ASSESSMENT OF COASTAL FLOOD RISKS IN PATUAKHALI DISTRICT

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Declaration

I hereby declare that the work contained in this thesis has not been previously submitted to meet the requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the Thesis contains no material previously published or written by another person except where due reference is cited. Furthermore, the Thesis complies with the PLAGIARISM and ACADEMIC INTEGRITY regulations of CUET.

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Dedication

To My Elder Brother

Approval/Declaration by the Supervisor

This is to certify that **Md. Ziaur Rahman** has carried out this research work under my supervision, and he has fulfilled the relevant Academic Ordinance of the Chittagong University of Engineering and Technology, so he is qualified to submit the following Thesis in the application for the degree of MASTER OF SCIENCE IN DISASTER & ENVIRONMENTAL ENGINEERING**.** Furthermore, the Thesis complies with the PLAGIARISM and ACADEMIC INTEGRITY regulations of CUET.

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Abstract

The coastal Patuakhali district is highly susceptible to catastrophic flooding due to its geophysical location and it is one of the most dangerous challenges for this nation to save the coastal settlements from these frequent and extreme flooding events. However, the risk posed by coastal flood occurrences can be reduced with the formation and effective implementation of a sustainable flood management strategy, which is only feasible if the flood risk is accurately assessed. Thus, there was an urgent need for a detailed flood vulnerability, risk, and capacity assessment study in this area. This study attempted to provide a comprehensive assessment and mapping of coastal flood risk identifying most flood-vulnerable areas in the coastal Patuakhali district towards achieving efficient flood mitigation strategies. For generating a comprehensive coastal flood risk scenario, this study simultaneously applied both the people’s perception-based risk assessment with the help of MCDA, AHP, GIS and Remote Sensing (RS) based advanced methodologies. Based on the combined assessments of both people's perceptions, experiences, GIS and RS-based mapping, this study predicted a high flood risk for the studied area. Firstly, from people’s perception and expert opinions-based approach, this study estimated a high flood risk (0.886) for the coastal Patuakhali district. Individual hazard scores of 0.765 and vulnerability scores of 0.644 obtained during this assessment weren't very high, but when combined, they produced a significant flood risk due to the lower community capacity (0.556) to withstand flood damage. Similarly, the flood risk map developed with the weighted overlay tool of ArcGIS classified the majority of Patuakhali district's central, north-central, southern, and south-eastern char and island area as being in a very high flood risk zone due to its high population density, development of in-built infrastructure, lower elevation, flat topography, and lack of vegetation cover. A total of 10 flood-causing factors were considered throughout the mapping process, and the study identified the low slope gradient and the area's closeness to a stream, river, and sea as the main causes of coastal flooding in this location. This study furthermore finds out a number of structural and non-structural coastal flood protection and flood risk mitigation solutions with the active involvement of community members for effective flood mitigation. For the greatest effect, this study also recommended combining the use of structural and non-structural flood mitigation strategies rather than using either one alone. Additionally, a sense of ownership about different flood protective structures should be created among the local community people through their pro-active engagement of them for the effective maintenance and sustainability of these structures. Finally, the results of this study will be highly helpful to the relevant authorities and decision-makers, assisting them in developing comprehensive flood risk management plans and long-term flood mitigation strategies for coastal Bangladesh.

বিমূর্ত

উপকূলীয় পটুয়াখালী জেলা তার ভূ-ভৌতিক অবস্থানের কারণে প্রায় প্রতিবছর বন্যা কবলিত হয়, এই ভয়াবহ বন্যার ঘটনা থেকে উপকূলীয় জনবসতি রক্ষা করা এই জাতির জন্য সবচেয়ে দুরূহ কাজগুলির মধ্যে একটি। একটি টেকসই বন্যা ব্যবস্থাপনা এবং যথাযত বাস্তবায়নের মাধ্যমে উপকূলীয় বন্যায় সৃষ্ট ঝুঁকি হ্রাস করা যেতে পারে। এক্ষেত্রে বন্যার ঝুঁকি সঠিকভাবে মূল্যায়ন অতীব জরুরী। এই গবেষণায় উল্লেখিত এলাকায় একটি বিস্তারিত বন্যার ঝুঁকি এবং সক্ষমতা মূল্যায়ন অধ্যয়নের জরুরি প্রয়োজন ছিল। এই গবেষণায় উপকূলীয় বন্যা ঝুঁকির একটি ব্যাপক মূল্যায়ন এবং মানচিত্র প্রস্তুত করা হয়েছে যাতে উপকূলীয় পটুয়াখালী জেলার বেশিরভাগ বন্যা ঝুঁকিপূর্ণ এলাকা চিহ্নিত করা হয় এবং কার্যকর বন্যা ঝুঁকি প্রশমন কৌশল চিহ্নিত করা যায়। এর জন্য এই গবেষণায় একই সাথে MCDA, AHP এবং GIS ও RS ভিত্তিক উন্নত পদ্ধতির সাহায্যে জনগণের উপলব্ধি এবং অগ্রসর প্রযুক্তি ভিত্তিক ঝুঁকি মূল্যায়ন উভয়ই প্রয়োগ করা হয়েছে যা সম্মিলিতভাবে উপকূলীয় বন্যা ঝুঁকির একটি বিশদ দৃশ্যকল্প প্রদান করে। জনগণের উপলব্ধি, অভিজ্ঞতা এবং GIS ও RS-ভিত্তিক মানচিত্র অঙ্কন উভয়ের সম্মিলিত মূল্যায়নের উপর ভিত্তি করে, এই সমীক্ষা উপকূলীয় পটুয়াখালী জেলার জন্য একটি উচ্চ বন্যার ঝুঁকির পূর্বাভাস দিয়েছে। প্রথমত, জনগণের উপলব্ধি এবং বিশেষজ্ঞের মতামত-ভিত্তিক পদ্ধতির ভিত্তিতে, এই সমীক্ষা উপকূলীয় পটুয়াখালী জেলার জন্য একটি উচ্চ বন্যা ঝুঁকি (০.৮৮৬) অনুমান করেছে। এই মূল্যায়ন থেকে প্রাপ্ত ০.৭৬৫ এর ব্যক্তিগত বিপদ স্কোর এবং ০.৬৪৪ এর দুর্বলতা স্কোর খুব বেশি ছিল না, কিন্তু বন্যার ক্ষতি সহ্য করার জন্য সমন্বিত ক্ষমতা অনেক কম (০.৫৫৬) থাকার কারণে একত্রিতভাবে তুলনামূলক একটি উচ্চ বন্যার ঝুঁকি তৈরি করেছে। একইভাবে, ArcGIS এর Weighted overlay প্রক্রিয়ার সাহায্যে তৈরি বন্যার ঝুঁকির মানচিত্র পটুয়াখালী জেলার বেশিরভাগ মধ্য, উত্তর-মধ্য, সবচেয়ে দক্ষিণ, দক্ষিণ-পূর্ব চর এবং দ্বীপ এলাকাকে এর উচ্চ জনসংখ্যার ঘনত্ব, অবকাঠামোর উন্নয়ন, নিম্ন উচ্চতা, জমির সমতল গঠন, এবং গাছপালা আবরণের অভাব এর কারণে উচ্চ বন্যা ঝুঁকিপূর্ণ অঞ্চল হিসাবে শ্রেণীবদ্ধ করেছে। মানচিত্র অঙ্কন প্রক্রিয়ার জন্য মোট ১০ টি বন্যা সৃষ্টিকারী বা প্রভাবিতকারী কারণ হিসাবে বিবেচনা করা হয়েছে এবং এই গবেষণার অনুসন্ধান থেকে নিম্নমুখী ঢাল এবং নদী ও সমুদ্রের কাছাকাছি দূরত্ব এই এলাকায় উচ্চ উপকূলীয় বন্যার প্রধান কারণ হিসাবে চিহ্নিত করা হয়েছে। উপকূলীয় আদিবাসী এবং বয়স্ক শিক্ষিত সম্প্রদায়ের সদস্যদের সক্রিয় অংশগ্রহণের মাধ্যমে এই গবেষণাটি কার্যকর বন্যা ব্যবস্থাপনা এবং বন্যা ঝুঁকি প্রশমনের জন্য বেশ কয়েকটি কাঠামোগত এবং অ-কাঠামোগত উপকূলীয় বন্যা সুরক্ষা এবং বন্যার ঝুঁকি প্রশমন সমাধান খুঁজে বের করে। সর্বাধিক কার্যকারিতার জন্য, এই অধ্যয়নটি দৃঢ়ভাবে এককভাবে যেকোন একটি কাঠামোগত এবং অ-কাঠামোগত বন্যা প্রশমন কৌশল ব্যবহার না করে কাঠামোগত এবং অ-কাঠামোগত বন্যা প্রশমন কৌশলগুলির সমন্বিত বাস্তবায়নের সুপারিশ করেছে। উপরন্তু, নকশা, বাস্তবায়ন, পরিচালনা এবং রক্ষণাবেক্ষণে স্থানীয় জনগোষ্ঠীর সক্রিয় অংশগ্রহণের মাধ্যমে গড়ে ওঠা বিভিন্ন বন্যা প্রতিরক্ষামূলক কাঠামোর উপর তাদের করণীয় রক্ষণাবেক্ষণ এবং স্থায়িত্ব নিশ্চিত করতে পারবে। পরিশেষে, এই গবেষণার ফলাফল সংশ্লিষ্ট কর্তৃপক্ষ এবং সিদ্ধান্ত গ্রহণকারীদের জন্য অত্যন্ত সহায়ক হবে, তাদের ব্যাপক বন্যা ঝুঁকি ব্যবস্থাপনা পরিকল্পনা এবং উপকূলীয় বাংলাদেশের জন্য দীর্ঘমেয়াদী বন্যা প্রশমন কৌশল তৈরিতে সহায়তা করবে।

Table of Contents

List of Figures

List of Tables

Nomenclature

Symbols

α	Local upslope drainage through a certain point per unit contour length
β	Local slope in radians
E	East longitudes
e	Margin of error
km/hr	Kilometre per hour
m	Meters
m/km	Meters per kilometre
mm/year	Millimetres per year
N	North latitudes
Z	Level of significance
$\circ$	Degree
$'$	Minutes
$''$	Seconds
°C	Degree Celsius

Acronyms and Abbreviations

AHP	Analytical Hierarchy Process
BBS	Bangladesh Bureau of Statistics
BPMSG	Business Performance Management Singapore
BWDB	Bangladesh Water Development Board
CR	Consistency Rate
CRU	Climatic Research Unit
DEM	Digital Elevation Model
EVM	Eigenvector Method

FGD	Focus Group Discussion
FFWC	Flood Forecasting and Warning Centre
GeoTiff	Geostationary Earth Orbit Tagged Image File Format
GIS	Geographic Information System
IWM	Institute of Water Modelling
IPCC	Intergovernmental Panel on Climate Change
ISRIC	International Soil Reference and Information Centre
KII	Key Informant Interviews
LULC	Land Use and Land Cover Change
MCDA	Multi-criteria Decision Analysis
MCDM	Multi-Criteria Decision-Making
NIR	Near Infrared
NDVI	Normalized Difference Vegetation Index
NASA	National Aeronautics and Space Administration
NetCDF	Network Common Data Form
OLI	Operational Land Imager
R	Visible Red
RS	Remote Sensing
SRTM	Shuttle Radar Topography Mission
TIRS	Thermal Infrared Sensor
TWI	Topographic Weightiness Index
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WGS	World Geodetic System

Chapter 1: INTRODUCTION

This chapter outlines the background (section 1.1) and context (section 1.2) of the research as well as its aim and objectives (section 1.3). Next, section 1.4 describes the significance and scope of this research. Finally, section 1.5 includes an outline of the remaining chapters of the Thesis.

1.1 BACKGROUND

Bangladesh is certainly one of the most impressive floodplain and delta areas in the world which is extremely exposed to sea level rise, coastal floods, cyclones, tidal surges, salinity intrusion, erratic rainfall, and drought, causing it to be one of the world's most vulnerable countries to climate change [1]. Among the natural hazards, coastal flooding and cyclonic storm surge have become the most commonly occurring and devastating in coastal Bangladesh. Bangladesh is known to the world as one of the most flood-prone countries in the world due to its unique geographical location [2]–[7]. Catastrophic floods occur once every ten years in Bangladesh; for example, floods in 1987, 1988, 1998, 2004, 2007, 2010, 2011, and 2017 [1]–[3], [5], [8]–[10]. In 1988, 1998, 2004, and 2007 catastrophic floods inundated more than 60% of the country, approximately 100,000 sq. km, for around three months [1], [11].

Usually, a flood is associated with dramatic congestion arising from the intense surface flow and heavy overland runoff caused by higher rainfall in the catchment area. The causes of occurrence and the nature of floods are highly regulated and immensely characterized by an area's climatic condition, hydrological situation, and physical settings. As Bangladesh is mostly a vast flat land with a coastline of 600 km and 50% of the land less than 8 m above sea level, coastal flooding is a common problem in this country, and extensive human, infrastructure, and economic losses could be anticipated [1], [7], [12], [13]. Furthermore, due to global warming, it is predicted that by 2100, the frequency of the most intense cyclones will increase significantly, and the strength of tropical cyclones will increase by 2% to 11% [14], [15]. The low-lying coastal belt of Bangladesh supposes to affect by flood disasters due to increasing global warming, climate change, and massive discharge of upstream water in the rainy season from the neighbouring country [2], [15]–[17].

Bangladesh's coastal areas are frequently inundated as a result of cyclone-induced storm surges and occasionally due to high water levels in the rivers caused by heavy rainfall in the upstream catchments of Ganges, Brahmaputra, and Meghna [18], [19]. These coastal floods are causing large numbers of fatalities and significant asset damage, as they often run deep with high flow velocities and powerful waves in densely populated areas. They also strike without warning, leaving vast populations vulnerable, with little or no time for warning and evacuation [20]. In response to this, there are only 123 polders, each encircled by earthen dikes built to protect the inland from flooding due to high tides in the coastal area of Bangladesh [18], [21]. These dikes' existing crest levels typically provide flood protection to a certain degree of flooding severity [22]. Cyclone-induced storm surges, i.e., Sidr (2007), Nargis (2008), Aila (2009), Mahasen (2013), Komen (2015), Roanu (2016), Mora (2017), Fani (May 2019), Amphan (May 2020), and Bulbul (November 2019), etc. in coastal Bangladesh caused fully or partially collapse of these dikes, resulting in flooding within the protected zones, property destruction, and casualty [18], [23]. Though the number of tropical cyclones and coastal flood-related damage and deaths casualties has declined dramatically from 2007 to 2020, the socio-economic effect of floods has increased as a result of demographic shifts, with agricultural and property losses accounting for a more significant part of total losses [24]–[29].

So far, there is no established correlation between inundation patterns and different climate change and meteorological circumstances as well as with the population dynamics. Furthermore, non-structural flood risk management measures, i.e., land-use zoning based on a flood risk map and a probabilistic flood map to pinpoint vulnerable areas, are unavailable in most of the coastal regions of Bangladesh [30]. The flood risk assessment supposes to reduce flood risk through mitigation efforts and better prepare for future flood threats by formulating flood management plans and policies at the national, regional, and local levels [31]. Non-structural strategies, such as land-use zoning with flood risk maps, can reduce flood risk and damage in the coastal zone and structural measures [18], [30], [32]. An assessment of coastal flood risk and vulnerabilities based on individuals' perceptions and experiences would provide more valuable insights for designing and implementing an effective flood management plan [3]. Additionally, a comprehensive spatial assessment of flood risk is also essential to produce a flood risk map by identifying and zoning the areas under flood risk to support mitigation strategies. Moreover, the rapid advancement of satellite-based technologies enabled the decision support system to develop accurate flood risk maps for effective flood management plans. Therefore, a comprehensive flood risk assessment was critical for the safety and security of lives and properties of coastal people by understanding flood exposure, people's socioeconomic vulnerability to floods, and their capacity to respond to floods [15]. In this situation, the aim of this research was to develop a comprehensive assessment and mapping of coastal flood risk along with vulnerable group and area identification in central coastal Patuakhali district. The findings of this study would help planners and policymakers in identifying the priority areas for planning any future flood management strategies in coastal Bangladesh.

1.2 CONTEXT

Bangladesh, a riverine nation, has been experiencing floods more frequently than ever in recent years as a result of its geomorphological, geographical, demographic, and socioeconomic characteristics [1], [2]. The Ganges, Brahmaputra-Jamuna, and Meghna rivers, which are all a part of the Himalayan drainage system, meet at the country's geographic center [8], [33]. Every year, substantial amounts of silt are deposited along river banks and in floodplains, continuously modifying the massive delta at the mouth of the Bay of Bengal and raising flood frequency and intensity [8]. Moreover, the increased volume of rainfall caused by climate change during recent years has intensified the flood problem in coastal Bangladesh [12]. This increasing trend in the frequency, intensity, and longevity of floods due to increased amounts of precipitation will also continue in the near future [22], [34], [35].

Additionally, the emissions of greenhouse gases are contributing to global warming, which is melting glaciers and raising sea levels. Global warming could lead to a rise in sea level by several tens of centimeters in the next 50 years and about one meter in the century [2]. Because of projected increases in rainfall intensity and sea level rise, the intergovernmental panel on climate change (IPCC) predicts that the frequency and magnitude of floods in many coastal regions around the world will increase; particularly low-lying coastal areas of Bangladesh are highly vulnerable to this effect [2], [17]. Bangladesh has experienced cyclones and several coastal floods in the past as a result of rising sea levels and climate change. The river's water level was above the danger level during the major floods that occurred in Bangladesh in 1987, 1988, 1994, 2007, 2010, 2011, and 2017 and caused a great deal of hardship for those who lived along its floodplain [3], [10].

The study area Patuakhali district is one of the most flood-prone areas of Bangladesh where almost every year flood takes place and the people of the area live the vulnerability of this natural hazard [132], [133], [134]. Furthermore, due to coastal flooding, the Global Facility for Disaster Reduction and Recovery (GFDRR) has rated the Patuakhali district as highly vulnerable [36]. They predict that the shoreline will be flooded by potentially damaging waves at least once in the next ten years. Besides, the probability, frequency, and magnitude of coastal floods are anticipated to increase in this region due to the risk of sea level rise and altering patterns of cyclonic storm events as a result of climate change scenarios [15]. Additionally, due to the geographical location and dense population, coastal flooding has a negative impact on human habitats and livelihood. The poor are more at risk from these floods and storm surges because they lack the resources to take protective measures and have a limited capacity to deal with the loss of property and income. The assets at risk from flooding can be enormous and include private housing, transport, public service infrastructure, commercial and industrial enterprises, and agricultural land [12]. They recommended developing an immediate action plan to reduce the risk of coastal floods and taking into account the impact of coastal floods at various project stages to manage flood risk effectively [36].

However, due to various structural and non-structural flood management measures done by the government, flood-related fatalities have dropped dramatically in recent years [2], [18], [21]. The socioeconomic impact of floods has increased as a result of demographic changes, with agricultural and property losses accounting for a larger portion of total losses even though the number of flood-related deaths has dramatically decreased from 29,375 in the 1970s to 2,404 in the 2017s [3]. Additionally, the number of existing coastal flood control structures in Bangladesh is not adequate to protect the coastal area in the upcoming days and new measures are urgently necessary. Moreover, insufficient water regulation facilities and lack of proper maintenance of these flood protective structural developments such as protective embankments and polders along the coastlines have been frequently blocking the excessive amount of freshwater coming from upstream areas during winter causing water congestion and coastal flooding [11], [37]. Most importantly there is still a lack of the proper integration of non-structural flood risk reduction measures with different flood protective structures in coastal Bangladesh for that maximum flood protection hasn't been ensured from these structures. These also lack sectoral and vulnerable area-specific flood risk assessment and risk management plans in coastal Bangladesh.

It is crucial to create an integrated flood risk management plan for coastal Bangladesh in order to overcome these challenges and safeguard the lives and way of life of residents of coastal Bangladesh. Increased flooding will have negative socioeconomic effects on human populations and their activities if there is no adequate plan in place to mitigate the danger of flooding. Therefore, flood risk assessment and comprehensive flood risk mapping was essential task for the formulation of an efficient flood management plan by understanding flood hazard, exposure, vulnerability, risk, and the capacity to respond to frequently occurring floods [1], [32]. Flood risk assessment plays an important role in reducing the loss from flood events through building resilience and increasing capacity to the effects of coastal flooding as well as build understanding on how flooding is likely to alter in the near future [3], [34].

Several researchers around the world have conducted several investigations till now to understand the vulnerabilities of flood risks. Some researchers predominantly used bio-physical indicators and people's perceptions for flood risk assessment and mapping [38], [39]. Some researchers have assessed and mapped flood risk by the combination of spatially available data and hazards and vulnerability index within a GIS and Remote sensing-based interface [40]–[44].

Though the world's research on flood risk assessment and mapping is quite advanced, it has been growing in a number of studies in Bangladesh for flood risk assessment and mapping. For example; Gain, et al. [45] employed an integrated approach to quantify flood risk in Dhaka's eastern section, including hazard, vulnerability, and tangible, intangible, direct, and indirect damage estimates. Another researcher investigated the livelihood and climatic vulnerability of the Jamuna River's riparian people in Bangladesh [46]. Brouwer, et al. [47] conducted another study on flood risk, this time concentrating on the susceptibility and adaptive coping mechanisms of households and the greater community. Islam, et al. [18] assess flood risk in the coastal area of Bangladesh due to cyclone-induced dike breaching. Another research by Mondal, et al. [3] estimated the flood risk to riverine households in the Teesta River of Bangladesh. Recently, Paul and Sakib [48] also conducted a study on the western coastal Bagerhat, Khulna, and Satkhira districts of Khulna to assess tropical cyclone risk using geospatial modeling with the help of AHP. They developed a comprehensive cyclone risk map and divided the total area into different risk categories in order to assist mitigation methods.

There also carried out some scientific studies on flood risk and vulnerability assessment in combination with the flood risk assessment using satellite imagery in Bangladesh. Islam, et al. [49] and Islam and Sado [50] assessed flood risk and vulnerability for a total of Bangladesh. Tingsanchali and Karim [51] have assessed flood risk for the southwest region, and Hoque, et al. [52] have assessed flood risk for the northeast region. Another research monitored the 2004 flood event using ground data, RADARSAT imagery, and GIS in the Meghna River basin in Bangladesh [53]. While Bhuiyan and Baky [54] have assessed flood risk for Sirajganj district, Dewan, et al. [55] assessed flood risk for Dhaka city using GIS and Remote sensing-based techniques. Researchers also used different hydrological and hydrodynamic modeling for the estimation of flood risk [56],

[57]. Another group of researchers, estimated climate-induced flood inundation using open-source SWAT and HEC-RAS model for the RCP8.5-SSP5 scenario for the Arial Khan River of Bangladesh [58].

Despite a large amount of existing scientific studies that have been conducted in Bangladesh for the assessment and mapping of flood risk, almost all of these studies were conducted in the south-eastern region, central region, and mid-south region of the country. Until now, no specific study has been carried out at the southernmost flood-vulnerable Patuakhali district for the assessment of coastal flood risk as well as mapping most vulnerable areas which can help the decision-makers and authority to better anticipate flood risk and to develop an appropriate coastal flood management plan. In general, everyone who is at risk of flooding makes the best precautions they can to protect their lives and property, but it is always the government authorities' responsibility to undertake comprehensive flood risk assessment studies and to create and implement a flood risk management strategy [36], [37]. But regrettably, the coastal municipality and any other government authorities haven't yet carried out any in-depth flood risk assessment in the coastal Patuakhali district, despite having a sufficient amount of experience and theoretical knowledge about the concepts and methods of historic coastal flood risk management in the coastal region.

1.3 AIMS AND OBJECTIVES

The overall objective of this study was to make coastal community informed about the actual hazard, vulnerability, capacity, and risk scenario of coastal flood and help decision-makers and government authorities to take appropriate measures to mitigate these risks. Here risk has been seen as a combination of hazard, exposure, and vulnerability of flood events. The specific objectives of this study are:

- to develop a comprehensive assessment of coastal flood risk in coastal Patuakhali;
- to categorize and map the most vulnerable areas exposed to the possibility of coastal flooding using GIS and Remote sensing;
- to identify potential measures for coastal flood risk reduction

For the accomplishment of the objectives of this research following research questions were considered:

- ✓ What are the existing flood hazards in the study area?
- ✓ What are the existing flood vulnerabilities in the study area?
- ✓ What is the extent of flood risk in the study area?
- ✓ What are the consequences of historic flood depth and duration in the coastal area?
- ✓ Which area is more vulnerable due to coastal flooding?
- ✓ Which mitigation measures, both structural and non-structural, are most effective in reducing the adverse impacts of floods?
- ✓ What actions are supposed to protect the coastal area from frequent coastal flooding?

1.4 SIGNIFICANCE AND SCOPE OF THE STUDY

Although most of the areas of Bangladesh are frequently affected by devastating floods, the southernmost coastal Patuakhali district of Bangladesh is the most vulnerable to coastal flooding as a result of its dynamic characteristics, climate change-induced sea level rise, and massive upstream water discharge [132], [133], [134]. As the intensity and frequency of flood occurrences increased and the country's overall flood status is rapidly deteriorating year after year, the nation must deal with the loss and destruction caused by this regular natural calamity. A series of rigorous scientific research and investigation activities should be conducted in this condition to comprehend the actual flood risk, risk priority area identification, and capacity against flood, as well as flood's various dimensions and behavior in coastal Bangladesh. For the assessment and mapping of flood risk, some previous scientific research has been conducted in Bangladesh but most of them were bounded at the south-eastern, central, and mid-south region of the country. However, no area-specific study has been done to date for a thorough evaluation of coastal flood risk and mapping of the most susceptible and flood-prone locations in the coastal Patuakhali district, where floods practically occur every year and cause significant losses and property devastation.

In addition, the majority of studies on flood and cyclone risk assessment in Bangladesh relied either on secondary data on flood risk and vulnerability, GIS and RS-based methodologies, or assessments based on people's perceptions of the risks. Whereas, a combination of public perception, experience, and professional knowledge on the occurrence, likelihood, exposure, striking season, impact, and susceptibility of flood events along with existing flood management capability with the wide range of available geospatial techniques and modeling would be very useful to assess coastal flood risk assessment. Moreover, people's perception, experience, and expert opinion-based flood risk assessment and risk mapping studies also failed to properly use local people's experience and knowledge to bring out appropriate indigenous flood mitigation strategies for coastal areas. But since these coastal indigenous people have lived in the coastal area for a long time and have experienced and fought against the majority of the devastating flood events, they would be more helpful for better understanding the actual flood risk of coastal areas and will offer more useful insights for designing and implementing flood management plans.

Though several studies have been conducted over the world to conduct flood vulnerability and risk assessment combining people's perceptions and geospatial technology, there is a lack of these kinds of studies in Bangladesh, especially the central coastal Patuakhali district. Additionally, there is a gap in the comparison of flood risk results obtained using geospatial techniques with perception-based approaches. These gaps, issues, and inappropriate methodologies in the previous literature had an inspiration to conduct a detailed flood risk assessment and flood risk mapping study in the coastal Patuakhali district. To address all these gaps, this study was designed for comprehensive assessment and mapping of coastal flood risk along with vulnerable group and area identification through the combination of both the people's perception-based risk assessment method and GIS and RS-based advanced techniques.

In this study, coastal peoples' perception and experiences of flood hazard, vulnerability, and capacity as well as their indigenous flood protective strategies helped a lot to better anticipate the actual flood risk of this area. This study's developed flood risk map also helped to identify the most flood-vulnerable areas using GIS and Remote sensing-based techniques. Finally, this integrated assessment provided a better understanding on the past, present, and future changing nature of coastal flood occurrence and its consequences in different parts of the district which will ultimately help better prepare for and manage the present as well. Moreover, as the coastal government and NGO authorities already have much experience in tackling coastal flood events previously, this detailed flood risk and vulnerabilities as well as flood risk mapping identifying the most vulnerable areas will provide them with more useful insights for designing and implementing an effective flood management plan. This study's findings will undoubtedly bring flood mitigation and planning to a new level for all stakeholders involved as well as will play an important role in the effective management of flood risk in coastal Bangladesh and taking decisions regarding any development activities in the coastal flood risk zones.

1.5 THESIS OUTLINE

Chapter 1 provides a comprehensive overview of the research, outlining its background, context, aim, objectives, significance, scope, and the remaining chapters of the thesis, followed by a detailed outline of the remaining chapters.

Chapter 2 reviews background literature relating to the concept and recognized of hazard, risk, vulnerability, and risk assessment; different types of floods that occurred in Bangladesh; the actual reasons for huge flood and coastal flood vulnerability in Bangladesh; previous flood risk assessment studies; and flood risk mapping studies using GIS and RS based technologies.

Chapter 3 describes the study area, research design, sampling, data collection, and research procedures. The methodology framework for flood risk assessment using people's perception and GIS and RS-based flood risk mapping is also briefly discussed in this chapter.

Chapter 4 describes all the result of this study concerning furnishing evidence to research question(s) as outlined in Chapter 1 where section 4.1 presents the demographic and socio-economic profile of the respondents; section 4.2 outline results summary for the hazard, vulnerability, capacity, and risk assessed; section 4.3 presented and described developed coastal flood risk for Patuakhali district along with all the prepared variables maps, and finally in section 4.4 this study proposed some structural and non-structural flood mitigation strategies.

Chapter 5 makes a structural discussion, meaningful interpretation, and critical evaluation of the significance of the results described in the previous chapter. This study's estimated coastal flood risk for Patuakhali district along with their GIS and RS-based map of flood risk is critically evaluated here with reference to previous pieces of literature. Finally, the effectiveness of all suggested flood risk mitigation strategies is also discussed in this chapter.

Chapter 6 summarizes the contents discussed in the introduction, methodology, results, and discussion section. It also contains general and key findings, conclusions, practical implication and limitations of this present study as well as direction and recommendations for future studies.

Chapter 7 provides a comprehensive bibliography of cited references from various sources, including journal articles, books, websites, and newspapers. This chapter ensures that readers can easily access the sources used in constructing the background and supporting the findings of this study.

Chapter 8 at the end of this study contains all the additional and supplementary information in three individual appendices that supports the findings and arguments of this study but too long or too detailed to include in the main body. Appendix A demonstrates the household survey questionnaire form, Appendix B provides the checklist used for the MCDA-AHP pairwise comparisons and Appendix C details the flood risk estimation for this study.

Moreover, this study includes a total of five footnotes using a superscript number to provide supplemental information such as additional examples or clarifications on a given topic where necessary.

Chapter 2: LITERATURE REVIEW

This chapter begins with a historical background (section 2.1) and reviews the literature on hazard, risk, vulnerability, and risk assessment (section 2.2); floods and coastal floods in Bangladesh (section 2.3); floods and coastal floods vulnerability in Bangladesh (section 2.4); analysis of previous flood risk assessment published studies (section 2.5); and previously published literature on GIS and RS based flood risk mapping (section 2.6). Section 0 highlights the implications of the literature and develops the conceptual framework for the study.

2.1 HISTORICAL BACKGROUND

Bangladesh is known as one of the most flood-prone countries in the world due to its geomorphological setting. Every year several flood events occurred in this country and the intensity and magnitude of these floods vary from year to year [1], [3], [8], [11], [30], [49], [51], [55], [59]. All historic floods of 1984, 1987, 1988, and 1998 were exceptional because of their area coverage and the destruction they caused. The flood event in 1998 has been called "the flood of the century' where around two-thirds of the country was inundated under water for a prolonged period [2], [11]. The damage caused by these floods was triggered by the high population density in the coastal area and the lack of combined structural and non-structural flood mitigation strategies [2]. Cyclonic storm-induced coastal floods caused significant loss of life and property and about 49% of the world total of deaths due to cyclones occurred in Bangladesh alone. If the climate change scenario and potential sea level rise combined with present cyclonic activity, the ferocity and extent of damage from different natural disasters like cyclonic storm-induced coastal flooding might increase and the coastal area of Bangladesh may suffer even more [2].

Floods in Bangladesh affected the total country including coastal areas. Cyclone and storm-induced coastal floods are solely attached to the coastal area in Bangladesh. The damage and casualties caused by the cyclone and severe cyclonic storm surge-induced flooding in Bangladesh are listed in Table 2.1.

Table 2.1 Casualties of the tropical cyclone and storm surge induced flooding [24]–[29], [60]–[63]

Event	**Maximum wind speed km/hr.**	**Maximum storm height (m)**	**Overall casualties**	**Casualties in coastal Patuakhali**
Sidr	260	5	3,500 deaths, 8.9 million affecting people, 55,000 physical injuries, impacted 2.30 million households, and 10007.65 km^2 of crops damaged	Caused 94 deaths, 96 disability, 1678 injuries and 3247 affected families. Fully impacted 9.11 km^2 and partially impacted 1.62 km^2 of cropland and damaged 12,970, households.
Aila	120	4	190 deaths, affected 40 million people, 7103 physical injuries and 7,000 km of road damaged, 500,000 houses were destroyed, and more than 230 km^2 of crops destroyed	Caused 5 deaths, 6 disability, 145 injuries and 5750 affected families. Fully impacted 9.74 km^2 and partially impacted 2.43 km^2 of cropland, and damaged 17,703 households.
Mahasen	85	3-3.5	17 deaths, 1.3 million people affected	Caused 1 deaths, 3 disability, 3 injuries and 500 affected families. Fully impacted 0.15 km^2 and partially impacted 56.74 km^2 of cropland, and damaged 2500 households.

Table 2.1 Casualties of the tropical cyclone and storm surge induced flooding (cont'd)

Event	Maximum wind speed km/hr.	Maximum storm height (m)	Overall casualties	Casualties in coastal Patuakhali
Komen	85	2	132 deaths, 510,000 houses damaged, 2700.148 km² crops of fields destroyed, and 2.6 million people affected	Affected 2,200 people and 440 household where 240 households required external assistance
Roanu	129	3	26 deaths, 40,000 houses damaged, 1,10,684 families were partially and 29,168 fully affected	1 death and 400 affected people. 1100 families were partially and 400 fully affected
Mora	130	2	9 deaths, 81 missing fishermen, 52,000 houses damaged and 3.3 million people affected	-
Fani	215	-	17 deaths, 832 injuries, 214.4834 km² of crops, and 13,000 houses damaged	20 villages flooded, 11 injuries, 2092 houses and 10 km embankment damaged, 3,300 tube-wells and 30 latrines were damaged
Amphan	180	3-5	26 deaths, 111.43 km embankment and 440 km of road damaged, 205,368 houses damaged and 2.6 million people affected	6 deaths, 40508 houses damaged, breach 1.92 km, and failure 17.26 km of embankments
Bulbul	130	3	25 deaths, 0.73 million people affected, 57970 household affected, 154291 houses damaged, and 1170 km² of crops affected	8 upazila affected, 2 deaths, 13759 people affected, and 3000 to 4000 houses destroyed,

Table 2.1 Casualties of the tropical cyclone and storm surge induced flooding (cont'd)

Event	Maximum wind speed km/hr.	Maximum storm height (m)	Overall casualties	Casualties in coastal Patuakhali
Yaas	150	1.8-2.4	1.30 million people affected, 26,000 houses destroyed, and inundated thousands of acres of cropland	waterlogged 223 villages, 3-kilometer dam washed away,41 km embankment damaged partly. Damaged 1500 fish farm worth of BDT 300 million

2.2 FLOODS AND COASTAL FLOODS

Usually, a flood is a situation or event where the water from different surface water sources flows beyond their normal limit and caused the presence of water on land that is normally dry [34]. Bangladesh generally experiences floods every year and based on their source of occurrence these floods are generally divided into four types and those are flash floods, rain-fed surface floods, river floods, and coastal floods [11], [30], [69]. The flood zonation map provides a clear idea about the aerial view of different flood occurrences (Figure 2.1) [11].

Flash floods generally occurred within a few minutes to a few hours' time period by the rapid rise and fall in the water level and lasting from several hours to a few days. Northernmost, north-central, and northeastern hilly areas of Bangladesh are generally affected by flash floods. These areas are lying downside of the hilly catchments of Bangladesh and India and due to heavy rainfall in both Bangladesh and Indian catchment area or only in India, the runoff quickly flow to Bangladesh's downstream part and caused flash flood [11], [30]. Rain-fed surface flood occurs due to excessive rainfall over an extended period of time and is triggered by different urban infrastructure, for example, poor drainage system leads to water clogging during intense rainfall and water flows out into streets and nearby structures. This type of flood also occurs in the Gangetic delta areas where most of the natural drainage systems have been disturbed due to different human activities e.g., the construction of unplanned rural roads and illegal occupation of river courses [11], [30].

River flood is the most commonly occurring flood phenomenon in Bangladesh. Normally 25-30% of land is inundated during monsoon season every year but during extreme river flood event 50-70% of the country are inundated [11], [30]. River flooding occurs due to heavy monsoon rainfall and melting snow in the upper catchment areas of the major rivers [11], [30]. Finally, Coastal flood mostly occurs along the extended 800 km coastline in the southern part of the country. Coastal floods are generally caused by cyclonic storm surges, sea level rises, and any other severe weather conditions which push water onshore that overwhelm low-lying land and become a serious threat to life and property [11], [30], [70].

A coastal flood is a potentially damaging flood event (or multiple events), that may cause damage to buildings and infrastructure in coastal regions, and/or the loss of life, injury, property damage, social and economic disruption, or environmental degradation. Coastal flood hazards are characterized by location, intensity, duration, frequency, and probability [34]. Coastal floods can originate from a variety of sources or a combination of sources which includes climate change-induced sea level rise, cyclones, high tides, storm surges, heavy rainfall, upstream river flows, and land use changes. The flood zonation map adopted from Choudhury, et al. [11] (Figure 2.1) reveals that, the coastal region of Bangladesh including Patuakhali district is frequently affected by tidal or coastal flooding. It also provides a clear idea about the aerial view of the overall flooding scenario of Bangladesh during historic flood in 1988.

Figure 2.1 shows the flooded area of this country after the 1988 catastrophic flood, the worst in Bangladesh's history, which occurred in August and

September. The flood submerged 61 districts, covering of the 164 km^2 area which is the 68% the total area, and affected 4.55 million people [71]. The extreme flood lasted nearly 90 days, causing widespread destruction and widespread destruction [72]. According to estimates, the 1988 flood caused damage to a total of 14,000 institutions and 400,000 houses, respectively [71]. The 1988 floods were primarily caused by heavy monsoon rainfall over the Ganges and Brahmaputra river catchments [72]. Actually, in 1988, the Brahmaputra-Jamuna River was 50 km wide, surrounded by Barind and Madhupur Tracts, while the Ganges River experienced narrower flooding. Moreover, The Jamuna River's backwater flooding extends beyond the Lower Atrai Basin, with less significant flooding in the north-east during the rainy season [73].

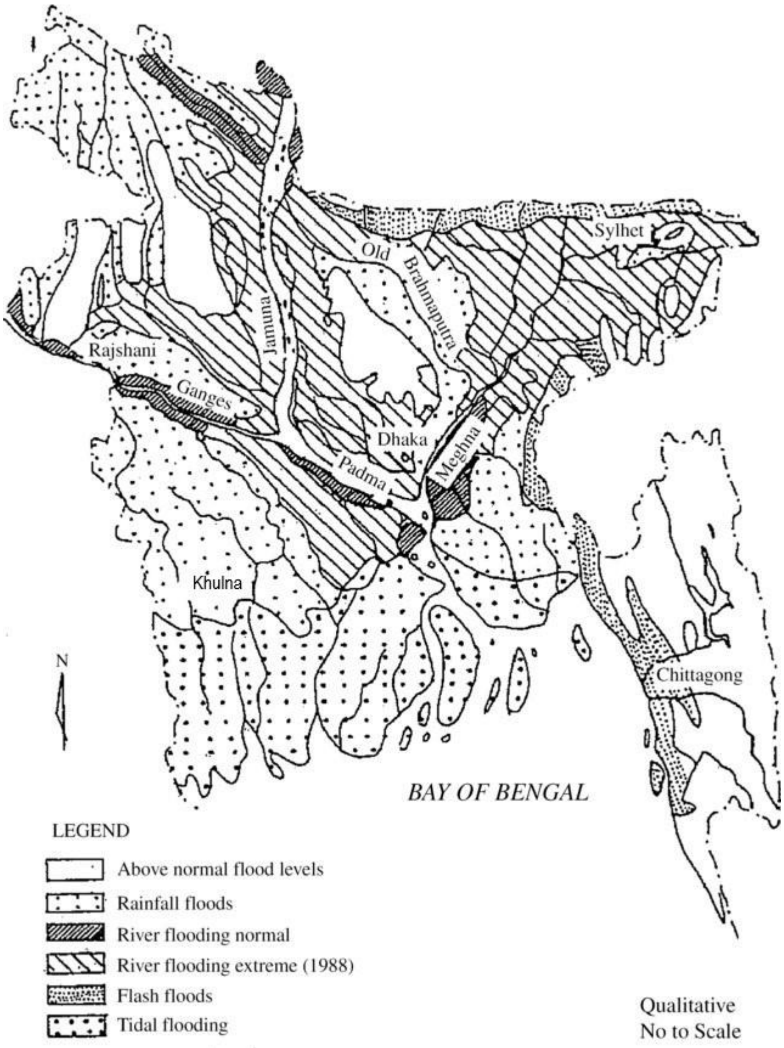

Fig. 2.1 Flood zonation map of Bangladesh in 1988 [11].

Coastal Patuakhali district is the most southern area of Bangladesh located near the Bay of Bengal is frequently impacted by coastal tidal flooding over the year. Coastal floods pose a significant threat due to the combination of storm surge, tides, river inflow, and waves, resulting in severe damage. In the recent past, flooding induced by tropical storms Aila, Sidr, Mohasen, Komen, Fani and Bulbul have affected this district and had substantial negative impacts on the lives, livelihood and property of coastal people as well as on the coastal infrastructure [60]. In September 2021, Patuakhali town and its surrounding areas under Kalapara, Rangabali, Golachipa, Dashmina, Baufal, and Mirzaganj upazilas experienced three to four feet of tidal water [74]. Moreover, In September 2022, heavy rain and tidal surges caused water to enter low-lying areas of Patuakhali, submerging them due to breaking embankments [75]. Over 50 villages including Chailabunia, Charmontaj, Kawkhali of Rangabali upazila, Charborhan, Bashbaria of Dashmina upazila and Lalua and Champapur of Kalapara upazila have been flooded due to this heavy rain and tidal surges.

2.3 HAZARD, RISK, VULNERABILITY, AND RISK ASSESSMENT

Generally, hazard is a potentially damaging physical event, phenomenon, or human activity that may cause the loss of life, injury, property damage, social and economic disruption, or environmental degradation [34]. Hazard usually refers to the possible future occurrence of any events that could have serious adverse effects on the vulnerable communities or areas at risk including loss of life, injury, other health impacts, damage or loss to property, infrastructure, livelihoods, ecosystems, and environmental resources [15], [16], [64], [65].

On the other hand, vulnerability refers to a set of physical, social, economic, and environmental conditions which exposed humans, communities, assets, or systems to suffer adverse effects when impacted by hazard events [15]. Understanding the level of flood vulnerability is an essential task as flood impacts different communities, people, and areas according to the degrees of their vulnerability [66]. The vulnerability of people, communities, and their systems can have three distinctive components e.g., exposure, susceptibility, and limited resilience. Exposure refers to physical vulnerability, susceptibility refers to socio-economic vulnerability and limited resilience refers to limited existing capacities e.g., lack of access to and mobilization of resources within the community [64], [67].

Risk is the combined function of the occurring probability of an event and the potential consequences of that event if occurs. Risk occurs only when and hazard event interacts with the vulnerable condition of the individual, community, system, and assets [34]. Risk refers to the possibility or likelihood of damage caused by the interaction of hazards and the vulnerability of systems, communities, or areas [64]. The risk is a combination of the likelihood or consequences of a hazardous event and the probability of occurring that hazardous event [16], [68]. Coastal flood risk is the combination of the probability (likelihood) of a coastal flood hazard event (or multiple events) and the associated negative consequences [34]. In this thesis, risk is mainly described as an interaction between coastal flood hazards and the vulnerability aspects of coastal communities.

Risk Assessment is a method to determine the nature and extent of risk by analyzing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed buildings, infrastructure, people, property, services, livelihoods, and the environment on which they depend [34]. Usually, risk assessment and mapping process is comprised of a series of activities, firstly, the review of different hazard characteristics e.g., location at risk, intensity, duration, frequency, and probability of the risk followed by the vulnerability and sensitivity analysis which includes physical, social, economic and environmental dimensions of vulnerability and lastly the capacity analysis of the extend of the capacity of the system, community and individuals to stand with if any disaster occurred hazard [34].

2.4 VULNERABILITY DUE TO FLOODS IN BANGLADESH

The riverine country Bangladesh has been experiencing floods more frequently than ever before in recent years due to its geo-morphological, demographic, and socio-economic character. As the country is located at the confluence of three main rivers: the Ganges, Brahmaputra-Jamuna, and Meghna, all of which are part of the Himalayan drainage system [8], [33], [76]. Additionally, it exaggerates a sophisticated river network that spans 370 km and takes up around 6% of the land. One significant aspect of the rivers is that 57 of them are across international borders, coming from Myanmar and India. These river systems drain a catchment of about 1.72 million km^2, out of which only 7% is located in Bangladesh and the rest 93% of the catchment is situated outside in China, India, Nepal, Bhutan, and Myanmar [76], [77].

Large amounts of silt are deposited along river banks and in floodplains every year, continuously changing and reshaping the massive delta at the mouth of the Bay of Bengal, increasing the frequency and intensity of floods [8]. It's crucial for Bangladesh since more than 93% of the upstream catchment area of the river systems of Bangladesh is located outside the country. Neglecting the significance of the massive flow from upstream basins could lead to erroneous flood estimates [76], [78], [79]. Additionally, the fact that the northeastern area of the country is bounded by the Himalayan range in the north and the southeastern region is encircled by extensions of the Arakan mountain ranges in the east and the Bay of Bengal in the west make it considerably more prone to flooding. Flooding in downstream northeastern Bangladesh, including the Sylhet and Netrokona districts and southern coastal plains of Barishal and Cox's Bazar belt areas, is caused by heavy rainfall in these southeastern mountains or considerable snow melt in the Himalayas [11], [30].

Coastal areas typically have the most dynamic ecosystems, and they are significant globally in terms of social, economic, and environmental factors. Most coastal nations are forced to rely on their coastal areas for both economic activity and tourism [67]. Due to extensive economic and tourism dependence there happened urbanization and infrastructure development made sudden changes in the coastal settlements and land use which ultimately made coastal areas more vulnerable to flooding events [34], [67]. The primary source of flood risk in the coastal Patuakhali district is from the Bay of Bengal where a lot of cyclonic storms are generated every year. Moreover, the majority of coastal land here is less than 4-7 m above mean sea level which is located between the extensive drainage network of the Ganges-Brahmaputra-Meghna River system on one side, and tidal and cyclonic activity from the Bay of Bengal on the other side which makes this area more vulnerable to frequent flooding [11], [77].

Since bringing the coastal area of Bangladesh under the protective embankments, coastal low-lying lands have been also protected from regular tidal inundation and salinity intrusion. On the other hand, because there lack of a proper water regulation system in place, these embankments continue to prevent an excessive amount of freshwater from arriving from upstream areas and an excessive amount of rainfall in the upstream area during the rainy season, which causes water congestion and coastal flooding [11]. Furthermore, the majority of Bangladesh's newly constructed feeder road network along the coast was not built with proper planning and design; as a result, it frequently lacks the necessary drainage infrastructure, such as culverts, bridges, and regulators, which now contributes more to coastal flooding [37], [80].

Furthermore, due to climate change the frequency and magnitude of flood events have been increasing all over the world and coastal areas are particularly at risk of flooding events now [6], [37], [81], [82]. With global warming causing a rise in sea levels, the vulnerability of coastal towns of Bangladesh to flooding risk during storms has increased [79]. Bangladesh is highly susceptible to sea level rise, with estimates from the World Bank indicating a 2%, 4%, and 17.5% increase in sea levels by 2020, 2050, and 2100 [83]. The Department of Environment's project, "Projection of Sea Level Rise & Assessments of its Sectoral (Agriculture, Water & Infrastructure) Impacts," indicates that the coastal area of Bangladesh experiences a sea level rise rate of 3.8-5.8 mm per year over the past 30 years [84], [85]. The study predicts that by the end of this century, 12.34%-17.95% of Bangladesh's coastal areas will be submerged in the sea due to rising sea levels [84], [85].

At present, 3.5 million people in Bangladesh are at risk of river flooding due to rising sea levels and intensifying monsoon seasons, making it one of the world's most vulnerable areas [86]. Climate experts predict that by 2050, rising sea levels will submerge 17% of the Bangladesh's land and dispense with 20 million people [87]. Bangladesh's coastal area and flood plain zone will be severely impacted by a one-meter sea level rise, with coastal resources, water resources, agriculture, and the ecosystem being most vulnerable [83]. Despite seasonal floods being a common occurrence in the country, climate change-driven sea level rise in Bangladesh is causing more frequent and intense floods, particularly in low-lying coastal areas in the Bay of Bengal [87]. Flooding by tropical cyclones will also increase in the future as a result of sea level rise (SLR) [88]. SLR and sea surface temperature (SST) will affect the cyclone-induced storm surge height in the Bay of Bengal [89]. In combination with these coastal embankments, several factors which are triggered under the changing climate including enhanced glacier melt in the Himalayas, the possibility of enhanced monsoon precipitation, and the possibility of an increase in intensity of cyclones are likely to contribute to increased flood risk that could be further exacerbated in coastal Patuakhali [37]. In addition, some areas of Bangladesh have experienced more precipitation due to the monsoon regime. As a result, floods will become more frequent, more intense, and last longer in the next decades [35]. Hence, a sustainable flood management plan considering climate change impact is necessary for Bangladesh.

2.5 PREVIOUS FLOOD RISK ASSESSMENT STUDIES

Coastal areas around the world are the most resourceful and have the most dynamic ecosystem hence a large number of the world's population lives there. But these areas are frequently affected by small to large-scale coastal flooding which has a massive threat to the population, infrastructure, and coastal ecosystems that exist there [90]. Therefore, the management of coastal flood risk should receive increased attention from all stakeholders, including the scientific community, policymakers, governments, and local indigenous people.

In order to effectively manage flooding, successful flood risk assessment is a crucial prerequisite [1]. At the national, regional, and municipal levels, flood risk assessment is now acknowledged as a crucial component for developing flood control plans and policies [31]. Coastal Flood Risk Assessments (CFRAs) offer a way to analyze the likelihood and effects of flooding occurrences, which are crucial in the development of coastal flood management and flood mitigation strategies that direct decision-making for the design of flood-resistant structures and infrastructure [34]. The impacts of floods can be reduced significantly through holistic flood risk management where risk assessment is the first step of flood risk management. Flood risk assessments provide a rigorous, logical, and defensible understanding based on which contributes on investment, planning, and design decisions [34].

Moreover, assessing the current risk of flooding is fundamental to understanding how it could change in the future [3]. While risk assessment provides crucial evidence for designing and implementing risk reduction measures, its measurement is very complex. Though the local community and individuals at risk of flood should take their level best preparations to protect their life and property from flood risk, the actual responsibility is to the responsible government authorities to conduct an overall flood risk assessment study and to formulate and execute the flood risk management plan [91], [92]. During recent years many initiatives have been taken and several scientific studies have been conducted all over the world to assess flood risk including coastal flood risk at both local, regional, national, and global levels are described in the Table 2.2.

Table 2.2 Summary of previous flood risk assessment studies

Reference	Tools and method used	Findings	Limitations
Roy, et al. [58]	IPCC AR5 risk framework incorporating vulnerability and exposure. Physics-based traditional numerical models -SWAT and HEC-RAS	✓ Measured potential flood depth, flood duration, flood area, flood hazard and risk ✓ Provide more reliable flood hazard and risk results for the Arial Khan River under future climate change scenarios ✓ Some medium-hazard zones fall into high-risk zones due to high exposure and vulnerability to flooding	✓ Used SWAT model has several parameters and model simplifications that introduce uncertainty in the basin mode
Islam [18]	Hydrodynamic model	✓ Inundation pattern in a protected area behind dikes due to floods caused by storm surges ✓ Possible critical locations of dike breaches ✓ Inundation extent and damage due to flooding corresponding to the developed scenarios ✓ Flood risk map ✓ Probabilistic flood map	✓ Lack of data on the existing conditions and previous history of breaching of the dike ✓ The effect of mangrove forest could not be determined ✓ For damages, exclusion of indirect damages

Table 2.2 Summary of previous flood risk assessment studies (cont'd)

Reference	Tools and method used	Findings	Limitations
Sazeed, et al. [5]	Statistical analysis of historical cyclone data and Digital Elevation Model	✓ Modelled storm surge inundation depth and spatial extent of inundation for Patuakhali district ✓ Results show that inundation in some places exceeds 6m excluding the tidal heights and sea level rise issues. ✓ The occurrence of a 100-year return period cyclone will cause 48.5% of the study area to be submerged under water	✓ The research was dependent on high resolution DEM ✓ Features like embankment, polder, etc were not incorporated into surge model ✓ Tidal height was not considered in the calculation of storm surge height
Monrat, et al. [94]	Belief rule-based expert system (BRBES)	✓ Visualized the real time flood risk ✓ Explored the challenges, opportunities and methods, required to leverage the potentiality of Big Data and BRBES to assess the risk of flooding	✓ Flood risk assessment required Big data ✓ These big data sources contain various types of uncertainties because of the presence of incomplete and inaccurate information
Nishat [93]	Warmest projection (RCP 8.5)	✓ Flood inundation map of the Brahmaputra River floodplain of Bangladesh ✓ A significant increase of high to very high hazard and risk zone by the end of 2100 under RCP8.5	✓ Considered only Brahmaputra river basin and it should be investigated for other flood-vulnerable rivers of the country as well

Table 2.2 Summary of previous flood risk assessment studies (cont'd)

Reference	Tools and method used	Findings	Limitations
Haque [33]	Input-Output model	✓ Results indicate that Dhaka, Rajshahi and Sylhet are more vulnerable to flood disasters compared to coastal regions ✓ Dhaka and Rajshahi faced major output loss, while Sylhet faced noteworthy income and employment loss due to flood disasters ✓ The study finds Barisal as the least affected region ✓ Loss of output and employment is maximum for agriculture sector for any region	✓ Data constraints
Gain, et al. [45]	Integrated flood risk assessment approach incorporating hazard, exposure and social dimensions	✓ Assessment of tangible, intangible, direct, and indirect categories of flood damages considering physical hazards and social vulnerabilities	✓ Exclusion of stakeholders during social and physical dimensions measurement.
Gain and Haque [70]	Geoprocessing tools and a Hydrodynamic model	✓ Flood hazard maps of the Balu-Tongikhal River system within the eastern part of Dhaka City are prepared ✓ Assessed expected damages of various land-use classes for different floods caused	✓ Only measured damage from the river flood (Balu Tongikhal River system) rather than combined effect from rainfall and internal drainage system

Table 2.2 Summary of previous flood risk assessment studies (cont'd)

Reference	Tools and method used	Findings	Limitations
Bhuiyan and Dutta [2]	Hydrodynamic model with combination of surface and river parts	✓ Estimated possible effects and spatial variability of sea level rise on floods in the coastal zone of Bangladesh ✓ Changes in flood characteristics between now and under sea level rise ✓ Estimated impact on population, infrastructure, and transportation	✓ -

National Research Council Canada provides a detailed guideline for the Coastal Flood Risk Assessment (CFRA). This guideline is very helpful for coastal flood-prone areas of Canada to properly conduct the coastal flood hazard and risk assessments to support appropriate design and rehabilitation of buildings and infrastructure. An effective way to engage a broad level of stakeholders, partners, and local people is the coastal flood risk assessment also demonstrated in this guideline [34]. Percival and Teeuw [64] conducted micro-scale level research in the UK to detailed assessment and mapping of coastal flood vulnerability and risk. They capture both pre and post-impact attributes of coastal flood vulnerability in order to understand detailed flood risk, which results in an opportunity to prepare for and adapt to future flood events at the local level.

Hadipour, et al. [67] tried to assess coastal flood risk by integrating three key flood risk components, hazard, social vulnerability, and exposure using a GIS-based spatial multi-criteria decision analysis approach in Bandar Abbas, Iran. To establish the role of people's capacity depending on social vulnerability, they also apply an analytical hierarchy process (AHP) model to weigh indicators of hazard, exposure, and social vulnerability components. In their investigation, they identified 14.8% of eastern, western, and central city areas at high and very high risk of flooding.

In Bangladesh, recently a researcher [94] developed a belief rule-based expert system (BRBES) to assess real-time flood risk in Chattogram, Bangladesh using a big data platform. His developed belief rule-based expert system has the capability of processing and visualizing coastal flood risk scenarios in real-time from the big data collected from different sensors. Another research [70] used an integrated approach to assess flood risk in the eastern part of Dhaka city by combing hazard, vulnerability, and tangible, intangible, direct, and indirect estimations of damages. Another recent study [46] assessed the livelihood and climate vulnerability of the riparian communities of the Jamuna River in Bangladesh.

Bhuiyan and Dutta [2] also conducted a study to analyze the vulnerability and impacts of coastal floods in the coastal zone of Bangladesh due to potential sea level rise. For this assessment, they use a hydrodynamic model combining surface and river areas for future flood simulation maps. They used a range of future sea level rise scenarios and estimated flood impact on the population, building infrastructure, and transportation facilities [2]. Additionally, Brouwer, et al. [47] investigated flood risk by focusing on the vulnerability and adaptive coping mechanisms of households and the larger community.

Despite the large amount of existing literature, there is still a scarcity of scientific literature on household-level flood risk assessments for riverine areas, which are usually located in hard-to-reach areas. Due to the scarcity of data on flood hazards, exposure, and vulnerability, effective riverine flood risk reduction policies and programs cannot be formulated [39]. However, a comprehensive and detailed flood risk assessment in the coastal Patuakhali district is absent still now. Therefore, understanding people's perception of their available measures and own capacities is critical, since people act upon their subjective perception rather than objective capacity.

Multi-Criteria Decision Analysis (MCDA) is a crucial method for analyzing complex decision problems, particularly in assessing flood risk. This approach considers multiple criteria and objectives, enabling decision makers to identify critical hazards and prioritize actions to reduce flood risk [95], [96]. Now a days, MCDA-based spatial decision mapping have become practical for administrators and planners to address ground-level flood management issues, considering cost and time effectiveness [97]. Among different MCDA techniques, Analytical Hierarchy Process (AHP) has become most widely used, popular, and recognized tools for analyzing complex spatial decision problems such as flood risk assessment and mapping in recent years [95], [97], [98]. AHP is a semi-quantitative decision-making approach that aids in group decision-making by breaking down problems into hierarchy structures [99]. It was developed by Satty in 1977 and uses a preference matrix to calculate weighting factors, comparing relevant criteria against each other with reproducible preference factors. This method allows planners to use their experience and knowledge effectively [99].

GIS-based AHP is a powerful tool for analyzing flood risk in specific regions and creating flood risk maps [98]. The AHP is a versatile and potent tool that ranks user-provided criteria and options based on pairwise relative evaluations, ensuring flexibility and power [95]. The AHP method was chosen for assessing flood risk in the coastal Patuakhali district due to its widespread use, ease of understanding, cost-effectiveness, and practical significance [98]. This method offers a precise way for calculating the weights of choice criteria and is a systematic method for analyzing complex judgments [96]. Further, the AHP method can be used specifically for flood risk assessment and mapping to achieve optimal decision-making in this study [97]. Additionally, AHP will aid in determining the relative significance and ranking of relevant influencing factors after constructing a pairwise-comparison matrix [100]. Again, the AHP method offers extensibility and robustness, allowing decision makers to modify, add or eliminate relevant criteria as needed [101]. Moreover, numerous researchers have utilized the AHP supported by some additional techniques such as GIS and AI techniques to analyze the flood risk assessment in their region and found it to be very useful in flood susceptibility studies [95], [98]–[102].

2.6 FLOOD RISK MAPPING USING GIS AND RS-BASED TECHNOLOGIES

Though the world's research on future flood hazard and risk assessment is quite advanced, it has hardly been investigated in Bangladesh. But in recent times researchers put much focus on the assessment and mapping of present and future flood risk using geospatial technologies in Bangladesh. Recently a study [48] on western coastal Bagerhat, Khulna, and Satkhira districts of Khulna tried to assess tropical cyclone risk levels using geospatial modeling with the help of AHP. They developed a comprehensive cyclone risk map and divided the total area into different risk level categories in order to assist mitigation methods. According to them, 37.31% of the area was in the high-risk zone and 4.77% area was in the very high-risk zone [48]. Another study [3] recently estimated the flood risk to riverine households in the Teesta River of Bangladesh.

On the other hand, another research [93] developed the flood inundation map of the Brahmaputra River floodplain of Bangladesh for the warmest projection (RCP 8.5) considering the upstream basin-scale flood input from the Brahmaputra basin. Another piece of research [58] quantified the integrated flood risk assessment under changing climate using the IPCC AR5 risk framework for the Arial Khan River. Further, a study [2] was also conducted in the coastal zones of Bangladesh for the assessment of flood risk and impact due to sea level rise using hydrological and hydrodynamic modelling. They found maximum flood depth in the Barishal and Patuakhali districts which are 40 and 53 cm respectively due to the 88 cm sea level rise scenario [2]. On the other hand, Islam, et a. [18] assess flood risk in the coastal area of Bangladesh due to cyclone-induced dike breaching.

Moreover, there also have been carried out a number of studies in Bangladesh using GIS-remote sensing and satellite imagery at the national [49], [50], regional [51], [52], and local levels [54], [55] for the assessment and mapping of flood risk and vulnerability. The summary of methods used, findings and limitations of these studies are described in the Table 2.3.

Table 2.3 Summary of previous GIS and RS based flood risk mapping studies

Reference	Tools and method used	Findings	Limitations
Siam, et al. [103]	Hybridized Deep Neural Network (DNN) and fuzzy AHP models	✓ Assess national-scale flood risk of Bangladesh ✓ About 20.45% of Bangladesh are at the moderate, high, and very high flood risk zones ✓ North-eastern region, and areas adjacent to the Ganges-Brahmaputra-Meghna rivers, have high flood damage potential	✓ Considered only 1 flood event due to the unavailability of long-term flood observation data at the national level
Hoque, et al. [52]	RADARSAT remote sensing, GIS and ground data	✓ Created maximum water extent map, inundation area, flood hazard and damage areas map ✓ Explored large inundation areas in the Maghna River Basin, around the north-eastern Bangladesh	✓ Estimation of the inundation area using RADARSAT satellite data and ground data had some inconsistencies
Das, et al. [108]	GIS and RS based HEC-RAS 1D/2D Couple Model	✓ Quantified the future flood hazard of the Surma-Kushiara River system	✓ Overlooking upstream basin runoff from the Meghna Basin

Table 2.3 Summary of previous GIS and RS based flood risk mapping studies (cont'd)

Reference	Tools and method used	Findings	Limitations
Sayed and Haruyama [71]	An integrated of GIS and remote sensing approach	✓ Measured flood risk and flood return period of Dhaka city ✓ 70% of Greater Dhaka district within moderate to very high hazard zone, especially surrounding city like Manikganj Sadar Upazila areas	-
Dewan, et al. [55]	GIS and RS Techniques, Synthetic Aperture Radar (SAR) data, ranking matrix in three-dimensional multiplication mode	✓ All possible combination of flood hazard maps was prepared using land-cover, geomorphology and elevation heights for flood-affected frequency and floodwater depth	✓ Unavailability of GIS data in digital format
Islam and Sado [50]	NOAA-AVHRR images with GIS and RS	✓ Flood hazard map for Bangladesh and a flood risk map for the administrative districts of Bangladesh ✓ 7.50% of areas are at very high risk and 16.34% are at high risk. ✓ The capital city also lies in a high-risk area	-
Gazi, et al. [105]	Multicriteria Evaluation (MCE), AHP, GIS and RS	✓ Flood hazard and flood susceptibility mapping in the food prone north-eastern part of Bangladesh ✓ Identified high, moderate and low flood potential zones ✓ Flood-susceptibility map categorized ~4241 km^2 (~ 20% area) area as the highest flood potential zone	✓ Lack of distinct LULC classes identification ✓ High resolution DEM ✓ Use of mouza wise village data

Table 2.3 Summary of previous GIS and RS based flood risk mapping studies (cont'd)

Reference	Tools and method used	Findings	Limitations
Hoque, et al. [106]	Spatial multi-criteria-integrated approach using geospatial techniques, Analytical Hierarchy Process (AHP)	✓ Spatial vulnerability mapping, spatial extents and levels of vulnerability and individual vulnerability component maps of Kalapara upazila ✓ The eastern and south-western portions of the study area are highly vulnerable to floods due to low elevation, closeness to the active channel and more social components than other parts	✓ Collecting quality and up to date spatial data for each criterion at the local level was highly challenging ✓ Lack of high spatial resolution topographic data, such as LIDAR
Hossain and Adhikary [107]	MCDA, AHP, GIS and RS	✓ Identified the flood susceptible zones in the six administrative districts (Khulna, Satkhira, Pirojpur, Bagerhat, Jhalokati, and Barguna) ✓ 318 km^2 (2%), 1553 km^2 (10%) 3556 km^2 (23%), 7190 km^2 (47%) and 2784 km^2 (18%) areas were in the very low, low, moderate, high risk flood susceptible zone respectively	✓ Didn't consider all the coastal areas of Bangladesh
Gain, et al. [45]	GIS and RS, HEC-RAS hydrologic model,	✓ Measured flood risk, hazard, vulnerability, exposure, susceptibility, coping and adaptive capacities for eastern part of Dhaka city including tangible and intangible costs ✓ Suggested an improvement of current early warning system for significantly reduces all damages (direct-indirect-tangible-intangible)	✓ Did not explicitly model future climate change impact including uncertainty

Table 2.3 Summary of previous GIS and RS based flood risk mapping studies (cont'd)

Reference	Tools and method used	Findings	Limitations
Ha-Mim, et al. [104]	AHP, MCDM, GIS and RS	✓ Generate comprehensive maps of flood-induced risks and vulnerability in the Barguna district ✓ The flood risk of the study area is quantified as very high (168 sq. km, 12.91%), high (321 sq. km, 24.74%), moderate (368 sq. km, 28.37%), low (316 sq. km, 24.37%), and very low (125 sq. km, 9.61%) ✓ Categorized southern and north-eastern parts of the study area as higher risk of potential flooding	✓ Considered only Barguna district for assessing flood risk
Zzaman, et al. [97]	AHP and Analytical Network Process (ANP), MCDA, GIS and RS	✓ 0.71 million people were prone to "very high" flood because of its lowland morphology, mild slope, and high drainage density ✓ 39% of roads, 43% of farming lands, and 25% of education buildings were observed to lie in the highest flood-prone area	✓ Considered equal weightage for all 12 factors ✓ Validation accounted only one single flood ✓ Limit the exposures to only people and physical elements

2.7 SUMMARY AND IMPLICATIONS

2.7.1 Summary

Bangladesh, a highly flood-prone country, experiences numerous annual flood events, with their intensity and magnitude varying from year to year due to its geomorphological setting. The Coastal Patuakhali district of Bangladesh, located at the edge of Bay of Bengal, is highly susceptible to catastrophic flooding, making it a significant challenge for the nation to protect its coastal settlements. Cyclone-induced storm surges in coastal Bangladesh have caused the collapse of embankments, leading to flooding, property damage, and casualties in protected zones, as seen in several recent storms such as Sidr, Nargis, Aila, Komen, Roanu, Mora, Fani, Amphan, and Bulbul. From 2007 to 2020, tropical cyclones and coastal flood-related damage and deaths have decreased significantly, but the socio-economic impact of floods has increased due to demographic shifts, with agricultural and property losses accounting for more. Efforts to mitigate the impact of these events limited to the construction of embankments and the implementation of early warning systems, but further measures are needed to effectively protect the coastal communities. All the secondary literatures on floods, flood vulnerability, damage, flood risk assessment and flood risk mapping has been discussed in this study are summed up within some critical subheading below;

Causalities of Flooding in the Coastal Areas of Bangladesh

- Bangladesh alone has experienced 49% of the world's total deaths due to cyclones and storm surge induced flooding
- Historic cyclone Sidr, Aila, Mahasen, Roanu, Bulbul and Amphan caused countrywide 3500, 190, 94, 17, 26, 26, death and 5, 1, 1, 2, 6 death respectively in the coastal Patuakhali district only
- In September 2021 and 2022, Patuakhali town and its surrounding areas experienced 0.92 to 1.22 meter of tidal water

Hazard of Coastal Flooding in Bangladesh

- Beside regular seasonal floods, climate change-driven SLR in Bangladesh is causing more frequent and intense floods, especially in low-lying coastal areas in the Bay of Bengal
- The primary source of flood risk in the coastal Patuakhali district is from the Bay of Bengal where a lot of cyclonic storms are generated every year

- Bangladesh's newly constructed feeder road network along the coast, largely unplanned and poorly designed, often lacks necessary drainage infrastructure like culverts, bridges, and regulators, contributing to increased coastal flooding

Risk of Coastal Flooding in Bangladesh

- The coastal land of Bangladesh is less than 4-7 m above mean sea level situated between the extensive drainage network of the Ganges-Brahmaputra-Meghna River system and tidal and cyclonic activity from the Bay of Bengal, making it more susceptible to frequent flooding.
- Coastal floods, triggered by storm surge, tides, river inflow, and waves, pose a significant threat and cause severe damage.
- Bangladesh is highly susceptible to sea level rise, with estimates from the World Bank indicating a 2%, 4%, and 17.5% increase in sea levels by 2020, 2050, and 2100
- 3.5 million people in Bangladesh are at risk of river flooding due to rising sea levels and intensifying monsoon seasons

Vulnerability of Coastal Flooding in Bangladesh

- Several geo-morphological, demographic, and socio-economic character made this country extreme vulnerable to flooding events
- 370 km long sophisticated river network of Bangladesh drains a catchment of about 1.72 million km^2, out of which only 7% is located in Bangladesh and the rest 93% of the catchment is situated outside in China, India, Nepal, Bhutan, and Myanmar and flow rate is out of control for these cross-boundary rivers

- Urbanization and infrastructure development have led to sudden changes in coastal settlements and land use, increasing vulnerability to flooding events in coastal areas
- Rising sea levels due to global warming have heightened the risk of flooding in coastal Bangladesh

Flood Zoning Map of Coastal Bangladesh

- Coastal Patuakhali district, located in Bangladesh's southern region near the Bay of Bengal, is frequently affected by cyclone induced tidal flooding throughout the year.
- Moreover, this area also experienced floods originates from a variety of sources or a combination of sources which includes climate change-induced SLR, heavy rainfall, upstream river flows, and land use changes.

Flood Risk Assessment Studies in Bangladesh

- Integrated flood risk assessment approach, Hydrodynamic model, Belief rule-based expert system (BRBES), Geoprocessing tools, Input-Output models are the commonly used tools for flood risk assessment in Bangladesh
- Most of the flood risk assessment studies conducted in Bangladesh lacks incorporating people's perception, experience, and expert knowledge
- There is still a scarcity of scientific literature on household-level flood risk assessments for riverine areas, which are usually located in hard-to-reach areas.

Flood Risk Mapping Studies in Bangladesh

- Most of the flood risk mapping studies conducted in Bangladesh only considered 1 flood event or smaller area due to the unavailability of long-term flood observation data at the national level
- They also lack combining people's perception, experience, and expert knowledge with the available wide range of geospatial techniques and modeling

2.7.2 Implications

Most of the studies conducted in Bangladesh and its coastal area for flood and cyclone risk assessment used either GIS and RS-based approaches or people perception-based assessment or based on available secondary data on flood risk and vulnerability. But, it would be very critical and useful to combine people's perception, experience, and expert knowledge with the available wide range of geospatial techniques and modeling to assess coastal flood risk assessment. As the indigenous people living in the coastal area for a long period and experiencing most of the devastating floods event, they would help for better understanding the actual flood risk of coastal areas and would provide more useful insights for designing and implementing flood management plans. Though several studies have been conducted over the world to conduct flood vulnerability and risk assessment combining people's perceptions and geospatial technology, there is a lack of these kinds of studies in Bangladesh, especially the central coastal Patuakhali district. There is also a lack of a fact-based comparison between the flood risk result getting from a perception-based approach and geospatial techniques. Additionally, most of the flood risk assessment studies conducted in Bangladesh have failed to establish a meaningful relationship among hazard, vulnerability, risk, and capacity.

Moreover, all of the existing flood risk assessment and mapping studies in Bangladesh have been conducted in the south-eastern, central, and mid-south regions of the country. So far quite a few studies have been conducted in the coastal region, especially in the Patuakhali district for the assessment of coastal flood risk as well as mapping the most vulnerable areas for the management of coastal flood risk. Additionally, for better understanding of the dynamics of present and future flood risks, which will ultimately help to prepare and mitigate flood risks, a broad-scale and detailed assessment of the coastal flood risk is therefore necessary under the projected climate change scenario and for the huge population that lives and engages in socioeconomic activity there. Finally, though coastal Bangladesh has experienced several historic flood events and the government and NGOs have much experience in tackling coastal flood events, there is still a lack in the construction of detailed and constructive flood risk management and response plans for coastal Bangladesh. Therefore, keeping all these issues and gaps in the previous literature, this study tried to make a comprehensive assessment and mapping of coastal flood risk for the coastal Patuakhali district through an integration of both the people's perception-based risk assessment method and GIS and RS-based advanced techniques.

Chapter 3: MATERIALS AND METHODOLOGY

This chapter describes the adopted method in this research to achieve the aims and objectives stated in section 1.3 of chapter 1. Starting with a flow chart, this chapter discusses the methodology used in the study, implementation, and the research design; section 3.1 provides a brief description of the study area; section 3.2 provides a conceptual framework of this study's methodology as well as research materials; section 3.3 details the methodology flood risk assessment; section 3.4 details the methodology flood risk mapping; finally, section 3.5 details the sampling procedure and participants in the study.

3.1 STUDY AREA DESCRIPTION

The study area, Patuakhali district, is located on the southern central coast of the Bay of Bengal, which is seriously affected by climate change-induced coastal flooding [109], [110]. The district is geographically located between the 21°48′ and 22°36′ North Latitudes and between 90°08′ and 90°41′ East Longitudes [5] (Figure 3.1). The lands are composed of alluvial soil deposits of the Meghna Basin and several char lands (riverine island) located in the southeast [111]. The average height from the sea surface ranges between 3 to 3.5 m, while average temperatures are highest at 33.3°C and lowest at 12.1°C. Being a district open to the ocean in the south, it has been very frequently affected by cyclones and associated storm surges [5]. Farmers and fishermen make up the majority of the population. Tourism and shrimp culture are other important economic activities. The Ministry of Land of Bangladesh divides land usage into four categories: rice fields, settlements, shrimp ponds, and water bodies (rivers and canals) [111]. As most of the people are engaged in the agricultural and fisheries sector here, the impact of frequently occurring floods and other natural calamities experienced here most. For this reason, this area was selected for the empirical part of this research.

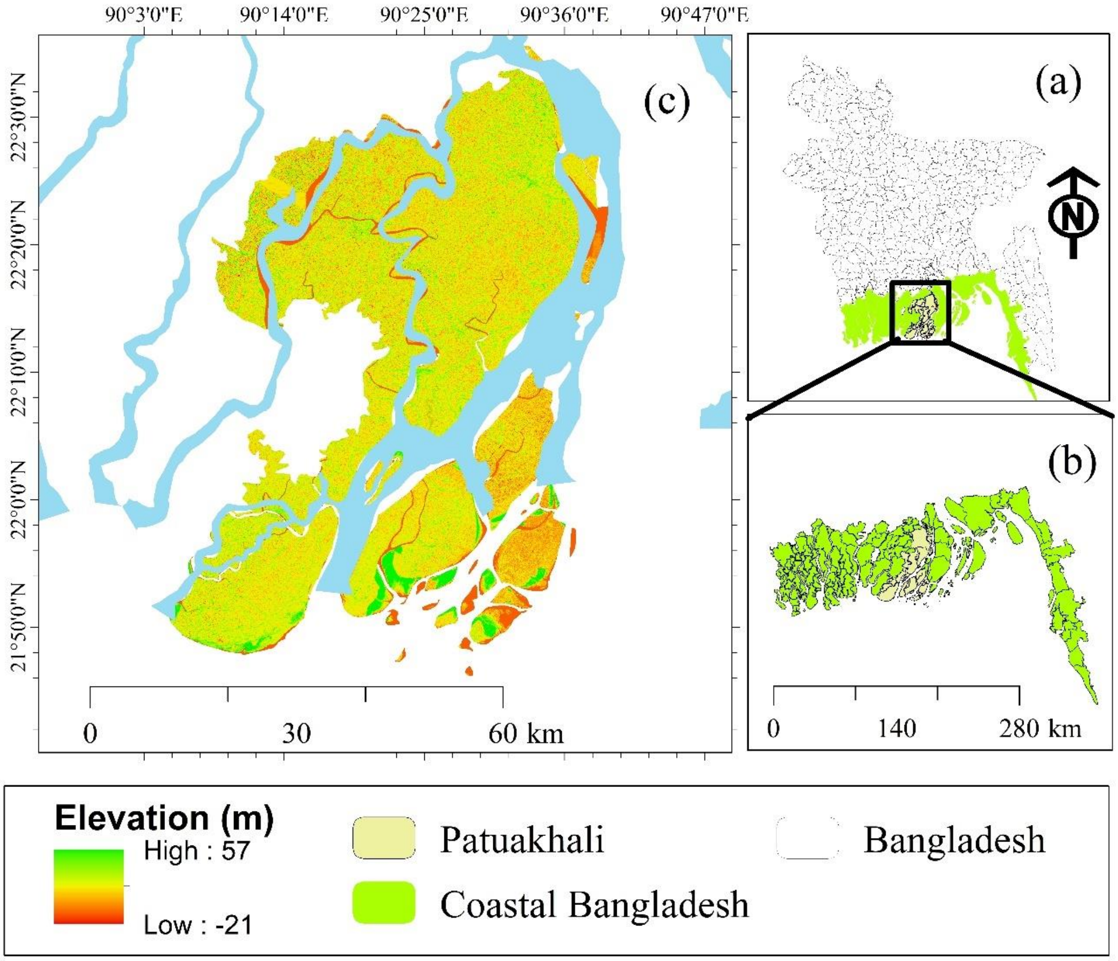

Fig. 3.1 The study area (Patuakhlai district) (a) in Bangladesh Map, (b) in coastal belt of Bangladesh, and (c) Patuakhali district

3.2 MATERIALS AND RESEARCH DESIGN

This study comprehensively assessed flood risk in the coastal Patuakhali district based on individual respondents' perceptions of flood hazard, vulnerability, and capacity along with available secondary data. The methodological framework of this research was based on risk identification, risk analysis, risk prioritization, and risk management (Figure 3.2) [34]. After the identification of flood risk and element at risk, risk analysis was performed by the combination of flood hazard, vulnerability to flood, and capacity to absorb flood risk.

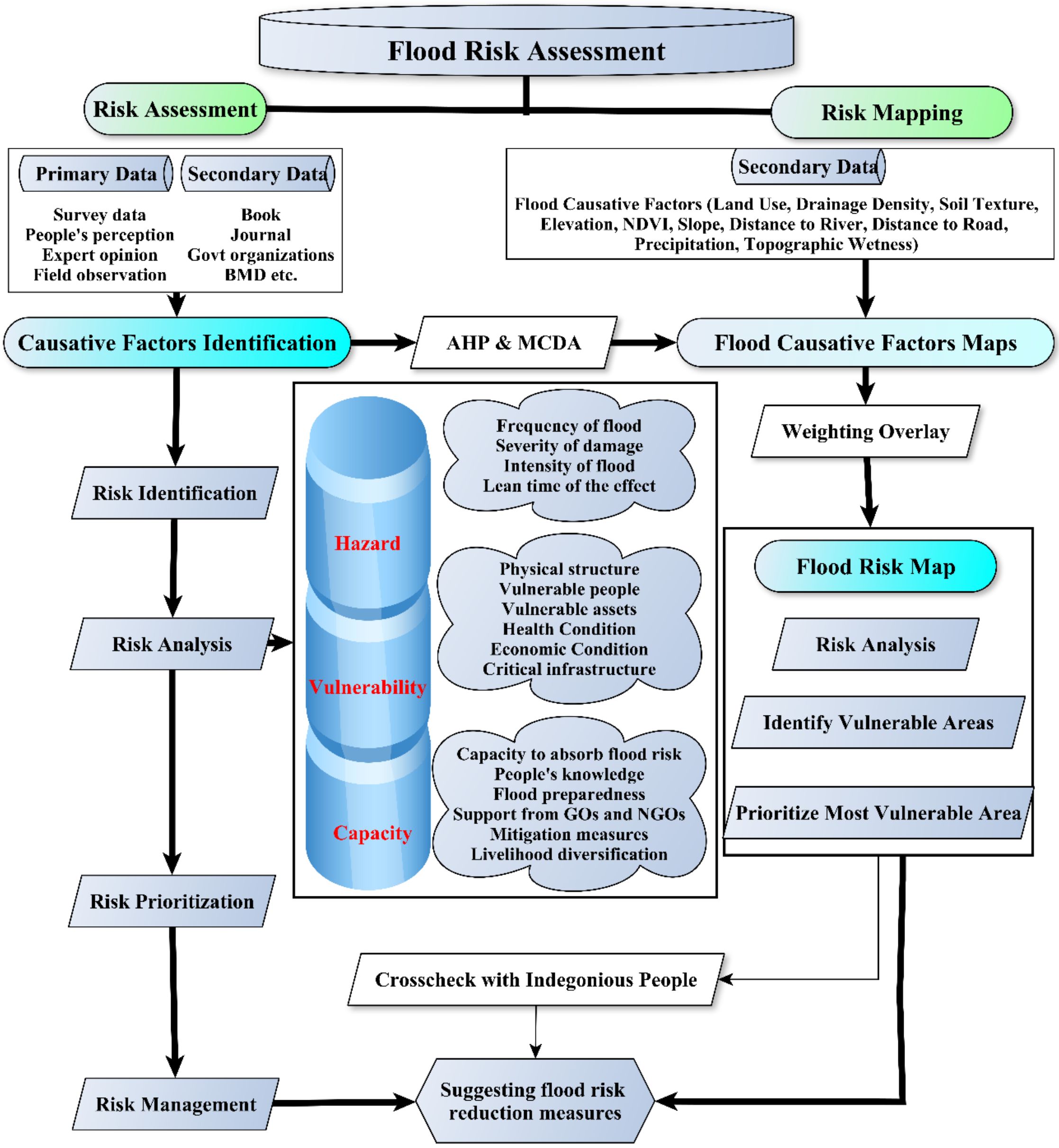

Fig. 3.2 Conceptual framework of flood risk assessment

Several indicators and criteria were evaluated for flood hazard, vulnerability, and capacity assessment. This study also developed a flood risk map identifying the most vulnerable areas using GIS and Remote sensing-based techniques. This study further incorporated a comprehensive Multi-Criteria Decision Making (MCDM) analysis with the help of the Analytic Hierarchy Process (AHP) for the flood risk mapping at the coastal Patuakhali district [67], [97], [107], [110]. Different hydro-geomorphological factors those play very important roles to control the flooding scenario in this district were considered for this study. Among all, this study mainly used ten hydro-geomorphological flood influencing variables and these are: land use and land cover, drainage density, soil texture, digital elevation, NDVI, slope gradient, distance or proximity to streams, distance to roads, annual rainfall and Topographic Wetness Index (TWI) for the mapping of coastal flood risk zone [67], [81], [107]. After the most vulnerable area and risk prioritization, this study formulated potential flood risk reduction measures for coastal Bangladesh based on respondents' perceptions, expert opinions, and a review of historical coastal flood events.

3.3 FLOOD RISK ASSESSMENT METHODOLOGY

3.3.1 Data Collection

The present study's investigation methodology involves the multistage complex analytical procedure of analysis and experimentation. Both primary and secondary data sources were extensively used in this study. The primary data was deposited to understand the people`s perception of flood risk and vulnerability. On the other hand, the secondary data was used to reveal the various hydrological situation, physiographic conditions, population settlement, preparation of vulnerability index, and analyze the risk of the study area. To assess respondents' perceptions of flood hazards, their vulnerability, and their capacity to mitigate flood risk, a stratified random sampling method was applied during a household survey where an adequate number of respondents from the coastal Patuakhali district of Bangladesh were interviewed. A semi-structured questionnaire was designed by considering various indicators used to collect the household data. The household-level face-to-face survey was developed in the form of a close-ended questionnaire with a few open-ended options. The questionnaire was divided into four different sections, highlighting (i) the socio-economic characteristics of the respondents; (ii) perception, knowledge, and attitude related to coastal flood hazards and vulnerability; (iii) household assets and livelihood strategies; and (iv) their coping strategies for flood risk reduction (Appendix A).

Required qualitative and in-depth information was collected through Key Informant Interviews (KII), Focus Group Discussion (FGD), life history, and transact walk. A semi-structured interview schedule was followed for KII to collect expert knowledge from the head of the villages, chairmen[1] of different Union Parishad[2], male and female members from the other union, members of disaster management committees, volunteers of the Red Crescent Society, religious leaders, teachers, fisherman, farmer, private sector and communities. The secondary data required for this section were collected from different journals, reports, research papers, websites, and government and non-government organizations, i.e., Disaster Management Bureau, Patuakhali Zila Parishad, Upazila Disaster Management Committee (UDMC), Food, Agriculture, Family Planning, Hospital authorities, The Bangladesh Bureau of Statistics (BBS) and local NGO's, etc. The spatial topographic and hydrologic data (flood data, elevation data, precipitation, soil, population and settlement data, etc.) required for flood risk mapping and zoning were obtained from a wide variety of sources including the United States Geological Survey [112], NASA Shuttle Radar Topography Mission (SRTM) [113], ISRIC World Soil Information [114], OpenStreetMap [115], and Climatic Research Unit (University of East Anglia) [116].

3.3.2 Flood Risk Assessment

Assessment of flood risk was done after passing through some sequential stages. Flood risk assessment involved the evaluation and mapping of flood hazards, identification of the elements at risk of flooding and their vulnerability

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[1] Administrative head of the Union. Every union parishad is headed by a chairman, and the inhabitants of the respective union directly elect chairman for five years terms.
[2] Union parishad, also known as union council, rural council, rural union and simply union, is the smallest and oldest rural administrative and local government unit in Bangladesh.

to a flood, formulation of flood risk-reducing measures, and finally, including flood risk mapping and flood vulnerable area prioritization [4], [117]–[119]. The sequential process given below was strictly followed for the flood risk assessment in this study:

Step 1: Flood hazard assessment was determined by scoring the frequency of flood, the severity of the damage, probability of flood occurrence, lean time of the effect, predictability of the flood hazards, etc. which are the criteria of flood hazard with a unique numeric number each. After that, the score of all codded criteria was summed up and then divided by the total score by the total number of the criteria.

Step 2: Flood vulnerability assessment was very much similar to hazard assessment. This was done by using different criteria of vulnerabilities, i.e., physical structure, vulnerable people, vulnerable assets, health conditions, economic conditions, the resiliency of the house, socio-economic condition of the people, and condition critical infrastructures, etc.

Step 3: The capacity to absorb flood risk of the at-risk community was assessed by using some criteria, such as people's knowledge, community flood preparedness, support from different GOs and NGOs, the current status of a flood preparedness plan, existing flood mitigation measures, community resource and livelihood diversification option of community people, etc.

Step 4: Finally, coastal flood risk for the study area was estimated by multiplying flood hazard and vulnerability against the capacity to absorb flood risk [64], [106], [120], [121] (Equation 3.1).

$$\text{Risk} = \frac{(\text{Hazard} \times \text{Vulnerability})}{\text{Capacity}} \tag{3.1}$$

Here, Risk = The chance of loss or damage arising when a hazardous element meets with a vulnerable condition.

Hazard = Any object, element, situation, physical event, or human activity that has the potential to trigger loss of life or injury, damage to property, social and economic stress, or environmental degradation.

Vulnerability = The state or condition which is susceptible to damage or loss and in that condition, which is not capable to cope with, withstand and recover from damage or loss.

Capacity = The strengths and resources available within a community, society, or organization that can reduce the level of risk or the effects of a hazard.

Step 5: Potential flood reduction measures were formulated by using card adoption techniques with the participation of community people. During different FGD meetings, community people wrote different measures which they think would be suitable for the flood risk reduction on large colored paper cards of different shapes, colors, and sizes. Illiterate people were helped by the facilitator or other community people to do so without being influenced. When all the cards were displayed, an open discussion was taking place among the community people to select the most appropriate coastal flood risk reduction measures.

3.3.3 Scoring Details for Flood Risk Assessment

For assessing coastal flood risk, this study assigned a score from 0 to 1 for all the response classes of each parameter used in this study based on their contribution to the hazard, vulnerability, and capacity. For example, a higher height of flood water during flood indicates higher risk as there would be higher damage from the higher flood thus a higher score (1) was assigned for the higher flood class and a lower score (0) for lower flood height class of that parameter and vice-versa [107], [134]. Every response class of each parameter was scored using these criteria. The scoring scale 0 to 1 was subdivided into 5 subcategories (0.20, 0.40, 0.60, 0.80, and 1.00) for 5 response classes, 4 subcategories (0.25, 0.50, 0.75, and 1.00) for 4 response classes, 3 subcategories (0.33, 0.67 and 1.00) for 3 response classes and 2 subcategories (0 and 1) for 2 response classes consequently. The scoring criteria and description of the hazard, vulnerability and capacity parameters used in this study for flood risk assessment are described in Table 3.1, Table 3.2 and Table 3.3 respectively.

Table 3.1 Scoring criteria and description of the hazard parameters

Parameters	Response classes	Score	Description
Chance/probability of future coastal flood occurrence	Very High (within a year)	1.00	High future probability indicates high hazard risk
	High (within 3 years)	0.80	
	Moderate (within 5 years)	0.60	
	Low (within 10 years)	0.40	
	Very Low (within 20 years)	0.20	
Likelihood of future damages by coastal floods	Very High (>80%)	1.00	A high likelihood of future damage means high hazard risk
	High (50-80%)	0.80	
	Moderate (30-50%)	0.60	
	Low (10-30%)	0.40	
	Very Low (<10%)	0.20	
Chances of losing coastal people's lives during a coastal flood	Very High (>80%)	1.00	Losing people's lives will increase the hazard risk
	High (50-80%)	0.80	
	Moderate (30-50%)	0.60	
	Low (10-30%)	0.40	
	Very Low (<10%)	0.20	
Maximum height of flood measured above the ground floor	Very High (>3 m)	1.00	Higher the flood height, the higher the hazard risk
	High (1.5- 3 m)	0.80	
	Moderate (0.92-1.5 m)	0.60	
	Low (<0.3 m)	0.20	
Maximum duration of staying in flood water (in days)	Very High (>15 days)	1.00	Long duration of flood water staying will increase the flood hazard
	High (>7 days)	0.80	
	Moderate (6-7 days)	0.60	
	Low (3-5 days)	0.40	
	Very Low (1-2 days)	0.20	
Impacts on the infrastructure	Very High	1.00	Infrastructure has more impact indicating higher hazard risk
	High	0.80	
	Medium	0.60	
	Low	0.40	
	Very Low	0.20	
Impacts on the crop agriculture sector	Very High	1.00	High impact on crop agriculture will increase hazard risk
	High	0.80	
	Medium	0.60	
	Low	0.40	
	Very Low	0.20	

Table 3.1 Scoring criteria and description of the hazard parameters (cont'd)

Parameters	Response classes	Score	Description
Impacts on the fisheries sector	Very High	1.00	High impact on the fisheries sector will increase hazard risk
	High	0.80	
	Medium	0.60	
	Low	0.40	
	Very Low	0.20	
Impacts on the livestock sector	Very High	1.00	High impact on livestock will increase hazard risk
	High	0.80	
	Medium	0.60	
	Low	0.40	
	Very Low	0.20	
Impacts on the sanitation	Very High	1.00	High impact on sanitation will increase hazard risk
	High	0.80	
	Medium	0.60	
	Low	0.40	
	Very Low	0.20	
Impacts on the health sector	Very High	1.00	High impact on the health sector will increase hazard risk
	High	0.80	
	Medium	0.60	
	Low	0.40	
	Very Low	0.20	

Table 3.2 Scoring criteria and description of the vulnerability parameters

Parameters	Response classes	Score	Description
Afraid of coastal floods	Very much Afraid (>80%)	1.00	More afraid people will be more vulnerable
	Afraid (50-80%)	0.80	
	Neutral (30-50%)	0.60	
	Slightly afraid (10-20%)	0.40	
	Not afraid (0%)	0.20	
Proximity to the flood-vulnerable area people live in.	Very Near (<30 m)	1.00	Close proximity to the vulnerable area increases the vulnerability
	Near (30-90 m)	0.80	
	Medium (90-150 m)	0.60	
	Far (150-300 m)	0.40	
	Very Far (>300 m)	0.20	
Population Density in the Coastal flood vulnerable area	High (>1000/km^2)	1.00	More density indicates more vulnerability
	Medium (500-1000/km^2)	0.67	
	Low (<500/km^2)	0.33	
Resiliency status of the community's houses against flood	High	0.33	High resiliency will reduce vulnerability
	Medium	0.67	
	Low	1.00	

Table 3.2 Scoring criteria and description of the vulnerability parameters (cont'd)

Parameters	Response classes	Score	Description
Socio-economic status of the community against flood	Weak Medium Strong	1 0.67 0.33	Weak socio-economic status indicates high vulnerability
Physical structure condition against flood	Weak Medium Strong	1.00 0.67 0.33	The weak physical structure indicates high vulnerability
Household access to tube well during coastal flooding	Yes No	0 1	Assess to drinking indicate low vulnerability
Household access to a toilet during coastal flooding	Yes No	0 1	Assess the toilet will reduce vulnerability
Household access to transportation during coastal flooding	Yes No	0 1	Assess transportation will reduce vulnerability

Table 3.3 Scoring criteria and description of the capacity parameters

Parameters	Response classes	Score	Description
Knowledge about the coastal flood striking season	Good Moderate Poor	1.00 0.67 0.33	Good knowledge will increase the capacity against flood
Receiving forecasting and early warning messages	Yes No	1 0	Early warning will increase the flood preparedness capacity
Alternative livelihood sources/options during the flood	Good Moderate Poor	1.00 0.67 0.33	Alternative livelihood during flood indicates the high capacity
People's capability to cope with the future coastal flood	Very High (>80%) High (50-80%) Moderate (30-50%) Low (10-30%) Very Low (<10%)	1.00 0.80 0.60 0.40 0.20	People's capability to cope with future coastal flood indicate their high capacity
Present status of the community flood preparedness plan	Good Moderate Poor	1.00 0.67 0.33	A good flood preparedness plan will improve capacity

Table 3.3 Scoring criteria and description of the capacity parameters (cont'd)

Parameters	Response classes	Score	Description
People taking shelter during the coastal flood	Shelter School building Roads Relative residence Own residence	1.00 0.80 0.60 0.40 0.20	Taking shelter in a well-structured shelter indicates a high capacity
Presence of active community volunteer groups	Yes No	1 0	Community volunteer groups will increase capacity
Availability of need-based relief during the coastal flood	Yes No	1 0	Getting relief after the flood will increase capacity
Existing govt. the resource to minimize coastal flood risk	Good Moderate Poor	1.00 0.67 0.33	Good government resources will increase capacity
Attending emergency/resiliency training on flood	Yes No	1 0	Attending training will increase people's capacity
Maintenance condition of existing embankment/polders	Very High High Moderate Low Very Low	1.00 0.80 0.60 0.40 0.20	Highly maintained embankment indicates high capacity which will reduce the flood risk
Maintenance of existing sluice gate	Yes No	1 0	Properly maintained sluice gate will increase capacity
Infrastructure conditions to cope with the coastal flood	High Medium Low No	1.00 0.75 0.50 0.25	Good infrastructure condition indicates the high capacity
Alternative livelihood options to cope with the coastal flood	High Medium Low No	1.00 0.75 0.50 0.25	High livelihood diversity indicates the high capacity
Preservation and availability of food to cope with the coastal flood	High Medium Low No	1.00 0.75 0.50 0.25	Preservation of dry food during flood indicates the high capacity
Embankment capacity to cope with the coastal flood	High Medium Low No	1.00 0.75 0.50 0.25	Good embankment condition indicates the high capacity

Table 3.3 Scoring criteria and description of the capacity parameters (cont'd)

Parameters	Response classes	Score	Description
Seed and fertilizer storage to cope with the coastal flood	High Medium Low No	1.00 0.75 0.50 0.25	Availability of seed and fertilizer after flood indicates the high capacity
Availability of relief to cope with the coastal flood	High Medium Low No	1.00 0.75 0.50 0.25	Proper accessibility of relief during flood indicates the high capacity

3.4 METHODOLOGY FOR FLOOD RISK MAPPING

3.4.1 Dataset and Sources

For flood risk mapping using GIS and RS-based approach, this study considered different hydro-geomorphological factors which play very important roles to control the flooding scenario in this district. Among all, this study mainly used ten hydro-geomorphological flood influencing variables and these are: land use and land cover, drainage density, soil texture, digital elevation, NDVI, slope gradient, distance or proximity to streams, distance to roads, annual rainfall and Topographic Wetness Index (TWI) for the mapping of coastal flood risk zone. All the spatial data required for the mapping and analysis of these flood influencing factors were collected from different well-established and reliable sources described in Table 3.4.

Table 3.4 Data sources for flood influencing variables

Data	Details	Data format	Data source	Reference
Land use and land cover (LULC)	Landsat 9 OLI/TIRS of January 2023	GeoTiff	United States Geological Survey	[112]
Drainage Density	From Shuttle Radar Topography Mission (SRTM GL1) Global 30 m data of February 2023	GeoTiff	NASA Shuttle Radar Topography Mission (SRTM)	[113]

Table 3.4 Data sources for flood influencing variables (cont'd)

Data	Details	Data format	Data source	Reference
Soil texture	SoilGrids250m 2017-2003 - Texture class (USDA system)	GeoTiff	ISRIC World Soil Information	[114]
Elevation	Shuttle Radar Topography Mission (SRTM GL1) Global 30 m of February 2023	GeoTiff	NASA Shuttle Radar Topography Mission (SRTM)	[113]
NDVI	Landsat 9 OLI/TIRS (Band 4 and 5) of January 2023	GeoTiff	United States Geological Survey	[112]
Slope	Shuttle Radar Topography Mission (SRTM GL1) Global 30 m of February 2023	GeoTiff	NASA Shuttle Radar Topography Mission (SRTM)	[113]
Distance to streams	OpenStreetMap stream shapefile of February 2023	Shapefile	https://extract.bbbike.org/	[115]
Distance to roads	OpenStreetMap Road shapefile of February 2023	Shapefile	https://extract.bbbike.org/	[115]
Rainfall	Gridded time-series dataset from 2011-2020	NetCDF	Climatic Research Unit (University of East Anglia) TS v4.06 Precipitation Data	[116]
Topographic Wetness Index (TWI)	From Shuttle Radar Topography Mission (SRTM GL1) Global 30 m data of February 2023	GeoTiff	NASA Shuttle Radar Topography Mission (SRTM)	[113]

3.4.2 Preparation of Variables or the Flood Influencing Factors Maps

The waterbody boundary of the Patuakhali district was extracted from the Landsat 9 OLI/TIRS dataset by using extract-by-mask tools in ArcGIS 10.8. Besides all the flood influencing factor maps were prepared by following standard techniques by using different spatial analysis tools from the ArcGIS toolbox [107], [122]. Such as the elevation map was prepared using SRTM 30 m global DEM data and the land use and land cover (LULC) map was created by the supervised classification of Landsat 9 OLI/TIRS image. The slope map was also prepared from SRTM 30m global DEM data using slope creation tools in Spatial analyst tools. Distance from streams or channels and distance from roads maps were prepared using Euclidian distance techniques under the hydrology tools from ArcGIS's spatial analyst tools. Soil texture and rainfall maps were prepared by digitizing and processing ISRIC's 250m soil texture data and Climatic Research Unit's world precipitation data respectively. A normalized Difference Vegetation Index (NDVI) map was prepared using the ratio between the visible red (R) and near-infrared (NIR) bands (Equation 3.2) where band 4 and band 5 represented R and NIR Respectively.

$$\text{NDVI} = \frac{(NIR - R)}{(NIR + R)} \tag{3.2}$$

Drainage Density and TWI maps were prepared using the SRTM 30m Global DEM data. The drainage density map was formulated by dividing the total length of all the stream channels in the drainage basin of Patuakhali with the total area of the drainage basin with the help of a density tool under spatial analyst tools [123]. Before estimating the TWI of Patuakhali district fill DEM, flow direction, flow accumulation, slope in degree, radians of slope, and tan slope features were estimated from the SRTM 30m Global DEM data using hydrology, map algebra, and surface tools under spatial analyst tools of ArcGIS. After that, TWI was calculated by using the equation 3.6 where α = Local upslope drainage through a certain point per unit contour length and β = Local slope in radians. Where, local upslope drainage per unit length was estimated from equation 3.3 and Tan slope was estimated from equation 3.5 with the help of equation 3.4 [97], [124].

$$\text{Local upslope drainage} = (flow\ accumulation + 1) \times cell\ size \tag{3.3}$$

$$\text{Radian of slopes} = \frac{(slope\ in\ degree\ \times\ 1.570796\ )}{90} \tag{3.4}$$

$$\text{Tan slope} = con\ (\text{Radian of slopes} > 0, tan\ (\text{Radian of slopes}), 0.001) \tag{3.5}$$

$$\text{TWI} = \ln \frac{\alpha}{tan\ \beta} \tag{3.6}$$

Finally, all the data which was in polygon data type format was systematically converted to raster data type using polygon to raster tools in ArcGIS.

3.4.3 Reclassification and Ranking of Flood Influencing Factors

When all the spatial distribution maps of flood influencing factors were prepared it was mandatory to define a unified classification scale, projection system, and cell size for all these datasets in the flood risk mapping process through weighted overlay technique. For that, all the prepared datasets were reclassified to the same scale ranges from 1 to 5 using the reclassify tools where 1 indicates very low and 5 indicate very high flood risk (Table 3.5). Besides there used a unified 30 m (X, Y) pixel size for all the datasets and they were also projected to the WGS_1984_UTM_Zone_46N coordinate system using the define projection tool.

Table 3.5 Attributes and ranking details of reclassified hydro-geomorphological flood influencing factors maps used for the flood risk mapping

Variables	Unit	Original class range	Reclassified risk class rank	Risk ratings
Land Use and Land Cover (LULC)	-	Water Body	5	Very high
		Vegetation	1	Very low
		Built up Area	2	Moderate
		Bare Land	3	Low
		Cropland	4	High
Drainage Density	m/km	0-0.38	1	Very low
		0.381-0.697	2	Low
		0.698-0.987	3	Moderate
		0.988-1.358	4	High
		1.359-2.309	5	Very high

Table 3.5 Attributes and ranking details of reclassified hydro-geomorphological flood influencing factors maps used for the flood risk mapping (cont'd)

Variables	Unit	Original class range	Reclassified risk class rank	Risk ratings
Soil Texture	-	Clay	5	Very high
		Silty Clay	4	High
		Clay Loam	3	Moderate
		Silty Clay Loam	2	Low
		Loam	1	Very low
Elevation	m	-21-1	5	Very high
		1.01-4	4	High
		4.01-7	3	Moderate
		7.01-12	2	Low
		12.01-57	1	Very low
NDVI	-	-0.16—0.007	5	Very high
		-0.006-0.112	4	High
		0.113-0.182	3	Moderate
		0.183-0.253	2	Low
		0.254-0.482	1	Very low
Slope	Degree	0-1.20	5	Very high
		1.21-2.9	4	High
		2.91-5.7	3	Moderate
		5.71-14.0	2	Low
		14.01-42.33	1	Very low
Distance to Streams/ Channels	m	0.0 - 0.005	5	Very high
		0.006 - 0.014	4	High
		0.015 - 0.023	3	Moderate
		0.024 - 0.037	2	Low
		0.038 - 0.075	1	Very low
Distance to Roads	m	0-0.003	5	Very high
		0.004-0.011	4	High
		0.012-0.022	3	Moderate
		0.023-0.037	2	Low
		0.038-0.077	1	Very low
Rainfall	mm/year	2343-2419	1	Very low
		2420-2495	2	Low
		2496-2570	3	Moderate
		2571-2646	4	High
		2647-2722	5	Very high
Topographic Wetness Index (TWI)	-	-20.206 - -15.672	1	Very low
		-15.671 - -12.649	2	Low
		-12.648 - -5.344	3	Moderate
		-5.343 - 1.836	4	High
		1.837 - 11.912	5	Very high

3.4.4 Weighting Flood Influencing Factors using AHP

There used a total of ten hydro-geomorphological flood influencing variables and each of these indicators have a different level of influence on the flood occurring in the coastal Patuakhali. For the formulation of an overall flood risk map by overlaying all of the factors, it was necessary to find out the amount of influence each factor have on the flooding. This study conducted a Multi-criteria Decision Analysis (MCDA) with the help of the Analytic Hierarchy Process (AHP) for weighting the influence percentage of each of the flood influencing factors in terms of flood occurrence, frequency, and flood impact in the coastal Patuakhali district [97], [107]. The AHP is a simple framework that aids in the decision-making process on different critical issues when there are available a lot of options and alternatives [59], [122]. This study mainly used the updated AHP Excel workbook template developed by the Business Performance Management Singapore (BPMSG) for MCDA of all flood influencing factors [107], [125], [126]. In the AHP template a total of 45 pairwise comparisons with selected 10 flood influencing factors were made (Appendix B) to rank their priorities and influence factors using the AHP with a consistency rate (CR) below 10% (0.1) [125], [126]. The relative importance of all criteria was defined in the pairwise comparisons assigning importance weight to each criterion using the AHP scale 1 to 9 developed by Saaty [127] where 1 indicates equal importance of two criteria and 9 indicates the extreme importance of one criterion over another [107] (Table 3.6).

The logarithmic scale of AHP (Equation 3.7) was used in this study where, Intensities x, with x = 1 to 9 (integer) are transformed into factors (C) using the following equation and respective 1/c is finally used as relationship value in the pairwise comparison matrix [125].

$$C = Log_2(x + 1) \tag{3.7}$$

Table 3.6 Explanation of the scale used for the pairwise comparison

More influence	Less influence	Scale definition
1	1	Equal importance
2	1/2	Equal to moderate importance
3	1/3	Moderate importance
4	1/4	Moderate to strong importance
5	1/5	Strong importance
6	1/6	Strong to very strong importance
7	1/7	Very strong importance
8	1/8	Very strong to the extreme importance
9	1/9	Extreme importance

For the pairwise comparisons of each participant, a square weighted matrix was generated with their relative importance weight where decision criteria were placed in the row and the relationship among all these criteria was placed in the matrix's columns. From these matrices, a consolidated weighted matrix was prepared using the geometric mean of all matrices (Table 3.7). The priority rank and the influence factors of all flood influencing factors were finally estimated using the Eigenvector Method (EVM). For calculating the normalized principal eigenvector from the consolidated weighted matrix all the criterion was normalized to the scale of 0 to 1 where 1 indicates the highest importance and 0 indicates the lowest importance. For the normalization, the sum of each column was calculated first from the matrix, and all the criteria in each column were divided by the sum of the respective column hence a normalized matrix was formulated. After that, the sum of each row was calculated from the normalized matrix to get the eigenvector, and each calculated value was further normalized to get the normalized principal eigenvector. Finally, the influence percentage and priority rank of all flood influencing factors were assessed from the calculated normalized principal eigenvector which is also called the priority vector [107], [122].

Table 3.7 Consolidated pair-wise comparisons matrix

Matrix	LULC	Drainage Density	Soil texture	Elevation	NDVI	Slope	Distance to streams	Distance to roads	Rainfall	TWI
LULC	1	1 3/5	1 5/7	1 1/6	1	3/8	2/5	1 1/6	1 2/3	2 3/7
Drainage Density	5/8	1	4/5	4/5	2/3	1/3	1/3	4/5	1 1/5	1 4/7
Soil texture	4/7	1 1/4	1	1	7/9	1/3	3/8	5/6	1	1 6/7
Elevation	6/7	1 1/4	1	1	4/5	3/8	3/8	1	1	2 1/7
NDVI	1	1 4/7	1 2/7	1 2/9	1	1/3	1/3	1	1 1/6	2
Slope	2 2/3	3	2 5/6	2 2/3	2 4/5	1	1 1/6	2 1/3	2 7/8	3
Distance to streams	2 3/5	3	2 3/4	2 3/4	2 4/5	6/7	1	2 1/3	2 8/9	3
Distance to roads	6/7	1 1/4	1 1/5	1	1	3/7	3/7	1	1 2/7	2 2/5
Rainfall	3/5	5/6	1	1	6/7	1/3	1/3	7/9	1	1 4/9
TWI	2/5	2/3	1/2	1/2	1/2	1/3	1/3	3/7	2/3	1

3.4.5 Flood Risk Map Preparation

This study mainly used a weighted overlay sum technique from the spatial analyst tools of ArcGIS for the preparation of a comprehensive flood risk map of Patuakhali district by overlaying all the considered flood influencing factors along with their influence weight to flood occurrence [48]. All the spatial distribution maps of flood influencing factors were prepared and the respective influence percentage of each factor for flood occurrence in the coastal Patuakhali district have already been assessed from the AHP [97], [106], [122]. Then all these projected and reclassified flood influencing factor map layers were combined using the weighted overlay sum techniques from the spatial analyst tools for the preparation of flood risk scenarios of Patuakhali district [107]. In this weighted overlay process, all the flood influencing factor layers were weighted by assigning their respective unique influence percentage values found from the AHP assessment. After that, the desired flood risk map of Patuakhali district was prepared and exported with desired resolution after inputting all the essential map elements there. Finally, the prepared flood risk map of Patuakhali district was further classified into very-low, low, moderate, high, and very-high risk levels for prioritizing high-risk areas while preparing mitigation strategies.

3.5 PARTICIPANTS

The study was conducted at the Kuakata Paurashava of Kalapara upazila, Patuakhali. Required data were collected from a sample rather than the whole population. Multi-stage and simple random sampling techniques are used for the selection of sample size. Patuakhali district[3] has 7 upazilas[4], from them most southern Kalapara upazila was selected first due to its high coastal flood risk [111]. From the Kalapara upazila, a 5 km radius area from the Bay of Bengal were selected for this study. The total number of households with in this 5 km radius area was 2085 [111].

For determination of sample size equation 3.8 and 3.9 were used [128]. In the case of the 95% confidence level and 7% margin of error, the sample size was 200. The sample size was calculated through the following equation:

Sample size = n

Total targeted population, N =2085

Confidence level = 95%

The margin of error, e = 7%

Chi-square at 95% level of significance, Z = 1.96

The estimated proportion of successes, Standard Deviation, p=0.5 (Male and Female base)

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[3] Second largest administrative division in Bangladesh. Bangladesh is divided into 64 districts or zila.
[4] This is the third largest administrative division in Bangladesh which function as a sub-unit of a district.

Estimated proportion of failures, q = (1-p) = (1-0.5) = 0.5

$$\text{First, Sample Size, } n_0 = \frac{Z^2 \times p \times q}{e^2} \qquad (3.8)$$

$$= \frac{(1.96)^2 \times 0.5 \times 0.5}{(0.07)^2}$$

$$= \frac{(1.96)^2 \times 0.5 \times 0.5}{(0.07)^2}$$

$$= 196$$

Then, adjusted sample size,

$$n = \frac{n_0}{1 + \left(\frac{n_0 - 1}{N}\right)} \qquad (3.9)$$

$$= \frac{96.04}{1 + \left(\frac{96.04 - 1}{2085}\right)}$$

$$= 179.24$$

The determined sample size from the total population was: 179.24; for conservative measure sample size was taken as 200.

Chapter 4: RESULTS

Chapter 4 describes all the results of this study with respect to furnishing evidence to research question(s) as outlined in Chapter 1. Section 4.1 presents the demographic and socio-economic profile of the respondents; section 4.2 outline the results summary for the hazard, vulnerability, capacity, and risk assessed; section 4.3 presented and described developed coastal flood risk for Patuakhali district along with all the prepared variables maps, and finally in section 4.4 this study proposed some structural and non-structural flood mitigation strategies.

4.1 RESPONDENT'S PROFILE

4.1.1 Demographic Characteristics

A diversified and wide range of respondents were covered for the assessment of coastal flood risk at Patuakhali district through household face-to-face survey, FGD, KII, and in-depth interviews.

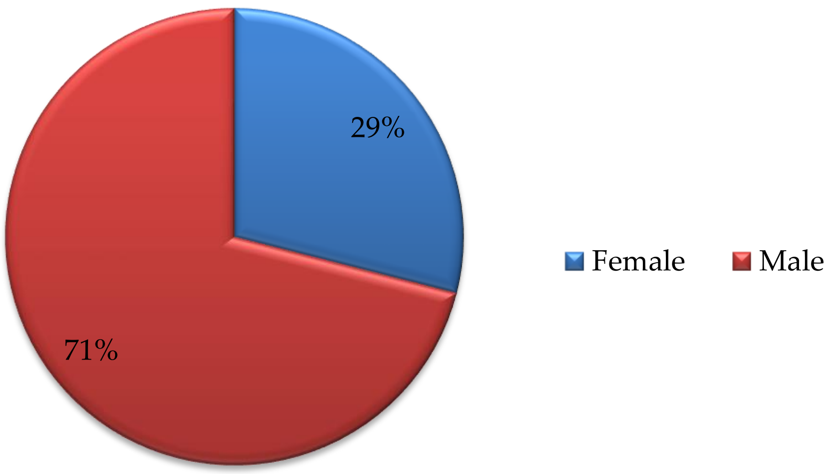

Fig. 4.1 Respondents' gender ratio

Both male and female respondents were covered through this data collection process. Though this study hoped for 50 percent participation for both males and females the target wasn't possible to cover due to the geographical location and conservative nature of the community. In this study, there was 71% male and 29% female participation through the data collection process (Figure 4.1).

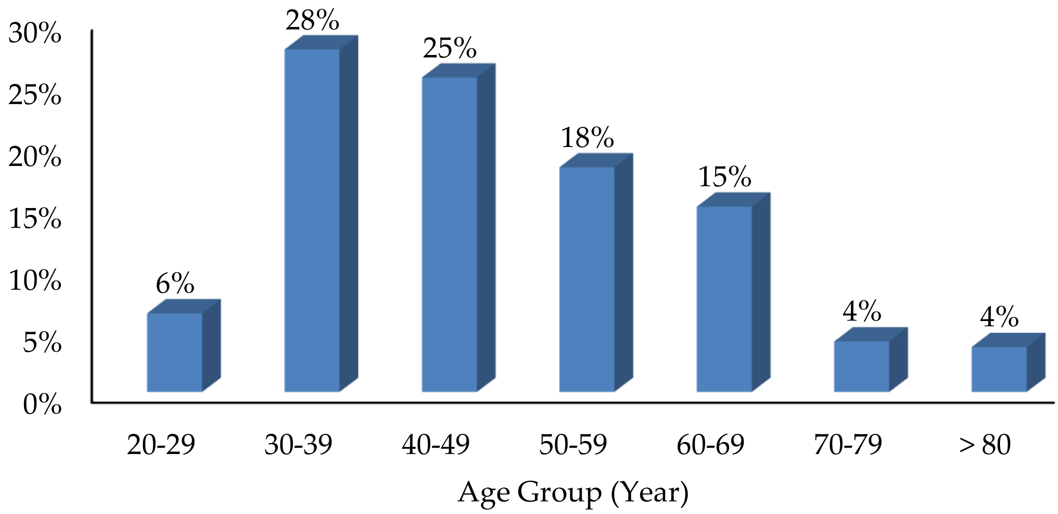

Fig. 4.2 Respondents’ age distribution

This study also tried to include a representation of different age groups for the data collection. According to figure 4.2, all age categories from 20 to above 80 years of age were covered in this study. Most of the respondents belong to the age group range from 30 years to 39 years followed by 40 years to 49 years and 50 years to 59 years old.

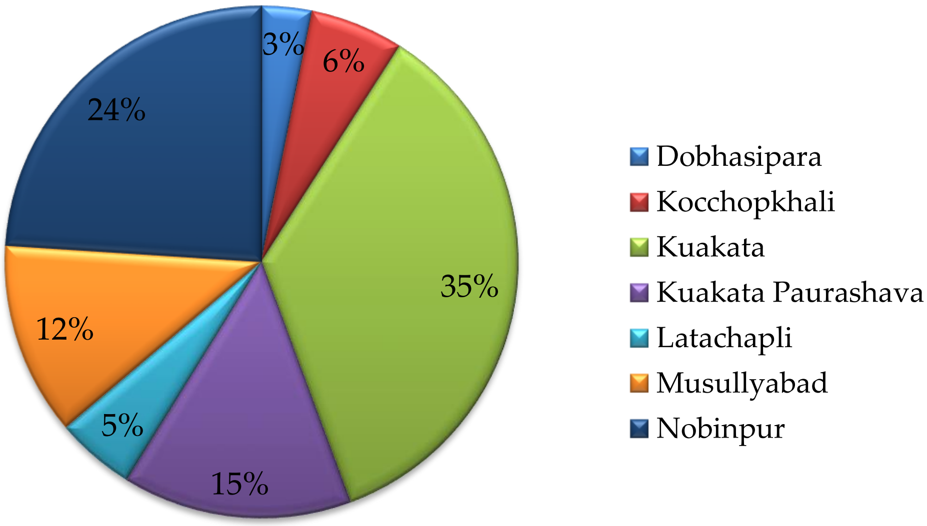

Fig. 4.3 Respondents' residence location

Figure 4.3 revealed the respondent's residence distribution. This study mainly conducted the primary data collection with an area of 5 km buffer from the Bay of Bengal. 35% of respondents were from the nearby Kuakata sea beach, 18% from the Kuakata Paurashava, and 12% from the Musullyabad village.

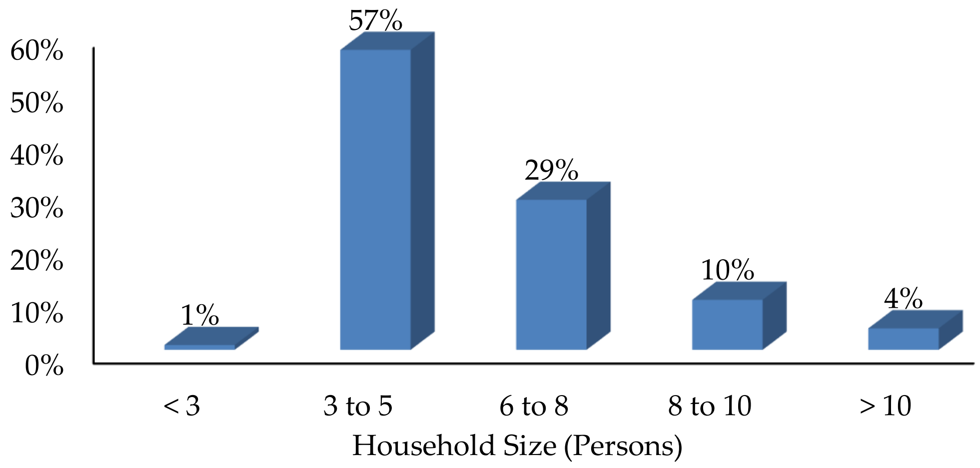

Fig. 4.4 Respondents' household size

According to figure 4.4, most of the respondents (57%) have a family size of 3 to 5 persons followed by 29% have a big family size of 6 to 8 persons while only 1% of respondents have a smaller family size of less than 3 persons.

4.1.2 Socio-economic Characteristics

Socioeconomic attributes of respondents who participated primary data collection process of this study were described in this section.

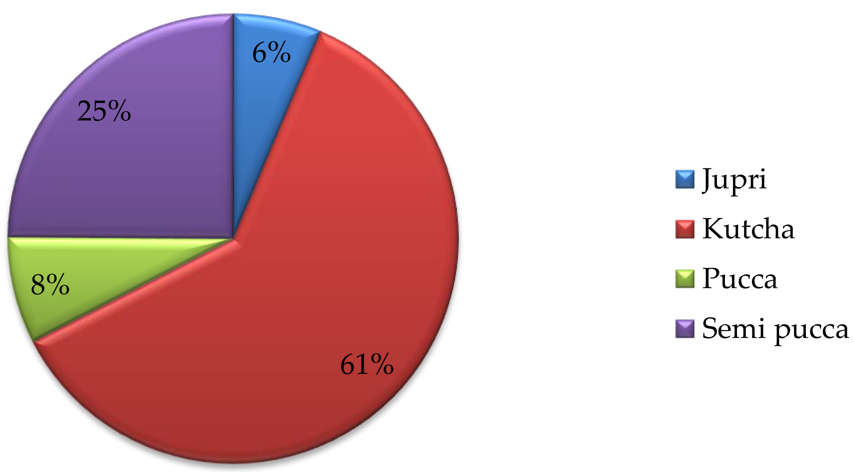

Fig. 4.5 Respondent's household structure

Figure 4.5 showed the household structure the respondent lives in. Around 61% of respondents live in a kutcha house and 25% of respondent lives in a semi-pucca house. There only 8% of respondents have pucca housing structure and 6% lives in jupri houses now.

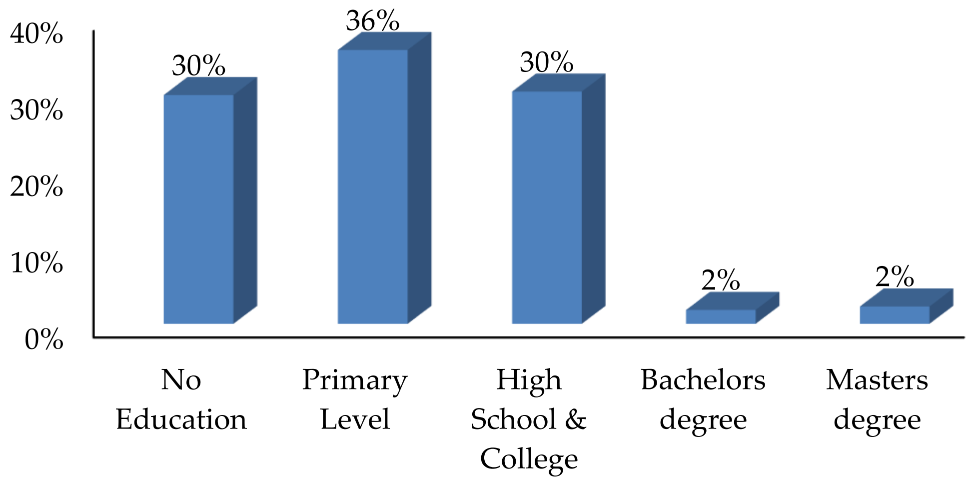

Fig. 4.6 Respondents' educational status

A major part of the respondents for this study (30%) didn't receive any scope of formal educational facilities **(**Figure 4.6**).** 36% have studied up to the primary level and 30% have the scope to go to higher school and colleges where only 2 and 3% of respondents have the scope to complete bachelor's and master's degrees respectively.

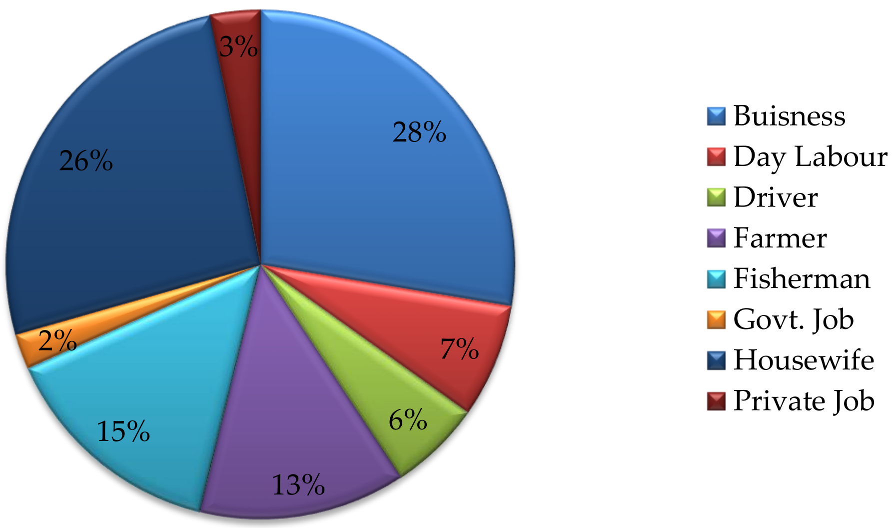

Fig. 4.7 Respondents' occupational status

Respondents who participated in this study have a diversified occupational variation and involve themselves within a wide range of occupations (Figure 4.7). 28% of respondents have business as their primary occupation and 26% of females have no occupational option rather housewife. 15% of respondents are involved with fishing and 13% are involved in farming.

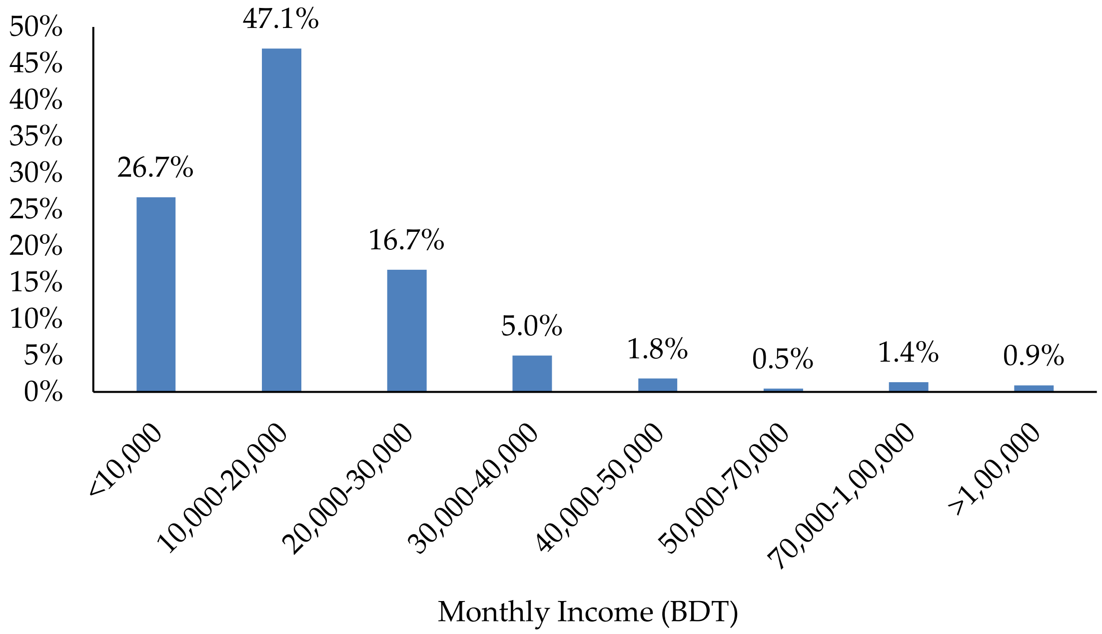

Fig. 4.8 Respondents' monthly household income status

Most of the respondents involved in this study belong to the lower-income and middle-income categories (Figure 4.8). About 47% of respondents have a monthly income of BDT 10000-20000 and 26.7% have a monthly income below 10000 BDT. On the other hand, only 0.9% have a monthly income above 100000 and 1.4% have a monthly income of 70000 to 100000 BDT respectively.

4.2 COASTAL FLOOD RISK

4.2.1 Flood Hazard Situation

The flood hazard scenario in Patuakhali district has several attributes and is estimated during hazard index assessment. Among them, flood occurring frequency, maximum water weight, and water staying duration in the historic flood, predictability month of flood occurring, probability or chance of future flood occurring, likelihood of future flood damage, and probable sectoral impact of the coastal flood are described in this section.

Flood Frequency

Flood hazard mostly depends on the frequency of flood occurring. The more frequent the flood event the hazard risk of flood events will rise. Figure 4.9 represents the frequent number of flood event experienced by different age group people in the study area.

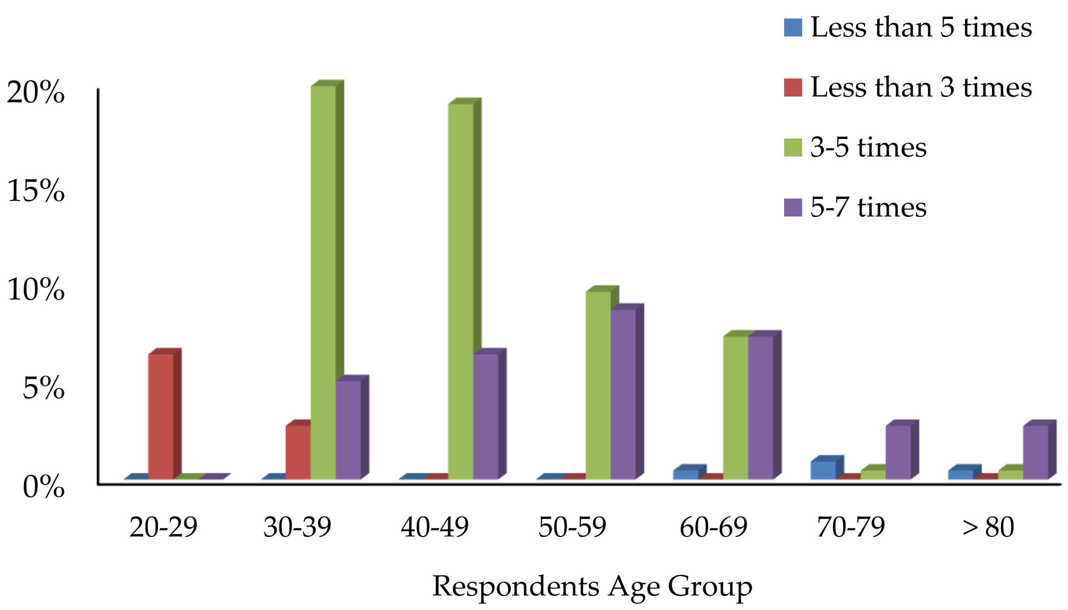

Fig. 4.9 Yearly flood (number) affected age groups

Figure 4.9 revealed that around 20% of the respondent from the 30 to 39 age group and 19% from the 40-49 age group generally experienced 3 to 5 flood events within a year. On the other hand, 9% of respondents aged 50-59 years, 8% of respondents from 60-69 years and 7% of the respondent from the 40-49 years age group experienced flood events 5 to 7 times in a year.

Maximum Water Level and Flood Duration

Maximum flood water level and duration of water staying during different historic flood events also shape the hazard scenario of any area. The historic flood that occurred in coastal Patuakhali usually didn't stay for a long time as respondents didn't experience any flood with more than 15 days of water staying and only 6% of respondents experienced 0.92 to 1.5 m depth flood with more ta 7 days water staying (Figure 4.11). 20% of respondents experienced 0.92 to 1.5 m moderate flood events which stayed for 6 to 7 days. 20% of respondents experienced 0.3 to 0.92 m lower flood events which stayed for 1 to 2 days. On the other hand, most of the high floods with 1.52 to 3.01 m depth mostly stayed for 1 to 5 days (Figure 4.10).

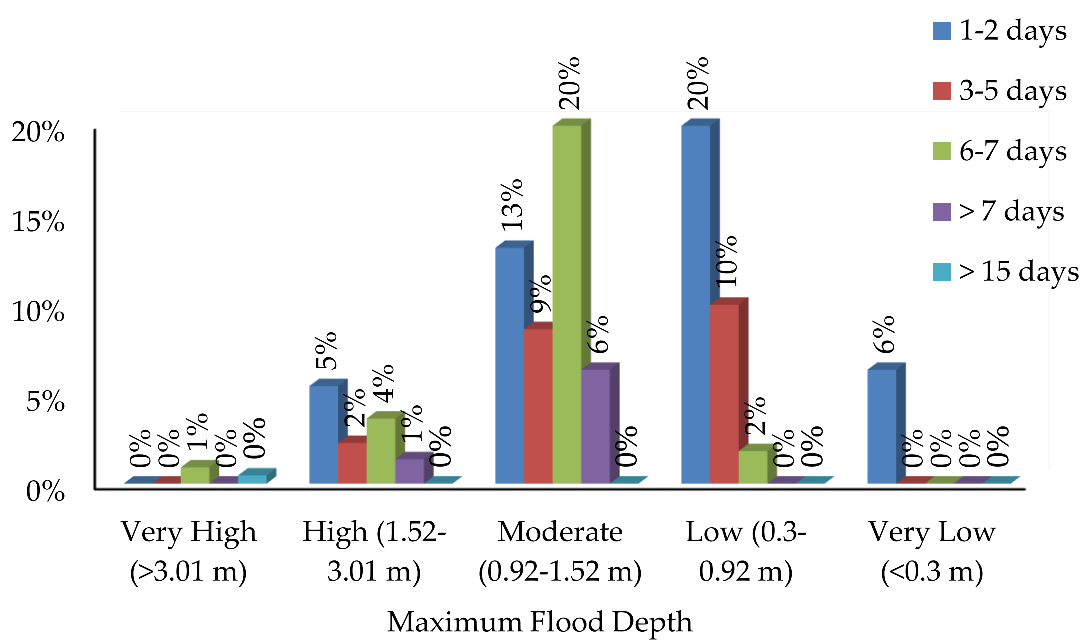

Fig. 4.10 Maximum flood depth and duration of inundation

Predictability of Flood Occurring

The predictability of occurring months of historic and future flood events can shape the flood hazard scenario. According to figure 4.11, 20.48% of floods occurred in October, 17.52% in July, 16.87% in November, 10% in both June and August, and 9% in December. From there 2 season of flood event can be distinguished which is June to August and October to December.

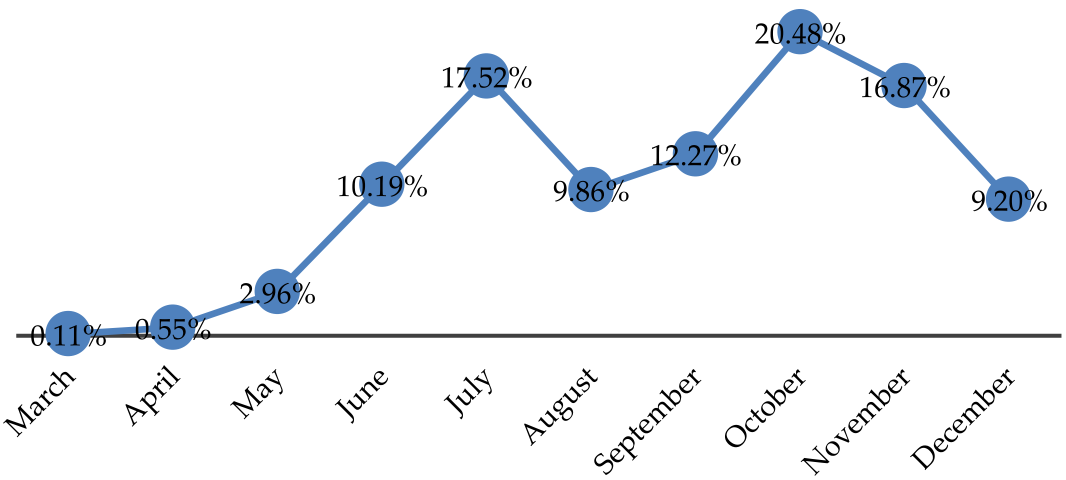

Fig. 4.11 Duration of coastal flood

Probability of Future Flood Occurring

Most of the respondents assumed a high probability of future catastrophic flood occurrence in the near future. According to 49% of the respondent, a catastrophic flood can occur once a year and 39% thought one catastrophic flood within every 5 years (Figure 4.12).

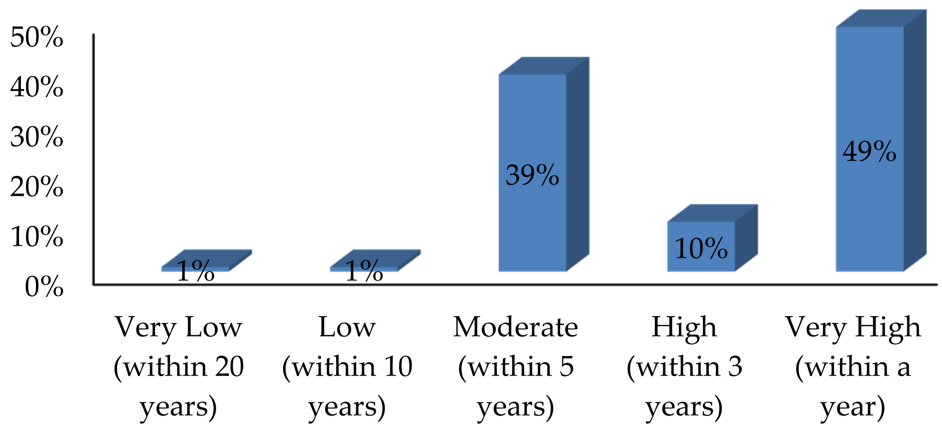

Fig. 4.12 Probability of future coastal flood occurrence

Future Flood Damage

The coastal flood caused huge damage to the lives and property of the coastal people especially in the Patuakhali district.

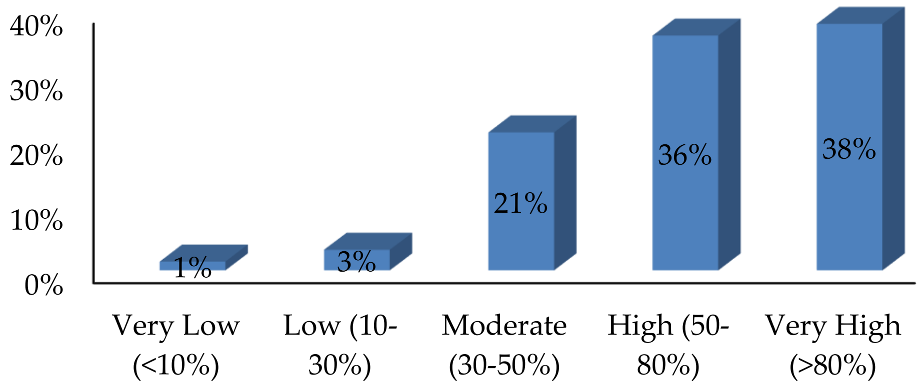

Fig. 4.13 Likelihood of future damages by coastal floods

Around 38% of respondents thought there is a very high possibility of property and infrastructure damage (more than 80% damage) by future coastal floods. 36% of respondents anticipate coastal flood can damage 50 to 80% of the property and 21% anticipate 30 to 50% property damage by future flood events (Figure 4.13).

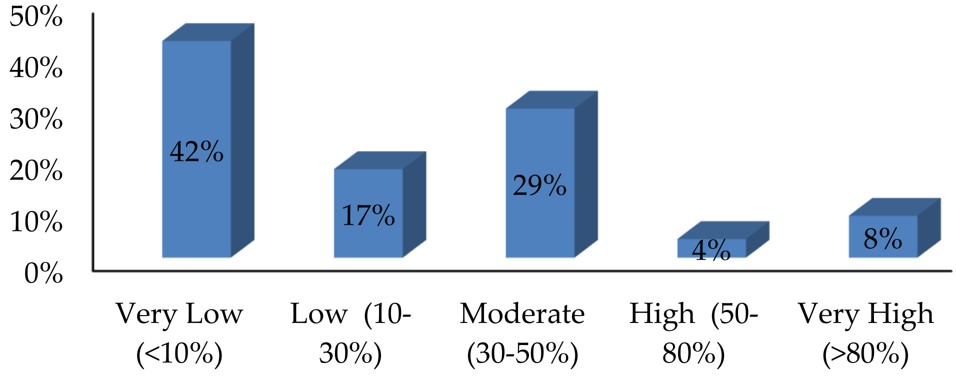

Fig. 4.14 Chances of casualities during a coastal flood

Though coastal flood causes huge damage to coastal infrastructure and property, the loss of lives due to coastal floods is very low. Around 60% of respondents shared that, there is a low and very low chance of the people's life loss due to upcoming coastal floods. This is due to modernized early warning and forecasting systems and the availability of news dissemination. On the other hand, 29% of respondents anticipate a moderate possibility for loss of lives and only 8% anticipate a high possibility of life loss due to future flood events (Figure 4.14).

Sectoral Impact of Coastal Flood

Coastal flood has a different level of impact on various sectors and anticipation of these impact levels was very crucial for flood hazard assessment.

Table 4.1 Respondents' perception of the sectoral impact of coastal flood

Sectors	**Impact**				
	Very Low	**Low**	**Medium**	**High**	**Very High**
Infrastructure	-	1%	3%	8%	88%
Crop agriculture	-	-	-	5%	95%
Fisheries	-	-	1%	12%	87%
Livestock	-	2%	21%	36%	40%
Sanitation	3%	5%	20%	41%	30%
Health	-	-	8%	41%	51%

Table 4.1 described the different levels of impact of coastal floods on different sectors according to coastal people's experience. Coastal floods have a very high-level impact of 88%, 95%, and 87% on coastal infrastructure, crop agriculture, and fisheries sectors respectively. The livestock, sanitation, and health sector are also high to very highly affected by the flooding condition in this area.

4.2.2 Flood Vulnerability Situation

There are several vulnerable conditions and events which can accelerate the risk of future coastal flood risk. Among them, proximity to the flood-vulnerable area people live in, population density in the coastal flood-vulnerable area, and resiliency status of the community's houses are described in this section.

Proximity to the Flood-Vulnerable Area People Live in

Proximity to the flood-vulnerable area increases the risk of life and property damage from coastal flood events.

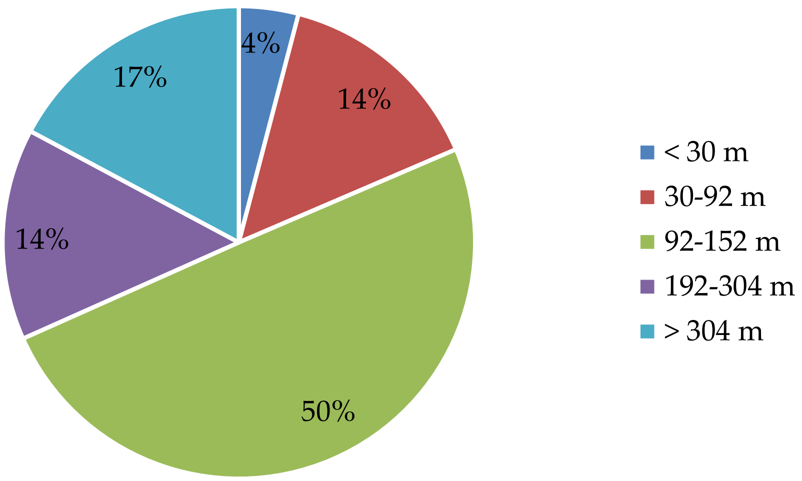

Fig. 4.15 Distance of residences in the flood vulnerable area

This study found most of the people in the coastal Patuakhali district live close to the flood-vulnerable area. Around 50% of coastal people live within a 92-152 m distance from flood-vulnerable areas. Only 17% of people live at a distance of more than 304 m from the vulnerable area while 14% of people live a distance of 30-92 m and 4% live less than 30 m from flood vulnerable area (Figure 4.15).

Population Density in the Flood-Vulnerable Area

Coastal areas all over the world have a very high population density due to their dynamic nature and wide range of resource availability.

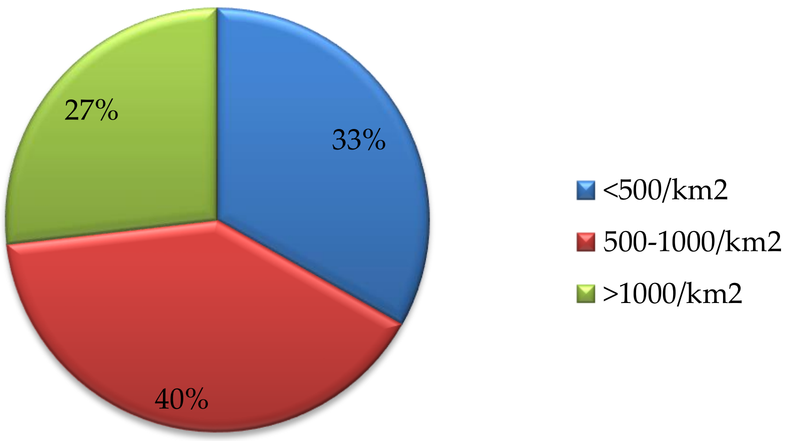

Fig. 4.16 Density of residences in the flood-vulnerable area

Coastal Patuakhali district also has a high density of people living in it. 40% of the area has a population density of 500-1000 km^2 and 27% area has a density of more than 1000 km² while only 33% area has less than 500 km² population density (Figure 4.16).

Resilience Status of the Community's Houses against Flood

Though coastal Patuakhali is very vulnerable to flood events, most of the houses and infrastructure aren't enough resilient to withstand these floods due to the low economic status of the community.

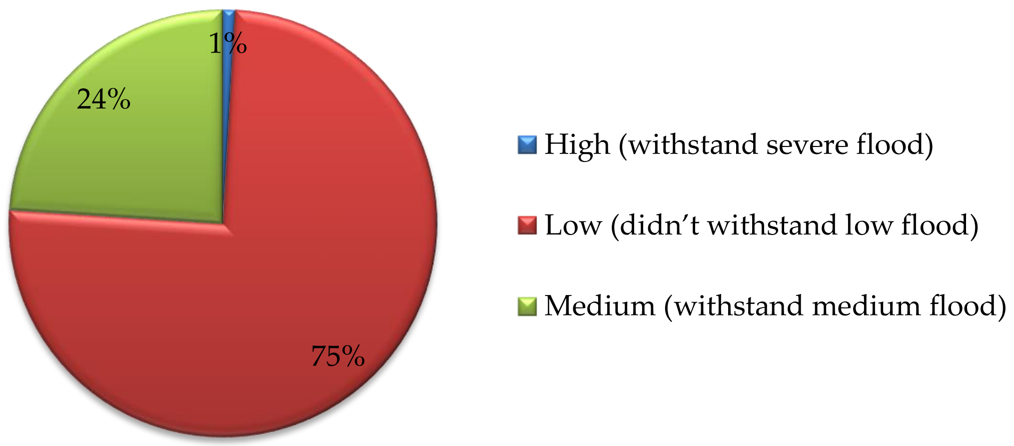

Fig. 4.17 Resilience status of the community's houses against flooding

According to coastal people, 75% of coastal houses aren't resilient enough and they will not even withstand a lower severe flood event. 24% of hose has a resiliency to withstand moderate-level flood event and only 1% of houses has a resiliency to withstand higher severe flood event (Figure 4.17).

4.2.3 Community Capacity Against Flood

Community capacity against any disaster such as flood depends on various factors. Among all these factors, alternative livelihood options during the flood, coastal people's capability to cope with the future coastal flood, flood shelter facilities during the coastal flood, maintenance condition of existing embankment and polders, and different infrastructural conditions to cope with the coastal flood will be discussed in this section.

Alternative Livelihood Sources during the Flood

An alternative livelihood option is very crucial for people with lower and middle income for a longer flood event or if the primary source of livelihood is damaged by the flood. The alternative source and livelihood options are not available in the coastal Patuakhali district during any flood event. About 89% of coastal community people have very poor condition with the alternative livelihood source and only 10% people has a moderate and 1% people has a secured alternative livelihood option in case there occurred a catastrophic flood event (Figure 4.18).

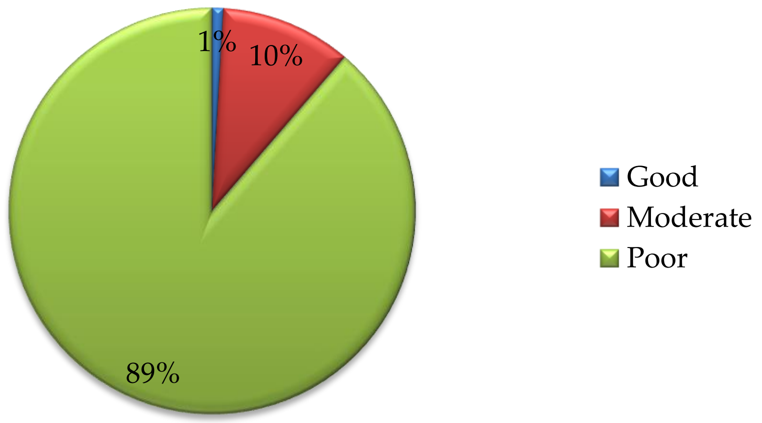

Fig. 4.18 Alternative livelihood sources or options during the flood

People's Capability to Cope with the Future Coastal Floods

People’s capacity and availability of resources to cope with future coastal floods will reduce the risk of coastal flood effects and damage.

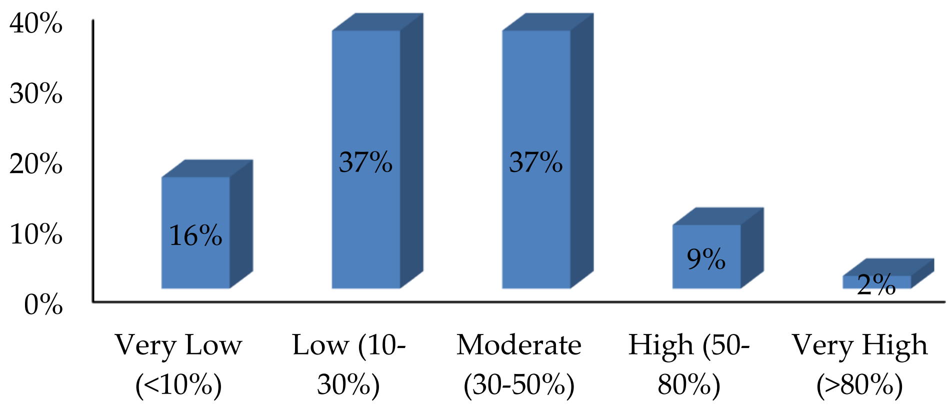

Fig. 4.19 People's capability to cope with the future coastal flood

Most of the coastal community people didn’t have enough capacity to withstand upcoming coastal floods. Figure 4.19 revealed that 37% of people thought that, they have low and moderate capacity against upcoming coastal flooding. Where only 9% of people have high capacity and 2% have very high capacity and resources against coastal flooding.

Shelter Facility

During any natural disaster taking shelter is the most common risk mitigation practice. Floods with a moderate to high level of severity force coastal communities to take shelter in a safe place, especially in the flood or cyclone shelter. Availability of shelter and the high rate of people taking place in this shelter increase capacity against coastal flood events.

This study founds, 65% of respondents usually evacuated and took shelter in well-established flood and cyclone shelters during all previous cyclonic storm and flood event. On the other hand, 18% of respondents didn’t leave their house in any kind of flood event, 12% take shelter in relatives' houses and 5% take shelter in the nearby school building and nobody take shelter in the high road or embankment during a flood (Figure 4.20).

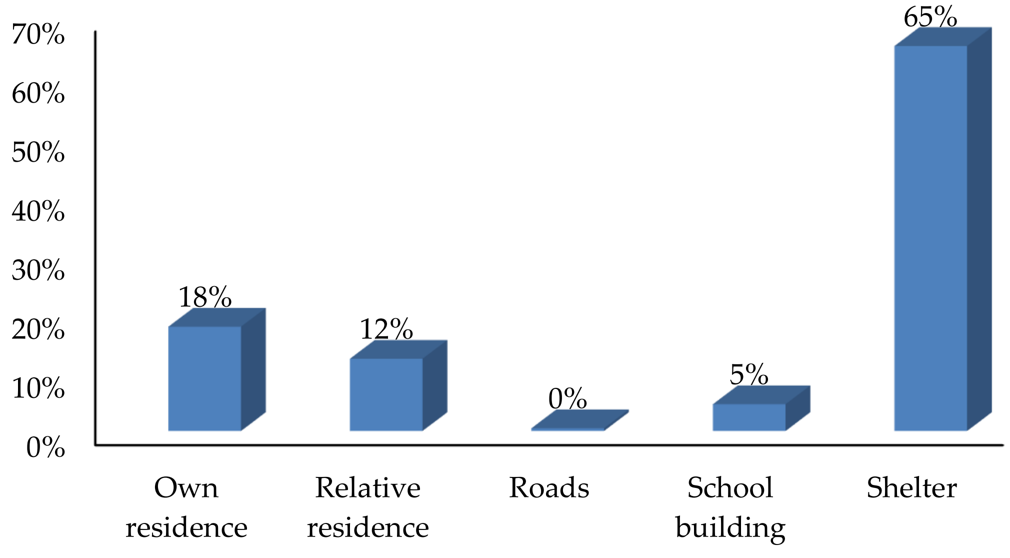

Fig. 4.20 Participants in the shelter during coastal flood events

Maintenance status of existing coastal Embankment and Polders

There are a lot of embankments, polders, and sluice gates established to keep the coastal area safe from cyclonic storms and flood events. Regular maintenance of existing flood embankments and polders increase the community's capacity and reduce the risk of flood hazard. According to the respondents, 43% of polders and embankments are being maintained moderately and 21% are maintained with high care while 34% of embankments have a very high maintenance status. On the other hand, 2% of embankments and polders have a poor maintenance status (Figure 4.21).

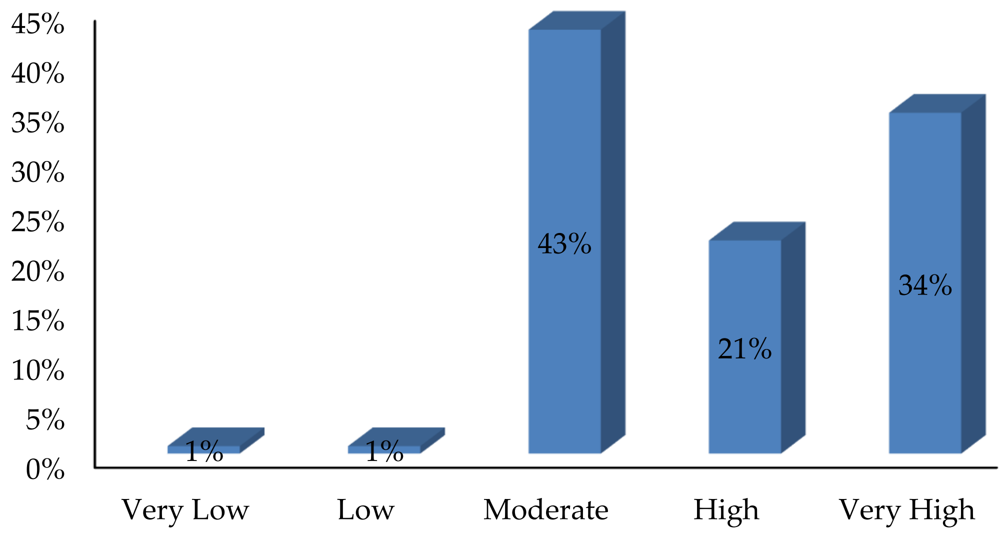

Fig. 4.21 Maintenance status of coastal embankments and polders

Sectoral Capacity to Cope with Future Coastal Floods

The different sectoral capacities of the Patuakhali district will increase the overall capacity of the coastal community to cope with potential future flood damages.

Table 4.2 Respondents' perception of the existing sectoral capacity to cope with coastal flood

Sector	Capacity			
	High	Medium	Low	Very low or no capacity
Infrastructure	3%	11%	84%	2%
Livelihood security	2%	10%	84%	5%
Preservation of food	3%	20%	73%	5%
Embankment and sluice gates	29%	69%	2%	
Power and energy backup	2%	22%	23%	53%
Seed, fertilizer storage		2%	11%	87%
Sufficient relief supply	1%	4%	51%	44%

Table 4.2 revealed that most of the sectors which have the potential to be affected by coastal flood devastation have a lower or no capacity at all to withstand these devastations. According to 84% of respondents, the infrastructure and alternative livelihood sector have a lower capacity, and the food preservation sector has a lower capacity according to 73% of respondents. 53%, 87%, and 44% of respondent thought energy backup, seed and fertilizer storage, and relief availability has very low or no capacity respectively to cope with the devastation of an upcoming flood event. On the other hand, according to all of the respondent's coastal embankments have moderate to high capacity to withstand flood devastation.

4.2.4 Estimated Coastal Flood Risk of Patuakhali District

Coastal flood risk for the study area was estimated by multiplying flood hazard and vulnerability against the capacity to absorb flood risk. First of all, flood hazard, vulnerability, and capacity index were estimated which is then used to quantify coastal flood risk index value using (Equation 3.1**).** For calculating all these indexes, a unified scale ranges from 0 to 1 was considered where 1 indicate higher value and 0 indicate lower value for hazard, vulnerability, capacity and risk. The detailed calculation of these index values is provided in Appendix C.

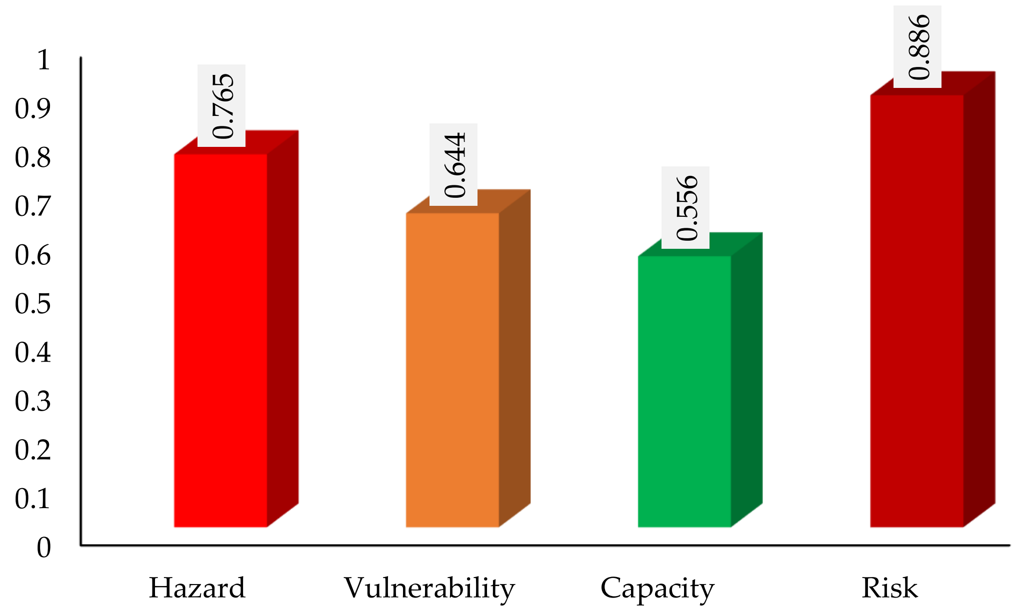

Fig. 4.22 Hazard, vulnerability, capacity, and risk score of the study area

This study estimated a high flood risk (0.886) for the coastal Patuakhali district which was estimated based on people's perceptions and expert opinions. The individual hazard score was found 0.765 and the vulnerability score was found 0.644 which wasn't very high but they combinedly generated a high flood risk due to lower community capacity available (0.556) against flood damage (Figure 4.22). If the community capacity could be increased the flood risk in this region will reduce ultimately.

4.3 MAPPING COASTAL FLOOD RISK

4.3.1 Flood Influencing Factors

Coastal flood scenarios are shaped and regulated through several factors combinedly known as flood influencing factors. This study considered ten flood influencing factors among them for mapping the coastal flood risk of Patuakhali district. All these flood influencing factors used in this study and their GIS and RS-based maps are well described in this section.

Land Use and Land Cover (LULC)

Land use and land cover map describe the distribution of different land use classes across the study area Patuakhali district. The water body in this map mainly represents the river and canal features within the considered area. Cropland area has high flood risk as these areas are mostly low laying areas. Though the build-up area has a higher elevation, the structure developed here generally blocked the natural flow of river and canal water flow and made it vulnerable to flood risk. On the other hand, vegetation area has low risk due to its capacity to reduce the impact of cyclonic storm surges and flood event [97]. Coastal Patuakhali district has dense vegetation mostly on the char land [5]areas in its southern part. The central, north-western, and northern part has dominant build-up areas which have more vulnerability to flood risk. Additionally, there is a strong river network surrounding this district and 2 or 3 major rivers along with Rabnabad channel also pass through this district which makes this district more vulnerable to flooding (Figure 4.23).

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[5] Char a tract of land surrounded by the waters of an ocean, sea, lake, or stream; it usually means, any accretion in a river course or estuary. Charland in Bangadesh are landmasses formed through the sedimentation of huge amount of sand, silt and clay over time carried by the Padma, the Meghna, the Jamuna and the Brahmapurtra with their numerous tributaries.

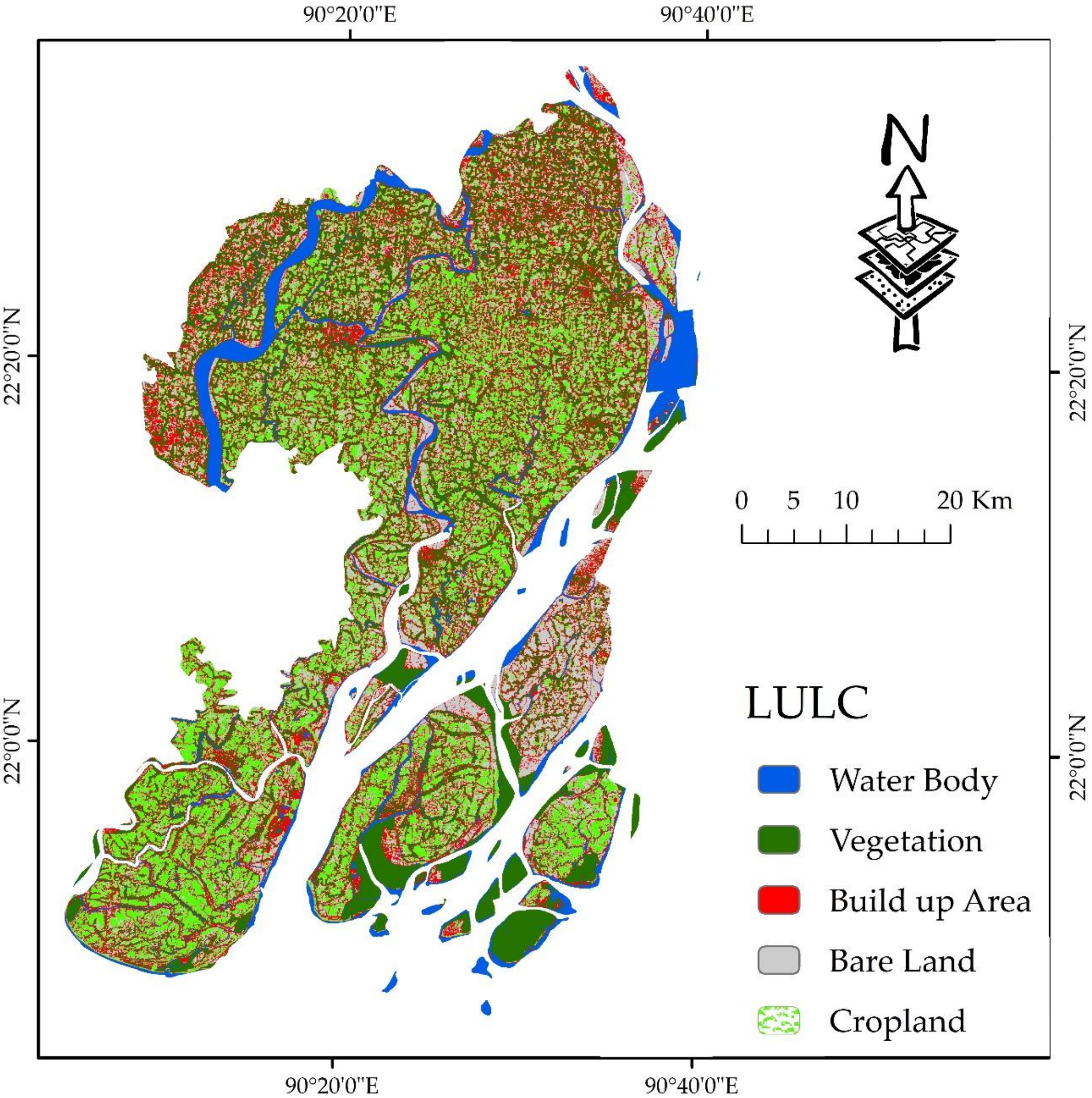

Fig. 4.23 Land Use and Land Cover map of Patuakhali district

Drainage Density

Drainage density is one of the most important floods influencing factors which control the runoff distribution and infiltration rate within the area. Drainage Density is the total length of all the streams and Rivers in a Drainage basin divided by the total area of the drainage basin. The central and northern part of the Patuakhali district has high drainage density which makes that area more vulnerable to flood. The south-central Kalapara upazila also has the highest drainage density compared to the borderline area of this district (Figure 4.24).

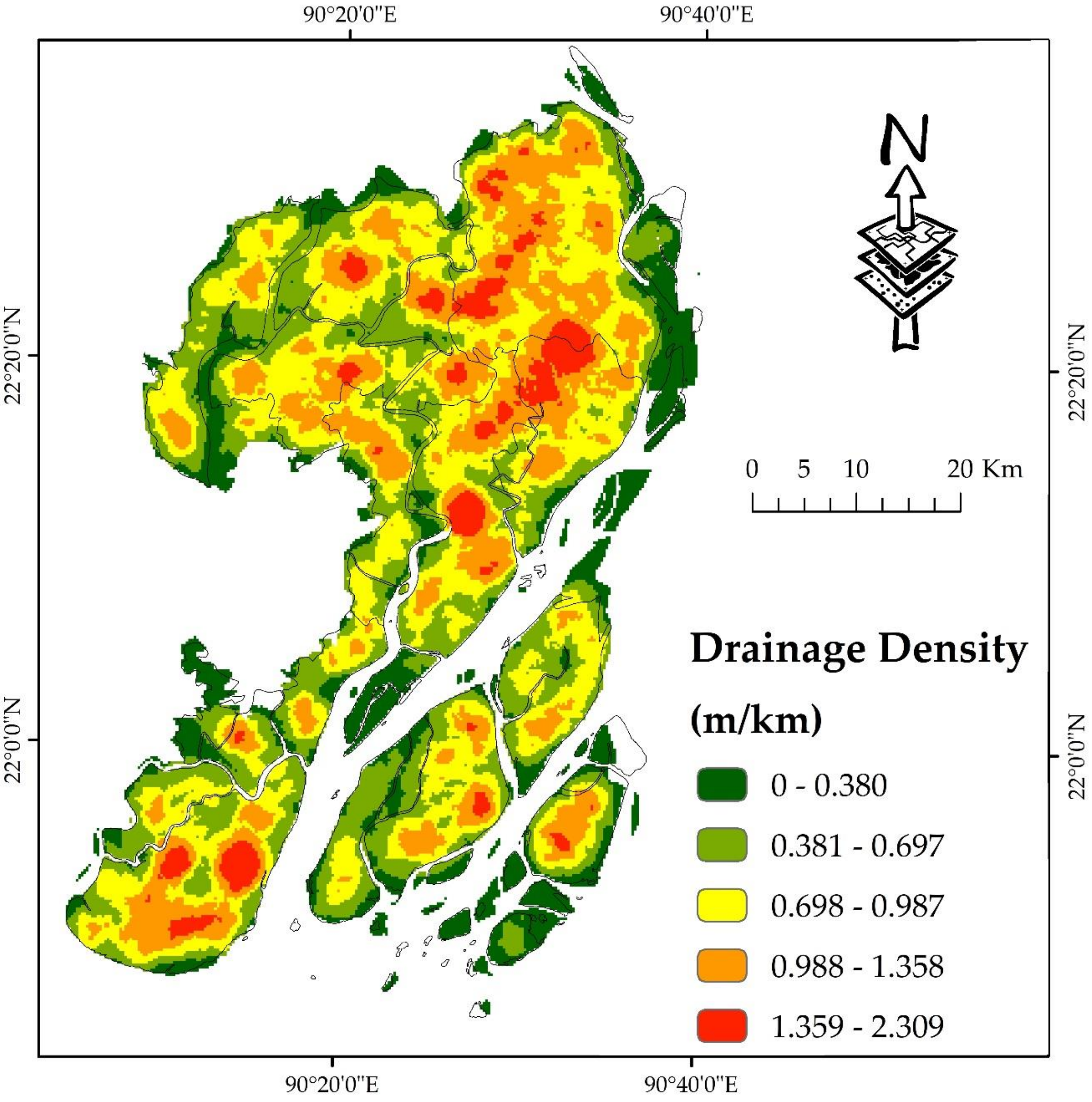

Fig. 4.24 Drainage density map of Patuakhali district

Soil Texture

Different soil texture has different level of water-holding capacity and these soil texture influence the water infiltration and water movement through the soil. Most of the land area in the coastal Patuakhali district has been developed with a clay loam texture which has a moderate water retention capacity (Figure 4.25). Thus, the soil texture features of Patuakhali district made this area moderately vulnerable to flood risk.

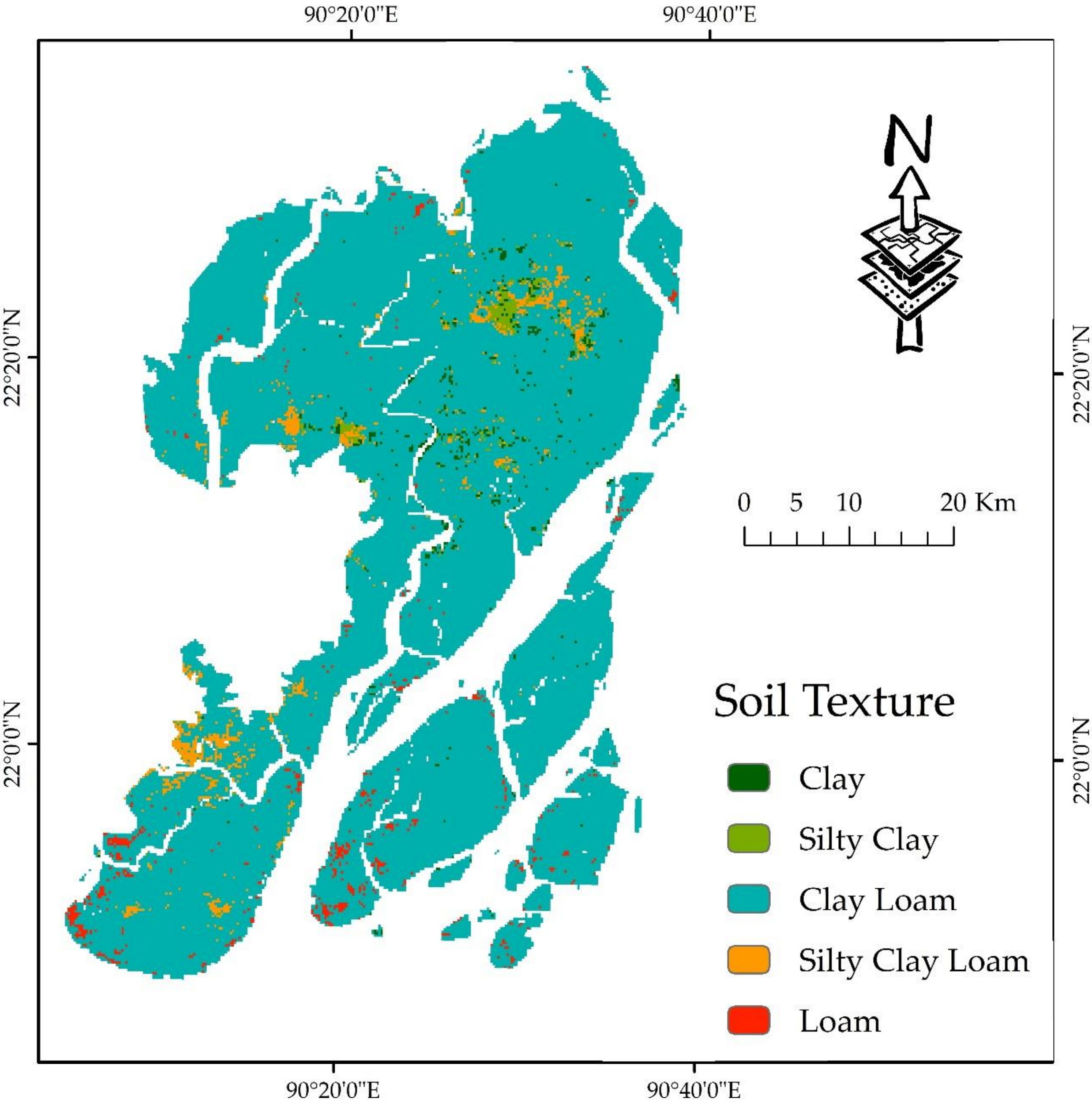

Fig. 4.25 Soil texture map of Patuakhali district

Elevation

The elevation map represents the meter of elevation of different places in the studied area from the mean sea level. The higher the elevation from the sea level the lower the chance of flooding. Additionally, the presence of lower elevated areas near the river or sea increased the vulnerability of flooding. The overall elevation of the coastal Patuakhali district is low and makes it moderate to highly vulnerable to flood. Most of the central and northern part of this district has an elevation ranging from 1.01 to 4.0 meter and the southern part has an average elevation of 4 to 7 meter. The south-eastern char and island area of this district has a lower elevation range from -21 to 1 meter (Figure 4.26).

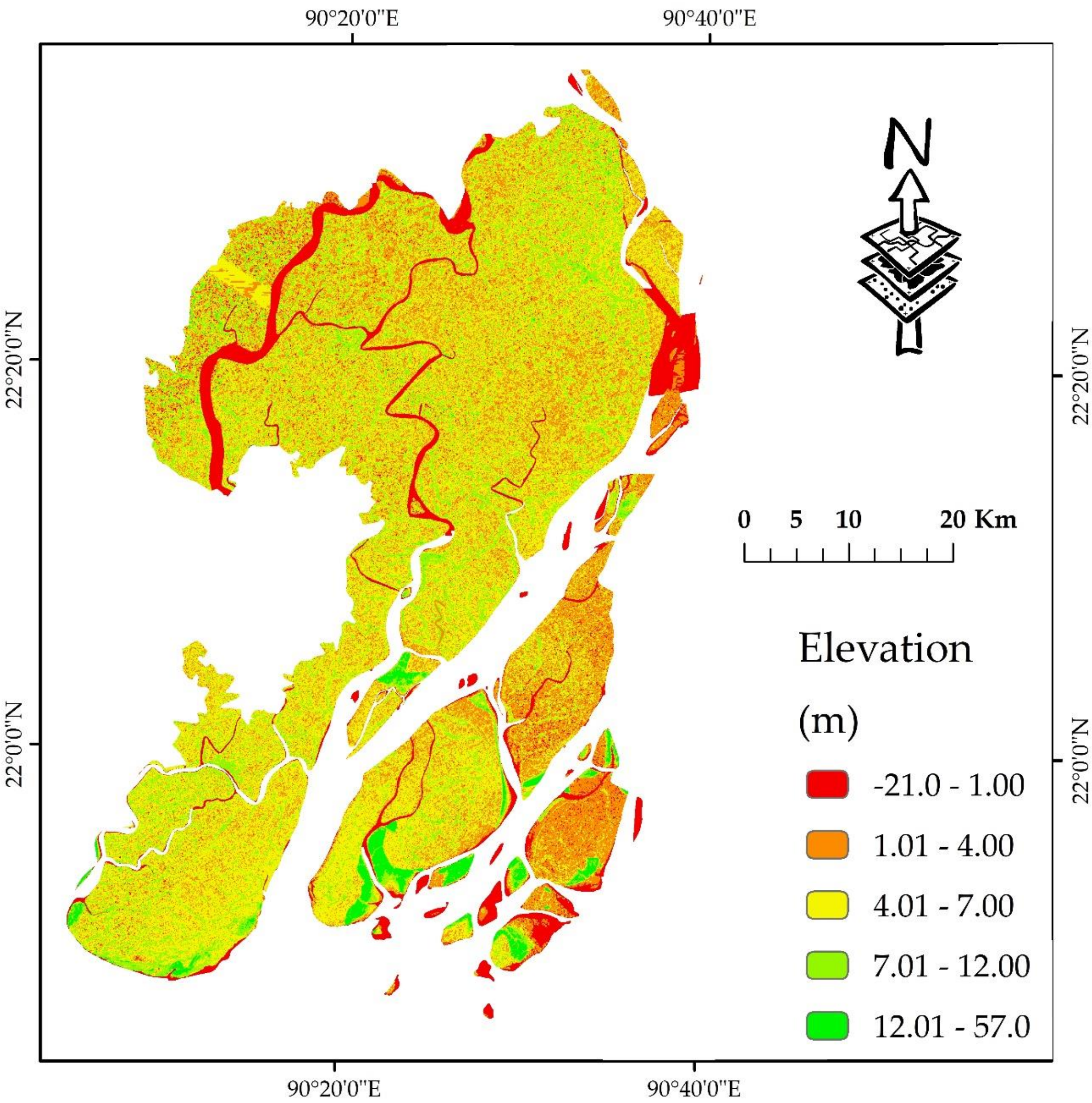

Fig. 4.26 Elevation map of Patuakhali district

NDVI

Normalized Difference Vegetation Index (NDVI) is used to quantify vegetation greenness and is useful in understanding vegetation density and assessing changes in plant health. The absence of vegetation in any area makes it more vulnerable to floods and cyclonic storms. In the southwestern and eastern part of the Patuakhali district, there is less vegetation which is also near the river channel and Bay of Bengal which combinedly makes it more vulnerable to flood risk. On the other hand, the central and northern part of this district has moderate to high vegetation according to the NDVI map (Figure 4.27).

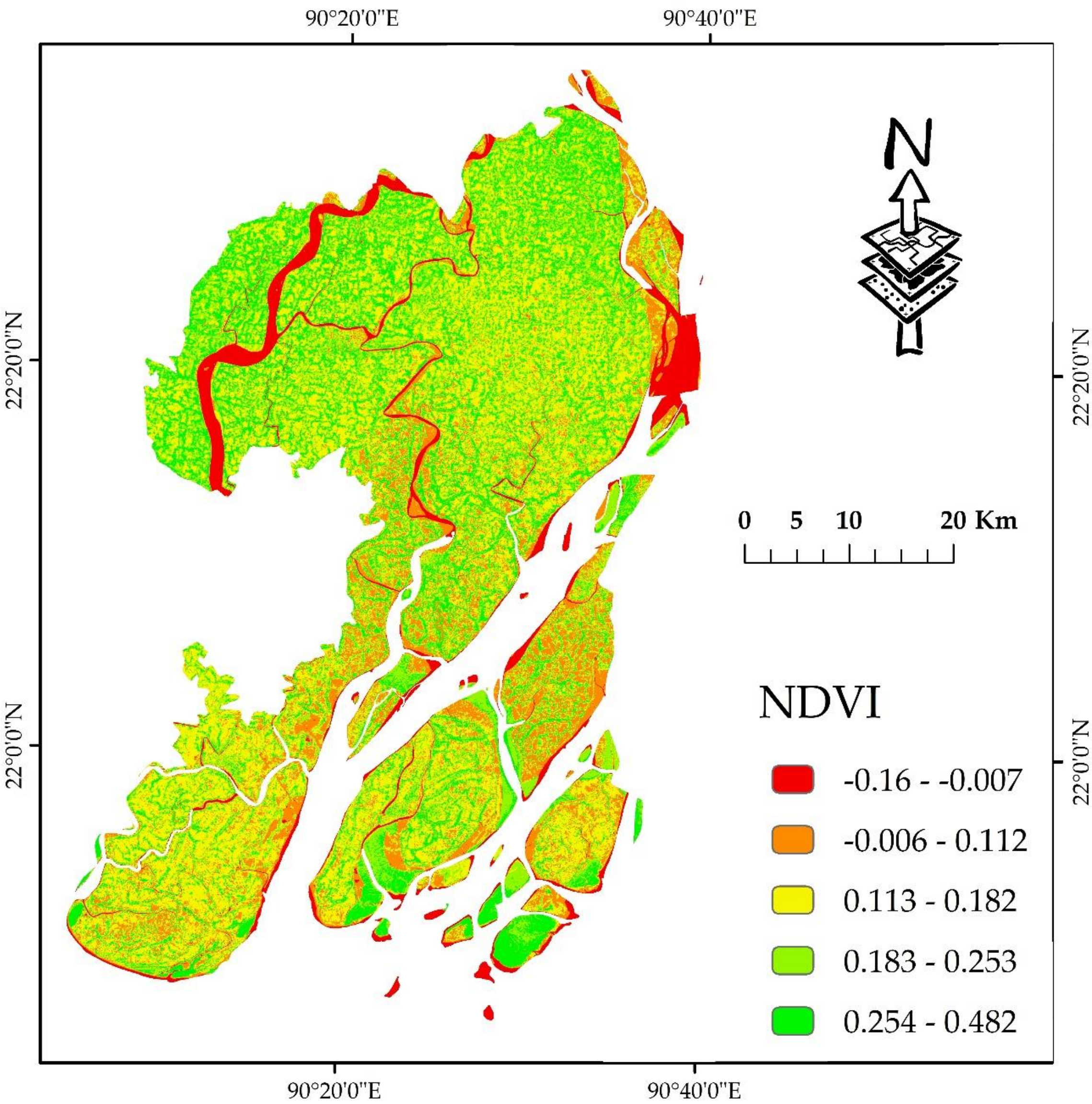

Fig. 4.27 NDVI map of Patuakhali district

Slope

The slope is one of the highest influential floods influencing factors for any area of the world as it directs the surface water runoff. Generally, the area which is flat and has less slope are more prone to flood and water logging because of lower surface runoff. Most of the Patuakhali district is generally flat and only have an average of 1^0 to 3^0 of slope which make this area very much vulnerable to flood risk (Figure 4.28).

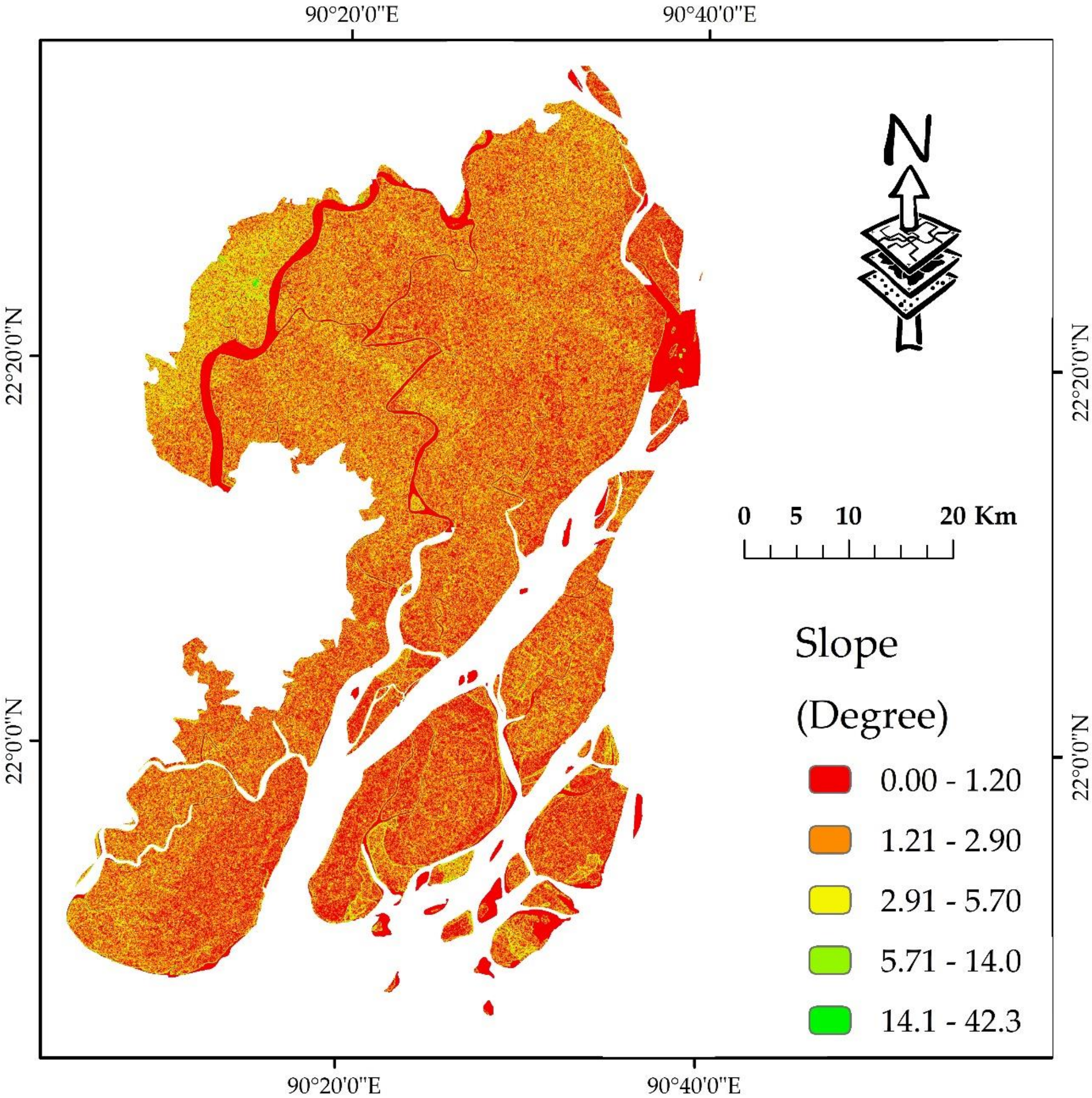

Fig. 4.28 Slope map of Patuakhali district

Distance to Streams or River Channel

Distance from streams, rivers, sea, and any other water body is another major flood influencing factor for any coastal area. The place closer to a water stream has more flood vulnerability compared to the place far from the stream. Most of the parts of the coastal Patuakhali district are situated very close to the river network and hence the distance to stream measure is also less which makes the area highly vulnerable to flooding (Figure 4.29).

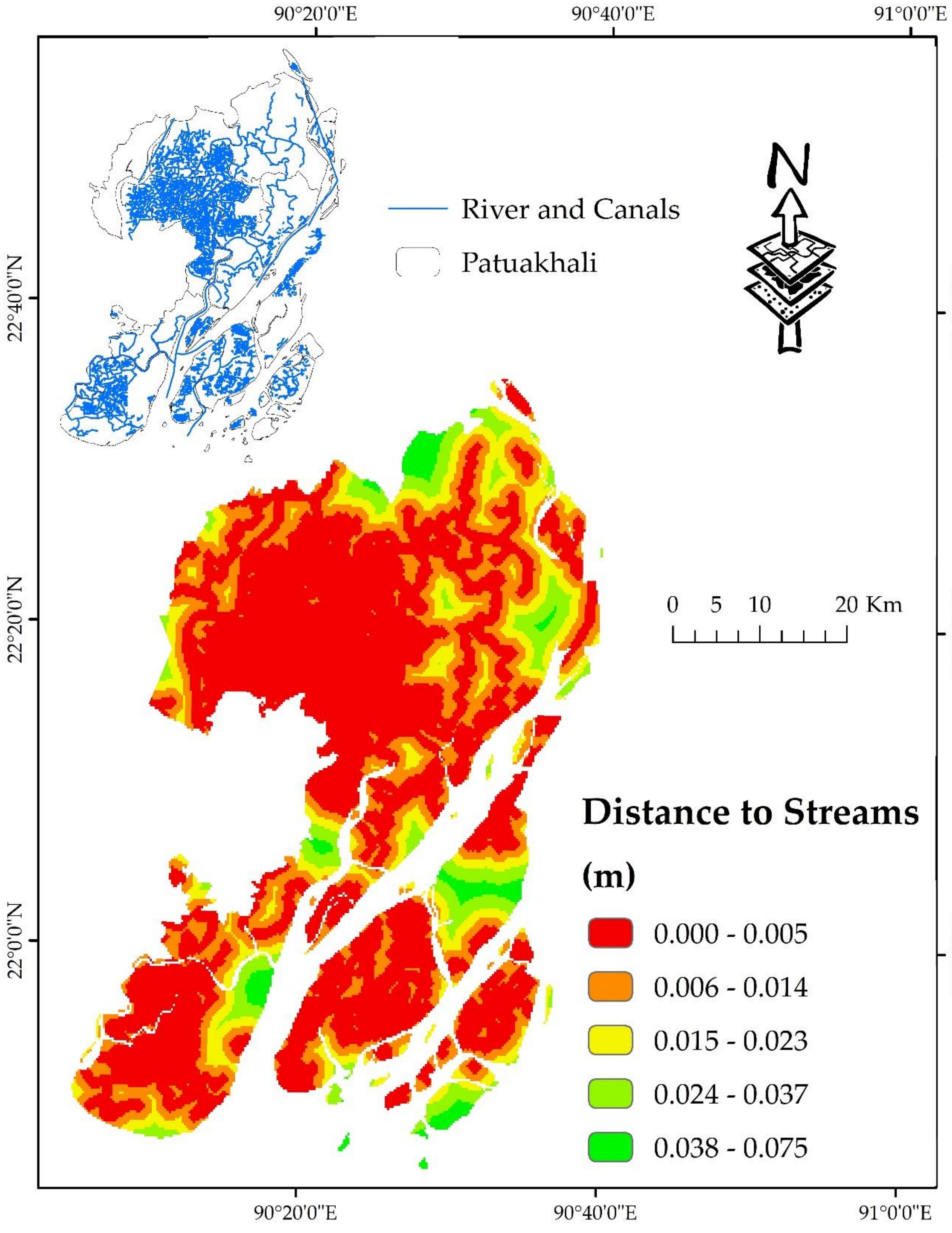

Fig. 4.29 Distance from streams map of Patuakhali district

Distance to Roads

Distance from roads is also an important factor that influences the occurrence of flood events. The presence of any roads and other road infrastructure creates disturbances to the natural flow of the water and thus occurs waterlogging and flooding. Coastal Patuakhali district has a strong road network makes most of the place closer to road infrastructure which also increases the vulnerability to flood (Figure 4.30).

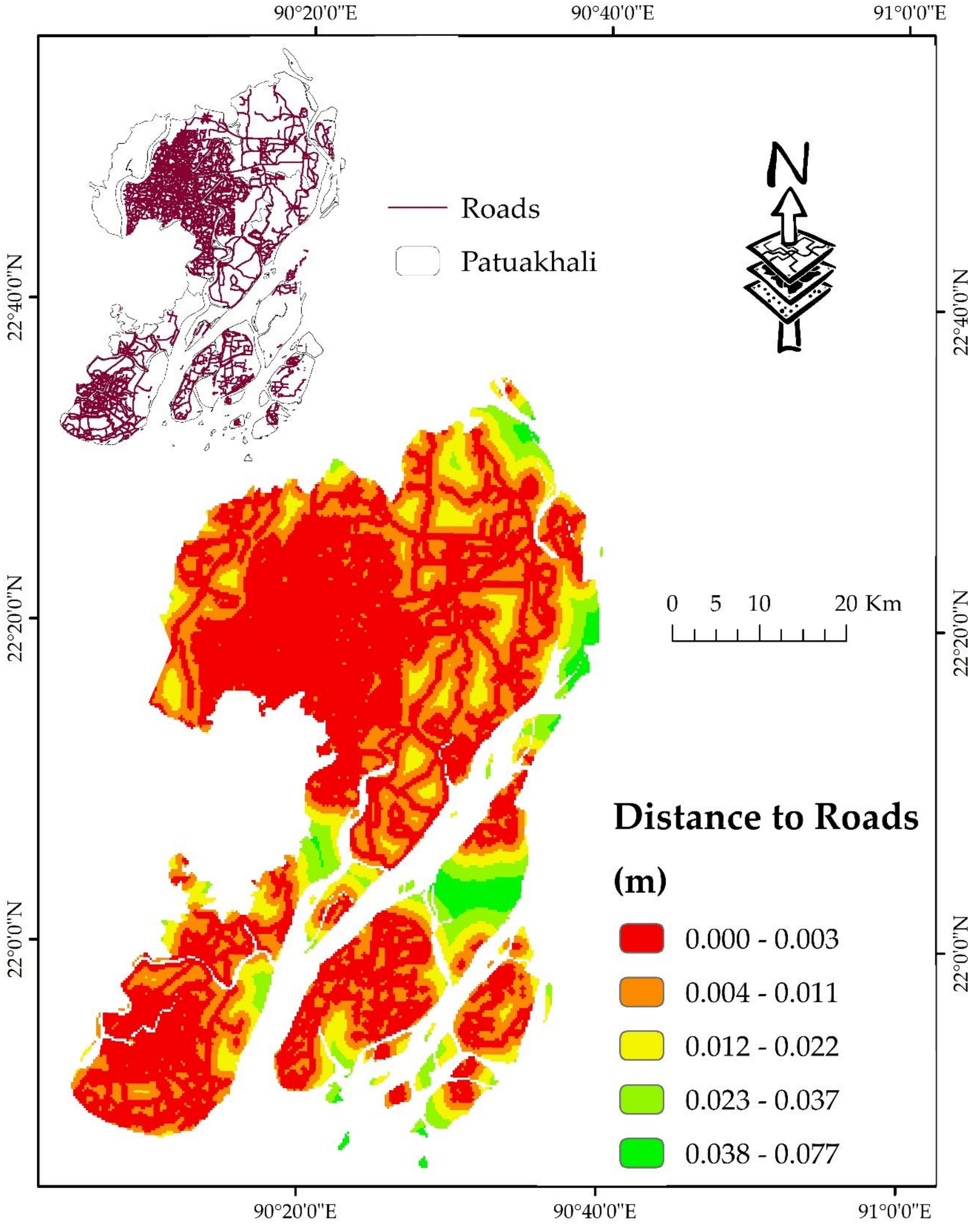

Fig. 4.30 Distance from roads map of Patuakhali district

Annual Rainfall

The rainfall map represents the average amount of yearly precipitation that occurred in the different parts of the Patuakhali district. The higher amount and prolonged rainfall create a greater amount of surface runoff and creates floods. The annual rainfall map of Patuakhali district was prepared using the gridded time-series rainfall data of this region (from 2011 to 2021) extracted from Climatic Research Unit, University of East Anglia.

According to the rainfall map, the coastal Patuakhali district experienced a higher amount of annual rainfall than the average rainfall recorded in Bangladesh in 2022 (Figure 4.31).

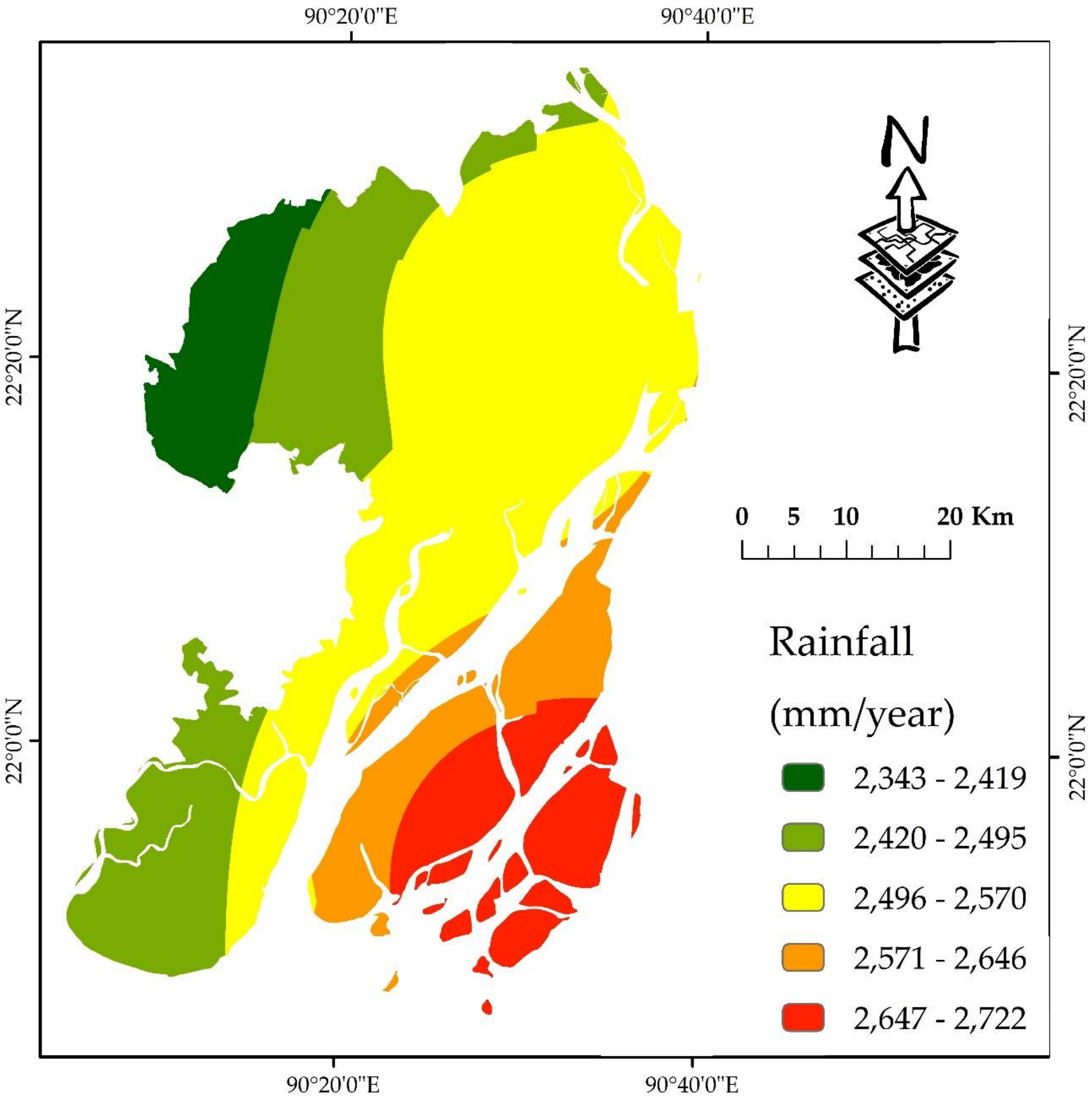

Fig. 4.31 Annual rainfall map of Patuakhali district

Topographic Wetness Index (TWI)

The topographic wetness index is used to quantify topographic control on hydrological processes which commonly combines local upslope contributing area and slope. The higher the TWI the lower the control on hydrological processes which finally creates higher vulnerability to flood. Most of the Patuakhali district has lower TWI which indicates a lower flood risk regarding topographic control of hydrological processes (Figure 4.32).

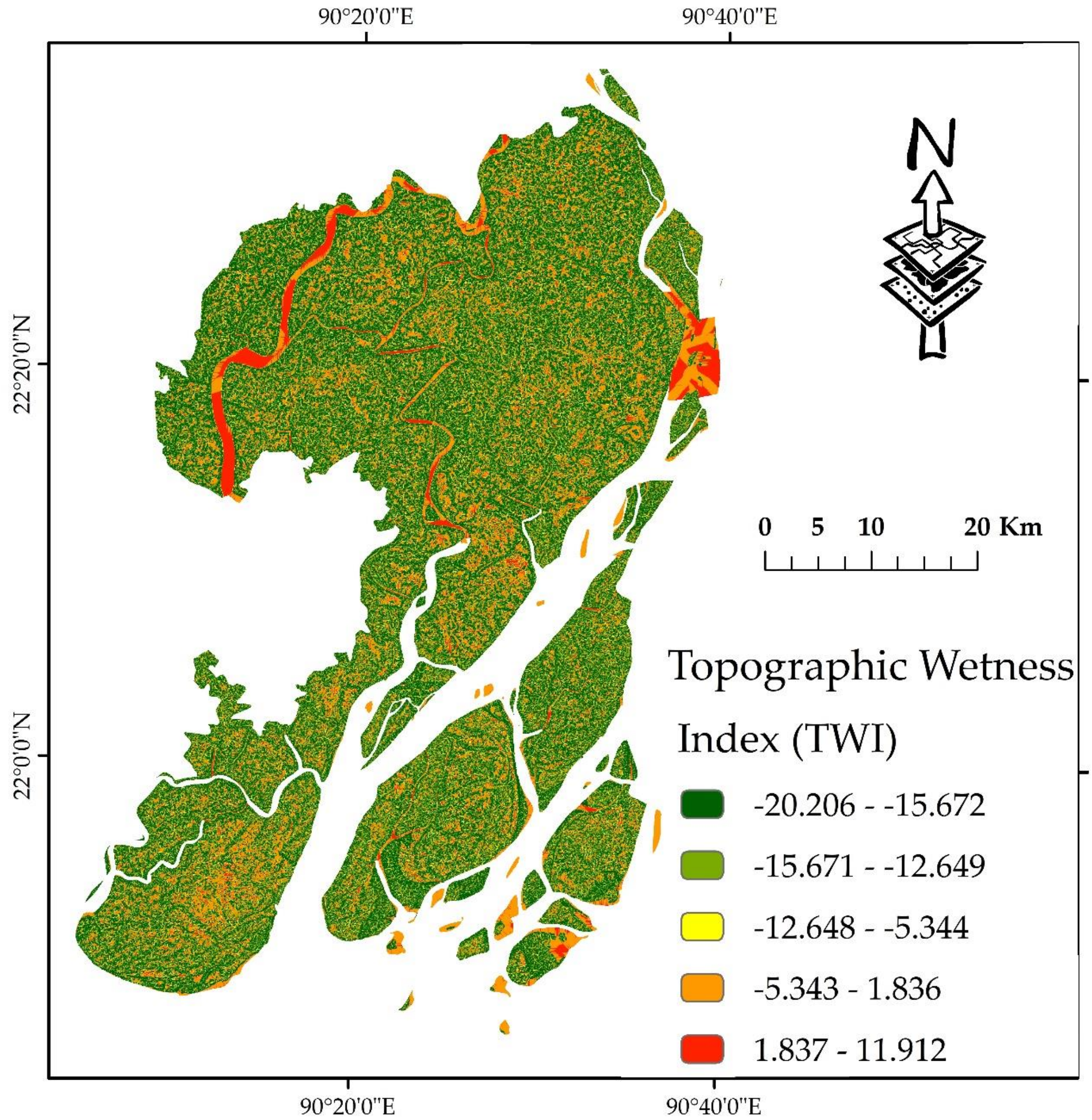

Fig. 4.32 Topographic Wetness Index (TWI) map of Patuakhali district

4.3.2 Influence Rank of Food Influencing Factors

The influence percentage and influence rank of all flood influencing factors were estimated using AHP based Multi-criteria Decision Analysis process in this study. The normalized matrix prepared from the pairwise comparisons of AHP analysis is arranged in Table 4.3 The dominant normalized principal Eigenvector of this matrix is also estimated from there. On a scale of 0 to 1 most of the criteria have less importance as they are close to 0. The slope has the highest normalized Eigenvector value which is 0.205 followed by distance from streams which got the second highest normalized Eigenvector value (0.197).

Table 4.3 Normalized pair-wise comparisons matrix

Matrix	LULC	Drainage Density	Soil texture	Elevation	NDVI	Slope	Distance to streams	Distance to roads	Rainfall	TWI	**Normalized principal Eigenvector**
LULC	0.09	0.10	0.12	0.09	0.08	0.08	0.08	0.10	0.11	0.12	0.0970
Drainage Density	0.06	0.07	0.06	0.06	0.05	0.07	0.07	0.07	0.08	0.08	0.0652
Soil texture	0.05	0.08	0.07	0.08	0.06	0.07	0.07	0.07	0.07	0.09	0.0720
Elevation	0.08	0.08	0.07	0.08	0.07	0.08	0.07	0.09	0.07	0.10	0.0783
NDVI	0.09	0.10	0.09	0.09	0.08	0.08	0.07	0.08	0.08	0.09	0.0859
Slope	0.24	0.20	0.20	0.21	0.23	0.21	0.23	0.20	0.19	0.14	0.2050
Distance to streams	0.23	0.19	0.19	0.21	0.23	0.18	0.20	0.20	0.19	0.14	0.1969
Distance to roads	0.08	0.08	0.09	0.08	0.09	0.09	0.08	0.09	0.09	0.12	0.0870
Rainfall	0.05	0.05	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.0663
TWI	0.04	0.04	0.04	0.04	0.04	0.07	0.07	0.04	0.05	0.05	0.0463

The influence percentage and priority rank of all flood influencing factors considered in this study were estimated from the Normalized principal Eigenvector value and represented in (Table 4.4). The slope degree of Patuakhali district got the highest weight percentage (20.50%) and ranked first flood influencing factor followed by the distance to stream (19.69%). LULC, NDVI, distance to roads, elevation, soil texture, and drainage density has a low to moderate contribution to occurring flood in the coastal Patuakhali district. On the other hand, the topographic wetness index has the lowest influence on the coastal flood occurrence in Patuakhali.

Table 4.4 Weights percentage and influence rank of all flood influencing variables

Sl.	Criterion	Weights (%)	Influence rank
1	Land use and land cover (LULC)	9.70	3
2	Drainage Density	6.52	9
3	Soil texture	7.20	7
4	Elevation	7.83	6
5	NDVI	8.59	5
6	Slope	20.50	1
7	Distance to streams	19.69	2
8	Distance to roads	8.70	4
9	Rainfall	6.63	8
10	Topographic Wetness Index (TWI)	4.63	10

4.3.3 Flood Risk Map of Patuakhali District

The flood risk map of the coastal Patuakhali district was prepared using a weighted overlay tool of ArcGIS combining all the flood influencing variables with their respective influence weight estimated through AHP and MCDA. Figure 4.33 represents the flood risk map of the coastal Patuakhali district developed in this study. This study categorized Patuakhali district into 5 risk zone i.e. very-low, low, moderate, high, and very-high risk zone based on their potential flood risk. In this categorization process, most of the central, north-central, and southern parts of the studied area fall into the higher-risk zone. The south-eastern char land and island area of Patuakhali district have a very high flood risk compared to other parts of this district. Furthermore, the central Patuakhali sadar area and Southern Kalapara upazila also have high flood risk according to this study’s investigation. On the other hand, most southern sea surrounding areas of this district are categorized as moderate risk zone though they are much more prone to cyclonic storm surges.

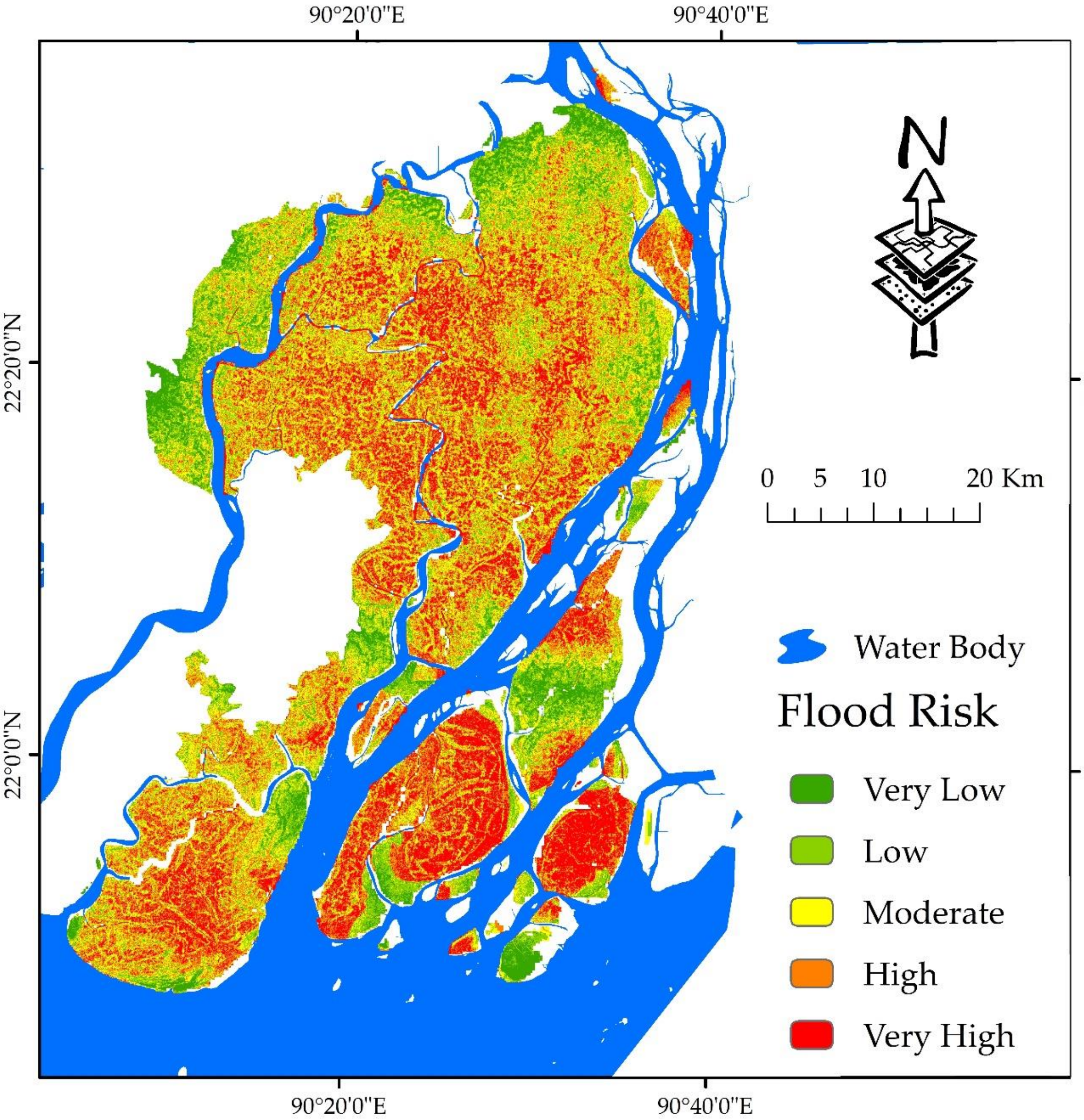

Fig. 4.33 Developed flood risk map of Patuakhali district

4.4 POTENTIAL FLOOD RISK MITIGATION MEASURES

After a successful assessment of coastal flood risk, potential flood risk map of Patuakhali district, risk zone categorization, and identification of the most vulnerable area, the last task of this study was to formulate effective strategies and measures for flood risk reduction. Potential flood reduction strategies and measures for the coastal Patuakhali district were developed with the participation of community people and based on their perceptions, and expert opinions. Before developing mitigation strategies, the actual reason behind the high risk of coastal flood in this area was analyzed by the community people. A lot of innovative and constructive flood risk reduction strategies were identified by the community where structural and non-structural strategies took place (Table 4.5).

Table 4.5 Potential flood risk mitigation strategies

Suggested Strategies	Responses (N)	Response (%)
Sector-specific basic vocational training and support for self-employment	147	9.98%
Engagement of local government to increase community capacity against flood	110	7.47%
Assistance from relatives in the pre, during, and post-flood period	2	0.14%
Awareness raising about different diseases outbreak	32	2.17%
Increase the resiliency of all houses and infrastructure	34	2.31%
Build sufficient flood shelter in the flood vulnerable areas	127	8.62%
Build or improve existing flood embankments and sluice gate	200	14.26%
Create alternative livelihood options for flood-vulnerable people	73	4.96%
Ensure fresh water for crop production	39	2.65%
Improve facility of existing flood shelters	100	6.79%
Improve flood shelter approach road for easy evacuation	105	7.13%
Increase the height of the sanitation basement	9	0.61%
Encourage people to pre-flood savings	17	1.15%
Prepare and maintain an effective flood management plan	88	5.97%
Provision of the community-based health care center	51	3.46%
Rainwater harvesting system for preserving the rainwater	34	2.31%
Raising the tube-well platform upper the high flood level	19	1.29%
Rising local government and community-level emergency disaster fund	25	1.70%
Salt-tolerant trees plantation along the coastline	15	1.02%
Support from NGOs for community capacity building against flood	108	7.33%
Increase the pond and fish enclosure’s bank height for flood protection	128	8.69%

4.4.1 Structural Measures

From the beginning of the coastal flood management and capacity building initiatives, structural development got the highest priority though still now some are lacking in terms of proper planning and maintenance of these structures. As the poor maintenance of coastal embankments, polders, and sluice gates influence the coastal flooding scenario most according to the coastal people, while developing flood mitigation strategies, firstly, all of them suggest building new embankment and structure where needed as well as improving the maintenance condition of existing flood embankments and sluice gate (Table 4.5). The need for sufficient new flood shelter construction in the most flood-vulnerable areas such as remote char land and islands is also highlighted in their proposal. There also have suggestions to improve the structural condition of existing flood shelters and make availability of all basic human needs and facilities during emergency periods along with the improvement of the shelter's approach road for easy evacuation. The resiliency of coastal houses and infrastructures should be improved and maintained according to the flood protection standard. To minimize damage to the drinking water and sanitation sector during a flood emergency, respondents have a suggestion to rise the tube well and toilet platform beyond the upper flood level as well as arrangement of rainwater harvesting system in all of the flood shelters.

4.4.2 Non-Structural Measures

Table 4.5 revealed that coastal people not only focused on the structural mitigation measures but they have provided equal importance to the non-structural mitigation and capacity-building strategies for reducing their risk of coastal flood events. Most of the respondents have a long desire to have a sector and vulnerable area-specific flood management plan for the coastal area. Ensuring available livelihood options for coastal people during the flood emergency period was also emphasized by respondents. For that, they have suggested arranging sector-specific basic vocational training facilities for them and helping them to become self-sufficient. Moreover, initiatives should take to establish local and community-level disaster and emergency funds as well as local people should be encouraged to have savings for emergencies. Local coastal people should be made aware of the outbreak and basic first aid treatment for different pandemic diseases during a flood to protect their children, women, and elder person from these diseases. Additionally, people also believed that adequate support from local government authorities, NGOs, and INGOs along with relatives and surrounding capable people could help coastal communities build their capacity and make them capable and strong enough to fight against flood both structurally, physically, and mentally.

Chapter 5: DISCUSSIONS

This chapter makes a structural discussion, meaningful interpretation, and critical evaluation of the significance of the results described in the previous chapter. This study's estimated coastal flood risk for Patuakhali district along with their GIS and RS-based map of flood risk is critically evaluated here with reference to previous pieces of literature. Finally, the effectiveness of all suggested flood risk mitigation strategies is also discussed in this chapter.

Due to flat topography and the presence of Himalayan mountains on the northern side of the country from where most of the rivers carry a lot of water, all the area of Bangladesh is highly vulnerable to flood and every year several flood events occurred in different parts of the country [1], [7], [12], [13], [30]. Bangladesh is known to the world as one of the most flood-prone countries due to its unique geographical location and coastal flooding has become the most commonly occurring and devastating in coastal Bangladesh [2]–[6]. Despite its huge importance and significance, the detailed flood risk and vulnerability assessment are often underestimated in coastal Bangladesh. Moreover, due to the interaction between land, sea, and atmosphere, as well as the highly dynamic nature of coastal zones, assessing and anticipating the actual risk of coastal flooding is truly a challenging endeavor. Therefore, a detailed flood risk and vulnerability assessment was essential for the coastal Patuakhali district which will ultimately help respective authorities to improve a detailed flood risk management plan and sustainable flood mitigation strategies in coastal Bangladesh [15] [64], [91].

This study applied a combination of people's perception-based risk assessment along with the MCDA, AHP, and GIS and RS-based flood risk mapping for the coastal Patuakhali district [106], [122]. This integrated GIS-based techniques and people's perceptions and knowledge while weighting different flood influencing factors for flood risk assessment through an analytical hierarchy process based multi-criteria decision analysis process combinedly provides a comprehensive scenario of coastal flood risk result [106]. In this process, people's perception-based process and GIS-based multi-criteria decision analysis mutually benefited from each other's. Moreover, the weighted influence score and rank of all flood influencing factors from AHP-based MCDA analysis helped this study to draw a coastal flood risk map correctly. On the other hand, prepared GIS maps of each factor assisted while assigning the correct weight or influence factor score [82]. There also have the scope to compare and triangulate results generated from each of the methods and thus a better anticipation of flood risk and risk zoning was possible. Similar to this study, some studies all over the world also applied AHP based MCDA method for the assessment of coastal flooding risk [129]–[131].

During the investigation, this study found, while all other parts of the country are affected by one flash flood, rain-fed surface flood, or river flood, the coastal area of Bangladesh are frequently affected by river flood and cyclone and storm surge induced coastal flood simultaneously [11], [30], [70]. The primary source of flood risk in the coastal Patuakhali district is found to be generated from the Bay of Bengal where a lot of cyclonic storms are generated every year [18], [19], [23]. Moreover, the majority of land here is less than 4-7 m above the mean sea level which makes this area more vulnerable to frequent flooding (Figure 4.27). This study found that the flood water here usually didn't stay for a long period of time and this is due to most of the coastal floods generated by cyclonic storm surges. Additionally, a coastal flood has a high probability to occur once every year and also has a high likelihood of property and infrastructure damage as well as loss of lives. Residence surrounding the Kuakata tourist spot was found to be experiencing frequent floods and the most devastating nature of flood people live far from this area as these areas mainly comprise different in-built artificial infrastructure where there also has less amount of vegetation to protect these infrastructures and people live in. The flood impact and devastation has increased in the coastal area as the coastal area has a high population density and around 50% of coastal people live with in a 92 to 153 m distance from the most flood vulnerable areas [110].

For the protection of this area from the severe devastation of floods and cyclonic storms, several structural developments such as protective embankments and polders along the coastlines have been taking place since 1960 to till now [12]. Though these structural developments protect the coastal area from regular tidal surges and coastal flooding, these embankments and polders frequently block excessive amounts of freshwater coming from upstream areas during winter causing water congestion and coastal flooding due to a lack of adequate water regulation system here. Moreover, the poor maintenance of these embankments and sluicegates influences the flooding scenario in coastal Bangladesh by long time trapping a huge amount of water coming from the sea during high tide and cyclonic storms and making the area vulnerable to coastal flood [11], [37]. Similar to this a recent in-depth study tried to assess the influence of coastal embankments in the flooding scenario in the southwestern coastal region of Bangladesh based on a GIS-based approach from 1988 to 2012. They also found that, due to inadequate drainage facilities, coastal embankments and polders have exacerbated more frequent coastal flooding and flood impacts during extreme cyclonic storm surge events [12].

While assessing the capacity of the coastal community against flooding, this study found there is still lacking alternative livelihood options available during any flood events. Most of the coastal community people didn’t have enough capacity to withstand upcoming coastal flood devastation though having moderate to high flood shelters available there. Furthermore, most of the sectors which have the potentiality to be affected by coastal flood devastation such as livelihood, food and agriculture, and infrastructure have appeared to have a lower or no capacity at all to withstand the devastations of coastal flood. Most importantly, most of the polders, embankments, and sluice gates don’t have up-to-the-mark maintenance capacity which makes the coastal area more vulnerable to coastal flood [12].

From both people’s perception and experience base assessment and the GIS and RS-based method in combination with AHP and MCDA, this study anticipated a high flood risk in the coastal Patuakhali district which is in line with findings of the flood risk assessment and mapping study conducted in the coastal Kalapara upazila of Patuakhali district [106]. Similar to this study’s findings, the Global Facility for Disaster Reduction and Recovery (GFDRR) has previously rated Patuakhali district as highly vulnerable to the effect of coastal flooding [36]. In this study, people’s perception and experience-based assessment of coastal flood risk for Patuakhali district revealed that there exists a high flood risk which measured at 0.886 on a low to high scale ranging from 0 to 1. Before risk analysis, calculated hazard, vulnerability, and capacity index value for the study area was 0.765, 0.644, and 0.556 respectively. All these indices' values highlighted that, though having a moderate hazard and vulnerability score, the low capacity to fight against coastal flood triggered the high coastal flood risk in the studied area. So, there in an urgent need to increase the capacity of coastal communities against coastal flooding besides flood risk management planning.

Similar to people’s perception-based assessment method, GIS and RS based method in combination with AHP and MCDA categorized most of the Patuakhali district into moderate to highly vulnerable risk zone. According to this process, the central, north-central, and southern regions of Patuakhali have higher flood risk compared to other areas. The central part of Patuakhali district has a high population density and has gone through advancement in infrastructural development in recent years which made this area more vulnerable to coastal flood risk. The south-eastern char land and island area of Patuakhali district have a very high flood risk compared to the southwestern area of this district due to having lower elevation and flat topography [106]. Another reason for this high vulnerability occurred as these areas are bounded by the major rivers and seas from all around. Furthermore, Southern Kalapara upazila and Kuakata tourist areas also have high flood risk according to this study's investigation. On the other hand, most southern sea surrounding areas of this district are categorized as moderate risk zone though they are much more prone to cyclonic storm surges. This happened due to the presence of dense vegetation area and vegetation barriers along the coastline. Moreover, these areas also have less building area compared to other parts of this district. All these findings are very much similar to another recent study conducted in the coastal Kalapara upazila of Bangladesh [106].

While, weighting the influence percentage of all flood influencing factors using the AHP-based MCDA process this study found flat slope gradient and the proximity to stream, river, and sea contribute most to the occurrence of coastal floods among all other factors. This occurred as the major source of coastal flood occurred from cyclonic storm surges, sea level rise, and upstream water overflow through river channels and other water streams. On the other hand, LULC, NDVI, distance to roads, elevation, soil texture, and drainage density has low to moderate contribution to occurring flood in the coastal Patuakhali district as they have less control over the coastal floodwater regulation.

As the coastal Patuakhali district is highly vulnerable to the risk and damage of coastal flooding, there requires urgent initiatives and strategies to mitigate the risk of coastal flooding as well as enhance coastal flood protection capacity. For effective flood management, flood mitigation activities should not be a standalone approach rather both structural and non-structural flood mitigation strategies should be integrated with different water and river management activities as well as urban planning and land use zoning. Furthermore, sustainable flood management should be ensured through the combination of both structural and non-structural measures at a time. Moreover, it should be planned and executed with a participatory approach through the proactive engagement of the community [30]. That's why, this study not only puts emphasis on different structural flood mitigation measures but equal importance was also on the non-structural flood mitigation and capacity-building strategies which will also bring sustainability to the flood risk reduction plan.

This study explored a set of structural and non-structural coastal flood protection and flood risk mitigation strategies with the active participation of community people which were based on their perceptions, and expert opinions. Bangladesh already has employed coastal embankment, polder, and sluice gates development towards management of coastal flooding, particularly from high tides and storm surges induced flood events. However, the poor maintenance of these coastal embankments, polders, and sluice gates became counterproductive and influenced the coastal flooding scenario most according to the coastal people [37]. Moreover, most of the coastal roads network in Bangladesh have been constructed completely ignoring the necessity of having drainage infrastructure such as culverts, bridges, and regulators, which ultimately increase the vulnerability of coastal flood risk [37]. So, this study suggested to improve the maintenance condition of existing flood embankments, polders, roads, and sluice gates as well as the design of all these infrastructures should be modified with the provision of adequate water drainage infrastructures and regulators.

Different aspects of climate change and climate change-induced adverse consequences should also be considered for existing embankments as well as for the newly designed embankment and structure where needed. A sense of ownership of these embankments, polders, and sluice gates should be created among the local communities as their active participation would be critical for the effective monitoring and maintenance of these coastal embankments and flow regulators. The National Water Policy 1999 has already given a clear mandate for the formation of associations of water users and water managers, and the participation of these local level organizations at all levels of planning and execution of projects, and more importantly, allowing them to take part in operations and maintenance activities [37].

Though Bangladesh has gone far with the plan to construct a sufficient amount of flood and cyclone shelters all over the world after independence, there is still a lack of sufficient flood and cyclone shelters in the coastal remote and vulnerable areas especially in the char lands due to high population density there. So, the construction of required flood shelters in the most flood-vulnerable areas such as remote char land and islands is very urgent. Besides, there is also a need to improve the structural condition of existing flood shelters with the provision of all basic facilities during emergency periods along with the shelter's approach road improvement for an easy evacuation process. Moreover, As the coastal community is frequently affected by severe cyclonic storms and flood events, the coastal development authorities should take immediate action to renovate all the coastal houses and infrastructure as per the flood protection standard to increase their resiliency. Additionally, rising the platform of coastal tube-well and toilet beyond the historic maximum flood height level could be a possible way for the provision of pure drinking water supply and basic sanitation facilities during flood emergencies in the coastal area.

Non-structural flood protection strategies mainly comprised effective early warning systems, different awareness-raising initiatives, and most importantly capacity building initiatives. For the development of the coastal community's capacity against flooding, there should have sector and area-specific flood management plans for the coastal area as different sectors and areas have different levels of flood vulnerability based on their susceptibility status. Ensuring sufficient livelihood options and availability of alternative options for the coastal marginalized people during the flood emergency period is another important task for their capacity development. Arrangement of sector-specific and skill-based basic vocational training facilities for these coastal people could help them to become skilled and self-sufficient as well as will explore the chance to engage in a diversified work environment. Moreover, the establishment of local and community-level emergency disaster funds will help the coastal community to bear the maintenance of local-level flood protective infrastructures and enable them to recover from small-scale flood damage. Individual household-level saving for emergencies will also support them during flood events. As different waterborne diseases are outbreaks during floods, coastal people should be made aware of the outbreak and first-hand treatment of these waterborne diseases.

Most importantly, an effective early warning and warning dissemination system for flood and cyclonic storm surges will make people save their life, property, and infrastructures by taking appropriate precaution strategies [110]. The ongoing trend towards more effective disaster early warning and response in Bangladesh is also a viable adaptation strategy for flooding that might result from enhanced cyclone intensity that is projected under climate change. Continuous monitoring of the formation of coastal floods and cyclones in the Bay of Bengal involving flood and cyclone modeling, and satellite-based technology; monitoring the gradual development and tracking; issuance of flood and cyclone warning well ahead of time for the people to take precautionary measures; evacuation from homesteads and relocation in multi-purpose shelters and concrete buildings all may be considered as highly useful and proven adaptation strategies. Already such measures have allowed thousands of coastal people to successfully avoid loss of lives during two high-intensity cyclonic events: one occurring in 1994 and the other in 1997 [37]. An integrated and comprehensive flood and cyclone tracking, warning, and dissemination system with the cooperation from both government and different NGOs such as BMD, Red-crescent, and CPP volunteers saving coastal people's lives and property from a long ago.

Finally, both structural and non-structural flood protection strategies are always mutually dependent for their maximum effectiveness in the most complex and dynamic coastal environment. Non-structural measures, knowledge, awareness, and capacity development helps for the need-based effective design and proper implementation of different structural measures as well as ensure the appropriate use and maintenance of these structures. On the other hand, different structural measures for flood protection inspire and helps the community and people to increase and value their awareness and capacity regarding flood risk as well as make them motivated to ensure the proper use of these structures.

Chapter 6: CONCLUSIONS

Chapter 6 summarizes all the previously discussed contents from the introduction, methodology, results, and discussion sections. It also contains general and key findings, conclusions, limitations, and practical implications of this present study as well as direction and recommendations for future studies.

6.1 KEY FINDINGS

During the literature review, this study found that the coastal municipality and any other government authorities or individuals haven't either yet done any detailed flood risk assessment or structural flood risk management plan for the coastal Patuakhali district. This study applied an integrated GIS and RS-based advanced techniques along with people's perceptions and knowledge-based methods in the most southern coastal Patuakhali district of Bangladesh for the assessment, mapping, vulnerable area categorization, and mitigation strategies for the coastal flood risk. The following conclusions were drawn from the results;

a) While all other parts of the country are affected by one of the flash floods, rain-fed surface floods, or river floods, the coastal area of Bangladesh are frequently affected by river flood and cyclone and storm surge induced coastal flood simultaneously.

b) The primary source of flood risk in the coastal Patuakhali district is found to be generated from the Bay of Bengal where a lot of cyclonic storms are generated every year.

c) The flood impact and devastation has increased in the coastal area as the coastal area has a high population density and around 50% of coastal people live with in a 92 to 153 m distance from the most flood vulnerable areas.

d) The poor maintenance of embankments and sluice-gates influences the flooding scenario in coastal Bangladesh by long time trapping a huge amount of water coming from the sea during high tide and cyclonic storms and making the area vulnerable to coastal flood.

e) The integration of GIS and RS techniques with people's perceptions and knowledge in this study provided the scope to compare and triangulate results generated from each of the methods and thus a better anticipation of flood risk and risk zoning was possible.

f) From both people's perception and experience base assessment and the GIS and RS-based method in combination with AHP and MCDA, this study anticipated a high flood risk in the coastal Patuakhali district.

g) Though having a moderate hazard (0.765) and vulnerability (0.644) score, the low capacity (0.556) to fight against coastal flood triggered the high coastal flood risk in the studied area.

h) In the flood causative factor-based GIS and RS mapping process, the central, north-central, southern, and south-eastern char and island area of Patuakhali district has been identified to have very higher flood risk compared to other areas of this district due to having high population density, infrastructural advancement, lower elevation, flat topography, and less vegetation coverage.

i) This study also recognized flat slope gradient and the proximity to streams, rivers, and sea as the most contributing factor to the occurrence of coastal flooding.

j) Structural and non-structural flood protection strategies are always mutually dependent for their maximum effectiveness in the most complex and dynamic coastal environment. So, flood mitigation activities should not be a standalone approach.

k) Both the structural and non-structural flood mitigation strategies should be integrated with different water and river management activities as well as urban planning and land use zoning.

l) There is an urgent need to increase the capacity of coastal communities against coastal flooding, effective warning systems, and community awareness beside different structural advancements for flood risk management.

m) Moreover, a sense of ownership of all the flood-protective structures should be created among the local people through the proactive engagement of the community with the design, planning construction, and maintenance of these structures for sustainable management of these structures.

n) All the findings of this study are very relevant for the respective authorities and decision makers which will ultimately help them to improve a detailed flood risk management plan and sustainable flood mitigation strategies for coastal Bangladesh.

o) These findings also imply that the combination of suggested structural and non-structural mitigation strategies could be a successful approach for coastal flood risk reduction and effective coastal flood management.

6.2 LIMITATIONS OF THE STUDY

Through the design, execution as well as during findings interpretation, this study took all the limitations of this study seriously and tried to overcome those. However, this study somehow failed to overcome some of its limitations. Among these limitations, firstly, this study didn't recognize the population dynamics of the coastal area while mapping the coastal flood risk. Additionally, through different global warming and climate change-induced phenomena such as sea-level rise, changing rainfall patterns, and changing the severity and extent of cyclonic storms, heat waves can have an impact on flooding scenarios and can exacerbate flood risks in coastal areas, particularly in Patuakhali district, all these are not considered in this present study. Moreover, the future climate change scenarios and their potential impacts on coastal flooding also didn't consider in this study.

6.3 PRACTICAL IMPLICATION

This study provides a comprehensive assessment and understanding of coastal flood risk in the central coastal Patuakhali district. The findings of this study will facilitate a better understanding of flood hazards, vulnerability, and risk for improved decision-making, mitigation measures, and preparedness activities in Bangladesh. The knowledge and information gathered from the flood risk assessment and flood risk maps in this study will be helpful in several ways, such as:

- ✓ Increased coastal capacity against flooding.
- ✓ Raise awareness among people at risk.
- ✓ Proper maintenance of flood-protective infrastructures.
- ✓ Provide land-use planning and urban development information, investment planning, and priority setting.
- ✓ Assess the feasibility and efficiency of structural and non-structural flood control measures.
- ✓ Creation of a local community-level disaster emergency fund.
- ✓ A sense of ownership among the local community on different flood protective infrastructures.
- ✓ Allow disaster managers as well as the local community to prepare for emergencies.

Assessment results of coastal flood risk, flood risk mapping, and the most vulnerable area identification in the coastal Patuakhali district will play an essential role in effective flood management in the coastal Patuakhali district.

Moreover, decisions regarding any development activities and public, private investment in the coastal flood risk zones of Bangladesh will be influenced by the findings of this study.

6.4 RECOMMENDATION FOR FURTHER STUDY

Future flood risk assessment and risk mapping studies should be on a broader scale and might consider population dynamics and different global warming and climate change-induced phenomena such as sea-level rise, changing rainfall patterns, changing the severity and extent of cyclonic storms, heat waves, etc. Future climate change scenarios and their potential impacts on coastal flooding should be also considered by these studies. A detailed future flood simulation model under the future climate change scenarios can be generated with the help of available GIS and RS-based technologies. Moreover, future studies should pay more attention to gaps in current disaster management policy and should also try to develop an effective policy for coastal flood management.

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Appendices

Appendix A: [Household Survey Questionnaire]

[N.B.: This questionnaire is only for academic purposes. All the information collected under the MSc research project entitled "Assessment of Coastal Flood Risks in Patuakhali District".]

Informed consent:

This questionnaire should be completed at the household level. Politely introduce yourself and ask permission before entering. Briefings explain the purpose of the questionnaire and ask permission. DO NOT PROCEED if permission is not given or if household members appear uncomfortable with the process. Instead, choose another household.

Village: …………………………… District: …………………………..

Name..		**Age**………
Gender:	☐ Male ☐ Female	**Family member:**
Level of education	☐ No Education ☐ Primary Level ☐ High School/College ☐ Bachelors ☐ Other	
Employment status:	☐ Employed	☐ Unemployed
Income level	☐ Less than 10,000Tk. ☐ 10,000 to 20,000Tk. ☐ 20,000 to 30,000Tk. ☐ 30,000 to 40,000Tk. ☐ 40,000 to 50,000Tk. ☐ 50,000 to 70,000Tk. ☐ 70,000 to 1,00,000Tk ☐ Up to 1,00,000Tk.	
Occupation		
Category of house	☐ Pucca ☐ Semi pucca ☐ Kutcha ☐ Jupri	

1. What is the primary livelihood strategy of your household?

☐ Crop Production	☐ Horticultural production
☐ Trading	☐ Manufacturing
☐ Livestock production	☐ Wage labor
☐ Fishing	☐ Other………………………………………..

2. Have you faced any coastal flood disasters?

☐ **Yes**	☐ No

3. How many times did you face a coastal flood in a year?

☐ Less than 5 times	☐ 5-10 times	☐ More than 10 times

4. **What is the predictability/occurring month of coastal flooding?**

☐ Anytime	Name of Month ……

5. **What do you think about the chance/probability of future coastal flood occurrence?**

Very High (within a year)	High (within 3 years)	Moderate (within 5 years)	Low (within 10 years)	Very Low (within 20 years)

6. **What is the likelihood of future damage by coastal floods?**

Very High (>80%)	High (50-80%)	Moderate (30-50%)	Low (10-30%)	Very Low (<10%)

7. **What are the chances of losing coastal people's lives during a coastal flood?**

Very High (>80%)	High (50-80%)	Moderate (30-50%)	Low (10-30%)	Very Low (<10%)

8. **What is the maximum height of flood measured above the ground floor during extreme coastal flooding?**

Very High (>3.01 m)	High (1.5 to 3.01 m)	Moderate (0.92 to 1.5 m)	Low (>0.3 m)	Very Low (<0.3 m)

9. **What is the maximum duration of staying flood water (in days) during extreme coastal flooding?**

Very High (>15 days)	High (>7 days)	Moderate (6-7 days)	Low (3-5 days)	Very Low (1-2)

10. **What type of impact has it on your livelihood because of coastal floods?**

Sector	**Priority**				
	Very High	**High**	**Medium**	**Low**	**Very Low**
Infrastructure:					
Crop Agriculture:					
Fisheries:					
Livestock					
Sanitation:					
Health:					
Others:					

11. **Considering you as a coastal community member, how much are you afraid of coastal floods?**

Very much Afraid (>80%)	Afraid (50-80%)	Neutral (30-50%)	Slightly afraid (10-20%)	Not afraid (0%)

12. **Do people live in a potential coastal flood-vulnerable area? What is the distance (In Meter)?**

Very Near (<30)	Near (30-92)	Neutral (92-152)	Far (152-304)	Very Far (>304)

13. **The density of the population living in the coastal flood-vulnerable area?**

☐ High (>1000/Km^2)	☐ Medium (500-1000/Km^2)	☐ Low (<500/Km^2)

14. **What is the resiliency status of the community's houses against coastal flooding?**

☐ High (withstand severe flood)	☐ Medium (withstand medium flood)	☐ Low (didn't withstand low flood)	☐ Others specify………………

15. **What is the socio-economic status of the community against coastal flooding?**

☐ **Weak** (economically not sound to run the livelihood as well as after a small flood)	☐ **Medium** (economically sound to run the livelihood as well as after a medium flood)	☐ **Strong** (economically sound to run the livelihood as well as after a strong flood)

16. **What is the physical structure condition of the community against coastal flooding?**

☐ Weak	☐ Medium	☐ Strong

17. **Does the household have access to a tube well for drinking water during coastal flooding?**

☐ **Yes**	☐ No

18. **Does the household have access to an improved toilet during coastal flooding?**

☐ **Yes**	☐ No

19. **Does the household have access to electricity during coastal flooding?**

☐ **Yes**	☐ No

20. **Does the household have access to public transportation during coastal flooding?**

☐ **Yes**	☐ No

21. What is your knowledge level about the coastal flood striking season?

☐ Good	☐ Moderate	☐ Poor

22. Do you get any forecasting and an early warning message about the coastal flood?

☐ **Yes**	☐ No

How can these facilities be improved?

....

23. Status of alternative livelihood sources/options during the flood?

☐ Good	☐ Moderate	☐ Poor

24. What do you think about people's capability to cope with the future coastal flood?

Very High (>80%)	High (50-80%)	Moderate (30-50%)	Low (10-30%)	Very Low (<10%)

25. Does your community have a flood preparedness plan?

☐ **Yes**	☐ No

If yes,

26. What is the present status of the community flood preparedness plan?

☐ Good	☐ Moderate	☐ Poor

Describe the existing community flood preparedness plan

…..…………………………………………………………………………………………………

27. Where do you take shelter during the coastal flood?

☐ Shelter	☐ School building	☐ Roads	☐ Own residence	☐ Relative residence

28. How far is the shelter from your house?

☐ Adjacent	☐ Medium	☐ Far away

29. Were there any extra facilities for women, children, and the disabled?

☐ Yes	☐ No

If yes, what type?

----

30. Does your community have any volunteer groups to help people during emergencies?

☐ Yes	☐ No

31. Did you get any relief during the coastal flood period?

☐ Yes	☐ No

If yes, from where?

----

32. What type of relief do you get after the coastal flood?

☐ Dry foods	☐ Medicines
☐ Blanket	☐ Oral saline
☐ Water purifying tablet	Others:……………………………..

33. Did you practice any indigenous knowledge during coastal flooding?

☐ Yes	☐ No

If yes, what type of indigenous knowledge?

----

34. What is the existing govt. resource level to minimize coastal flood risk?

☐ Good	☐ Moderate	☐ Poor

35. Have you any structural or non-structural assets /facilities to protect from cyclone-induced damage?

☐ Yes	☐ No

If yes, what type?

----

36. Did you attend any coastal flood emergency or resiliency-related training programs?

☐ Yes	☐ No

If yes, the attempt of the program was-----------------?

☐ Not effective	☐ Moderately effective	☐ Highly effective	☐ Very highly effective

37. Is there any embankment/polders in this area?

☐ Yes	☐ No

If yes, then please write down about its maintenance.

----

38. Is there any sluice gate in this area?

☐ Yes	☐ No

If yes, does it maintain properly?

☐ Yes	☐ No

39. What capacities exist in your locality or own to cope with the coastal flood?

Sector	*Priority*			
	No	*High*	*Medium*	*Low*
Infrastructure:				
Alternative livelihood:				
Preservation of food:				
Embankment:				
Power backup:				
Seed, fertilizer:				
Receiving relief:				
Others:				

40. What strategies will be suitable for the potential flood risk reduction?

☐ Create alternative livelihood options	☐ Arrange the sector basis training system for establishing the self-employment
☐ Pre-disaster savings	☐ Support from NGOs
☐ Rising disaster fund	☐ Assistance from the local government
☐ Rising house plinth level	☐ Build more flood shelter
☐ Build or improve flood embankments and sluice gate	☐ Improve flood shelter approach road
☐ Build flood-resilient house	☐ Improve the facility of the existing flood shelter
☐ Increase the height of the bank of ponds ☐ and gathers	☐ Raising the platform of the tube well upper the high flood level
☐ Salt-tolerant trees plantation	☐ Increase the height of the sanitation basement
☐ Rainwater harvesting system for preserving the rainwater	☐ Awareness raising about different diseases
☐ Ensure fresh water for crop production	☐ Provision of the community-based health care center
☐ Assistance from relatives	☐ Prepare an effective flood management plan
☐ Others……………………………………………………………………………………	

Thanks for Your Cordial Cooperation

……………... ……………………………………

Signature of the Interviewer Signature of the Interviewee

Appendix B: [Checklist for MCDA-AHP Pairwise Comparison]

Please define which criterion is more important, and how much more on a scale of 1 to 9 where 1- Equal Importance, 3- Moderate importance, 5- Strong importance, 7- Very strong importance, 9- Extreme importance (2,4,6,8 values in-between).

Table 6.1 Checklist for the pairwise comparisons in the Analytical Hierarchy Process (AHP)

Comparison Number	**Option A**	**Option B**	**More important? (A or B)**	**Importance Scale (Use a scale of 1-9)**
1.	LULC	Drainage Density		
2.	LULC	Soil texture		
3.	LULC	Elevation		
4.	LULC	NDVI		
5.	LULC	Slope		
6.	LULC	Distance to streams		
7.	LULC	Distance to roads		
8.	LULC	Rainfall		
9.	LULC	TWI		
10.	Drainage Density	Soil texture		
11.	Drainage Density	Elevation		
12.	Drainage Density	NDVI		
13.	Drainage Density	Slope		
14.	Drainage Density	Distance to streams		
15.	Drainage Density	Distance to roads		
16.	Drainage Density	Rainfall		
17.	Drainage Density	TWI		
18.	Soil texture	Elevation		
19.	Soil texture	NDVI		
20.	Soil texture	Slope		
21.	Soil texture	Distance to streams		
22.	Soil texture	Distance to roads		
23.	Soil texture	Rainfall		
24.	Soil texture	TWI		
25.	Elevation	NDVI		
26.	Elevation	Slope		
27.	Elevation	Distance to streams		
28.	Elevation	Distance to roads		
29.	Elevation	Rainfall		
30.	Elevation	TWI		
31.	NDVI	Slope		

Comparison Number	Option A	Option B	More important? (A or B)	Importance Scale (Use a scale of 1-9)
32.	NDVI	Distance to streams		
33.	NDVI	Distance to roads		
34.	NDVI	Rainfall		
35.	NDVI	TWI		
36.	Slope	Distance to streams		
37.	Slope	Distance to roads		
38.	Slope	Rainfall		
39.	Slope	TWI		
40.	Distance to streams	Distance to roads		
41.	Distance to streams	Rainfall		
42.	Distance to streams	TWI		
43.	Distance to roads	Rainfall		
44.	Distance to roads	TWI		
45.	Rainfall	TWI		

Appendix C: [Flood Risk Estimation]

Coastal flood risk for the study area was estimated by multiplying flood hazard and vulnerability against the capacity to absorb flood risk.

Table 6.2 Estimation of coastal flood risk

Parameters	Total Score	Average Score	Flood Risk
Hazard Parameters			**0.885504**
What do you think about the chance/probability of future coastal flood occurrence?	179	0.809954751	
What is the likelihood of future damage by coastal floods?	179.6	0.812669683	
What are the chances of losing coastal people's lives during a coastal flood?	96.6	0.437104072	
What is the maximum height of flood measured above the ground floor during extreme coastal flooding?	119.8	0.542081448	
What is the maximum duration of staying flood water (in days) during extreme coastal flooding?	87.6	0.39638009	
What type of impact has on infrastructure because of coastal floods?	213.6	0.966515837	
What type of impact has on the crop agriculture sector because of coastal floods?	218	0.986425339	
What type of impact has it had on the fisheries sector because of coastal floods?	215	0.972850679	
What type of impact has on the livestock sector because of coastal floods?	183	0.828054299	
What type of impact has on sanitation because of coastal floods?	172.4	0.780090498	
What type of impact has on the health sector because of coastal floods?	194.8	0.881447964	
Hazard Score		**0.764870424**	
Vulnerability Parameters			
Considering you as a coastal community member, how much are you afraid of coastal floods?	105.78	0.478642534	
Do people live in a potential coastal flood-vulnerable area? What is the distance (in feet)?	121	0.547511312	
The density of the population living in the coastal flood-vulnerable area?	142.05	0.645681818	
What is the resiliency status of the community's houses against coastal flooding?	151.5	0.685520362	

Parameters	Total Score	Average Score	Flood Risk
What is the socio-economic status of the community against coastal flooding?	204.5	0.925339367	
What is the physical structure condition of the community against coastal flooding?	210.77	0.953710407	
Does the household have access to a tube well for drinking water during coastal flooding?	64	0.28959276	
Does the household have access to an improved toilet during coastal flooding?	95	0.429864253	
Does the household have access to public transportation during coastal flooding?	184	0.836363636	
Vulnerability Score		**0.643580717**	
Capacity Parameters			
What is your knowledge level about the coastal flood striking season?	161.69	0.731628959	
Do you get any forecasting and an early warning message about the coastal flood?	213	0.963800905	
Status of alternative livelihood sources/options during the flood?	82.09	0.371447964	
What do you think about people's capability to cope with the future coastal flood?	108	0.488687783	
What is the present status of the community flood preparedness plan?	81.43	0.368461538	
Where do you take shelter during the coastal flood?	171.2	0.774660633	
Does your community have any volunteer groups to help people during emergencies?	142	0.642533937	
Did you get any relief during the coastal flood period?	131	0.592760181	
What is the existing govt. resource level to minimize coastal flood risk?	86.19	0.39	
Did you attend any coastal flood emergency or resiliency-related training programs?	33	0.149321267	
What is the maintenance condition of existing embankment/polders?	160.2	0.724886878	
What is the maintenance condition of the existing sluice gate in this area?	152	0.687782805	
What is the condition of infrastructure in your locality or own to cope with the coastal flood?	118.25	0.535067873	
What is the condition of alternative livelihood in your locality or own to cope with the coastal flood?	115.5	0.522624434	

Parameters	Total Score	Average Score	Flood Risk
What is the condition of preservation of food in your locality or own to cope with the coastal flood?	121	0.55	
What is the condition of embankment in your locality or own to cope with the coastal flood?	181	0.819004525	
What is the condition of seeds and fertilizer in your locality or own to cope with the coastal flood?	63.5	0.288636364	
What is the condition of receiving relief in your locality or own to cope with the coastal flood?	89.5	0.404977376	
Capacity Score		**0.555904635**	