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Monitoring of Coastal Geo-Environment for Hazard Mitigation: A Case Study of Machilipatnam Region, Andhra Pradesh, India

M.V. Ramana Murty[1*], Ch. Ravi Kumar[1], K. Srinivasu[1], R. Kannan[1], B. Sundar[1]

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ABSTRACT

The coastal zone is highly dynamic, which responds in various ways to human interventions and extreme weather events. Tropical storms cause enormous damage to the coastal region and its communities during landfall. Many of the world's largest deltas are densely populated and are increasingly vulnerable to natural disasters. The Krishna district within the river delta, is amongst the few districts with very high proneness to cyclone hazards. Machilipatnam in Krishna district is one of the oldest coastal towns in Andhra Pradesh, situated on a series of ancient beach ridges. Two major storms struck this region in the last half-century causing large scale devastation. The extent of inundation from multiple flood events can be a very good indicator for flood hazard zonation. The lateral expansion of Machilipatnam town is analysed in GIS environment based on time series satellite data. The developmental activities in the near shore zone are modifying the pristine coastline configuration. This is evident from shoreline monitoring. It is observed that there is a net increase in the extent of mangroves, indicating a better protection to the town against tropical storms. The unplanned growth of aquaculture may be an amplifying factor for coastal flooding, particularly if it is interfering with the drainage system. In addition to the existing flood protection measures, the areas suitable for shelter belt plantation and mangrove regeneration are identified for coastal vulnerability reduction.

INTRODUCTION

Coastal zone is one of the most complex environments, where continuous interactions exist between land, ocean, and air. Further, a wide range of human activities in this coastal zone altered the natural environment. In spite of various benefits being offered to humans, man-made activities are exerting tremendous pressure in the coastal zone. The population explosion in the coastal zone is negatively impacting the bio-geo environment. Depending on the degree of human interventions in the coastal zone, irrespective of population size, indirectly leads to increased coastal erosion, soil salinization, saline water intrusion in newer areas, amplified coastal flooding, etc., due to unhealthy land use practices (Patel *et al.*, 2022; Thiam *et al.*, 2021; Sukumaran, 2020). Flooding due to tropical storms and tsunamis are adversely affecting the coastal population and infrastructure.

The poorest of the poor are the worst affected, as they are compelled to settle in low lying flood prone areas. In order to mitigate the effects of the natural disasters, both structural and non-structural methods are adopted (Yang & Liu, 2020). Over the years, storm forecasting has significantly improved even in the tropical region. The advance forewarning in most of the places provide ample time to evacuate the vulnerable population. Various parameters are used to assess the vulnerability of the region. Mahapatra *et al.*, (2015) attempted an integrated coastal vulnerability index for the South Gujarat coast using five physical variables (coastal slope, coastal landforms/features, shoreline change rate, mean spring tidal range, and significant wave height), and four socioeconomic variables (population density of adjacent coastal villages, land use/land cover, proximity to road network and settlement). Ramana Murty *et al.*, (2023) analyzed the inundation based socio-economic vulnerability in the Krishna river delta region by considering five variables (women population, children, aged, literacy, and non-workers). The usefulness of remote sensing data, insitu observations, numerical modeling, and GIS analysis tools serve as a broad indicator of a threat to people living in the coastal zone (Srinivasa Kumar *et al.*, 2010). They developed the coastal vulnerability index for Orissa state using eight relative risk variables. Pramanik *et al.*, (2016) constructed the coastal vulnerability index due to the sea level rise in Krishna–Godavari delta region to enhances the subjective attributes, and its useful in summarizing the vulnerability assessment results with the stakeholders and decision makers. Based on the socioeconomic and infrastructural vulnerability indices, the highly vulnerable districts are identified, which are expected to face substantial amount of challenges in coping with cyclones (Mazumdar & Paul, 2016).

The resultant scenario of both physical and human-induced changes is important from a sustainable development perspective. The study on spatial patterns in the framework of past and present scenarios may lead to better understanding of social and economic developments. Mapping is an essential tool for monitoring and managing human activities in the coastal zone. The effective management practices depend on the knowledge of coastal zone and suitable response by concerned government agencies (Nayak, 2017). The information on

[1] Andhra Pradesh Space Applications Centre (APSAC), Labbipet, M.G. Road, Vijayawada, India
[*] Corresponding author's e-mail: moidavrm64@gmail.com

the varied aspects of the coastal zone and their impacts can be obtained from space borne sensors. Reshma and Mani Murali (2018) studied the decadal change using remote sensing and Geographic Information System (GIS) techniques in Krishna-Godavari delta region in the east coast of India from 1972 to 2014. They observed that high erosion in northern part of the Krishna delta is due to the reduction in size of the spit.

Since prehistoric times the coast has provided people with habitat, food, trade ways, and facilitated socio-economic networking (Harff *et al.*, 2019). The coastal areas are amongst the most preferred regions for various activities leading to population concentration. Settlements are concentrated within 5 km of coastlines worldwide, whereas average population densities are higher at elevations below 20 m throughout the 100 km width of the near-coastal zone (Small & Nicholls, 2003). With the major technological development in the recent past, people began to influence the geo-environment actively. Hence, the human population of the coastal zone is expected to experience increased threats caused by natural and anthropogenically accelerated changes. Urban areas in the delta are expanding more rapidly than rural areas. This trend is expected to continue in near future, unless necessary infrastructure and suitable employment facilities are created in rural areas.

The global dataset show that 339 million people reside in river deltas and 89% of them live in the same latitudinal zone of the most tropical cyclone activity (Edmonds *et al.*, 2020). They further calculated that 41% (31 million) of the global population exposed to tropical cyclone flooding live on deltas, with 92% (28 million) in developing or least developed economies. The population of 87 mandals of Krishna river delta region constitutes about 83,23,072 (Ramana Murty, 2021). The region's vulnerability further increases due to the impact of the tropical storms, if they are sediment starved, as in the case of Krishna river delta. Amongst the thirty three major deltas of the world, Krishna delta is affected mainly due to reduced aggradation and accelerated compaction (Syvitski *et al.*, 2009). They further estimated that the flood vulnerable in deltas could increase by about 50% under the current projected values for sea-level rise in the twenty-first century.

This figure could increase if the capture of sediment upstream persists and continues to prevent the growth and buffering of the deltas. Rao *et al.*'s (2010) indicated that predominant erosion along the sediment-starved coast during the past five decades, is due to the construction of dams in the upstream of Krishna delta. The vast amount of material added till the construction of dams and reservoirs resulted in formation of bars and barrier spits close to the Krishna river mouths (Rao, 1985). Similarly, the Mahanadi delta was once a prograding delta of the Holocene is now retreating due to sediment starvation and sea-level rise, and experiencing decline in income from agriculture or fisheries, degradation of mangroves with loss of biodiversity and human migration (Hazra *et al.*, 2020). This problem will disproportionately impact people on river deltas, particularly in developing and least-developed economies. Furthermore, 80% (25 million) live on sediment-starved deltas which cannot naturally mitigate flooding through sediment deposition. In recent years, intensive development activities together with sea-level rise, and groundwater abstractions among other activities have seriously threatened the sustainability of many deltas and their estuaries (Loucks, 2019). Most of the coastal ecosystems exhibit extreme variations in areal extent, spatial complexity, and temporal variability (Klemas, 2011). Protecting them requires the ability to monitor their biophysical features and controlling processes spatially over time.

Study Area

Masulipatnam (now Machilipatnam) is one of the ancient coastal towns along East coast of India. The ancient inscription on a pillar of the mandapam in Ramalinga temple, Masulipatnam dates back to twelfth century (Mackenzie, 1883). The Kistna (now Krishna) district manual also indicates that the great storm of 13th October 1779 caused damage to the factory buildings in Masulipatnam. Another storm of 1st November 1864 washed away several people and a 12 feet deep inundation recorded in a Dutch factory. The farthest extent of deluge due to storm surge was reported to have reached 17 miles inland, with an estimated human loss of about 30,000. Another severe cyclone of the last century that hit Machilipatnam coast on 23rd October 1949, had a maximum wind speed of about 130 kmph. During this storm, about 750 lives were lost and about 30,000 cattle perished.

A devastating tropical cyclone that crossed the coast near Chirala in Andhra Pradesh on 19th November 1977 had claimed over 10,000 human lives. As a result of this event, a peak storm surge occurred on the right of landfall point with a height exceeding over 15 feet near Sorlagondi, and spreading beyond 40 miles inland (Subbaramayya *et al.*, 1979). The cyclonic storm that crossed the coast near Machilipatnam on 9th May 1990 caused enormous damage to the delta region (Rao, 1994). Machilipatnammandal(Figure-1)happens to the largest mandal of the district, with 29 villages experiencing recurring storms. It is one of the four coastal mandal with significant human population associated with extensive mangrove vegetation. Machilipatnam town is not only the headquarters of the mandal but also for the Krishna district.The proneness of this region due to frequent inundation caused by the series of cyclonic storms, and degradation to bio-geo-environment is examined spatially within the Machilipatnam mandal.

METHODOLOGY

In the present study, Machilipatnam town in particular and the mandal in general are studied from the coastal inundation perspective using multi-temporal satellite imagery and topographic maps. The degree of coastal

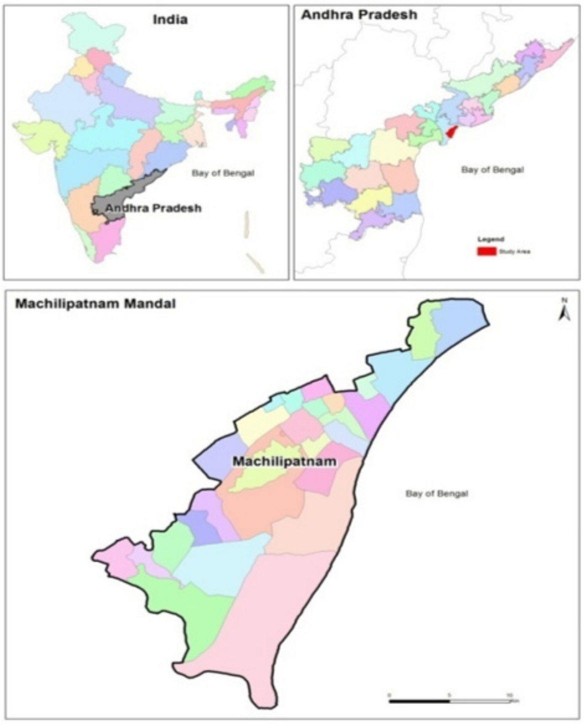

Figure 1: Location map

inundation is assessed based on three different flood events (May, 1990; October, 2005; and September, 2016). The areas which are under deluge in all the flood events is categorized as extremely vulnerable compared to the areas which are inundated in any one of the events (Figure 2). The spatio-temporal extents are significant from an inundation point of view. The extent of aquaculture and mangroves in the mandal is important from environmental perspective. The coastal zone of Machilipatnam constitutes sandy beaches, river deltas, wetlands, coastal plains, beach ridges, and other coastal features. The changes in the shoreline configuration are studied from temporal data-sets. The lateral expansion of Machilipatnam town is analysed in GIS environment based on time series data from topographical maps (1938-41 and 1969), satellite images (1990, 1999, and 2010) including the latest Sentinel imagery of 14th June 2022. The population of the mandal during the year 2011 is compared with 2001 census. Finally, based on the existing flood protection measures (natural and structural), resultant changes, etc., new areas are proposed for mitigating the impact of coastal flooding.

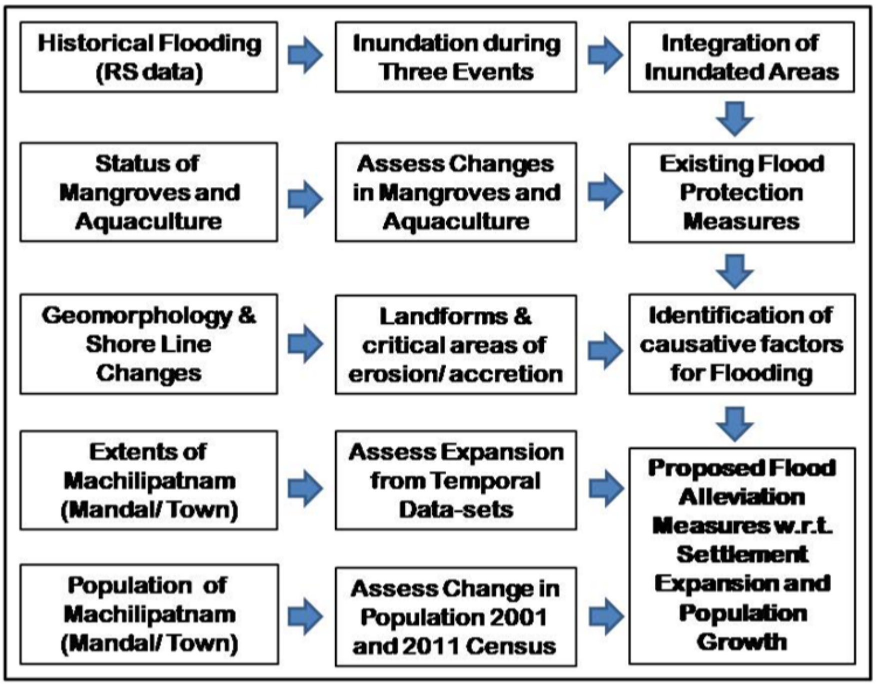

Figure 2: Methodology adopted for flood alleviation

RESULTS AND DISCUSSIONS

Machilipatnam and its environs in the Krishna river delta is considered to be the rice bowl of the State. This fertile region of the delta constitutes a well distributed drainage network coupled with timely releases from canals for irrigation enabling better agricultural productivity. This region is morphologically even without much undulations. The maximum elevation in the mandal is about 3.5m. Flat topography, frequent storms, land use changes, etc. necessitates a detailed investigation on the present geo-environmental status in relation to the past. Inundation based flood hazard; distribution of mangroves & aquaculture; geomorphology & shoreline changes; spatio-temporal variations of Machilipatnam mandal and town; population; and existing/ proposed flood reduction measures are discussed.

Inundation based flood hazard

The temporal satellite datasets/ layers are obtained from NRSC and through open source for the three flood events (i.e., Landsat TM of 18th May 1990; IRS LISS-III imagery of 22nd September 2005; and Microwave SAR data of 23rd / 25th / 27thSeptember 2016) for Machilipatnam mandal. The maximum extent of inundation during each of the three flood events is observed to be about 159 km^2 (May 1990), 198 km^2 (October 2005), and 26 km^2 (September 2016). The extent of flood inundation is extracted from the satellite data/ layers during three different flood events and integrated in GIS environment. The integrated flood extents are re-classified into three categories based on the frequency of inundation. The Very Highly Flood Affected Areas (VHFAA) includes those areas which are under inundated during all the three flood events of May 1990, October 2005 and September 2016 (Figure 3). The Highly Flood Affected Areas (HFAA) are those regions that are under inundation in any of the two flood events; and Moderately Flood Affected Areas(MFAA) are under inundation during only one of the three flood events. The extents of flood hazard classes in Machilipatnam mandal i.e., VHFAA, HFAA, and MFAA are about 18.63 km^2 (5%), 63.65 km^2 (16%), and 176.56 km^2 (43%) respectively.

The extent of unaffected or least affected area in the mandal constitutes about 148.67 km^2 (36%).The significant extent of inundation in all the three flood events is observed mostly in the east of Machilipatnam town in the reserved forest area near P.T.Palem, and Polatitippa. Peddapalem villages in north-eastern parts of the mandal is also identified as VHFAA. The HFAA is observed mostly in the east, south and south east of Machilipatnam town. The MFAA is also observed mostly in the southern half in comparison to the northern half. The unaffected or least affected areas in the mandal are observed in the north and NE parts of Machilipatnam. Most of these least affected areas are associated with landforms like beach ridges or ridge & swale complex. Further, flood receding/ infiltrating from these areas are relatively faster.

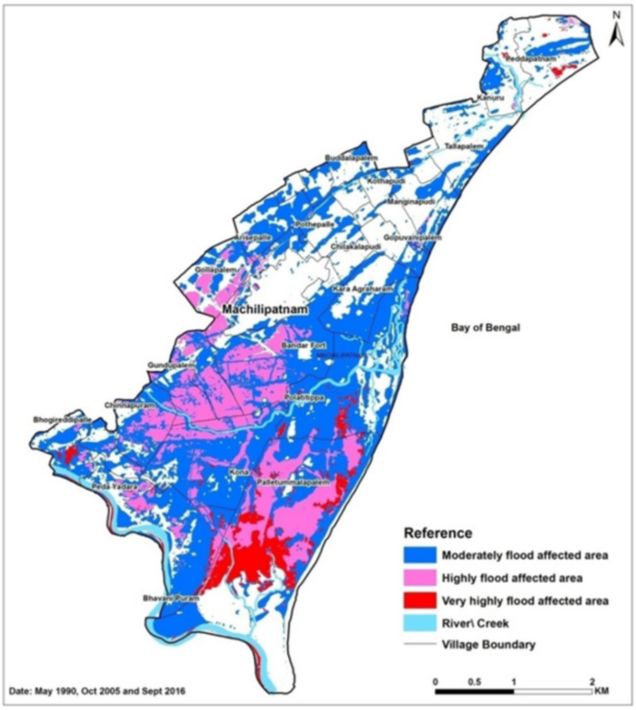

Figure 3: Combined inundation from three flood events

Mangroves zonation and Aquaculture

One of the important features of coastal ecosystem includes mangroves. These mangroves are significant for mitigating the adverse effects of natural disasters, particularly coastal flooding and erosion. Empirical studies of storm surge and tsunami protection by mangroves have historically been difficult, but the development of remote-sensing and GIS technologies is making it easier to assess damage after natural disasters (Marois & Mitsch, 2015). Through the natural processes, mangroves essentially contribute in land accretion. The temporal changes in extents of mangroves and aquaculture are monitored based on the image data of 1990, 1999, 2010, and 2022 (Figure 4). It is observed that the net extent of mangroves gradually increased between the years 1990 and 2022 from 2,995 ha. to 5,266 ha. This increase in mangroves is a positive indication for protection of town in minimizing the impact from tropical storms. This geospatial gain/ loss can be extracted easily using union function in ArcGIS. It is observed that there is a natural regeneration/ plantation between 1990 & 1999, 1999 & 2010, and 2010 & 2022 to the extent of about 1698 ha., 1609 ha., and 1822 ha., respectively. In spite of the net increasing trend, there is a loss in the extent of mangroves between 1990 & 1999; 1999 & 2010; and 2010 & 2022. It is observed that there is a minimum loss of about 799 ha. between 2010 & 2022; and a maximum loss of about 1050 ha. during 1990 & 1999.

The causative factors in loss of mangroves are important from management and conservation perspective. Effective governance structures, better planning for rehabilitation of degraded mangroves, education and awareness building in local communities are needed to conserve, protect and restore the valuable mangrove wetland ecosystems (Sahu *et al*., 2015). Proactive engagement with governments and the public in these potential regions of mangrove expansion may help with conservation efforts (Romañach *et al*., 2018). Mangroves and brackish water aquaculture are two competing land use/land cover classes. The shrimp aquaculture is accountable for the large-scale changes in the mangrove lands of Andhra Pradesh (Jayanthi *et al*., 2022).

The bio-geo environmental conditions for mangroves and brackish water aquaculture are very similar. It is also observed (Figure 4) that there is a huge increase in the extent of aquaculture from just 981 ha. in the year 1990 to about 10,066 ha. in the year 2022. The aquaculture tanks are significantly concentrated in south and south-eastern parts of Machilipatnam town. Pedayadara village in NE of the mandal is completely occupied with aquaculture. In the process of expansion, environmental aspects are compromised. Indiscriminate growth of aquaculture within and around the lake is observed to be increasing the flood hazard (Ramana Murty & Mruthyunjaya Reddy, 2010). Further, these ponds are interfering with the natural creeks/ drains and may causes hindrance to natural flood flow leading to increased area under inundation. Such aquaculture ponds are observed near north-west of Rudravaram, east of Ranganayakulapeta, south-east of Pallepalem and south-east of Chinnapuram village. In addition to this, longer duration of flooding and increased depth of inundation can be experienced. Hence, the impact of storms shall be severe in regions of unplanned expansion of aquaculture.

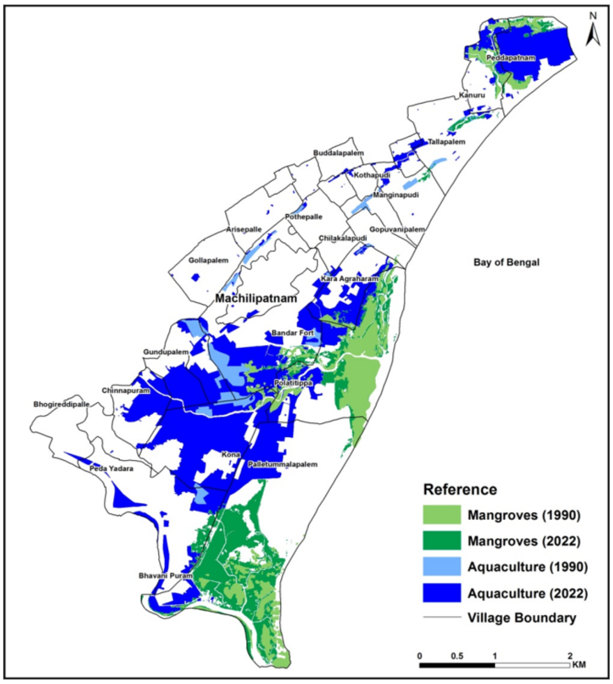

Figure 4: Extents of Mangroves and Aquaculture during 1990 and 2022

Flood Geomorphology and Shoreline Changes: Geomorphological understanding of floods derives from geological tradition of studying indices of real processes operating in the past, instead of using mathematical (model) manipulation of idealized parameters that are assumed to have flood-like properties (Baker, 1994). Coastal geomorphology is one of the popular ways of assessing flooding. Different landforms respond to flooding in different ways (Ramana Murty *et al*., 1993). In the present study, three different geomorphic units of different origin i.e., marine, fluvial, and fluvio-marine are identified (Figure 5). Sandy Beach, Bar, Tidal Flat, Tidal

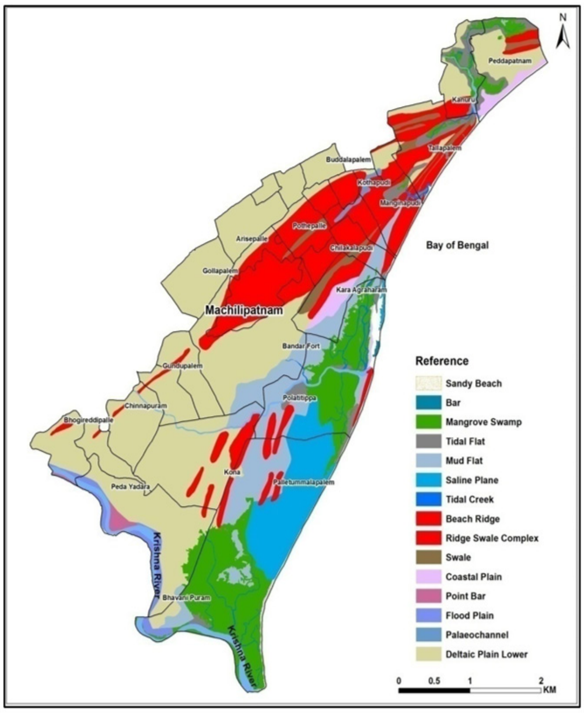

Figure 5: Geomorphology of Machilipatnam Area

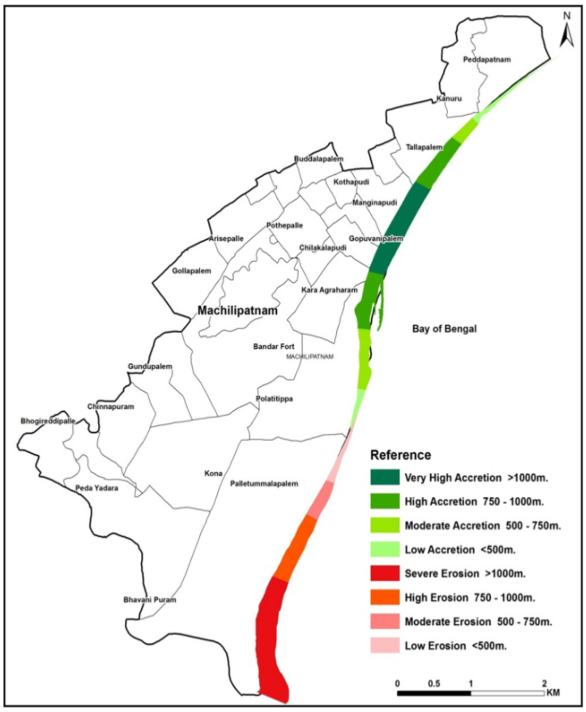

Figure 6 : Shoreline changes between 1938-41 and 2022

Creek, Mangrove Swamp, Mud Flat, Saline Plane, Coastal Plain, Ridge &Swale Complex, Beach Ridge, Swale, etc., are included under marine landforms; Flood Plain, Point Bar, Palaeo channel, etc. are included under fluvial landforms; and Lower Deltaic Plain under fluvio-marine landforms. The range of a coastal flooding is a result of the elevation of floodwater that penetrates inland which is controlled by the topography of the coastal land exposed to flooding. Coastal flooding is mainly a natural event, but due the human intervention in the form of land use changes to the coastal environment can aggravate the situation.

Coastal landforms are moderately modified by diurnal, and seasonal variations; and extremely altered by severe storms. The shoreline, particularly the beaches, generally undergoes constant adjustment towards a dynamic equilibrium. However, anthropogenic changes along the coast may alter the stability to such a degree that it never reaches coastal stability. The 44.40 km long shoreline of Machilipatnam mandal is analysed based on 1938-41 and 2022 satellite images (Figure 6). It is observed that in a span of 81 years about 26.33 km long shoreline is under accretion, and about 18.07 km long shoreline is under erosion. The Shoreline changes are classified into eight categories based on the width of erosion/ accretion. They include: Very High Accretion (VHA); High Accretion (HA); Moderate Accretion (MA); Low Accretion (LA); Severe Erosion (SE); High Erosion (HE); Moderate Erosion (ME); and Low Erosion (LE). The lengths of different accretion classes include: VHA: 5.86 km; HA: 6.73 km; MA: 5.11 km; and LA: 8.63 km (Table-1). The lengths of four erosion classes include: SE: 7.21 km; HE: 4.09 km; ME: 2.35 km; and LE: 4.42 km. The combined stretch of Severe Erosion (SE) and High Erosion (HE) having width of over 750m, constitutes over 25% of total shoreline is of immense concern. The united lengths of Low Accretion (LA) and Low Erosion (LE) having widths less than 500m., comprising of about 29.4% can be considered as stable shoreline. The South-Eastern part of the mandal is under different degree of erosion, while the North-Eastern part is mostly accretion. Erosion immediately north of northern distributary of river Krishna can be attributed reduced sediment supply due to the construction of dams in the upstream (Rao *et al.*, 2010).

This eroded material is carried away by the northeast flowing littoral currents, and depositing in the north and northeast region. The Odissa coast is also exhibiting unique reasons for erosion with various degrees of combinations of sediment depletion, human activities, high frequency of cyclones and floods, sea level rise, etc. (Murali *et al.*, 2015). With the completion of Machilipatnam Deep Sea Port project in this region, the shoreline scenario is likely to change further.

The union operation on polygon feature in GIS environment enables measurement of spatial changes in the coastal zone. The total area gained and lost constitutes about 18.01 sq km and 16.05 sq km respectively. There is net gain of about 1.96 sq km. It is observed that mangroves, tidal creeks and tidal flats along the southern coast are subjected to Severe Erosion (SE); sandy beach, tidal creeks and tidal flats constitute part of HE, ME, and LE classes. Apart from erosion, the land added in the process of accretion in a span of about eight decades is observed to be transformed into different land use/ land cover classes. Sandy beach, tidal creeks and plantations

Table 1: Extent of Erosion/ Accretion between 1938-41 and 2022

Sl. no.	Erosion/ Accretion Class	Width (m.) of Erosion/ Accretion Class	Length (km.) of Erosion/ Accretion	Erosion/ Accretion Area (sq.km.)
1	Very High Accretion	> 1000	5.86	6.41
2	High Accretion	750 - 1000	6.73	6.59
3	Moderate Accretion	500 - 750	5.11	3.37
4	Low Accretion	< 500	8.63	1.64
5	Severe Erosion	> 1000	7.21	9.51
6	High Erosion	750 - 1000	4.09	3.73
7	Moderate Erosion	500 - 750	2.35	1.68
8	Low Erosion	< 500	4.42	1.13

are predominant under Very High Accretion (VHA); mangroves, plantations, creeks, spit, aquaculture, tidal flat, beach classes are under HA; mangroves, plantations, creeks, bar, beach are under MA; and beach, plantation, mudflat and tidal flat are under Low Accretion (LA).

Spatio-temporal variations of Machilipatnam mandal and town

The spatio-temporal change in the extent of settlements in Machilipatnam mandal is a attempted based on the Survey of India toposheets (1969), and satellite images of years 1990, 1999, 2010, and 2022 (Figure 7). The total number of revenue villages including the Machilipatnam town in the mandal is 29. Each of these revenue villages constitutes 3 to 5 hamlets. It is observed that the number of settlements are not uniform in the last five decades. The number of settlements during the years 1969, 1990, 1999, 2010, and 2022 in Machilipatnam mandal are 96, 104, 111, 112, and 118 respectively.

This increase can be attributed to the movement of rich farmers and the associated laborer to establish close to the agricultural fields. As this allows the farmers to closely monitor, have extra space for agriculture operations, etc. The total extent of these settlements during the year 1969 is 11.29 sq km; while its 26.87 sq km during the year 2022. Thus there is an overall increase in the extent of all settlements in the mandal by about 15.58 sq km (@ 29.4 ha/ year) between 1969 and 2022. However, the rate of expansion is not uniform. Based on the available data, the rate of expansion during the initial period is larger than the recent. It is observed that the rate of growth is 55 ha per year between 1969 and 1990 within a span of 21 years. But between the years 1990 and 2022, the rate of growth is just 13 ha per year. The severe cyclonic storm of May 1990 could be the discouraging factor. The area of Machilipatnam town alone constitutes about 69%, compared to the extents of remaining villages in the mandal. Hence, the changes in Machilipatnam town is analysed separately.

The urban landscape has been changing more rapidly than rural areas with time. The geospatial information on changes are very important to urban developers and planners. Multi-temporal data from historical maps and satellite images enable measurements of spatial variations

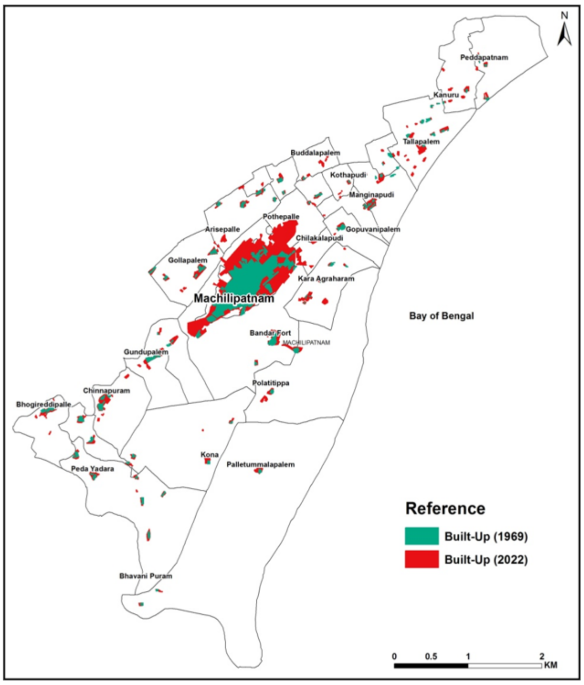

Figure 7: Growth of Machilipatnam Mandal

over different period. It is observed that Machilipatnam town has grown from 473 ha.(1938-41) to about 1846 ha. in the year 2022 (Figure 8). There is clear distinction in the expansion of Machilipatnam town till the year 1990 and thereafter. It is observed that the town has grown @ 52 ha. per year during 1938 and 1990; while during the years 1990 and 2022 the growth has been significantly reduced thereafter to about 32 ha. per year. One of the factors for this reduction could be the impact of May 1990 cyclone. In addition to this, the groundwater from shallow aquifers of Machilipatnam mandal is not suitable for domestic and irrigation purposes as the values of EC and some of the chemical constituents are more than permissible limits (Krishna, 2013). These two aspects could be determining factors for moderate growth of the town in the recent time. The development of town is predominantly along the major axis (NE-SW) of the beach ridge & swale complex. The extent of growth in NE (Potlapalem village) is about 3308 m, and by about 1837 m. is SW direction (Rudravaram village). The growth of settlement perpendicular to this axis, i.e., in NW (along National Highway 65) and SE (Kara Agraharam village) directions are by about 577 m. and 806 m. respectively. The growth in the remaining directions is in the range of 0 to 450 m., except along the Pedana road (1161 m) in North.In the coming years, the predominant growth of Machilipatnam town is likely to continue in the NE direction. This is because of the favourable geomorphic set-up in that direction. Hence, necessary amenities like protected water supply, flood proofing infrastructure, etc is to be developed in this region. Further, there is need to restrict over withdrawal of ground water from shallow aquifers. Else, the sensitive balance between the fresh water over the saline water could be disturbed (Seenipandi *et al.*, 2019).

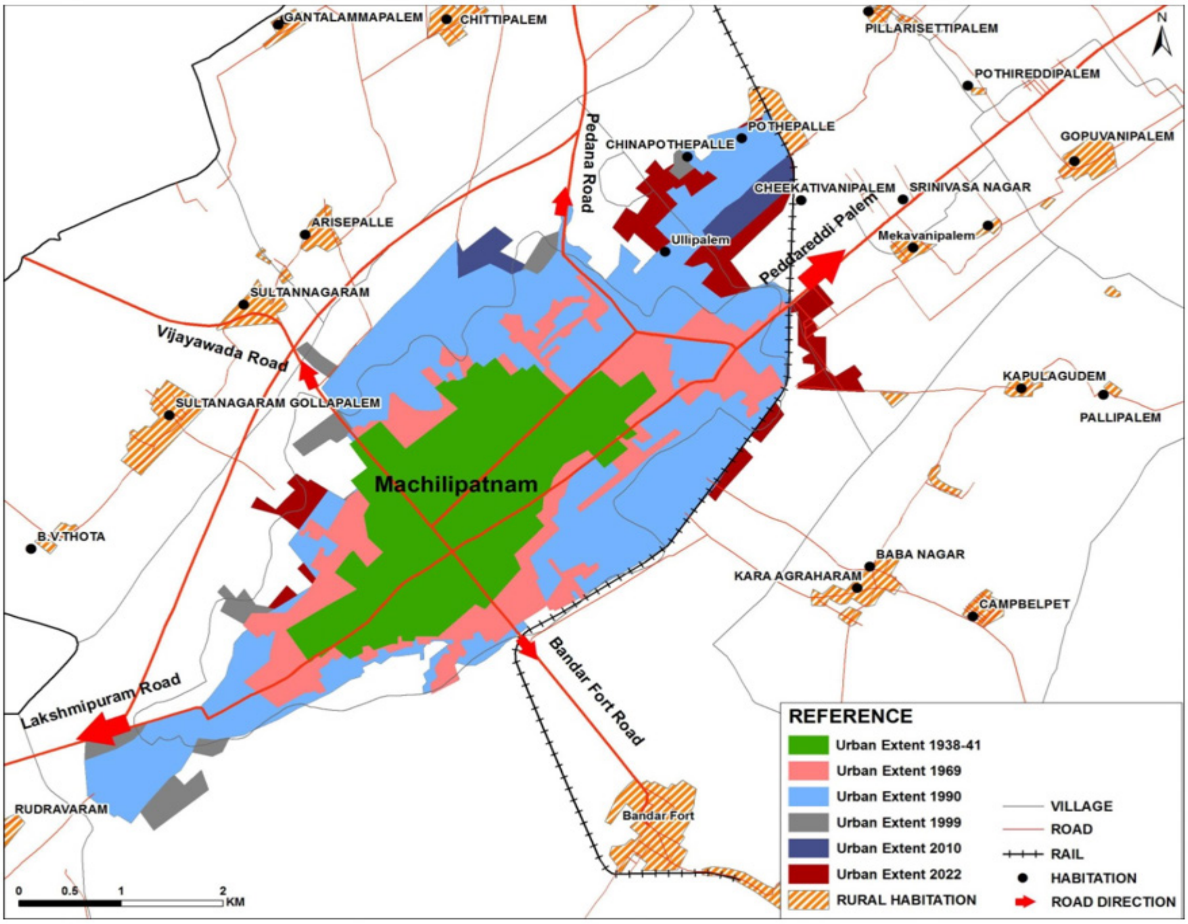

Figure 8: Urban Extension and predominant growth direction.

Population

The population census is collected on selected demographic and socioeconomic characteristics of the population at a fixed interval (e.g. 1991, 2001, 2011, etc). The data collected through the census is useful for planning and policy making. In the present case, the population census of Machilipatnam town and mandal is collected. As per the census, the population of the Machilipatnam town has increased from 39,507 in the year 1901 to 1,69,892 in 2011 (Census of India, 2011). Further, as per the 1901 and 1911 census, the population of Machilipatnam town was more than Vijayawada town indicating its importance. There after the population of Vijayawada had a rapid rise by about 600% compared to the population of Machilipatnam town in the year 2011. Various factors leading to the stunted growth of Machilipatnam town includes recurring storms leading to frequent inundation, mostly low lying areas, limited portable ground water, away from major road/ rail connectivity, limited employment opportunities to all sections of population, etc. Above all, the most striking observation is reduction in population of the Machilipatnam town from 1,75,305 to 1,68,946 between the years 2001 and 2011.

The total population of the Machilipatnam mandal during the years 2001 and 2011 (Census, 2011) is observed to be 2,50,521 and 2,38,962 respectively (Figure 9a and 9b). There is an overall reduction in the mandal population by 11,559 persons. The population of each village in the mandal during 2001 and 2011 is classified into five classes (0 to 1000, 1000 to 2000, 2000 to 3000, 3000 to 5000, and > 5000). In addition to Machilipatnam town, the reduction in village population is observed in Tallapalem (-572); and Chinnapuram village (-845). Further, Pedayadara village (NE of Machilipatnam mandal) was in the class of >5,000 in 2001 census has gone down to 3,000 to 5,000 class in census 2011. Similarly, Rudravaram, Gundupalem, and Pedapatnam villages were in the range of 2,000 to 3,000 as per 2001 census, have come down to 1,000 - 2,000 range in 2011 census. Chilakalapudi village in NE of Machilipatnam Town is the only village in the mandal which recorded the population increase by 1356. In addition to the factors mentioned for reduction in population, changing land use pattern is also observed to be one of the important factors. Large tracks of agricultural lands are converted into aquaculture (Ramana Murty & Mruthyunjaya Reddy, 2010), not only increasing the flood vulnerability but also leading to reduction in employment opportunities.

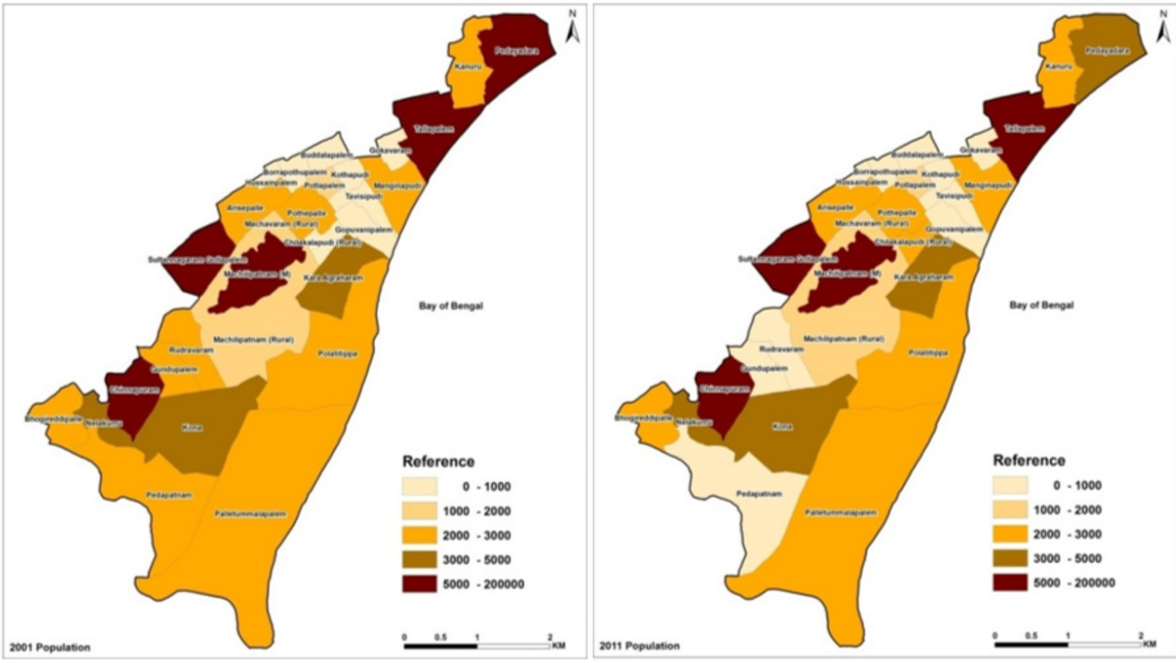

Figure 9a and 9b: Population classes based on 2001 and 2011 census

Existing and proposed flood proofing measures

Recurring storms in the Krishna river delta is resulting in loss of several thousand human lives. In order to protect the human population in particular; and livestock, and agricultural fields in general, flood/storm protection measures are to be adopted. These could be structural measures or environmentally friendly non-structural measures. Embankment is one of the popular measures adopted to help protect people, livestock, dwellings, and croplands from storm surge. Apart from building embankment, the other important structural measures against tropical storms, includes cyclone shelters, improved road links, culverts/bridges, drains, etc. In order to protect Machilipatnam mandal from storm surges / tidal waves, Kona Tidal Bank (Saline Embankment) is made (Figure 10).It is spread between Polatitippa and Kammavaricheruvu villages having a stretch of about 18.55 km in Machilipatnam Mandal. There are few settlements close to this tidal embankment. Apart from tidal embankment, there are other embankments along river Krishna (16.27 km), and along major drains (10.77 km) of the mandal. These other embankments are designed to restrict the flood waters to contain within either banks of river/ drain.

The role of non-structural methods in handling disasters has been gradually evolved by the community with the traditional knowledge. These have been time tested, economical, cost effective, user friendly, and can be done by involving local people. One of the important non-structural and environmental friendly measure is development of mangrove forest. Mangroves act as a bio-shield for protecting life and property from storm surge and strong winds. They also protect the coastline from erosion and deposition of sand. The total extent of existing mangroves as assessed based on the latest satellite imagery of 2022 constitutes about 5,266 ha. Potential areas for regeneration are identified in degraded areas, and generation of mangroves in suitable areas based on the landforms and tidal influence are identified. The shelter belt plantation is another important non-structural measure for protection from stormy winds. The total extent of potential zone constitutes about 478 ha. These shelterbelts are barriers of trees planted parallel to the shoreline to reduce the wind velocities and protect human habitations and agricultural crops from physical damage. The shelterbelt is mostly planted with casuarina all the sandy stretch of coastline.

The total coastline length with shelterbelt plantation constitutes about 38.29 km. In addition to this, other potential sites, particularly coastal dunes and beach ridges are identified for shelter belt plantation. It is observed that there is apossibility of plantation near villages Gollagudem, Giripuram, and Pallipalem for an addition length of about 5.66 km. Another important aspect of flood impact minimization is drainage improvement. The efficient drainage system of an area can remove the storm water with ease without inundating the surrounds for longer duration. The total length of drains in the mandal is about 268 km. The major issue with drains in the river delta region are, either they are silted up or choked with weeds. It is observed that about 25.5 km of drain length is occupied with aquatic vegetation. Such choked drains are observed near the villages Garaladibba and Pallepalem which needs to be improved at least to it designed capacity. Any hindrance to drains due to aquaculture also needs to be identified and necessary alleviation measures may be adopted. In the present study, only some of the feasible structural and non-structural measures are discussed.

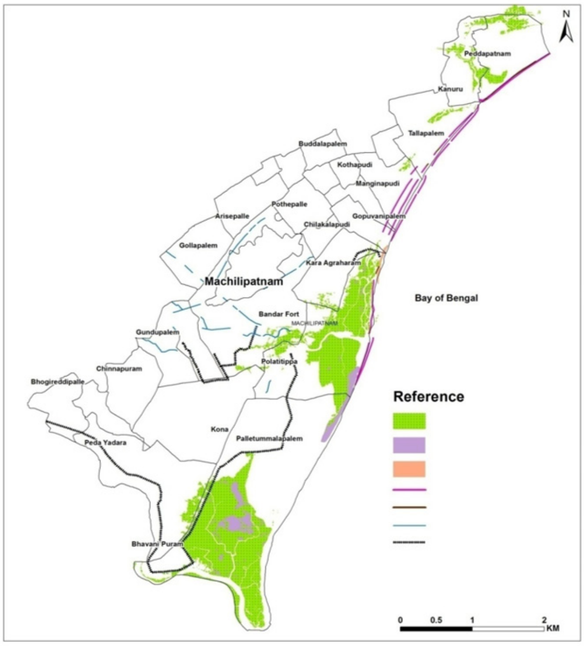

Figure 10: Proposed Flood Alleviation measures

CONCLUSION

Coastal flooding results in loss of human lives and destroys livelihoods, infrastructure and other assets. Deltas are extremely vulnerable to coastal flooding. Amongst the global deltas, the Krishna river delta is identified as one with greater peril as there is virtually no aggradation. The protection of human life in deltas against coastal flooding is essential component of disaster minimization. Human migration to the coastal zone is a common phenomenon elsewhere, but population reversal is observed in most of the villages of Machilipatnam mandal. Recurring tropical storms and natural resources degradation of historical Machilipatnam town resulted in stunted growth in comparison to the other towns of the State. The land use/ land cover modifications mayfurther increase the flood vulnerability of the region. In order to alleviate coastal flooding, adoption of suitable structural and non-structural are a prerequisite. The Kona tidal embankment between Polatitippa and Malakayalanka villages protects Machilipatnam town from coastal flooding. Apart from the tidal embankment, there are embankments along Krishna river and drain to prevent from overflowing. Regular maintenance and strengthening of these embankments is to be taken up before the two main cyclone seasons i.e., May, and September-November. In addition to the structural measures like flood embankment, multi-purpose cyclone shelter, all-weather roads, etc. can effectively minimise the vulnerability of the region. There is a need for improving the carrying capacity of drains, nalas, etc. The total length of drains/ nalas in the mandal constitutes about 268 km. About 25.5 km of this drain length is observed to be choked with weed, which needs clearance. Ecosystems-based approaches, like restoration of mangrove vegetation on coastal mudflats, and shelter belt plantation preferably with casuarina on coastal dunes/ beach ridges help mitigate the impacts of storm surge and strong winds. There is a need for land use policy to protect the mangroves outside the reserved forest areas in privately owned lands by allocating alternate resource space, and monitoring periodically. The satellite image of the year 2022, compared to the imagery of 1990 indicates a substantial increase in the extent of mangroves. Healthy coastal ecosystems would support coastal fisheries and eco-tourism too. Adoption of appropriate environmental friendly flood protection measures would significantly reduce the coastal vulnerability to Machilipatnam towns and its environs.

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