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Storm Surge Hazard Assessment Along the East Coast of India using Geospatial Techniques

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Abstract: The study aims to estimate the extent of inundation and depth due to a storm surge event by selecting a worst-case cyclone track scenario for Andhra Pradesh, Odisha and West Bengal on the basis of historic data. Storm surge model results for the Orissa cyclone suggest that over 2,150 km^2 of land is inundated with an extent of 45 km from the shoreline and 1,100 km^2 area submerged with 1-2 m from the ground. Andhra's model suggests that about 450 km^2 of the area is inundated due to which the majority of the area is submerged <1 m from the ground. The West Bengal model is carried out using a synthetic track with a wind speed of 155 knots based on the recent cyclonic storm in Bangladesh. The result shows 5,400 km^2 of land submerged by <1 m about 2,700 km^2 of the area was submerged by 1-2 m of water. The most affected areas were South 24 Parganas and parts of Bangladesh.

Key words: Cyclonic surge, East Coast of India, inundation depth, geographic information system.

Introduction

The Indian subcontinent is one of the most cyclone-affected regions on the globe. The strong winds from the cyclone do considerable damage to the coastal structures and heavy precipitation from the cyclone can cause flooding in the rivers (NASA Space Place, 2018). Approximately 80% of all the cyclones made landfall on the eastern coast alone (Fitchett and Grab, 2014) and have affected habitats greatly. It's a need to study frequent and intensive cyclones and their impact on the socioeconomic conditions of the living population (Cutter et al., 2000; Hinkel et al., 2014; Nicholls et al., 2008). The east coast of India experienced about 308 cyclones between 1891 and 2000; among them, 103 cyclones were severe (Mohapatra 2015; Rao et al., 2007; Suchitra, 2015). Climate change and the resulting sea-level rise can significantly increase the vulnerability of coastal populations (Fang et al., 2017; Hinkel and Klein, 2009; Kumar and Kunte 2012; Mukhopadhyay et al., 2011; Ravishankar et al., 2004). Hence it is essential to assess the impact of storm surges based on the historical trend for preparedness and resilience (Frank, 1977).

The geospatial technique helps to prepare multi-layer information, management action plans and spatial relationships between natural hazards and exposure (Basheer Ahammed and Pandey, 2019). Studies showed that satellite remote sensing offered a high temporal resolution for monitoring land-use change at lower costs than those associated with the use of traditional methods (Basheer Ahammed and Pandey, 2019; Fang et al., 2014; Mahendra et al., 2011). GIS-based decision support systems will work effectively even in the worst situations. This study assessed the cyclone density for the entire mainland coast of India and selected high

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density areas to run storm surge models in order to estimate coastal inundation. This facilitates the coastal managers in each state to manage the disaster.

Study Area

The study area lies between India's Eastern Ghats and the Bay of Bengal and extends from the Ganga delta to Kanyakumari (Figure 1a). It is about 3500 km long and stretches covering four maritime states namely Tamil Nadu, Andhra Pradesh, Orissa and the state of West Bengal in the North and also covers 32 coastal districts (10 in Tamil Nadu, 9 in Andhra Pradesh, 9 in Orissa and 3 in West Bengal). The coastal length of Tamil Nadu is 906.9 km, Andhra Pradesh is 973.7 km, Odisha is 476.4 km and West Bengal is 157.5 km (http://www.quickgs.com/coastal-length-of-indian-states). It is an important region for agriculture and economic activities. It is fed by four major rivers: Cauvery, Godavari, Krishna and Mahanadi and receives good rainfall. The area has experienced rapid growth due to migration and accelerated urbanisation with its four major ports, fueled by industrialisation and economic activity over the past few decades (Kadarpeta et al., 2015).

Data Used and Methodology

Historical cyclone tracks for the Bay of Bengal from 1842 to 2016 (Figure 1b) were retrieved from International Best Track Archive for Climate Stewardship (IBTrACS) (KNAPP). A fishnet of $1^{o}\times1^{o}$ for the entire country was generated, and the frequency of cyclones in each of the grids was calculated using ArcGIS software 10.3. Storm surge inundation modelling in ADCIRC was carried out using a cyclone track which is in line with wind speed. Input such as bathymetry is essential for modelling in ADCIRC. Bathymetry is available as point data from GEBCO. The level and extent of inundation are obtained in the form of point data from the result of the model. The points are interpolated to obtain continuous data. Subtracting water level from elevation gives the level of inundation. The inundation levels were classified into 4 classes: 0-1 m, 1-2 m, 2-3 m and 3-4 m. The area of extent for each class was calculated using a field calculator in ArcMap 10.3 for each site. A worst-case scenario was analysed based on a very severe cyclonic storm in Bangladesh that occurred recently. The synthetic path was constructed at the West Bengal – Bangladesh border using the wind speed values of the recent very severe cyclonic storm in Bangladesh.

Results and Discussion

The results of the current study highlight the highly vulnerable areas based on inundation extent and depth.

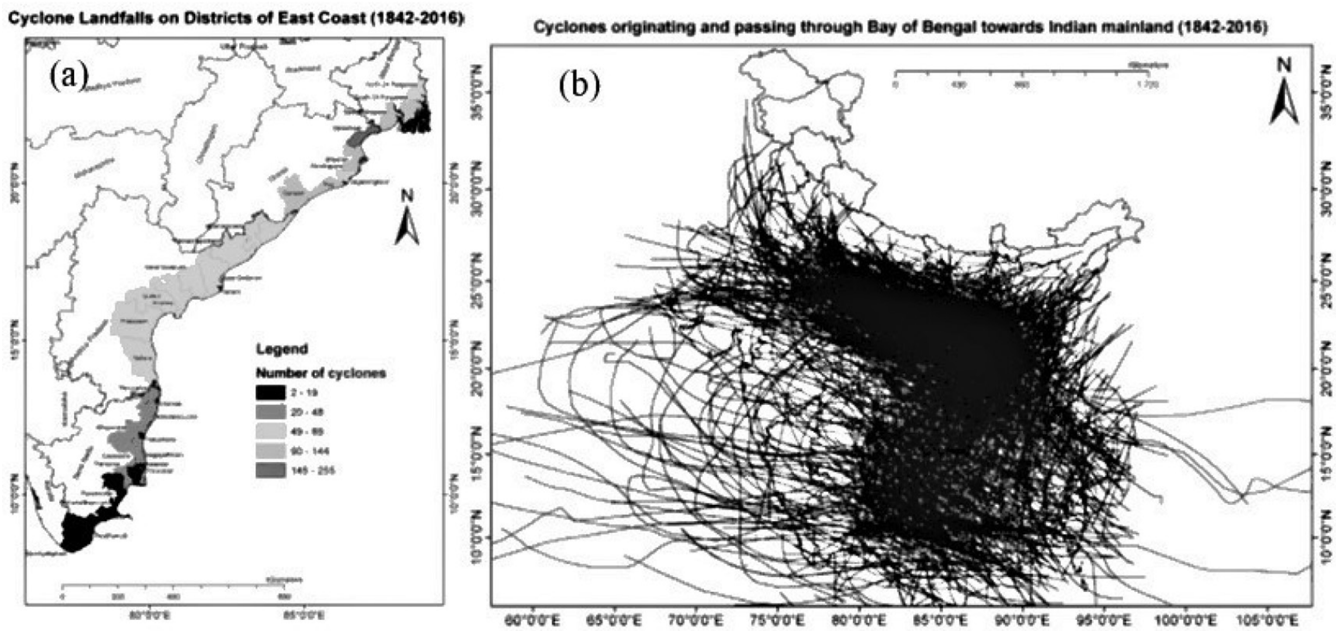

Figure 1: (a) Study area of Indian east coast with cyclone density at district level (b) based on the cyclone track data recorded during 1842-2016 (Source: IBTrACS).

Analysis of Historical Cyclone Tracks

The historical cyclone tracks recorded during 1842-2016 were assessed to calculate the cyclone density and frequency. The results reveal the varying density and frequency of the cyclones along the east coast at grid levels (Figure 2a) and at the district level (Figure 1a). It was observed that the majority of cyclones enter India via Orissa – West Bengal coast and move ahead. The grid which is formed at the border of Orissa-West Bengal and extends towards the sea is seen to have the highest cyclone count of 297. This means 297 cyclones have occurred in an area of 13,200 km^2 (1×1 degree) in the past 173 years. The highest density was recorded in the Bhaleshwar district in Odisha (Figure 1a).

The map represents the distribution of frequency of cyclones (Figure 3a) that has occurred in the past. The highest frequency observed was to be 1.8 per year in the northern Orissa at Bhaleshwar district and West Bengal covering Midnapore and South 24 Paraganas coasts. In Figure 2b, the grids with black colour show the areas which experience more than one cyclone per year on average. The medium gray coloured grids experience up to one cyclone per year on average. Some parts of Andhra Pradesh experience a cyclone in 2-4 years. This analysis clearly highlights Orissa and West Bengal coasts experience the most frequent as well as dense cyclones. The assessment of total cyclones recorded at each district along the east coast, Baleshwar district of the state of Orissa and a few coastal districts of West Bengal (East Midnapur; South 24 Parganas and North 24 Parganas districts) was recorded more than 145, the highest number of cyclones in the past. Bhadrak, Kendrapara, Puri and Ganjam districts of Orissa state recorded several cyclones between 90 and 144. Whereas all Andhra Pradesh districts recorded cyclones between 49 and 89.

Storm Surge Modelling Results of Orissa

The cyclone tracks selected for Orissa to study was the super cyclone of 1999 which was known worst event in the area. The cyclone track of the 1999 Orissa Super Cyclone made landfall near the Paradeep coast (Figure 3a). The resultant different inundation depth (water level above ground) was estimated using storm surge modelling, which depicts a maximum surge inundation of up to 4 m (Figure 3b). An inundation level of 3-4 m covered an area of 5.9 km^2 in patches near the coast was recorded and a 2-3 m inundation level covered 143.3 km^2 extended up to hinterlands in the vicinity of rivers and creeks. However, the majority class was 1-2 m inundation level covered 1,146.3 km^2. There are a few areas of 833.2 km^2 of slightly elevated areas that were recorded up to 1 m inundation. It was also observed that there are some areas not inundated but

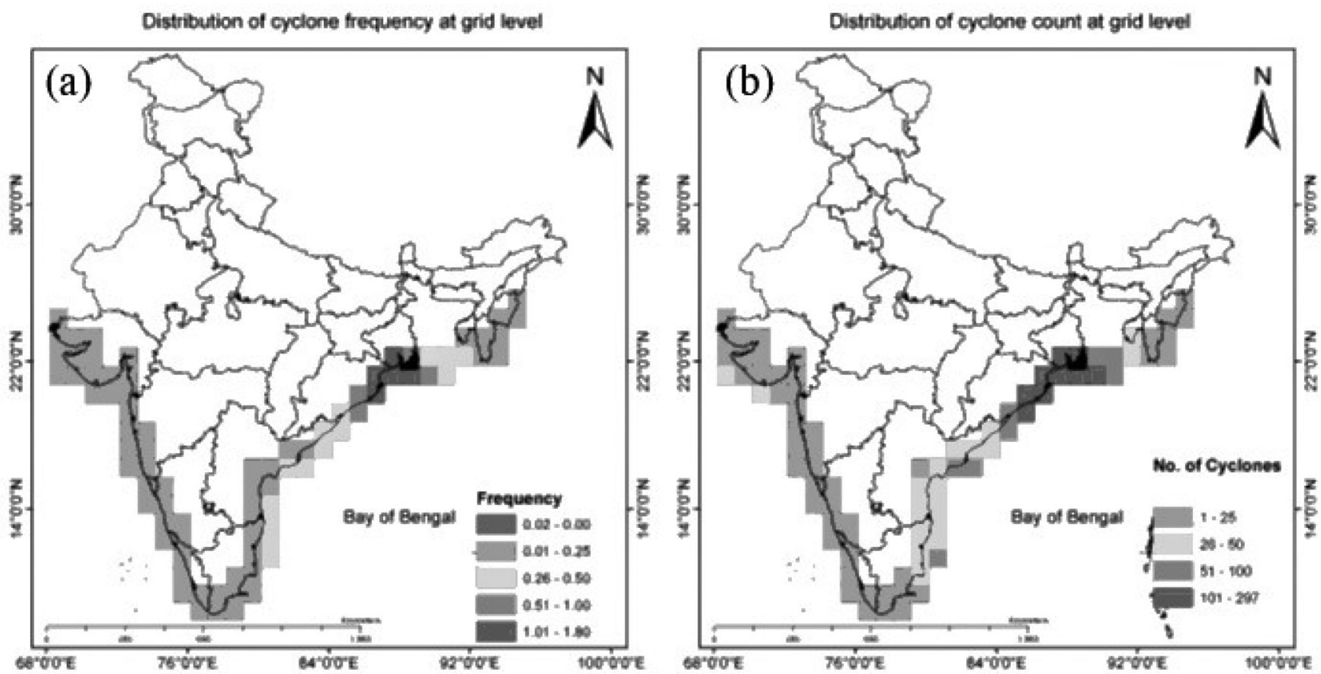

Figure 2: (a) Frequency and (b) density of cyclones along the Indian mainland coast estimated based on the historical cyclones recorded during 1842-2016.

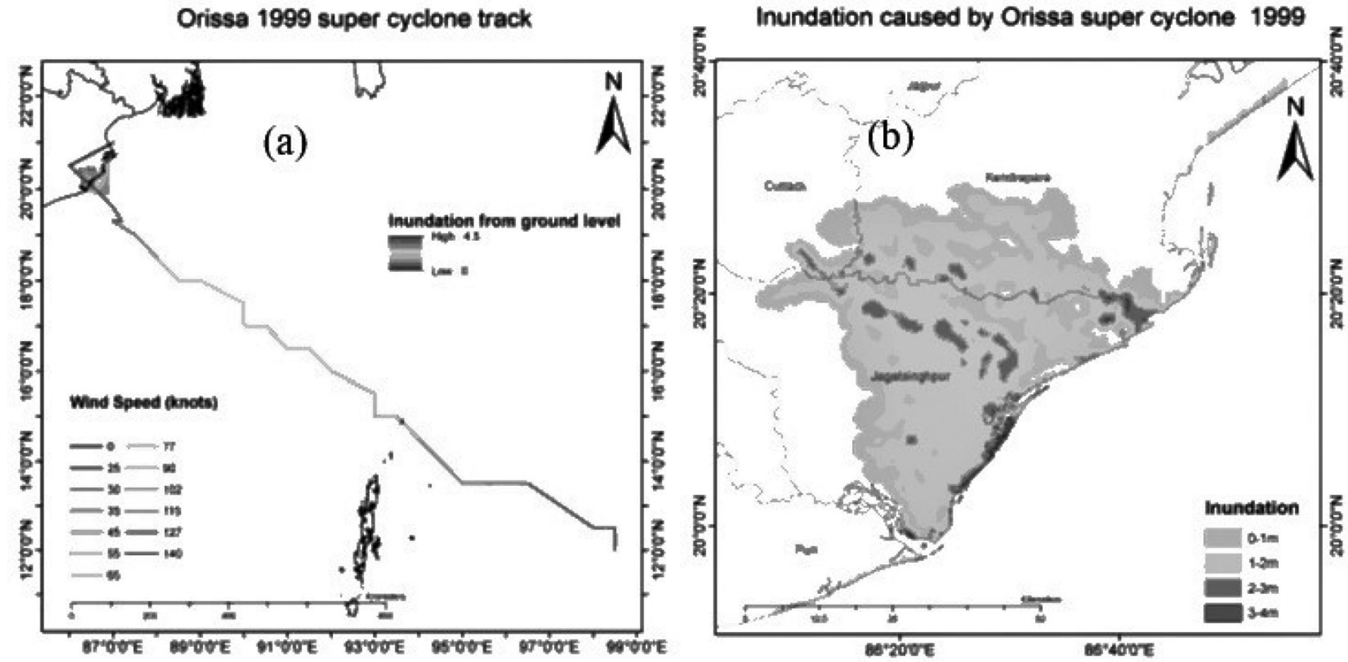

Figure 3: (a) 1999 Orissa Super Cyclone track with different wind speeds overlaid on storm surge model results and (b) estimated Inundation depth based on the storm surge model results.

surrounded by inundation which were also vulnerable as these areas get stranded during an event of a cyclone.

On the whole, an area of 2128.7 km^2 was under inundation which extended up to 45 km hinterland from the coast (Figure 3b). Jagatsinghpur district was observed to be affected the most among two other districts, Kendrapara and Cuttack. The larger inundation was observed at the cyclone landfall area and the river systems act as corridors for inundation and carried inundation deep into hinterlands.

Storm Surge Modelling Results of Andra Pradesh

Andhra Pradesh's coast has experienced more than 62 cyclones including depression, cyclone surge, and severe cyclone surges in the past 40 years. Among these, 32 cyclones affected the Krishna–Godavari region, comprising four districts and around 7% of the area observed high vulnerability (Basheer et al., 2019). The cyclone tracks selected for the Andhra Pradesh coast was the Very Severe Cyclone of 1996 which made landfall near Mummidivaram of East Godavari District (Figure 4a).

The storm surge simulation results of the Very Severe Cyclone of 1996 which hit the Andhra coast reveal a maximum inundation depth of 2-3 m covering an area of 12 km^2, 48.9 $km^2$of area was inundated with a depth of 1-2 m and the majority of the area of 376.1 km^2 was inundated up to 1 m of water from the ground (Figure 4b). A total of 437.6 km^2 of the coastal area was inundated by storm surge and Mummidivaram was the most affected taluk followed by Kakinada and some parts of Ramachandrapuram (Figure 4b). Even Razole and Amalapuram taluks in the south recorded coastal inundation.

Storm Surge Modelling Results of West Bengal

The synthetic track with a hypothetical wind speed value of 155 knots was used to run a storm surge model for parts of West Bengal (Figure 5a). The maximum inundation depth due to storm surge was 5.5 m and the maximum extent was up to 145 km inland (Figure 5b) from the coast. Large inundation was observed in West Bengal and Bangladesh in the Sundarban area (Figure 5b).

Inundation was carried deep inland up to 145 km as a combination of the strong event and creek systems of Ganga-Brahmaputra. The large amplitude of surge heights was observed along the coasts of Bangladesh. The maximum area inundated in the eastern parts of south 24 Parganas district and southern parts of North 24 Parganas district (Figure 5b). A maximum level of inundation depth of 3-4 m was observed in the vicinity of creeks in West Bengal. The maximum area (5439.67 km^2) was under 1 m of inundation.

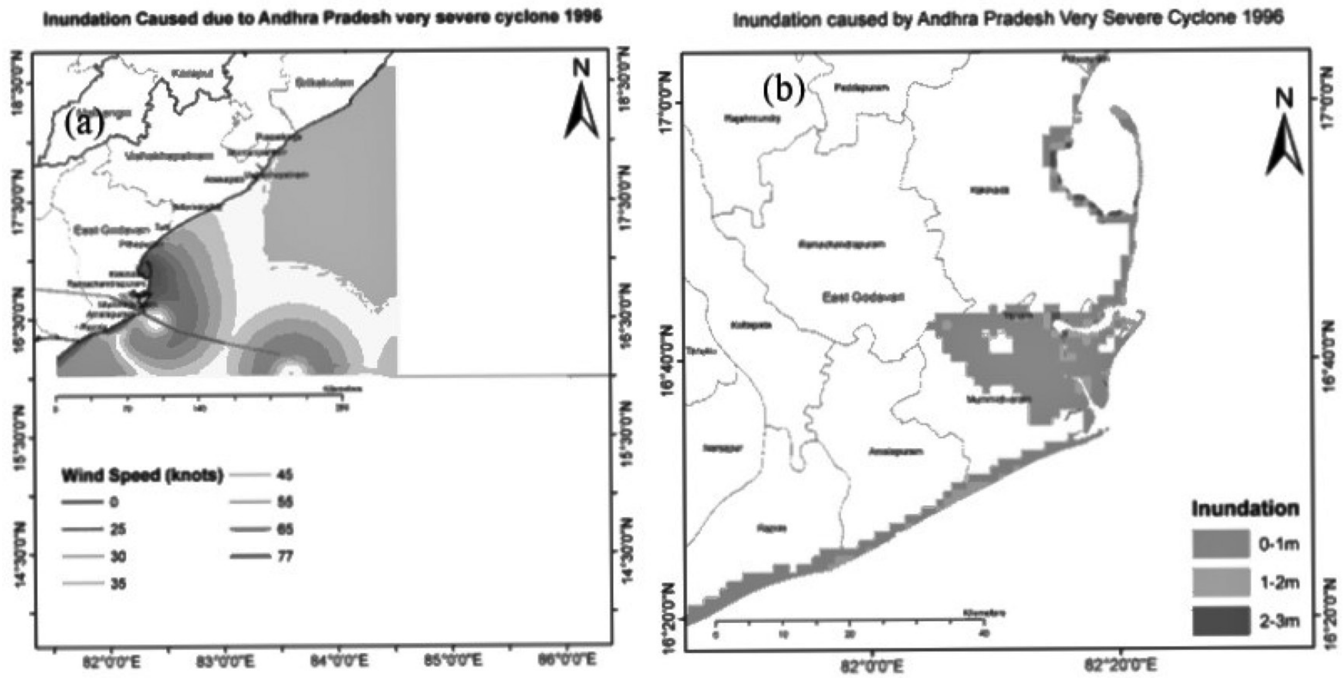

Figure 4: (a) Andhra Pradesh Very Severe Cyclone track of 1996 with different wind speeds overlaid on storm surge inundation and (b) Inundation.

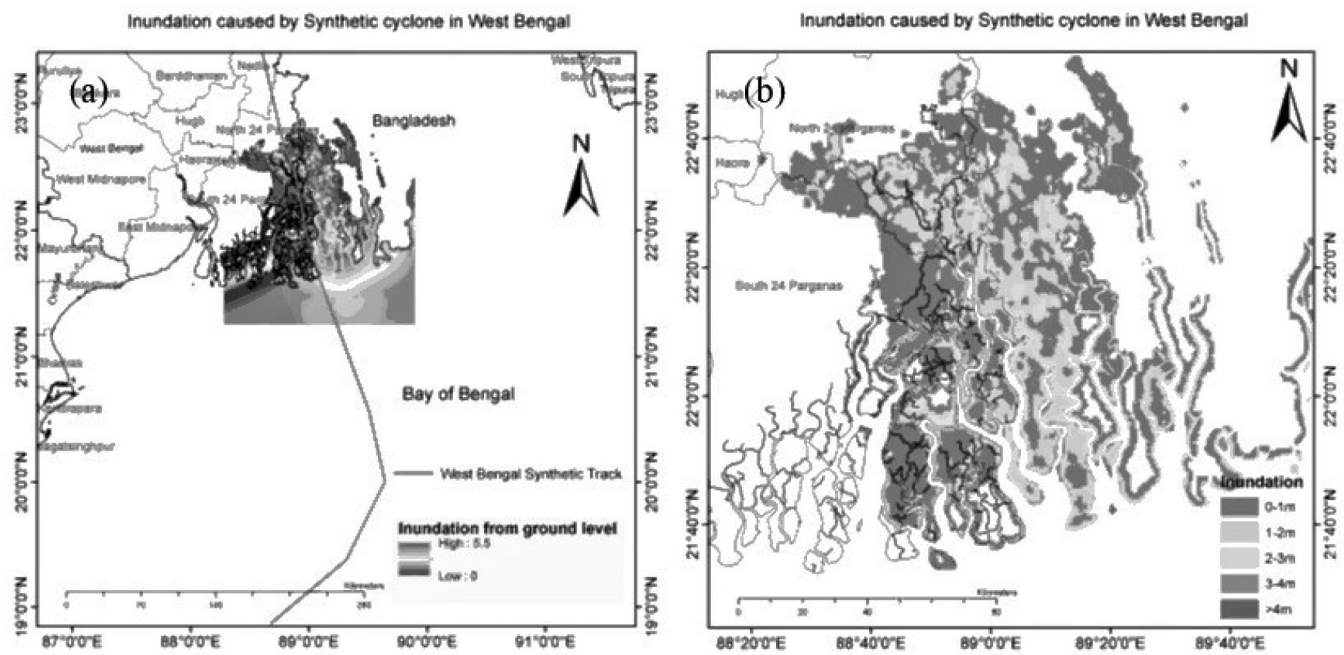

Figure 5 (a) West Bengal Synthetic Super Cyclone Track used for storm surge modeling and (b) resultant inundation depth.

Followed by 1-2 m inundation recorded at 2674.79 km^2. Inundation of more than 4 m was recorded in 25 km^2 along the banks of major creeks and small islands in distal parts. A total of 9036.92 km^2 area was inundated due to this storm surge event (Figure 5b).

The analysis of the historical cyclones revealed that Orissa and West Bengal states are highly vulnerable to cyclones with high count and frequency. The storm surge modeling was carried out in each state considering the worst event in the past for Orissa and Andhra

Pradesh. In the case of West Bengal synthetic worst case was considered. The results of these storm surge simulations suggest the large inundation in Orissa and West Bengal. A moderate inundation was recorded on the Andhra Pradesh coast. This may be due to the strength of the event and the large low-lying coastal areas exposed to the cyclones in Orissa and West Bengal whereas the strength of the cyclone that occurred in Andhra Coast was not as great as the ones that occurred in West Bengal and Orissa coast. And also, the presence of a low-lying large delta on the West Bengal coast may have facilitated inundation extent and inundation levels. The large parts of coastal zones in West Bengal and Odisha are highly exposed to inundation due to low lying areas resulting in high vulnerability due to storm surges.

Conclusion

The current study is an attempt to demonstrate the geospatial techniques to assess the probability (based on historical tracks), intensity and vulnerability (based on the modeling) of the cyclonic surge and their impact on the coastal environment. The results of the current study reveal that Orissa and West Bengal coasts are highly vulnerable to cyclonic surges that hit these areas. The study further highlights the role of the large river/creek systems of major deltas in Orissa and West Bengal in carrying inundation into much higher hinterlands. These areas are highly exposed to cyclonic-induced storm surges due to large low-lying coastal areas. Whereas the Andhra Pradesh coast is moderately vulnerable when compared to the above areas. The modelling result can be further enhanced by the use of synthetic worst-case scenarios generated based on historical tracks. The use of very high-resolution bathymetry and topography can also improve the modelling results to assess the storm surge risk and vulnerability. The results in this study are based only on the simulation modelling and have not been verified on the ground as the events are historical and no data exists regarding the extent and inundation to verify. The method needs to be validated from the ground during an actual event in order to determine the accuracy of the model.

Coastal residents can scale back the harm done by a storm surge by protecting native wetlands. Wetlands, such as swamps, estuaries, and mud flats, act as sponges for tropical cyclones. As the cyclone makes landfall, the marshy land and plants absorb the water and the energy of the storm surge. Silt and swamp vegetation hinder the intensive part of the storm surge from striking homes and businesses. The results of the current study are useful for coastal cyclone disaster management in order to make decisions on preparedness and disaster risk reduction. These results can also be used for coastal future development purposes.

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