Geospatial Tools Based Analysis of Tsunami Vulnerability Assessment for Cuddalore Coast Tamil Nadu, India

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Abstract: *The 2004 Sumatra tsunami left a deep and dark footprint on coastal Cuddalore in south east India, which was one of the worst affected districts in the main land. Assessment of natural hazards typically relies on analysis of past occurrences of similar disaster events. Assessment of tsunami hazard to the Indian coast poses a scientific challenge because of the paucity of both historical events and data. However, construction of the tsunami hazard maps is the key step in tsunami risk assessment and forms the basis for evacuation and future land use planning along coastal areas. To this end, a set of inundation scenarios were built based on realistic tectonic sources that can generate tsunamis in the Indian Ocean. From the past historical records three earthquake sources have been identified and a hypothetical worst case scenario was also generated. Numerical models were constructed to predict the extent of inundation and run-up in each case, using a finite difference code on nested grids derived from the high resolution elevation and bathymetry datasets collected for the study area. The model was validated using field data collected immediately after the 2004 tsunami and was then used to generate the other inundation scenarios. Tsunami hazard maps for coastal Cuddalore was prepared by overlaying the numerical model outputs along with details on geomorphology, elevation, cadastral land parcels, infrastructure, high tide line, and coastal regulation zones.*

Key Words: *Tsunami hazard database, tsunami inundation maps, GIS, Cuddalore, Tamil Nadu, India.*

1. INTRODUCTION:

Tsunami is a Japanese world tsu- harbor nami-wave (harbor wave). A tsunami is a series of ocean waves generated by any rapid large-scale disturbance of the seawater. Most tsunamis are generated by earthquakes, but they may also be caused by volcanic eruptions, landslides, undersea slumps or meteoric impacts. These waves travel across the ocean at very high velocities, often in exceed of 450km/hr, and posses very long wavelength and wave periods. Tsunami causes loss of human lives and property, catastrophe to coastal areas. The study area Cuddalore is a coastal district of Tamil Nadu along the southeast coast of India. This was one of the worst affected area in Tamil Nadu during 2004 Sumatra Indian Ocean tsunami with a death toll of 500 casualties, with the entire coastal villages have been destroyed. It is surrounded by Bay of Bengal on the East, Nagapattinam on the south and Pondicherry in the north side. The geographical extent of the area is 78º 38' to 80 º 00' E longitudes and 11º 11' to 12º 35' N latitudes (Fig.1.). The Cuddalore district has a coastal length of 58 Kms and the coastal zone is low lying with gentle slope resulting in large inundation, thus increasing the vulnerability of the region. The Bay of Bengal is one of the six regions in the world where severe tropical cyclones originate in the months of May, November, and December. The storm surges are well known for their destructive potential and impact on human activities due to associated strong winds along the coast and heavy rainfall. The study area is well connected with national highway networks (NH45A) and state highways connecting Cuddalore Town to other parts of Cuddalore district. In this context, this work aims to assess the tsunami vulnerability area using based field data and geospatial tool analysis.

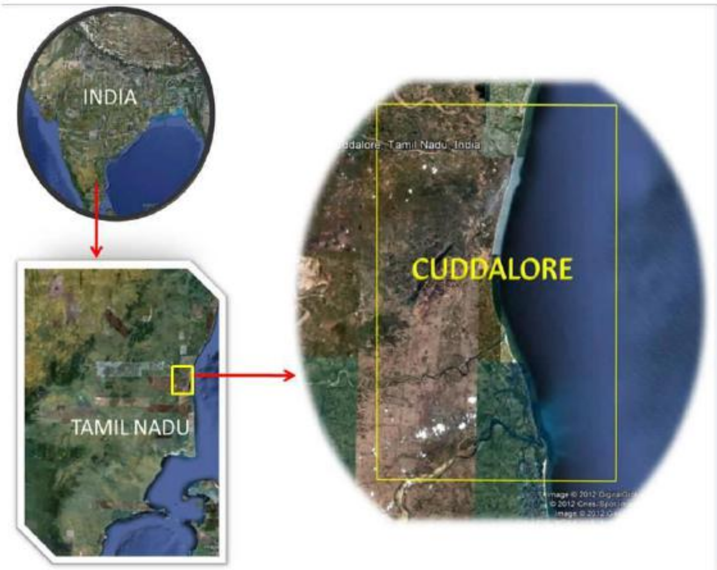


Figure.1. Location map of the study area

2. LITERATURE REVIEW:

A tsunami can have a period in the range of ten minutes to two hours and a wavelength in excess of 500 km (Prager, 1999). In the deep ocean, a tsunami is barely noticeable and when it approaches the land and shallow water, the waves slow down and become compressed, causing them to grow in height up to 30m. Murty (1999) has reported a few more earthquakes on the coast of Myanmar (formerly Burma). Alami and Tinti (1991) evaluated the tsunami hazard along the Moroccan coast by comparing tsunami data with the set of available earthquake data. Jaffe and Gelfenbaum (2002) used tsunami deposits to create geological records of not only of a single tsunami but also of the effects of past tsunamis. Kurian et al., (2006) investigated the inundation characteristics and geomorphological changes resulting from the 26th December 2004 tsunami along the Kerala Coast, India. The Papathoma Tsunami Vulnerability Assessment (PTVA) Model was developed to provide first order assessments of building vulnerability to tsunami and the output of the model assessment is a “Relative Vulnerability Index” (*RVI*) score for each building (Papathoma and Dominey-Howes, 2003; Papathoma et al., 2003). However, on 26 December 2004, the mega thrust earthquake with a magnitude of 9.3, originated off west coast of northern Sumatra Island, in a seismically active zone close to sunda trench at a water depth of 1300 m and with the epicenter located at a shallow depth of 10km below the ocean floor, in the Indian Ocean. These waves travelled through the Indian ocean and hit along the Coromandel coast of India, particularly Tamilnadu, and parts of Andhra Pradesh at around 8.45IST with a wave ht of 3 to 10m. Cuddalore (11^{o} 28’ 10”N to 11^{o} 42’15”N) district, in Tamil Nadu, south east coast of India is a large industrial town and was one of the worst tsunami affected coastal areas in mainland India.

3. MATERIALS AND METHODOLOGY:

This work was carried out to study possible risks of an earthquake induced tsunami inundation on densely populated coastal areas of Cuddalore by applying numerical models and GIS. Large scale tsunami hazard maps were generated using the different inundation scenarios and stored as a spatial database which would be of immense use for tsunami mitigation and planning operations. Numerical modeling is an excellent tool for understanding past events and simulating future ones. The study uses the TUNAMI N2 model which is based on linear theory in deep waters, shallow-water theory in shallow waters and run-up on land with constant grids. Since the source parameters that triggered the December 2004 tsunami are well known, the model was first set to capture this event. In addition, since accurate measurements on inundation was available for coastal Cuddalore, the model results were validated using field observations collected immediately after the tsunami. The methodology adopted in collection of inundation and run-up height can be referred in Pary et. al., (2008). The model results obtained using the high resolution bathymetry and elevation data were validated using field observations. The model once validated was then used to generate different scenarios of inundation and run-up by varying the source parameters that actually trigger the tsunami. On the basis of the model predicted inundation large scale tsunami hazard maps were prepared for coastal areas of Cuddalore.

4. ANALYSIS AND FINDINGS:

Numerical Modelling of Tsunami

The tsunami modeling process can be divided into three parts: generation, propagation, and inundation (Synolakis 2003). Generation modeling forms the first stage in the modeling of tsunami and includes the calculation of initial disturbance of the ocean surface due to the earthquake-triggered deformation of the sea floor. Most studies of tectonic tsunamis use Mansinha and Smylie's (1971) formula to predict seafloor displacement due to an earthquake and to model initial water displacement (Legg et.al. 2004). In this study the algorithm of Mansinha and Smylie (1971) was used to calculate the seafloor deformation. The input seismic parameters used in this study are shown in table 1 and the corresponding initial surface elevations are shown in the Figure. 2.

The TUNAMI N2 numerical model was used for simulation of propagation and amplification of tsunami wave along the coast. It solves nonlinear shallow water equations in Cartesian coordinates using the leap-frog scheme of finite differences (Yalciner et al. 2004). One set of four-level nested grids, where the grid resolution increases in the coastal areas was used to calculate the tsunami run-up along the Cuddalore coast (Fig. 3 & 4).

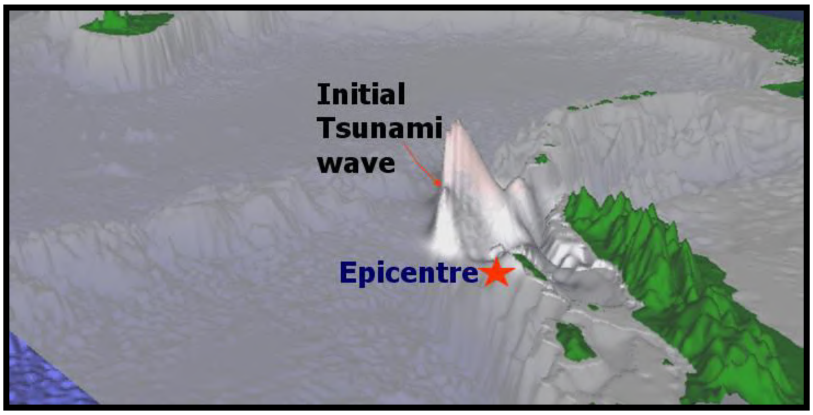


Figure (2) Tsunami Generation

Table.1. Fault Parameter of 2004 Sumatra Tsunami

Parameters	Block-1	Block-2	Block-3	Block-4	Block-5
Longitude	95.10	93.90	93.41	92.10	92.00
Latitude	2.50	4.33	5.80	9.10	10.50
Fault length(km)	220	150	390	150	350
Fault width (km)	130	130	120	95	95
Slip amount (m)	15	15	06	06	06
Strik angle(deg)	330	340	338	356	10
Dip angle(deg)	12	12	12	12	12
Rake angle(deg)	90	90	90	90	90
Focal Depth(km)	25	25	25	25	25

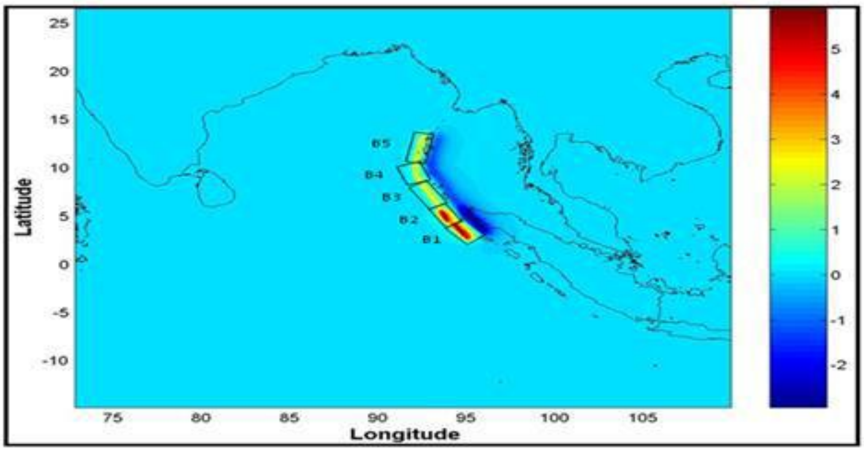


Figure.3. Initial Sea Surface Elevation of 26 Dec, 2004 Sumatra Tsunami

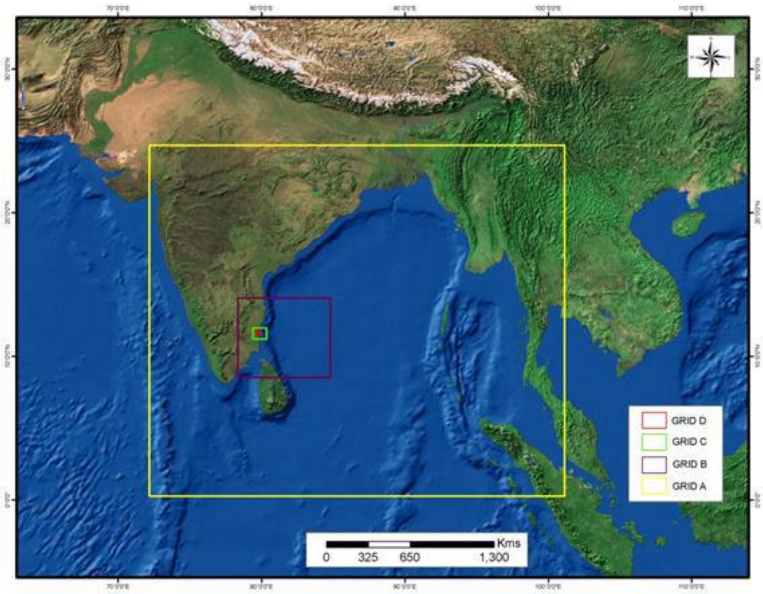


Fig.4. Nested grids for the Study Area

Elevation and Bathymetry Data for the Model

To reproduce the correct wave dynamics during inundation, accurate and high resolution bathymetry and topography data are essential. For this study elevation datasets were collected using The Shuttle Radar Topography Mission (SRTM) for a distance of 90m from the coast. On the sea side, high resolution bathymetry data was obtained from single beam echo sounder and was further supplemented by C-Map and NHO charts for near-shore areas. The General bathymetric chart of the oceans (GEBCO) digital atlas (IOC et al., 2003) was used to populate the deep sea regions. The datasets were built so as to capture the actual topographic and bathymetry conditions in the study area using the highly precise SRTM data and the offshore areas were populated using global bathymetry datasets (Figure.5).

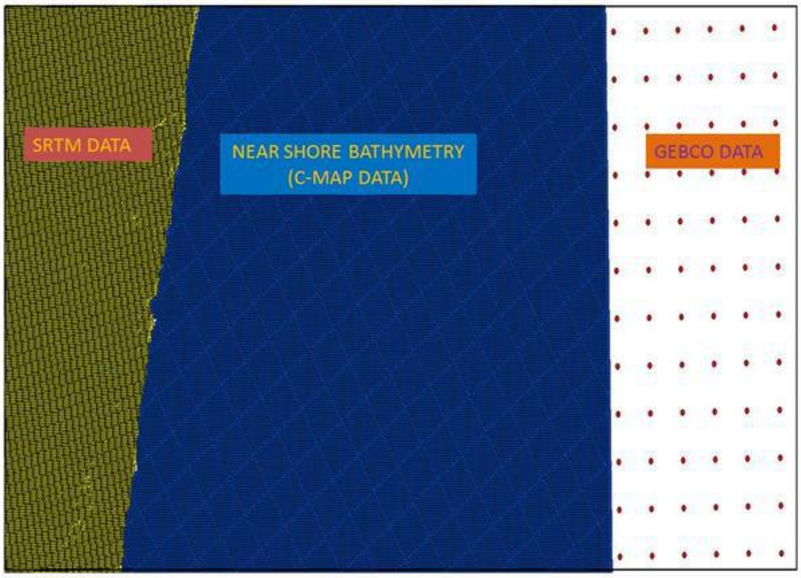


Figure.5. Merged Bathymetry Datasets

Krigging interpolation technique was used to generate the seamless grid containing both elevation and bathymetry datasets (Figure.2). The model was simulated for 2004 Sumatra earthquake parameters using a constant time step for all the grids. The model results were validated using field data on inundation that was collected along the Cuddalore coast immediately after the 2004 tsunami.

Generation

The generation stage of tsunami evolution includes the formation of initial disturbance of the ocean surface due to the earthquake triggered deformation of the sea floor. This initial water surface disturbance evolves into a long gravity wave radiating from the earthquake source. Modeling of the initial stage of the tsunami generation is closely linked to studies of earthquake mechanisms. The basic parameters which are essential for the stimulation of tsunami include the fault area (length and width), angle of strike, dip, and slip depth of fracture, dislocation and moment magnitude of the earthquake.

Propagation

Tsunamis travel outward in all directions from the generating area, with the direction of the main energy propagation generally being orthogonal to the direction of the earthquake fracture zone. Their speed depends on the depth of water, so that the waves undergo accelerations and decelerations in passing over an ocean bottom of varying depth. In the deep and open ocean, they travel at speeds of 500 to 1000 km per hour (300 to 600 miles per hour).

The distance between successive crests can be as much as 500 to 650 kilometers (300 to 400 miles). However, in the open ocean, the height of the waves is generally about 30 to 40 cm even for the most destructive tsunamis, and so the waves pass unnoticed. Specifically tsunami waves undergo a process of wave refraction and reflection throughout their travel. The accurately model tsunami propagation over such a large distances, the parameter like earth curvature, coriolis force and the information on ocean parameters such as tides, currents, waves are required because the dispersion of the tsunami wave depends on above parameters.

Run-up (Inundation)

The propagated tsunami wave from the deep water undergoes changes causing increase in the wave height at coast due to near shore bathymetry and coastal morphology such as inlets, sand dunes, water bodies etc. As near shore bathymetry and land topography play a major role in simulating run-up, a suitable methodology has been developed for integration of data from various sources. The tsunami inundation and run- up height depends on the configuration of the shelf and slope of the coast, coastal geomorphologic features, and the orientation of the coastline, vegetation, wave height and direction of approach generated from the Arakan region because of its proximity and orientation of the coastline. The results of the model in terms of inundation and run-up were compared for selected locations along the Cuddalore coast (Table 2).

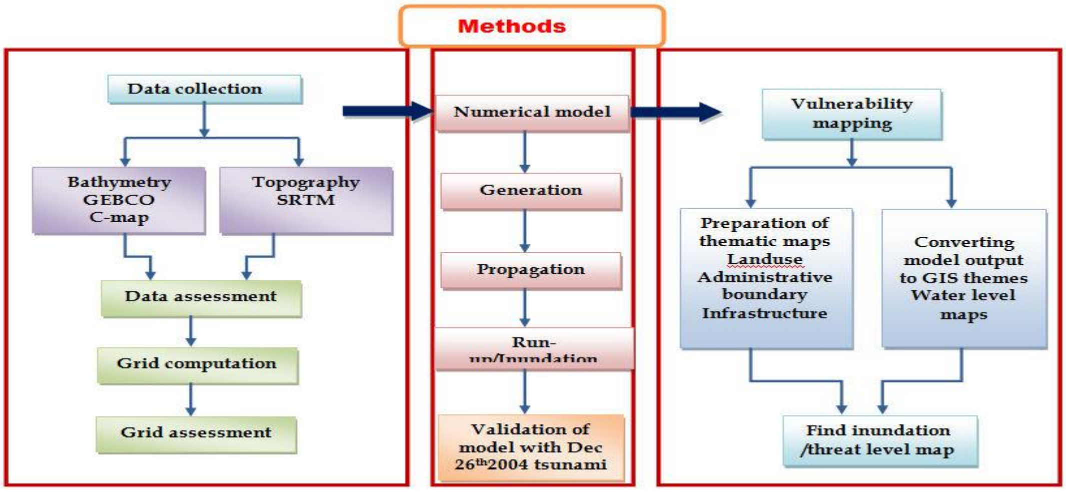
S.No	Latitude	Longitude	Observed inundation(**)	Predicted inundation	Predicted run -up	Location
1	11.715	79.769	1000	1010	3.16	CUDDALORE OT
2	11.52	79.768	664	790	3.04	ARYAGOSHTI
3	11.536	79.761	416	340	3.27	VILLANALLUR
4	11.549	79.759	366	360	3.1	SILAMBIMANGALAM
5	11.564	79.757	391	370	3.42	PERIYAPATTU
6	11.578	79.757	514	300	3.64	ANDARMULLIPALAYAM
7	11.594	79.757	573	270	3.53	KAYALPATTU
8	11.612	79.759	343	330	3.41	TRICHOPURAM
9	11.629	79.761	729	343	3.49	THIYAGAVALLI
10	11.449	79.765	1510	880	2.41	KILLAI
11	11.49	79.76	3000	3360	3.41	PARANGIPETTAI
12	11.585	79.756	360	240	3.32	AYYAMPETTAI
13	11.549	79.757	430	170	3.25	SAMYAR PETTAI
14	11.514	79.767	710	520	3.1	PUDHU PETTAI
15	11.514	79.772	460	280	3.5	PUDHU KUPPAM
16	11.605	79.759	---	140	2.68	PERIYA KUPPAM
17	11.641	79.764	-- -	330	3.08	SANGOLI KUPPAM
18	11.72	79.782	---	401	3.53	SINGARATHOPE
19	11.735	79.786	350	650	3.46	SILVER BEACH
20	11.443	79.805	3200	3600	2.25	PATTANACHERY
21	11.745	79.788	--	240	2.46	DEVANAMPATTINAM
22	11.681	79.772	230	120	1.7	RAJAPETTAI
23	11.62	79.76	300	230	1.4	THAMNNAPETTAI
24	11.636	79.763	110	160	1.3	CHITRAPETTAI
25	11.754	79.79	---	247	3.26	THAZHAM KUDA

High run-up height | Low run-up height | Low inundation | High inundation

Table (2) Cuddalore District Inundation and Run-up

Numerical modeling Methods

Numerical modeling of tsunami is very important for understanding past events and simulating future ones. Bathymetry and elevation data are the principal datasets required for the model to capture the generation, propagation and inundation of the tsunami wave from the source to the land. Elevation data was derived from the Indian remote Sensing satellite SRTM, while bathymetry was obtained from C-Map for near shore areas and GEBCO for off shore areas.TUNAMI-N2 model simulations reproducing tsunami propagation, run up, and inundation levels were carried to study the tsunami hazard level along the coast. In this paper, numerical simulation was attempted to generate inundations due to various historical earthquakes. A hypothetical worst-case scenario was simulated by loading the 2004 Sumatra earthquake parameter on 1941 north Andaman source. Field data collected using ArcPad GPS,is considered as the primary source of information of the extent of inundation and elevation measurements. Ground truth data was also collected for the preparation of the landuse maps of coastal areas. Finally, the tsunami hazard maps for Cuddalore was prepared by incorporating the results of the numerical model on the extent of inundation and run-up, along with details on land use, elevation, infrastructure, Coastal regulation buffer zones etc (Fig.6).



Field Measurements for Inundation

Immediately after the tsunami, field measurements on inundation and run-up were collected along the Cuddalore coast using Realtime Kinematic Global Positioning System (RTK GPS). During field survey it was observed that maximum inundation was upto 2km from the shore in low-lying areas and landforms in these areas were totally destroyed or modified Conversely, it was also observed that landforms such as sand dunes have acted as a barrier in the inundation of tsunami water and as a result the width of area of inundation was found to vary from place to place depending on landforms found along the Cuddalore coast. The villages affected by tsunami in Cuddalore district and the extent of inundation collected from field measurements are given in Figure (7).

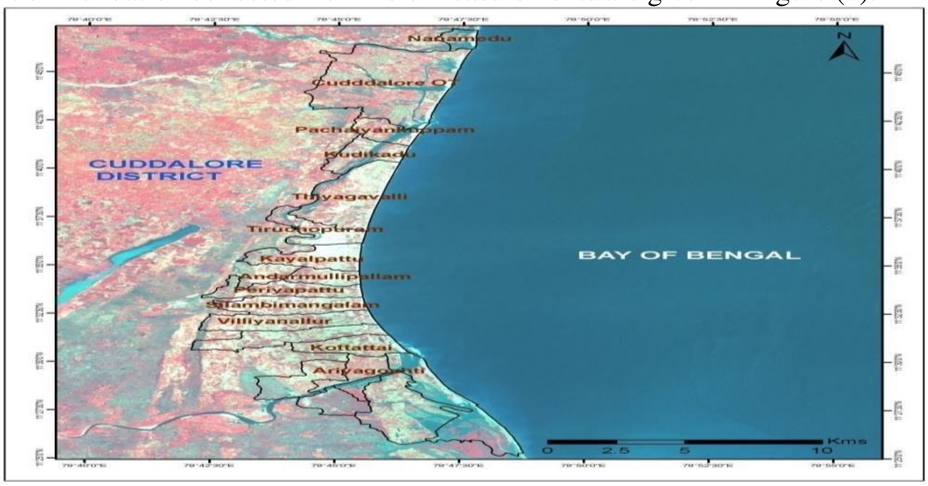


Fig.7. Cuddalore coastal village boundary overlayed over Landsat Image

Generation of tsunami hazard map for Cuddalore

Hazard zone classification

By studying inundation due to the various historical and hypothetical sources the coastal areas of Cuddalore were classified into different risk zones based on the extent of inundation and water level at coast (Fig.8). Since inundation due to 1881 Car Nicobar source and 1941 North Andaman source produced no significant impact on the coast both in terms of inundation and water these sources were classified as low risk. 2004 Sumatra earthquake which caused maximum destruction along the Cuddalore coast was classified as high risk while the hypothetical worst case scenario generated by loading the 2004 Sumatra source parameters on Car Niocbar was classified as Maximum risk since both inundation and water level were very high for this scenario. The water levels showing the extent of run-up in the high risk areas were prepared from the results obtained from the numerical model for the 2004 Sumatra earth quake scenario and was overlaid on the tsunami hazard map.

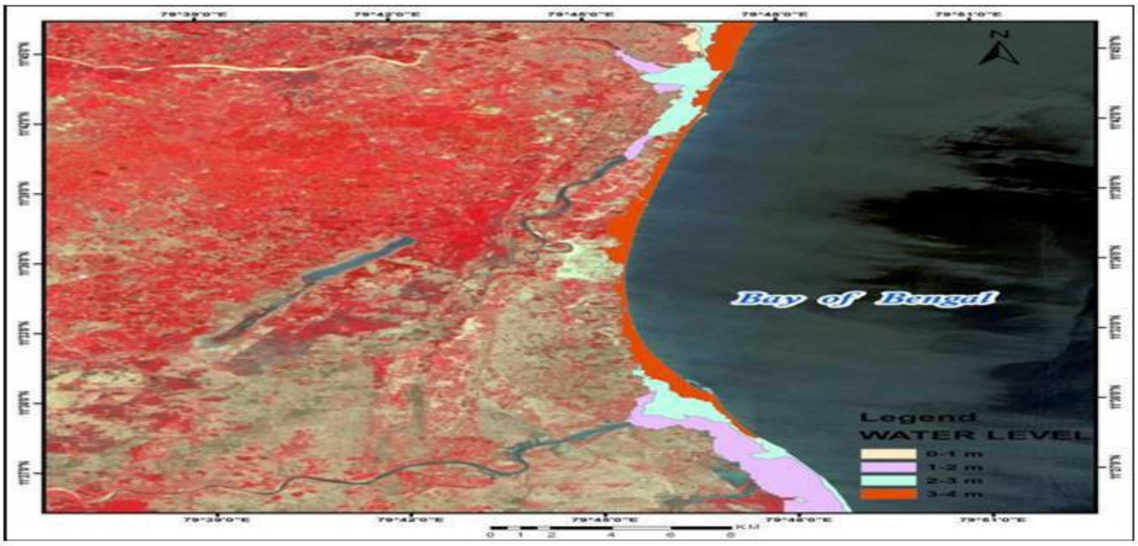


Figure.8. Water Level Map Overlayed with Lantast Image

Geomorphology

Geomorphology and IRS LISS III remote sensing data were used to generate the geomorphology of Coastal Cuddalore. The Satellite data were rectified using Ground control points collected from field using a high precision GPS. The geomorphology details coupled with the information of extent of inundation would be a valuable tool in future planning. The spatial data for the preparation of geomorphology maps were extracted from Survey of India Toposheet and IRS LISS III satellite data.

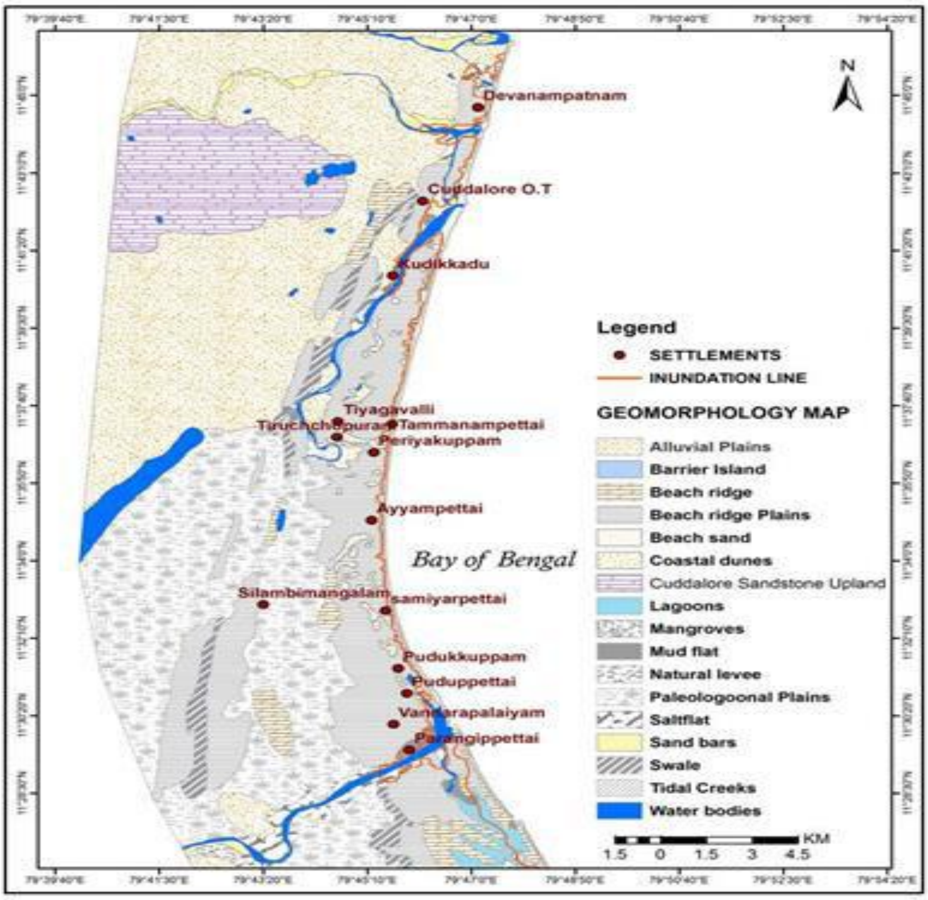


Fig.9. Geomorphology map for Cuddalore

Infrastructure details

Extensive field surveys were undertaken in Cuddalore to create spatial database on the major infrastructure in the coastal areas. An asset database was generated showing the location of schools, cyclone shelters, hospitals, public amenities etc present in the study area. These details were also overlaid on the tsunami hazard map so as to identify the infrastructure at risk in the event of a tsunami.

High tide Line and CRZ buffers

The high tide line (HTL) pertaining to the coast was overlaid and 200m, 500m and 1Km lines indicating the Coastal regulation Zone corridors were generated and plotted on the hazard maps to show the vulnerability of the area even beyond the coastal regulation zones.By overlaying all the above mentioned thematic layers in GIS, small scale inundation maps on 1:25000 scale were generated for coastal districts of Cuddalore.

Tsunami Hazard Vulnerability Map for Cuddalore

The final tsunami hazard vulnerability map was prepared by integrating all the variables like Tsunami inundation and run-up level, infrastructure map, landuse and landcover, elevation and geomorphology map, safer zones and escape way were also demarcated (Fig.10). The disaster and vulnerability maps can be used for further analysis and rescue management with other thematic layers such as safe shelter places and network maps. This map plays a vital role during the event of tsunami for management and mitigation activities and also helpful in defining the limits of construction of new essential facilities and special occupancy structures in tsunami flooding zones.

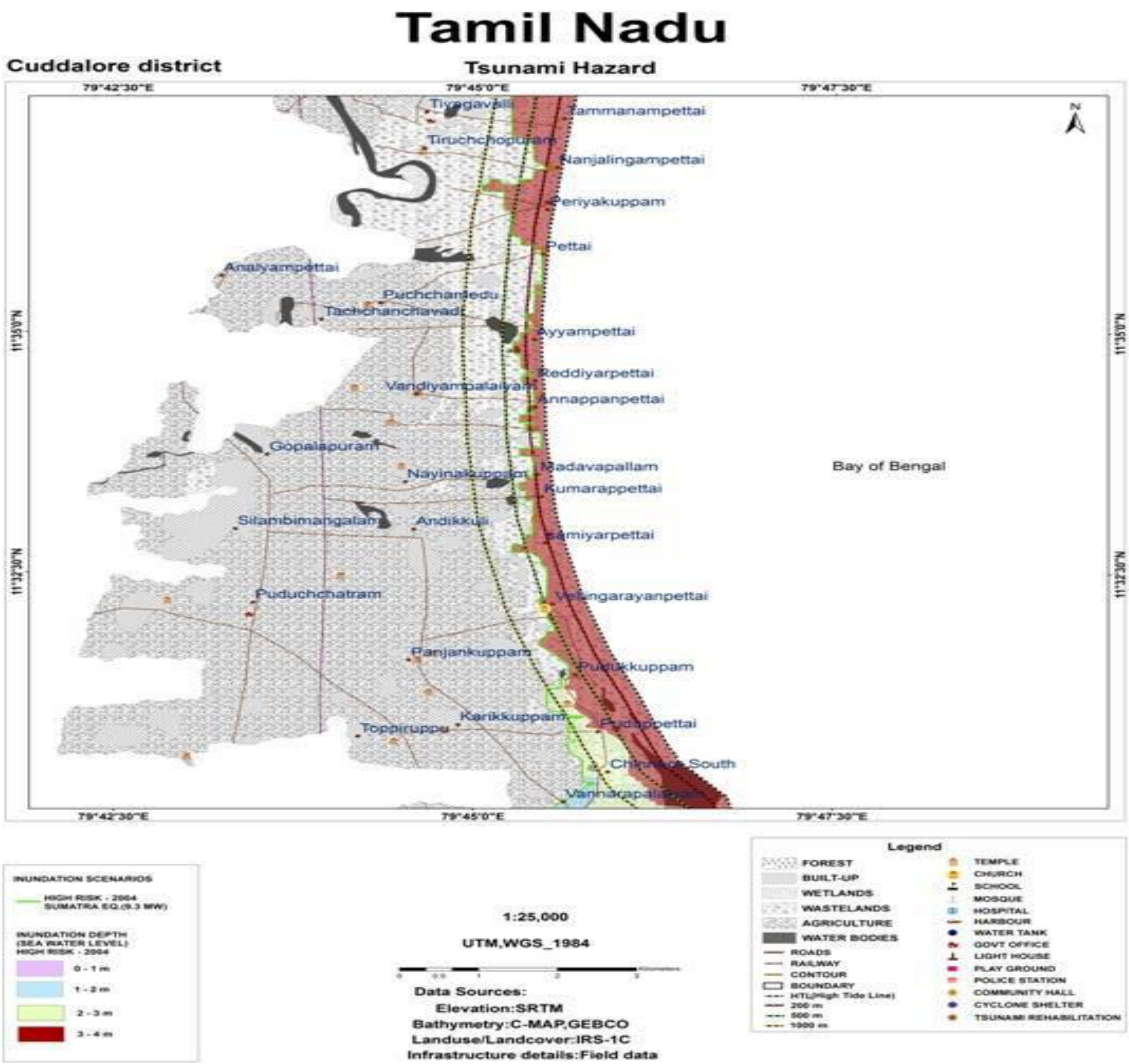


Fig10. Vulnerability map of Cuddalore

Tsunami wave propagation

The simulation is carried out for duration of 6 hours and the propagation states at 5, 30, 60, 90, 120, 180, 190, 300 minutes are shown in the figures below (11) and (12). The Inundation and Run-Up is shown in table.3.

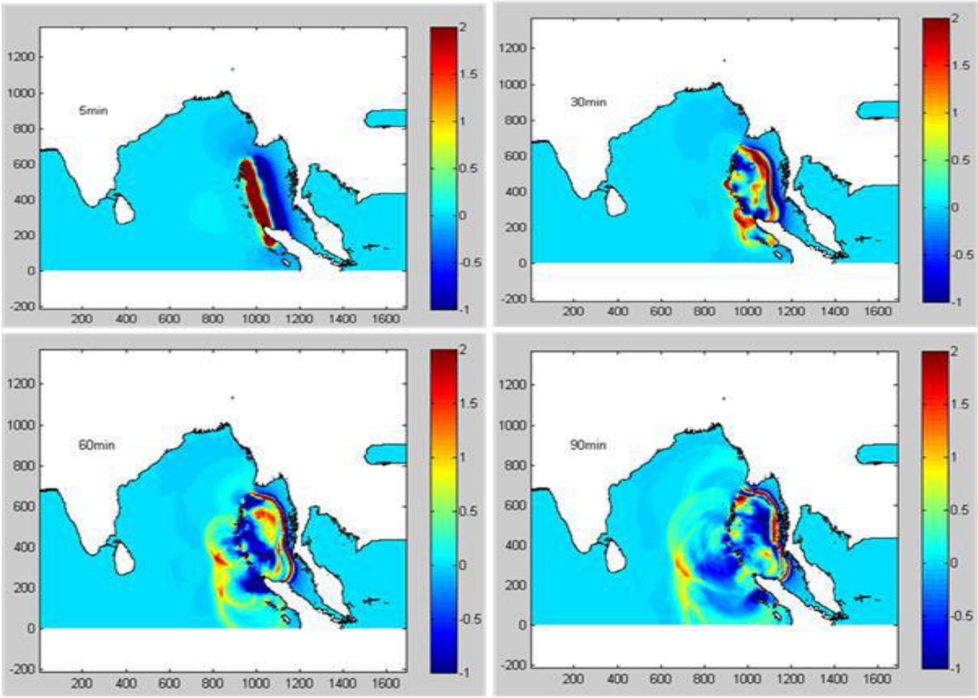


Figure. 11 Tsunami wave propagation of various times (5 minutes, 30 minutes, 60 minutes and 90 minutes)

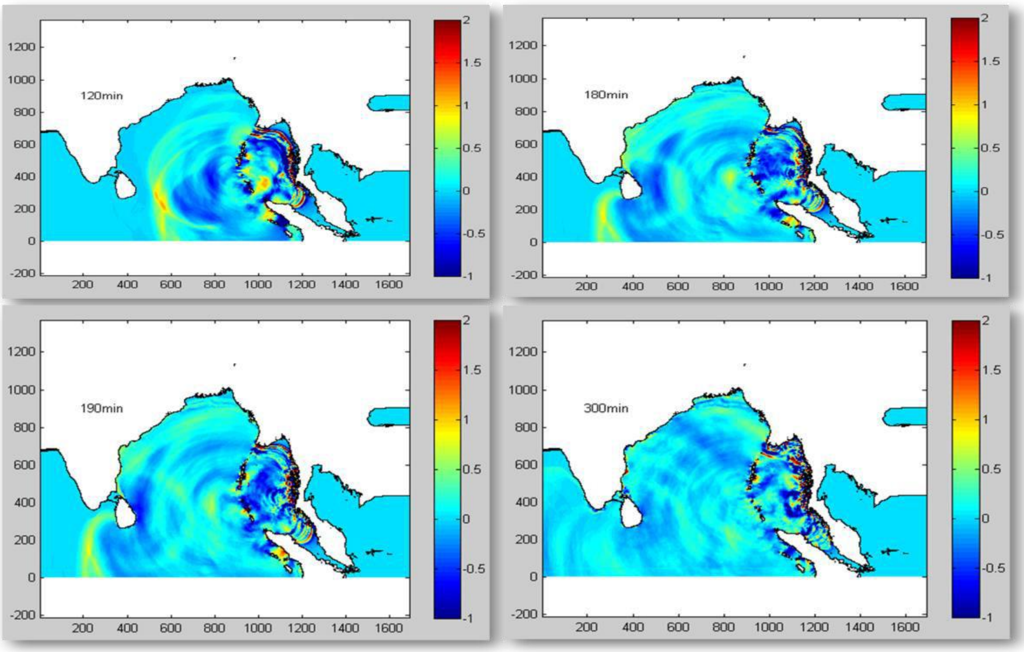


Figure. 12. Tsunami wave propagation of various times (120 minutes, 180 minutes, 190 minutes and 300 minutes)

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Table 3 Cuddalore District Inundation and Run-Up

High run- up height | Low run-up height | Low inundation | High inundation

5. CONCLUSION:

The tsunami event on 26th Dec 2004 that devastated east coast of India was one of the largest natural hazards faced by the people of this region. The stimulation result shows the time taken to reach the Cuddalore coast is about 2.15hrs. The river system acts as a flooding corridor which takes the tsunami water for longer distances. Mangroves act as natural barriers which protects the coast during the event of tsunami. The geomorphological features such as beach, beach ridge and sand dunes acts as barriers and prevented tsunami water upto some extent whereas swales, creeks and inlets allow the tsunami water for larger distances. Near shore seafloor topography, elevation of coastal landforms, and occurrence of natural coastal barriers like coastal dunes, coastal vegetations, etc are the physical parameters vital in controlling the impact of tsunami waves. The maximum inundation is observed at Vellar river is around 3.3 kms mainly due to successive wave propagations through creek. In river mouths like Chinna Vaikal (Pichavaram) and Coleroon the tsunami water reached a maximum distance of about 2.5 kms and run up of 3.0m.

Simulation results for 2004 Sumatra earthquake showed a maximum run-up of about 3–4 m while the maximum inundation was about 3.0 km inland. The maximum inundation is observed in the river mouth of Gadilam, Uppanar and Vellar and the minimum was observed around Rasapettai, Tammanapettai and Kudikadu village, where the height of the beach ridge ranges from 5 to 7 m. The areas adjoined to the river mouths of Vellar, Chinna Vaikal (Pichavaram) and Coleroon were flooded due to the disastrous event. The inundation observed in Devanampattinam silver beach was 650m with a run-up height of 3.56m. The inundation is observed in Cuddalore OT is 1000m with a run-up of 3.16m. The maximum run-up was observed at Andarmullipalayam is 3.64m and minimum at is Chitrapettai 1.30 m. The maximum inundation was observed at Pattanacheri and Parangipettai were 3.6km and 3.3km. The inundation at Silambulingam, Periyapattu, Kayalpattu, Trichopuram were 360m,370m,270m, 330m and run up ranges from 3.2 to 3.4m. In Ayyampettai, Samiyarpettai,Pudhupettai the run-up height was 3.1 to 3.3m.Tne minimum inundation was observed at Chitrapettai (160m) and Samiyarpettai inundated(170m) with a run -up height of 1.30m, and 3.25m. The inundation at Pudhu Kuppam, Sangoli Kuppam,Periya Kuppam were 280m, 330m and 140m with a run-up height ranges from 3.5m, 3.08m, and 2.68m.It is observed that maximum the water has inundated through the river system and it is controlled by elevated landmass in the coast. The southern part of Cuddalore coast shows more inundation than northern part even it comprises of sand dunes in this region because of river system. The inundation varied from place to place depending on the type of landforms and vegetation cover along the coast. The extent of inundation showed that geomorphological features such as beach ridge and sand dunes restricted the inundation whereas swales, creeks and inlets allow the tsunami water for larger distances. Conversely, landforms have also acted as a controlling factor of tsunami waves. Pichavaram mangroves which acts as a buffer zone during the recent Tsunami and the energy of the tsunami waves has been dissipated making the waves ineffective to move further.

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