Physical vulnerability influencing criteria (Elevation)

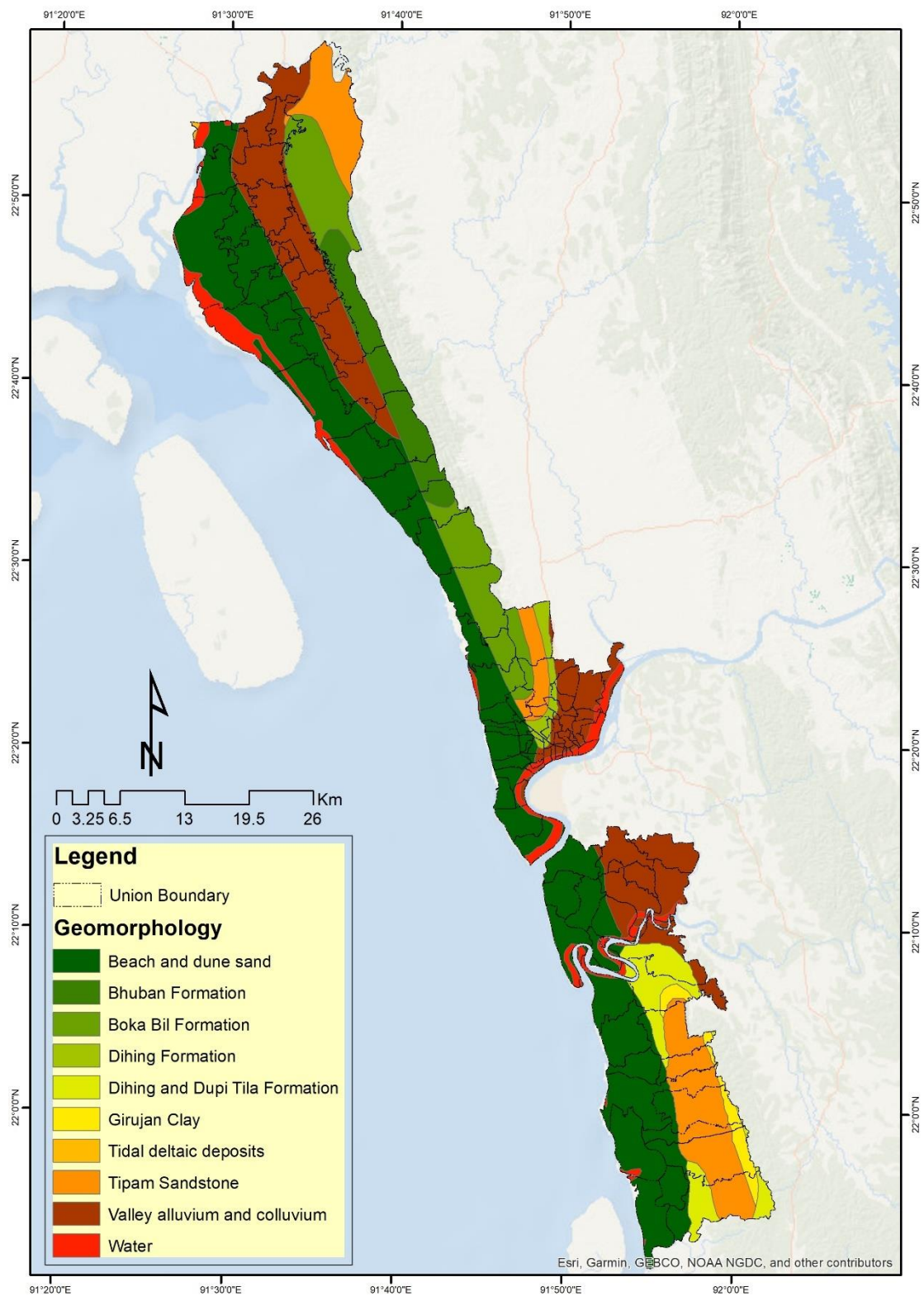


Fig. 3.3 Physical vulnerability influencing criteria (Geomorphology)

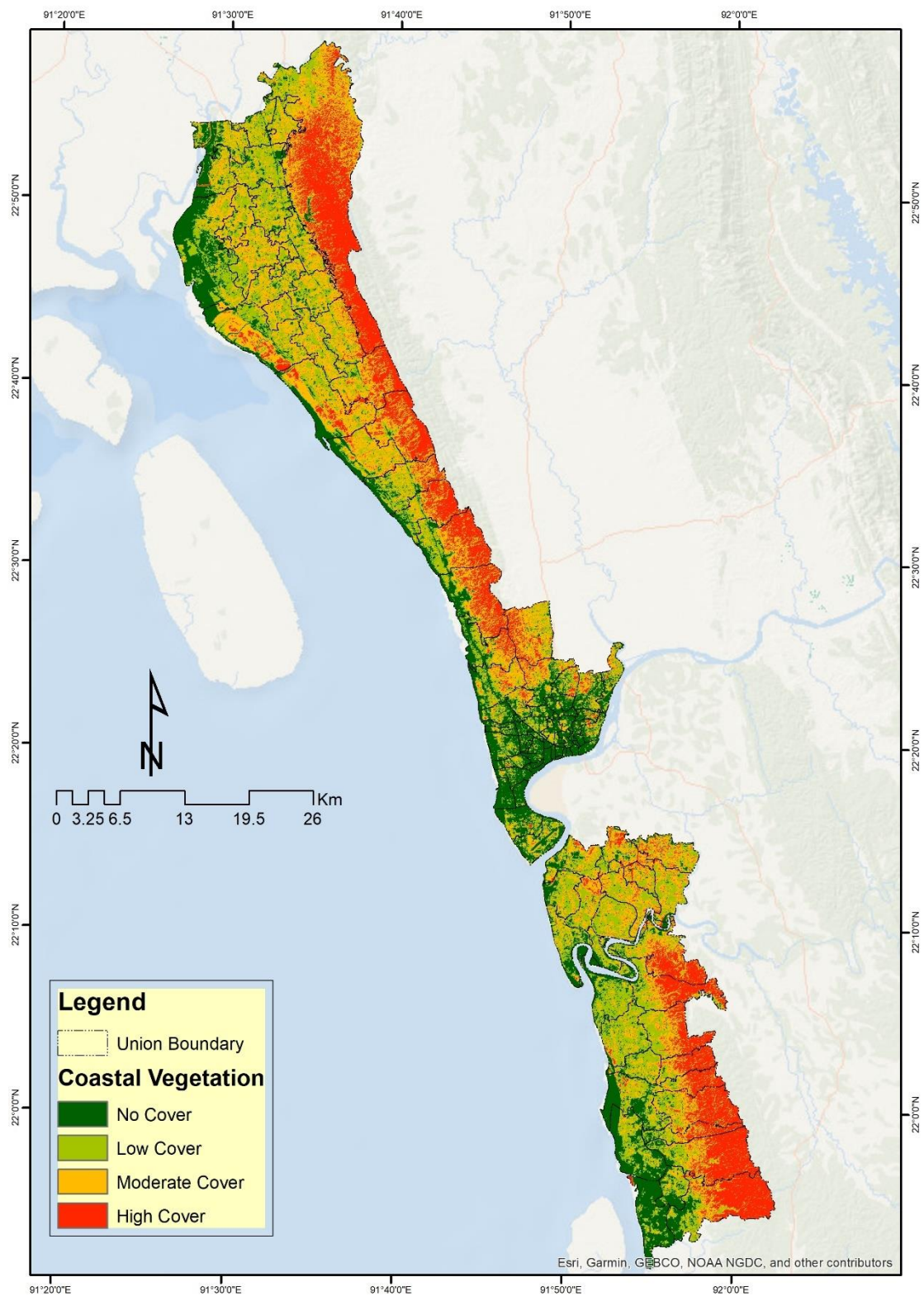


Fig. 3.4 Physical vulnerability influencing criteria (Coastal Vegetation)

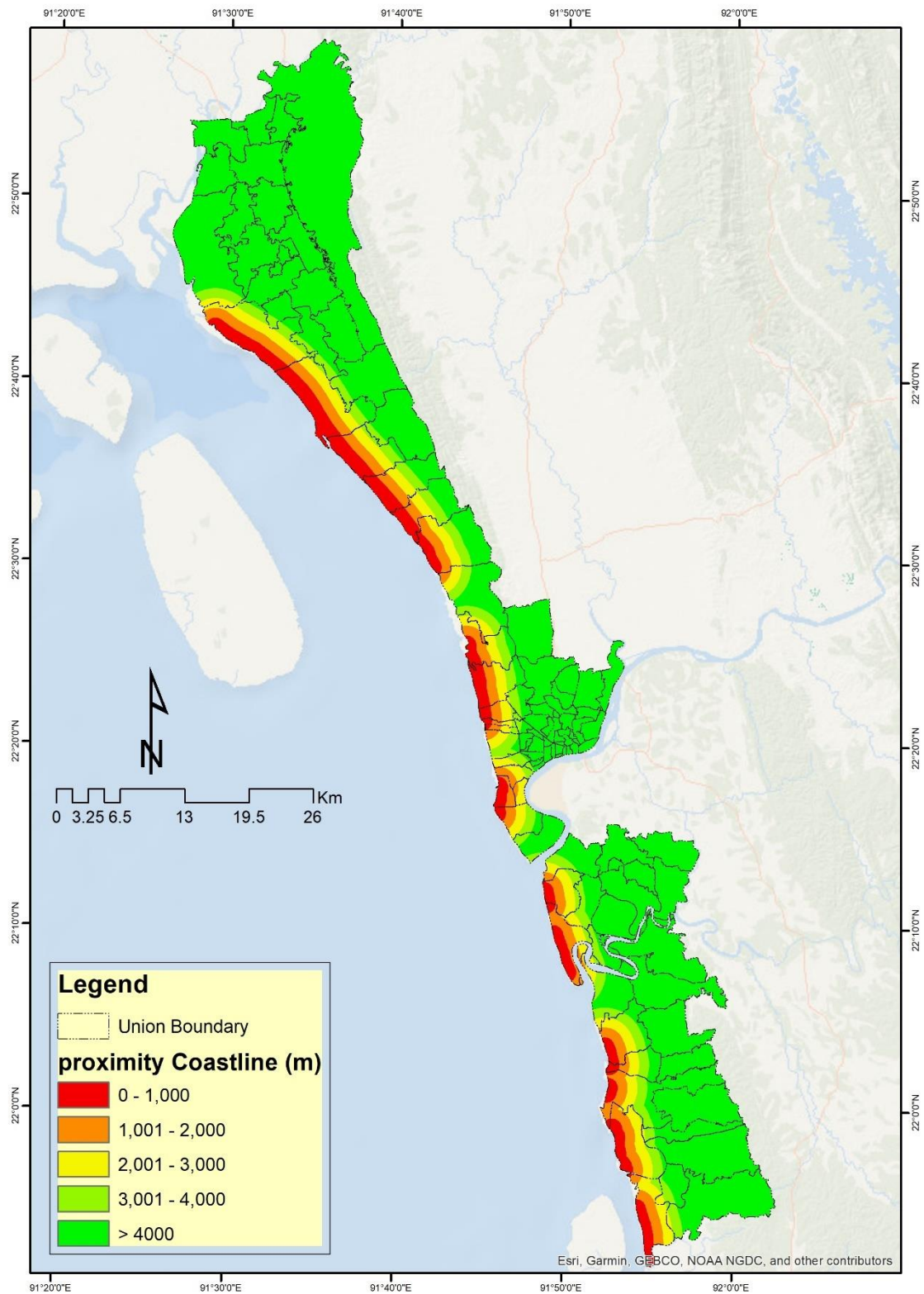


Fig. 3.5 Physical vulnerability influencing criteria (Proximity to Coastline)

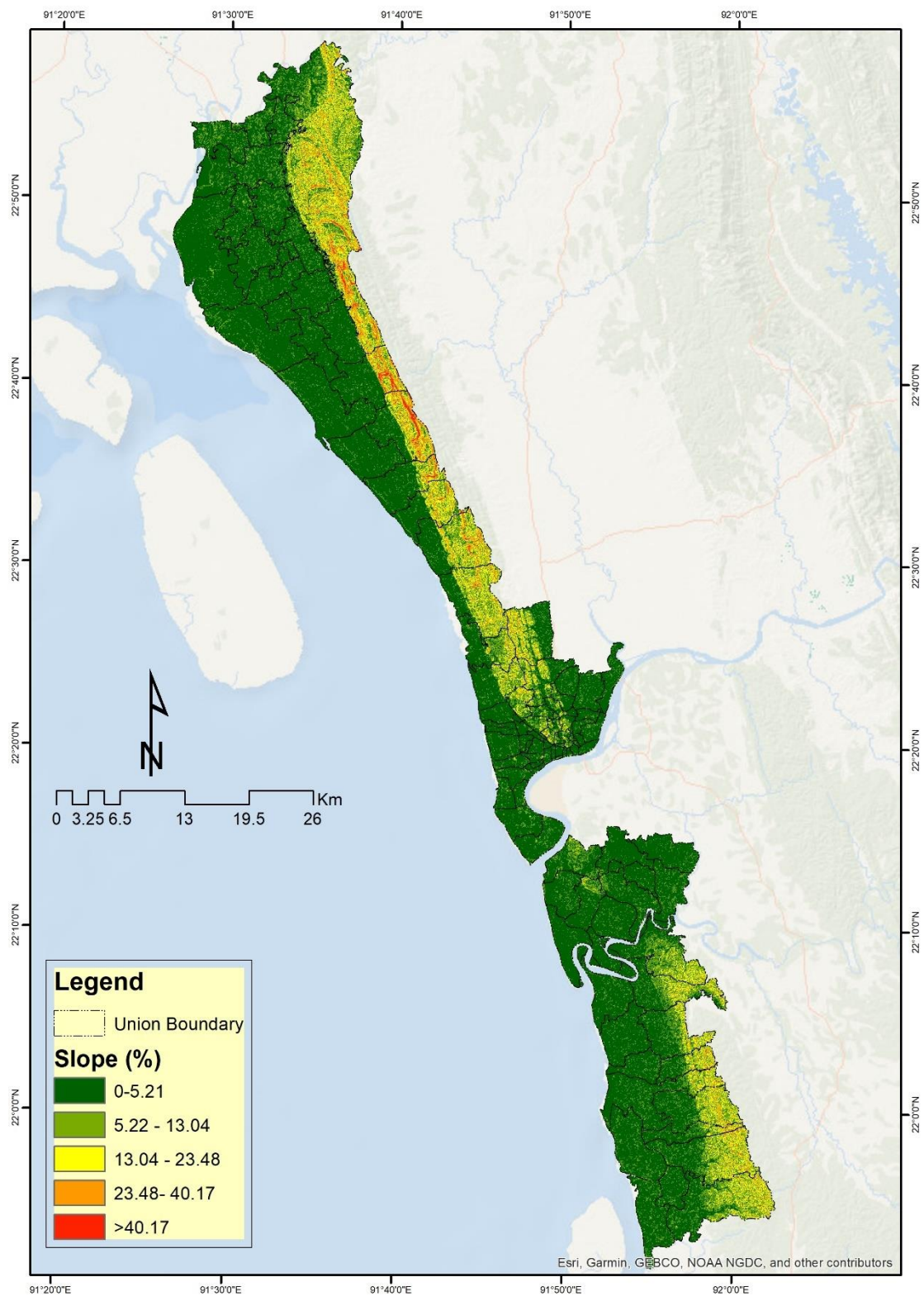


Fig. 3.6 Physical vulnerability influencing criteria (Slope)

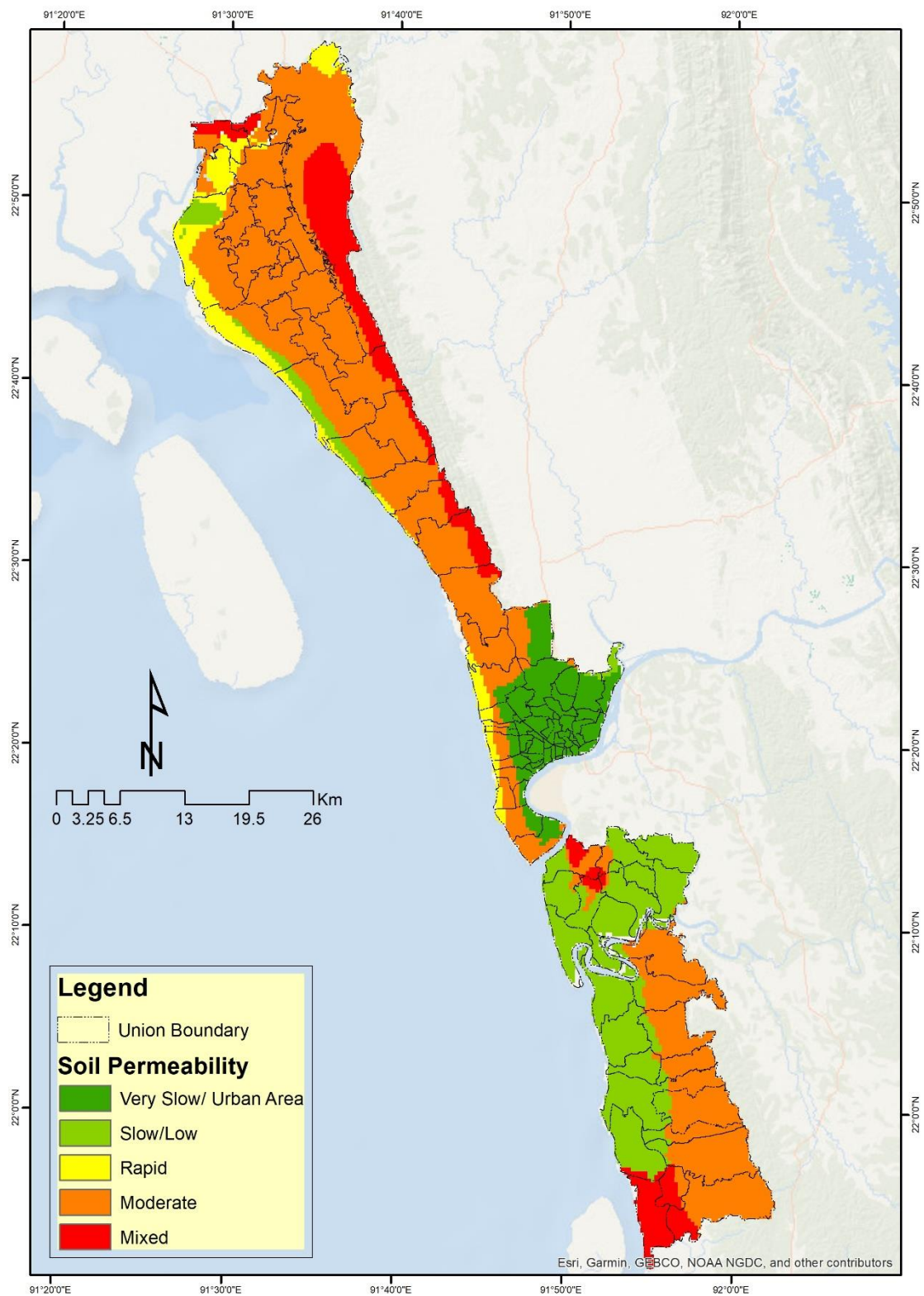


Fig. 3.7 Physical vulnerability influencing criteria (Soil Permeability)

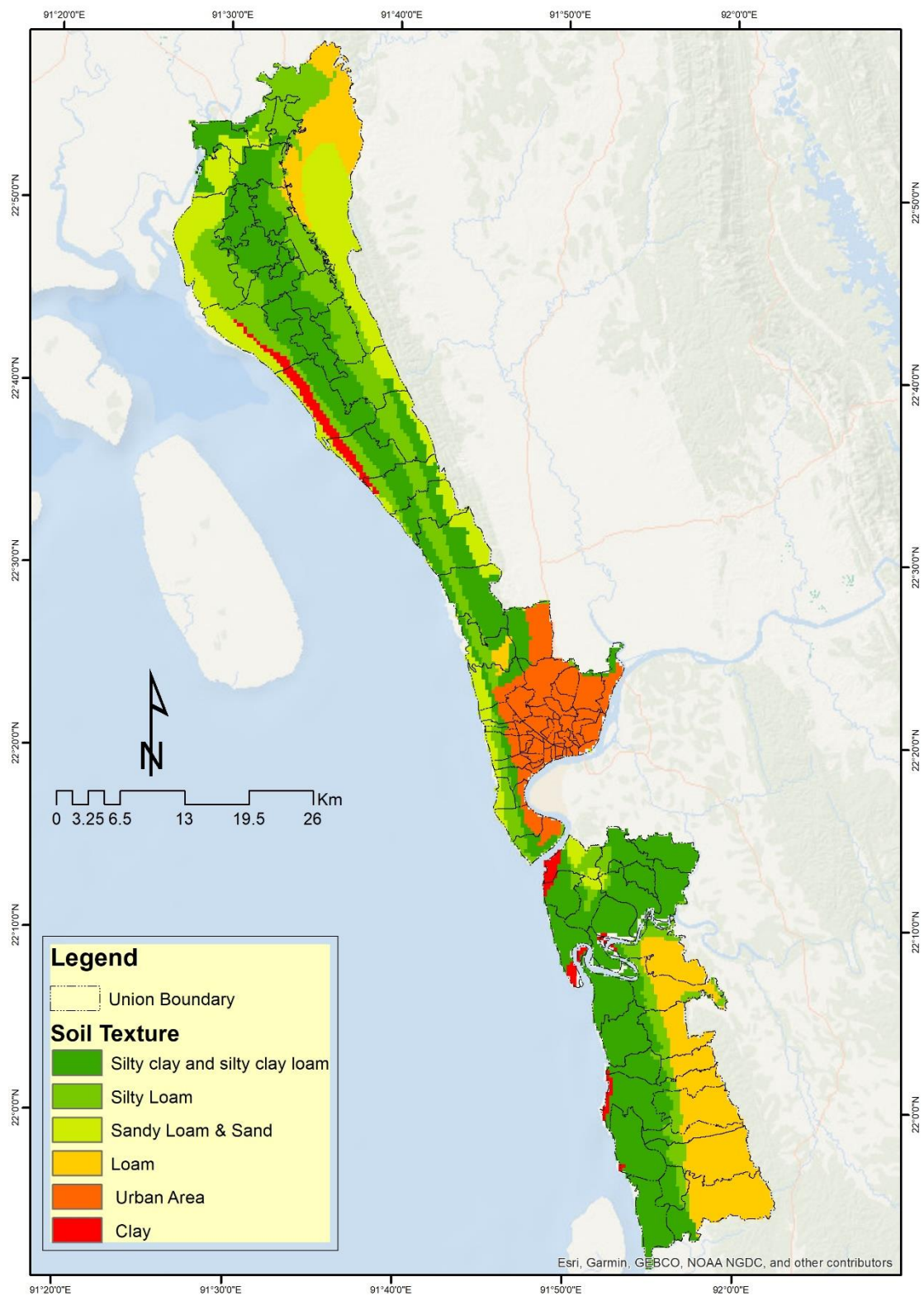


Fig. 3.8 Physical vulnerability influencing criteria (Soil Texture)

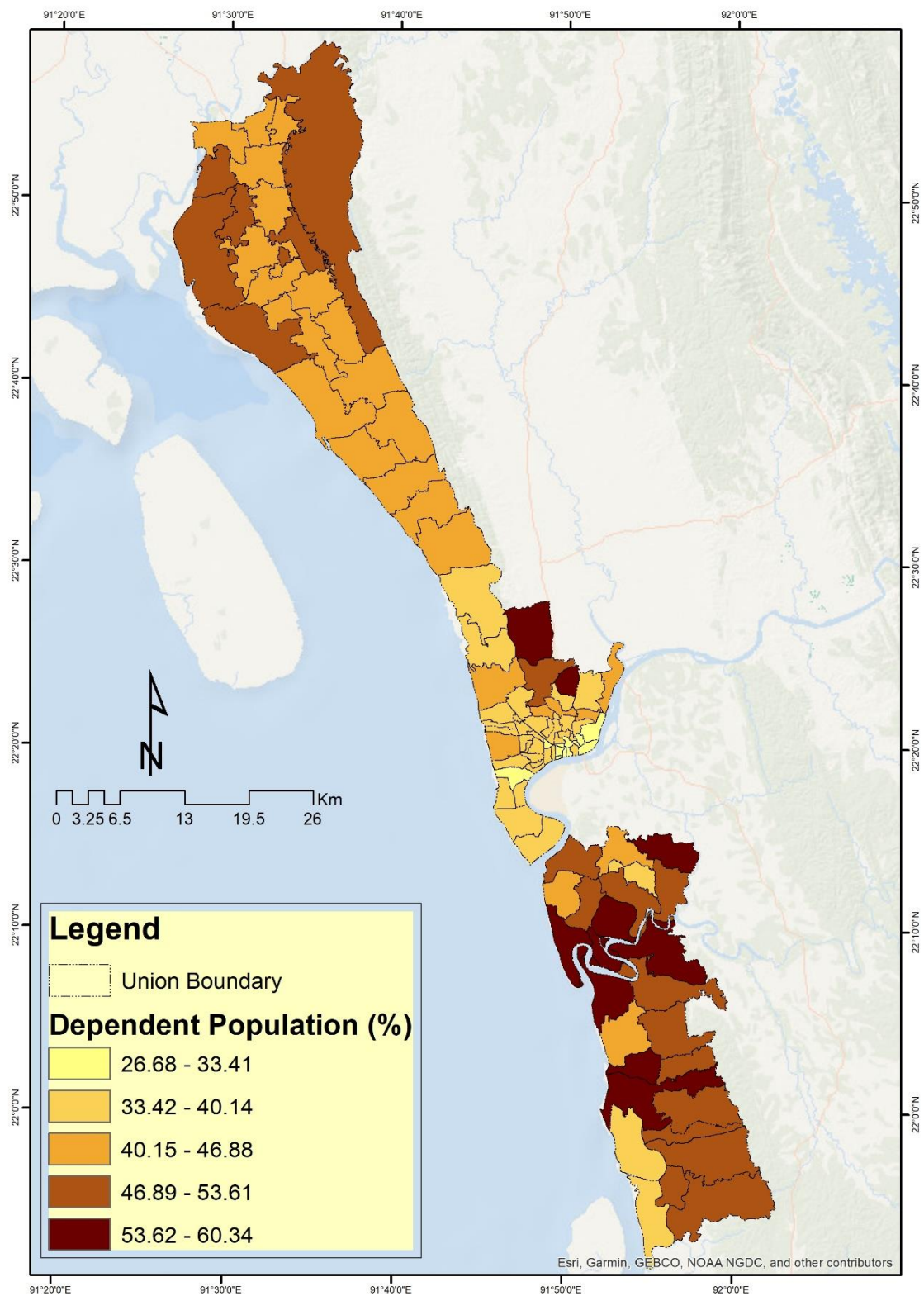


Fig. 3.9 Socio-economic vulnerability influencing criteria (Dependent Population)

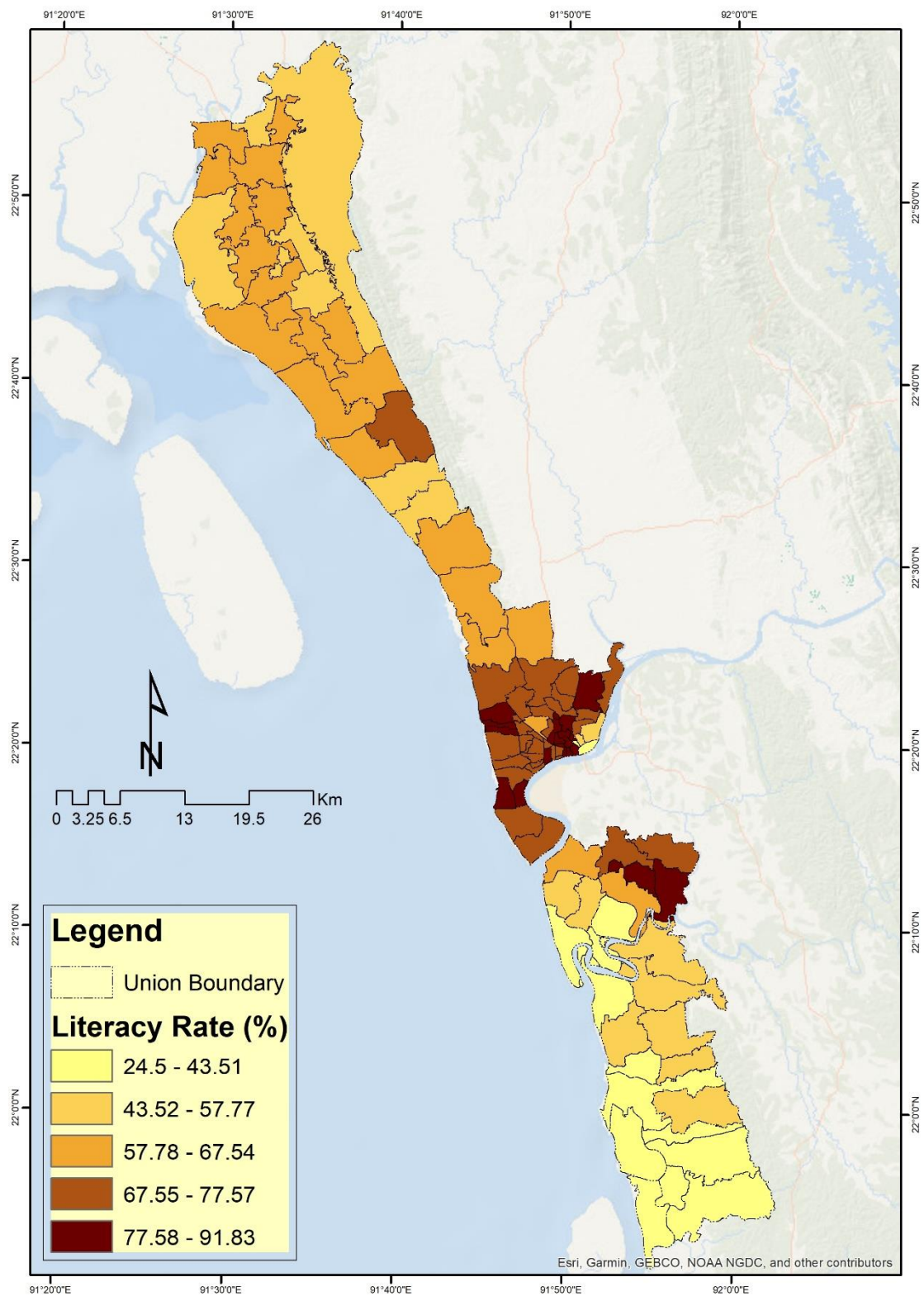


Fig. 3.10 Socio-economic vulnerability influencing criteria (Literacy Rate)

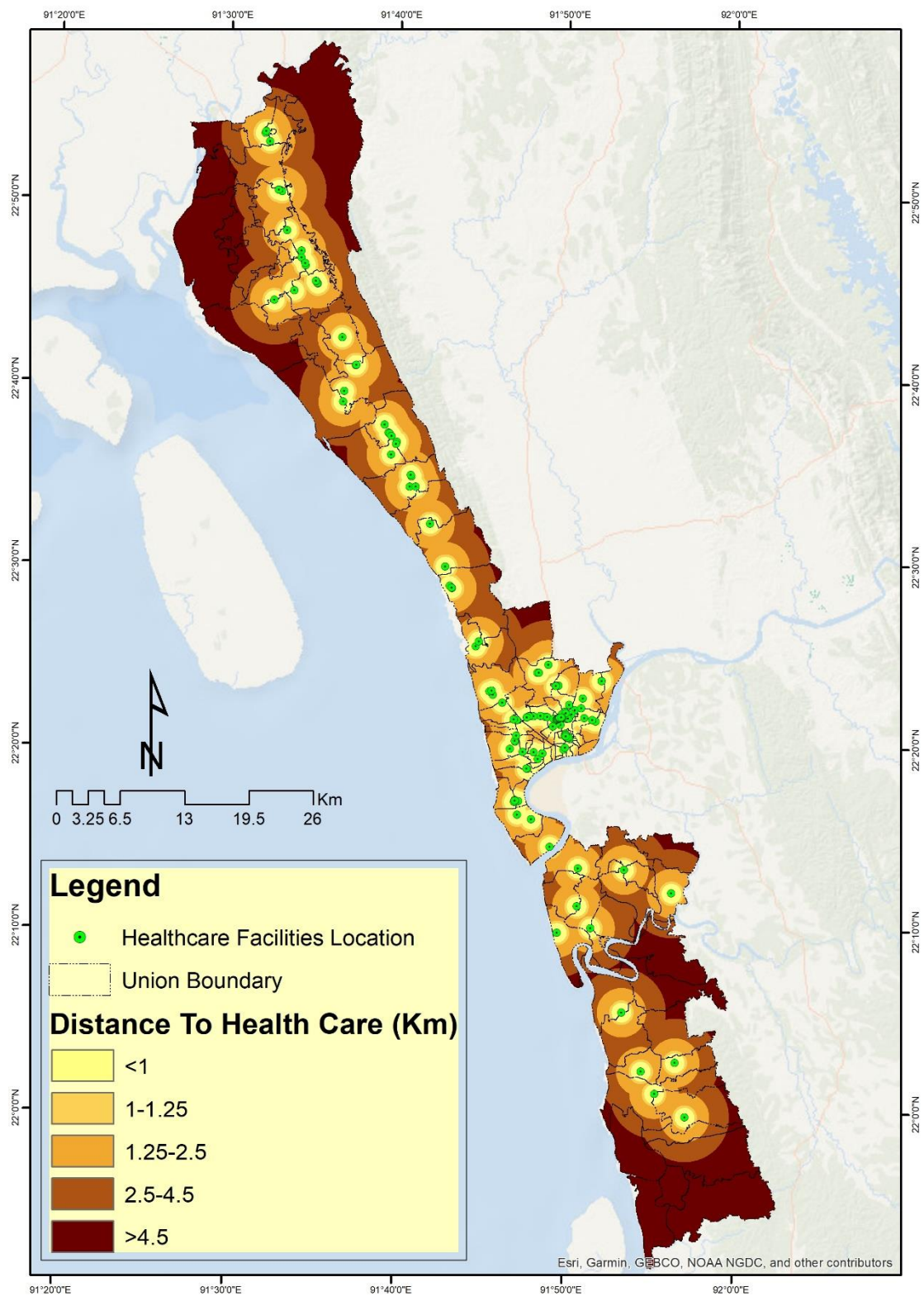


Fig. 3.11 Socio-economic vulnerability influencing criteria (Distance to Healthcare)

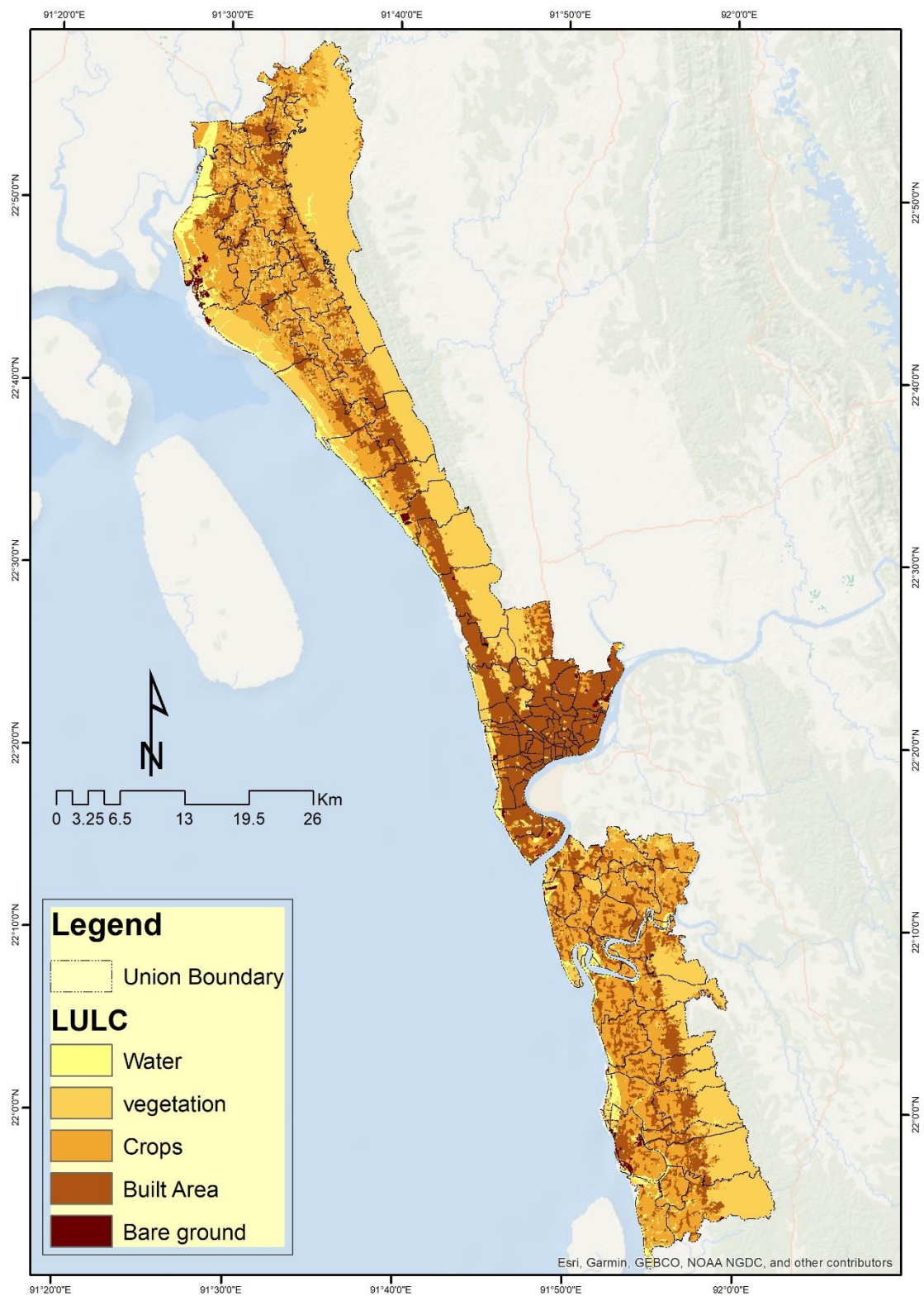


Fig. 3.12 Socio-economic vulnerability influencing criteria (LULC)

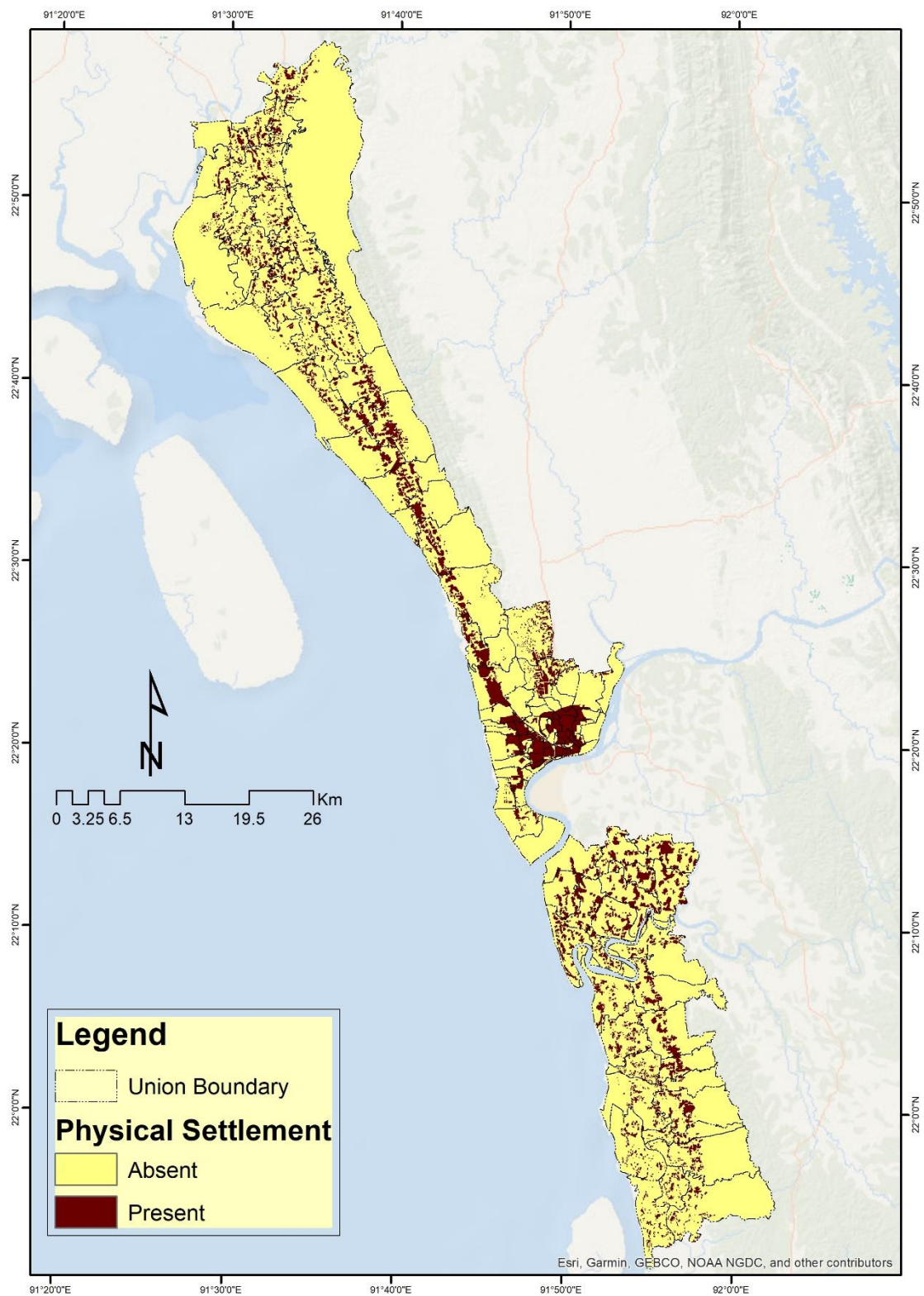


Fig. 3.13 Socio-economic vulnerability influencing criteria (Physical Settlement)

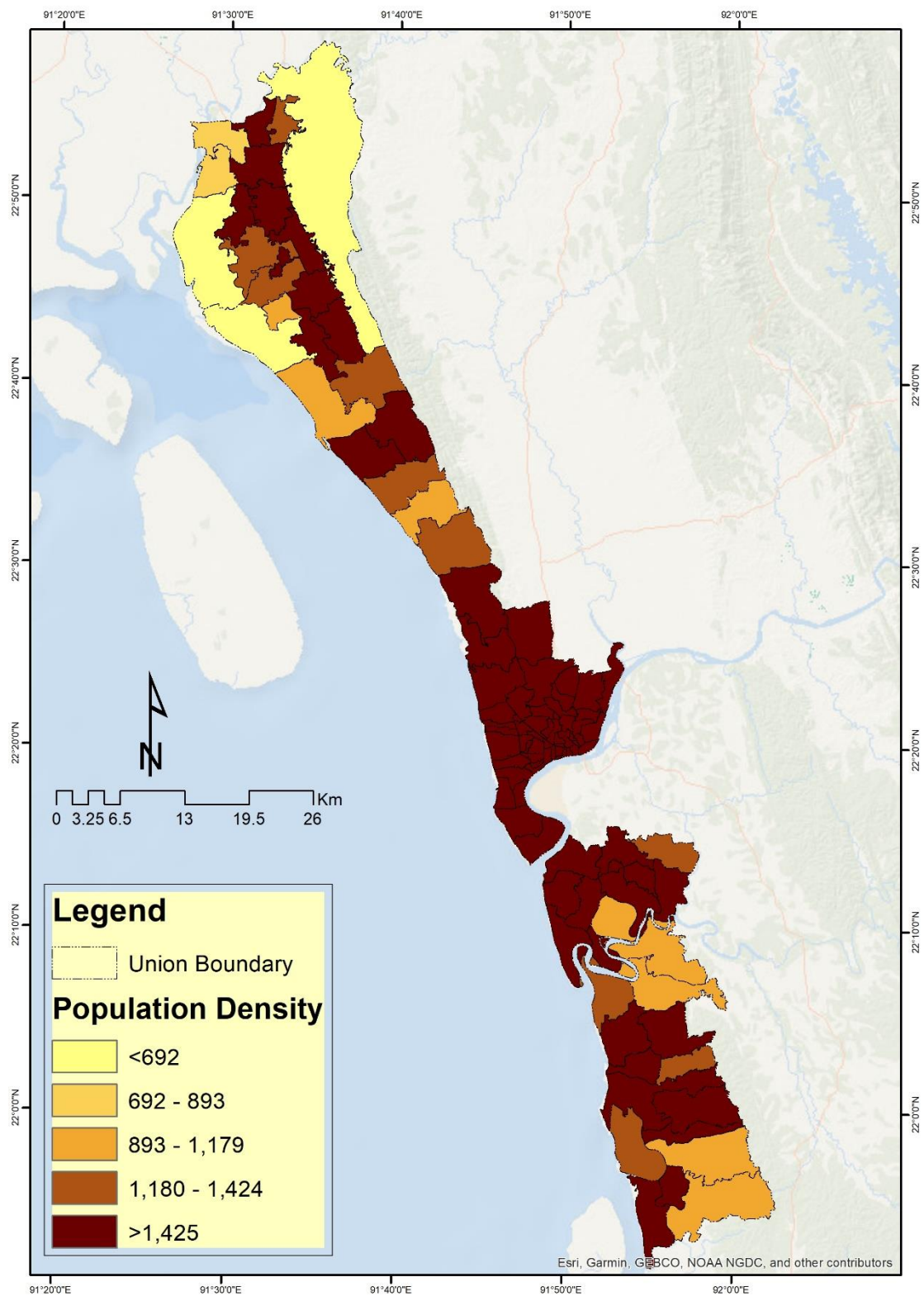


Fig. 3.14 Socio-economic vulnerability influencing criteria (Population Density)

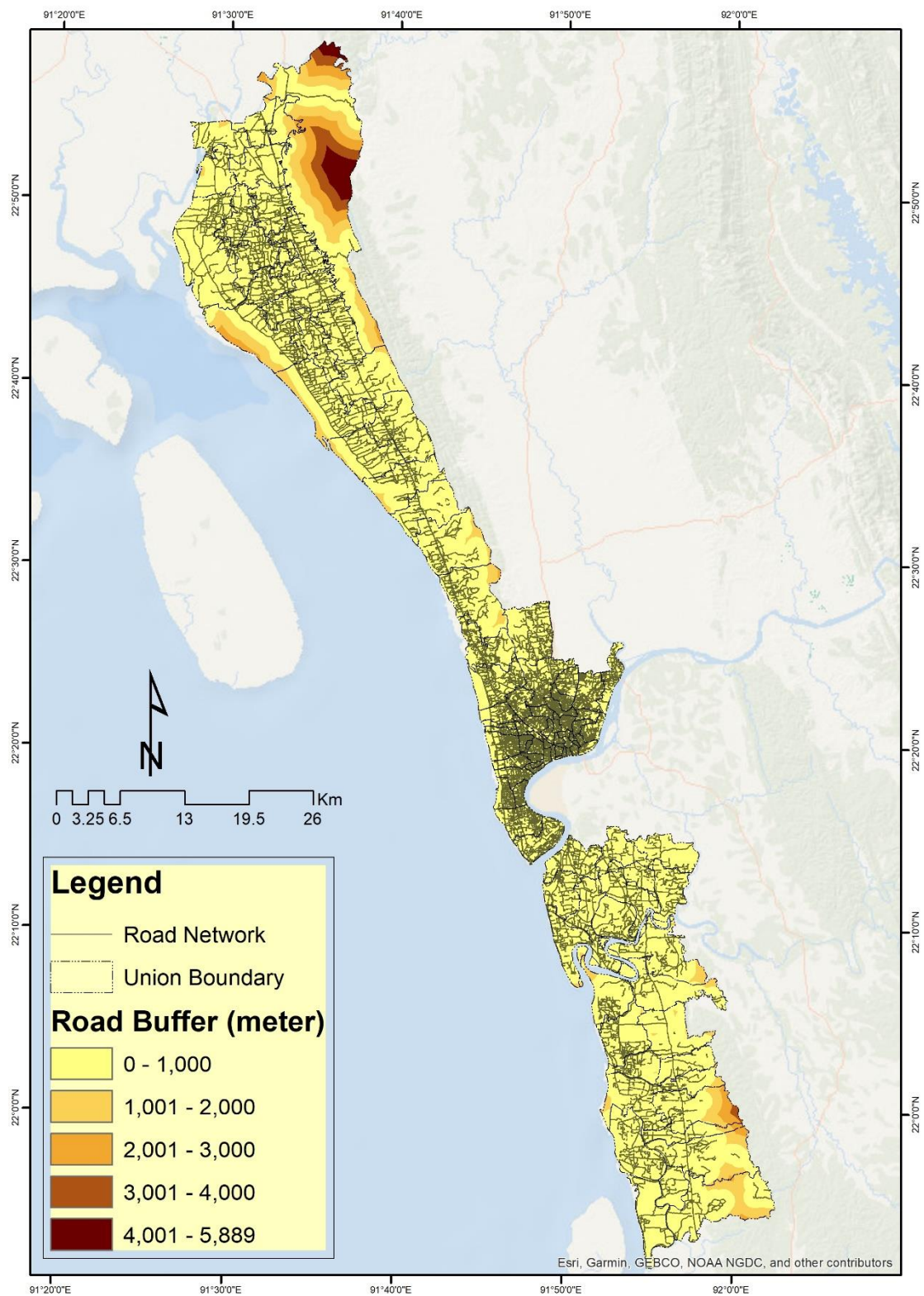


Fig. 3.15 Socio-economic vulnerability influencing criteria (Road Buffer)

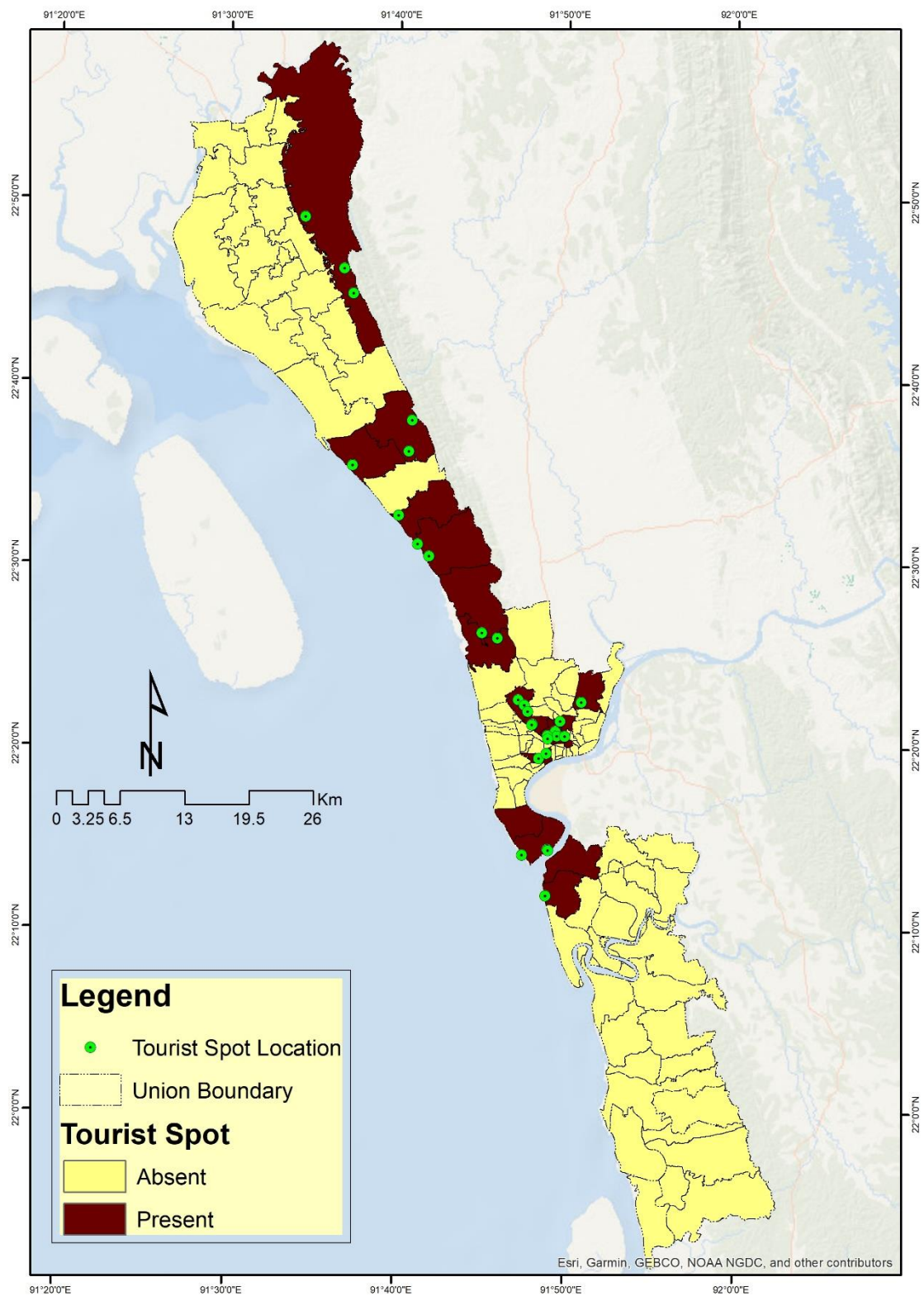


Fig. 3.16 Socio-economic vulnerability influencing criteria (Tourist Spot)

Table 3.2. Physical and socio-economic criteria used in this study

Variables	Criteria	Description	Data Sources and References
Physical vulnerability	Elevation	Coastal erosion is directly influenced by the spatial variations in elevation of the earth's surface [147].	Alaska Satellite Facility [148]
	Slope	Steep slopes contribute significantly to the vulnerability of coastal communities to erosion. Areas with steeper slopes are more vulnerable to coastal erosion [146], [149].	
	Geomorphology	Geomorphology plays a significant role in vulnerability assessment, as rocky coasts are less vulnerable compared to beach and dune sands [150].	Geological Survey of Bangladesh [151]
	Soil texture	Soil texture was classified based on its composition, with clay soil being more resistant to coastal erosion, while sandy soil is more erodible [146].	Bangladesh Agriculture Research Council [148]
	Soil Permeability	Soil permeability plays a crucial role in coastal erosion as it influences the rate at which water infiltrates the soil, affecting the stability of the coastline and the likelihood of erosion, particularly in areas with high rainfall or tidal activity [152].	
	Proximity to coastline	Areas along the coast, beaches, and islands are more vulnerable to erosion hazards compared to inland areas [146].	Estimated from coastline shapefile data
	Coastal vegetation	Vegetation plays an important role in intercepting coastal erosion. Areas with dense vegetation cover are less vulnerable to erosion [153].	Esri Global Land Cover Map [151]

Socio-Economic Vulnerability	Population Density	Higher population densities in exposed coastal areas indicate greater vulnerability to erosion impacts [154].	WorldPop: Open Spatial Demographic Data and Research [63]
	LULC	The LULC map generates the spatial location of settlements, agricultural lands, and other land cover classes, indicating the areas that are more vulnerable and likely to be affected by coastal erosion [154], [155].	Earth explorer [151]
	Dependent Population	Dependent populations, such as children and elderly individuals, are more vulnerable as they are unemployed or unable to earn [154].	Bangladesh Bureau of Statistics (BBS) [63]
	Tourist spots	Tourist spots are sources of income and employment for local people, and the presence of cultural heritage can make the region more vulnerable [154], [156].	Bangladesh Tourism Board (BTB) [63]
	Road Network	The road network plays a major role in communication, transportation of products, and attracting tourists in the coastal region [157].	Local Government Engineering Department (LGED) [63]
	Literacy Rate	Higher literacy rates indicate that more people will be aware of erosion and can prepare themselves for future consequences [158].	https://data.humdata.org/dataset/bangladesh-healthsites
	Proximity to health facilities	The distance to healthcare can impact coastal erosion indirectly by affecting the community's ability to respond to and manage health-related issues arising from erosion, thus influencing local resilience and adaptation strategies in vulnerable coastal areas [157].	https://data.humdata.org/dataset/bangladesh-healthsites
	Physical Settlement	The proximity of settlements to the coastline increases erosion risks, as areas near beaches, coastlines, and islands are more vulnerable than inland areas [159].	LGED

3.2.4.3 Data Ranking and Standardization Techniques

Using a five-point Likert scale in vulnerability ratings improves the effectiveness of vulnerability assessments by offering clarity, differentiation, standardization, prioritization, and adaptability. Each spatial criterion layer received vulnerability ratings on this scale, ranging from 1 (indicating extremely low vulnerability) to 5 (signifying very high susceptibility), as detailed in Table 3.3. These ratings were then analyzed using Principal Component Analysis (PCA) to assess their relative contributions to erosion vulnerability. A normalization method was used to ensure consistency, converting all alternative ranking values into a single range between 0 and 1 using a linear scale transformation equation (3.4) [160].

$$Z = \frac{(X-\mu)}{\sigma} \quad (3.4)$$

Where Z is the standardized variable, X is the original variable, μ is the mean of the variable, and σ is the standard deviation of the variable.

Table 3.3. Required data and Ranking of alternative criteria following the contribution to CEV

Variables	Criteria	Classes	Rank	Rating	Data Type	Classification method & Source
Physical Variables	Proximity to coastline (Km)	>4	1	Very Low	GRID	Manual classification
		3-4	2	Low		
		2-3	3	Moderate		
		1-2	4	High		
		<1	5	Very High		
	Coastal Vegetation	High Cover	2	Low	GRID	Vegetation density Classification
		Moderate cover	3	Moderate		
		Low cover	4	High		
		No cover	5	Very High		
	Soil Texture	Clay	1	Very Low	Polygon	Soil texture classification
		Silty clay and silty clay loam	2	Low		
		Silty loam	3	Moderate		
		Loam	4	High		

		Sandy, Sand, and sandy loam	5	Very High		
	Elevation (m)	>29.31	1	Very Low	GRID	Natural break classification
		6.37-29.3	2	Low		
		2.4-6.36	3	Moderate		
		1.71-2.39	4	High		
		<1.7	5	Very High		
	Slope (%)	0-0.01	1	Very Low	GRID	Manual classification
		0.02-0.05	2	Low		
		0.06-0.3	3	Moderate		
		0.3-1.8	4	High		
		1.81-10.33	5	Very High		
	Geomorphology	Dihingand DupiTiila formation, Girujan Clay, Bhuban formation, BokaBil Tipam Sandstone	1	Very Low	Polygon	Geomorphological Classification
		Valley alluvium and colluvium, Tidal mud, Marsh clay and peat, Mangrove swamp deposits, Lakes	2	Low		
		Estuarine deposits, Alluvial silt and clay, Chandina alluvium	3	Moderate		
		Alluvial silt, Deltaic silt, Tidal deltaic deposits	4	High		
		Newly formed ocean and riverine deposits, Tidal sand, Deltaic sand, Beach and dune, Alluvial sand	5	Very High		
	Soil Permeability	Very Slow/Urban area	1	Very Low	Polygon	Soil Permeability Classification
		Slow	2	Low		
		Mixed	3	Moderate		
		Moderate	4	High		
		Rapid	5	Very High		
	Population Density (Sq.km)	<692	1	Very Low	Polygon	Manual classification
		693-893	2	Low		
		894-1178	3	Moderate		
		1179-1424	4	High		
		>1425	5	Very High		

Socio-economic Variables	LULC	Water bodies	1	Very Low	GRID	Hybrid Classification
		Mangrove and Vegetation	2	Low		
		Bare land/ Beach	3	Moderate		
		Cropland, Salt cultivation	4	High		
		Settlement	5	Very High		
	Dependent Population (%)	24.50–43.11	1	Very Low	GRID	Natural break classification
		43.12–57.77	2	Low		
		57.78–67.54	3	Moderate		
		67.55–77.57	4	High		
		77.58–91.83	5	Very High		
	Tourist spots	Absent	2	Low	Polygon	Manual classification
		Present	4	High		
	Road Network (Km)	> 4 km buffer	1	Very Low	Polyline	Manual classification
		3-4 km buffer	2	Low		
		2-3 km buffer	3	Moderate		
		1-2 km buffer	4	High		
		<1 km buffer	5	Very High		
	Literacy Rate (%)	65.57–91.85	1	Very Low	polygon	Natural break classification
		50.44–65.56	2	Low		
		38.55–50.43	3	Moderate		
		27.75–38.54	4	High		
		<27.74	5	Very High		
	Proximity to health facilities	Less than 1 Km	1	Very Low	GRID	Manual classification
		1-1.25 Km	2	Low		
		1.25-2.5 Km	3	Moderate		
		2.5-4.5 Km	4	High		
		> 4.5 Km	5	Very High		
	Physical Settlement	Absent	2	Low	polygon	Manual classification
		Present	4	High		

3.2.4.4 Principal Component Analysis (PCA) based weightage calculation

Principal Component Analysis (PCA) was used to identify the overall vulnerability and determine the weightage for measuring socioeconomic and physical vulnerability [161]. Also, PCA is a dimensionality reduction technique commonly used in machine learning and data analysis, while this is a crucial method for (CEVI) as it helps to identify the most important variables contributing to vulnerability, reduces dimensionality, and improves the accuracy

of the index [162], [163]. Compared to other methods, PCA offers greater effectiveness in managing high-dimensional data and uncovering meaningful patterns, making it a preferred approach for CEVI development. Its computational efficiency and ease of interpretation support streamlined and insightful analysis of coastal erosion vulnerability. It works by transforming the original variables into a new set of uncorrelated variables called principal components. Standardization involves centering the data (subtracting the mean) and scaling it (dividing by the standard deviation) (Equation 3.4).

The covariance matrix is a measure of how much two variables change together. PCA must understand the relationships between different variables in the dataset. Equation 6 (for a pair of variables X and Y):

$$Cov(X, Y) = \frac{\sum (X_i - \bar{X})(Y_i - \bar{Y})}{n-1} \quad (3.5)$$

Where, $Cov(X, Y)$ is the covariance between variables X and Y, X_i and Y_i are individual data points, $\bar{X}$ and $\bar{Y}$ are the means of variables X and Y, respectively, n is the number of data points. Eigenvectors and eigenvalues are the key components of PCA. The eigenvectors represent the directions of maximum variance, and the eigenvalues indicate the magnitude of variance in those directions (Equation 3.6).

$$\text{Covariance Matrix} \times \text{Eigenvector} = \text{Eigenvalue} \times \text{Eigenvector} \quad (3.6)$$

Sort the eigenvalues in descending order. The eigenvectors corresponding to the largest eigenvalues contain the most information about the data. Multiply the standardized data by the selected eigenvectors to obtain the new, lower-dimensional representation. Equation 8 (for a single principal component) [164]:

$$PC_1 = Z_1 * \text{Eigenvector}_1 \quad (3.7)$$

Where, PC_1 is the first principal component, Z_1 is the standardized data, and Eigenvector_1 is the first eigenvector.

3.2.4.5 Calculation of Overall Vulnerability Ranking

Finally, an erosion vulnerability assessment was carried out using a weighted overlay technique in GIS software, incorporating physical and socio-economic vulnerability layers with assigned weights. This calculated physical and socio-economic erosion vulnerability which were categorized into five vulnerability classes: very low, low, moderate, high, and very high. The overall erosion vulnerability was then calculated by combining these vulnerabilities using a weighted overlay technique. The final overall erosion vulnerability index was also categorized into the same five-level vulnerability classes.

3.2.4.6 ROC Curve and Precision-Recall for Model Acceptability Analysis

To assess the predictive accuracy of the coastal erosion vulnerability model, both Receiver Operating Characteristic (ROC) curve analysis and precision-recall analysis were employed. The ROC curve stands as a standard diagnostic measure for binary class problems by showing the connection between true positive rates and false positive rates at different threshold points [165]. It provides a comprehensive view of a model's performance across all possible classification thresholds, rather than relying on a single cut off. The Area Under the ROC Curve (AUC-ROC) represents a single numerical indicator that expresses how well the model identifies between coastal erosion vulnerable and non-vulnerable locations. When AUC reaches a value of 0.5, it indicates no discriminatory power yet an AUC value of 1.0 indicates perfect discrimination in classification tasks.

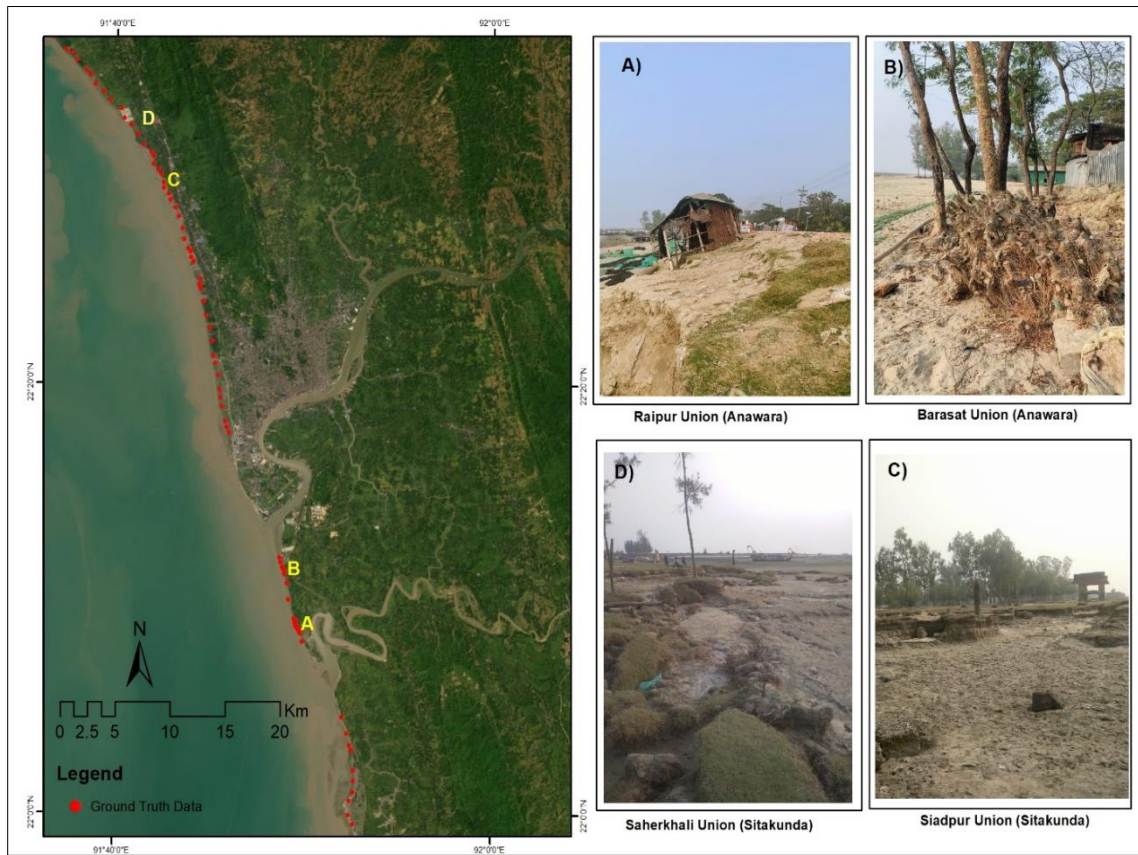


Fig. 3.17 Distribution of ground truth data over the study area

Testing the model required comparing its vulnerability score output to 185 ground-truth validation points (Fig. 3.17), which originated from field surveys and publications alongside inputs from the Bangladesh Agricultural Research Council (BARC). The observed erosion conditions served as the basis for the binary classification of each validation point. Performance assessment was achieved through AUC calculation with the ROC curve generated by continuous threshold variations. In addition to ROC analysis, the model effectiveness was assessed through precision-recall analysis because the dataset contained erosion events that were not uniformly distributed throughout its samples. Precision reveals how many positive cases exist among all identified cases, while recall defines the proportion of genuine positives the model successfully detects from all actual positives.

3.2.4.7 Techniques for shoreline change rate-based vulnerability assessment and validation

Five principal steps were employed to analyse shoreline changes from LANDSAT images. ArcGIS software was used for image processing after radiometric correction. Here, Normalized Difference Water Index (NDWI) is also computed to differentiate land and sea areas, which is a crucial step. Coastline envelopes are generated between water and non-water; which is the next step. Digital Shoreline Analysis System (DSAS) is employed to determine change statistics, and the results aid in analysis. Ultimately, shoreline change is ascertained, completing the analysis of shoreline movement.

Shoreline change was measured using Linear Regression Rate (LRR) and End Point Rate (EPR) methods. The binary threshold method separated water body and non-water body pixels to obtain the shoreline. Shoreline change studies were carried out over four different years: 1990, 2000, 2010, and 2023.

The equation of NDWI by [2] was utilized for the calculation of the Multispectral Scanner (MSS) and for calculating the Thematic Mapper (TM) , Enhanced Thematic Mapper Plus (ETM+) remote sensing images using [166] Modified Normalized Difference Water Index (MNDWI) equation. The NDWI Equation 3.8 for MSS images is stated below:

$$NDWI = \frac{p_{GREEN} - p_{NIR}}{p_{GREEN} + p_{NIR}} \quad (3.8)$$

Where stands for the near-infrared and green band reflectance. Positive values of NDWI analysis are assigned to water bodies, whereas negative values are assigned to soil, vegetation, and other components. Conversely, the equation 3.9 for MNDWI is applied on Operational Land Imager (OLI) images, that is:

$$MNDWI = \frac{p_{GREEN} - p_{MIR}}{p_{GREEN} + p_{MIR}} \quad (3.9)$$

Where stands for mid-infrared and green band reflectance. Positive values of MNDWI analysis are assigned to water bodies, whereas negative values are assigned to soil cover, vegetation, and other components. After NDWI and MNDWI analysis, the land and water values were separated and classified using the binary threshold method.

Coastlines from each image were extracted and supplemented into a digital shoreline analysis system to perform shoreline change statistics. EPR and LRR represent the Shoreline Change Envelope (SCE) and the rate of coastline change in DSAS. These parameters are common in shoreline change statistics. This method calculates the rate of change of the shoreline by dividing the distance calculated by the year interval, as shown below (Equation 3.10).

$$EPR = (D1 - D2) / (t1 - t2) \quad (3.10)$$

where, D1-D2 is the distance between the new shoreline and the old shoreline, and t1-t2 is the time interval between two shoreline positions.

Root Mean Square Error (RMSE), a commonly used shoreline change rate estimation validation method, is calculated based on the difference between predicted and observed shoreline positions. It is calculated following equation 3.11,

$$RMSE = \sqrt{\frac{(X_a - X_o)^2}{N}} \quad (3.11)$$

Where, X_a and X_o are the predicted and observed shoreline positions, respectively, and N is the number of observations. A lower RMSE value denotes a higher accuracy of shoreline change rate estimation. Ultimately, RMSE is used to understand the performance of the model and to compare separate methods of predicting shoreline position and analyzing change; larger RMSE values indicate less accurate models and smaller RMSE values indicate more accurate models. observed point taken from the extracted shoreline of NDWI images and

actual point taken from Google Earth images. Data were collected from the same month to ensure better validation.

3.2.5 Coastal Erosion Impact and Adaptation Strategies

Coastal erosion is one of the principal environmental concerns due to which millions of people living in the coastal regions of the world are affected. The aftermath poses a great range of results and impacts the loss of the territory, the displacement of the people, the degradation of the coast's ecosystems, and the damage to the infrastructure and the lives of the people. These consequences are more devastating in regions like Chattogram, Bangladesh, where the population is both highly exposed to natural hazards and at a high density.

3.2.5.1 Sample size and Survey Location determination

The Cochran formula is commonly used for calculating sample size when dealing with a large population. The formula is as follows:

Let's choose a 95% confidence level ($Z \approx 1.96$), a conservative estimate of the population proportion ($p=0.5$), and a margin of error of $E=0.05$.

$$n = \frac{1.96^2 * .5 * (1-.5)}{(.05)^2} \quad (3.12)$$

$$n = 384.16$$

The adjusted population sample size is:

$$n_f = \frac{384.16}{1 + \frac{384.16}{1755337}} \quad (3.13)$$

$$n_f = 384.0759$$

Therefore, a sample size of approximately 384 would be the minimum required for a 95% confidence level and a margin of error of 0.05 in a population of 1,755,337.



Fig. 3.18 Surveys conducted with the community people: (a) female respondents, (b) marketplace, and (c) school teacher, (d) elderly People

Based on the population sizes of each of the six clusters, the sample size of 384 has been proportionately distributed using cluster sampling, so larger clusters like Chattogram city (Mainly Vatiary, Halishahar) receive a greater percentage of the sample with 100 samples, while smaller clusters like Anowara and Bashkhali are assigned 80 and 70 samples, respectively. By providing greater representation to regions with higher populations, such as Sitakunda (100 samples) and Mirsharai (34 samples), this allocation helps to maintain statistical correctness. Some of the photos from the field visit are presented in Fig. 3.18.

3.2.5.2 Survey Questionnaire Design

A structured questionnaire was developed through a multi-phase approach, assessing the impacts of coastal erosion and corresponding adaptation strategies adopted by various affected communities. Extensive reviews of relevant literature and government reports alongside previous studies commenced the design process, identifying key variables related to the environmental aspects of coastal erosion. A draft questionnaire was constructed within this framework, comprising five major sections, namely (i) household demographic information, (ii) causes of coastal erosion, (iii) Impacts of coastal erosion (iv) Household adaptation capacities, and lastly (v) adaptation strategies applied by local affected communities.

To ensure the relevance, completeness, and clarity of the questions, a preliminary pilot survey was conducted with a purposive sample of twenty respondents from vulnerable coastal households. The pilot study enabled overcoming several challenges including vague terminology, redundant questions, and troublesome response patterns. This step provided insight regarding modification of question wording, rearrangement of sections for enhancing logical sequencing, and incorporation of local specific answer choices including sharecropping and erosion control. The developed questionnaire contained a combination of Likert scales, categorical, and open-ended questions to capture quantitative data as well as qualitative insights. This responsive approach allowed for context-specific refinements while maintaining rigor so that the primary data collected in the field was authentic and methodologically sound.

3.2.5.3 Erosion impacts on communities' household's assessment

Adaptation Resources were identified at the first stage of the study. The households were asked to rate the effects of coastal erosion on coastal

communities using high, medium, low, or none with a corresponding score of 3, 2, 1, and 0, respectively. Hence, the scale score ranged from 0 to 30, where 0 indicated no effect and 30 indicated a high effect. The statements were ranked in order of priority based on how much of an impact coastal erosion has on them. A Weighted Average Index (WAI) [167] for the impacts of coastal erosion was computed to find out the important strategies in the study area (Equation 3.14).

$$WAI = \frac{F_h \times 3 + F_m \times 2 + F_l \times 1 + F_n \times 0}{N} \quad (3.14)$$

Where, WAI = weighted average index, F_h = frequency of responses with high effect, F_m = frequency of responses with moderate effect, F_l = frequency of responses with low effect, F_n = frequency of responses with no effect, and N = total number of responses.

3.2.5.4 Determination of the household's capacity and adaptation strategies for coastal erosion

The extent of the practice of different coastal erosion adaptation strategies by the households was assessed by asking them about the frequency with which they practiced the adaptation strategies. The responses obtained from the households were scaled as regularly, occasionally, seldom, and not at all, with a corresponding score of 3, 2, 1, and 0, respectively. The scores ranged from 0 to 42, where 0 indicated no practice and 42 indicated widespread practice. Based on the scores, the respondents were categorized into three coastal erosion adaptation strategy segments—low, moderate, and high practicing. An adaptation strategy index (ASI) (Equation 3.15) for individual adaptation strategies was computed to determine how many households reported using the coastal erosion adaptation strategies.

$$ASI = AS_r \times 3 + AS_o \times 2 + AS_s \times 1 + AS_n \times 0 \quad (3.15)$$

Where, ASI = Adaptation Strategy Index, AS_r = number of responses with regular practice of coastal erosion adaptation strategies, AS_o = number of

responses with occasional practice of coastal erosion adaptation strategies, AS_s = number of responses with rare practice of coastal erosion adaptation strategies, AS_n = number of responses with no practice of coastal erosion adaptation strategies.

The calculation of Overall Adaptive Capacity for households facing coastal erosion requires a Entropy-based weighted method that follows this formula (Equation 3.16) [168]:

$$AC = \frac{W \sum_{i=1}^n AC_i}{N} \quad (3.16)$$

where W is the Entropy based Weight, AC is the Adaptive Capacity, N is the total number of factors considered and AC_i is the is the adaptive capacity of the i th factor. The method commences by acquiring data from multiple sources that influence household adaptive capacity including physical aspects, socio-economic elements, and environmental conditions with infrastructure qualities. Entropy based Weightage is performed on the standardized data to reduce dimensionality and extract weights (W) that reflect the contribution of each factor to the total variance explained by the principal components. The adaptive capacity (AC_i) for each factor was then assessed, often using normalized indices, expert judgment, or specific scoring methods relevant to resilience and adaptation. The overall adaptive capacity (AC) was calculated by multiplying each AC_i by its corresponding Entropy weight (W), summing the weighted capacities, and then normalizing this sum by dividing by the total number of factors (N).

3.2.5.5 Results and Discussion

The methodology successfully integrated geospatial techniques to assess coastal erosion vulnerability, identifying critical areas along the Chattogram coastline that are highly vulnerable due to both physical and socio-economic

factors. Through a household questionnaire survey, the research uncovered significant impacts of erosion on local dynamics, cultural practices, and traditional livelihoods, illustrating the socio-cultural dimensions of environmental change. Additionally, the study identified various adaptive strategies employed by local communities, emphasizing their resilience and the importance of community-driven approaches in addressing the challenges posed by coastal erosion. A methodological flow chart is presented in Figure 4.1.

3.3 ETHICS AND LIMITATIONS

3.3.1 Ethical Consideration

All ethical issues were properly considered during data collection and analysis. Verbal consent was obtained, and respondents were informed that their participation was voluntary. All personal information was kept confidential.

3.3.2 Limitations

The study faced limitations due to minimal ground-truthing, as the vast coverage area made extensive field validation challenging. The spatial and temporal resolution of available geospatial data may have missed fine-scale coastal features and short-term erosion events. Additionally, socio-economic data were only available at the union level, limiting local-scale analysis. The study presents a static snapshot, excluding projections related to sea-level rise, land-use changes, or climate-driven impacts. The study includes a limited number of limited number of women respondents due to their low desire to participate in answering questions about coastal erosion. As a result, conclusions may lack a balanced gender perspective and they cannot fully represent women's ideas and experiences regarding coastal management.

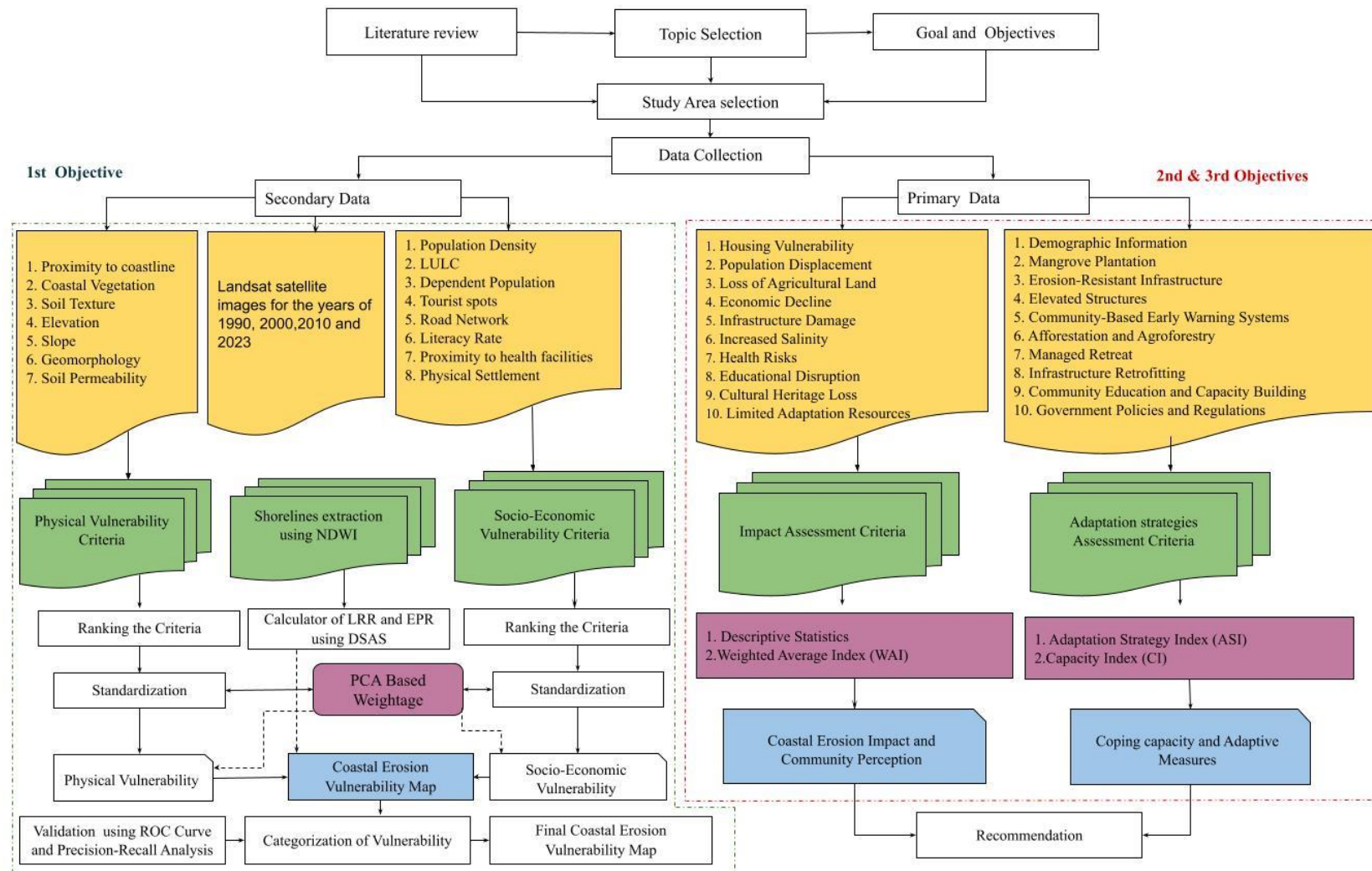


Fig. 3.19 Methodology Flow Chart of the Study

Chapter 4: COASTAL EROSION VULNERABILITY

This chapter examines vulnerability within the study area in terms of identifying and analysing the different components that contribute to the varying levels of risk. How susceptible or at risk an area is depends greatly on several factors. This section outlines how vulnerability was assessed, the methods used, the selected indicators, and how the data were integrated and interpreted. The systematic examination of vulnerability paves the way for more focused policy suggestions and intervention recommendations as well as more effective strategies for managing risks in the future.

4.1 JUSTIFICATION AND CALCULATION OF INFLUENCING POWERS OF DIFFERENT FACTORS IN COASTAL EROSION VULNERABILITY

The suitability of Principal Component Analysis (PCA) application for both social and physical vulnerability datasets has been confirmed through the Kaiser-Meyer-Olkin (KMO) Measure and Bartlett's Test of Sphericity results (Table 4.1). The social vulnerability dataset shows a KMO value of 0.757, which indicates acceptable to good sampling adequacy because the variables exhibit appropriate common variance suitable for dimensionality reduction. Bartlett's Test/result demonstrates a Chi-Square value of 723.611 with degrees of freedom at 28 and produces p-values below .001 which establishes that the correlation matrix lacks identity matrix characteristics, indicating significant relationships between variables. The physical vulnerability dataset exhibits a KMO value of 0.674, which indicates PCA applicability, although the value falls within the mediocre range. The Bartlett's Test results at a highly significant level (Chi-Square = 1251.273, df = 21, $p < .001$) show that the variables demonstrate strong correlations

with each other. These results support the appropriate use of PCA methods to reveal natural patterns and lower the dimensionality within each dataset.

Table 4.1. Justification of principal component weighting factors

KMO and Bartlett's Test					
Social Vulnerability			Physical Vulnerability		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.757	Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.674
Bartlett's Test of Sphericity	Approx. Chi-Square	723.611	Bartlett's Test of Sphericity	Approx. Chi-Square	1251.272
	df	28		df	21
	Sig.	.000		Sig.	.000

In the case of influencing powers of different factors in (CEV), the road buffer has the highest eigenvalue (0.0511) and contributes significantly to social vulnerability with a weight of 33.41%, while the second most important factor is literacy (25.17%) (Table 4.2). Also, other factors, such as population dependency and population density, play a role, but their influence gradually diminishes. Additionally, factors such as distance to healthcare have low weight (2.15%), while the cumulative weights of these factors sum to 100%, highlighting their contribution to overall social vulnerability.

Furthermore, in the case of physical vulnerability, among the seven factors, proximity to the coast accounts for the most significant eigenvalue (0.0660), and weight is 47.86%. Also, soil texture plays a significant role (16.61%), while factors such as soil shape, permeable soil, and slope contribute marginally. Factors such as Normalized Difference Vegetation Index (NDVI) and elevation have the least weight, which collectively accounts for 100%. Combining social and physical vulnerability, the study gives the highest weightage to physical vulnerability (78.23%) as compared to socio-economic vulnerability (21.77%). This indicates that physical factors play a significant role in identifying all weaknesses in this case. The cumulative weight of all weaknesses is also 100%.

Table 4.2. Eigenvalue and weightage value of PCA criteria

Social Vulnerability Weightage Value				
PC Number	Name of PC	Eigen Value	Weight age	Accumulative of Weightage
1	Road Buffer	2.846	33.41	33.41
2	Literacy Dependent	1.257	25.17	58.58
3	Population	1.013	13.38	71.97
4	Population Density	0.815	9.65	81.61
5	Physical Settlement	0.633	6.90	88.52
6	Tourist Spots	0.571	5.84	94.36
7	Land use	0.483	3.49	97.85
8	Distance to Healthcare	0.386	2.15	100.00
Physical Vulnerability Weightage Value				
PC Number	Name of PC	Eigen Value	Weight age	Accumulative of Weightage
1	Proximity Coastline	2.689	47.86	47.86
2	Soil Texture	1.877	16.61	64.47
3	Geomorphology	0.891	11.18	75.65
4	Soil Permeability	0.552	9.24	84.90
5	Slope	0.500	7.87	92.76
6	NDVI	0.369	3.80	96.56
7	Elevation	0.122	3.44	100.00
Overall Vulnerability Weightage Value				
PC Number	Name of PC	Eigen Value	Weight age	Accumulative of Weightage
1	Physical Vulnerability	57.8920	78.23	78.23
2	Socio-Economic Vulnerability	16.1061	21.77	100.00

4.2 ANALYSIS OF VULNERABILITY TO UPAZILAS/THANAS LEVEL

This section focuses on the analysis of vulnerability at different administrative levels within the study area. This study analyses data at different geographic levels to identify vulnerable areas that are at greater risk through local vulnerability pattern assessment. The evaluation focuses on different

indicators consisting of environmental conditions, socio-economic aspects, and physical hazard exposure for each Upazila/Thana unit.

4.2.1 Distribution of Physical vulnerability within the study area

Fig. 4.1 and 4.2 represent the overview of physical vulnerability to coastal erosion in various Upazilas/Thanas (sub-districts) of the Chattogram district. Sitakunda is identified as the most vulnerable area with substantial land areas in the very high (37.23 sq. km), high (67.72 sq. km), medium (41.58 sq. km), and low (103.51 sq. km) categories, indicating widespread susceptibility to coastal erosion. In addition, Banshkhali also faces significant vulnerability, especially in the very high category with 14.66 sq. km, and notable areas in the high (38.02 sq. km), medium (49.56 sq. km) and low (224.43 sq. km) categories. Also, Mirsharai exhibits the largest vulnerability in the very high and high categories (10.07 and 20.52 sq. km, respectively), while its low and medium categories (336 sq. km and 71 sq. km, respectively) also show substantial exposure. On the other hand, smaller areas such as Patenga, Anowara, and Halishahar have moderate to low vulnerability, with Anowara standing out for its considerable area in the very low category (55.23 sq. km), indicating relatively less vulnerable. Meanwhile, places like Pahartali, Chattogram Port, and Bayejid Bostami have low vulnerability in higher categories but show substantial land areas in the very low category, especially Bayejid Bostami (32.27 sq. km). A few Upazilas, including Bakalia, Chandgaon, Double Mooring, Khulshi, Kotwali, and Panchlaish, have little to no susceptibility in the higher-vulnerable categories but show some susceptibility in the very low category, indicating that they are no vulnerability to the problems associated with coastal erosion.

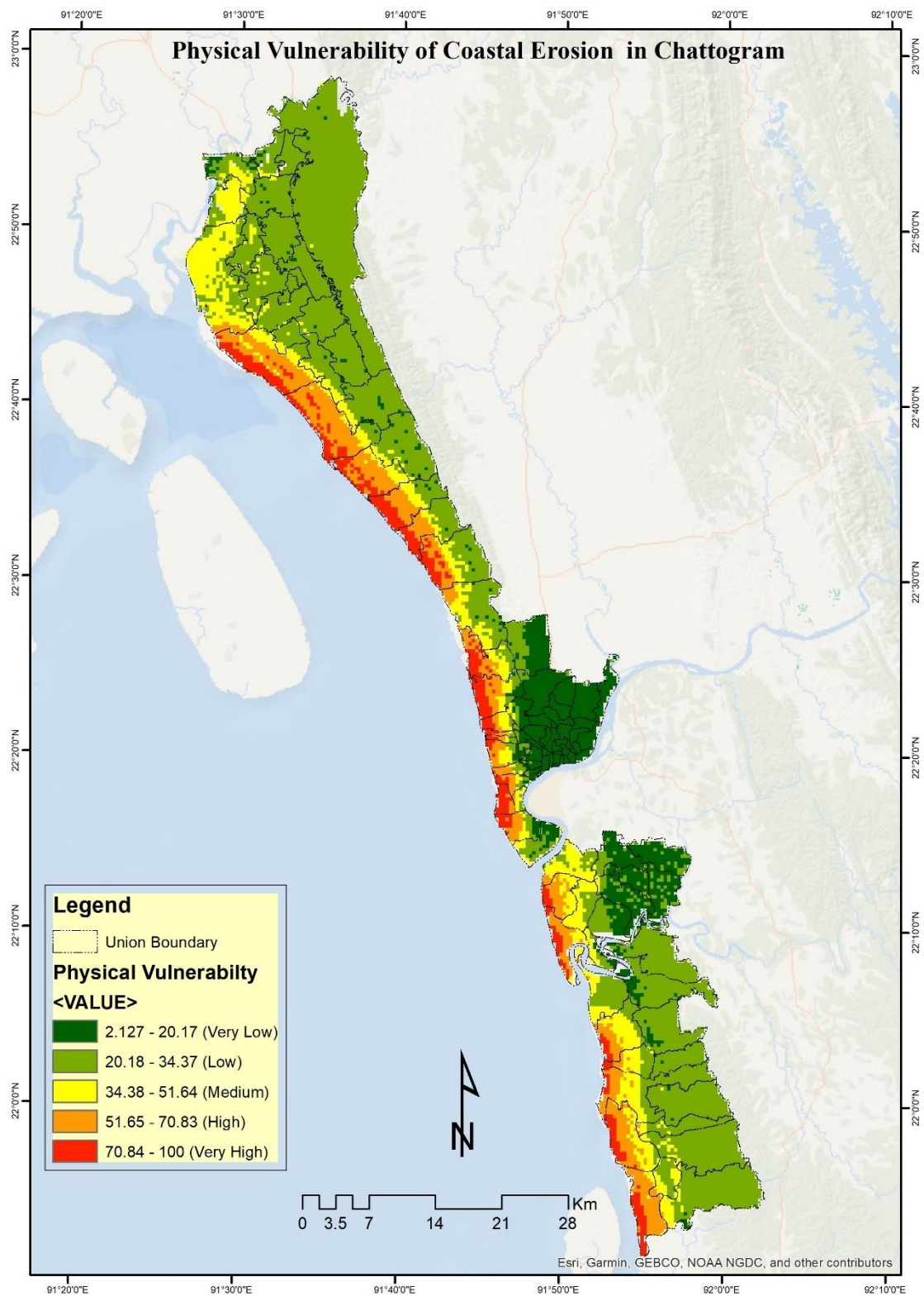


Fig. 4.1 Physical vulnerability to coastal erosion map

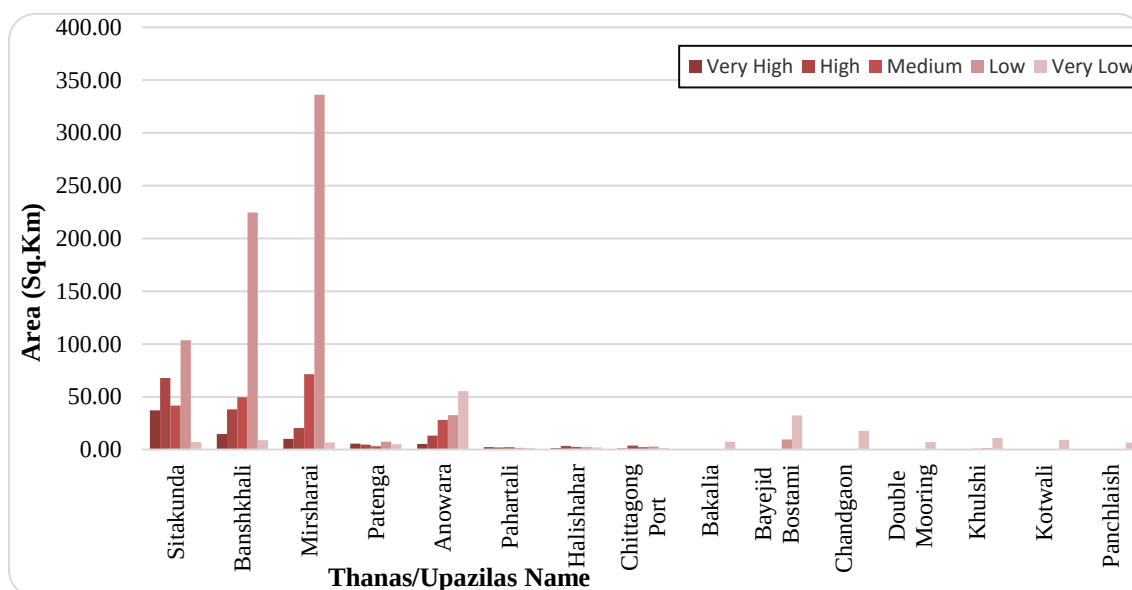


Fig. 4.2 Upazila-wise physically vulnerable areas with highlighted severity levels

4.2.2 Distribution of Socio-Economic vulnerability within the study area

Furthermore, Fig. 4.3 and 4.4 represent the socio-economic vulnerability to coastal erosion throughout various Upazilas, highlighting widespread differences in exposure levels. Banshkhali stands with 104.09 sq. km classified as very high vulnerability and 201.35 sq. km as high, suggesting that a massive part of the populace and infrastructure in this vicinity is tremendously prone to coastal erosion. Additionally, Anowara reveals different aspects from very high to very low, with 44.60 sq. km within the very high class and 42.06 sq. km categorized as high, even though it additionally has a huge place (55.23 sq. km) in the very low category, indicating an extra combined vulnerability profile. On the other hand, Mirsharai and Sitakunda display special developments, with medium and low vulnerability dominating their landscapes. Mirsharai has 179.51 sq. km inside the medium category and 132.62 sq. km classified as low, while Sitakunda shows 129.11 sq. km as medium and 64.17 sq. km as low. In contrast, Bayejid Bostami, Bakalia, and Chandgaon have minimum regions within the very high and high classes but extra significant quantities in the low and very low classes.

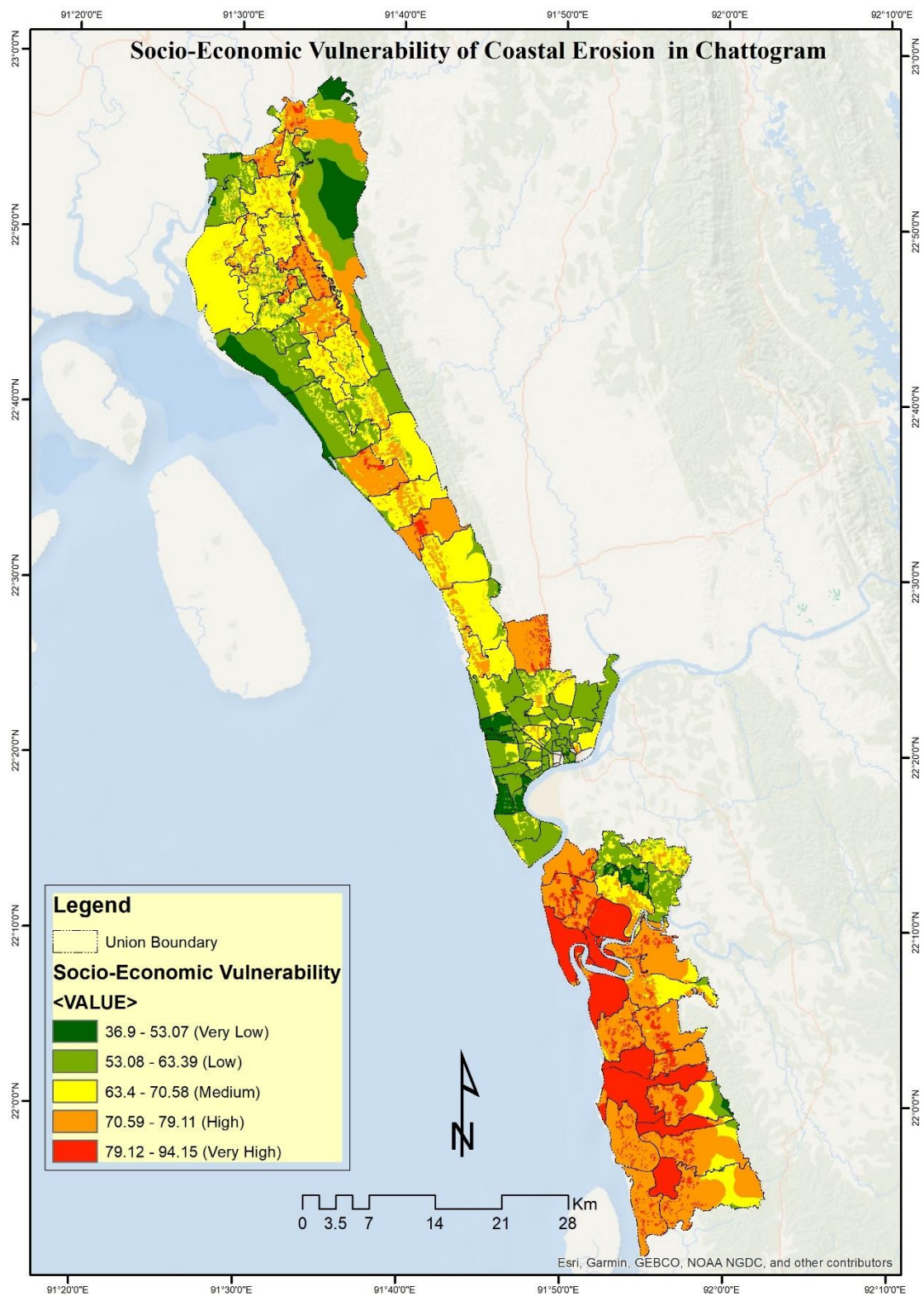


Fig. 4.3 Socio-economic vulnerability to coastal erosion map

For instance, Bayejid Bostami has 32.27 sq. km within the very low class, indicating that a big part of the location is less susceptible to coastal erosion.

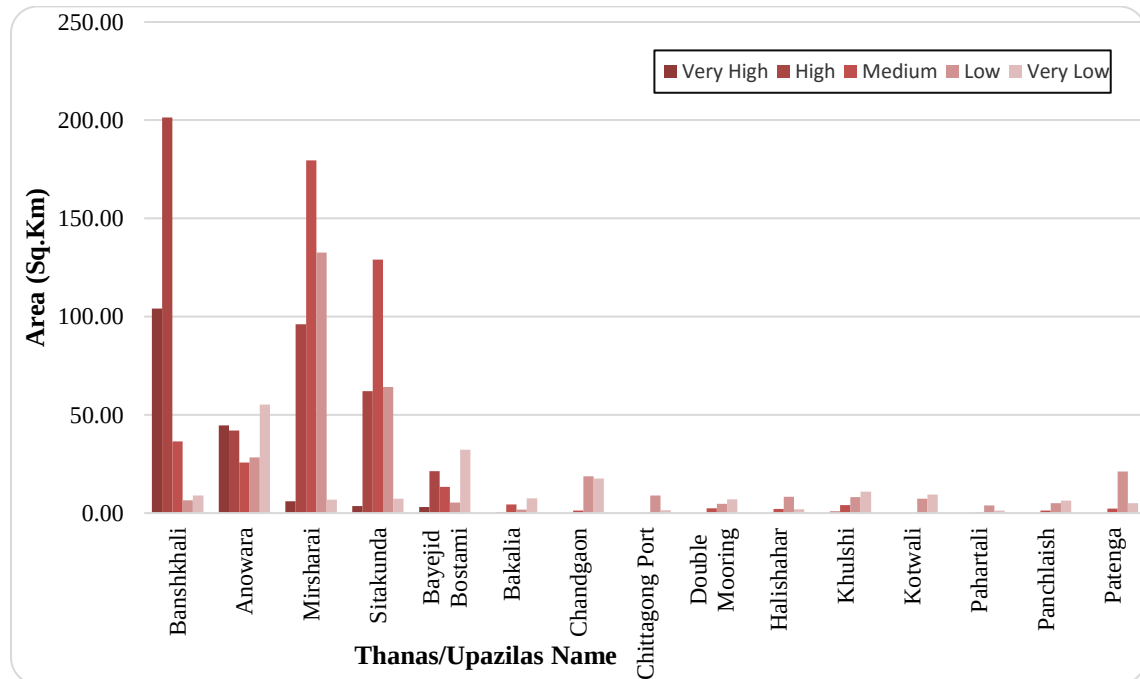


Fig. 4.4 Upazila-wise socio-economically vulnerable areas with highlighted severity levels

4.2.3 Analysis of overall vulnerability within the study area

Moreover, Fig. 4.5 and 4.6 show the vulnerability of various Upazilas/Thanas to coastal erosion, while Upazilas such as Sitakunda, Banshkhali, and Mirsharai show significant exposure to erosion in the very high category. For instance, Sitakunda has a vulnerability of 53.22 Sq.km while Banshkhali and Mirsharai also show notable vulnerability at 20.16 and 9.92 Sq.km, respectively. Sitakunda (90.19 Sq.km) and Banshkhali (48.72 Sq.km) again show high vulnerability alongside Mirsharai (74.99 Sq.km). Mirsharai (86.47 Sq.km) and Banshkhali (58.17 Sq.km) dominate in the medium category, indicating moderate but still concerning levels of vulnerability. Mirsharai (314.63 Sq.km) and Banshkhali (203.42 Sq.km) appear highly prominent in the low category, suggesting some areas within these Upazilas may face less immediate but still substantial risks from coastal erosion.

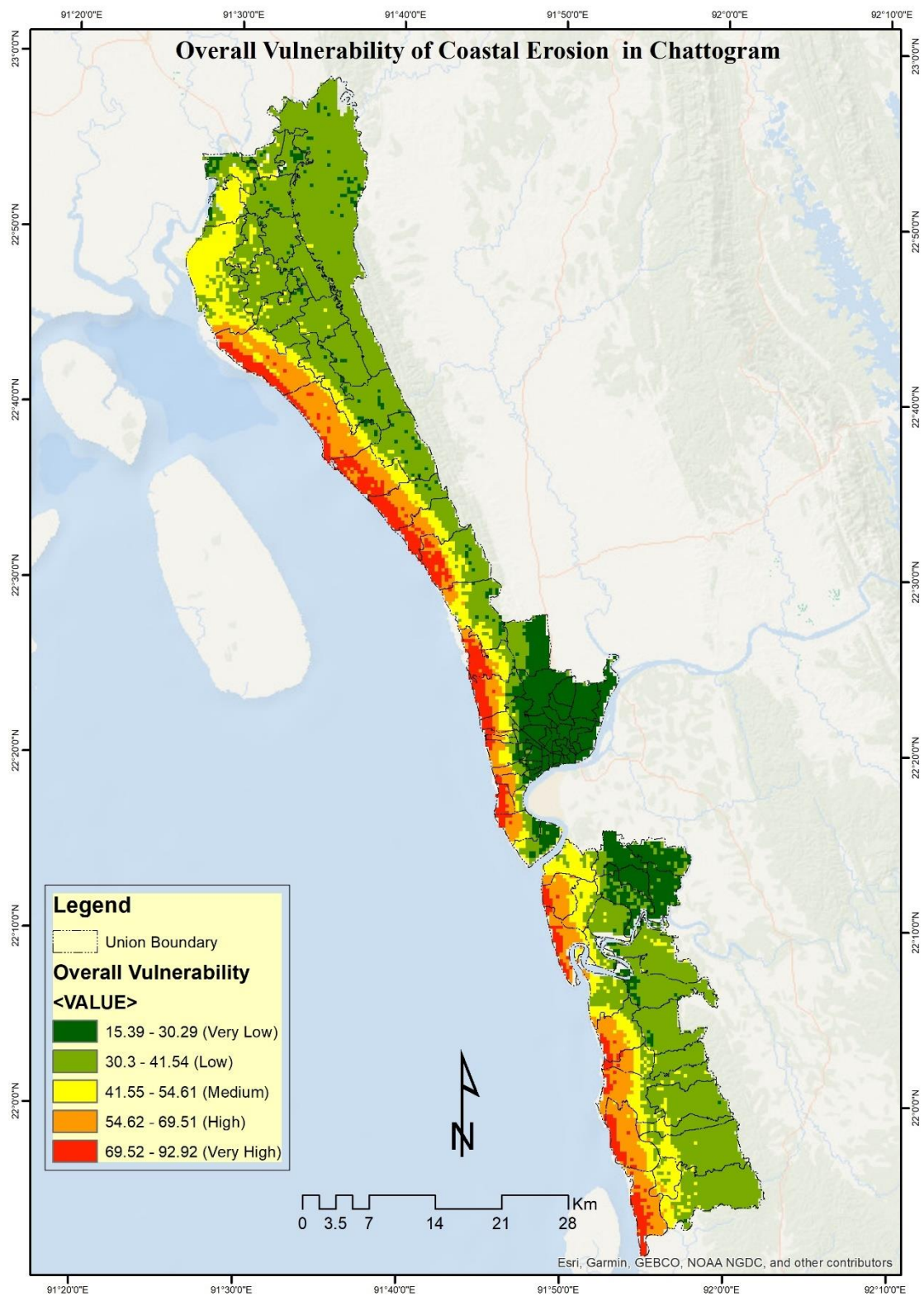


Fig. 4.5 Spatial distribution of CEVI map demonstrating overall vulnerability to coastal erosion

The Upazilas of Anowara (50.28S q.km), Halishahar (56.01 Sq.km), and Pahartali (54 Sq.km) are examples of locations where erosion risks are categorized as very low. In contrast, some areas, including Khulshi, Bayejid Bostami, Chandgaon, and Double Mooring, have moderate to low vulnerability. At the same time, Kotwali, Panchlaish, and Bakalia only exhibit data in the very low category, indicating minimal exposure to erosion risks.

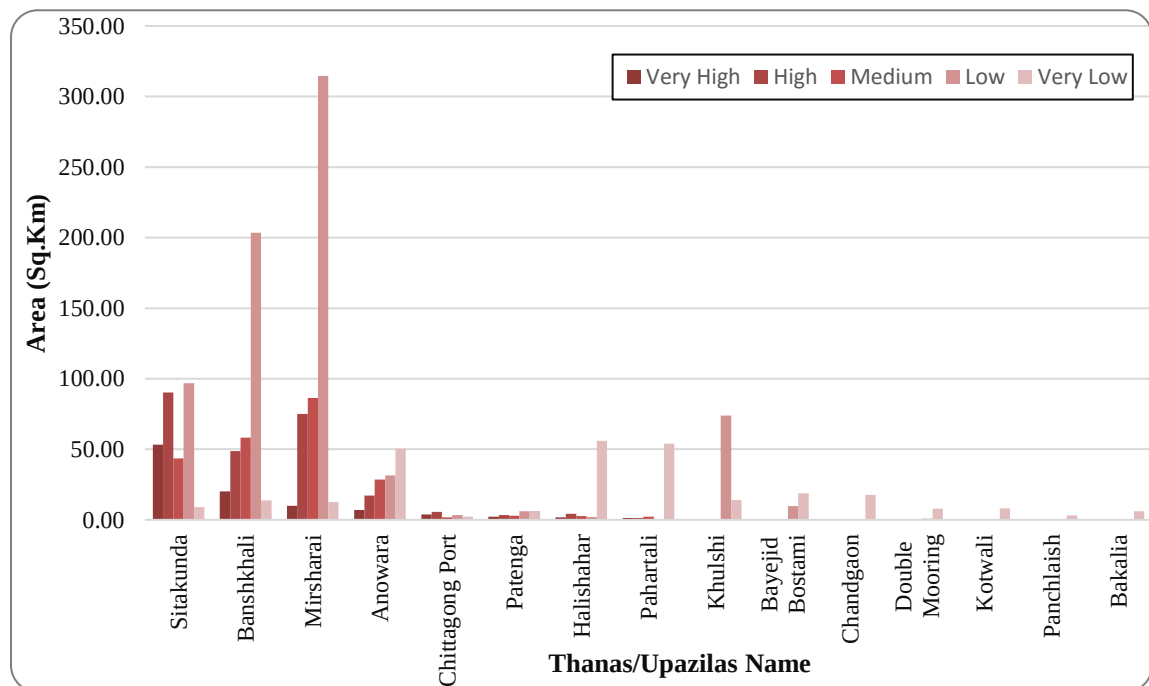


Fig. 4.6 CEVI comparison across different Upazilas

4.3 VALIDATION OF THE RESULTS USING ROC CURVE AND PRECISION-RECALL ANALYSIS

Vulnerability assessment from coastal erosion resulted in an overall strong performance model with an AUC value of 0.909 which signifies a high level of accuracy in the model's ability to distinguish between vulnerable and non-vulnerable areas (Fig. 4.7). Therefore, it effectively predicts the susceptibility of the regions to erosion. The confidence interval for the AUC, ranges from 0.867 to 0.943, which reinforces the reliability of the model. The upper and lower limits of this interval suggest that the model's performance is consistently strong, meaning

that it can accurately predict the outcomes. Compared to [63], who reported an AUC of 0.852 (success rate) and 0.801 (prediction rate) using an AHP-based model, the current study exhibits improved predictive capability. The higher AUC value and the inclusion of a confidence interval in this research reinforce the model's strength in effectively identifying regions susceptible to coastal erosion, potentially reflecting enhancements in data quality, criteria selection, or methodological rigor.

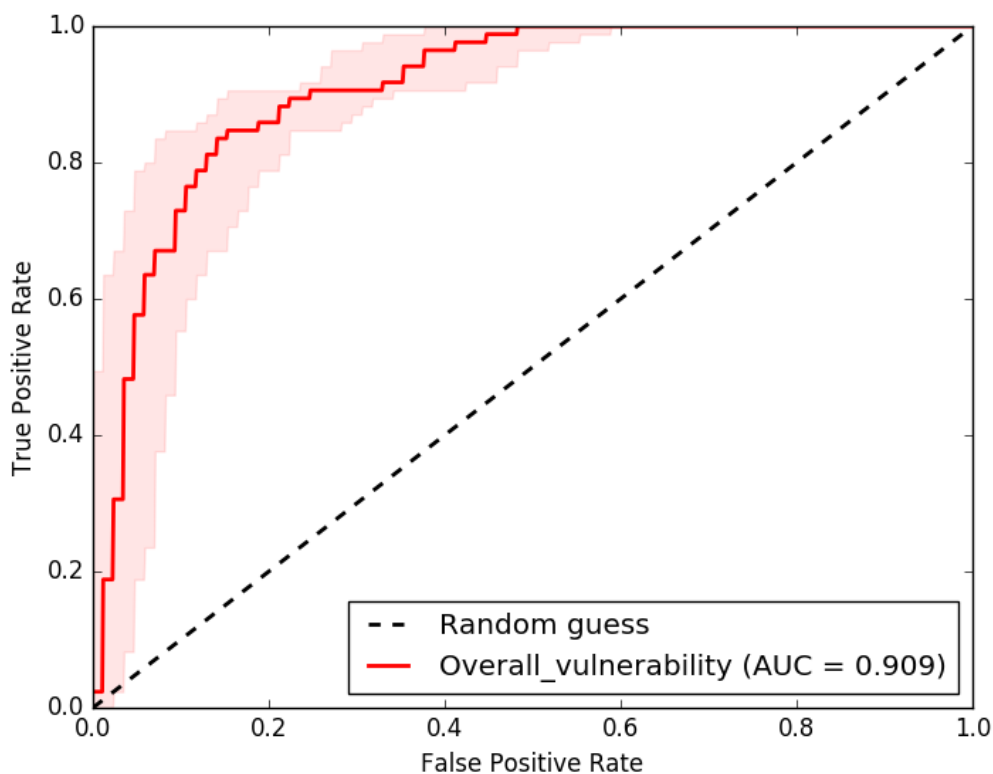


Fig. 4.7 Accuracy analysis using ROC curve

A precision-recall analysis of coastal erosion vulnerability enables assessment of how well the classification model detects vulnerable regions. Precision stands at 0.927 (Fig. 4.8 & Table 4.3) based on calculations because the model correctly identifies high coastal erosion vulnerability in 93 percent of its predictions.

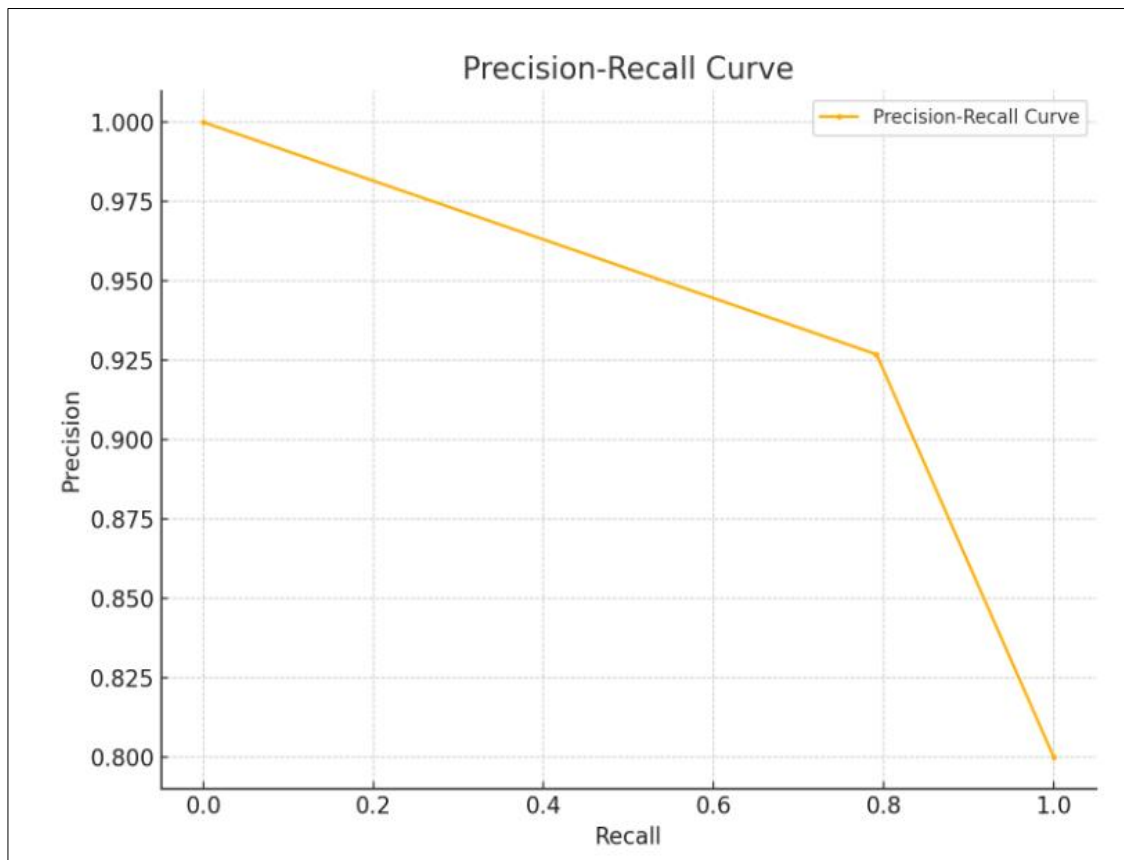


Fig. 4.8 Model validation using precision-recall analysis curve

The model shows robust reliability for positive predictions because it achieves high precision rates that prevent unnecessary alerts. The recall value amounted to 0.782, which indicates that the model detects 78% of the total highly vulnerable land zones. The model demonstrates effective accuracy in identifying coastal erosion vulnerability zones by showing high precision rates.

Table 4.3. Precision-Recall analysis for model validation

	Predicted Data		
Ground Data		Highly Vulnerable	Low Vulnerable
	Highly Vulnerable	TP= 117	FN=33
	Low Vulnerable	FP=9	TN= 26
Precision Value		= $117/(117+9)$	0.927
Recall Value		= $117/(117+33)$	0.782

4.4 ASSESSMENT OF VULNERABILITY BASED ON SHORELINE CHANGE IN THE CHATTOGRAM COASTAL DISTRICT

Statistical analysis of EPR and LRR data reveals significant variations in erosion rates across different unions, highlighting varying susceptibility levels (Figures 4.9–4.11 and Table 4.4). Erosion indicates maximum end point rate of -79.87 meters (extreme erosion), and mean rate of -6.62 meters, which means that the shorelines are retreating continuously. On the other hand, accretion has a maximum rate of 27.47 meters, and the average rate of gain was 5.51 meters, indicating areas of shoreline gain. These opposing forces reveal the complexity of coastal processes with continuing monitoring and management interventions required to manage the effects of climate change and anthropogenic activities on coastlines.

Table 4.4. Descriptive Statistics of Shoreline Change Rate

Change Types	Statistics	End Point Rate (m)	Linear Regression Rate (m)
Erosion	Max.	-79.87	-75.94
	Min.	-0.04	-0.02
	Mean	-6.62	-4.34
Accretion	Max.	27.47	32.26
	Min.	0.02	0.02
	Mean	5.51	5.62

Sakerkhali Union experiences severe erosion, with EPR ranging from -79.87m/year to -10.67m/year, while LRR indicates comparatively lower rates. Saidpur Union also faces high erosion risks, with EPR values from -10.67m/year to -55.06m/year. Bhatiary Union exhibits moderate erosion, with EPR ranging from -10.49m/year to -19.29m/year. Ward No. 38 & 39 show varying erosion levels, requiring localized protection measures. Baharcchara faces severe erosion, with EPR values between -20.89m/year and -58.74m/year, necessitating urgent

intervention. The findings emphasize the need for targeted erosion control strategies, community involvement, and continuous monitoring.

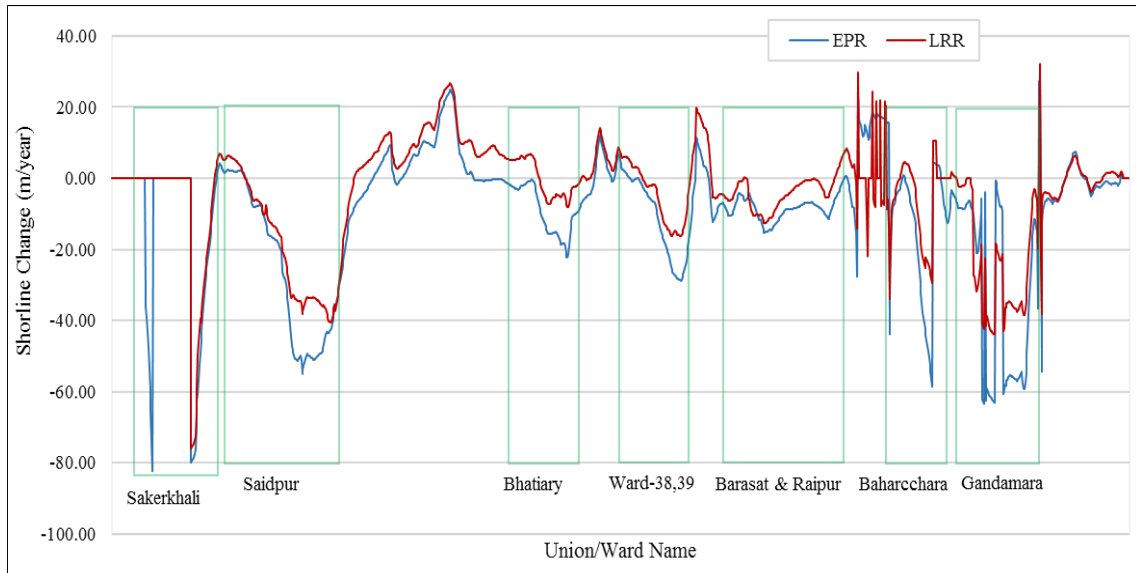


Fig. 4.9 Union/ ward-based shoreline change (m/year)

On the other hand, the deposition pattern in Barabkunda initially shows an annual accumulation of 4.28 m/year and 7.80 m/year, followed by a steady increase until it reaches 12.97 m/year (EPR) and 17.63 m/year (LRR). The measured values exhibit changes after reaching their peak, indicating shifting shoreline patterns. During the measurement period, Banshbaria's shoreline experienced an initial increase in deposition rates from 17.21 m/year (EPR) to 21.34 m/year (LRR), reaching maximum values of 24.92 m/year (EPR) and 26.75 m/year (LRR) before beginning a downward trend.

Furthermore, Salimpur presents a moderate accumulation pattern, as EPR measurements start at 1.55 m/year, reach a maximum of 12.17 m/year, and then gradually decline over time. In Ward 40, wave deposits reveal a significant decrease in accumulation rates. The measured values initially recorded 11.58 m/year (EPR) and 19.81 m/year (LRR) before dropping to 2.21 m/year (EPR) and 12.95 m/year (LRR), suggesting either continuous erosion or reduced sediment availability.

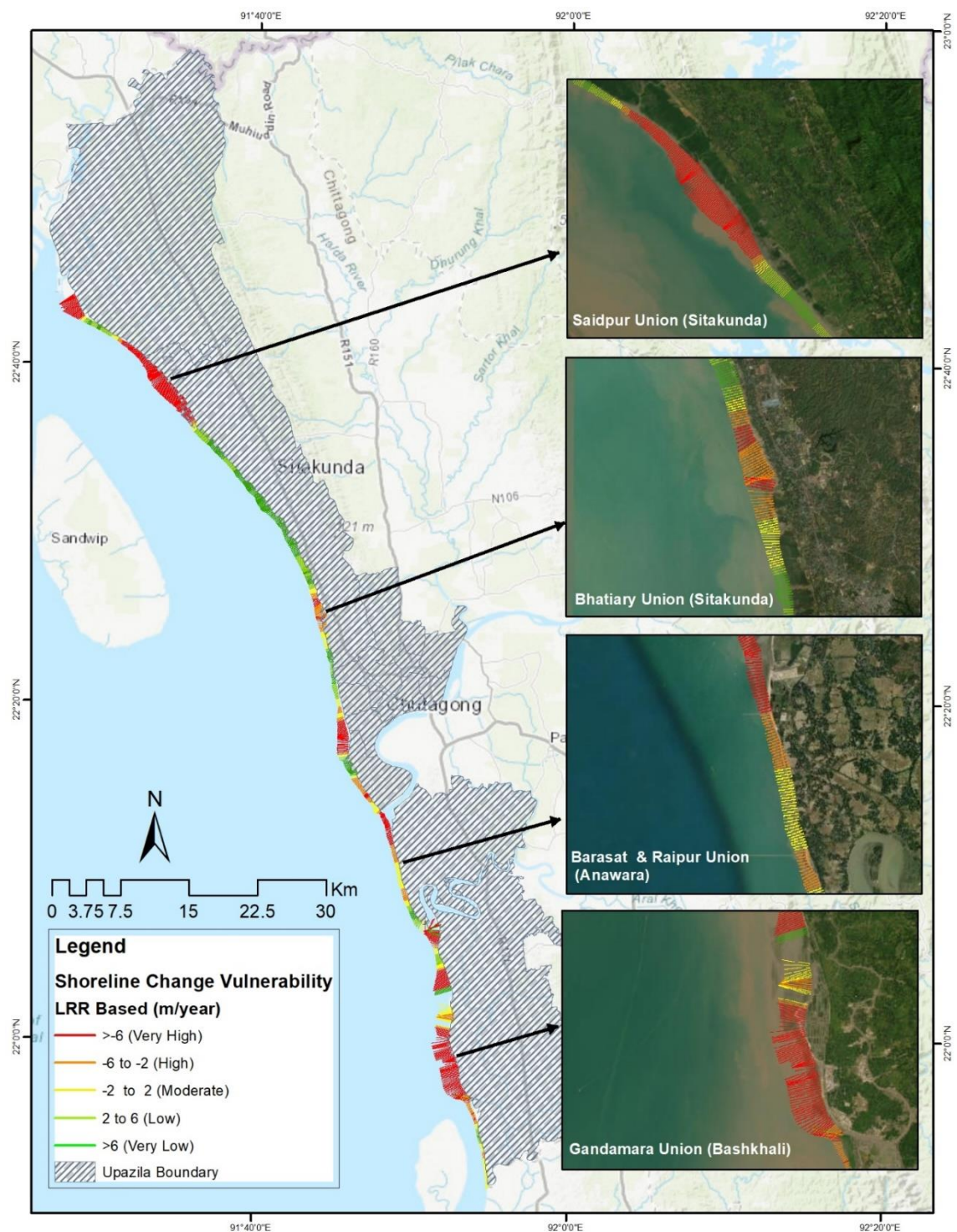


Fig. 4.10 EPR-based (m/year) shoreline change vulnerability of the Chattogram Coastal District

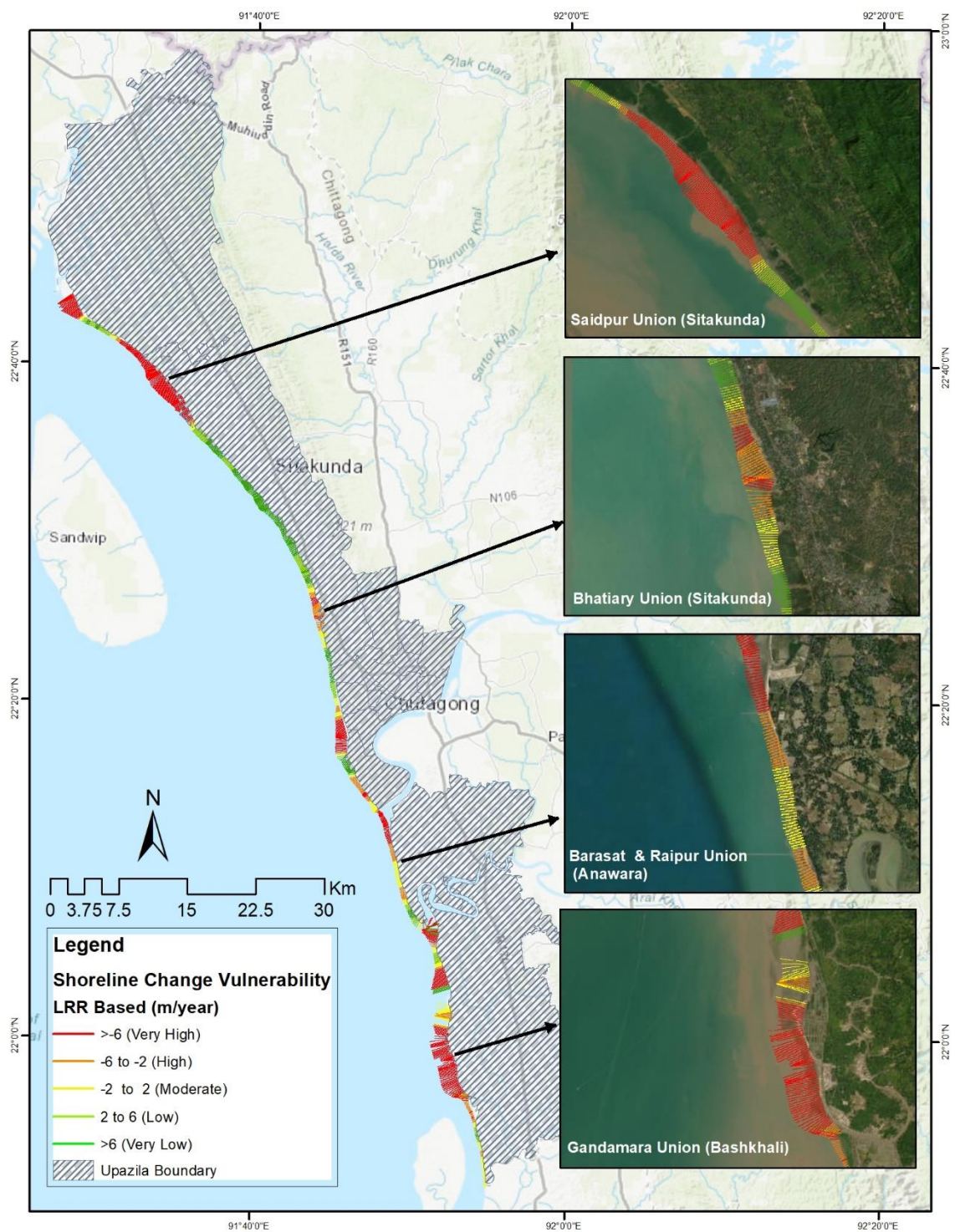


Fig. 4.11 LRR-based (m/year) shoreline change vulnerability of the Chattogram Coastal District

4.5 VALIDATION OF SHORELINE CHANGE IN THE CHATTOGRAM COASTAL DISTRICT

To evaluate shoreline position accuracy, Root Mean Square (RMS) error analysis assesses shoreline location predictions for 1990 and 2023 (Table 4.5). The analysis, based on 100 shoreline points, incorporates Maximum RMS Error, Minimum RMS Error, Standard Deviation, and Average RMS Error as statistical measures. A comparison shows that prediction accuracy at the most deviating points improved from 28.79 meters in 1990 to 25.56 meters in 2023. Accuracy remained perfect at certain points in both years, as the Minimum RMS Error stayed at zero. However, the Standard Deviation of RMS Error indicates a slight decline in measurement consistency, shifting from 9.33 meters in 1990 to 9.24 meters in 2023. The Average RMS Error increased from 8.62 meters to 8.86 meters, reflecting a minor overall decline in prediction accuracy. This variation stems from factors such as natural coastal dynamics, shoreline erosion and accretion, sea-level rise, and human activities. Notably, multiple prediction points align precisely with observational data, as indicated by zero RMSE values. Despite slight fluctuations, the RMSE results confirm that shoreline prediction models maintain reliable accuracy.

Table 4.5. Validation of Shorelines shifting between actual and observed data using RMSE methods

Year	No of actual and observed point	Max RMS Error (in meter)	Min RMS Error (in meters)	Standard deviation of RMS Error (in meters)	Average RMS Error (in meters)
1990	100	28.79	0	9.33	8.62
2023	100	25.56	0	9.24	8.86

4.6 COMPARISON OF INDICATORS BASED VULNERABILITY AND SHORELINE CHANGE BASED VULNERABILITY RESULT

The study incorporates an area-based vulnerability analysis described in Section 4.2.3 and shoreline change-based vulnerability assessments through EPR and LRR measurements presented in Section 4.4. The area-based assessment shows that coastal erosion affects broad areas of Upazilas and Sitakunda, Banshkhali and Mirsharai prove most vulnerable to erosion. The analysed Upazilas demonstrate extensive land areas located throughout very high, high and medium vulnerability zones which predicts substantial eroded zones. Halishahar along with Pahartali and Kotwali demonstrate minimal exposure to coastal erosion although they hold urban and interior characteristics. The shoreline change-based analysis delivers detailed local results by evaluating how much sea-level changes affect environmental zones. Sakerkhali (Mirsharai upazila), Saidpur (Sitakunda Upazila) and Baharcchara (Banshkhali) unions demonstrate severe erosion conditions through End Point Rates of -79.87 m/year which represents fast shoreline erosion. The calculated rates of deposition at Barabkunda and Banshbaria experienced initial high values before they began to decrease thus indicating the onset of shoreline erosion. The rate-based assessment technique shows how erosion processes shape by hydrodynamic conditions across space and time throughout Salimpur and Ward 40. The shoreline change analysis through rate-based measurements delivers essential details about coastal dynamics which combined with area-based assessments help develop purposeful adaptive management strategies for erosion control.

4.7 DISCUSSION OF RESULTS

This study has determined the vulnerability of coastal erosion in the Chattogram district, highlighting the influence of both physical and socio-economic factors. The results show that physical vulnerability plays a dominant

role in determining areas vulnerable to coastal erosion, with proximity to the coastline, soil texture, and geomorphology being the most influential factors. Socio-economic vulnerability, on the other hand, is influenced by factors such as dependent population, literacy rates, and road buffers. Sitakunda, Banshkhali, and Mirsharai have been identified as the most vulnerable Upazilas, both physically and socio-economically, requiring immediate intervention. In contrast, areas like Anowara, Haliashahar, and Pahartali show mixed profiles, with some resilience but lingering socio-economic vulnerability. The study has also highlighted the importance of considering both physical and socio-economic factors in vulnerability assessments and has demonstrated the effectiveness of the PCA method in determining areas vulnerable to coastal erosion.

Findings reveal extreme erosion rates in Sakerkhali (-79.87 m/year), Saidpur (-64.42 m/year), and Baharcchara (-61.92 m/year), underscoring the urgent need for erosion control measures. In Saidpur and Sakerkhali, erosion is driven by excessive sand extraction, mangrove deforestation, embankment damage from the ship-breaking industry, and high-water velocity. Studies by [169], [170], and [171] confirm that Bangladesh's ship-breaking industry accelerates sand extraction, leading to coastal erosion, mangrove deforestation, and embankment damage. These impacts weaken coastal protection, reduce biodiversity, and increase flood risks and land subsidence due to heavy machinery use, waste disposal, and pollution. In Baharcchara, key factors include the absence of embankments, mangrove deforestation, and increased water velocity during the rainy season, aligning with the findings of [172]. The lack of embankments allows rising seas and storms to push wetlands inland, while barriers block natural migration. Deforestation weakens coastal protection, and stronger water flow disrupts sediment deposition, eroding soils and hindering mangrove recovery [173]. Meanwhile, Barabkunda and Banshbaria exhibit significant sediment

accumulation, with EPR measuring 12.97 m/year and LRR at 17.63 m/year. Another site recorded an EPR of 24.92 m/year and an LRR of 26.75 m/year, indicating positive sediment dynamics. Similarly, Hastuti et al. (2024) found that Bali Province's shoreline decreased from 668.64 km to 662.59 km between 2016 and 2021 due to erosion, with an average retreat of -1.21 m/year, particularly in Klungkung Regency. However, human activities such as land reclamation, harbor, and airport construction led to a net land increase of 1.25 km², while structural interventions like breakwaters and seawalls helped mitigate erosion. In Chattogram, Bangladesh, coastal plantations act as natural barriers against hazards, while embankments support land accretion.

Moreover, Salimpur and Ward 40 exhibit declining deposition rates, with Salimpur's accumulation dropping from 12.17 m/year to lower values and Ward 40 decreasing to 2.21 m/year (EPR), possibly indicating shoreline erosion. Excessive sand extraction, human activities, and infrastructure development in these areas have intensified erosion, surpassing deposition over time. In contrast, Barabkunda and Banshbaria experience extensive sediment buildup, whereas Salimpur and Ward 40 show declining deposition, likely due to shoreline retreat or changes in sediment transport. Coastal processes, hydrodynamic conditions, and human activities influence these variations in sediment supply and deposition patterns. [175] highlight that dam construction reduces sediment flux, contributing to delta erosion, while dredging and land reclamation alter tidal dynamics, shifting erosion and deposition zones. Similarly, [176] found that deltas rely on river sediment to counter erosion and sea-level rise, but human interventions reduce this supply, leading to shoreline retreat and ecosystem loss. Additionally, waves and currents impact sediment distribution, making smaller deltas particularly vulnerable.

In future studies, PCA will enhance methodological transparency and reproducibility by systematically identifying and weighting key vulnerability factors, enabling consistent, data-driven assessments across diverse contexts. The study's findings have significant implications for disaster risk reduction and management strategies in the Chattogram district. The results suggest that a multi-dimensional approach is needed to address both immediate physical threats and underlying socio-economic conditions. This approach should include community engagement, education programs, and sustainable development practices that empower communities to adapt and thrive in the face of adversity. Based on the observations of this study, some recommendations are presented from three aspects: policy, implementation, and research in Table 4.6.

Table 4.6. Recommendations from three aspects: policy, implementation, and research based on vulnerability

Aspects	Recommendations
Policy	✓ Formulation and proper implementation of coastal protection legislation and policies with a focus on mitigating erosion. ✓ Encouragement of community involvement of community in managing coastal erosion to improve resilience and sustainable management of resources. ✓ Allocation of sufficient economic resources by identifying the most vulnerable areas as 'hotspots.
Implementation	✓ Construction of embankments and other community-led measures in erosion-prone areas. ✓ Protection of mangrove forests and enhance mangrove/ coastal plantations.

	✓ Implementation of advanced early warning systems using geospatial technology, which may help communities to take action quickly. ✓ Empowerment of local communities by increasing awareness and education programs on river bank erosion and relevant factors.
Research	✓ Further research should be conducted on physical and socioeconomic factors of coastal erosion with a focus on sea level rise and climate patterns. ✓ Study on nature-based solutions that could sustainably minimize erosion impacts. ✓ More study on the effectiveness of locally-led adaptation practices. ✓ Regular development of vulnerability maps using advanced remote sensing and GIS technologies.

Furthermore, the interaction between social elements, like literacy rates, economic balance, and environmental risks, highlights the need for incorporated procedures in disaster preparedness that encompass both physical and societal dimensions. These findings are in keeping with a study conducted by [177], which highlighted the significance of socioeconomic factors in disaster impact reduction and management. Findings reveal that physical vulnerability, specifically proximity to the coast, soil texture, and geomorphology, plays a dominant role in determining areas vulnerable to coastal erosion. This is consistent with preceding research that has emphasized the significance of physical criteria in coastal erosion vulnerability assessment [42]. The study's results additionally highlight the importance of considering each physical and socio-economic element in vulnerability assessments. The overall vulnerability map, which combines physical and socio-economic vulnerability, affords extra

comprehensive expertise of the region most at risk of coastal erosion. The high accuracy of the general vulnerability map including a strong overall performance version indicates that the model is powerful in distinguishing between susceptible and non-vulnerable regions, which is crucial for figuring out regions that require monitoring and intervention.

Moreover, it is important to understand how government policies can mitigate or exacerbate these vulnerabilities; Communities with supportive legislation and resource allocations tend to exhibit greater resilience to natural disasters compared to communities experiencing neglect or discriminatory practices [178]. Therefore, multi-dimensional policies to address immediate physical threats and underlying socio-economic conditions will be essential for communities to cope with coastal erosion and other climate-related challenges. This approach should include community engagement, education programs, and sustainable development practices that empower communities to adapt and thrive in the face of adversity. The findings of this study can inform disaster risk reduction and management strategies in the Chattogram district, contributing to the development of more effective measures.

Chapter 5: COASTAL EROSION IMPACTS AND LOCAL ADAPTATION STRATEGIES

Resilient coastal management plans require an assessment of coastal erosion impacts and adaptive strategy effectiveness. This study investigates physical and social aspects and economic consequences that result from coastal erosion, particularly within the vulnerable zone of Chattogram, Bangladesh. This analysis reviews the different types of adaptation solutions used by both communities and governments to lessen these effects. This study investigates multiple approaches to analyse their strengths and weaknesses to establish holistic knowledge about enhancing resilience as well as vulnerability reduction strategies. These findings provide necessary information to support upcoming policy development and planning of sustainable coastal zone management in regions facing heightened climate change and human-made threats.

5.1 DEMOGRAPHIC CHARACTERISTICS OF THE RESPONDENT

The study's respondents were predominantly men, comprising 95% (n=364) of the total sample (n=384), while only 5% (n=20) were women (Table 5.1). Sociocultural factors may explain this gender imbalance in community coastal management roles. Respondents were evenly distributed across age groups, ensuring a well-represented perspective on both immediate and long-term adaptation strategies. The survey included 2% children under 18 (n=7), 37% young adults (18-35 years, n=142), 37% middle-aged individuals (36-50 years, n=143), and 24% older adults (above 50 years, n=93). Most participants were married (86%, n=332), reflecting a family-oriented community structure conducive to adaptation measures. Respondents were categorized by family size: 53% (n=203) belonged to medium-sized families (5-6 members), 35% (n=134) to large families (more than 6 members), and 12% (n=47) to small families (2-4

members). Larger families may face greater challenges in relocating or adapting to coastal changes, influencing the design of support programs.

Table 5.1. Background information of the survey respondent (n = 384)

Aspects		Number (n)	Percentages (%)
Gender	Male	364	95
	Female	20	5
Age (years)	Below 18	7	2
	18-35	142	37
	36-50	143	37
	Above 50	93	24
Marital status	Married	332	86
	Unmarried	51	13
Family Size	Small (2-4)	47	12
	Medium (5-6)	203	53
	Large (above 6)	134	35
Education Levels	No formal education	110	29
	Primary (Class of V)	170	44
	SSC (Class of X)	70	18
	HSC (Class of XII)	26	7
	Graduation or more	7	2
Type of Houses	Kaccha	222	58
	Semi Pacca	142	37
	Pacca	19	5

Furthermore, educational attainment among respondents was notably low, with 28% (n=110) having no formal education. Primary education was completed by 44% (n=170), while 18% (n=70) attained a Secondary School Certificate. Additionally, 7% (n=26) held a Higher Secondary Certificate, and only 2% (n=7) had a graduate degree or higher. Low education levels may limit community awareness of coastal risks and adaptation strategies, highlighting the need for accessible communication and training initiatives. Housing conditions further contribute to vulnerability. The majority (58%, n=222) lived in kaccha (temporary) dwellings, 37% (n=142) in semi-pacca (semi-permanent) structures, and only 5% (n=19) in pacca (permanent) houses. The susceptibility of temporary

housing to coastal erosion and extreme weather underscores the urgent need for resilience-focused adaptation strategies.

5.2 EXPLORING THE FACTORS CONTRIBUTING TO COASTAL EROSION IN CHATTOGRAM

Fig. 5.1 illustrates that lack of a protective barrier (No embankment or vegetative barrier) is the leading cause of coastal erosion, accounting for 29.31% of total damage. Urgent enforcement of effective coastal management strategies is needed to mitigate erosion. Natural barriers, such as mangroves and coastal forests, play a crucial role in erosion control, yet cyclone-induced vegetation damage contributes 16.55% to total causes. Human activities, particularly illegal sand extraction, account for 13.79% of coastal degradation. Other significant factors include vegetation cutting (11.38%) and embankment damage from storm surges (9.66%). Additionally, high water velocity combined with high tides causes 16.56% of natural erosion, while storm surges and shipyard development collectively contribute 2.76%. Both natural and human factors significantly impact coastal stability, underscoring the need for sustainable erosion control measures.

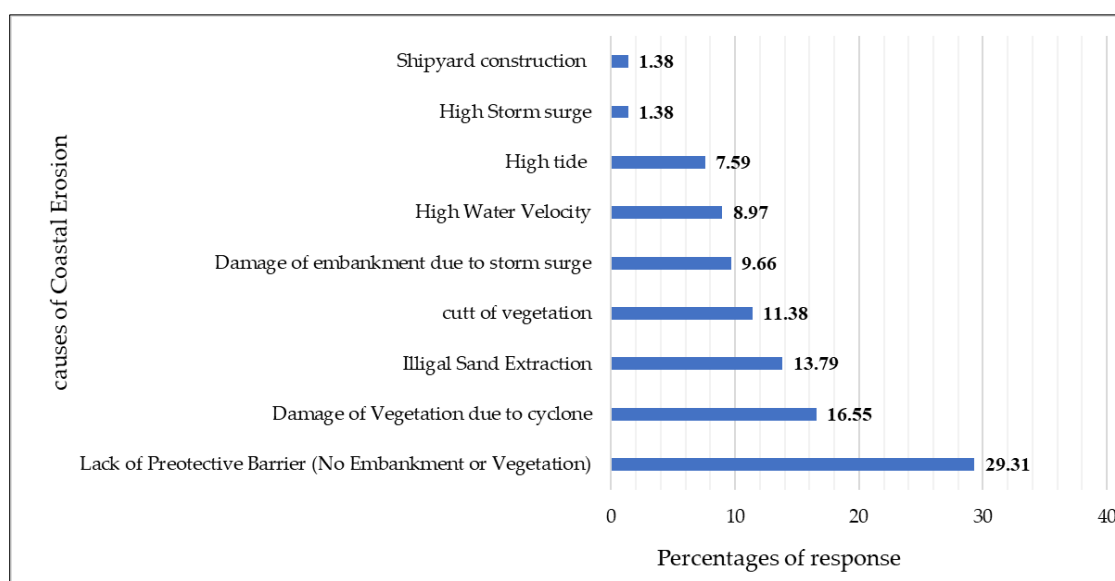


Fig. 5.1 Reasons behind the coastal erosion in the Chattogram Coastal District

5.3 ASSESSMENT OF EROSION IMPACTS ON COMMUNITIES' HOUSEHOLDS

Table 5.2 presents an analysis of coastal erosion impacts by examining various factors contributing to coastal community vulnerability. The assessment uses a Weighted Average Index (WAI) system to rank impacts based on their significance, categorized into severity levels: high, moderate, low, or none.

Table 5.2. Rank order of the community people's perceived impacts of coastal erosion

Aspects	Statement	Level of Impacts				WAI	Rank order
		High	Moderate	Low	No		
Community Dynamics	Increase storm surge height and frequency	194	157	29	4	2.41	1
	Population displacement	185	120	68	11	2.25	3
	Contamination of water	173	102	75	34	2.08	4
	Houses are washed away	121	143	89	31	1.92	6
	Physical damage to houses or buildings	97	151	87	49	1.77	8
	Destruction of communication/ damage to the road	68	180	103	33	1.74	9
	Washed out of latrine and waste	0	96	143	145	0.87	15
Traditional Livelihood	Damage to vegetation	193	143	32	16	2.34	2
	Increased Salinity	159	117	74	34	2.04	5
	Loss of income	123	142	74	45	1.89	7
	Loss of crops	99	93	71	121	1.44	10
	Loss of livestock	34	110	138	102	1.20	12
	Loss or unavailability of cooking materials	44	73	173	94	1.17	13
Cultural Practices	Damages of religious places	62	85	108	129	1.21	11
	Reduce the meal	29	86	174	95	1.13	14
	Damage education institution	0	47	89	248	0.48	16

According to the assessment results, the increased height and frequency of storm surges stand out as the most significant impact of coastal erosion, with a Weighted Average Index (WAI) value of 2.41. Participating communities expressed strong concern over the intensifying storm events, which heighten flood risks and property damage. Also, vegetation destruction ranks as the second most severe consequence of coastal erosion, with a WAI of 2.34, indicating serious damage to local ecosystems. Population displacement follows as the third-ranked impact, with a WAI of 2.25, highlighting the significant movement of affected communities.

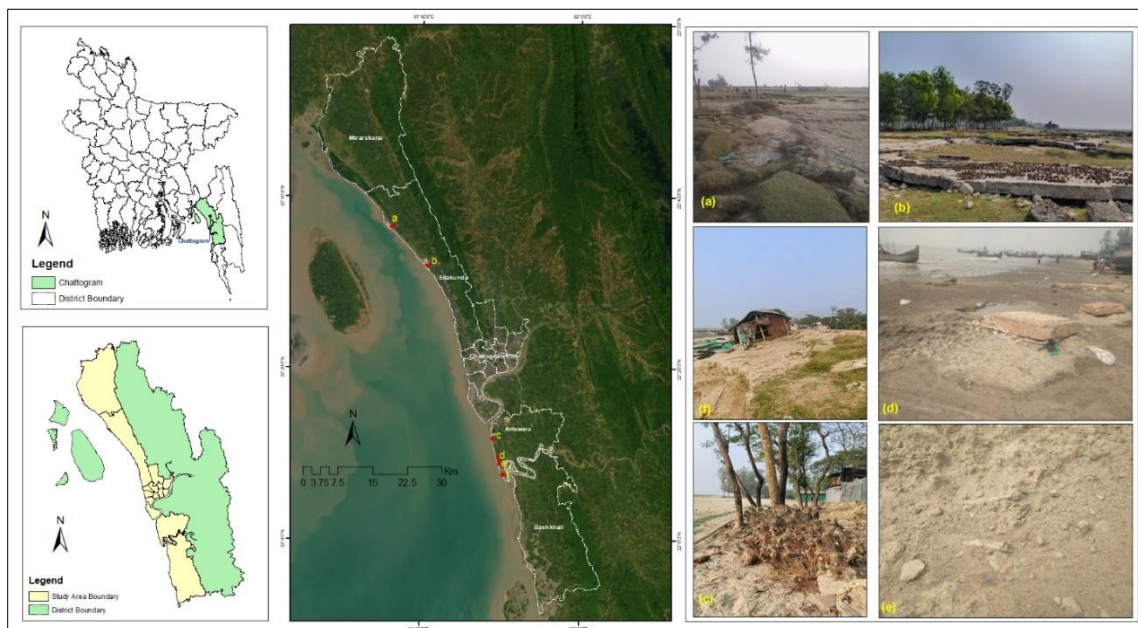


Fig. 5.2 Impact of coastal erosion in different locations (a) Household land (b) Demolished Household Structure (c) Impacted vegetation (d) Demolished religious Place (Mosque) (e) Demolished Graveyard (Skeleton shown in Photo) (f) Damaged structure and earthen embankment.

Furthermore, the combined effects of water contamination (WAI 2.08) and increased salinity (WAI 2.04) pose substantial risks to both human health and agricultural systems. Physical damage to houses and infrastructure is considered less severe compared to ecological and social impacts. Additionally, despite

environmental challenges posing the most immediate threats, social (WAI 1.89) and environmental (WAI 1.77) consequences remain significant. WAI data also suggest that crop losses and the devastation of educational facilities rank lower in the assessment hierarchy compared to storm surges and population displacement, as they are perceived as lesser threats to communities. Impacts of coastal erosion in different locations of the Chattogram district are presented in Fig. 5.2.

5.4 ANALYSIS OF ADAPTATION CAPACITY FOR COASTAL VULNERABLE COMMUNITY

The Capacity Index (CI) score of 22.58 (Table 5.3) assesses the resilience of a vulnerable coastal community by considering various environmental and anthropogenic factors. The capacity index score for water flow velocity is 8.53, making it the most prominent indicator, as powerful water currents significantly impact coastline stability, potentially leading to shoreline damage and flooding events. The stability of soil types (3.28) and the quality of vegetation cover (2.96) provide fundamental defenses against land erosion, as vegetation naturally reduces soil displacement. Slope stability (3.04) has a moderate influence on resilience, as certain areas remain susceptible to landslides and soil displacement.

Table 5.3. Community people's perceived Capacity Index (CI) for coastal erosion

Indicators	Average standardized Value	Weightage Value (%)	Indicator-wise CI Score	Overall CI Score
Water flow velocity	0.18	47.81	8.53	22.58
Soil type stability	0.20	16.59	3.28	
Vegetation cover quality	0.22	13.19	2.96	
Slope stability	0.34	8.96	3.04	
Human activities	0.49	7.10	3.50	
Erosion control measures	0.20	6.36	1.26	

Furthermore, human activities, including deforestation, land development, and infrastructure expansion (3.50), contribute to increased vulnerability in the region. Erosion control measures (1.26) have the lowest impact, emphasizing the need for improved strategies to mitigate coastal degradation.

5.5 HOUSEHOLDS' ADAPTATION STRATEGIES FOR COASTAL EROSION

The study focused on the adaptation strategies employed by coastal communities during erosion events. Fifteen adaptation strategies were identified through questionnaire-based survey methods. Survey respondents were assigned scores based on a measurement scale ranging from 0 to 45. The results classified participants into categories based on their total scores, representing low to high levels of adaptation strategy usage. Fig. 5.3 illustrates the survey results, showing the frequency with which participants adopted different adaptation strategies.

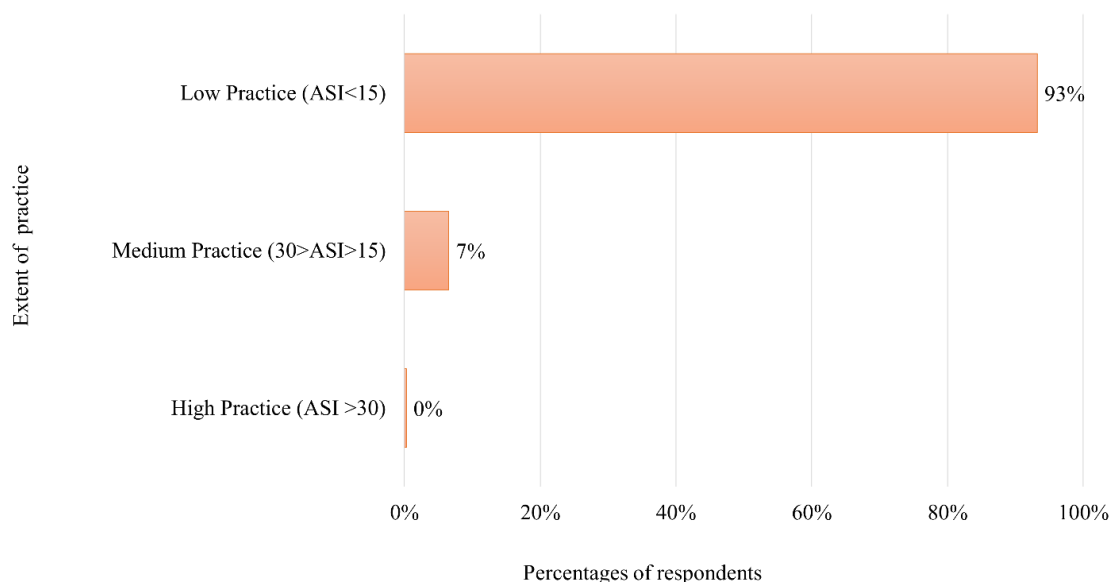


Fig. 5.3 The extent of the practice of the coastal erosion adaptation strategies by the respondent

Table 5.4. Rank order of the adaptation strategies employed by community members based on the extent of practice (n = 384).

Statement	Extent of Practice				ASI Value	Rank order
	Regular	Occasional	Rare	No		
Migration to outside of the village	59	105	75	145	462	1
Cultural practices and indigenous knowledge	54	54	127	149	397	2
Natural barriers and vegetation planting	31	46	115	192	300	3
Sale of land	18	40	66	260	200	4
Loan from relatives for protect house	-	38	103	243	179	5
Community-led monitoring and maintenance	4	14	139	227	179	6
Sold domestic animals like cow, goat	3	42	59	280	152	7
Crop diversification	5	35	46	298	131	8
Sharecropping	5	36	42	301	129	9
Loan from bank for protect house	0	22	69	293	113	10
Adaptive Infrastructure	2	16	74	292	112	11
Help from government	4	29	25	326	95	12
Sustainable land use practices	3	8	35	338	60	13
Help from non-government organizations	2	4	13	365	27	14
Innovative solutions and technology	-	5	12	367	22	15

Findings indicate that most respondents (93%) exhibit a low level of coastal erosion adaptation strategies, with ASI scores below 15, suggesting insufficient effective adaptation measures. Seven percent of respondents engage in moderate coastal erosion mitigation ($15 < \text{ASI} < 30$), primarily due to uneven yet substantial

mitigation efforts. Also, the responses show no participants practicing at a high level ($ASI > 30$), indicating the absence of effective proactive measures within the community. A widespread deficiency in adoption exists regarding practical coastal erosion management strategies, largely because stakeholders and residents lack awareness of effective solutions or have insufficient resources and support from governing bodies.

The study evaluates community adaptation to coastal erosion using the Adaptation Strategy Index (ASI), which quantifies strategy implementation across four levels: regular, occasional, rare, and non-existent. The findings, based on responses from 384 individuals, reflect shared community experiences.

Migration outside the village ranks as the most preferred adaptation strategy, with an ASI score of 462. Many community members view migration as essential for safety and livelihood preservation. Traditional methods and local wisdom hold the second-highest ASI value (397), serving as primary tools for managing environmental changes. Vegetation planting and natural barriers, recognized as crucial ecological solutions, score 300 on the ASI metric. Land sales rank fourth (ASI 200), often driven by economic pressures from coastal erosion. Two key strategies—taking loans from family members for home protection and community-led home maintenance programs—share an ASI value of 179. Lower ASI scores for animal sales, crop diversification, and sharecropping suggest these strategies are infrequently used. Community reliance on government (ASI 95) and non-government organizations (ASI 27) for coastal adaptation remains minimal. Innovative solutions and technology receive the lowest ASI value (22), indicating barriers to adoption or a lack of awareness regarding their benefits.

The coastal communities of Chattogram, like many vulnerable deltaic regions of Bangladesh, reveal an adaptation landscape that is heavily reactive and driven by distress rather than resilience. The prioritization of migration and

reliance on indigenous practices underscore a adaptation mechanism rooted in immediate survival rather than long-term sustainability. While traditional knowledge is valuable, the limited engagement with ecological restoration, institutional support, and technological innovation suggests a critical gap in structured adaptation. The minimal role of government and non-governmental actors reflects a governance vacuum, while the underutilization of modern strategies points to a lack of accessible knowledge, financial mechanisms, and infrastructure. For coastal Chattogram to build adaptive resilience, it is imperative to shift from passive displacement to community-based, anticipatory adaptation frameworks that integrate local knowledge with technical solutions, policy alignment, and equitable resource allocation.

Furthermore, enhancing adaptive capacity in coastal Chattogram requires a multi-level governance approach that fosters collaboration between local communities, scientific institutions, and administrative bodies. Investments in early warning systems, embankment reinforcement, and ecosystem-based adaptation, such as mangrove afforestation must be paired with education and skill-building programs that empower households to understand and implement diverse strategies beyond migration. Equally important is the need for inclusive planning processes that recognize socio-economic disparities, ensuring that the most vulnerable groups are not left behind in resilience efforts. Integrating adaptation into local development planning, backed by targeted funding and technical assistance, could transform the current landscape of fragmented and low-intensity responses into a more cohesive and sustainable adaptation system for the future.

5.6 DISCUSSION OF RESULTS

Coastal regions in Bangladesh face severe vulnerabilities, including erosion, tropical cyclones, and floods, resulting in loss of life, infrastructure damage, and environmental degradation [33], [34]. Chattogram experiences significant annual erosion [35], while climate change, particularly sea level rise, is expected to exacerbate these issues, increasing socio-economic risks and environmental threats [69]. Effective adaptation is essential to mitigate these impacts on livelihoods, agriculture, and the coastal environment [28]. This study quantifies shoreline change rates along the Chattogram coast over 33 years (1990–2023), analyzing spatial patterns and trends. It also explores adaptation and mitigation strategies to enhance community resilience and promote sustainable coastal management.

Increasing exposure to coastal erosion risks is evident, as over half of the homes are kaccha structures, and 35% of families have more than six members. The high demand for resilient housing underscores the need for targeted support within adaptation frameworks. Findings indicate that coastal erosion in the Chattogram district is primarily driven by anthropogenic activities, exacerbated by inadequate mitigation efforts. [179] highlights that unplanned urbanization and industrialization accelerate erosion due to environmental mismanagement, lack of planning, and unchecked development, further threatening biodiversity, human health, and climate stability. Strategic policy interventions are essential to address these issues. Additionally, vegetation degradation from cyclonic disturbances and unsustainable sand extraction intensifies erosion. Effective responses require a multifaceted approach, including stringent regulatory enforcement, ecosystem restoration, and sustainable coastal management [180]. Vulnerabilities vary across communities, making demographic factors crucial in tailoring adaptation strategies [181].

The combination of higher storm surges and damaged vegetation is the most critical driver of coastal erosion (WAI = 2.41), with vegetation destruction ranking nearly as significant (WAI = 2.34). This aligns with [182], who found that storm surges and vegetation loss accelerate shoreline retreat. Similarly, Devoy (2008) highlighted that rising sea levels and intensifying storms exacerbate coastal erosion, threatening infrastructure and livelihoods. Coastal erosion also contributes to population displacement (WAI = 2.25), as seen in the Solomon Islands, where rising sea levels have forced communities inland [184]. Water contamination (WAI = 2.08) and rising salinity (WAI = 2.04) further endanger human health and agriculture. In the study area, saline water intrusion reduces agricultural productivity, aligning with FAO's (Food and Agriculture Organization) Global Map of Salt-Affected Soils, which reports that 1.381 million hectares (10.7% of global land) suffer from salinity, worsening food insecurity [185]. Freshwater shortages due to erosion also increase skin-related diseases, supporting findings by [186].

The Capacity Index (CI) score of 22.58 reflects moderate community resilience, with erosion control measures showing the weakest capacity (CI = 1.26) and water flow velocity the highest (CI = 8.53). This underscores the urgent need for stronger coastal protection and better management of human activities. The Adaptation Strategy Index (ASI) reveals that 93% of respondents implement inadequate adaptation measures (ASI < 15), with none exceeding a score of 30, highlighting a lack of awareness, resources, and institutional support. These findings align with [187], who attribute Bangladesh's weak coastal adaptation to financial constraints and inadequate institutional backing. Without external aid, many resorts to high-interest loans from local lenders [188], further deepening financial vulnerability. While vegetation planting is a common strategy, its effectiveness remains limited without broader ecosystem-based adaptation [189].

Moreover, the study found migration to be the most preferred adaptation strategy (ASI = 462), as residents see relocation as the best defense against coastal erosion, aligning with findings by [190]. Traditional methods remain the second-most favored approach (ASI = 397) despite their cultural significance. However, low adoption of modern technology (ASI = 22) underscores the need for education and resources to integrate innovative solutions, as [191] also observed in climate-vulnerable regions.

Despite moderate resilience, communities remain at risk due to high water flow, human-induced changes, and inadequate prevention measures. Strengthening vegetation cover, enforcing erosion control regulations, and managing human activities effectively can improve coastal resilience. The most effective strategies combine traditional knowledge with modern techniques. Supporting community-led initiatives and increasing access to innovative solutions will enhance long-term coastal protection. Table 5.5 presents key recommendations from policy, research, and implementation perspectives.

Table 5.5. Recommendations from three perspectives: Policy, Research, and Implementation, based on impacts and adaptation strategies

Aspects	Recommendations
Policy	✓ Introduce coastal management rules to control sand extraction, ship-breaking, and unplanned urbanization to reduce human-caused erosion.
	✓ Include coastal resilience in national and local development plans, focusing on protecting ecosystems and using land sustainably.
	✓ Support community-based adaptation by providing financial help, technical support, and legal backing for sustainable solutions.
	✓ Align coastal management with climate adaptation plans by adding early warning systems, flood control, and better land use planning.

	✓ Improve monitoring and enforcement by using satellite data and field assessments to track shoreline changes and take timely action.
Research	✓ Use satellite images and models to study shoreline changes and predict long-term erosion trends. ✓ Research how coastal erosion affects livelihoods, migration, and local economies to create better adaptation plans. ✓ Test nature-based solutions like mangrove planting, dune protection, and artificial reefs to prevent erosion and support wildlife. ✓ Check how strong coastal embankments, roads, and homes are against erosion and rising sea levels to improve disaster readiness. ✓ Study traditional erosion control methods used by communities and find ways to include them in modern resilience plans.
Implementation	✓ Build and maintain strong embankments, revetments, and breakwaters in erosion-prone areas while protecting nature. ✓ Help people find safer lives, like eco-tourism, fish farming, and climate-friendly farming to reduce dependence on risky coastal areas. ✓ Teach communities about erosion, early warnings, and safe land use through workshops and training programs. ✓ Work with businesses and NGOs to support projects like planting trees, restoring habitats, and building flood-resistant homes. ✓ Create local teams to track and manage coastal erosion while involving communities in decisions.

Chapter 6: CONCLUSIONS

This chapter aims to integrate the main insights of the study and examine their impact. It restates the study aims, outlines the study findings, discusses the results concerning previous studies and literatures as well as to other real-world practices. This chapter identifies the shortfalls of the work carried out and proposes new lines of inquiry directed towards other work in the area. By doing so, the final argument is constructed, which amplifies the significance of the study for scholarly and occupational spheres.

6.1 GENERAL

Coastal erosion in the Chattogram district results from both natural forces and human activities. High water flow accelerates land degradation, worsened by storm surges, high tides, and cyclones that damage vegetation. The lack of proper embankments leaves the coast vulnerable, while existing structures often fail due to poor maintenance. Additionally, unregulated shipyard construction and illegal sand extraction destabilize shorelines. Poor-quality housing materials further increase vulnerability, highlighting the urgent need for sustainable coastal management, strict regulation, and ecosystem restoration. Although natural factors contribute to erosion, human activities and poor management remain the primary drivers. Addressing this requires comprehensive policies, habitat restoration, and sustainable development. The environmental and economic impacts necessitate an integrated approach to enhance resilience. Policymakers must act urgently to prevent further destruction, protect ecosystems, and support vulnerable communities.

6.2 KEY FINDINGS

Here are the major findings from coastal erosion vulnerability in the Chattogram district:

- a) The analysis suggests that physical vulnerability plays a dominant role in figuring out typical vulnerability to coastal erosion, accounting for 78.23% of the whole weight, even as socio-economic vulnerability contributes 21.77%. This suggests that physical factors, together with proximity to the coastline (47.86%) and soil texture (16.61%), are the most influential in identifying erosion-vulnerable regions. In evaluation, social vulnerability is prompted using factors like road buffer (33.41 %) and literacy rate (25.17%), indicating that access to infrastructure and education level additionally play crucial roles in determining vulnerability, though to a lesser extent compared to the physical aspect.
- b) Upazilas consisting of Sitakunda, Banshkhali, and Mirsharai become the most physically vulnerable areas. Sitakunda, specifically, has the highest exposure with 37.23 sq. Km categorized as "Very High" vulnerability, and also 67.72 sq. Km within the "High" category. This suggests that significant areas in Sitakunda are instantaneously vulnerable to erosion. Banshkhali and Mirsharai also demonstrate large areas under threat. By contrast, Upazilas like Anowara and Patenga show lower physical vulnerability, with a significant part of their areas falling beneath the "Low" or "Very Low" categories.
- c) Banshkhali and Anowara show the highest socio-economic vulnerability, facing compounded risk due to each physical vulnerability and weaker socio-economic conditions. In contrast, Mirsharai and Sitakunda, while physically vulnerable, show less socio-economic vulnerability, likely due to higher resilience factors like higher literacy rates or decreased

population dependency. Upazilas like Bayejid Bostami, Bakalia, and Chandgaon exhibit lower socio-economic vulnerability, which may be attributed to stronger social infrastructure and fewer dependent populations.

- d) Sitakunda, Banshkhali, and Mirsharai are the most vulnerable Upazilas both physically and socio-economically, with significant areas classified within the "Very High" and "High" vulnerability categories, requiring immediate intervention. In contrast, areas like Anowara, Halishahar, and Pahartali showed mixed profiles, with some resilience but lingering socio-economic vulnerability. Upazilas together with Khulshi, Bayejid Bostami, and Chandgaon show minimal exposure to high vulnerabilities, indicating higher protection against coastal erosion.
- e) The model's high accuracy, with an AUC of 0.909 and a confidence interval of 0.867 to 0.943, confirms its reliability in predicting coastal erosion vulnerability. This analysis is crucial for guiding decision-makers in prioritizing regions for intervention and improving disaster preparedness strategies.
- f) The high physical vulnerability in Sitakunda and Banshkhali requires structural measures, while socio-economic vulnerabilities in Banshkhali and Anowara highlight the need for community resilience strategies. In contrast, lower vulnerable areas like Khulshi and Bayejid Bostami may serve as models for mitigating erosion vulnerability in highly vulnerable areas.
- g) The statistical analysis of EPR and LRR data underscores the profound differences in erosion intensity among unions. Sakerkhali, Saidpur and Baharcchara face critical erosion challenges that require immediate

attention high erosion rates (up to -79.87 m/year), while Bhatiary is marked by relatively lower erosion rates.

- h) The respondents (93%) from the sampled households show low to non-existent adaptation strategy implementation ($ASI < 15$), and no participants reported using advanced adaptation mechanisms. As before, migration remains the most widely used option while technological and institutional responses are still lacking.
- i) Improper application of erosion control measures (29.31%) along with anthropogenic activities such as sand mining and timber harvesting have a marked impact towards degradation. These social factors render the community even more vulnerable. Elevated community types combined with low educational attainment and inadequate educational facilities intensifies the risk within the society.

6.3 LIMITATION OF THE STUDY

Here are some limitations of the research on quantifying Chattogram coastal erosion vulnerability: How local adopts? that could be addressed by future researchers:

- a) High-quality and long-term data on coastal erosion may be limited or unavailable.
- b) High-resolution spatial data require for Coastal erosion studies, which may not be available or too costly to obtain. In the case of Chattogram, the analysis may be conducted at a broader scale, overlooking local variations in erosion rates and vulnerabilities.
- c) The temporal scope of the research may limit insights into long-term trends, as coastal erosion is influenced by both immediate and gradual

environmental changes that require a more extensive timeframe for accurate assessment.

- d) The study's focus on specific geographic areas may limit the generalizability of the results to other regions facing similar challenges.
- e) In light of these considerations, future studies should aim to incorporate a broader range of data sources and methodologies, including longitudinal studies that track changes over time and comparative analyses across different regions.

6.4 PRACTICAL IMPLICATION

This study provides crucial insights for disaster risk reduction and coastal management planning in Bangladesh. By developing a CEVI that integrates both physical and socio-economic factors using geospatial technologies, the study offers a comprehensive and location-specific vulnerability assessment model. The identification of high-risk zones such as Sitakunda, Banshkhali, and Mirsharai enables policymakers and local authorities to prioritize interventions and allocate resources efficiently to mitigate erosion-related hazards.

Furthermore, the findings of this study serve as a valuable guide for urban planners, engineers, and environmental managers in designing sustainable infrastructure and coastal defense systems. The dominance of physical vulnerability, particularly from proximity to the coastline and soil texture, underscores the need for site-specific engineering solutions, such as erosion control structures or coastal vegetation buffers. Meanwhile, the socio-economic insights, especially related to education, healthcare accessibility, and population density highlight the importance of community-based adaptation measures, including awareness programs and capacity-building initiatives.

Moreover, the study's methodological framework, particularly the use of PCA and the high model accuracy, establishes a replicable model for other vulnerable coastal regions. Stakeholders from different sectors like government, NGOs, and international development organizations can apply this framework to scale assessments across Bangladesh or adapt it to similar coastal contexts globally. This research enhances the foundation for integrated coastal zone management (ICZM) and supports the long-term resilience of coastal communities facing climate-induced threats.

6.5 RECOMMENDATION FOR FURTHER STUDY

Future research should use long-term data to track how coastal erosion and vulnerability change over time. This would help us understand how weather and climate affect erosion and how communities are at risk. It would also help in planning better and faster responses. The model could be improved by adding future climate predictions, like sea level rise and stronger storms. Using water movement (hydrodynamic) models along with maps and satellite data could give more accurate results. Furthermore, future studies should also look into how local people see erosion and the ways they already adapted to it. Including their views and knowledge would make the findings more useful for real-life solutions.

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Appendices

Appendix A: Questionnaire of the survey

Questionnaire Survey on

Exploring Vulnerability to Coastal Erosion and Local Community Adaption in
Chattogram, Bangladesh

MURP Thesis: Department of Urban and Regional Planning, CUET, Chattogram
(Used only for Academic Purposes)

Village:	Union:	Upazila:
Survey Location:	Questionnaire No:	

Section 1: Personal Information

Sl.	Question	Response
1	Gender	Male..... 1 Female..... 2
2	Age (Years)	
3	Education level	Primary.....1 SSC..... 2
4		HSC.....3 Graduation or more 4
		No formal education.....5
5	Marital status	Married 1 Unmarried 2
6		Widow3 Separated 4
7	Number of family members	
8	Head of house	Male..... 1 Female..... 2
9	Type of house	Kacca 1 Pacca..... 2
		Semi pacca 3
10	Occupation	
11	Annual Income of Household	

Section 2: Impacts information

SI.	Aspects	Response			
		None (0)	Low (1)	Medium (2)	High (3)
1	Loss of income				
2	Loss or unavailability of fuel				
3	Houses are washed away				

4	Increased Salinity				
5	Population displacement				
6	Damages of religious places				
7	Loss of livestock				
8	Damage education institution				
9	Loss of crops				
10	Damage of vegetation				
11	Physical damage of houses or buildings				
12	Destruction of communication/ damage to road				
13	Contamination of water				
14	Reduce the meal				
15	Washed out of latrine and waste				

Section 3: Capacities information

SI .	Aspects	Response				
		5	4	3	2	1
1	Soil type stability	No signs of erosion	Minimal erosion	Some erosion, but relatively controlled	Noticeable erosion, but not severe	Severe erosion visible
2	Vegetation cover quality	Fully mature, dense vegetation	Dense vegetation cover, with minimal to no bare soil visible	Fairly even distribution of vegetation with some bare patches	Patchy vegetation with significant bare spots	Sparse or no vegetation present
3	Slope stability	Completely stable with no signs of surface movement, cracks, or slumping	No visible signs of movement or cracks, and the slope appears undisturbed	Some surface runoff and minor cracks, but no major slumping	Minor to moderate slumping or surface cracks	Landslides, slumping, or visible cracks are present
4	Human activities	No development	Very little construction	Some small-scale	Smaller-scale	Large-scale infrastructure

		nt or alteration of the coastline	on or human alteration near the coastline	development with efforts to minimize environmental disruption.	construction projects near the riverbank, that disrupt the natural terrain.	e projects with little regard for environmental protection.
5	Water flow velocity	Water barely moves	Water flows slowly	Water moves at a moderate speed,	Water flows at a high speed, during rainy seasons	Flow is very fast
6	Erosion control measures	Multiple strategies actively working together.	Well-planned and maintained measures, such as vegetated buffers, terraces, or rock walls.	Techniques such as plantings, simple riprap, or erosion control mats being used.	Some attempts at erosion control that are poorly implemented or maintained.	Riverbank is entirely unprotected and vulnerable to erosion.

Section 4: Adaptation strategies information

SI.	Aspects	Response			
		Regular practice (4)	Occasional practice (3)	Rare practice (2)	No practice (1)
1	Help from government				
2	Help from non-government organizations				
3	Loan from bank for protect house				
4	Loan from relatives for protect house				
5	Sold domestic animals like cow, goat				
6	Sale of land				
7	Sharecropping				
8	Migration to outside of the village				

9	Crop diversification				
10	Natural Barriers and Vegetation Planting				
11	Community-Led Monitoring and Maintenance				
12	Sustainable Land Use Practices				
13	Adaptive Infrastructure				
14	Cultural Practices and Indigenous Knowledge				
15	Innovative Solutions and Technology				

Section 5: Others Information related to coastal erosion impacts and adaptation strategies

Appendix B: Field Visit and Erosion Impact Photograph

Observational data and photos showcase coastal erosion together with its effects on the research site based on fieldwork.



Data collection from community people about the Impacts of coastal erosion



Damage embankment due to coastal erosion



Damage road and vegetation due to Coastal erosion



Damage to buildings due to Coastal erosion

Appendix C: Definition of different terminology

Adaptation strategies	Definition
Migration Towards the Outside of The Village	Relocating to safer inland places because living along the coast has become too dangerous due to erosion. This kind of conflict often happens after people lose their land, homes, or work.
Cultural Practices and Indigenous Practices	Using old techniques and wisdom shared in the community to make changes in construction, seasons, and shoreline resources.
Natural Barriers and Vegetation Planting	Eco-friendly methods of planting trees, grasses, mangroves, and the restoration of natural areas to address shore erosion and wave-induced damage by enhancing shoreline stabilization through the growing of vegetation.
Sale of Land	Sometimes, families in these areas sell their land in an emergency to move, rebuild, or recover from damage caused by erosion. This happens because economic strains and fewer choices are involved.
Loan from Relatives for House Protection	Borrowing money from wider family and social networks to mitigate losses through strengthening, raising, or repairing homes as a short-term, reactive measure to coast-related impacts.
Community-led Monitoring and Maintenance	Local groups are organizing themselves to track shoreline changes, repair small infrastructure, and raise awareness, promoting community ownership of coastal protection.
Sold Domestic Animals (e.g., Cow, Goat)	Selling their livestock helps fishermen earn funds to act quickly, for example, by fixing their houses, relocating, or purchasing things for coastal protection.
Crop Diversification	By moving from planting only one type of crop to planting a variety that can withstand saline soils, flooding, and uncertain weather, we protect the food supply in areas that erode.
Sharecropping	Sharing the work on another farmer's fields for a portion of the yield is a common way of making money for the landless, who are sometimes forced to do this after erosion destroys their own land.

Getting a house loan from the bank for protection	Being qualified to apply for official financial funds to address house reinforcement or build safer houses. Eligible persons find it difficult to take advantage due to assets, collateral, or simply not hearing about them.
Adaptive Infrastructure	Designing and building (or renovating) housing and infrastructure that can resist erosion from the sea and other risks along the coastline.
Government Assistance	National or local authorities giving support with funding, resources, training, or relocation help to cope with erosion problems.
Recommended Practices for Land Use	To stop soil eroding, places can use buffer zones, limit how coastal buildings are constructed, and don't build or farm a few meters from the shore.
Support offered by NGOs	With NGO help, communities can be trained, assisted technically, provided with aid, and informed about the need to adapt in ways that could sustain their resources over time.
Solutions and technology that are new and effective	Reliable erosion prevention can be achieved with modern tools such as erosion models, GIS systems for mapping erosion, early warning systems, apps on mobile devices and engineered tools.