Demarcation of coastal vulnerability line along the Indian coast

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Abstract: Delineation of vulnerability line for coastal region due to dynamic coastal processes and natural coastal hazards is a complex task due to high regional variability and site specific coastal characteristics. A methodology is developed using multidate satellite data, high resolution DEM and in-situ wave and tidal observations on GIS platform to delineate the vulnerability line. Three coastal regions viz. Dahej, Bharuch district, Gujarat, Paradip, Orissa and Nellore, Andhra Pradesh coast have been considered. Changes along the shoreline are considered as net impact of dynamic coastal processes and are mapped using multidate satellite data. Vulnerability due to coastal erosion has been assessed based on rate of coastal erosion. Coastal erosion for the next 25, 50 and 100 years are modeled and demarcated. Vulnerability due to coastal flooding is assessed using predicted sea level rise and storm surge events. Maximum tidal elevations, predicted sea level rise, return interval of storm surge events and maximum wave run up were considered for estimating flood height and accordingly flooding scenarios are simulated using high resolution DEM. Vulnerability line has been demarcated by integrating the shore displacement line and flood lines using GIS. The landward extent of either of the shore displacement line or flood line i.e., whichever is towards the land is demarcated as vulnerability line.

Keywords: Vulnerability Line, DEM, Coastal erosion, Shoreline changes, Flooding scenarios, GIS, Multi-date satellite data

1. Introduction

Besides, home to a large population, coastal area contains most sensitive ecosystems like beaches, mudflats, mangroves, coral reefs, wetlands etc. Coastal areas are subjected to major proposition of natural calamities like tsunami, storm surges and cyclones. Moreover the coastal areas are the region supposed to be affected adversely with the expected sea level rise. India has a long coastline of around 7,500 km and protection of life, property and environment in the coastal zone is a major areas of concern. Increasing population and developmental activities along the coast have necessitated enforcement of coastal environmental law such as CRZ notification 1991 and 2011 of government of India. At present the activities along the coast is regulated in India under CRZ notification 2011 where the coastal regulation area has been defined.

Any inundation event of similar magnitude shall have different consequences at different coasts. The coast with higher elevation will be protected against an inundating event than a low laying coast. Indian coastline has a wide range of geomorphic features where coast may be found as low laying like tidal mudflats, deltaic coast and elevated coast like beach ridges, cliff etc. In India with a long coastline, the inundating events also show high spatial variability. The coast subjected to sporadic events of inundations like storm surges, tsunami etc also show a spatial variability. While considering the non-uniformity of coastal geomorphology and spatial disparity of the inundation events, arbitrary protected zones cannot be justified on any scientific background. The rise in sea level is another major threat faced along the coastal region where the inundation scenarios shall change temporally (IPCC, 2001). In the present study more scientific reasoning are introduced for delineating the coastal vulnerability line based on the individual coastal characteristic and its inundating events where the physical response of coastal environments to water level changes and changes in the shoreline over a period of time are analyzed in GIS platform.

Vulnerability is the degree of exposure of objects, such as coastal landform features, to the impacts of the hazards. Hazard is a physical process or event – such as sea level rise or storm surge. The term risk refers to the combination of hazard and vulnerability. The anticipated Sea Level Rise (SLR) due to global warming (Gormitz, et al., 1982; Hekstra, 1988; Church and Gregory, 2001; IPCC, 2001; Houghton et al., 2001; Lambeck and Chappell, 2001), is expected to flood the coastal zones, as the coastal zones are predominantly low lying flat lands and packed with river mouths, creeks, estuaries, backwaters, mangrove systems, deltas, swales, mudflats, saltpans etc. A SLR of 0.48 - 1.0 m by 2100 AD has been widely accepted and is ascribed to combination of thermal expansion of ocean water and melting of glaciers and ice sheets on land. The SLR estimated along the coasts of Northern Indian Ocean, from tide gauge records longer than 40 years, yielded a regional average of 1.29 mm/year (Unnikrishnan and Shankar, 2007). Several case studies have developed methods for vulnerability mapping (Dutrieux et al., 2000; Harvey et al., 1999a; 1999b; Klose et al., 2001; Morton, 2002; Thieler et al., 2001; Pendleton et al., 2004; Sharples, 2004). Remote sensing and Geographical Information System (GIS) techniques for the Indian coast have proved to be extremely useful for understanding coastal processes and mitigating coastal zone hazards (Desai et al., 1991; Nayak, 1996; Navalgund et al., 1998; Nayak et al., 2001; Rajawat and Nayak, 2000; 2004; Rajawat et al., 2005, Ajai et al., 2012).

Assessment of coastal vulnerability is done mostly on the basis of vulnerability indices. Mukhopadhyay et al. (2012) have reviewed the hazard and vulnerability assessment done along the coasts. The Coastal Vulnerability Index (CVI) was developed by Gornitz et al. (1994) where the approach was to consider parameters to assess the vulnerability of a coastal area to anticipated SLR. Abuodha and Woodroffe (2010), Kumar et al. (2010), Rao et al. (2008) have also followed CVI technique to assess the vulnerability of a coast. Synthesis and Upscaling of Sea Level Rise Vulnerability Assessment Studies (SURVAS) and Dynamic Interactive Vulnerability Assessment (DIVA) tool are other commonly used techniques through which the vulnerability of a coast is assessed.

The present study has more holistic approach where the rise in sea level, coastal elevations, shore line changes and historic inundating events are considered and the results obtained predicts the region likely to get inundated during an event in the future. Three study areas have been considered in this work. These are Dahej near the Narmada estuary (Gujarat) along west coast, Paradip (Orissa) and Nellore (Andhra Pradesh) along east coast of India (Figure 1). These areas were chosen by considering diversity of the coastal configuration, population pressure and level of development activities along the coast.

Figure 1: Location map of the study area (1-Dahej, 2-Paradip, 3-Nellore)

2. Methodology

Approach for demarcation of vulnerability line using remote sensing and GIS techniques includes i) Preparing shoreline change maps using old topographical maps and recent satellite data (Resourcesat-1/Cartosat-1 data); ii) Delineation of shore displacement line using shoreline change data; iii) Analysis of past wave/tidal data for flood height computations; iv) Generation of DEM from available data sets (topographical maps with 0.5 m contour interval); v) Utilisation of inundation models for simulating inundation patterns and delineation of flood line; vi) Vulnerability/Hazard/ Setback line delineation using integrated analysis in GIS. Figure 2 shows the flow chart summarizing the approach used.

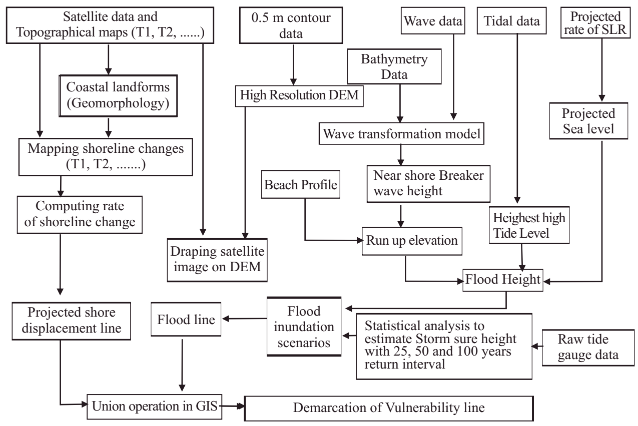

Figure 2: Flow chart showing the methodology for demarcation of vulenrability line

2.1 Delineation of the shore displacement line

Highest of the High Tide Line (HTL) has been considered as shoreline. Shoreline change is the horizontal movement of a specific shoreline. SOI Topographical maps (period of survey 1960 or before) and old satellite images were used to delineate HTL corresponding to the time t1. Resourcesat-1 LISS-IV/Cartosat-1 data of recent years were geo-referenced and interpreted to delineate shoreline for time t2. The horizontal displacement of shoreline has been measured based on HTL of 2005. Shoreline changes were used to compute an annual rate of displacement. Line topology has been built for all the shoreline vector files (Arc Info Coverage) and two attribute fields have been created viz. “YEAR” and “TRANSECT”. The “YEAR” attribute field for all the shorelines was filled with corresponding year of survey of topographical map or year of acquisition of the satellite images. All the shorelines of a particular study area were then appended. Transect-wise analyses of the distance between shorelines of two or more years have been carried out. Finally, transect-wise annual rates have been calculated and future projection of shoreline (i.e. shoreline position for the next 25, 50 and 100 years from the current shoreline has been carried out. The projected shoreline is designated as the shore displacement line.

2.2 Delineation of flood line

Historic data on tides, sea level rise and the annual maximum water levels recorded by tide gauges were analyzed to determine flood heights. Depending upon availability of these datasets flood height could be estimated for following two scenarios:

i) In the first scenario flood heights are considered only for the projected sea level rise for next 25, 50 and 100 years coupled with highest high tide levels.

ii) In the second scenario flood height are estimated considering storm surges. Storm surge height is estimated using the following two approaches:

a) In the first approach storm surge heights is estimated using the annual maximum water levels recorded by tide poles and calculating maximum flooding levels for the return intervals of 25, 50 and 100 years. Hourly tide gauge data are analysed for extreme sea level by Unnikrishnan et al. (2004). A statistical analysis involving the r-largest annual maximum method, the joint probability method (JPM) as well as the revised joint probability method (RJPM) is performed to estimate the return periods of extreme sea level. JPM gave an underestimate of levels for long return periods, which is improved in RJPM. The results of RJPM and r-largest methods are consistent and are within 95% confidence limits.

b) In the second approach maximum wave run up elevation based on the analysis of historic wave data is utilized to estimate storm surge heights. Apart from the data available in Centre for Earth Science Studies (CESS), Thiruvanthapuram, the recorded data on maximum wave is collected from National Institute of Oceanography (NIO), Goa and National Institute of Ocean Technology (NIOT), Chennai. The waves are recorded at different depths ranging from 2300 m to 15 m. The highest wave reported is taken and transformed to the breaking zone using the MIKE-21 Nearshore Spectral Waves (NSW) model. This model is a wind-wave model that describes the growth, decay and transformation of wind-generated waves and swells in nearshore areas. The model takes into account the effects of refraction and shoaling due to varying depth, local wind generation and energy dissipation due to bottom friction and wave breaking. The model also takes into account the effect of wave-current interaction, if present. The bathymetric data is essential to compute the breaker wave heights using the MIKE21 model. The hydrographic charts, with maximum resolution, available in C-MAP for the locations is selected for computation of bathymetric grids and in turn the wave transformations. The C-MAP bathymetry is provided by the ICMAM Directorate, Chennai. Sea Level rise for next 25, 50 and 100 years coupled with highest high tide levels have been added.

Contour maps with 0.5 m contour interval have been prepared for the three study areas by Survey of India through detailed filed surveys. Digital Elevation Model (DEM) has been generated using this data for all the three test sites using ERDAS Image processing s/w. Resourcesat-1 LISS-IV image has been draped over the DEM and flood inundation modelling has been done for different scenarios of flooding levels using Water Layer sub-module of ERDAS Imagine 9.0 Virtual GIS module. Figure 3 shows the DEM for the three sites.

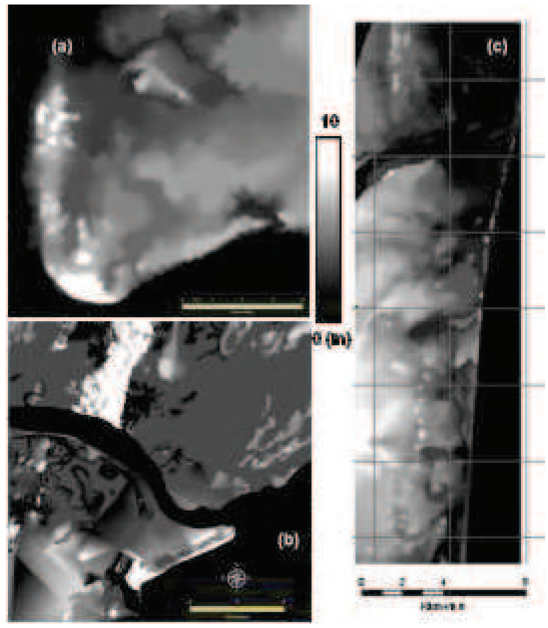

Figure 3: DEM generated for a) Dahej b) Paradip and c) Nellore

3. Results and discussions

3.1 Shore displacement line

For Dahej, shoreline has been interpreted from the topographical maps 46 C/10 and 46 C/14 for the year 1872 and 1972. Shoreline for the period 1991 has been taken from the archived database and shoreline for the year 2005 has been interpreted using Resourcesat-1 LISS-IV data of March 03, 2005. Transects at 500 m spacing have been generated (total 36 transects) and transect-wise analyses of the displacement of shorelines for the period between 1872 and 2005 have been carried out. Interpretation of shoreline for Paradip was done from the topographical maps 73 L/11 and 73 L/15 for the year 1929-30. Shoreline for the period 1993 has been taken from the archived database and shoreline for the year 2005 has been interpreted using Resourcesat-1 LISS-IV data of 2005. For Paradip transects are separated by 50 m (total 360 transects) and displacement of shorelines for the period between 1929 and 2005 were analysed. Nellore shoreline for 1991 was interpreted from the topographical maps 66 B/2 SE and 66 B/3 NE for the corresponding year.

For 2006 shoreline corresponding Resourcesat-1 LISS-IV data of February 18, 2006 has been interpreted for delineating

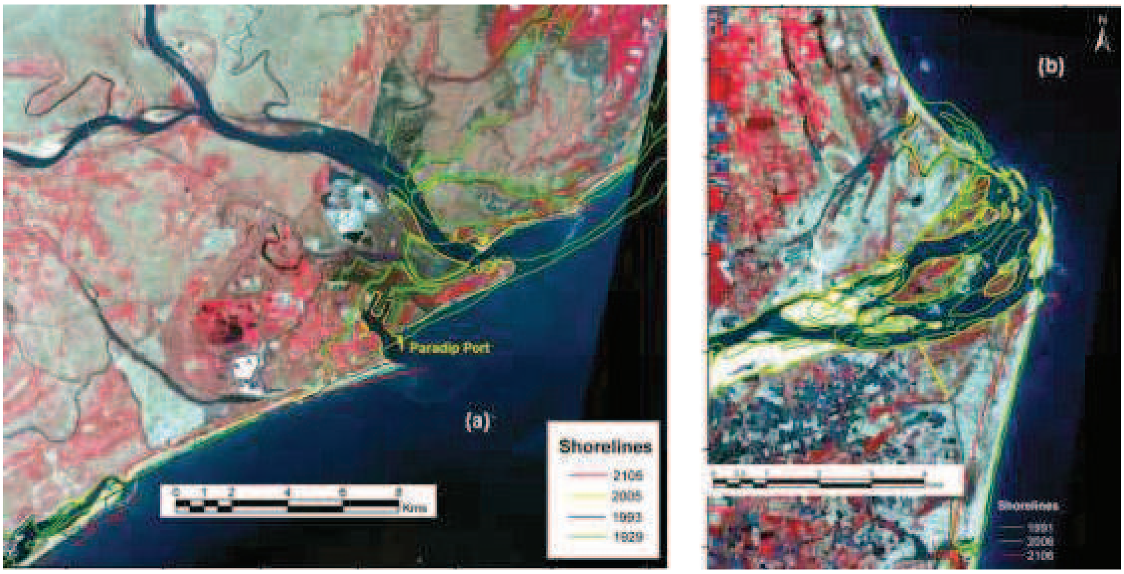

Figure 4: Shoreline displacement map showing the projected shore line of a) Paradip and b) Nellore for next 100 years

shoreline. Transects at 50 m spacing have been generated (total 538 transects) and transect-wise analyses of the displacement of shorelines for the period between 1991 and 2006 have been carried out.

Transect-wise annual rates of shoreline change have been calculated and future projections of shoreline for next 25, 50 and 100 years are carried out. Figure 4 shows the displacement of shoreline as projected for next 100 years for Paradip and Nellore.

3.2 Flooding scenario due to projected sea level rise

Flooding scenarios under normal conditions were generated for all the three sites. The past sea level changes and its future projections for a century are noted from the website of Intergovernmental Panel on Climate Change (IPCC, 2001). IPCC has given projections for the period up to 2100. Since Indian coasts fall in the average/below average category (Unnikrishnan et. al., 2006) the maximum sea level rise that can be expected along the Indian coasts shall be well within the 49 cm rise in 100 years. This value is considered for the computation of flooding. The tide data used for the calculations are taken from the Indian Tide Tables from 1979 to 2006. The highest tidal height are noted from the daily heights given in the tide table. These data are reduced to Mean Sea Level (MSL) from the datum levels provided in the tables.

Flood height considering projected sea level rise along with the Highest High Tide Level (HHTL) for next 25, 50 and 100 years for Dahej coast is 5.73 m, 5.86 m and 6.10 m; Paradip coast is 1.53 m, 1.65 m and 1.90 m; and for Nellore coast is 0.96 m, 1.08 m and 1.35 m respectively. Figure 5 shows Resourcesat-1 LISS-IV FCC draped over DEM showing flooding scenario for the year 2105 for Dahej coast in the Gujarat State. Flooding due to projected sea level rise for Paradip is also shown in Figure 5.

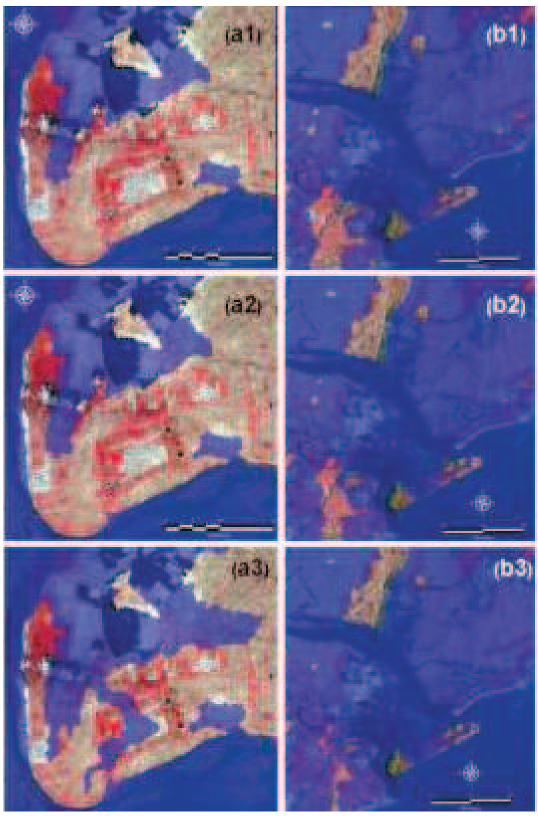

Figure 5: Inundation scenario under sea level rise for a) Dahej and b) Paradip projected to 1) 25 years 2) 50 years and 3) 100 years

3.3 Flooding scenario due to storm surge for specific return interval

Flooding scenario due to storm surge for specific return interval has been generated for the Paradip coast. During the period of analysis (1974–1988) by Unnikrishnan et al. (2004), two to four storm surge events were identified in a year, on an average for the Paradip. Flood height for storm conditions computed for return interval of 25, 50 and 100 years for the Paradip area are 4.36, 4.63 and 4.89 m respectively. Figure 6 shows Resourcesat-1 LISS-IV FCC imagery draped over DEM and inundation due to storm surge with return interval of 25 years. In this scenario the entire study area is observed to be inundated and is seen as blue. It is not possible to demarcate the flood line as the entire study area is inundated.

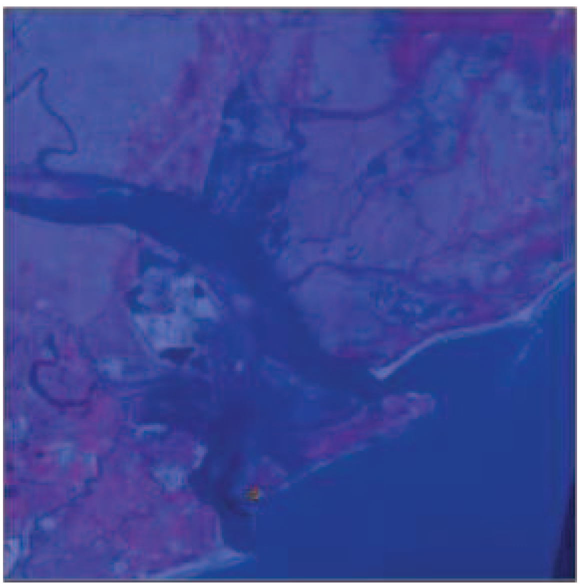

Figure 6: Inundation for storm surge with return interval of 25 years at Paradip

3.4 Flooding scenario due to maximum wave run up

Flooding scenario due to maximum wave run up has been generated for two sites i.e., Nellore and Dahej. The wave height was computed as explained in 2.2 and the height at around 10 m water depth is taken as the breaker wave height. The probable maximum breaker wave height around 10 m depth for the Dahej coast is 3.7 m. Field experiments conducted by CESS have concluded that the ratio of run-up height/breaker height is nearly equal to 0.7. This value is the same as the value reported by the Federal Emergency Management Agency (FEMA) (www.fema.gov). They suggested that breaking wave elevation, which is 70% of the breaking wave height, has to be considered for calculating flood levels. Thus 70% of the breaker wave height is considered as the inundation level due to breaking waves.

The wave's contribution to the flooding levels is calculated in the light of the above, and the values obtained for the Dahej coast is 2.59 m. This height is added to HHTL and predicted SLR for the period 2030, 2055 and 2105 and it comes out to be 8.32 m, 8.45 m and 8.69 m respectively and or Nellore coast this heights are 3.74 m, 3.86 m and 4.13 m for the respective years. Figure 7 shows the flood inundation in the Dahej and Nellore area for the year 2105.

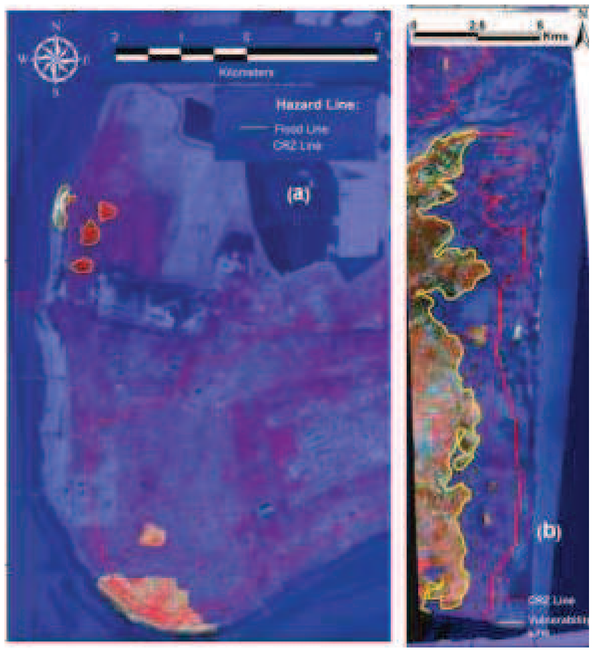

Figure 7: Flood inundation in the a) Dahej and b) Nellore area for the year 2105 under maximum wave run up

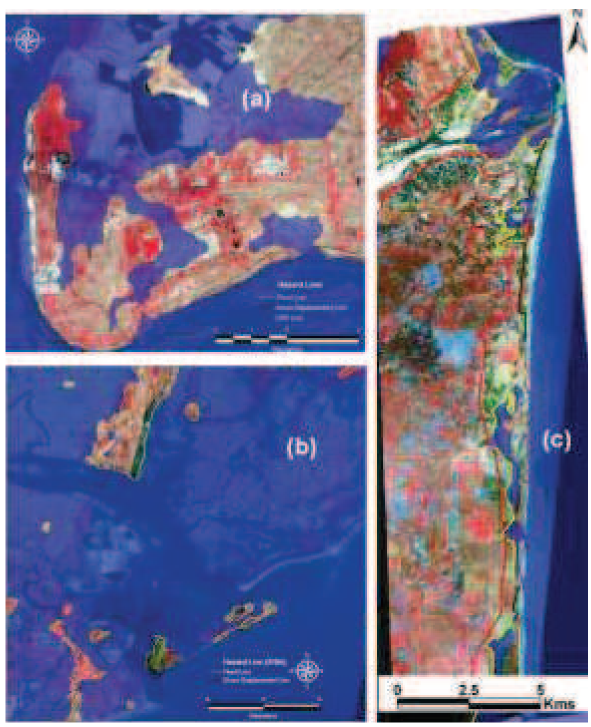

Figure 8: Vulnerability line demarcated under the sea level rise for the Dahej, Paradip and Nellore coasts

3.5 Delineation of the vulnerability / hazard / setback line

Vulnerability line is delineated by taking union of the shore displacement line and flood line i.e. it is considered as the landward extent of flood line or shore displacement line (whichever is maximum towards land) using GIS. Figure 8 shows the Vulnerability Line demarcated for the sea level rise for the Dahej, Paradip and Nellore coasts.

4. Conclusion

The present study presents an approach to demarcate vulnerability line for the selected regions of the Indian coast considering union of shore displacement and flood line under various hazard scenarios for next 25, 50 and 100 years. The study suggests that for demarcating setback line for implementing CRZ notification, shore displacement line and flood inundation due to projected sea level rise may be adopted. The methodology incorporates the coastal response to the change in the inundation height with time. Inundations under severe conditions were observed to affect the entire study area especially in Paradip which is deltaic in nature. The method will be useful to the coastal zone management authorities and coastal zone planners in ensuring the coastal protection as well as implementation of CRZ notification.

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