An advanced GIS based approach for the assessment of coastal inundation in the storm surge region (Krishna District) of Andhra Pradesh, INDIA

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Abstract
Climate change leads coastal areas to suffer from rising sea levels, flooding, storm surges and cyclones which can cause irreparable harm to people and their assets. The mapping of these alterations to the coastline can assist in sustainable coastal development and surveillance. The current research emphasized the susceptibility of coastal inundation in the Krishna District of Andhra Pradesh, which is the State's most vulnerable place to flooding and cyclonic storms. The Indian Meteorological Department website (mausam.imd.gov.in) was accessed to get latitudinal and longitudinal data on cyclonic storms that hit the area recently. The satellite imagery was acquired from Google Earth and USGS (earthexplorer.usgs.gov) to map the coastal settlements within 25 km radius of the coastline and to generate Digital Elevation Model (DEM) to identify the coastal inundation vulnerability up to 5.0 M contour elevation (2m, 3m, 4m and 5m).

According to findings, there was a small impact of coastal inundation up to 4 meter sea level rise, so the research primarily concentrated on the assessment of coastal inundation with 5 meter sea level rise. A total of 512 settlements studied for coastal inundation encompassed an area of about 11405.4 hectares. The DEM identified that a large number of settlements in the Krishna District are on the verge of coastal inundation. About 125 settlements (24.5% settlements) with an area of approximately 2099.5 hectares are most vulnerable to coastal submergence, accounting for 18.5% of the studied area. This damage exposure assessment helps local government and policymakers to counteract extreme inundation events.

Keywords: Digital Elevation Model, Coastal Inundation, Natural Disasters, GIS, Cyclone, Vulnerability.

Introduction

The coastal zone is the area where the hydrosphere, geosphere, anthroposphere, atmosphere and ecosphere meet. Since prehistoric times, the coast has offered people a place to live, is a source of sustenance and is facilitating socio-economic networking[21]. However, coastlines are also acknowledged as areas that are threatened, as they are places where increasing sea levels, floods, storms, tsunamis, erosion and silting pose a threat to people's ability to make a living[7,20,57]. In recent years, these threats have become even more apparent due to climate change and other environmental processes that are connected to it[10,21]. Due to increased human activities and economic activities (agriculture, aquaculture, tourists, industries, trades and transit) in coastal areas, these coastal areas are more susceptible to the damaging impacts of natural catastrophes[19,23,42]. Approximately forty percent of the world's population resides within sixty kilometers of a coastline while more than twenty-five percent of India's population is within fifty kilometers of the coast[51]. Natural processes, specifically those influenced by climate change, in conjunction with human activities, are becoming significant elements contributing to coastal areas' vulnerability[9]. Mean sea level rise, extreme events like flash floods and cyclone-induced storm swells are substantial dangers for susceptibility in India's coastal regions, which are experiencing a quick increase in risk[13,34,36].

The increase in sea level is one of the most disturbing and expensive consequences of climate change which influences the continued sustainable development of coastal regions[25,45]. The battle against sea level rise may appear hopeless, especially in low-lying coastal locations where many ecosystems may be severely damaged or eliminated[8]. The rising sea levels and the effects that this will have on shoreline areas are attracting an increasing amount of attention, not only from the scientific community but also from the media and the general population.

According to the Intergovernmental Panel on Climate Change (IPCC 2007), anthropogenic global warming is anticipated to continue to increase the mean global sea level throughout the remainder of this century and beyond. Countries with a large population and diverse economic operations face a significant risk from rising sea levels. Increase in the atmospheric concentrations of greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs) that humans cause, may result in unprecedented rises in the average temperature of the Earth[47].

The average temperature of the Earth's surface has been rising and glaciers and sea ice are disappearing due to global warming. These are just some of the obvious repercussions that global warming has already brought about[18,31,53]. Countries in the tropics and subtropics, especially those near

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the shore, are feeling the effects of climate change. The Indian coast receives significant damage due to the frequent high tides and storm surges[43,50].

Andhra Pradesh is a State in India vulnerable to many different types of natural disasters, particularly cyclones and the storm waves they bring. These storms cause a great deal of destruction and loss of life. Over the previous 40 years, the coast of Andhra Pradesh was hit by 62 cyclones including depressions, cyclone surges and catastrophic cyclone surges (Table 1). Thirty-two cyclones hit the Krishna-Godavari basin, consisting of East Godavari, West Godavari, Krishna and Guntur[6]. Such catastrophic events like violent cyclones, flash floods and rising sea levels due to climate change result in the increasing inundation of the coastal areas[29].

The GIS can be used to map out the areas that will be inundated[57]. The mapping and frequent updating of coastline changes have extensively used remote sensing & GIS technology in recent years. Additionally, it has been utilized in the monitoring and evaluating alterations due to coastal inundation in coastal environments[3].

There are several models for the coastal inundation assessment using remote sensing and Geographic information system (GIS). It can manage, manipulate and analyze spatial data and information like digital elevation models (DEM) and vertical land motion (VLM). In this study, several hydrodynamic approaches are considered to develop an advanced GIS based DEM for assessing the impacts caused by coastal inundation.

Study Area

Krishna district can be found at coordinates 15°43′ N and 17°10′ N latitude and 80°0′ and 81°33′ E longitude on a world map. Krishna district is part of the Andhra Pradesh State on India's southeastern shore, with its district headquarters based in Machilipatnam.

Table 1
Major cyclones that hit Andhra Pradesh (A.P.), India in recent past

S. N.	Type/name	Period	Areas Affected
1	Cyclonic storm Ogni	29-30 Oct. 2006	Ongole district
2	Severe Cyclonic Storm (Laila)	17-20 May 2010	Prakasam, Krishna and Guntur dislicts
3	Very severe cyclonic storm (Phaillin)	08-12 Oct. 2013	Srikakulam district
4	severe cyclonic storm (Helen)	20-22 Nov 2013	Krishna, Visakhapatnam, East Godavari, Guntur, Srikakulam
5	Very severe cyclonic storm (Lehar)	23-28 Nov 2013	Total Coastal A.P.
6	Very severe cyclonic storm (HudHud)	07-14 Oct. 2014	Visakhapatnam, Viziananagaram and Srikakulam districts.
7	cyclonic storm (Roanu)	17-22 May 2016	Rainfall over Coastal Andhra Pradesh
8	Very severe cyclonic storm (Vardah)	06-13 Dec 2016	Heavy Rainfall over Nellore, Chittoor, Anantapurnam and Cuddapah districts.
9	Very severe cyclonic storm (Titli)	08-12 Oct. 2018	Srikulam and Viziangaram districts
10	Cyclonic storm (Gulab)	24-28 Sept. 2021	Srikakulam and Vizianagaram districts

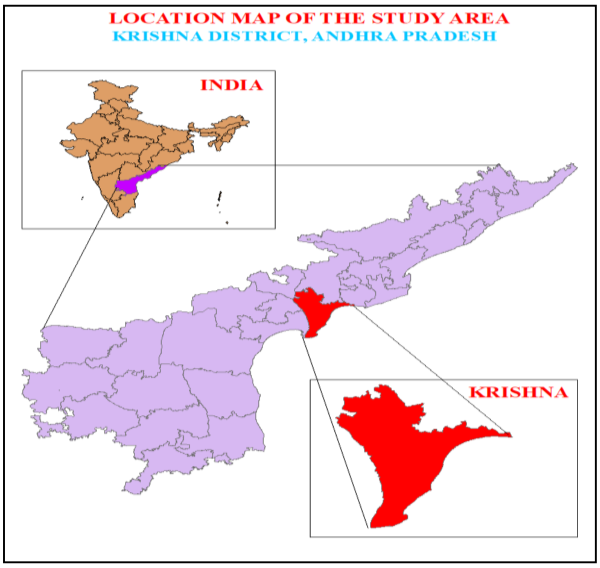

Fig. 1: The study area Map

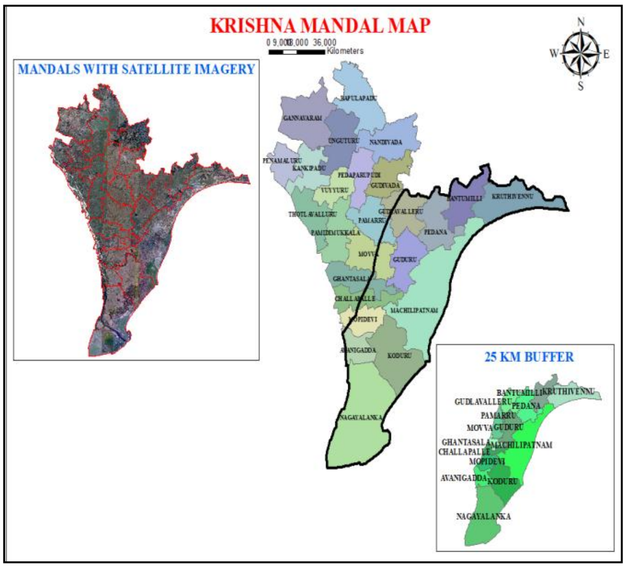

Fig. 2: Study area Mandal Map

The Gulf of Bengal bounds the coastal district to the east, the Guntur district to the west, the Eluru district to the north and the NTR district to the south. The district has three revenue divisions namely Machilipatnam, Gudivada and Vuyyuru, each headed by a sub-collector. These revenue divisions are divided into 25 mandals in the district. The Machilipatnam revenue division has 10 mandals: Avanigadda, Bantumilli, Challapalli, Guduru, Koduru, Kruthivennu, Machilipatnam, Mopidevi, Nagayalanka and Pedana. There are 8 Mandals in Gudivada revenue division: Gudivada, Gudlavalleru, Nandivada, Pamarru, Pedaparupudi, Gannavaram, Bapulapadu and Unguturu. The Vuyyuru has 7 Mandals: Vuyyuru, Pamidimukkala, Kankipadu, Penamaluru, Thotlavalluru, Movva and Ghantasala.

According to a study published in 2016 by the National Disaster Management Authority (NDMA), the coast of Andhra Pradesh is the second most cyclone-affected area in India after Odisha. It is also the second most flood-prone region in India after Kerala. The Ministry of Environment and Forests of the Government of India (2012) reported that along the coast of Andhra Pradesh, both the frequency and severity of cyclonic activity and the associated storm surges have increased due to climate change. The Krishna district is part of the Andhra Pradesh coast, which is especially vulnerable to natural catastrophes.

Material and Methods

The present study assesses coastal inundation in one of the most vulnerable districts of Andhra Pradesh State, India[23]. First, satellite imagery of the research region was obtained using Google Earth, a free open-source program designed specifically for this purpose. December 2020 Landsat/ Copernicus satellite imagery was used to create the satellite picture mosaic for this research.

The satellite image provides a birds-eye perspective of the study region, making it ideal for conducting in-depth research and analysis. The ArcMap 10.5 software was used to create a buffer of 25 kilometers with the assistance of the district boundary map obtained from the local administrative department.

The buffer was employed to determine the locations of the communities that were within 25 kilometers boundary of the shore. After that, Google Earth was used to depict the communities digitally. Different topo sheets, Google Earth Pro and Landsat 8 imagery acquired from the USGS were used to collect the data necessary to compile various types of maps (Base map, location map, drainage map etc.) for the study region. This data was then used to create the necessary maps. Google Earth Pro, ArcMap 10.5 and Global Mapper were also utilized in data examination and interpretation.

The process of carrying out this research includes, among other things, the digitization of surface features, the creation of drainage, contour and surface maps and the analysis of these maps. However, the most important steps in this study are the development of the contours and the generation of the digital elevation model (DEM). This study relies on a detailed examination of the digital elevation model to determine which locations will be inundated due to rapid flooding, cyclonic storms and in the event of an increase in sea levels.

Base maps are the basis on which other maps, called layers, can be overlaid to provide a complete view of an area. They contain geographical data for research and essential knowledge on terrain, roads, landmarks, municipal borders and other themes. Making a single base map out of multiple feature, vector, or web layers is possible. The base map was produced by digitizing prominent habitations, waterways, highways, railways etc., from different topo sheets and Landsat 8 imagery. After the base map, the inputs were exported to ArcMap software for further processing and compilation. The satellite imagery of Landsat/Copernicus from Google Earth was used to prepare the drainage map of the study area. The major streams and rivers were digitized in Google Earth and saved as Keyhole Markup Language (KML) files. The KML files were then transferred and processed in ArcMap 10.5 for map preparation. The drainage map shows various rivers and streams that flow across the district[27].

The data about different inputs (latitude and Longitude) was acquired from the website of the Indian Metrological Department (mausam.imd.gov.in) and the data was processed in ArcMap 10.5 to prepare the historical cyclone track map. The map was prepared for severe cyclonic storms that hit Andhra Pradesh coast in the recent past. The Cyclone track map serves as a general guideline for numerical models and it helps to evaluate and assess risk factors along the coastal belts[40]. Google Earth was used to collect the data to compile the contours. The data was processed using ArcMap 10.5 and the contours for the research region were produced with a one-meter interval between them.

The region that will be inundated as a consequence of rising sea levels can be mapped using DEM data[32]. Digital elevation models (DEMs) are numerical representations of topography that consider both position and scale, with each grid cell having an associated elevation number[15].

Due to its broad access and straightforward data format, it is widely used in fields as diverse as land-use planning, geomorphic feature derivation, hydrological modeling, topographic mapping and telecoms. To determine the inundation zones along the coastal zone, a digital elevation model (DEM) in conjunction with overlay approaches in GIS is leveraged[15,58].

Based on the predicted SLR and elevation data, the influence of rising sea levels in the Krishna coastal areas is evaluated to prevent the potential of submerged land areas in the future. The flow chart of this study's methodology is described in fig. 3.

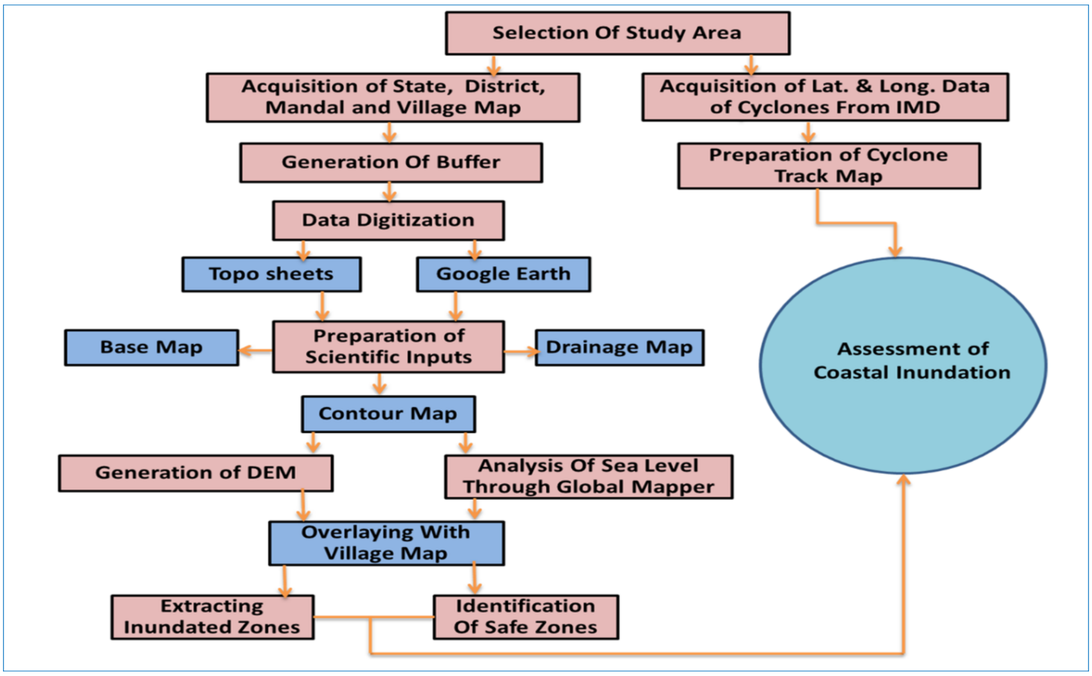

Fig. 3: Schematic diagram of the methodology

Development of Digital Elevation Model (DEM): The vulnerability may be described as the risk of loss and the extent to which valuable assets are exposed to a risk. It may be represented in several ways, suggesting a loss of effectiveness, value or stability. The vulnerability can be assessed by developing the digital elevation model with remote sensing and GIS applications. The DEM is a tool that can be used to identify topographic features, geomorphometric parameters and other data related to the terrain[4,24]. The region that will be inundated as a result of increasing water levels can be mapped using DEM data which can be used to produce the image.

Studying the impacts of coastal inundation requires data on the elevations of the land surface[49]. Using contour data sampled at one-meter intervals from satellite images obtained via Google Earth, a digital elevation model (DEM) was created. This data was processed in preparation for DEM using GPS visualizer software and ArcMap 10.5; the following procedures are included in the process:

- The creation of stream mode paths on Google Earth imagery for the research region with the results being stored as a KML file.
- The KML file was then processed by GPS visualizer, a free application, to transform the GPX file with elevation.
- ArcGIS 10.5 software was used to perform the conversion which resulted in the GPX file being saved as a point-type shape layer.
- After undergoing Kriging interpolation, the point layer was converted into a raster and contour was then generated from the raster.
- Using the ArcGIS 10.5 software, a DEM was created by converting contours to tin and then converting the tin to raster.

Coastal inundation modeling: There are several potential variables to investigate disaster impacts such as sea-level rise, flood speeds and flood durations. In this study, DEM data is used to assess how coastal flooding caused by increasing sea levels and coastal floods affects the region. For the current study, inundation maps are generated by combining current and prospective environmental factors with a GIS-based inundation model. The input required by the inundation model is a digital elevation model and the difference in sea level rise. The DEM was used to identify the areas vulnerable to inundation by assigning a value of 2m, 3m, 4m and 5 meters (m) to a hypothetical scenario in which the sea level rises. This allowed for the determination of the locations that were at risk of being flooded. This was done to obtain a comprehensive picture of the study's susceptible region.

By analyzing the digital elevation model (DEM), contour map and sea level footage obtained from Global Mapper, as well as by superimposing digitized communities on top of inundated regions, the areas that were most likely to be affected by the inundation, are identified. In the event of a natural catastrophe, places and communities located above the contour elevation of five meters are designated as secure zones and are considered as rehabilitation zones.

Risk impact assessment: Risk impact evaluations for communities often include evaluating the monetary cost of serviceability, functionality, or integrity losses in light of a hazard scenario[54,55]. This is not the same as a disaster exposure assessment. It explains how natural and man-made disasters influence one another in the ecosystem. The exposure is calculated by superimposing the built assets on top of flood-affected areas while considering many extreme storm surge scenarios. The effect is the product of each asset's exposure and vulnerability.

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a) The structural damage in the affected area can be estimated by:

$$D_s = C_b \times F_a \quad (1)$$

where D_s is the damage loss of the structures, C_b is the construction cost of a building per unit area and F_a is the ground floor area of the affected building.

b) The damage of the affected road can be calculated by:

$$D_r = R_c \times L \quad (2)$$

where D_r is the road damage loss, R_c is the construction cost per unit length of roads and L is the total length of the roads in Affected area.

c) The damage loss for the electrical facilities, particularly for each substation and transmission tower can be estimated by:

$$D_e = C_c \times D_s(h) \quad (3)$$

where D_e is the damage loss of a substation, C_c is the average construction cost per substation and $D_s(h)$ is the damage rate for substations submerged at a given water depth h.

d) The damage to Agricultural revenue can be estimated by:

$$A_r = A_l \times V_r \quad (4)$$

where Ar is the agriculture revenue, A_l is the land under agricultural in hectares and V_r is the value revenue per hectare.

Results and Discussion

The increase in sea level, which is a direct consequence of climate change, poses a significant risk to both the environment and the human population. The primary factors that contribute to the quickening of the increase in sea level are changes in temperature, atmospheric pressure, cyclonic activity and ocean circulation.

According to some studies, approximately 400 million people who live less than 20 kilometers from the shore or less than 10 meters below mean sea level (MSL) will be in danger of experiencing the effects of the increase in sea level[39,44]. The impacts of coastal inundation at different intensities were spatially examined in order to evaluate the impact on the study area. The analysis is briefly described as follows:

Cyclone track map: Flooding caused by tropical storms is a major threat to human life and the ecosystem everywhere. Rising shoreline susceptibility is primarily caused by changes in ocean circulation, temperature, air pressure and cyclonic storms[2,26,37]. According to a study by the Indian Ministry of Environment and Forests (2012), impacts of climate change on air and sea-surface temperatures have been linked to increased frequency and intensity of cyclonic activity and related storm waves in coastal Andhra.

It can be observed from the map (Fig. 4) clearly that most of the cyclones made landfall in the Andhra Pradesh State's coastal region. The study by the National Disaster Management Authority (NDMA) states that the Andhra Pradesh coast is the second-most cyclone-affected area in India (after Orissa) and the second-largest susceptible region to floods (after Kerala). It is clear from the statistics on cyclones that whenever they make landfall along the shore, there is destruction to both people's lives and their possessions due to storms and inundation. The map of cyclone tracks makes it abundantly evident how vulnerable is the shore of Andhra Pradesh to the various types of cyclonic storms.

Coastal inundation impact analysis: Assessing hazards, exposures, vulnerabilities and impact risks may give significant information that may aid decision-making at different sizes and degrees of complexity. The following spatial analyses, such as base map, drainage map and contour map, were discussed to develop and analyze the effects of coastal inundation on sea level rise and coastal flooding. Base maps are the foundation for the maps upon which other maps, also known as layers, can be superimposed to provide a more comprehensive overview of a particular region of interest. Base maps can be found in almost any geographic information system. They provide essential information on landforms, roadways, monuments, governmental boundaries etc. and contain the geographical data required for analysis.

It is the crucial component that will serve as a basis for creating all kinds of maps[30]. The risk of flooding in communities that are situated in close proximity to significant rivers and other waterways is made abundantly clear by the base map (Fig. 5). When a cyclone hits, these waterways will almost certainly overflow which will cause significant damage to the communities that are nearby.

GIS data and drainage maps complement one another, offering an invaluable contribution to the strategic administration and control of water resources[27]. The rainfall season may result in rivers, streams and waterways in the region of research reaching or exceeding their maximum capacity, which leads to widespread inundation. The proximity of the study area to the ocean increases the likelihood that it will be swamped to some degree as storm surges and other forms of extreme weather increase the risk of saltwater flooding in low-lying littoral zones and coastal floodplains[28]. The findings of the analysis of the drainage map (Fig. 6) made it abundantly evident that the communities close to the most critical streams and rivers put them in danger of being flooded during the expected and unexpected heavy rainfall.

It was found that the Krishna River, running close to the boundary of the study area, poses a threat to the low-lying areas during monsoon season and an unexpected cyclone period due to heavy rainfall that results in flooding[38]. It is evident that the strategic management and control of water resources is greatly aided by combining GIS data with drainage maps[27].

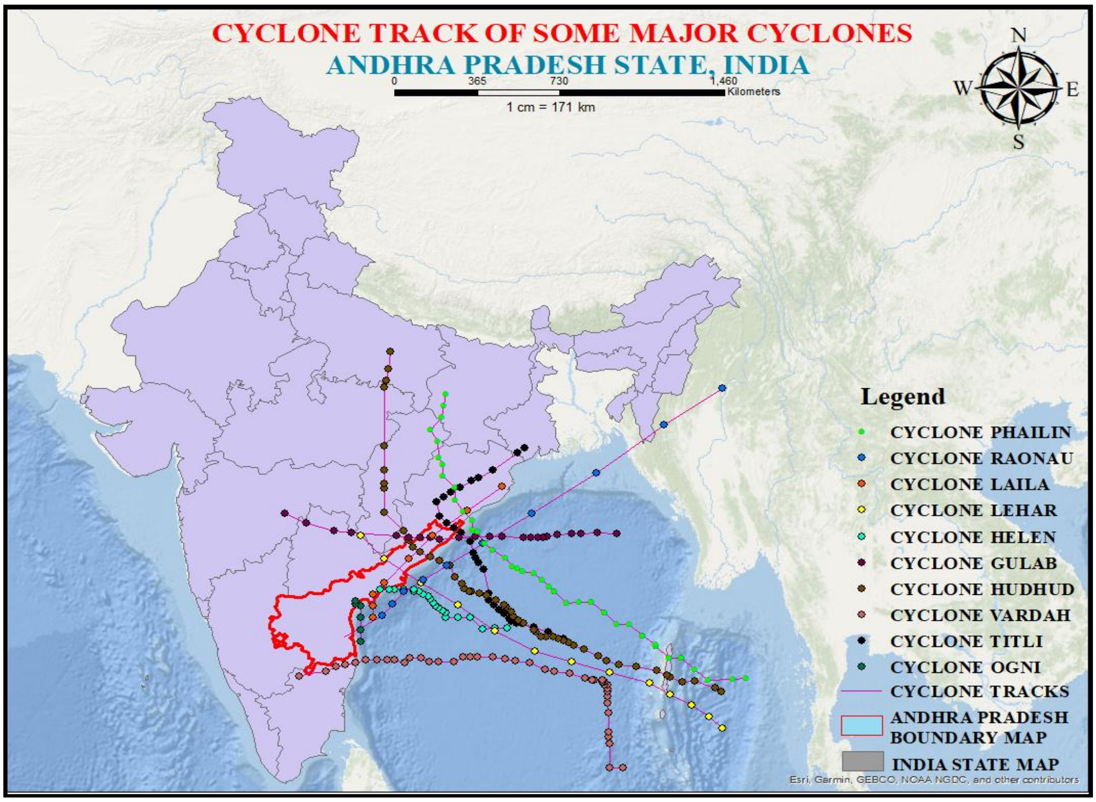

Fig. 4: Cyclone Track Map

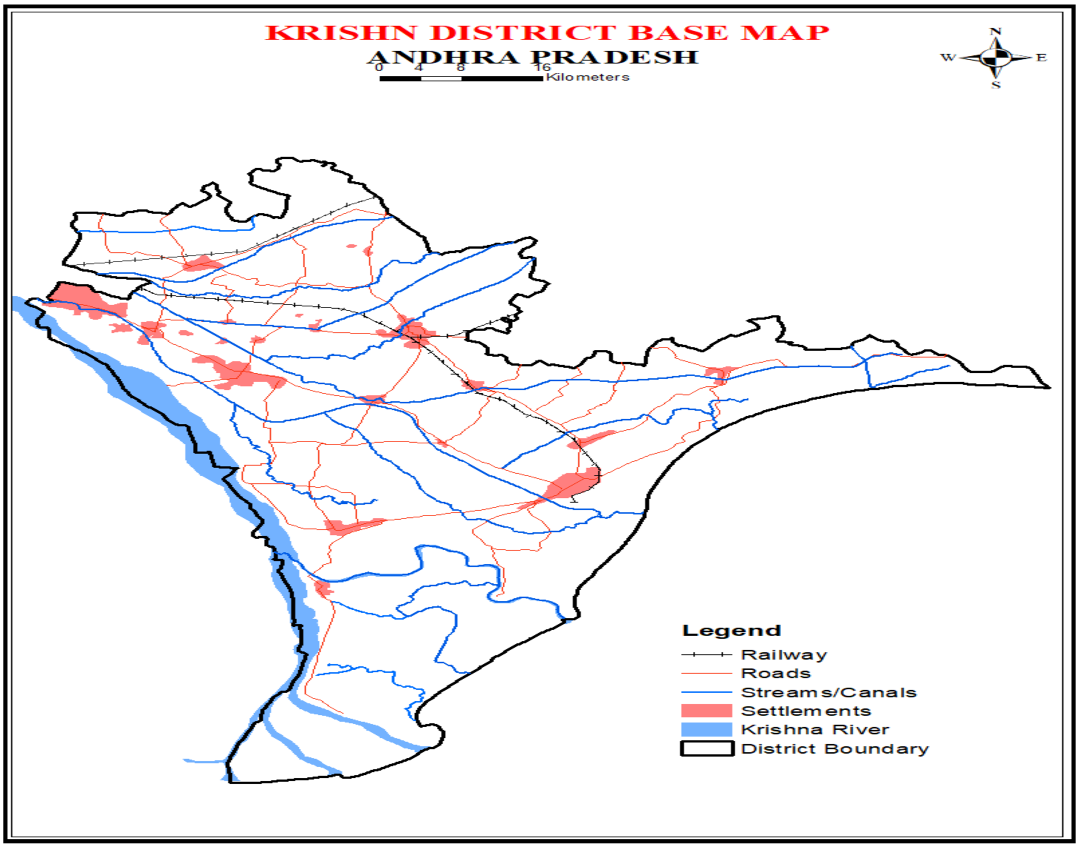

Fig. 5: Base map of the study area

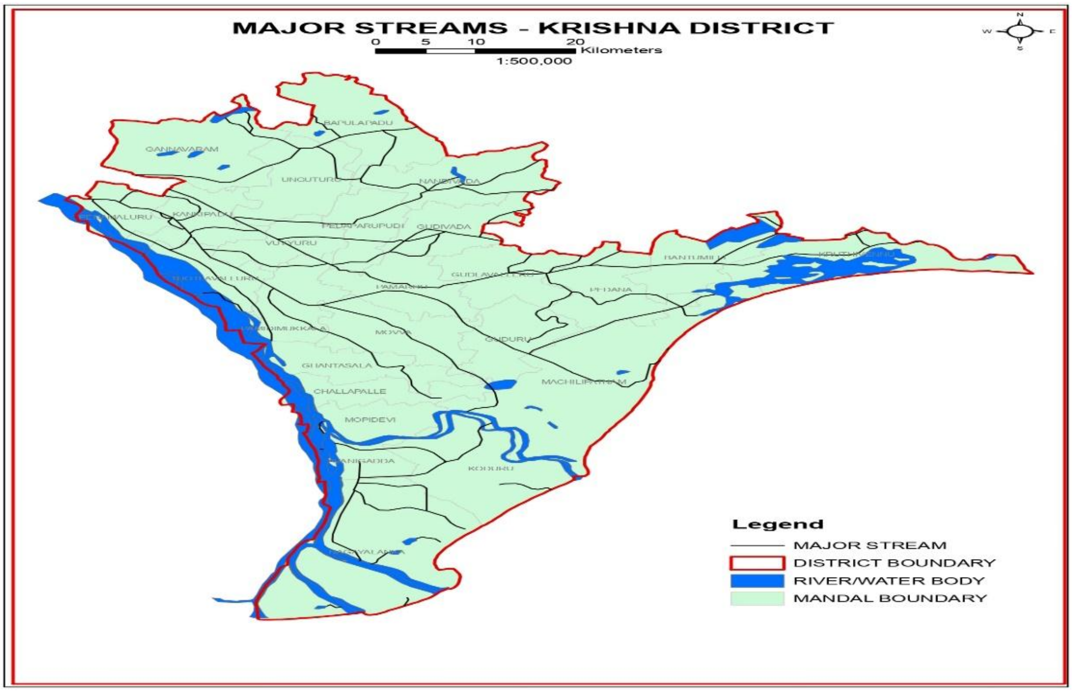

Fig. 6: Map showing the major streams and rivers of the study area

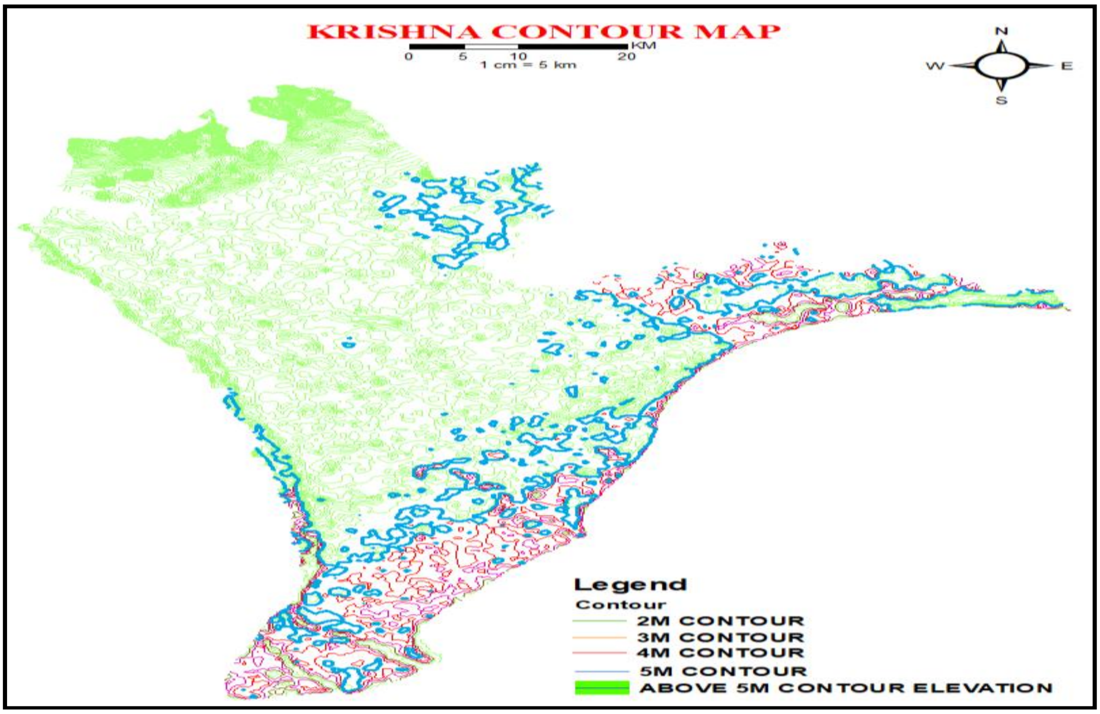

Fig. 7: Map showing the contour elevation of study area

The difference between the mean sea level and the elevation of the study area was depicted through contours. This method was carried out to assess the effects of increasing sea levels up to a height of five meters. The contours (Fig. 7) were generated using satellite data; these contours show the difference between the mean sea level and the elevation of the study area. The contours on the map are shown in 2m, 3m, 4m, 5m and above 5m elevation classes. The areas with elevation greater than 5m can be categorized as high-elevation regions. After doing the assessment, it was concluded that there is no risk of inundation to the settlements with a 2m rise in sea level. Some minor risk of inundation was seen in some of the mandals with a 3m and 4m rise in sea level.

The major effect due to coastal inundation on settlements was seen with a 5m rise in sea level. This shows that most of the communities in this region that were examined, could be flooded as a result of five-meter increase in sea level. Because of the rise in sea level and an increase in the regularity of storm surges, there is a tremendous potential for coastal inundation[16].

Sea level rise (SLR) implications: The implication of SLR can be interpreted in terms of an increase in damage loss given the exceedance probability or an increase in exceedance probability given the amount of damage loss. Using the software program Global Mapper, the water level map was generated (also known as the surface level; fig. 8). In order to analyze the effects of rising water levels, this map was utilized[1]. The areas in danger of flooding due to an increase in sea level of 3m, 4m and 5 meters were identified by superimposing the 3, 4 and 5 m contours on the water level images. As shown in fig. 8, the probability of damage loss by coastal inundation resulting from 2 m SLR is negligible.

The coastal inundation is increasing in the southeast direction with the 3 m, 4m and 5 m SLR. From the results, it was observed that the areas above the 5 m baseline height are considered to be secure. As a result of these findings, it is evident that there is a high risk of coastal inundation in the South and East coastal mandals of the study area. The increasing number of people living in coastal areas is one trend that may be exposed to flooding threats, potentially resulting in significant damage claims[55]. Given the aforementioned uncertainty concerning the size and timing of rises in sea level, the present scenario may be used to assess adaptation methods in terms of their effectiveness against various magnitudes of environmental change.

DEM for analyzing the coastal inundation impact: The Digital Elevation Model, or DEM, has found widespread application in various fields including flying modeling, engineering works, surface analysis and flood risk evaluation. Over the past few years, it has become increasingly evident that DEM is being employed in a high capacity to predict and assess flood risk[46]. The DEM combined with GIS mapping techniques is useful for locating the coastal regions prone to inundation[32]. Using the DEMs and the SLR levels for the current and future scenarios, the inundating model is used to map the associated inundation extent on an inundation map.

The DEM (Fig. 9) was examined in three dimensions with the global mapper and ArcScene programs by utilizing contour elevations (2, 3, 4 and 5 meter) to determine which parts of the research area would be flooded. The elevation statistics was categorized to acquire the region with high elevation. This shows that the area is at risk of being flooded and is known as susceptible to inundation. On the DEM map, the regions of low elevation are represented by blue patches and the habitations that are located on these blue patches, are the ones that are at risk of being flooded. It was determined which regions were susceptible to damage by superimposing a digitized built-up layer on top of DEM data.

At first, the analysis of coastal inundation was done for the SLR of 2 meters and it was seen that there is not any impact of SLR on the settlements (Fig.10). Then the assessment was done to check the risk of coastal inundation on settlements due to 3 meter SLR. By going through the proper analysis, it was concluded that there are minor risks of coastal inundation in a couple of mandals. The settlements that are on the verge of coastal inundation due to 3 meter SLR rise are mentioned in table 2 as well as on the map (Fig. 10).

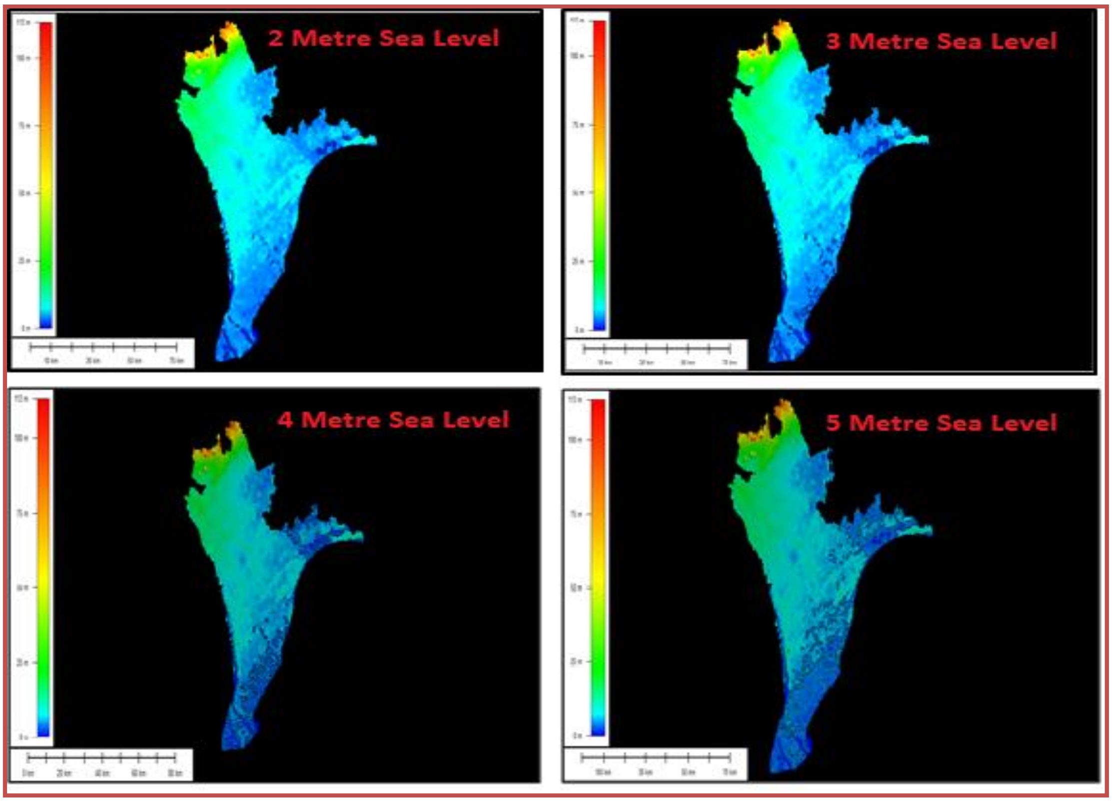

Fig. 8: The sea level map of the study area

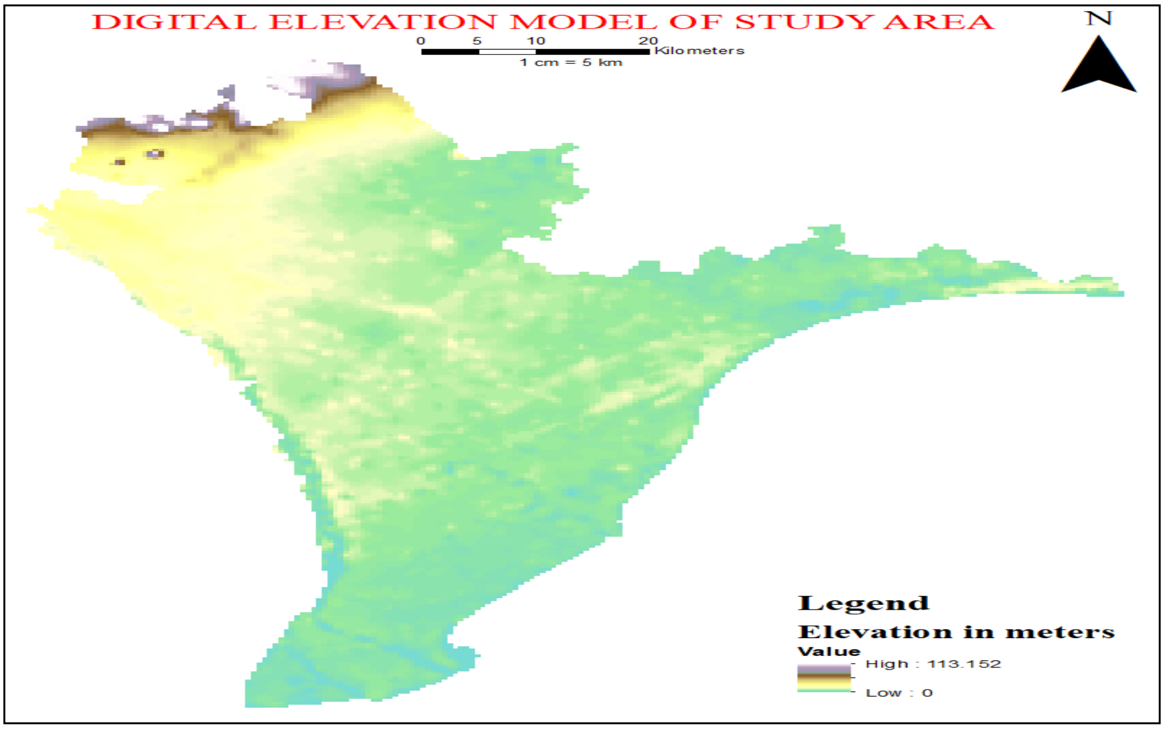

Fig. 9: Digital elevation model of the study area

Table 2
The name of the settlements at the risk of coastal inundation with 3 m MSL

Mandal Name	Habitations (Villages/Hamlets/Towns) To Be Affected
Nagayalanka	Elachetladibba and Nagayalanka
Koduru	Potumeeda

Table 3
The names of the mandals and settlements at the risk of coastal inundation 4 m MSL

Mandal Name	Habitations (Villages/Hamlets/Towns) To Be Affected
Nagayalanka	Barrankula, Edurumondi, Elachetladibba, Etimoga, Nachurgunta, Nagayalanka, Nali, Parrachivara, Sorlagondi,
Bantumilli	Arthamuru, Narrasappacheruvu, Nagannacheruvu
Koduru	Irala, Peda Godumotu, Potumeeda, Ramakrishnapuram, Utagundam,
Kruthivennu	Interu, Padatadika

The analysis of 4 meter sea level rise shows a potential danger of inundation on the settlements in four mandals i.e. Nagayalanka, Koduru, Bantumilli and Kruthivennu (Fig. 10). The highest affect was seen in Nagayalanka mandal, with most of the settlements at the risk of inundation. The affected settlements are listed in table 3.

The most significant impact of coastal inundation was seen due to five meter sea level rise. Almost all the mandals that fall under the 25 km buffer zone from the coastline are seen to be affected by rise in sea level. That is why the primary focus of the research was mainly concentrated on the assessment of inundation due to five meter sea level rise as there is a potential threat to a large population of the Krishna district. As per the analysis of sea level rise (5 meters), a significant portion of the study area is on the brink of coastal inundation (Fig. 11). As a result of information gained from digital elevation models and GIS software, the investigation concluded that the region that will be flooded, would be a total of 2099.5 hectares. Figure 11 illustrates the regions that will be flooded or inundated when the sea level rises by 5 meters. The decision-making process based on this coastal inundation report exposed substantial doubts. However, the end goal is to make investments that will enhance people's lives now and in the future[54].

Risk impact analysis: Risk-based decision-making may help to make the best decision possible by considering the potential drawbacks of available alternatives in the context of large amounts of uncertainty. But if decisions are made based on the potential impact of an extremely unlikely hazard occurrence, communities may be unprepared for catastrophes[12]. An area of 11405.4 hectares of coast was mapped in the region under investigation with 18.5% of that marked coast being classified as highly vulnerable due to the possibility of an increase in seal level (SLR). This makes it pretty evident that the Krishna coastal area is highly susceptible to sea level rise in the future and as a result, a wide variety of LULC features, such as coastal dunes, coastal villages, aquaculture ponds, wetlands, salt pans, beaches and agricultural land are at a high risk of flooding. The summary of the current study is presented in the form of a Pie Chart in figures 12 and 13.

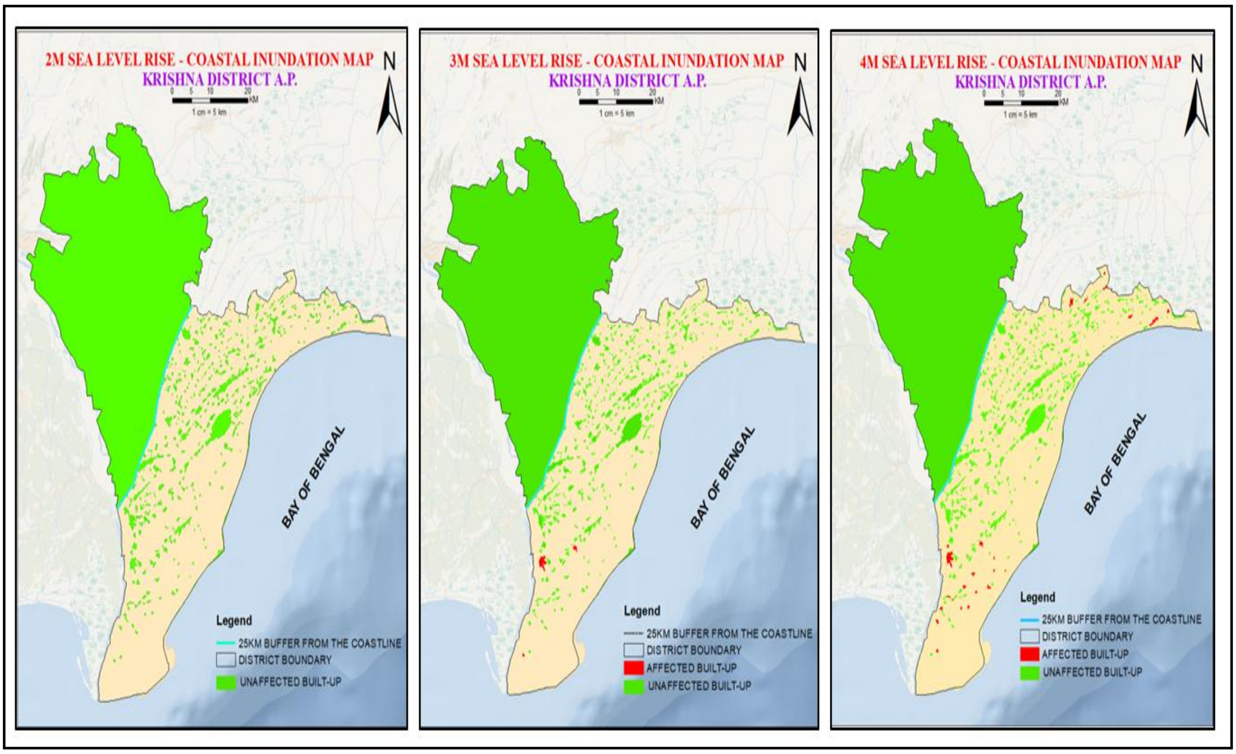

Fig. 10: Coastal Inundation Map for 2m, 3m and 4m SLR

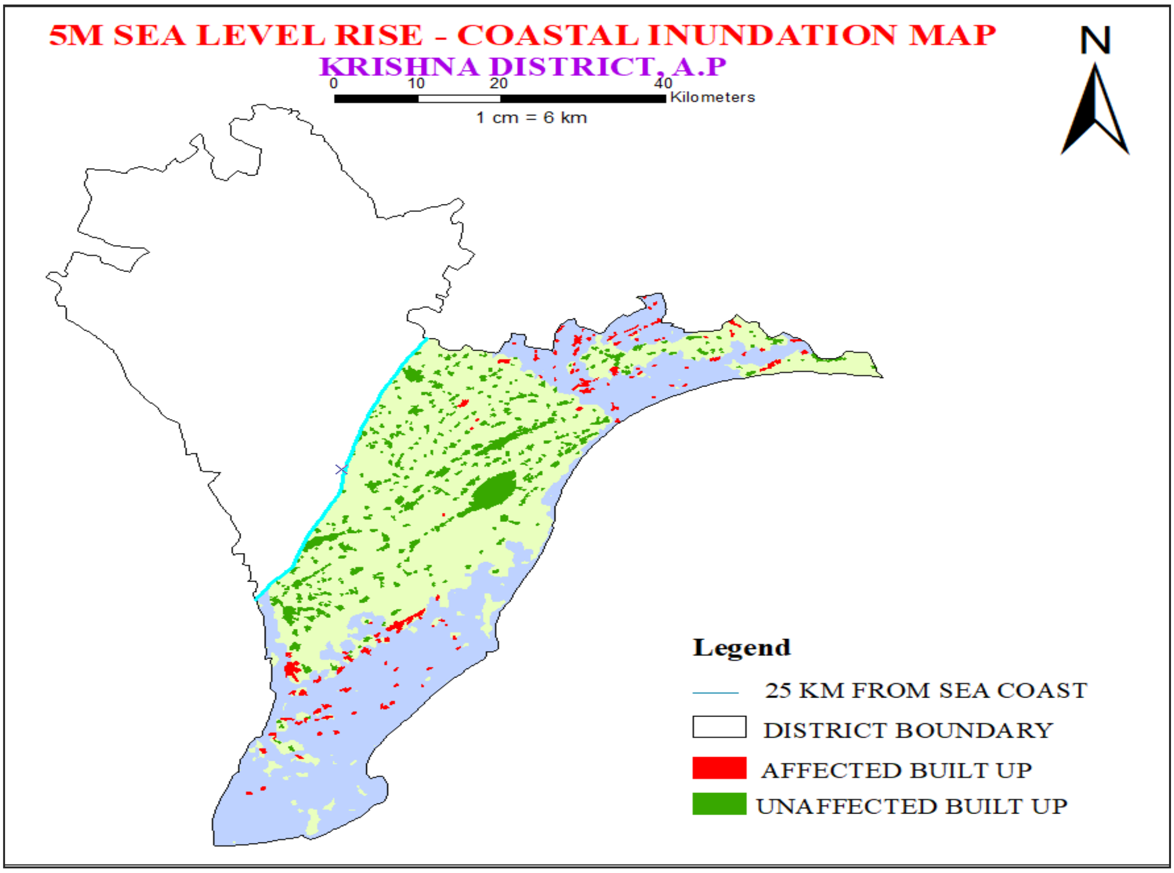

Fig. 11: The affected and unaffected settlements as a result of inundation due to 5m SLR

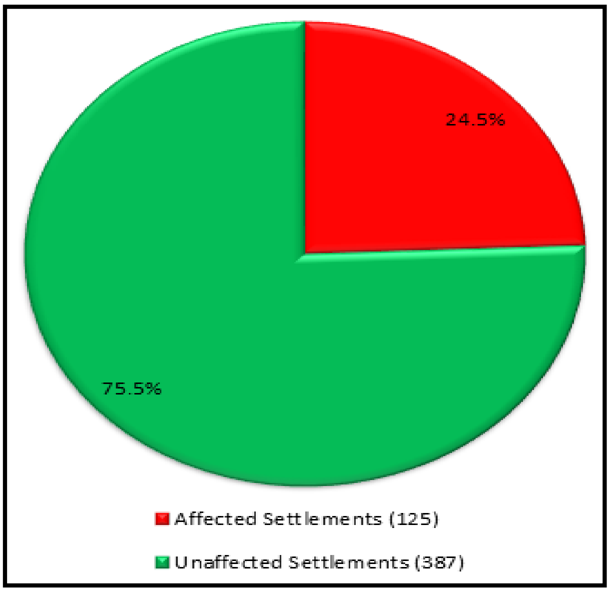

Fig. 12: Graph showing the inundation affect on Settlements due to Sea level rise

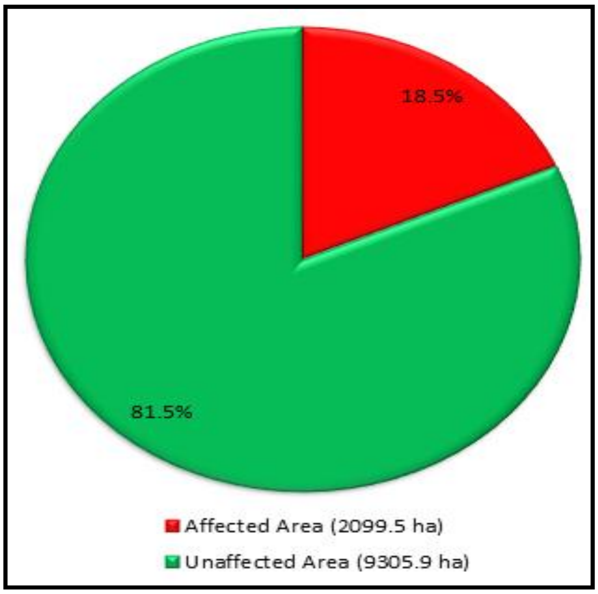

Fig. 13: Graph showing the inundation affect in terms of the area due to Sea level rise

Table 4
Presenting the majorly affected settlements (towns and villages)

Mandal Name	Habitations (Villages/Hamlets/Towns) to be Affected
Nagayalanka	Barrankula, Bahavderapalle, Chodavaram, Dindi, Edurumondi, Elachetladibba, Etimoga, Ganaspeswaram, Gullalamoda, Nachurgunta, Nagayalanka, Nali, Parrachivara, Puullaiah Galli Dibba, Sorlagondi, Kothapalem, Talagadadeevi, T. Kothapalem
Bantumilli	Amudalapalle, Arthamuru, Chantumidi, Chorampudi, Korlapadu, Malleswaram, Meddetipalle, Narrasappacheruvu, Narayanapuram, Pedatummidi, Ramavarapumodi, Satuluru, Vadla Goruva, Nagannacheruvu
Pedana	Chennuru, Jinjeru, Singarayapalem, Kumarigunta
Koduru	Chintakolla, Hemsaladeevi, Irala, Koduru, Palakayatippa, Mandapakala, Peda Godumotu, Potumeeda, Ramakrishnapuram, Utagundam, Ullipalem, Jarugavanipalem
Kruthivennu	Interu, Komallapudi, Matlam, Chinapandraka, Munipeda, Paschaparam, Podu, Tadivennu, Padatadika
Machillipatnam	Puddapatnam, Kammavari Cheruvu
Gudlavalleru	Vedlamannadu
Avanigadda	Venkanuru

According to JCSS (2008), the risk expression may become more sophisticated and complicated when using a more in-depth e-systems approach and the extent of the associated repercussions may increase accordingly.

Five hundred twelve (512) habitations have been evaluated for potential coastal inundation, covering an area of 11,405.4 hectares. Specifically, 125 communities, comprising an area of 2099.5 ha (18.5% area approx.), are highlighted as being particularly at risk from coastal inundation. This totally represents approximately 24.5% of the settlements of the research region. This study pinpointed the areas in question by using GIS software, digital elevation model data and digital picture processing. Table 4 displays the susceptible habitations that are considered under the danger of coastal inundation within the 25 km boundary from the coastline.

Following the analysis, several secure locations have been identified (Fig. 14) to facilitate the rehabilitation of the people whenever there is a risk of natural disasters such as floods, cyclones, tsunamis and so on. The region above the 5 m elevation is deemed safe, shown in the map and it can be designated as the zone for rehabilitation for safeguarding the local people during coastal inundation, particularly during the southwest monsoons. 387 settlements, or approximately 75.5% of the settlements in the research region covering an area of 9305.9 hectares are found to be safe and secure from coastal inundation.

It is essential to pinpoint the safeguarding regions for the people who are close to vulnerable areas. This will allow people to move to these zones to escape the threat posed by potential natural catastrophes.

Table 4 summarizes the primary potential regions that are regarded as secure and have been designated as zones for rehabilitation in the event of coastal inundation whereas the map (Fig. 15) is showing the percentage of both vulnerable and safe built up.

The costs of coastal inundation may be evaluated economically in terms of property damage or in terms of human lives lost, but there are only two ways in which the presence of a hazard may have an impact. There are numerous more ways in which these costs can be quantified. This example demonstrates the cumulative impact that exposure, livelihood and vulnerability have on physical assets[56]. This allows for the possibility of adequately representing the uncertainty surrounding the impacts of coastal flooding and the introduction of the concept of risk.

The damage loss for the structures in the affected region is estimated for the single settlement as 1650000 INR (INR - Indian Rupees). The rate of construction per square foot in India is around 1500 INR and the average total area for one single settlement is around 1100 square feet. Fig. 15 shows the percentage of vulnerable and safe built-up areas present in the study area. The damage loss for 1 km road in the study area is estimated as 3000000 INR economic losses.

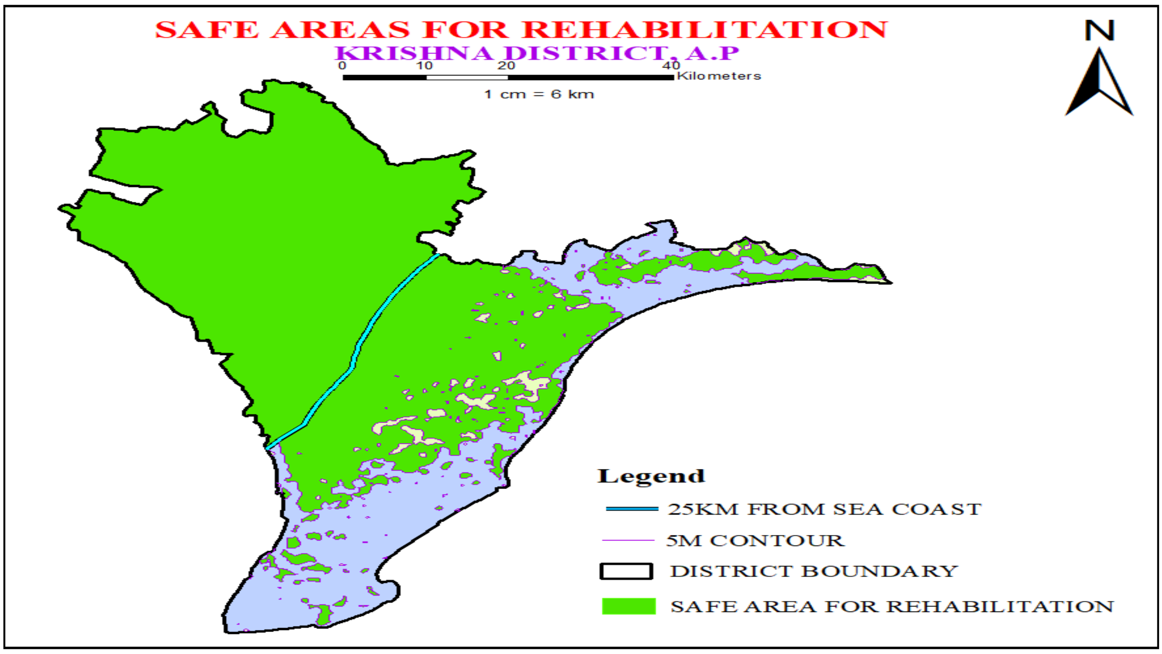

Fig. 14: Safe areas for rehabilitation

Table 4
Presenting the Safe Areas for Rehabilitation

Mandal Name	Habitations (Villages/Hamlets/Towns) to be Affected
Nagayalanka	Nangegadda, Kammanamolu
Bantumilli	Jyapuram, Mulaparru, Korlapadu, Nageswara Rao Pet, Lakshmi Narayana Puram
Pedana	Pedana, Kamalapuram, Mutchilliguntа, Nadupuru, Kopapalle
Koduru	Uvllipalem, Narasimhapuram, Ligareddy Palem, Chinnagudumotu, Jayapuram, Krishnapuram, Vishwanadhapalli
Kruthivennu	Lakshmipuram, Chandala, Nidammaru, Peda Gollapalem, Yetiporu
Machillipatnam	Kanuru, Achyyaripalem, Jonnalavaripalem
Gudlavalleru	Vemavaram, Vemavarapalem, Nagavaram
Avanigadda	Bandalai Cheruvu, Aswaraopalem

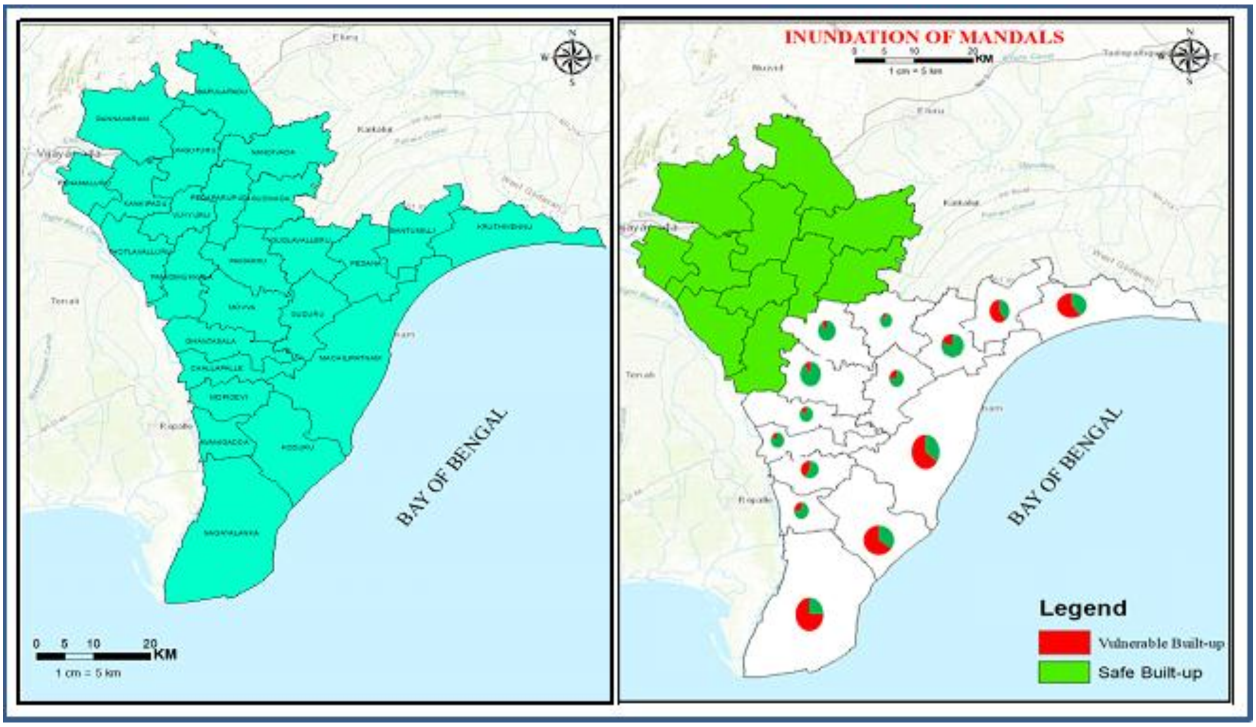

Fig. 15: Map showing the percentage of both vulnerable and safe built up

According to a report by Deccan Chronicle, every year, 20 km of roads are getting damaged in Krishna district due to natural disasters and causing a damage loss of approximately 60000000 INR. Every mandal in the study area has an electrical substation and the construction cost of each substation is approx. 3000000 INR. The monsoon winds, unseasonal storms and cyclones in the study area are causing high damage to electric polls and power distribution lines[41]. If the SLR rises more than 2m in the study area, the impact on the substation starts and it will be 60000000 INR economic losses for a single substation.

Most of the land use type present in the study area is agricultural lands. The total revenue generated per acre of agricultural land in this region approximately is 25000 INR. The mandals affected by coastal inundation cover around 2224 hectares of land. Hence, the average agricultural loss by coastal floods per year will be 137390000 INR.

Conclusion

A geographic information system (GIS) decision support model modified from its initial application of mapping permanent coastal inundation is being put to use in the inundation mapping and damage exposure assessment associated with extreme coastal flood incidents in the severe storm surge area of India. Coastal inundation mapping is crucial for finding possible impact regions and inundation levels to evaluate the intensity of flood risks which is essential for a comprehensive understanding of flood risk. Digital elevation model (DEM) is a component of geographic information system that has seen significant application in evaluating the possibility of inundation. The application of DEM for the assessment of flood risk has identified that the flood-affected area's elevation strongly influences the inundation.

The DEMs are used to create three-dimensional representations of land surfaces. Therefore, mapping the area under investigation with DEM, image processing and geographic information system software helped to identify the regions affected by the increase in sea level. A total of five hundred and twelve habitations were evaluated in this study for coastal inundation. In this, 125 communities which cover approx. 24.5% of the study area were under severe risk and 387 communities covering an area of approx. 75.5% of the study area was found to be safe from coastal inundation. To lessen the possibility for harm from storm tide occurrences, proactive adaption measures should be taken without regard to the cost-benefit analysis. Existing houses and infrastructure may need to be retrofitted, critical infrastructure may need to be protected from floods and storm tidal defenses may need to be constructed.

The process will not only make it possible to create a more accurate determination of inundated areas, but it will also help to improve the accuracy of the determination. The various land use classifications that are impacted by the inundation may also be approximated with this study which will be helpful for managers and decision-makers who are attempting to devise alternative plans for dealing with the difficulties created by sea-level rise along the shore of India. The impact evaluations from this study are helpful in various applications such as harbor planning and constructing maritime infrastructure, establishing rehabilitation centers and other similar endeavors. Planners and administrators can use this information to develop efficient adaptation strategies for sustainably managing disasters over the long term.

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