Coastal vulnerability assessment for southeast coast of India using Coastal Hazard Wheel

Palpanabhan Kasthuri Bavinaya[1], Moorthy Prabhakaran[1], Tune Usha[3], Gowrappan Muthusankar[2] and Chokkalingam Lakshumanan[1*]

1. Centre for Disaster Management and Coastal Research, Department of Remote sensing, Bharathidasan University, Tiruchirappalli, Tamil Nadu, INDIA
2. French Institute of Pondicherry, Puducherry, INDIA
3. National Centre for Coastal Research (NCCR), Ministry of Earth Sciences, Govt. of India, Pallikkaranai, Chennai, Tamil Nadu, INDIA
*drlaks@bdu.ac.in

Abstract

Rapid urbanization coupled with climate change increases the vulnerability of coastal areas to different types of hazards. To understand and assess the vulnerability of the coastal environments, a published methodology Coastal Hazard Wheel (CHW) was adopted for the coastal taluks of Tamil Nadu. This methodology provides information on vulnerability of the coast by five major hazards. They are: Ecosystem Disruption, Gradual Inundation, Saltwater intrusion, Coastal Erosion and Flooding. The vulnerability assessment is carried out based on the datasets namely geomorphology, wave exposure, tidal range, flora/fauna, sediment balance and climate. The coastal regions of Tamil Nadu are evaluated based on the vulnerability severity levels of the hazards. The assessment depicts that 46% of the Tamil Nadu coastline is highly vulnerable to flooding, making flooding the most prevalent coastal hazard. About 10% of the coastal areas have very high vulnerability to saltwater intrusion, 43% of the coastal areas have high vulnerability to erosion, 54% of the coastal areas have high vulnerability to gradual inundation and 58% of the coastal areas are moderately vulnerable to ecosystem disruption.

These appraisals are useful to support management decisions at local, regional and national level for the coastal management, mitigation and adaptation in response to climate and sea level change. Four types of ecosystems are based on their habitat type and distribution. They are marine, estuarine, coastal interface and coastal freshwater. The habitats on these ecosystems vary depending on their adaptability. These ecosystems also provide protection to coasts from the effects of climate change. They act as a basin during flooding from high rainfall and storm surges. Carbon sequestered within oceans is called blue carbon. Mangroves and salt marshes act as a reservoir of this carbon. Only 2% of the earth surface is covered by these ecosystems but stores ten times more carbon per unit area than other ecosystems. Non climatic pressure on ecosystems also increases rapidly due to rapid urbanization, industrial and agricultural outlets.

Keywords: Vulnerability, Coastal Hazard Wheel, Tamilnadu, Hazards.

Introduction

Coastal zones are influenced more by climate change and have adverse impacts on associated coastal landforms[19]. There is an increasing trend in the population density, settlements and developmental activities along the urban areas adjacent to the coast as they offer attractive settlings[5]. This increasing trend leads to the development of ten largest cities of the world along the coast[10]. Intense physical, ecological and social interactions occur in the coastal areas and make the coastal environments fragile[11]. Coastal zones being naturally dynamic and highly productive face severe impacts from natural disasters like tsunami, cyclonic storms and increased sea surface temperature as a result of global climate change over the past century[12]. The coastal hazards and geological process are interrelated and make significant impact on coastal areas[9].

There is an increasing stress in the coastal zone due to human population growth, migration, trade and commerce, tourism and deteriorating water quality because of high biological productivity and being an important component of global life system[18]. Coastal environments are dynamic systems where the changes occur continuously in large scales[7]. Coastal developments in developing countries are rapid without prior investigations of natural dynamics, therefore for sustainable and safe development, thorough knowledge about the nature of coastal environments and its adaptability to various developments are important[3].

In order to understand and assess the vulnerability of the coastal environments, a published methodology Coastal Hazard Wheel (CHW) was adopted for the coastal districts of Tamil Nadu. This methodology provides information on vulnerability of the coast by the five major hazards like Ecosystem Disruption, Gradual Inundation, Saline water intrusion, Erosion and Flooding. To demarcate the areas that are prominent to hazards and to provide management options, coastal hazard wheel is an excellent tool that provides clear cut information about the scale of hazards in coastal environment[31].

Study Area

Tamilnadu is situated in the south-eastern extremity of the Indian Peninsula, bordered by Bay of Bengal in the east, Arabian Sea in the west, Indian Ocean in the south and has a

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coastal stretch of 1076 km which is along 13 coastal districts covering 35 taluks from latitude 8^0 5' to 13^0 35'N and longitude 76^0 15' to 80^0 20'E. From March to May, the hot season begins having the hottest temperature peaking above 40^0 C. Tamilnadu receives rainfall from both southwest (SW) and northeast (NE) monsoon, the annual average rainfall is about 914.4mm of which 48% (438.9mm) is received through NE monsoon and 35% (320.04mm) through SW monsoon[24]. The trend of drainage is from west to east into the Bay of Bengal. Rivers like Cauvery, Palar, Gadilam, Vaigai, Thamirabarani and some distributaries drain into the coast. During heavy monsoon rainfalls the river inflows increases thereby increasing the sediment supply in the coast[14]. Figure 2 represents the study area for vulnerability assessment.

Tamilnadu coast is more prominent to natural hazards which include tropical cyclones and coastal flooding. The coastal stretch is composed of rocky shores, coastal plains, sand dunes, lagoons, river mouth, sand spit, mangroves, marshy land, estuaries and beaches. Kanniyakumari which is in the southernmost tip is composed of rocky shores. In the eastern part of the study area, the coast is remarkably straight with well-formed beaches. Marina beach in Chennai is the second largest beach in the world which extends about 12km[29]. The area is spatially dominated by older coastal plain and older deltaic plain. About 5.56 million people of total population in Tamilnadu are dependent on the coast and their main source of income is from fishing and agricultural activities.

Human induced global warming and climate change add adverse impact over coastal ecosystems. Increase in carbon dioxide emission from industries, aerosol from vehicles and cement manufacture raised the global temperature largely in the past three decades[12]. Climate change and its related impact have adverse effect on coast and surrounding areas. Rise in sea levels increases the flood levels[28]. The migration of large population along coast increases the vulnerability where the exposure to coastal floods is high[27]. It is estimated that even a 1m rise in sea level could displace a million local people form the coast[16]. The relative sea level rise for Tamilnadu is less than 1mm/year compared with global average which is 1-2mm/year[22,30].

One to two tropical cyclones originate from both Southeast Arabian Sea and Northern Bay of Bengal every year and make massive destruction in the coastal environments[8]. The intensity of this tropical cyclones and storm surges is more at the landfall and decreases after travelling longer distance from the coast[21]. The developmental activities along coast induce coastal erosion in the upstream and accretion in the downstream of the coastal structures[25]. Natural and anthropological activities keep on modifying the shoreline and control the rate of erosion and accretion[17,26]. Coastal erosion causes numerous threats to the resources present along the beaches[19]. Sand mining, legal and illegal dredging from estuaries, beaches and from upstream of rivers result in sediment deficit in some locations of the coast.

Shore protection measures like seawall, breakwaters and revetments are constructed along coast which thereby induces erosion and accretion. Increase in water demand leads to excessive extraction of ground water and over exploitation of surface water places significant stresses on the water resources. Population increase with climate change increases the pressure on mangrove forests and estuaries and disturbs the stability of the services these ecosystems provide[10].

Material and Methods

Google Earth Imagery serves as a crucial resource for hazard assessment within the ArcGIS platform. To facilitate this process, a geodatabase is established to store hazard values and layer templates. For the purpose of digitizing the coastline, a line shapefile is generated with the WGS 1984 coordinate system. The coastline is meticulously digitized at a zoom level of 1:1000 scale, intentionally leaving gaps to accommodate river mouths and tidal inlets. This digitized coastline forms the foundational framework for the subsequent categorization of coastal hazards. The coastline is then divided in accordance with its classification category and a CHW code is incorporated into the attribute table.

Additionally, hazard values are linked to the attribute table of the coastal classification file. The hazard maps are subsequently generated by leveraging these hazard values and the coastal classification information. Ultimately, various maps are created to represent Ecosystem Disruption, Gradual Inundation, Saline Water Intrusion, Erosion and Flooding. These maps are visually distinguished by utilizing four distinct color codes that correspond to four distinct hazard ranges which are low, moderate, high and very high.

Coastal Hazard Wheel framework: To understand the hazards and its profile, there is a need to develop methodology and tools to assess vulnerabilities[5]. The CHW framework is a graphical representation of the hazards and provides management options for coastal planners (Figure 1). CHW is useful for the identification of hazard hotspots, its range of severity and to provide management options for a particular coastal area.

In this framework, the coastal geology forms the basis in which the main dynamic parameters that play significant effect on coastal environment, are added[2]. The framework starts from the centre with coastal classification and moves outwards with inherent hazard level and coastal classification in the outermost circle. The order of the coastal classification from the centre is as follows: Geology, Wave exposure, Tidal range, Flora/Fauna, Sediment balance and Storm climate. Following the coastal classification, the inherent hazard level of hazards like ecosystem disruption, gradual inundation, saltwater intrusion, erosion and flooding is mentioned. Each category is represented by a new circle. The inherent hazard levels are classified as very high, high, moderate and low. The CHW is shown in fig. 1.

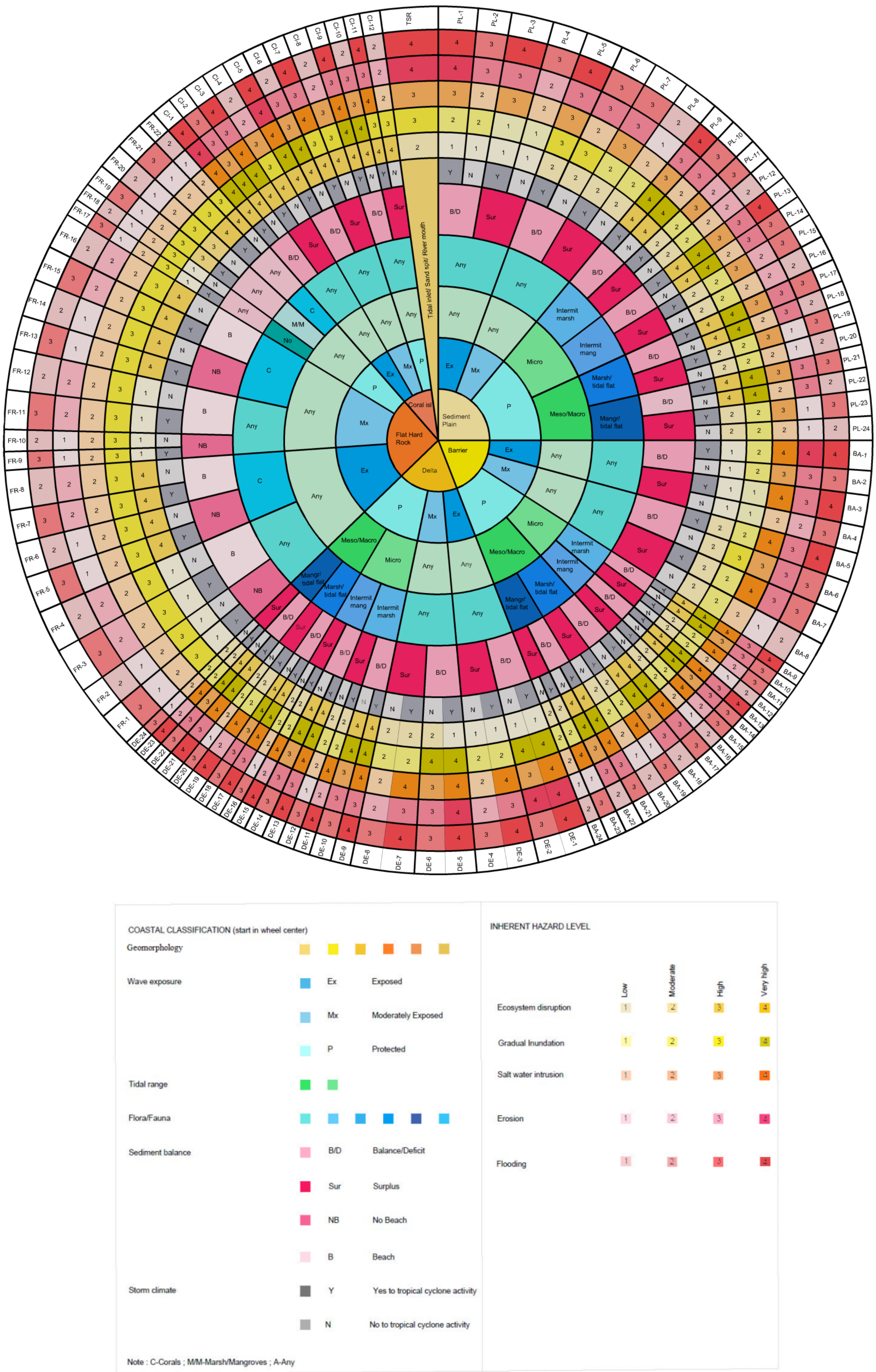


Figure 1: Coastal Hazard Wheel (Modified from CHW 3.0, Lars Rosendahlappelquist, 2016)

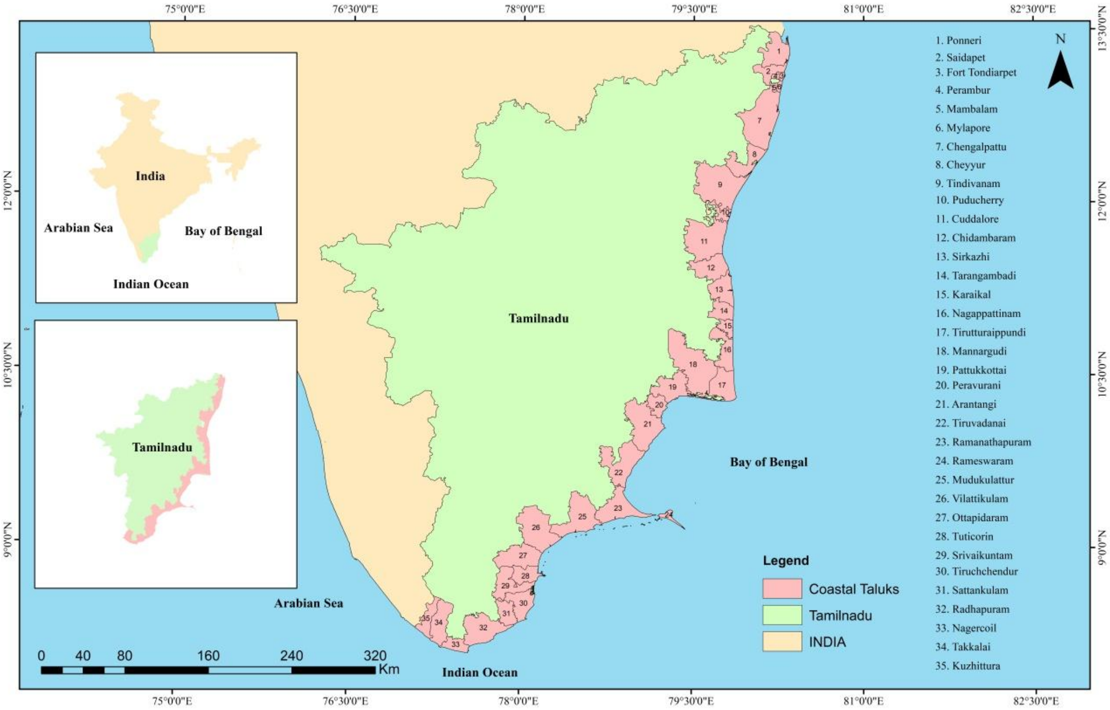


Figure 2: Study area – Coastal taluks of Tamilnadu

Data for Hazard assessment: The vulnerability assessment relies on information sourced from the original CHW framework paper, scientific literature and additional resources. Geomorphology and land use data for the year 2018 are generated using Google Earth imagery. Wave, tide and storm climate maps from the published CHW framework paper authored by Appelquist and Balstrøm[2] and Masselink et al[15] employed for further categorization.

Geomorphology: Coastal and hydrodynamic aeolian processes control the formation of various landforms[1]. Human interventions on the coast accelerate the balanced system and make the coastal system fragile[23]. The geomorphology map is prepared using Google earth imagery, 2018. Tamilnadu has a wide variety of landforms which includes pediplains, older deltaic plain, older coastal plain, younger coastal plain, alluvial plain, salt pan, mud flat, marsh, aquaculture, teri sand, younger flood plain, salt flat, creek, sand dune, beach ridge, lagoon, mangrove swamp, estuary, beach, structural hill, tidal flat, mouth bar, swamp, spit, sea wall and denudational hill. Based on the geological settings, the coast is grouped into sediment plain, barrier, delta/low estuary island, sloping soft rock coast, flat hard rock coast and tidal inlet/sand spit/river mouth.

The coast of Tamilnadu is mainly composed of marine sediments and is classified as sediment plain. Areas with shore protection structures like seawall, mangroves and developmental infrastructures are grouped as barrier. Creek, lagoon, estuary, marsh and swampy areas are grouped as delta/low estuary islands. The flat hard rock category was assigned to the coastline characterized by the presence of hard rock formations. Tidal flat, spit, salt pan, salt flat, mud flat and mouth bar are grouped as tidal inlet/sand spit/river mouth.

Wave exposure: The coastal taluks of Tamil Nadu are situated in an area protected from the west coast swell. The categorization of wave exposure is determined by the continuous occurrence of significant wave heights for a duration of 12 hours per year[31]. In Tamil Nadu, the mean significant wave height typically falls within the range of 0.6 to 1.2 m[22]. Specifically, the coastal taluks extending from Kodikarai to Mandapam experience low exposure, with significant wave heights ranging from 0.6 to 0.8 meters and are classified as protected. The coastal taluks spanning from Ponneri to Tiruturaipundi and from Ramanathpuram to Ottapidaram encounter moderate exposure, with significant wave heights ranging from 0.8 to 1.0 meters and are categorized as moderately exposed.

In contrast, the district of Kanyakumari, being surrounded by the sea on all three sides, experiences a greater impact from waves, with wave heights reaching 1.2 meters and is classified as exposed.

Tidal range: Tidal range is the vertical difference between the highest high tide and lowest low tide. Tidal data is collected from WX tide (a free windows tide and current prediction program) for the four stations of Madras, Cuddalore, Nagapattinam and Tuticorin. Coastal areas with high tidal range are considered as highly vulnerable and areas with low tidal range are protected. The coastline of Tamilnadu is subjected to micro tides ranging from 0.4 to 1.3m, therefore the micro tide category is applied for the entire coast.

Flora/Fauna: Google earth imagery and information on geographical location are used for the determination of the spatial extension and type of coastal vegetation[31]. Tamilnadu has a sheltered coast with coastal plains and barriers in which some type of mangrove vegetation is found in protected areas with very low tidal range and is of intermittent type. Coastal vegetation of intermittent types is found in moderately exposed coast. The distribution of coral reefs surrounding a series of 21 islands is located between Tuticorin and Rameswaram[6].

Sediment Balance: The prediction of sediment balance hinges on the assessment of shoreline changes rates, a process facilitated by the End Point Rate (EPR) method embedded within the Digital Shoreline Analysis System (DSAS). The coast where there is no change in the coastline, is termed as balanced, coastal areas subjected to erosion is termed as deficit and the accreted coast is termed as surplus. Coastal taluks from Chengalpattu to Tirutturaippundi, Kodiakarai, Tiruchchendur and from Nagercoil to Takkalai are subjected to erosion. Accretion is noticed in some site-specific areas like Marina beach, Pudukuppam, Samiyarpettai, Vedharanyam, Manamelkudi, Kuttam and Muttom. Most of the coastal taluks have sediment in balanced condition.

Storm Climate: Cyclones of high intensity are being formed in Bay of Bengal. When the intense heat on the oceans increases, the humidity and unstable air masses raise and end up in cyclone. Tamilnadu is frequently subjected to tropical cyclones every year. It is more prominent that during northeast monsoon, maximum rainfall and occasional cyclones happen. The historical tropical cyclone track is downloaded from Cyclone eAtlas – IMD.

Results and Discussion

The results obtained from the application of the CHW framework for the Tamilnadu coast of length 1076 km illustrate the prevalence of different coastal hazards and its inherent hazard level in the coastal environment. The extent of hazards may vary for a particular coastal area. The most common coastal types in Tamilnadu in terms of length and percentage are shown in table 1.

The distribution of hazards in percentage with respect to the coastal length of Tamilnadu and hazard levels is shown in table 2. From the table, it is seen that flooding is the most prevailing hazard, 62 percent of the coastline is endangered to high or very high intrinsic hazard for flooding. The hazard of gradual inundation is also relatively high as 56 percent of the coastline has high or very high intrinsic hazards for gradual inundation. 55 percent of the coastline is threatened to erosion, 46 percent of the coastline has high or very high intrinsic hazards for saltwater intrusion and 5 percent of the coastline is attributed to ecosystem disruption, making ecosystem disruption the least inherent hazard.

The hazards of ecosystem disruption, gradual inundation, saltwater intrusion and erosion and flooding for Tamilnadu are shown in figures 3 and 4 respectively. The hazard class 1 is the low intrinsic hazard, 2 is moderate intrinsic hazard, 3 is high intrinsic hazard and 4 is very high intrinsic hazard. The maps show a clear overview of areas where special attention and management options are to be provided.

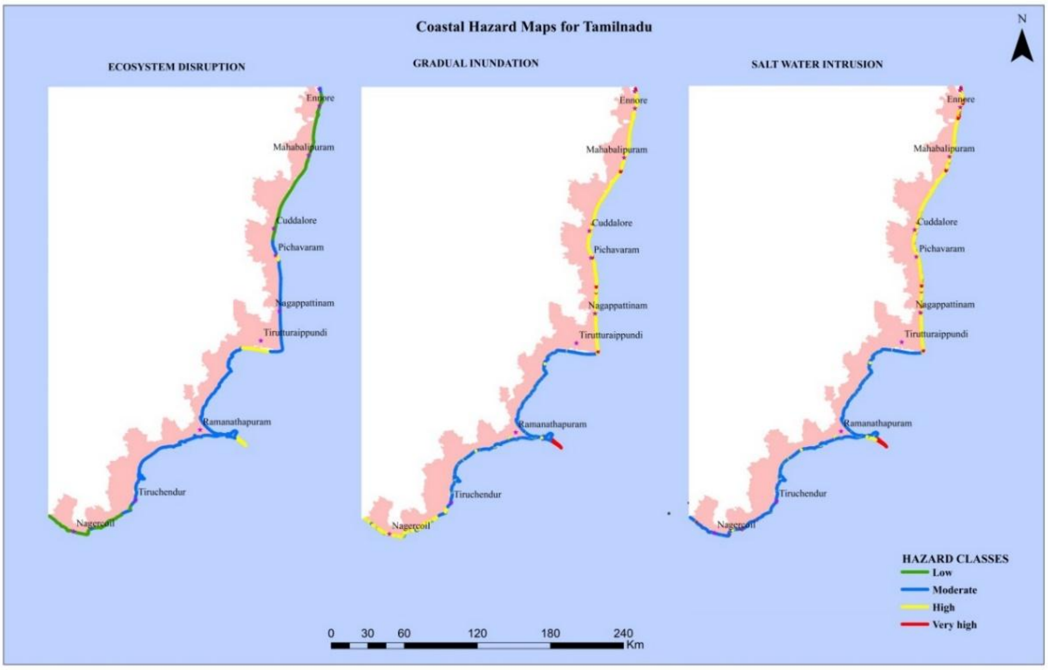
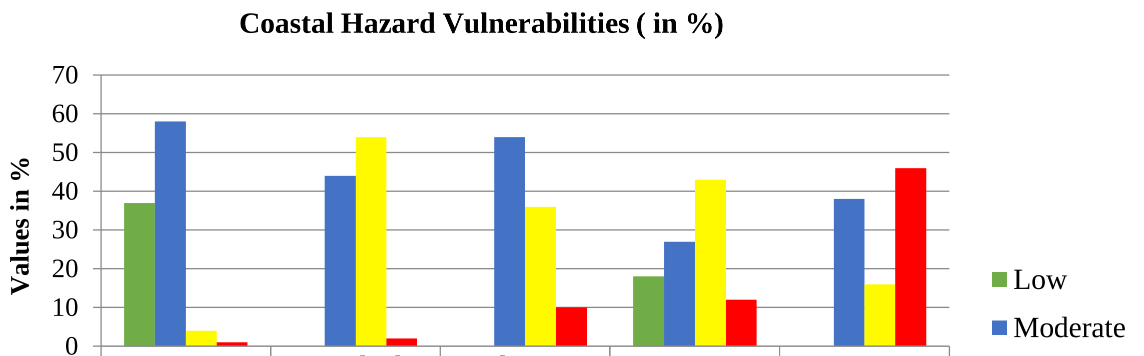


Figure 3: Coastal Hazard Maps representing Ecosystem Disruption, Gradual Inundation and Saltwater Intrusion

Table 1
The most common coastal types in Tamilnadu

Coastal Type	Length (Km)	Percentage (%)
Sediment Plain (PL5)	310.50	28
Sediment Plain (PL12)	224.40	20
Sediment Plain (PL8)	89.96	8
Tidal inlet/Sand spit/River mouth (TSR)	88.31	8
Flat Hard Rock (FR3)	75.718	7
Barrier (BA5)	67.428	6
Barrier (BA8)	48.324	4
Flat Hard Rock (FR1)	42.078	4
Sediment Plain (PL16)	40.295	3.5
Delta (DE16)	29.674	2.5

Table 2
The dissemination of hazard sketch in percent for Tamilnadu



	Ecosystem Disruption	Gradual Inundation	Saltwater Intrusion	Erosion	Flooding
Low	37	0	0	18	0
Moderate	58	44	54	27	38
High	4	54	36	43	16
Very high	1	2	10	12	46

Vulnerabilities

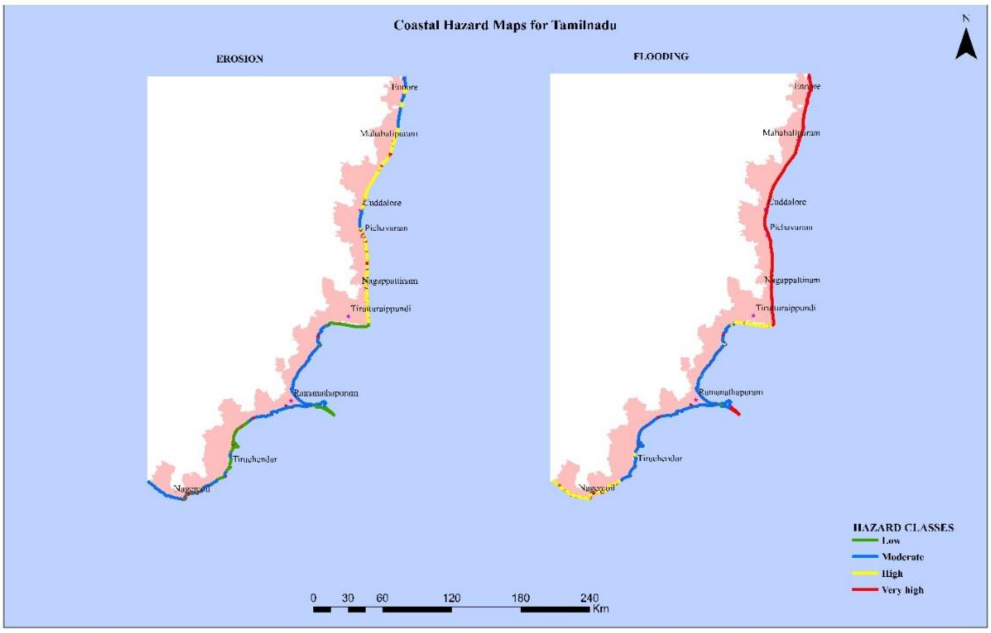


Figure 4: Coastal Hazard Maps representing Erosion and Flooding

The Tamil Nadu coastline demonstrates relatively lower to moderate risks of causing disruptions to ecosystems whereas elevated hazard levels are specifically observed within mangrove and salt marsh environments. The hazard of gradual inundation fluctuates between moderate and high; the hazard is very high in estuaries and its associated areas. The hazard of gradual inundation is unified in areas with high erosion and low-lying areas. The scarce saltwater intrusion is high on the northern coast of Tamilnadu and is moderate in the southern coast.

Erosion is high and very high in the exposed coasts and in estuaries; the hazard is moderate and low in areas with fluvio-marine and calcareous gritty sandstone deposits. Larger sections of Tamilnadu coast are subjected to high or very high hazard for flooding, making flooding the most dominant hazard for Tamilnadu coastal areas.

The hazard of ecosystem disruption is dominant in protected estuaries with mangroves. Clearing mangrove forest for aquaculture activities with global sea level rise adds up the stress on these marine environments. Mangroves are the protected ecosystems which provide valuable ecosystem services and act as a breeding ground for millions of marine species and play a major role in flood protection. Restoration of mangroves and protection of mangrove forests are mitigative measures to control the loss of valuable species and property loss. Inundation is associated with the low-lying estuary coasts. Construction of dikes may limit the level of inundation. The inherent level of saltwater intrusion is related to the extraction of groundwater from freshwater aquifers. Increase in demand of ground water increases the extraction of ground water which thereby provides a path for the replacement of freshwater aquifers with salt water. Constant monitoring and maintaining proper balance between water being pumped and the recharging rate may control the intrusion of salt water into coastal aquifers. Erosion is a general hazard along Tamilnadu coast; sandbags, beach nourishment and coastal plantation may limit the impacts of erosion. Flooding is the most prevailing hazard in the coastal areas of Tamilnadu.

Construction of seawall, beach nourishment and establishing flood warning system and flood shelters would be the appropriate management options for minimizing the property loss and to safeguard human population. Since the range of hazards along Tamilnadu coast is of different extensions, the management options which are more appropriate in managing several hazards at the same time should be provided. The boundary for developmental activities along the coast should be established to safeguard the rich biodiversity of the coast.

- The Coastal hazard wheel framework was found to be the suitable assessment procedure to get an overview of the hazard profiles and to identify the hotspots where developmental activities may get affected by coastal hazards.
- The severities of the hazards are of different extents and therefore the most appropriate management options may be adopted in the hazard hotspots.
- Monitoring the hazard hotspots and the developmental activities along the coastal stretch might reduce the level of severity the coast faces.
- Any developmental activities along the coast should be done only after proper scientific studies so that our valuable coastal resources could be protected leading to sustainable development.

Conclusion

The hazard maps created serve as valuable tools for pinpointing hotspots and anticipating regions where additional human development could pose substantial risks. The CHW framework stands as a fitting assessment method for evaluating hazards in Tamil Nadu. The scale of hazards may fluctuate due to global climate change and relative sea-level rise. However, effective management and mitigation strategies have the potential to alleviate the broader environmental consequences of these hazards on the coastal environment.

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