Assessment and Modeling the effect of Tsunami waves in the Nagapattinam coast of India using Geoinformation and Numerical Model

Rahul Prakash Srivastava

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by

Rahul Prakash Srivastava

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Thesis Assessment Board :

Prof. Freek van der Meer, ITC (Chairman)
Dr. R.K.Mazari (Expert)
Mr. P L N Raju (IIRS Supervisor)
Dr. D. Mitra (IIRS Supervisor)

Thesis Supervisors :

Dr. D. Mitra (IIRS Supervisor)
Mr. P L N Raju (IIRS Supervisor)
Drs. M.Damen (ITC Supervisor)

INDIAN INSTITUTE OF REMOTE SENSING, DEHRADUN, NATIONAL REMOTE SENSING AGENCY, DEPARTMENT OF SPACE, GOVERNMENT OF INDIA, INDIA
&
INTERNATIONAL INSTITUTE FOR GEO-INFORMATION SCIENCE AND EARTH OBSERVATION ENSCHEDE, THE NETHERLANDS

I certify that although I may have conferred with others in preparing for this assignment, and drawn upon a range of sources cited in this work, the content of this Thesis Report is my original work.
Signed…………….

Disclaimer

Dedicated to the Tsunami victims

Abstract

The Tsunami event of December 26, 2004 in the Indian Ocean that rocked the Sumatra Island in Indonesia had a profound impact on the south-eastern coast of India. In general, the state of Tamil Nadu in India suffered maximum damage in terms of life and property. The present study focuses its realm on the extent of inundation and damage to various landcover classes in the Nagapattinam area that suffered 6065 casualties, the maximum anywhere in India. The research takes into its gamut the model simulation of tsunami waves using a numerical model, *Tunami N2*. Fumihiko- Imamura from Tahuko University, Japan authors the model Tunami N2. It has been used for the generation, propagation and amplification of the tsunami waves. The model results show the propagation of the sea waves for the event of December 26, 2004 taking into account the fault geometry, bathymetry and initialisation conditions for running the model. The model incorporates ETOPO-5 and near-shore bathymetry data that is an important parameter in the model. It shows the arrival time of the tsunami waves at the south-eastern coast of India. The tsunami waves reach the Indian coast in 180 minutes that is in agreement with the real tsunami event of December 26, 2004. It also gives the amplitude of the tsunami waves. The model results are validated with the field observations and tide gauge measurements.

Key words: *Tunami N2, Bathymetry, surface deformation, fault geometry.*

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DSC	Decision Support Centre
NRSA	National Remote Sensing Agency
GMT	Greenwich Mean Time
DMSP	Disaster Management Support Programme
GEOSS	Global Earth Observation System of Systems
DEM	Digital Elevation Model
DART	Disaster Assistance Response Team
METU	Middle East Technical University
IOC	Intergovernmental Oceanographic Commission
UNESCO	United Nations Education, Scientific and Cultural Organisation
TIME	Tsunami Inundation Modeling Exchange
ATG	Acaustic Tide Gauge
RTKGPS	Real-time Kinematic Global Positioning System
POM	Princeton Ocean Model
MOM	Modular Ocean Model
FSDN	Federation of Seismic Digital Networks
CMT	Centroid-moment-tensor
CRZ	Coastal Regulation Zone
NGDC	National Geophysical Data Centre

1. Introduction

1.1. General Introduction

Tsunamis are giant waves that threaten life and property near coastal areas. They occur after large disturbances such as earthquakes, volcanic eruptions, and deep sea landslides. The 20th century had seen a great deal of growth and development of the coastal areas in most countries because of the inherent social as well as economic benefits that churn themselves out for the common good of all, and more specifically the coastal communities. The utilization of the coastal zone has assumed prime importance in India because of the population explosion, technological advancements as well as the demands of the economy. Though Tsunami are rare events but historical records prove that these are disasters that are infrequent, but have a catastrophic impact on the entire social set up of the coastal zone (Hubert CHANSON 2003). The Tsunami waves travel at a rapid pace, flooding and damaging the coastal communities as well as disturbing the ecological balance. They travel inland along riverbeds as continuous single standing waves that have effect on inland communities and contaminate rivers with saline water.

On December 26,2004 an earthquake of magnitude 9.0 on Richter scale occurred off the west coast of Sumatra in the Indonesian Archipelago at 06:29 hrs IST (00:59 hrs GMT) (epicentre 3.4 N, 95.7 E). The earthquake occurred along the plate boundary that is marked by the subduction zone between the Indian plate and the Burmese microplate. This is the fourth largest earthquake in the world since 1900. An approximately 1200 km of the plate boundary slipped and the width of the rupture was 100 km. This resulted in the upliftment of the sea floor, which resulted in Tsunami killing thousands of people across different countries. Indonesia was the worst affected followed by Sri Lanka, India, Thailand, Somalia, Maldives, Malaysia and Myanmar. The earthquake registered 9.0 in moment magnitude and was the biggest in four decades. It had a catastrophic impact on the life of the people. According to reports from Government of India, 10,881 people in India lost their lives from the disaster and 5,792 were missing, with 6,913 injured. Tamil Nadu was the worst effected with 7,983 deaths reported. The earthquake set off giant tidal waves of 3 to 10 meters in height, which hit the southern and eastern coastal areas of India and penetrated inland up to 3 km causing extensive damage. Approximately 2,260 km of the coastal area besides the Andaman & Nicobar Islands were affected. Many sectors have been severely affected and the economy has faced a big setback in such times. Coastal fisheries and agriculture were the worst affected economic activities. The total damage to these sectors alone is estimated to be about Rs. 163.2 crores ($ 37.5 million).

This tragedy calls for urgent set up of “regional early warning systems” in the Indian Ocean. To plan, for the Tsunami hazard, there should be good understanding not only of the physical nature of the phenomena and its manifestation in each geographical location, but also about various physical, social and cultural factors in order to effectively plan for the mitigation of its effects. The Coastal community had been shattered after the aftermath of the Indian Ocean Tsunami but in the absence of a proper and accurate monitoring system, it is imperative for us to understand the process of natural defence against such a disaster.

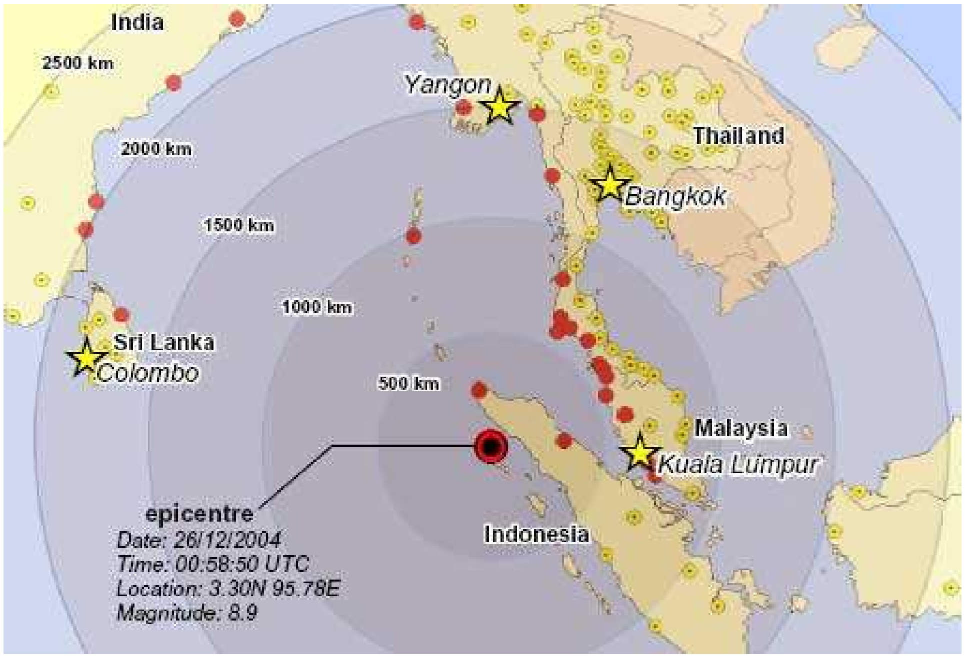

Figure 1 : Epicenter of the earthquake

(Source: UN Office for the Coordination of Humanitarian Affairs - www.reliefweb.int)

We need to understand the basic premise for the existence of the coastal environment and its inhabitants. Nature has provided barriers, which if properly managed, can be effective tools for sustainable coastal development.

1.2. Role of Remote Sensing

Remote sensing can play an effective role as satellite images can help in producing inundation maps which can be of great importance in planning for the evacuation as well as vital input for the early warning and monitoring systems in case of a Tsunami disaster. In the wake of the tragic tsunami, the Indian Government has committed to developing a tsunami early warning system for the Indian Ocean. The warning system, which will cost $ 27 Million, will be operational in 2 to 3 years time. The warning system would involve installing Deep Ocean Assessment Reporting Technology at a depth of six kilometres in the Indian Ocean and Bay of Bengal.

Various initiatives have been taken in the wake of the tsunami disaster of December 26, 2004 in the field of Remote Sensing in India. Decision Support Centre (DSC) located at the National Remote Sensing Agency (NRSA), Hyderabad under the Disaster Management Support Programme (DMSP) of Department of Space is proposed to be a single window support for the monitoring and assessment of all natural disasters using spaceborne and airborne data. This facility has interface with the Ministry of Home affairs, Government of India during all major disasters. DSC took immediate steps to acquire satellite data over the disaster affected area, programmed the satellite to tilt the cameras and maximise visibility for data acquisition. Visible and NIR data from space platforms such as IRS P4 and P6 provided rapid assessment of disaster affected areas within 24 hours. The aftermath of the tsunami disaster raised queries regarding the adequacy of remote sensing data and its availability, forecasting/early warning system. While the ability to save lives by forecasting the magnitude and nature of natural disaster is still elusive to our scientific strength, the reduction of post-disaster sufferings is achievable with the aid of spaceborne remote sensing. The East and west coast of India are prone to risks as the epicentre can be in the eastern or western segment of the circumpacific belt. Thus, vulnerability analysis, finer level coastal morphologic maps, DEM, bathymetry and spatial models are required to give a better understanding of the disaster and risk assessment.

With all the International aid as well as the scientific accomplishments, it is imperative to understand the natural barriers that acted as balance and supported many life forms long the entire coastline. The presence of mangroves, sand dunes, casuarina plantations and ridges to name a few have acted as natural barriers against the incoming tidal waves. Thus, the focus should also be on natural and ecofriendly approaches to minimize the damages that have been caused due to these disasters. There is a need for concerted effort at a global level to recuperate from the losses suffered and to join hands in fighting the menace through technological cooperation as well as sustainable use of our natural resources. Various International agencies have come up with their own plans of handling this natural disaster but a collective and concerted effort is the need of the hour.

1.3. Tsunami Forecasting

Tsunami needs to be detected directly instead of relying on earthquake precursors as all the tsunami are not generated by earthquakes. It can be attributed to other factors like volcanic eruptions or submarine landslides. Tsunami forecasting depends largely on two parameters:

- Exact location of epicentre (seismographs)
- Early detection of changes in submarine topography (pressure system like DART system)

A forecasting system is being planned for the Indian Ocean depending on the above two parameters. Deploying additional buoys and connecting them to the deep sea pressure sensors and communication satellites. It is also planned to improve the network and upgradation of existing seismic stations. A global initiative called GEOSS (Global Earth Observation System of Systems), for which India is a signatory, is pursuing the need to develop global access to a pooled resource of Earth observation information. (Navalgund 2005)

1.4. Historical Tsunamis in South Asia

Although not as frequent as in the Pacific Ocean, tsunamis generated in the Indian Ocean pose a great threat to all the countries in the region.

Table 1. **Run-up level for Tsunami occurred between 1700 and 2004 in the Indian Ocean**

S.No.	Name of affected locations	Run-up heights (m)	Year/Date	Earthquake magnitude at source	Source Location
1.	Tributaries of the Ganges River (Bangladesh)	1.83	12.04.1762	NA	Bay of Bengal
2	---	---	1847	---	Great Nicobar Island
3.	Port Blair, Andaman Islands	4.00	19.08.1868	MW 7.5	Bay of Bengal
4.	Car Nicobar Island, Nicobar Islands	0.76	13.12.1881	MS 7.9	Car Nicobar Islands, Andaman Sea
5.	Dublat, India	0.30			
6.	Nagapattinam, India	1.22			
7.	Port Blair, Andaman Islands	1.22			
8.	Chennai	1.5 (wave height)	26.08.1883	Krakatao volcanic eruption	Islands of Java and Sumatra
9.	Andaman & Nicobar Islands	NA	26.06.1941	MW 7.7	Andaman Sea
10.	Mumbai, India	1.98	27.11.1945	MS 8.3	Arabian Sea
11.	Karachi, Pakistan	1.37			
12.	Ormara, Pakistan	13.00			
13.	Pasni, Pakistan	13.00			
14.	Victoria, Mahe Islands, Seychelles	0.30			
15.	Not felt in India	--	19.08.1977	MS 8.1	West of Sumba Island, Indonesia
16.	Cocos Island, Australia	0.30	18.06.2000	MS 7.8 MW 7.9	Arabian Sea

Source: (National Geophysical Data Centre 2005)
(www.ngdc.noaa.gov/nmdc/servlet/ShowDatasets)

Although the majority of the reported tsunamis are from littoral countries of the Pacific Ocean, there are a few cases of tsunamis in the Indian Ocean. The approximate length of the Indian coast is about 7600 kilometers. The coasts run from north to south and have two arms in the east and west with a tapering end at Kanyakumari. The tsunamigenic earthquakes occur mostly at the following three locations in the Indian Ocean:

(i) The Andaman sea,
(ii) Area about 400-500 kilometres SSW of Sri Lanka (Ceylon)
(iii) The Arabian Sea about 70-100 kilometres south of Pakistan Coast -- off Karachi and Baluchistan (2005)

(Source: http://palkbay.wikicities.com/wiki)

The oldest record of tsunami is available from November 326 BC earthquake near the Indus delta/Kutch region. Alexander the Great was returning to Greece after his conquest and wanted to go back by a sea route. But an earthquake of large magnitude destroyed the mighty Macedonian fleet (Lietzin, 1974). The earliest record of tsunami is reported to be about 1.5 meters at Chennai (formerly Madras) which was created due to the August 8, 1883 Krakatoa volcanic explosion in Indonesia. An earthquake of magnitude 8.25 occurred about 70 kilometers south of Karachi (Pakistan) at 24.5˚ N and 63.0˚ E on November 27, 1945. This created a large tsunami of about 11.0 to 11.5 meters high on the western coasts of India in the Kutch region. An earthquake of magnitude 8.1 occurred in the Andaman Sea at 12.9˚ N and 92.5˚ E on June 26, 1941 and a tsunami hit the east coast of India. As per non-scientific/journalistic sources, the height of the tsunami was of the order of 0.75 to 1.25 meters. At the time no tide gauge was in operation. Mathematical calculations suggest that the height could have been of the order of 1.0 meter. There are a few more cases of earthquakes of magnitude less than 8.0 that have given rise to some smaller tsunamis.(T.S. Murty 1999) has reported a few more earthquakes on the coast of Myanmar (formerly Burma).

1.5. The event of December 26, 2004

On December 26, 2004, an earthquake of magnitude 9.0 on Richter scale occurred off the west coast of Sumatra in the Indonesian Archipelago at 06:29 hrs IST (00:59 hrs GMT). The epicentre of the earthquake was located under seawater at 3.4N 95.7E. The earthquake occurred along the plate boundary marked by the subduction zone between the Indian plate and the Burmese microplate.(Navalgund 2005) The focal depth of the earthquake was 30 km. The earthquake, the biggest in four decades generated huge tsunami waves. It had a catastrophic impact on the life of the people and coastal ecosystem in Indonesia, Sri Lanka, Thailand, India and Somalia in the India Ocean. The Tsunami claimed more than 250,000 human lives in these countries. The aftershocks of this earthquake, numbering more than 250 in the magnitude range $5<M<7.3$, had a compounding effect on coastal communities and ecosystem. The earthquake of 26 December 2004 is not an unusual one from the Plate Tectonics point of view. It has occurred in the vicinity of seismically active zone, close to Sunda Trench in the water depths of about 1300m. The high magnitude, 9.0 of the earthquake and its shallower epicentre have triggered Tsunami in the northeast Indian Ocean.

Its impact on the Nagapattinam area had been catastrophic with around 6065 number of deaths in the area. The table below shows the death toll in the Nagapattinam district. This data is collected from the Nagapattinam Collectorate during the fieldwork in the month of August.

Table 2: Death Toll

S. No.	Category	Number of deaths	Percentage
1	Adult Male	1883	31%
2	Adult Female	2406	40%
3	Male Child	887	15%
4	Female Child	889	15%
	Total	6065	100%

Source: (Collectorate, Nagapattinam)

Table 3: Information on Nagapattinam and Tamil Nadu-Tsunami Impact

S. No.	Details	Tamil Nadu	Nagapattinam	Percentage
1	Loss of Life	8018	6065	76%
2	Missing	1126	791	70%
3	Unidentified	1764	1733	98%
4	Injured	3446	1922	56%
5	Persons Evacuated	4.7 lakhs	1.96 lakhs	42%
6	Loss of Livestock	17404	11983	69%

Source: (Collectorate, Nagapattinam)

1.6. Relevance of Study

The study has a lot of relevance after the aftermath of the 26 December 2004 tsunami event. There had been debates about as to how to prevent loss of human life and property in the national and International platforms. There has been active lobbying for constructing man-made defences like the sea walls to prevent such large-scale devastation. But such an alternative has a lot of implications taking into consideration the economy of various countries and the coastal communities interest. The natural defences like sand dunes, casuarinas and mangrove plantations are a potent resource, which can be utilized to minimize the loss of life and property in the coastal regions. The extent of inundation with will provide an insight into the damage to various landcover classes in the region. Since Nagapattinam is a backward area with agriculture and fishing the main source of livelihood in the region. It will provide information regarding the area that came under tsunami inundation and the loss in area of various landcover classes in the region. For the study, eight landcover classes that includes agriculture, saltpans, surface water bodies, wasteland, scrubs, settlements, other vegetative cover and mud flats are chosen to assess the damage to these classes due to tsunami inundation. The simulation will provide an idea of the mechanism of tsunami on the south-eastern coast that faced the fury on December 26 2004. The model simulation shows the initialisation of the tsunami due to various fault parameters like dip angle, slip angle, strike angle, length and width of the fault rupture. The sea bottom deformation resulting in sea surface perturbations, and bathymetry are vital inputs for the simulation. These have been incorporated in the numerical modeling of tsunami waves. This will be an input for the evacuation plans in case of an event like Tsunami. Thus, the study is relevant in the present context as well holds good in terms of its future prospects.

1.7. Problem Definition

On December 26, SE Asia was struck by an earthquake triggered Tsunami. As the Tsunami waves threaten all communities along the coast, it is imperative to assess the impact as well as the various measures that can be taken to safeguard against the Tsunami disaster. Even when the monitoring systems are in place, it is difficult to accurately predict the timing, impact as well as extent of inundation along the coastal areas (U.C.MOHANTY 2004). The inundation maps for the region is a vital input for the evacuation process to be carried out in case of a disaster, but the lack of data is a hindrance in effective relief work as well as management of the evacuation of the people.

A study pertaining to the impact of tsunami and its subsequently inundation along the coast with varied topography, bathymetry and natural barriers lends itself credibility (Chaiwut Sittibutra 2005). With the south-eastern coastline of India having all these features, this study will definitely ensure the impact of various coastal features on the extent of inundation. The Tsunami had an impact on the south-eastern coast of India but with varied coastal features along the shoreline, the extent of inundation was different at places.

Within the entire region, there are areas that are more vulnerable to Tsunami impact than others. The prime reason behind this was the various natural as well as artificial barriers that gave resistance to the incoming waves like nature of the shoreline, bathymetry, landuse practices and the natural cover e.g. the presence of mangroves, sand dunes, casuarina plantations. Various factors have worked as “nature’s defence” and areas which had these factors had survived better than areas which have been modified by aquaculture, urban development and tourism (TINTI 1997). This study will assess the impact on various landcover classes in the Nagapattinam region due to tsunami inundation. It will also mark the extent of inundation. Moreover, the simulation of wave propagation using Tunami N2 in a grid environment depends largely on the availability of various parameters. The use of remote sensing images and Field work are key elements to the Tsunami study along the south eastern coast of India (H.L.Davies 1998). Thus, a detailed study of the impact of the tsunami on the Nagapattinam coast of India is imperative to our understanding of the damage that took place on December 26, 2004 and plan for a systematic approach to minimize the loss of life and property in case of such a happening.

1.7.1. Research Objectives

- To map the extent of inundation for the Nagapattinam area with IRS P6 LISS III post-tsunami satellite image

- To assess the impact of the December 26 Tsunami waves to various landcover classes in the study area due to Tsunami inundation

- To simulate the propagation of tsunami waves using Tunami N2 numerical model for the south-eastern coast of India.

1.7.2. Research Questions

- What is the extent of inundation mapped from Post-tsunami IRS P6 LISS III satellite image for the Nagapattinam area?

- What is the effect of tsunami inundation on various landcover classes in the Nagapattinam area using Pre and Post IRS P6 LISS III and AWiFs satellite image?

- Which are the essential model parameters that play a vital role in the propagation of tsunami waves from the epicentre in Sumatra region to the south-eastern coast of India?

1.7.3. Expected Output

The output for the given study on Tsunami damage can be categorised into two aspects. The first part deals with the extent of inundation in the Nagapattinam area due to Tsunami and the damage due to inundation to various landcover classes. This is carried out using Pre and post tsunami satellite images of the Nagapattinam area. IRS 1D LISS III and AWiFs images with resolution of 23.5 and 56 m are used to map the extent of inundation, prepare a landcover map and generate a map for the damage to various landcover classes due to tsunami inundation. Another part deals with the simulation of the Tsunami waves along the south-eastern coast of India using Tunami N2. This simulation deals with the magnitude and location of the earthquake due to the tectonic setting of the plates, fault geometry, bathymetry of the ocean etc. The output for the model is to show the propagation of tsunami waves from the Sumatra region to the coast of India. The model is run for every 10 minute interval. Moreover, it will also give information regarding the amplification of tsunami waves. Here, the bathymetry of the ocean and the fault geometry play a vital role in the initialisation of the waves.

1.8. Tunami N2 model

The generation, propagation and amplification of Tsunami waves are modeled using Tsunami N2 software. Tunami N2 is authored by Fumihiko Imamura in Tahoku University, Japan, and developed in Middle East Technical University (METU) and in the University of Southern California. It is an outcome of UNESCO TIME Project. It is used for modeling wave propagation using the non-linear shallow water wave equations. The model has been used to simulate December 26 Tsunami and the computed maximum water surface elevations reached at each grid point and travel time curves during propagation of Tsunami in Indian Ocean have been calculated for the event. The outcome for result achieved is shown in the figure below:

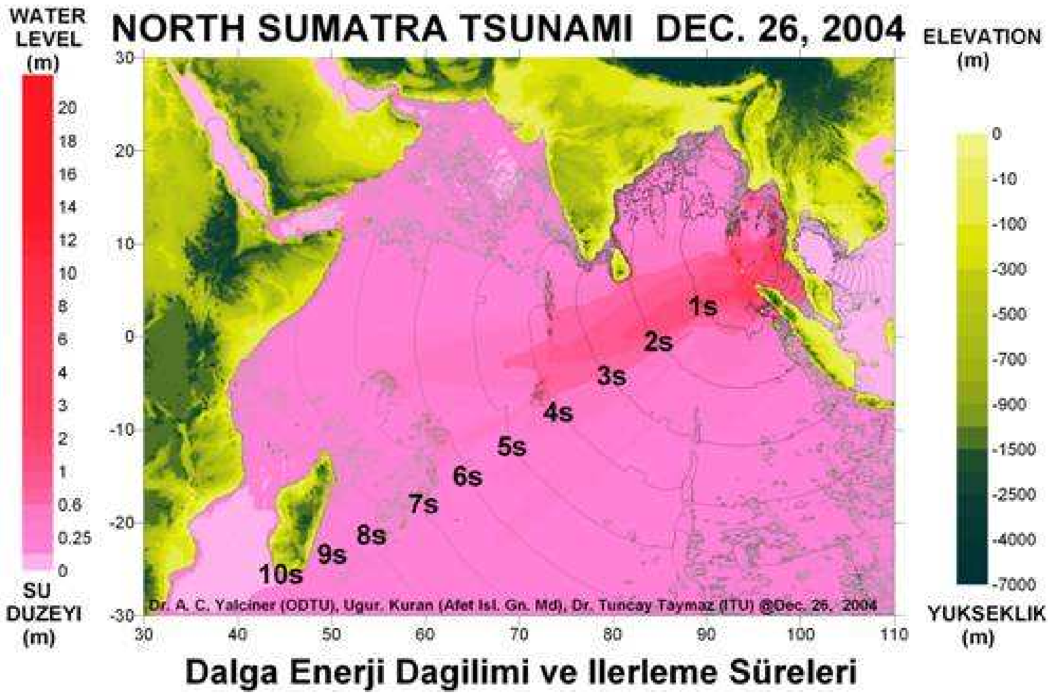

Figure 2: Computed maximum water surface elevation at each grid point using Tunami N2 model

Source: http://ioc.unesco.org/iosurveys/Indonesia/yalciner/yalciner3.htm

Various other models are also considered for the simulation of the tsunami waves of December 26, 2004. Princeton Ocean Model, MOST and Modular Ocean Model are reviewed for the simulation purpose. The model code for the Tunami N2 and Princeton Ocean Model were available in the institute. Tunami N2 is given preference over other models as it had been used often to simulate tsunami due to earthquake, volcanic eruptions and submarine landslides. It gave an insight into the working of the model.

1.9. Organisation of the Thesis

Chapter 1 is the Introduction of the Research work,

Chapter 2 deals with the Literature reviewed for the research in terms of Numerical Modeling of Tsunami in the Indian Ocean and the mapping of the extent of inundation.

Chapter 3 showcases the study area for the research work,

Chapter 4 elaborates the methodology for the image processing and numerical modeling; it also incorporates the fieldwork activities and the data collection phase,

Chapter 5 shows the results and analysis of the research work, and

Chapter 6 deals with the conclusions and recommendations for the research.

2. Literature Review

2.1. Tsunami waves

Tsunami waves are defined as surface gravity waves that occur in the ocean as the result of large-scale short term perturbations (underwater earthquakes, eruption of underwater volcanoes, landslides, rockfalls, pyroclastic avalanche from land volcanoes entered in water, asteroid impact, underwater explosions, etc) (Narcisse Zahibo 2005)

The characteristic parameters of Tsunamis' are: duration, length, propagation speed and heights. Tsunami waves of the seismic origin are usually very long (50-1000 km), for example the source of the December 2004 Tsunami in the Indian Ocean (magnitude 9.0-9.3) has approximated dimensions: length, 670 km; width, 150 km; and height, 12 m. (Narcisse Zahibo 2005)

Earthquakes of large magnitude generally above *M* 7.0, occurring in shallow depths of seabed fault zones, cause rapid and vertical displacement of sea water. This results in the generation of tsunamis. The tsunamis in turn generate a series of deep ocean waves that have larger wavelengths, greater amplitude, period and velocity compared to normal waves. These waves with tremendous energy propagate in the deep sea at a speed of 750–900 km/h. When they encounter shallow waters of islands and landmass, their velocity decreases but change in total energy of the tsunami remains constant. At locations like open coast beaches, bays and harbours, due to shoaling effect, the height of the waves increases causing rise in sea level even to an extent of 30 m at the coast. Thereafter, the seawater penetrates the coast with high speed and causes extensive inundation, which is called run-up. Run-up is usually expressed in meters above normal tide or mean sea level. Figure1 shows a schematic representation of different aspects of inundation, including measurement of maximum run-up height.

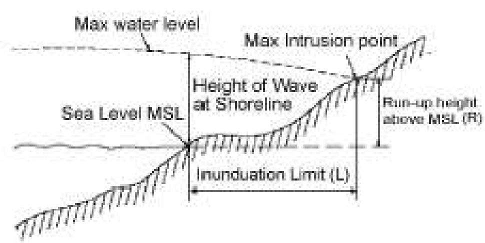

Figure 3: Schematic diagram showing measurement of run-up

Run-up values can be used for determining the extent of vulnerability of human settlement, in coastal villages or towns and therefore they are useful in coastal land use planning. Run-up levels from the same tsunami within a coast or island vary depending on the geomorphology (shape) of the coast and land cover in the coastal areas. Tsunami waves travel far inside the land through estuaries and backwaters. The Acaustic Tide Gauge (ATG) of the National Institute of Ocean Technology (NIOT), located inside the Port Blair bay (Chattam Island) which was set only for normal tidal variations could record the sea water level up to 3.5 m on 26 December 2004. This is about 2.5 m more than the normal tide level. Run-up measurements at different sites along the Andaman & Nicobar and Tamil Nadu coasts were made using Realtime Kinematic Global Positioning System (RTKGPS). All run-up measurement levels were corrected to tide and reduced to mean sea level. Locations where run-up level measurements were carried out are mentioned in Table 4.

Table 4: Run-up level of sea water during tsunami at selected locations in Andaman & Nicobar and Tamil Nadu coast

Location	Maximum run-up level (m)	Distance of sea water inundation inland (m)
Andaman and Nicobar Islands		
South Andaman (Port Blair)		
JNRM College, Aberdeen	2.9	130
Bamboo Flat	3.5	250
New Wandoor	3.7	215
Wandoor	3.9	215
Chidiyatopu	4.5	130
Sippighat (Creek)	2.0	2000
North Andaman		
Diglipur	1.5	100
Rangat	1.5	200
Little Andaman		
Hut Bay	5.0	1200
Car Nicobar		
Malacca	7.0	1000
Great Nicobar		
Campbell Bay (Central)	3.0	300
Campbell Bay (North)	6.0	50
Tamil Nadu Coast		
Nagapattinam (lighthouse transect)	3.9	750
Chennai (Besant Nagar)	2.8	200
Chennai (Kattupalli)	1.8	190
Chennai (Kalanji)	1.4	45
Sathankuppam (Pulicat)	3.5	80

In general the extent of vertical run-up of seawater during tsunamis depends on the earthquake parameters, geographical location, velocity of tsunami waves and their frequency, near-shore bathymetry, beach profile and land topography. Due to these parametric variations, the run-up levels and landward penetration characteristics of seawater were location-specific and varied within a location. Nagapattinam area is a low-lying area that makes the region more vulnerable to inundation of seawater during storms, tsunamis etc. Low-lying areas adjoining the creeks, which facilitate travel of tsunami waves far inland, are also vulnerable.
The run-up distances of seawater during tsunamis are as a result of combination of various factors. Even though the inundation of sea water is greater where the beach/land-slope is gentle, the run-up distances can also vary among the gentle land-slope areas wherever they are traversed by streets and houses of different density.(M.V.Ramanamurthy 2005).

The problem of tsunami risk is very complex and should include in its gamut human, economic, ecological, and social as well as technical factors. The statistical approach with the mathematical concepts of probability is applicable to the occurrence of natural hazards such as tsunamis. Although the actual distribution of tsunamis is not known, it appears to follow a Poisson distribution. The main characteristic of this distribution is an exceedance (cumulative) frequency of events; from the mathematical theory of extreme statistics, it is known that the cumulative frequency has to be a power function of Tsunami runup height.(George D. Curtis 1999)

2.2. The Great Sumatra Earthquake of 26 December 2004

The 26 December 2004 Sumatra-Andaman earthquake was the largest seismic event on Earth in more than 40 years, the third most fatal earthquake ever. It released 4.3*10∧18 J, equivalent to a 100-gigaton bomb.(Bilham 2005) These giant earthquakes occur where large oceanic plates underthrust continental margins. They involve huge fault areas, typically 200 km wide by 1000 km long, and large fault slips of 10 m or more. Such events dwarf the contributions to plate motion of vast numbers of lower magnitude earthquakes. The death toll associated with the tsunami is due to the dense population of the affected areas.

2.2.1. Plate Geometry and Setting

The earthquake of December 26, 2004 ruptured the boundary between the Indo-Australian plate, which generally moves northward at 40 to 50 mm/year, and the south-eastern portion of the Eurasian plate, which is segmented into the Burma and Sunda subplates. The plate boundary from the East of the Himalayas trends southward through Myanmar, continuing offshore as a subduction zone along the Andaman and Nicobar Islands south to Sumatra. From this location, it turns eastward along the Java trench. A plate silver, referred to as the Andaman or Burma microplate, has sheered off parallel to the subduction zone from Myanmar to Sumatra. This is because of the highly oblique motion between the Indo-Australian plate and the Burma subplates. Oblique, but predominantly thrust, motion occurs in the Andaman trench with a convergence rate of about 14 mm/year. The Andaman Sea ridge-transform system, an oblique back-arc spreading center, accommodates the remaining plate motion, joining with the Sumatra Fault to the south. Underthrusting along the Sunda trench, with some right-lateral faulting on the inland Sumatra Fault, accommodates interplate motion along Sumatra.

2.2.2. The mainshocks

The 2004 mainshock rupture began at 3.4N 95.7E at a depth of about 30 km, at 00:59 hrs GMT. The Harvard centroid-moment-tensor (CMT) solution indicates predominantly thrust faulting on a shallowly (8°) dipping plane with a strike angle of 329°. The rake angle (110°) indicates a slip direction ~ 20° closer to the trench-normal direction than to the interplate convergence direction, consistent with some long-term partitioning of right-lateral motion onto the Sumatra Fault.

2.2.3. Aftershock geometry

The most notable aftershock feature for the 26 December 2004 tsunami event is a swarm of strike-slip and normal faulting events in the Andaman Sea back-arc basin involving more than 150 magnitude 5 and greater earthquakes that occurred from 27 to 30 January 2005. This has been the most energetic swarm ever observed globally, though previous swarms of events have occurred in this region.

Although aftershock mechanism variability and uncertainty in the location makes it difficult to constrain the fault geometry, the megathrust appears to be about 240 km wide along northwestern Sumatra, extending to a depth of about 45 km. The thrust plane appears to be no more than 160 to 170 km wide, extending to a depth of about 30 km along the Andaman and Nicobar Islands.

2.2.4. Magnitude, source strength and energy

The Harvard CMT solution for the 2004 earthquake, based on global Federation of Seismic Digital Networks (FSDN) recordings of 300~s to 500~s period surface waves, has a seismic moment M (o) = 4.0*10∧22 Nm that is comparable to the cumulative seismic moment for all the earthquake of the preceding decade. This moment yields M (w) = 9.0, the seismic magnitude for the earthquake. Uniform slip of about 5.0 m over a 1300-km long fault varying in width from 240 to 160 km with rigidity μ = 3.0 * 10∧10 N/m∧2 would account for the CMT seismic moment estimate. For an assumption of uniform faulting geometry, the strength of the seismic waves excitation for periods great than 500 s was enhanced by a factor of 1.5 to 2.5 compared with that at 300 s. the moment magnitude for the Sumatra earthquake may thus be greater than 9.0 by 0.1 to 0.3 units.

The energy radiated by seismic waves E (r) is an important macroscopic seismic parameter, because the amount of potential energy partitioned to E (r) reflects the physical process of the source. The E (r) for the 2004 earthquake has been estimated to be 1.1*10 ∧ 18 J from P waves at 11 stations over a distance range of 45° to 95°.(Thorne Lay 2005)

2.3. Lethal Combination

A lethal combination of huge magnitude and shallow depth led to high vertical displacement of the Burma plate that acted like a great piston deforming the sea. The aftershocks in the Burma plate went further to fracture and move the Burma plate boundary by 1000 km. The U.S. Geological Survey has called this event a mega thrust earthquake referring to the large cracking of the plate boundary. According to them, mega thrust earthquakes often generate large tsunamis that can cause damage over a much wider area than is directly affected by ground shaking near the earthquake's rupture.

Shallow focus earthquakes measuring 6.5 can also cause tsunamis, but these will die after some distance. The vast expanse of the Indian Ocean posed little challenge to the movement of the killer tsunami. Since a large amount of pent-up energy in the compression zones along the plate boundaries has been released in the earthquake of 26 December 2004, it will take years for another incident of the sea magnitude to recur.(Department of Ocean Development 2005)

2.4. Source: Seismic Dislocation

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2.5. Numerical Modeling of Tsunamis

Tsunami models are often based on the shallow water equations, both in linear and non-linear approximation, that are usually solved numerically by means of finite difference or finite-elements methods. Moreover, Finite element methods are one of the most powerful numerical approaches to compute the evolution of tsunami waves over basins of any shape.(A. Piatanesi 1996). For the modeling of tsunami generation, we assume that the seismic deformation on the sea floor pushes up the overlying water instantaneously that is the feature for the sea bottom deformation reflecting the initial water surface elevation.(Shunichi Koshimura 2001) Various models have bee used to model the tsunami waves. Tsunami Inundation Mapping efforts (TIME) monitors advances in tsunami modeling and incorporates improved technology into its mapping efforts. Numerical modelling efforts in Indonesia by Hamzah Latief were carried out after the tsunami of December 26, 2004 under the Tsunami Research Group Marine Research Center ITB and the tsunami simulation was uploaded on 1st January 2005. (Latief 2005)

2.5.1. Finite Difference and Finite Element Models

The MOST (Method of Splitting Tsunami) model developed by Titov of PMEL and Synolakis of University of Southern California uses a finite difference model to divide its computational domain. The MOST model is currently being used to develop inundation maps in California and Washington. The ADCIRC model utilizes a finite element method to divide its computational domain. The ADCIRC model is currently being used by the Oregon Graduate Institute to develop inundation maps.(2005)
Source: (http://www.pmel.noaa.gov/tsunami/time/background/models.shtml)

2.5.2. Tunami N2 Model

The Numerical simulation of Tsunami waves in the framework of the 2D hyperbolic system is widely relevant in the tsunami practice, and the various numerical codes are applied to determine tsunami characteristics. One of them is TUNAMI developed in Tohuko University (Japan) and provided through the Tsunami Inundation Modeling Exchange (TIME) program. This model is often used to simulate real events; in particular, authors applied it to study the tsunami events in Mediterranean, Caribbean and Black Seas. Taking into account that the characteristic wavelength exceeds the water depth, the popular models to describe the tsunami propagation are based on the various approximations of the shallow-water system . The Earth sphericity and rotation are essential for tsunami waves in the open ocean, and here the shallow water system becomes

$$\frac{\partial M}{\partial t} + \frac{gh}{R\cos\theta}\frac{\partial \eta}{\partial \varphi} = fN, \quad \frac{\partial N}{\partial t} + \frac{gh}{R}\frac{\partial \eta}{\partial \theta} = -fM,$$
$$\frac{\partial \eta}{\partial t} + \frac{1}{R\cos\theta}\left[\frac{\partial M}{\partial \varphi} + \frac{\partial}{\partial \theta}(N\cos\theta)\right] = 0,$$

where θ and φ are latitude and longitude, R is the radius of the Earth, f is the Corilolis parameter, M and N are discharge fluxes along the latitude and longitude, h (x, y) is the unperturbed basin depth.
The non-linear shallow-water system is an effective tool to compute the propagation and run-up of tsunami waves. In most of the cases, numerical simulation of the tsunami propagation from the source is performed for relative large depths (more 10-20 m) and non-linear effects are not manifested for such depths. The reproducing of the non-linear effects in tsunami wave fields require high resolution bathymetric maps and long computations. This is the primary reason that the non-linear theory of water waves is applied mainly to describe the run-up stage, but not the tsunami propagation. (Narcisse

Zahibo 2005). Moreover, the numerical simulation exercise rests on the reliability of data obtained. The International Oceanographic Commission of UNESCO in a guide has summarized these experiences. One of the problems with organization of field surveys is the choice of coastal locations for which the tsunami runup heights measurements should be made.(Byung Ho Choi 2002). Another prime concern is the identification of the sources of the earthquakes that generate tsunamis is a difficult task and that the joint collaboration of various disciplines such as geology, seismology and tsunami modeling is needed in order to get some focus on the solutions to the imposing problems. But sometimes an interdisciplinary approach is unsuccessful and is unable to lead us to unambiguous results.(Stefano Tinti 2003).

Various tsunami investigations have a major role in determining the location and focal parameters of the tsunamigenic earthquakes. Since broadband seismic stations are fewer in number in the global arena, the tsunami data is insufficiently covered. An example in seismology of the tsunami data is provided by the so-called tsunami earthquakes whose occurrence was first recognized by Kanamori (1972). (Stefano Tinti 1996)

2.6. Princeton Ocean Model

Princeton Ocean Model (POM) is a sigma coordinate, free surface, primitive equation ocean model, which includes a turbulence sub-model. It was developed in the late 1970's by Blumberg and Mellor. The model has been used for modeling of estuaries, coastal regions and open oceans. The model has been used for modeling of estuaries, coastal regions and open oceans.

2.6.1. Attributes of the model

The principal attributes of the Princeton Ocean model are as follows:

- It contains an imbedded second moment turbulence closure sub-model to provide vertical mixing coefficients.
- It is a sigma coordinate model in that the vertical coordinate is scaled on the water column depth.
- The horizontal grid uses curvilinear orthogonal coordinates and an "Arakawa C" differencing scheme.
- The horizontal time differencing is explicit whereas the vertical differencing is implicit. The latter eliminates time constraints for the vertical coordinate and permits the use of fine vertical resolution in the surface and bottom boundary layers.
- The model has a free surface and a split time step. The external mode portion of the model is two-dimensional and uses a short time step based on the CFL condition and the external wave speed. The internal mode is three-dimensional and uses a long time step based on the CFL condition and the internal wave speed.
- Complete thermodynamics have been implemented.

3. Study Area

3.1. General Introduction

Nagapattinam is situated in the middle of the Cauvery delta, a lowland area below sea level in parts and extending far inland. The area has been vulnerable to coastal flooding due to the gentle slope of coastal land. Moreover, the effect of Tsunami wave diffraction caused by the Northern tip of Sri Lanka, presence of creeks like Vedaranyam Canal facilitated the seawater inundation up to 2.2 km inland. It had been severely hit by the Tsunami waves due to which more than 6065 people lost their lives in Tamil Nadu, and Nagapattinam was the worst hit accounting for 1700 deaths as on 27.01.2005 (Source: http://nagapattinam.nic.in). The area of study to map the extent of inundation and assess the damage to various Landcover classes has been done for the Nagapattinam taluk while the modeling of tsunami waves has been carried out for the south-eastern coast of India using Tunami N2 and Princeton Ocean Model. India has an extensive coastline of nearly 7,600 km. The state of Tamil Nadu has a coastline of 950 km and has different varieties of coastal habitats like coral reefs, mangroves, sea weeds and sea grass beds, salt marshes, sand dunes, ports and fishing harbours. The state of Tamil Nadu has the geographical extent of 1,30,058 kms and has a population of 62,110,839 (Census 2001). There are 13 coastal districts with a population of 2,03,77,522. The creeks are comparatively less in Tamil Nadu coast and are dynamically changing due to seasonal variations. The Cuddalore coast in Tamil Nadu has sandy beach in the northern part while the southern part is covered by swamps and mangrove forests (Hindu 2005)

3.2. Historical Significance

Nagapattinam is a unique District with all its historical and cultural significance. Nagapattinam is one of the constituents of Chola Mandalam, acclaimed as the most prominent among the ancient Tamil Kingdoms. Its salient features have contributed to the glory of the Cholamandalam. Coastal town Nagapattinam was the headquarters of a region during the Chola period. This region has been named after Kshathiriya sigamani. One of the titles of Raja Raja Cholan. Nagapattinam was also known as ‘Cholakula Vallippatinam’. It is as early as 3rd century B.C. that the accounts of the town are found in the Burmese historical text of the period. The same text gives evidences of a Budha Vihar built by the great Ashoka, which finds mention in the book by Chinese traveller Hieun Tsang. In ancient Buddhist literature, Nagapattinam is mentioned as Padarithitha. According to scholars, avurithidal the name of the part of Nagapattinam might have been derived from the word ‘’Padarithitha” which is the name of the fruit tree “Bhirtree” very common in this region.

In 1658, the Dutch tried to evict the Portugese town Nagapattinam to establish the commercial centre there under the agreement reached between King Vijaya Nayakkar of Thanjavoor and the Dutch on 05-01-1662. The following ten villages namely Nagapattinam Port; Puthur; Muttam, Poruvalancheri, Anthonippettai, Karureppankadu, AzhingiMangalam, Sangamangalam, Thiruthinamangalam, Manjakollai, Nariyankudi were transferred from the Portugese to the Dutch.

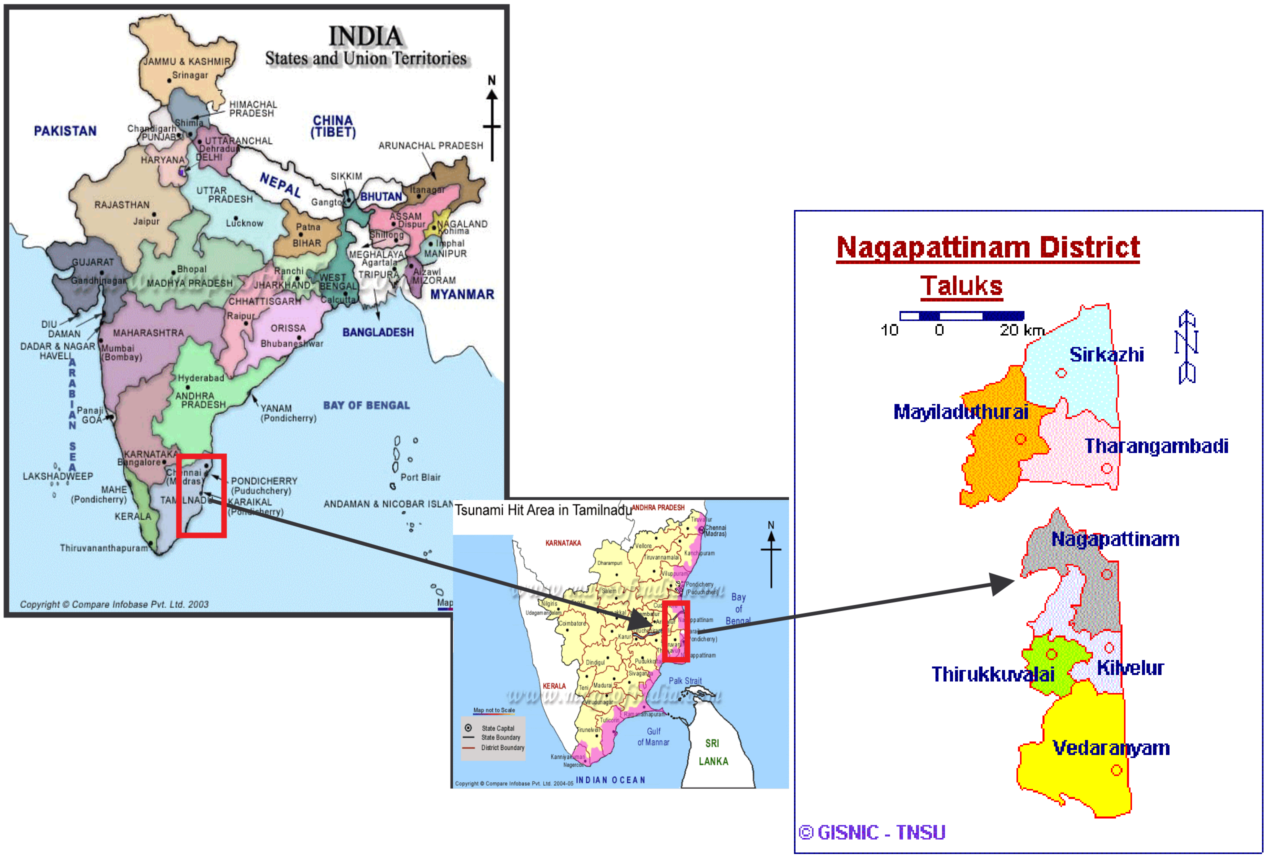


Figure 4: Study area: Nagapattinam

(Source : Maps of India www.mapsofindia.org)

3.3. District History

Nagapattinam district, the land of communal harmony, was carved out by bifurcating the composite Thanjavur district on 18.10.1991. This district has traditionally been referred to as East Thanjavur and Paddy granary of South India Nagapattinam District lies on the shores of the Bay of Bengal between North Latitude 10°10'N and 11°20’N East Longitude 79°15' E and 79°50'E. This is peninsular delta District surrounded by Bay of Bengal on the East, Palk Strait on the South and land on the West and Northern Side. This District is predominantly, a Coastal District having a large coastline of 141 kilometers. This District has a numerous places of historical importance. Nagapattinam is an old Port Town. This District is having an area of 2715.83 sq. km in its fold. The District Headquarters is Nagapattinam. This district is enveloping 11 Panchayat Unions, 3 Municipalties, 9 Town Panchayats on its Development Side. On the Revenue Side, it is housing 2 Revenue divisions with 4 and 3 Taluks respectively and 523 revenue Villages.

3.4. Coastal Regulation Zone of Nagapattinam District

3.4.1. Geographical Location

This coastal zone starts north of Kolidam river and ends with east of Atirampattinam. Geographically, it lies between 79º37'30"- 79º50'12"E longitude and 10º15'-11º12'46" N latitude.

3.4.2. Physiography

The stretch consists of a narrow region of sandy beach along the coast in the delta region of the Cauvery river. There are Salt pans as well as permanent Vedaranyam swamp region with mangrove forest.

3.4.3. Geology and Geomorphology

The coastal sands of recent age overlie the tertiary rocks. The geomorphologic features observed in this area are sub aerial delta, strand plain, crevasses, chennies, cuspate bars, estuarine and swamps. Their distributory flood basins comprising brown and reddish gray silty clay and fine sands cover the large part of the delta. South bound long shore currents from the Kollidam river mouth to Point Calimere straighten the coastline of Nagapattinam.

3.4.4. Distribution of Coastal Regulation Zone

The different coastal regulation zone of the Nagapattinam district are presented in Table 5

Table 5: Coastal Regulation Zone of Nagapattinam

CRZ-I Sq. km	CRZ-II Sq. km	CRZ-III Sq. km	LTL km	HTL km	100 line km	200 line km	500 line km
27.74	5.07	35.64	203	256.18	Nil	51.94	126.06

The Coastal Regulation Zone has been established to create an Information system for effective management of the Coastal zone of Tamil Nadu.(2005)
(URL: **http://www.annauniv.edu/iom/Nagapattinam.htm**)

3.5. Impact of December 26, 2004 tsunami waves on Nagapattinam

One of the critical factors that led to massive devastation in the area of Nagapattinam is the topography of the area. The situation in Nagapattinam was compounded by a combination of features on the entire profile of the area. The narrow beach, shallowness of the continental shelf, the absence of sand dunes and the near flat-shore all acted against the coastal town of Nagapattinam, which is one of the most backward areas in the state of Tamil Nadu. It was because of the presence of these features that the amplitude of the waves increased and resulted in unprecedented devastation. When waves were in deeper water, there velocity was more but as they approached shallower water, their velocity got reduced but the amplitude went up. As the coastal belt of Tamil Nadu was more or less perpendicular to the epicenter of the earthquake of December 26, the seismic ocean waves travelled towards the coast but the presence of Sri Lanka disturbed their course. (Ramakrishnan 2005)

4. Materials and Methods

In the present study on the December 26 Tsunami event in the Indian Ocean, Remote Sensing and Geographic Information System (GIS) techniques have been applied to obtain landcover estimates of the Nagapattinam area. Satellite images and ancillary data have been obtained from various sources to carry out the study. Collection of data for the study is a vital aspect in any research. Methodology has been illustrated for inundation extent due to tsunami, damage assessment to various landcover classes in the region and modeling the tsunami event of December 26, 2004 with Tunami N2 model. In this chapter, the methodology for inundation extent mapping and damage assessment for landcover classes is discussed first and then the methodology for Tunami N2 modeling is discussed.

4.1. Collection of data

This study deals on one hand with the mapping of the extent of inundation for the Nagapattinam area and assessment of the damage to various landcover classes in the region due to tsunami. On the other it encompasses the numerical modeling of tsunami waves with Tunami N2 model. Thus, data collection was an intrinsic part to the study in all its dimensions. The foremost part was the satellite images of the Nagapattinam area. Pre-Tsunami and Post-Tsunami imageries were required to generate landcover map and affected area map of the Nagapattinam region. Mapping the extent of inundation was done using Post-tsunami satellite image. Topographic maps of the region obtained from Survey of India (SOI) at 1:50000 were used to georeference the images. These satellite images were obtained for the study:

Table 6: Satellite Data for the study

S. No.	Satellite image	Spatial Resolution (m)	Date of Acquisition
1	IRS-P6 LISS III (Pre-tsunami)	23.5	15 August 2004
2	IRS-P6 AWiFS (Pre-tsunami)	56	18 December 2004
3	IRS-P6 LISS III (Post-tsunami)	23.5	05 January 2005
4	IRS-P6 AwiFS (Post-tsunami)	56	28 December 2004
5	ASTER (Post-tsunami)	15 - 90	27 January 2004

The IRS P6 LISS III and AWiFS Post and Pre tsunami satellite images were obtained from National Remote Sensing Agency, Hyderabad. ASTER image Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) post-tsunami image was procured from Anna University, Chennai. Though the ASTER image could not be used for mapping the extent of inundation because the satellite image had dense clouds over the maximum part of the Nagapattinam area. IRS P6 LISS III satellite image with a spatial resolution is appropriate to map the extent of inundation and preparation of landcover maps from pre-tsunami image. In addition to the satellite images, various ancillary data is collected for the study. The ancillary data is shown in Table 7. The topographical maps for the study area at a scale of 1:50000 are obtained from Survey of India. Bathymetry data for the numerical modeling part of the study is a vital input. ETOPO 5 bathymetry is obtained from NOAA's National Geophysical Data Center (NGDC). Moreover, to incorporate near-shore bathymetry of the region, National Hydrographic Charts were obtained from NHO, Dehradun. The bathymetry data available for the region is at 5-minute interval. Data pertaining to the inundation extent and run-up is collected from National Institute of Oceanography, Goa. This data is used for the validation of the numerical model output. Population data for the Nagapattinam region is obtained from the Census of India website. The census for the population count is held in a decade and is available at the census website. Since Nagapattinam region is prone to cyclones, various studies have been carried out on the region that gives information regarding the nature of the shoreline and other shoreline features like plantations, sand dunes, creeks, etc. Socioeconomic data is collected from the Collectorate in Nagapattinam. This is collected to get an idea of the amount of damage in terms of life and property that had taken place in the region. The data also gave an insight into the reconstruction activities in the region, and other measures taken by the government and non-government organisations.

Table 7: Ancillary data for the study

S. No.	Ancillary data	Source
1	Topographical Maps (1:50000)	Survey of India
2	Bathymetry data	NOAA's NGDC site (ETOPO-5) and NHO, Dehradun (Near-shore bathymetry)
3	Inundation Extent and Run-up	NIO, Goa
4	Population data	Census 2001
5	Shoreline features	Literature and Field visit
6	Socioeconomic data	Collectorate, Nagapattinam

The fault data used to compute the tsunami source for simulation are given in Table 8.

Table 8 : Fault data

S.No.	Fault data	
1	Epicenter Eastern coordinate	93.13° N
2	Epicenter Northern coordinate	03.70° E
3	Fault Length	443 km
4	Fault Width	170 km
5	Strike angle	329°
6	Slip angle	110°
7	Dip angle	8°

Source: The IOC/UNESCO Indian Ocean Tsunami Post Tsunami Field Survey Site(2005)

The data pertaining to the fault is an essential requirement for the numerical modeling of tsunami waves. Fault geometry is created using the data listed above in Table 8. The data forms the base of the modeling as it is used in the initialisation of the conditions for the propagation of the tsunami waves. The given data set is obtained from the IOC/UNESCO Post Tsunami Field survey site and is used for modeling the event of December 26, 2004 using Tunami N2 model. The fault length and width give information regarding the area of the rupture and these are used to compute the surface perturbation at the epicentre due to the sea bottom deformation.

4.2. Field Survey

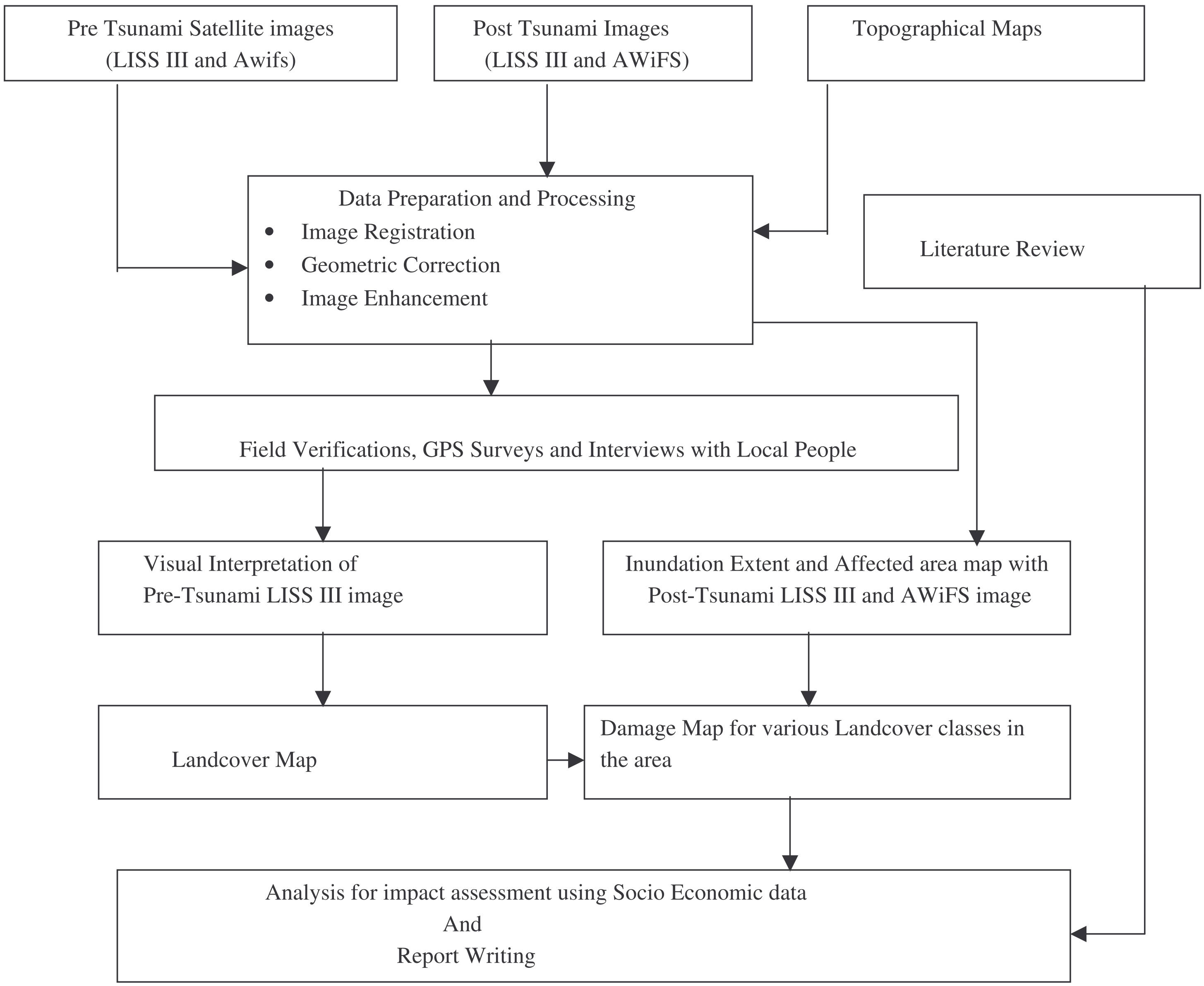
Field survey is an essential component in a study related to the hazards of tsunami. It also gives an insight into the problem and addresses varied concerns. The fieldwork was done from 6th August to 12th August 2005. The fieldwork included GPS surveys along the entire coastal stretch from Nagapattinam to Point Calimere, interviews using a questionnaire, field pictures and video, and data collection from the Nagapattinam Collectorate. The fieldwork was carried out in accordance with IOC/UNESCO guidelines for Post-Tsunami Field Survey Manual. Data had to be collected in terms of GPS points in the area, collection of socio-economic data like the number of deaths in the villages of Nagapattinam. The field visit gave insights regarding the inundation extent and the obstacles that came across people when the tsunami wave approached them. It also gave information regarding the enormity of damage for houses near the coast. Watermarks present in some areas that gave information regarding the inundation extent of tsunami waves in the region. It is validated with the data collected from the survey that was conducted immediately after the tsunami event. The questionnaire is prepared using the format used in the manual and interviews were taken with different sections of society. They included family members of the victims, fisherman, village people and other eyewitnesses of the event. The questionnaire used to interview the coastal community during the fieldwork is shown in Appendix 2.

A visit to Indian Institute of Technology (IIT), Kanpur was made to get an idea of the numerical simulation. Various research papers were collected from IIT on the various techniques that have been used in the simulation of tsunami event. Papers from an International Conference on Tsunamis held in February 2005 at Chennai gave vital insights into the progress that has been made in the domain of numerical simulation. The list of collected relevant literature on tsunami modeling is given in the references. Visit to saltpans in the area provided information regarding the damage that was caused to them due to the tsunami waves. Construction activities for the people who were displaced and were staying in temporary shelters are shown in the field photograph. One noticeable feature during the visit was the effort of non-government organisations in the area for rehabilitation and relief.

Some field photographs of the area are given in Appendix 1.

4.3. Flowchart of Methodology: Inundation Extent and Damage

Flowchart of methodology: Tsunami Inundation



4.4. Data Processing

Raw satellite images of the given area had to be pre-processed. Satellite images contain geometric distortions that make them unsuitable for standard map projection that is a prerequisite for perfect registration. This distortion is due to variability in altitude, velocity of sensor platform, curvature and rotation of the earth. Geometric and Radiometric correction are applied to correct for these distortions and produce an image with geometric integrity of the map. Hence, geometric and radiometric correction play a vital role during the pre-processing stage of the image for further analysis of satellite data.

The satellite images are georefernced with respect to the toposheets of the area. For the purpose of classification, IRS P6 LISS III Pre-tsunami satellite image is used, while for the extent of inundation, the post-tsunami IRS P6 LISS III and AWiFS satellite images are used. The rectification procedure consists of determining locations on the raw image, to which coordinate values are assigned. It involves identification of the features on the image for which real world coordinates are known to some degree of confidence. The points on the image, to which the coordinate values are assigned, are referred to as Ground Control Points (GCP's). In case of satellite images for the Nagapattinam area, topographic maps were already available from Survey of India. By tagging coordinate values to the features on the image, a "geometry" for those points in the image is established. Running the rectification process produces a new image on which the pixel values of the raw image are arranged to fit the geometry dictated by the GCP's. The image was rectified by selecting 20 ground control points uniformly distributed over the entire study area using second order polynomial equations and nearest neighbor resampling technique to limit the root mean square (rms) error within the permissible limit of 0.5. The rectification applied on the image resulted in a root mean square (rms) error of 0.03 pixels. The rectified georefereneced image is used for visual interpretation to prepare a landcover map and Tsunami affected map of the Nagapattinam region.
(Source: http://www.geoplan.ufl.edu/classes/urp6905/page.htm)

Image interpretation is an analogue classification of an image by the interpreter. As the human eye is incapable of observing light outside the visible spectrum, false colors are used to visualize reflection in the infrared light spectrum. The elements of image interpretation i.e. tone/color, size, shape, shadow, texture, pattern, location and association are regarded as being of general significance irrespective of the precise nature of the imagery. The classification scheme is generated and the entire study area is classified into eight landcover classes by visual image processing using the elements of image interpretation.

Visual Interpretation is the technique adopted for generation of landcover map from the georeferenced pre-tsunami satellite data. Applying different band combinations, areas affected by tsunami are visually interpreted and screen digitization is carried to extract the inundation extent map from post-tsunami satellite data. An effective, visual interpretation of satellite imagery, comparing the spectral characteristics of various land features in multiple bands of the available satellite data will provide better separation or contrast between various landcover classes.

In the present tsunami study to map the extent of inundation and damage to various landcover classes in the Nagapattinam area, various possible band combinations viz. True color composite (321), Near Infrared (432) are attempted to distinguish and identify various classes in the region from pre-tsunami and post-tsunami satellite imagery. Eight classes have been chosen to prepare the landcover map of the Nagapattinam area. The classes are chosen on the basis of landcover present in the Nagapattinam region. Since the area is a backward region and the primary occupation of the people is agriculture. The impact on agriculture needs to be ascertained in the region. The presence of Vedaranyam canal in the area brought seawater and inundated the agricultural fields and saltpans in the region. In the present study, a Clipping technique is applied wherein the pre-tsunami landcover map is clipped with that of post-tsunami inundation map. The technique will extract the change in landcover affected by

Tsunami in the Nagapattinam region. The pre-tsunami landcover map is selected and the inundation extent map is used as the input for clipping the data set. The operation gives the resultant map showing the inundation extent area with all the landcover areas that are present in the inundation extent map.

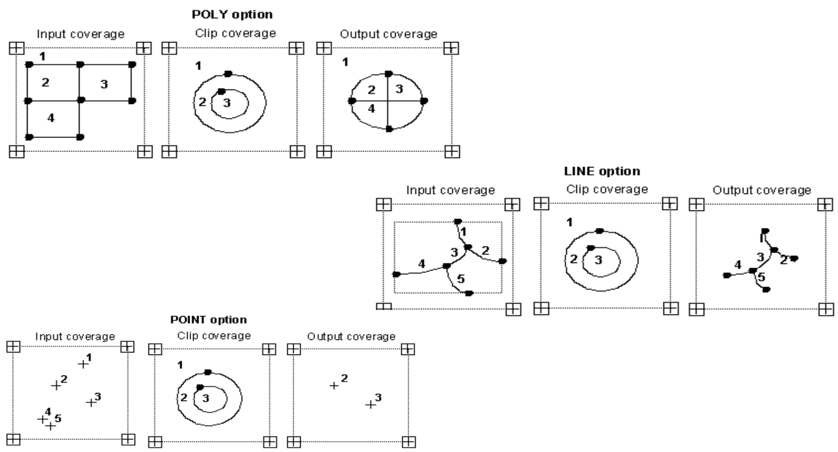
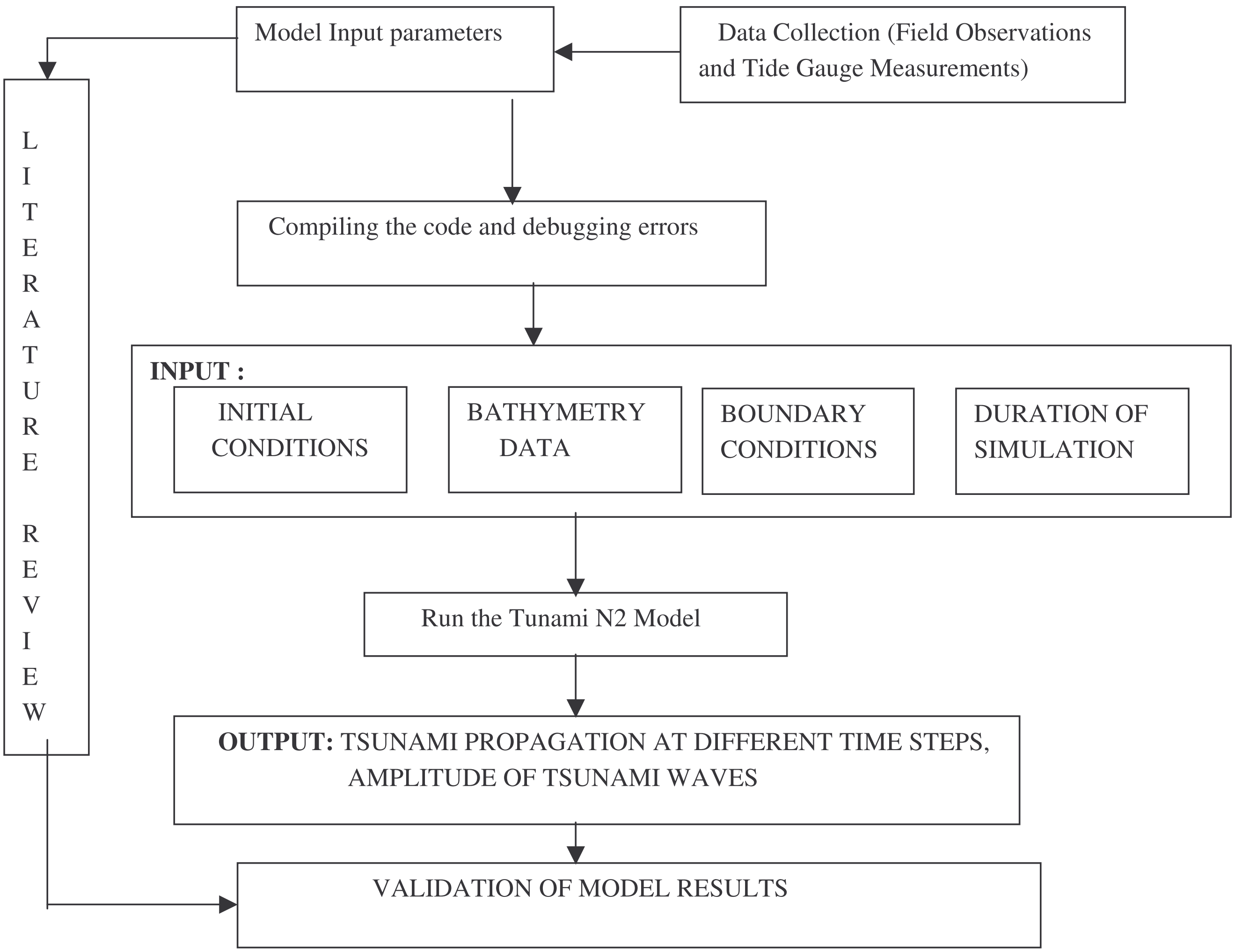


Figure 5: Clipping Technique

(Source: ArcGIS User Manual)

The Change detection technique employed gives the percentage change in all the landcover classes due to tsunami inundation for the event of December 26 2004 in the Nagapattinam region. The analysis carried out after change detection for the Nagapattinam area incorporates socio-economic data collected during the field visit from the Collectorate in Nagapattinam. Though with the non-availability of village boundary map for the Nagapattinam taluk, a GIS approach to show the database of every village in the analysis phase with the socio-economic data could not be carried out.

4.5. Flowchart for Numerical Modeling



4.6. Numerical simulation of December 26, 2004 tsunami event

The Tsunami event of December 26, 2004 has been modeled with TUNAMI N2 model. The shallow-water wave equations are used to describe the propagation of tsunami waves. For the study of tsunami generation, the most adequate mathematical model is the solution of a closed system of equations of the dynamic theory of elasticity, describing the oscillations of layered elastic half-space (the model of the Earth crust and the upper mantle) coupled with an overlying compressed liquid layer (the model of the ocean). There are two underlying solutions to the problem of tsunami generation. They are:

a) Determination of static bottom deformation due to a buried seismic source, and

b) Calculation of tsunami propagation within the framework of the long wave theory in an ocean with the variable using the solution obtained at first stage as the initial condition for the tsunami generation.(Viacheslav K.Gusiakov)

This approach is widely applied in the numerical modeling when parameters of seismic sources are known. The figure below shows the Sumatra subduction zone:

Figure 6: Base Map of the Sumatra Subduction Zone (USGS 2005)

(walrus.wr.usgs.gov/.../ sumatraEQ/tectonic.html)

4.6.1. Shallow Water wave equations

Tsunamis are very long gravity waves (i.e., many tens to hundreds of kilometers), propagation is described using depth-averaged, hydrostatic, shallow-water wave equations:

$\partial (\eta + h) / \partial t + \nabla . [\mathbf{v} (\eta + h)] = 0$ ……………..Continuity Equation

$\partial \mathbf{v} / \partial t + (\mathbf{v} . \nabla) \mathbf{v} + g \nabla\eta = 0$ ……………..Momentum equation

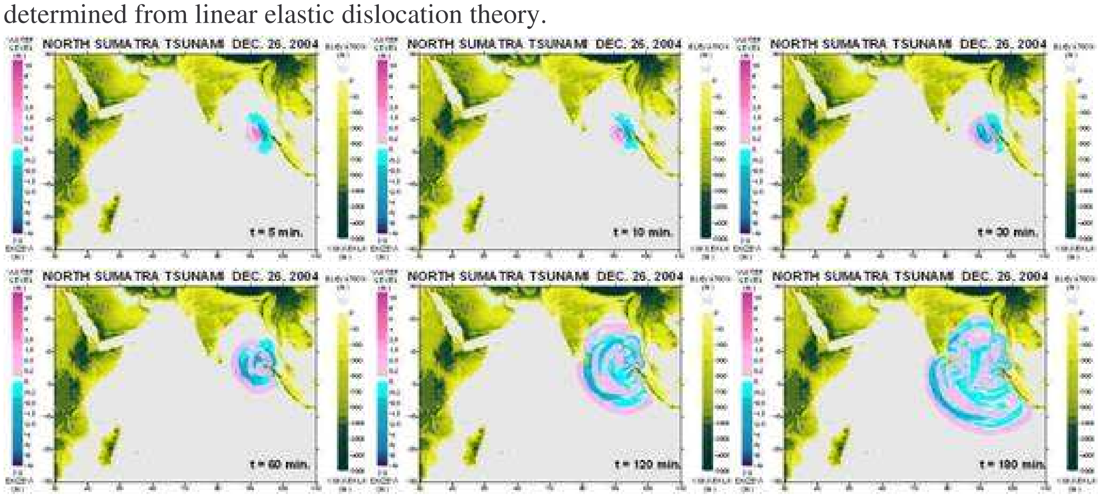
(Source: Geist, E. L. (1998). "Local tsunamis and earthquake source parameters." Advances in Geophysics **39**: 117-209.)

where $\mathbf{v}$ = v (i) and (i = 1,2) are the depth-averaged components of horizontal velocity, η and h are the water surface elevation and water depth relative to a reference state, respectively, and g is the gravitational acceleration.

4.6.2. Co-seismic surface deformation and numerical modelling

Tsunami propagation code TUNAMI N2 developed at Tohoku University, Tokyo, Japan is chosen for numerical modeling of tsunami waves. In this model, sets of non-linear shallow water equations with bottom friction are discretized by the leap-frog finite difference scheme. This technique is applied because it is difficult to solve the governing non-linear equations analytically. However, a finite difference scheme using a staggered leap-frog scheme provides a numerical simulation.(Monzur Alam Imteaz and Imamura 2001)

The model is widely used to simulate tsunami propagation. The Tunami N2 model has been used to simulate the tsunami propagation under the Tsunami Inundation Modeling Exchange Programme (TIME). The model has successfully simulated the propagation of tsunami event of December 26, 2004. The model applications for this event have been done by Ceren Özer, Hülya Karakuş, Gülizar Özyurt *and* Ilgar Şafak at Middle East Technical University (METU), Ankara-Turkey and Efim Pelinovsky and Andrey Zaitsev from Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia. The initial wave for simulation has been computed by the fault data. This is the same fault data that is being used in the present work. The sea state at 5, 30, 60, 120, 180, 240, 300, 360, 420, 480, 600 minutes in Indian Ocean are presented in Figure 7. The first step in the gravity wave formalism is to determine the static vertical displacement of the seafloor. It is in the first step that earthquake source parameters relate directly to tsunami generation. The displacement field is determined from linear elastic dislocation theory.



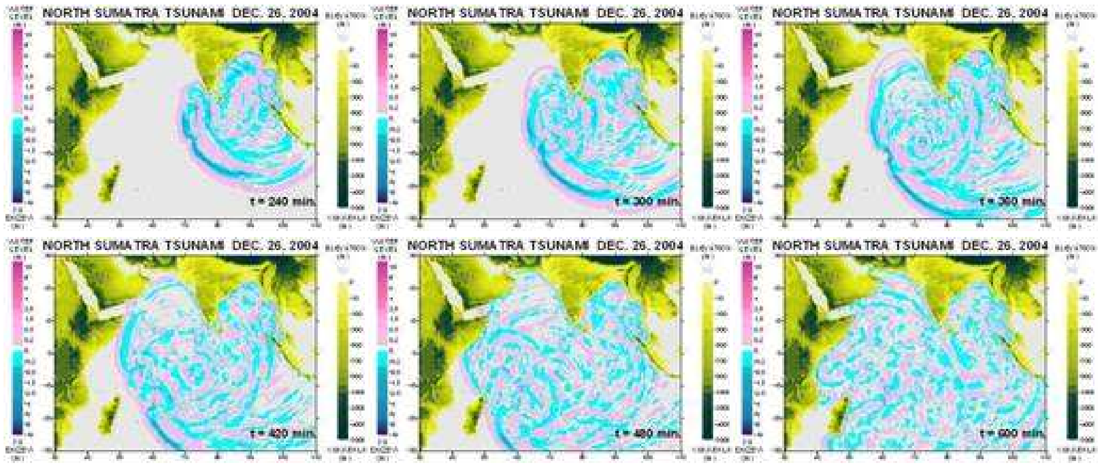


Figure 7: Sea state at 5, 30, 60, 120, 180, 240, 300, 360, 420, 480, 600 minutes in the Indian Ocean

Source: http://ioc.unesco.org/iosurveys/Indonesia/yalciner/yalciner3.htm

4.6.3. Static displacement for a point source

The governing elastostatic equilibrium equation for an isotropic and homogeneous solid is

$$(\lambda + \mu)\nabla(\nabla.\, u) + \mu\nabla * \nabla \mathbf{u} + \rho f = 0$$

In the electrostatic equation, ρ is the density, λ, μ are the Lame constants, u is the vector displacement field, and f is the body force per unit mass. The static displacement for a double-couple system of forces is (in polar coordinates r, θ, φ):

$$U(r) = M/\, 4\Pi\mu\, r*r\, (1 + \Gamma/2) \sin\theta * \sin\theta * \sin 2\phi$$

$$U(\theta) = M/\, 4\Pi\mu\, r*r\, (½ + \Gamma/2) \sin 2\theta * \sin 2\phi$$

$$U(\phi) = M/\, 4\Pi\mu\, r*r\, (1 + \Gamma) \sin\theta * \cos 2\phi,$$

where

$$\Gamma = (\lambda + \mu)/(\lambda + 2\mu)$$

and M is the moment of the force couple.

(Source for all the above-mentioned equations: Geist, E. L. (1998). "Local tsunamis and earthquake source parameters." Advances in Geophysics **39**: 117-209.)

The ETOPO-5 bathymetry along with the near shore bathymetry is combined for the purpose of simulation. Earthquake depth is an important consideration in the generation of numerical model. Because seafloor shifts cause tsunamis, the distance of the fault from the sea floor is important. Presumably, deep earthquakes would produce less potent tsunamis than similar shallow earthquakes. (Ward) For the modeling of tsunami generation, it is assumed that the seismic deformation of the sea floor pushes up the overlying water instantaneously, that is, the feature of the sea bottom deformation reflects the initial water surface elevation.(Shunichi Koshimura 2001) Using Okada's elastic formulas, it is possible to compute what should be the surface deformation depending on the hypothesis of the rupture itself. Usually, only the vertical component of the ocean bottom is considered for tsunami generation. The fault parameters needed to compute surface deformation are the fault location, geometry (strike, and dip), and size (length L and width W). (Satake 2002)

Based on the above mentioned parameters, the vertical seismic deformation of the land and sea bottom is estimated by using the theory of Okada (1985) to compute the static displacement due to inclined and tensile fault in a half space. The simulation is done for 300 minutes and 10 minute is the time interval for showing the tsunami propagation state.

The simulation is performed in LINUX environment and Ferret is used for the analysis of the propagation. It must be taken into consideration that the model is not operating system dependent, and thus can be performed in other environments as well.

4.7. Algorithm of Numerical simulation

This in brief is the algorithm to run the numerical simulation due to tsunami taking into consideration the sea surface deformation and bathymetry data.

Set up parameters
Rescale bathymetry data
Read bathymetry data
Compute Surface water displacement
Read initial condition h (i, 1)
While (it < it (end)
    Set land boundary
    Set ocean boundary
Run numerical simulation
Validate the model results

In this numerical modeling of tsunami waves using TUNAMI N2 model, “partially coupled” model is used because it allows to consider the ocean with variable depth and to transfer the initial tsunami heights from the epicentre region to the coast. *(LV Chubarov)*

4.8. Parametrization for Tunami N2 model

Tunami N2 model is used for the modeling efforts focusing on the near-field tsunami propagation within the tsunami source region. Initialization for the generation and bathymetry are the main parameters for numerical modeling of tsunami waves. For the modeling of tsunamis, the ETOPO 5 bathymetry data obtained from NOAA Satellite and information service’s National Geophysical Data Center (NGDC) is used. The near shore bathymetry obtained from National Hydrographic Office is used to incorporate with the ETOPO 5 bathymetry. The spatial grid size of each grid is 9000 m. Initialization of the tsunami model requires fault data that is obtained from the IOC/UNESCO Indian Ocean Tsunami Post Tsunami Field Survey Site. The fault data includes fault length, fault width, dip angle, strike angle, slip angle, maximum positive and negative amplitude, epicenter coordinates, focal depth and displacement. Moreover, coastal bathymetry data obtained from National Hydrographic Office, Dehradun had to be incorporated with the ETOPO 5 bathymetry data to give a better simulation result. The near shore bathymetry data is prepared using NHO Chart and a software code is written in FORTRAN to incorporate the near-shore bathymetry with the ETOPO 5 bathymetry data. The computational domain for the numerical simulation is considered from 45 N – 105 N and –20 E – 30 E. The source is taken at 93.13°N and 03.70°E. This is the location where the earthquake happened on 26 December 2004 in the Sumatra region.

5. Results and Discussions

5.1. Inundation Extent

The observation points obtained from National Institute of Oceanography, Goa during the field survey are along the Tamil Nadu coast. The worst affected area of Nagapattinam showed longer penetration of seawater (750 m) up to an elevation of 3.9 m due to the gentle slope of coastal land combined with the effect of tsunami wave diffraction caused by the northern tip of Sri Lanka. The run-up levels and inundation extent are shown in figure 8.

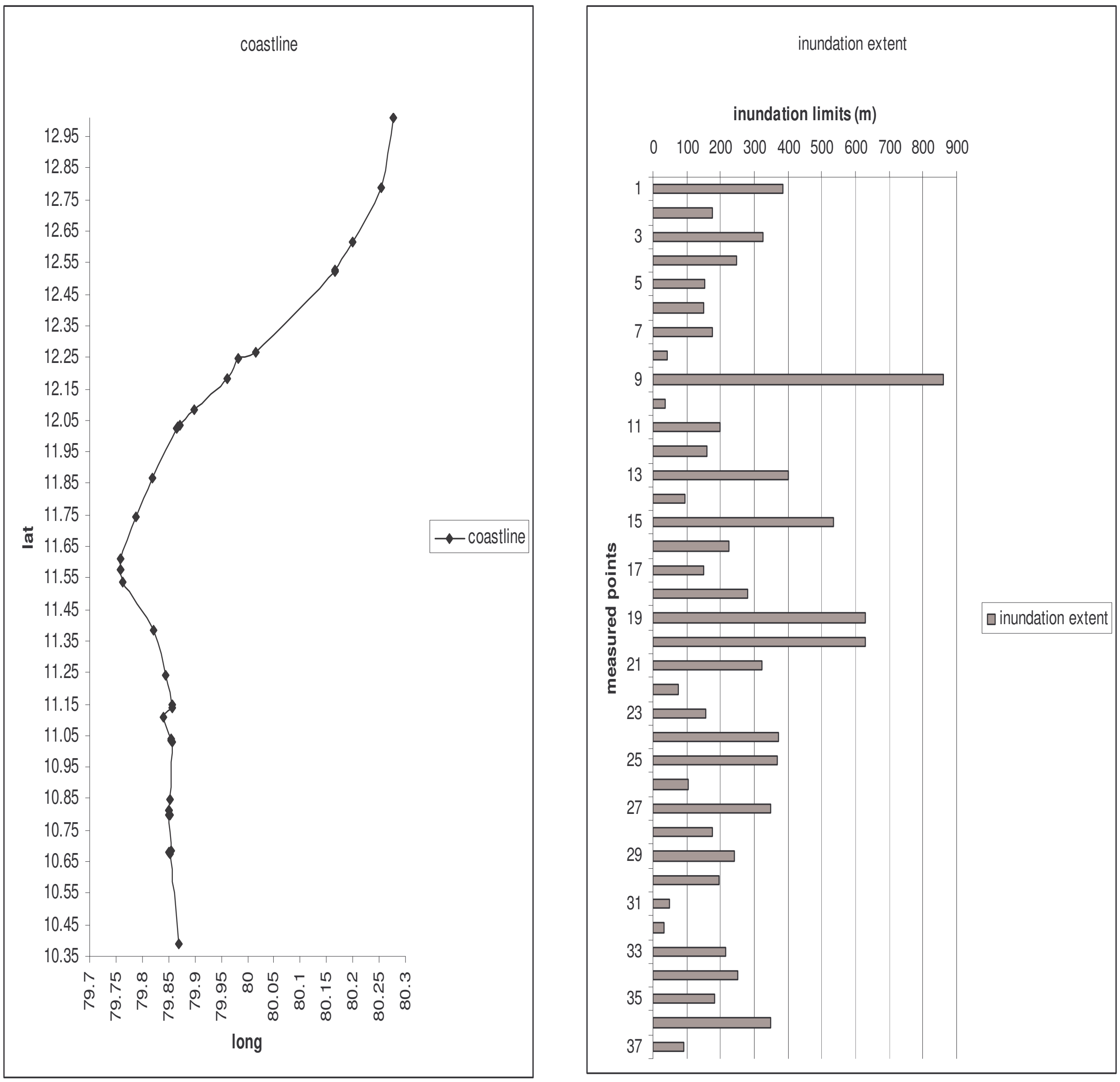


Figure 8: Observations for various stations and inundation extent

(Source: National Institute of Oceanography, Goa)

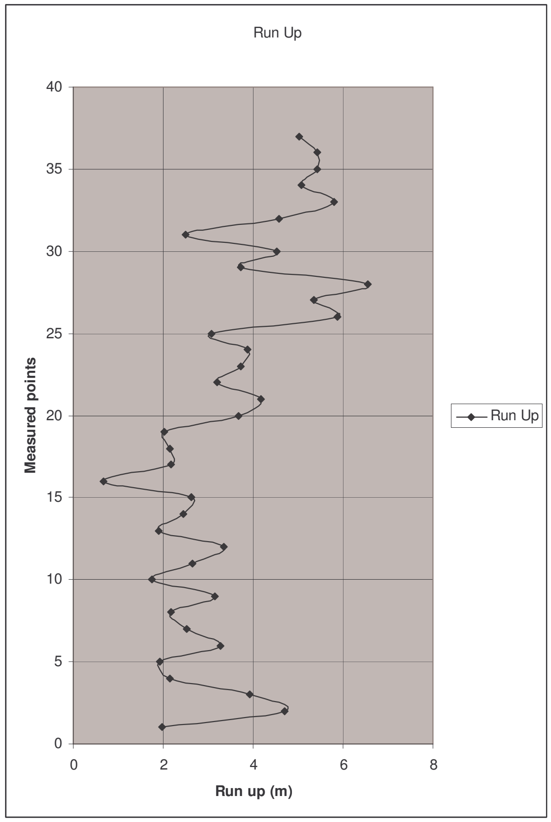


Figure 9 : Run-up measurement

(Source: National Institute of Oceanography, Goa)

According to the field survey and the data obtained from National Institute of Oceanography, Goa who conducted a post tsunami field survey in the month of January 2005 and a comparative study with Car Nicobar islands, shows penetration of seawater into a relatively short distance in Nagapattinam that has higher coastal land-slope value than Car Nicobar Islands. This is mainly due to higher density of houses and streets in Nagapattinam and also non-occurrence of land subsidence unlike in the Car Nicobar. Presence of creeks like Vedaranyam canal in Nagapattinam facilitated seawater inundation up to 2.2 km inland.

Inundation limits were ascertained based on visual observations at the location from the shore and debris line that is present on the shore in case of open lands and watermarks left by receding waters on walls (both inside and outside) of houses. There were eyewitnesses who gave vital insights regarding the extent of inundation during the field survey. The inundation limit shows the vulnerability of the southern region of Tamil Nadu coast due to its flat topography compared to the northern region. The tsunami wave attack normal to the coast has a higher impact on inundation limits and run-up heights than an oblique attack. However, inundation would be larger only if there is no obstruction to the water flow and the topography of the region is conducive for transport of this water mass. It is observed that regions where the hinterland is unprotected by coastal dunes and casuarinas plantations had higher inundation values compared to the areas that are protected by dunes and casuarinas. Moreover, wherever there were openings in the dunes either due to anthropogenic or other reasons, inundation was higher as these openings provided a gateway for the water mass to travel through them inland. The inundation is high at certain places because of the Nagapattinam region's low-lying presence.

Tsunami impact although infrequent, they are among the most terrifying and complex physical phenomena and have been responsible for great loss of life and extensive destruction to property. Because of their destructiveness, tsunamis have important impacts on the human, social and economic sectors of societies. The Tsunami inundation extent map is shown here which is generated with LISS III satellite image of 05 January 2005.

5.1.1. Inundation Extent Map

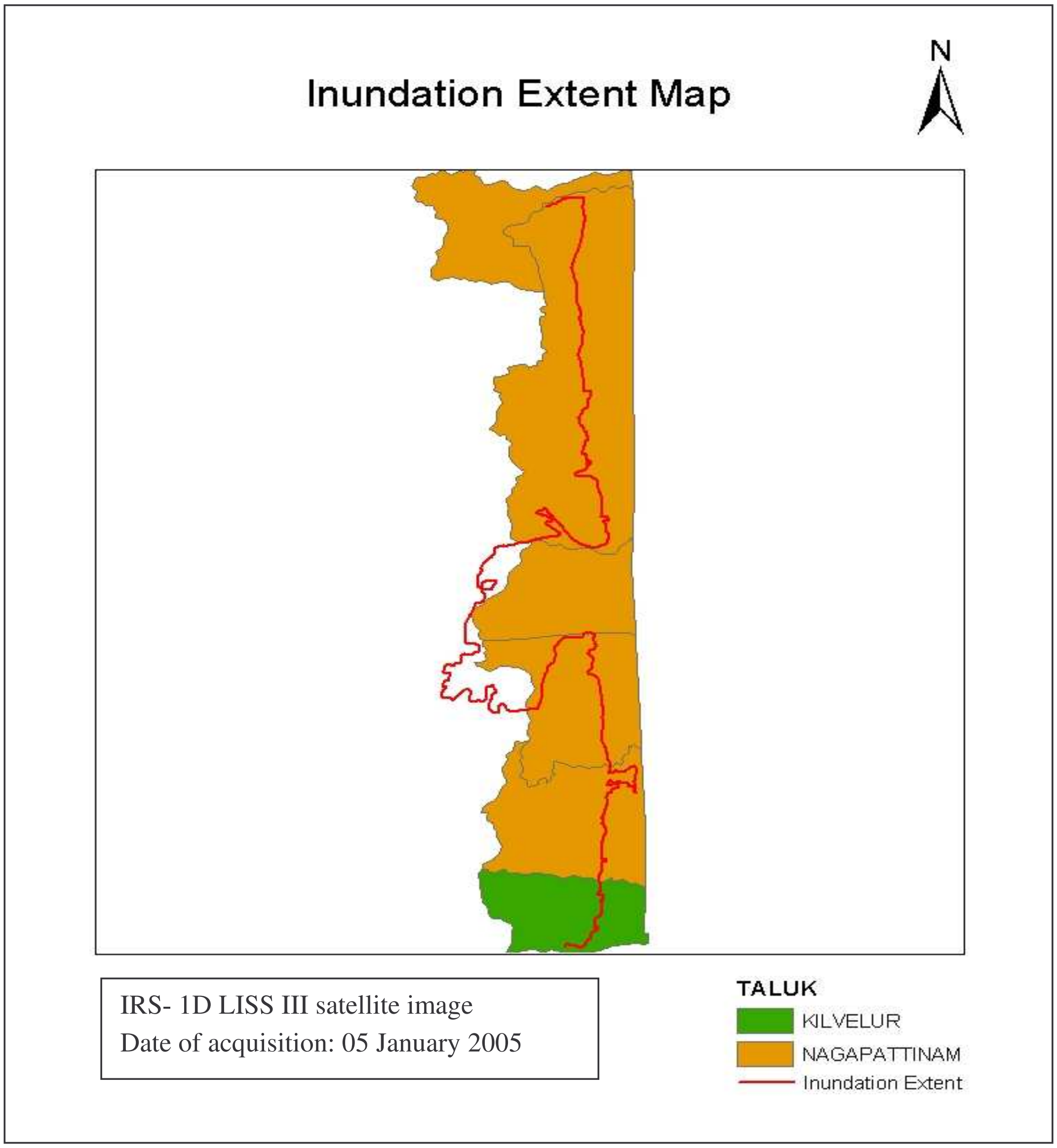


Figure 10: Inundation Extent Map of Nagapattinam

(Main Source: Department of Ocean Development and Field Observations)

This hazardous incident emphasizes immediate need of generating landcover maps of hazard prone areas which will be useful for the decision makers in planning strategy for the restoration of ecology, rehabilitation and reducing the possible impact of the hazard in future. The present study provided an opportunity to estimate the tsunami impact on various landcover in the Nagapattinam area in Tamil Nadu through visual interpretation technique. Pre and Post-Tsunami LISS III Satellite data is acquired from National Remote Sensing Agency (NRSA), Hyderabad. Geometric rectification is carried to provide latitude and longitude information into raw satellite scene using raster based geometric corrections. Rectification carried out in geographic projection is re-projected in shape of polygonal projection and the scene is geocoded using Survey of India (SOI) toposheets. Different scenes are merged together to get one combined False Color Composite (FCC). Satellite image is displayed in three bands 3,2,1. Change maps are prepared to depict changes under different landcover classes.

The landcover map generated from IRS-P6 LISS-III with 23.5m spatial resolution on 1:50,000 scale clearly bring out the spatial information on settlement/built-up area, agriculture lands (upland/ crop/ fallows), other vegetation cover (vegetation and plantation), surface water bodies (River /canals), mud flats, salt pans, waste lands and the scrubs (shown below in Fig 11) and the Tsunami affected map generated from IRS-P6 AWiFS with 56m spatial resolution on 1:50,000 scale brings out the spatial information on tsunami affected area (shown below in Fig 13). Land cover maps were generated using Pre-tsunami LISS-III satellite images and intersected with tsunami inundation map derived using Post-tsunami LISS III satellite images to extract the tsunami affected various landcover classes (shown below in 16). The damage assessment to various landcover classes is done comparing statistics generated for different classes of landcover. ASTER satellite images were available but they could not be used since the study area part in the Post-Tsunami ASTER image had clouds. The landcover classes are delineated from the Pre-tsunami LISS III satellite image using techniques of visual interpretation. Recognizing targets is the key to interpretation and information extraction. Observing the differences between targets and their backgrounds involves comparing different targets based on any, or all, of the visual elements of tone, shape, size, pattern, texture, shadow, and association. Tone, shape, pattern, texture and association are the key elements that have been used to prepare the landcover map with Pre-tsunami LISS III satellite image of the Nagapattinam area.

5.2. Landcover classes

The satellite data of the study area are procured from IRS-P6 LISS-III. The IRS P6 satellite data were geo-referenced and suitable Image enhancements are applied to facilitate the delineation and interpretation of different thematic information. The landcover map that is prepared from the pre-tsunami LISS III satellite image is divided into eight classes. They are Settlement/Built-up area, agriculture, surface water bodies, other vegetative cover which includes all rivers and canals in the area, other vegetative cover, mud flats, salt pans, wastelands and scrubs. The entire study area covers an area of 551 sq. km. In the satellite image, the village settlements are seen as cluster of discrete red patches, due the presence of tree cover in from of orchard. However the Settlement/built-up amount to an area of 47.26 sq. km are delineated from satellite image i.e. the 08.56 percent of the total geographical area of the Nagapattinam taluk. Since the pre-tsunami image for landcover map is from the month of August, the agricultural lands of upland agricultural areas, standing crop of Rabi and harvested fallows could be segregated from the satellite image. The agricultural area accounts to 373.01 sq. km that amounts to 67.60 percent of the total geographical area of the Nagapattinam taluk.

The surface water bodies could be delineated from the satellite image that encompasses an area of 12.28 sq. km. It comprised of the rivers and canal (like Vedaranyam canal) in the Nagapattinam taluk. Other vegetative cover present in the region includes casuarinas plantations. It accounts to an area of 61.81 sq. km that is 11.20 percent of the total geographical area of the study region. Mudflats present in the region were delineated from the satellite image that covers an extent of 26.18 sq. km (04.74 percent of the total geographical area) in the region. The coast of Tamil Nadu supports a lot of coastal communities and people are engaged in the production of salt. There are saltpans in the region that are categorized amongst the lancover classes. They cover an area of 02.81 sq. km that amounts to 00.51 percent of the total geographical area of the Nagapattinam taluk. Wastelands and Scrubs are also delineated from the pre-tsunami LISS III satellite image. They amount to an area of 03.58 and 24.86 sq. km respectively that is 00.65 and 04.51 percent of the Nagapattinam taluk.

5.2.1. Landcover map of the Nagapattinam area (Pre-tsunami)

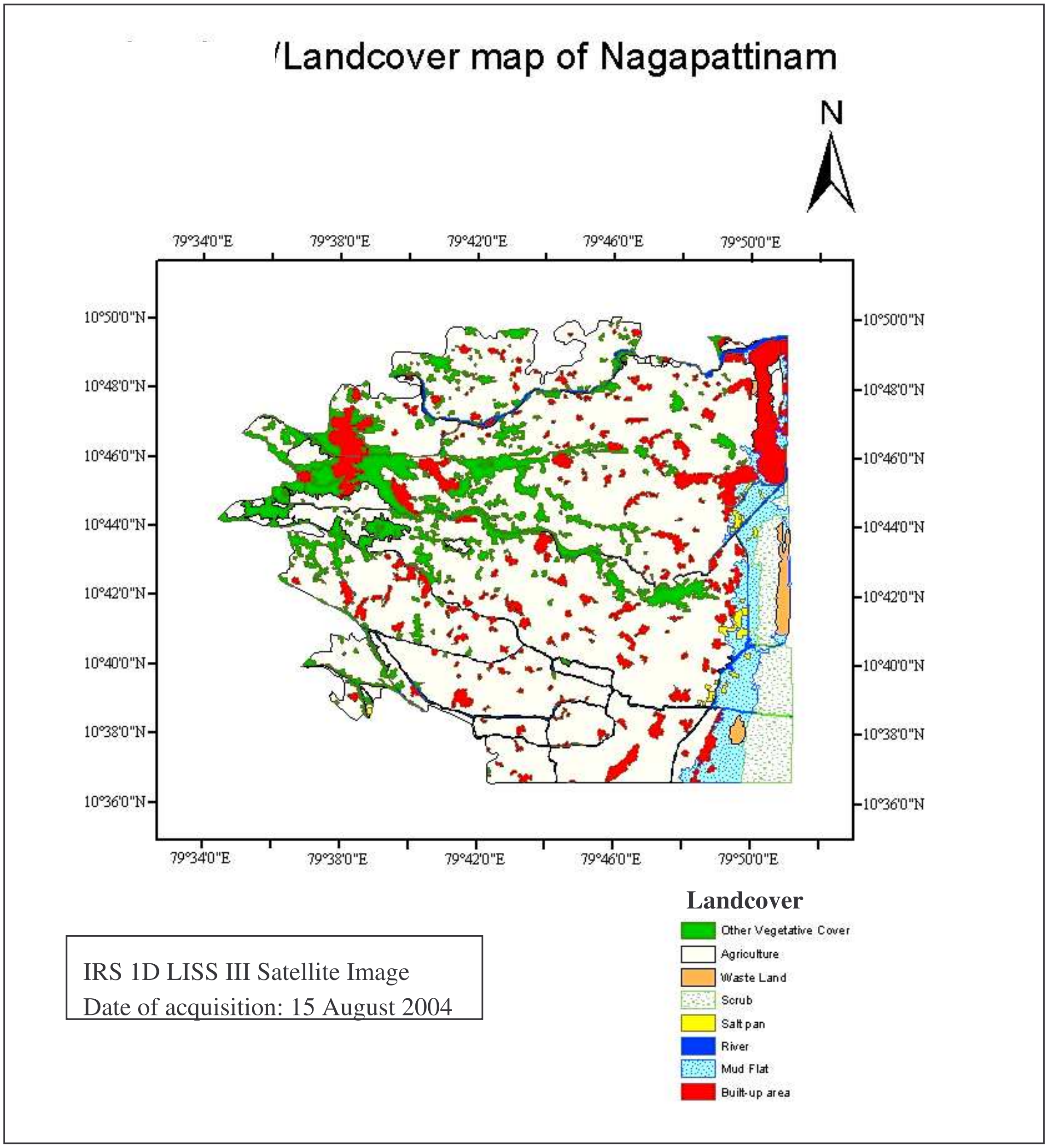


Figure 11: Landcover map of Nagapattinam

The above landcover map is prepared with pre-tsunami IRS P6 LISS III satellite image of 15 August 2004. This is done through visual interpretation technique of classification. Various classes are shown with different colors as shown in the legend on a scale of 1:50,000. The software used for this purpose are ERDAS 8.7 and ARC GIS 9.0. The composition of the map is done in Arc Map.

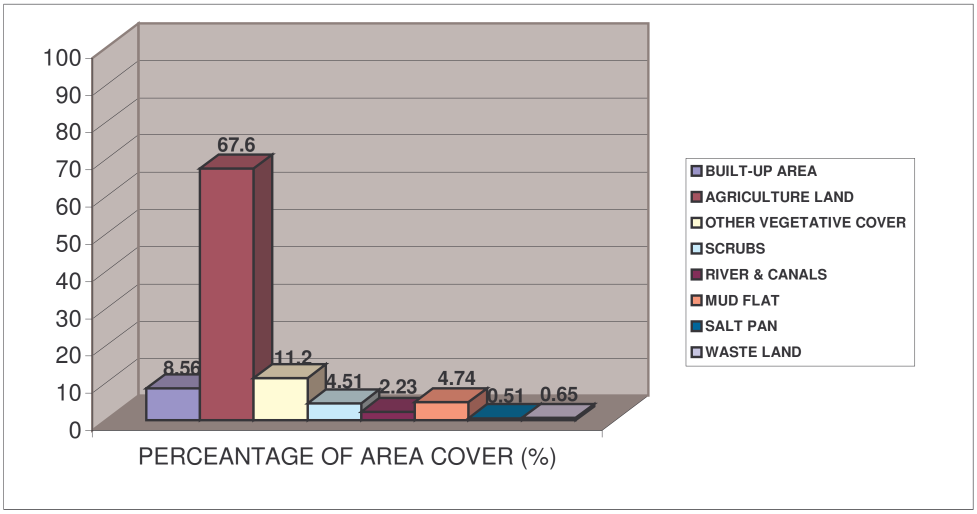


Figure 12: Landcover percentage for each class in Nagapattinam

Table 9: Landcover in Nagapattinam

SL.NO	LANDCOVER in NAGAPATTINAM	AREA COVER (Sq.Km)	PERCEANTAGE OF AREA COVER (%)
1	BUILT-UP AREA	47.26	08.56
2	CROP LAND	373.01	67.60
3	OTHER VEGETATIVE COVER	61.81	11.20
4	SCRUBS	24.86	04.51
5	RIVER & CANALS	12.28	02.23
6	MUD FLAT	26.18	04.74
7	SALT PAN	02.81	00.51
8	WASTE LAND	03.58	00.65
9	TOTAL AREA	551.79	100%

The Landcover map prepared from Pre-tsunami LISS III satellite image of 15 August 2004 gives information regarding the various landcover practices that are carried in the Nagapattinam region. It is a backward region in the state of Tamil Nadu and the mainstay of livelihood in the region. In the landcover map prepared shows the maximum area is covered with agriculture and other vegetative cover in the Nagapattinam region. People in Nagapattinam work in saltpans that covers an area of 2.81 sq. km. Seawater intruded in the agricultural fields and saltpans and thereby, has now rendered the soil of the agricultural land to be saline. The Rivers and Canals in the area cover an area of 12.28 sq. km. The Vedaranyam canal present in the region allowed deep intrusion of the seawater in the Nagapattinam region.

5.2.2. Affected area map of the Nagapattinam area

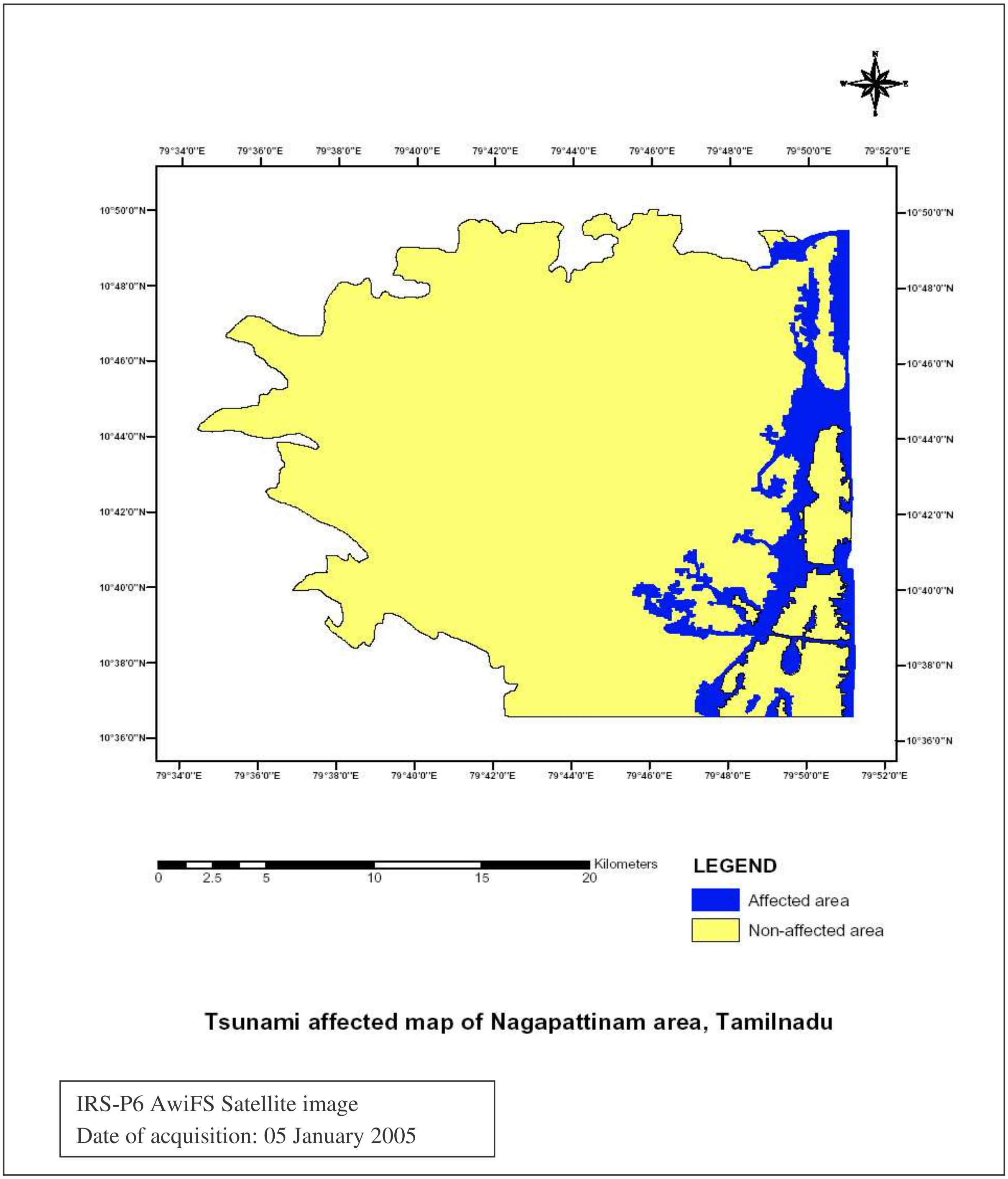


Figure 13: Affected area map of Nagapattinam

Table 10: Inundated and Non-inundated area in Nagapattinam

S.No.	Class	Total area (sq. km)	Percentage of area cover (%)
1	Affected area	49.55	08.98
2	Non-Affected area	502.24	91.02
3	Total area	551.79	100

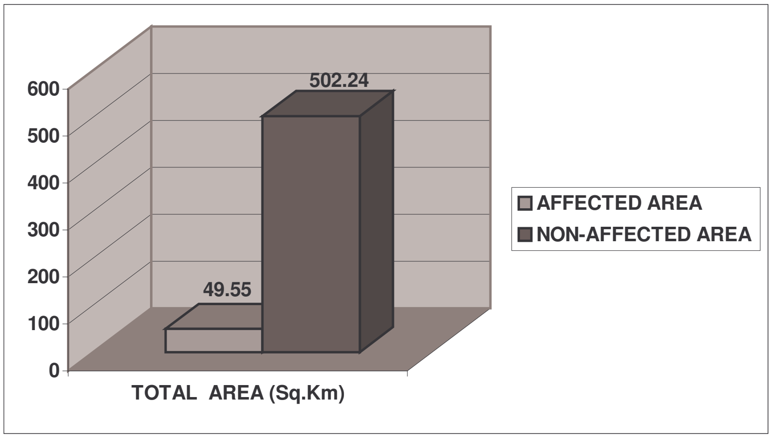


Figure 14: Comparison of affected and non-affected area in Nagapattinam

The Tsunami affected amount to an area of 49.55 Sq. Km that is delineated from the post-tsunami AWiFS satellite image i.e. 08.98 percent of the total geographical area of the Nagapattinam Taluk. The extent of inundation is mainly due to the topography of the area. It is a low-lying area and inundation is far inland in the Nagapattinam taluk. Using the field visit done in the month of August, watermarks were clearly visible along the shore. Though there were variations in the extent of inundation that was mainly due to the density of the houses, presence of sand dunes, and casuarinas plantations.

5.3. Changes in landcover classes of the Nagapattinam area

A comparative analysis for the pre and post-tsunami Nagapattinam area change maps give an insight regarding the damage that is caused to various landcover classes in the region. Nagapattinam was the worst affected district due to the Tsunami on 26th December 2004 and accounted for 76% of the total death in Tamil Nadu Nagapattinam is socially and economically a backward region. The main livelihood for people in the area is fisheries and agriculture. Tsunami damaged the roots of their survival and with the extent of inundation, there is widespread poverty owing to loss of livelihood. People who were engaged in agricultural practices and saltpans lost their lives and their families are living in temporary shelters managed through the efforts of government and non-governmental organizations (NGO). Appendix 4 shows the details regarding the number of temporary shelters in the Nagapattinam area.. Apart from death and destruction of houses, thousands of boats and catamarans were destroyed apart from extensive damages to the fishing harbours, fish landing and auction centres in Nagapattinam. Damage is basically due to the salinization of ground water and sand entering agricultural and horticultural fields. Moreover, the damages due to tsunami had a cascading effect on the coastal economy and religious tourism in places like Velankanni and Nagore.

5.3.1. Landcover affected by Tsunami in Nagapattinam

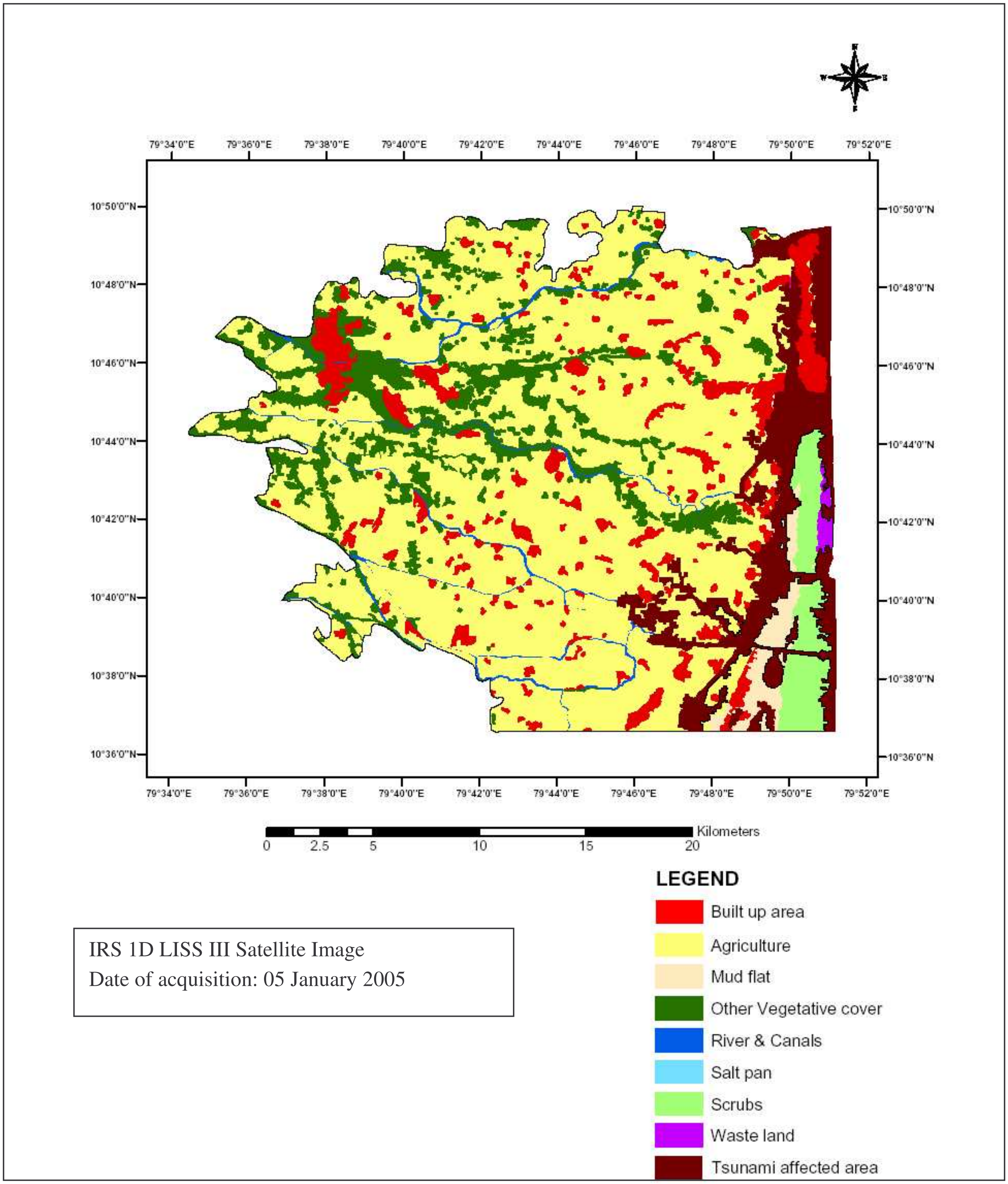


Figure 15: Landcover affected by Tsunami in Nagapattinam

5.3.2. Post-Tsunami changes in Landcover of Nagapattinam

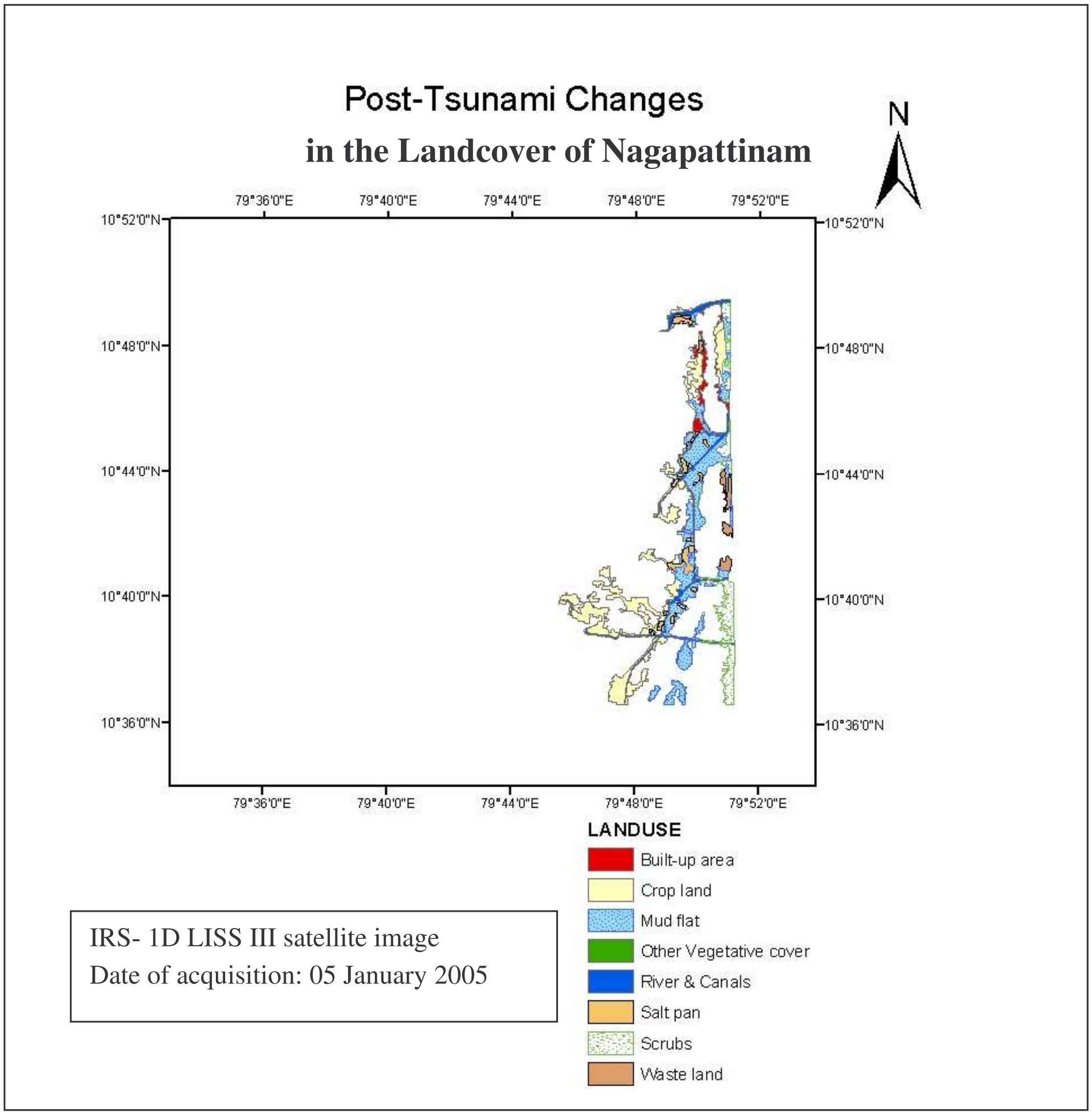


Figure 16: Post-Tsunami change map of Nagapattinam

Table 11: Area affected by Tsunami

S.NO	LAND COVER	TOTAL AREA (Sq.Km)	AREA AFFECTED BY TSUNAMI (Sq.Km)	Percentage (%)
1	BUILT-UP AREA	47.26	02.17	4.58
2	CROP LAND	373.01	16.47	4.41
3	OTHER VEGETATIVE COVER	61.80	0.03	0.04
4	SCRUBS	24.86	06.73	27.06
5	RIVER & CANALS	12.28	04.12	33.54
6	MUD FLAT	26.18	15.21	58.89
7	SALT PAN	02.81	02.72	97.5
8	WASTE LAND	03.58	01.89	52.97

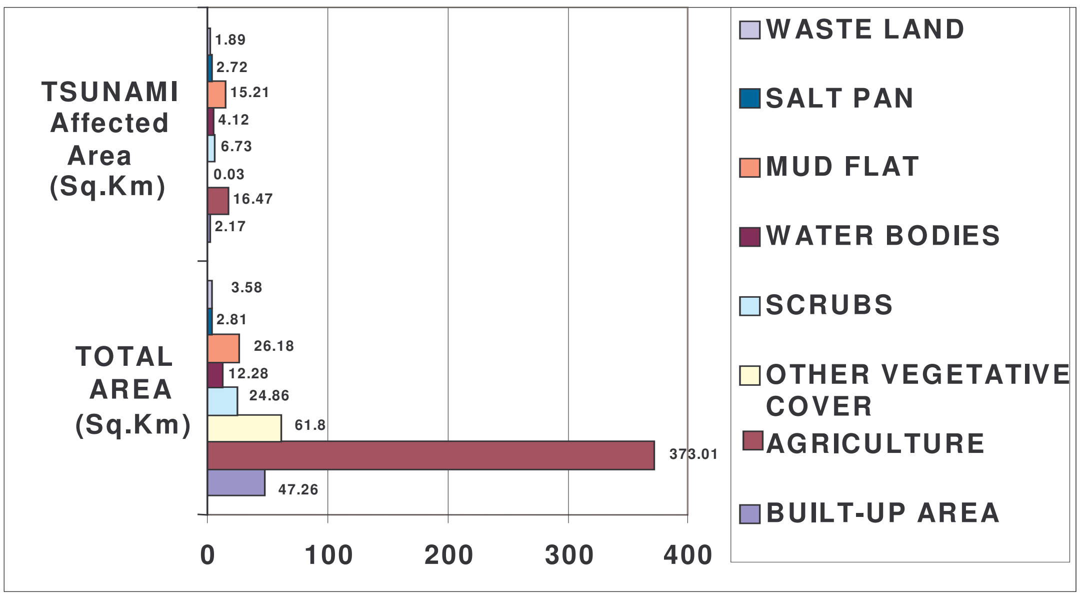


Figure 17 : Comparison between Total area and the area affected by Tsunami (Sq.Km).

A comparison is shown between the pre-tsunami landcover map and the post-tsunami inundation extent map. The map shows the inundation extent in the landcover map. In the total area of the Nagapattinam region that is 551 sq. km, approximately 50 sq. km is inundated with seawater. The inundation is due to the low-lying presence of the Nagapattinam region and the presence of creek like the Vedaranyam in the region. The inundation varies at several places in the region that is mainly due to the density of houses at specific locations, presence of sand dunes, and casuarinas plantations in the region. The heavy loss due to tsunami inundation has left the economy of the region shattered. The saline agricultural lands, the affected saltpans have left the coastal community in disarray.

5.4. Numerical Modeling with Tunami N2 model

Tunami N2 is used for modeling the propagation of tsunami waves focusing on the near-filed tsunami propagation within the tsunami source region. In this model, a set of non-linear shallow water wave equations with bottom friction terms are discretized by the leap-frog finite difference scheme. Tunami N2 is widely used as a model for the generation, propagation and amplification of tsunami waves. After the earthquake of December 26, 2004, International Oceanographic Commission (IOC) / United Nations Educational Scientific and Cultural Organisation (UNESCO) have used the Tunami N2 model to show the propagation of tsunami waves in the Indian Ocean at various time intervals. For a given source region condition, the Tahuko University model Tunami N2 is used to simulate propagation of tsunami waves over a long distance. The model can estimate the arrival time of the tsunami at a coastal region, provided the source region information and bathymetry data are accurate. (Philip L-F Liu and Yim)

For the modeling of tsunami propagation, ETOPO-5 digital bathymetry grid available at NOAA's National Geophysical Data Center (NGDC) is used. The 9 km * 9 km grid is used for the propagation model.

5.5. Tsunami Source Model

In order to study the propagation of tsunami waves from the Sumatra region where the megathrust earthquake happened on December 26, 2004 to the south-eastern coast of India, a tsunami simulation is performed by utilizing a numerical simulation method, Tunami N2. The simulation of tsunami waves aims to show the propagation state of the sea waves at different time intervals. Thus, it calculates the arrival time of tsunami waves and tsunami height in space and time. In the numerical simulation of tsunami, it is assumed as shallow water waves, where wavelengh is much larger than the depth of the sea floor. For the modeling of tsunami waves, certain governing equations are applied in the method that are as follows:
Continuity Equation:

$$\partial\eta/\partial t + \partial M/\partial x + \partial N/\partial y = 0$$

Whereas the governing equation for this propagation model is:

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)+gD\frac{\partial \eta}{\partial x}+\frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2}=0$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)+gD\frac{\partial \eta}{\partial y}+\frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2}=0$$

(Source: Geist, E. L. (1998). "Local tsunamis and earthquake source parameters." Advances in Geophysics **39**: 117-209.)
Where x and y are space coordinates in horizontal direction, t is time, M and N are discharge in x- and y-direction respectively, η is the water elevation, D (= h + η) is the total depth where h is water depth and n is the Manning roughness coefficient. In the numerical simulation, tsunami source – the source that generates tsunami wave – usually is assumed as vertical deformation on the sea floor caused by earthquake faulting. For the modeling of tsunami generation, it is assumed that the seismic deformation on the seafloor pushes up the overlying water instantaneously, that is, the feature of the sea bottom deformation reflects the initial water surface elevation. The result of seismic deformation

modeling is determined from the fault source parameters. In the simplest case, the fault geometry is created for the Sumatra earthquake using the fault parameters of the rupture area. An ellipsoidal geometry is created which incorporates the length, width and strike angle of the fault. The seismic model is created to incorporate the fault parameters that are the first step for the propagation of tsunami waves. This is the generation mechanism of the seismic model that is a prerequisite for the initialisation of the Tunami N2 model.

The earthquake source parameters play a pivotal role in the initialization of the model. Without accurate source parameters and coseismic displacement calculations, the best hydrodynamic model is prone to yielding erroneous results. The first step in the modeling of tsunami waves is to determine the static vertical displacement of the sea floor. It is in the first step that earthquake source parameters relate directly to tsunami generation. Because for the purpose of synthesizing the tsunamis, only the coseismic surface displacement arising from the earthquake rupture is considered. (Geist 1998) The estimated sea floor deformation is, then used as an initial model for the tsunami simulation.

The earthquake ruptured a surface of at least 400 km long and 100 km wide, with an average slip of 10-15 meters, and local maximum of 20-25 meters. This gives a magnitude Mw ~ 9. Some models even use a longer rupture, up to 800 km further north, almost to the Andaman Islands. However, most of the aftershocks (some of them being large earthquakes with magnitudes larger than 7) occur in this area, 1000 km north of the main shock. The dip angle of the subduction plane interface is as small as 10°. This low angle explains why the width of the fault plane is so large (> 100 km) and the magnitude as high as ~9. An earthquake in this area was not unexpected. The Sumatran subduction is where the convergence between the Indo-Australian plate and the Sundaland plate occur at 4-5 cm/yr.(Vigny 2005). In the propagation of tsunami waves using the Tunami N2 model, the seismic model is the first prerequisite for the initiation of the tsunami waves. In the tsunami simulations carried out after the event of December 26, 2004, the sea surface perturbation is considered for the initiation of the first tsunami wave based on the fault parameters. The creation of the fault geometry and the sea surface perturbation are interlinked in the process of tsunami simulation. In the present simulation, the fault geometry is created using a simplistic case of half-ellipsoidal model on the basis of fault parameters available from the IOC/UNESCO site that had carried the tsunami simulation using the Tunami N2 model. Using the equation for the area of an ellipsoid, the fault model is created to initialise the tsunami propagation model. The result shows a vertical displacement of 25 m at the point of epicentre that is considered to be the maximum height of the initial wave after the earthquake happened in the Sumatra region. An area for the rupture zone is considered for the initiation of the propagation using the half-ellipsoidal model. The creation of the ellipsoidal fault model is done using a FORTRAN program. The initial wave for simulation is computed by the fault data available from the IOC/UNESCO Tsunami site. (http://ioc.unesco.org/iosurveys/Indonesia/yalciner/yalciner3.htm)

5.6. Role of Model Parameters

The numerical model can be explained in two processes. One, when the seismic model is used for the generation of tsunami waves. This is done by creating a fault geometry using the fault parameters for the event of December 26, 2004. It takes into account the rupture length, width of the rupture zone,

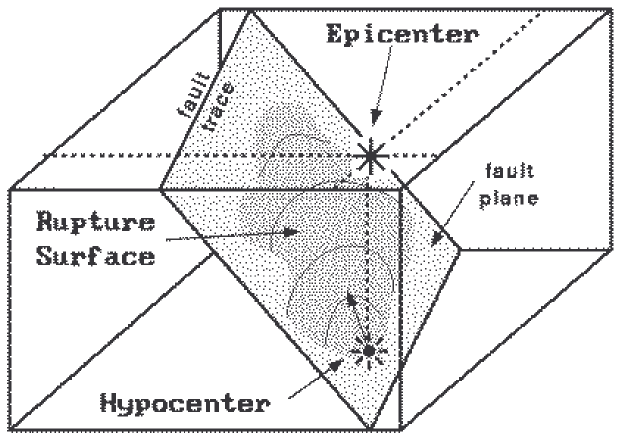


Figure 18: Fault plane

(Source: http://www.ig.utexas.edu/research/projects/eq/faq/basics.htm)

strike angle that the fault trace makes with a line on the surface of the earth pointing north. In the numerical modeling of tsunami waves, bathymetry and initial conditions are the vital parameters in the model. Bathymetry is a key input in the model as it determines the accuracy of the results. With the variation in sea level, it is important to have bathymetry data that showcases the real event during the simulation process. In the model, coastal bathymetry is also incorporated with the ETOPO-5 bathymetry data. Initial conditions pertain to the generation mechanism of the initial wave that is discussed earlier in section 5.5. Thus, The bathymetry file and Initial condition file are inputs to the model for the propagation of tsunami waves.

5.7. Assumptions for the model

The generation, propagation and amplification of tsunami waves is done with the Tunami N2 model for the event of December 26, 2004. To perform the simulation, various assumptions have been made in the present study. The fault model that is a prerequisite for the simulation is created using the simplistic case of creating a half-ellipsoid for the rupture zone. This simplistic case is referred from the profiles of vertical static displacement for the seismic source. (LV Chubarov)

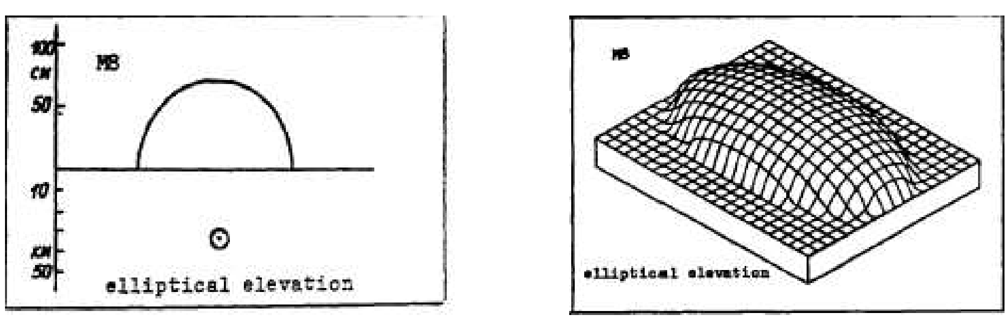


Figure 19 : Profile and perspective view of vertical static displacement for the elliptical seismic model
(Source: Tsunamis and earthquake mechanisms in the Island Arc Regions, Science of Tsunami Hazards)

The major and minor axes in the ellipsoidal model are the length and width of the fault rupture. Though bottom friction is varying and has a direct relationship with the depth of the ocean, the bottom friction coefficient that contributes to the modeling of tsunami waves is kept constant in the Tunami N2 model. Most earthquakes start with the greatest amount of slip near the epicentre. The exception to this rule is what happened in December 26, 2004 earthquake, where it started with a little slip, then a big burst occurred later farther away from the epicentre. But due to unknown distance from where exactly the event happened, the fault rupture at the epicentre is considered for the creation of the of fault geometry.

5.8. Tsunami Propagation

Tunami N2 model is used for the propagation of tsunami waves for the event of December 26, 2004. The tsunami propagation states at every ten-minute interval are simulated for the event of December 26, 2004 that happened in the Sumatra region of the Indian Ocean at 06:29 hrs (IST) and reached the coast of India at 9:15 hrs (IST). The simulation is carried out for duration of 5 hours and the propagation states at 5, 30, 60, 90, 120, 180, 190, 300 minutes are shown in the figures below.

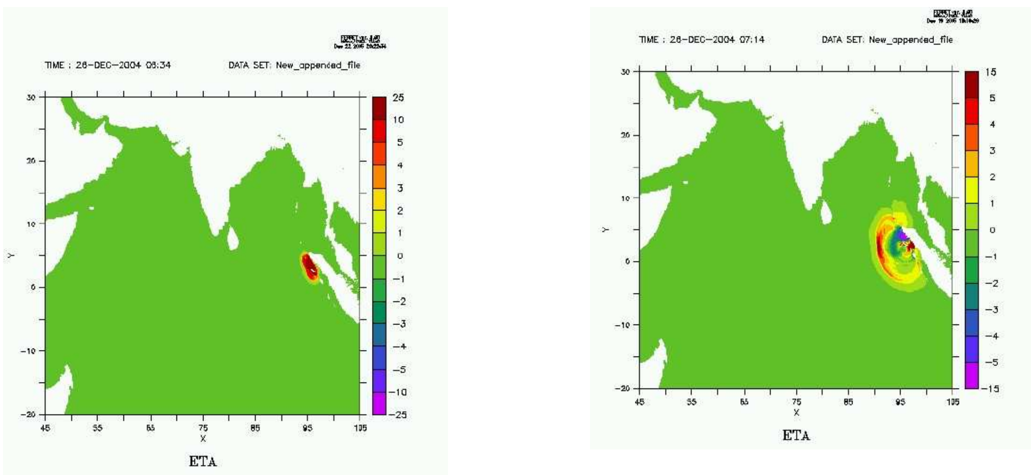


Figure 20 : Tsunami propagation at t = 5 minutes and t = 30 minutes

The above simulation describes the initiation of the propagation in the Sumatra region for the event of December 26, 2004. The propagation starts at 06:29 hrs (IST) and reaches the coast of India at 09:15 hrs (IST). Because of the variability in the bathymetry of the Indian Ocean and the earthquake that triggered the tsunami waves, the wave amplitude varies with the propagation of waves. At t=5 minutes, the wave amplitude that is shown in the bar with different colours next to the simulation figure shows red at the point of epicentre. This indicates the wave height on the landmass to be in the range of 9-10 m on the land-ocean boundary. At t = 30 minutes, the wave starts propagating towards the Andaman Islands and the coast of India and Sri Lanka. The wave amplitude varies with the forward motion of the tsunami waves. Boundary conditions play a significant factor in the separation of the land and ocean boundary. The figures above show a numerical model for the propagation of the tsunami generated by the earthquake. The study area was 60 x 50 that ranges from 45° to 105° East and from -20° to 30° North. The computational grid is divided into the horizontal components of space and time. The $\Delta x = \Delta y = 5$ minutes that is 9000 m and $\Delta t = 9$ seconds for the computational grid. The red color indicates that the water surface is higher than normal, while the blue means lower. Because of the fault geometry, the waves propagating to the East (towards Thailand and Myanmar) begin with a receding wave, which explains why the sea started to retreat minutes before flooding the coast. On the contrary, to the West (towards India and Sri Lanka), a large wave suddenly hit the coast without warning.

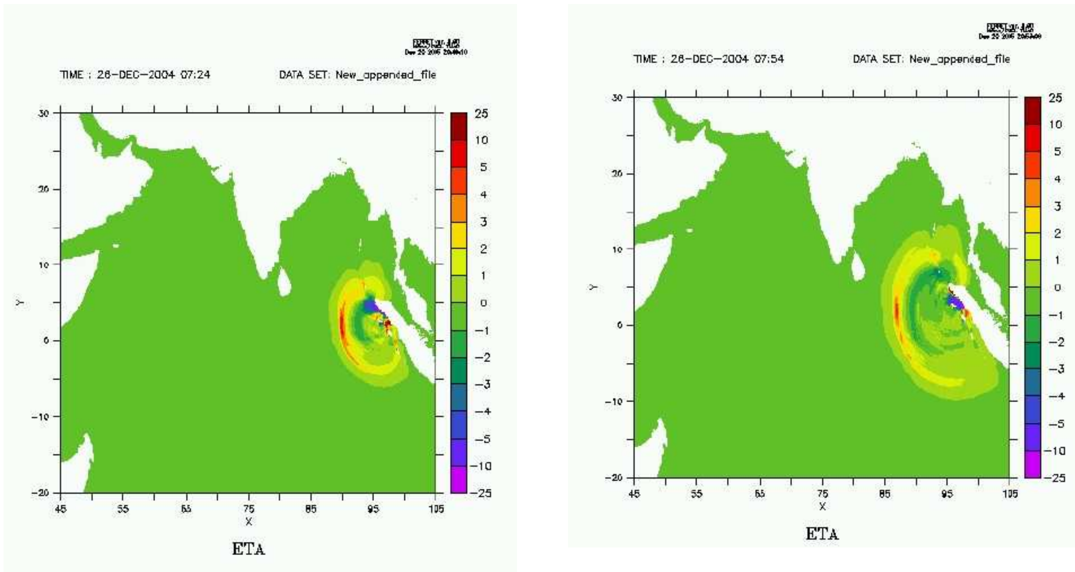


Figure 21: Propagation at t = 60 minutes and t = 90 minutes

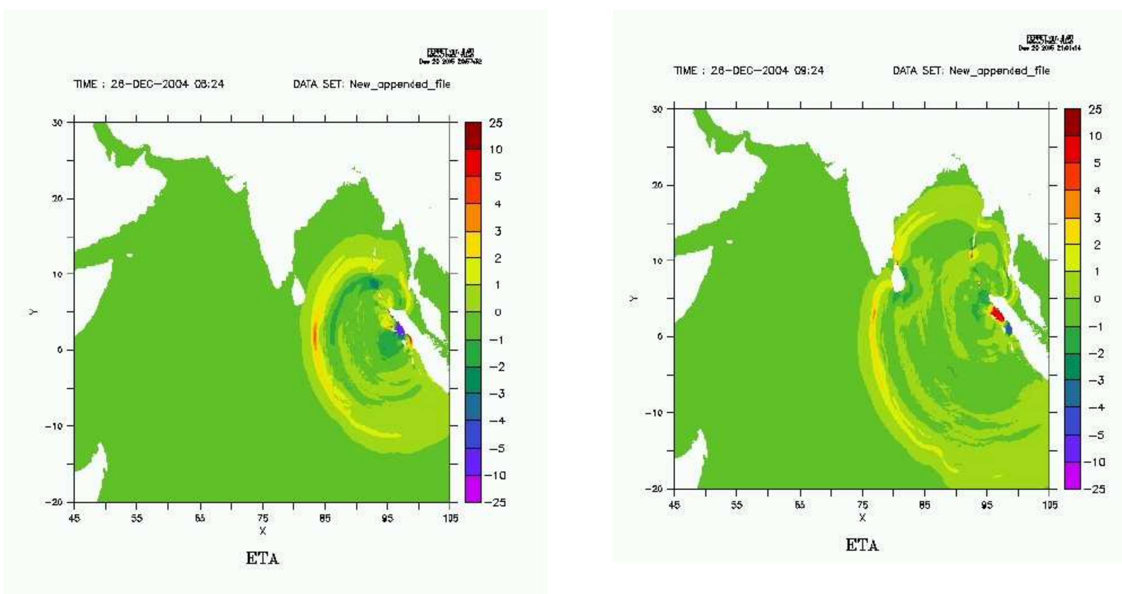


Figure 22: Propagation at t = 120 minutes and t = 180 minutes

The figures above show the propagation state of tsunami waves after 5, 60, 90, 120 and 180 minutes. It could be observed from figure 22 that at t = 180 minutes the tsunami waves have reached the south-eastern coast of India. It had hit the Sri Lanka coast and the wave amplitude in the Indian coast shows the wave height to be in the range of 7-8 m. Since, near shore bathymetry is incorporated in the model, its affect can be visualized from the event at t = 180 minutes. The Andaman Islands had suffered a lot of damage due to tsunami that can be gauged from the figure above that shows wave amplitude of 4–5 m in the Andaman region. In the model, the near-shore bathymetry of the Andaman region is not incorporated but without the absence of near-shore bathymetry of the region, it shows an amplitude of approximately 5 m that provides insight into the event of December 26, 2004 and the damage it caused in these regions.

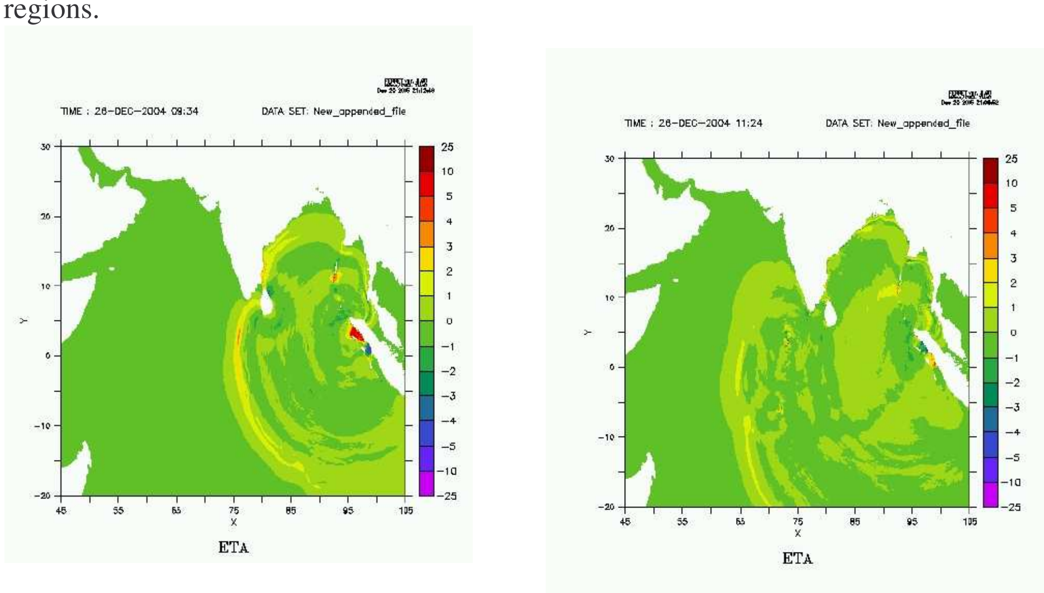


Figure 23 : Propagation at t = 190 minutes and t = 300 minutes

The above figures show the propagation of tsunami waves when t = 190 and t = 300 minutes. At t = 190 minutes, the wave amplitude at the coast of India can be observed to be in the range of 4 – 5 m and this is attributed to the incorporation of the near-shore bathymetry. The last simulation state at t = 300 minutes is shown in fig 23. In the model simulation, maximum wave amplitude for the entire duration of simulation is shown in figure 24. It shows the maximum amplitude of the tsunami waves at any given time during the simulation time of 300 minutes. The bar on the right indicates the wave amplitude in meters. The figure shows maximum amplitude in the Sumatra region

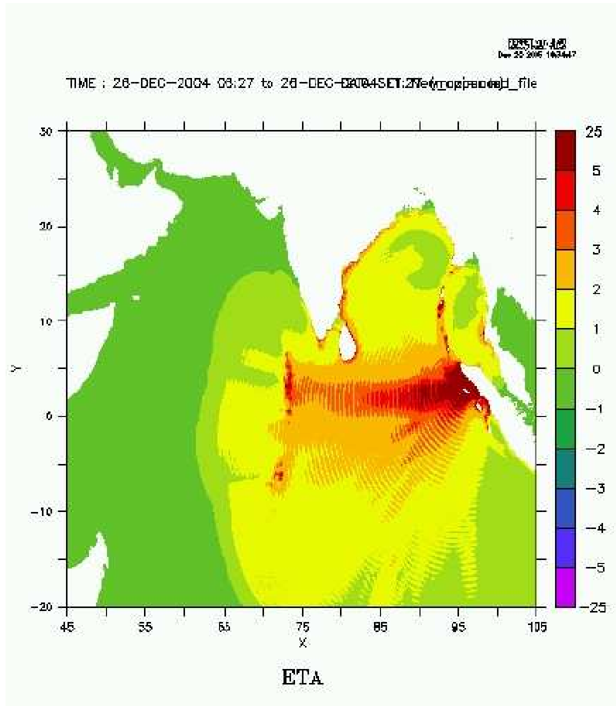


Figure 24 : Maximum wave amplitude

As the deep ocean tsunami approaches a distant shore, amplification and shortening of the wave occurs. This shows a trend that suggests the direction of the dissipation of wave energy. The dissipation is perpendicular to the major axis of the ellipsoidal fault plane. Another noticeable feature is the symmetry of the amplified waves. This can be attributed to the bathymetry of the ocean. Though ETOPO-5 bathymetry is used for the propagation of tsunami waves. The maximum amplification can be observed to be in the range of 4-15 m that suggests the wave height to be in the range of 8 – 30 m. The Sumatra region shows a higher amplification of the tsunami waves that caused tsunami waves to be of the height of 30 m in the region. The figure shows the directional focus of the tsunami-generating energy. In the earthquake that triggered the tsunami on December 26, 2004 a lot of energy in the initial earthquake rupture occurred in deep water (about 1 to 2.5 miles). This generated a lot of amplification of the tsunami waves. According to Eric L. Geist, USGS tsunami expert, the more the amplification of the waves, the bigger the run-ups. The primary direction of the tsunami-wave “focusing” and the tsunami energy was focused to the west, towards Sri Lanka and India, and to the East, towards Thailand.(Release 2005)

The curves below in figure 25 shows the maximum amplitude for various locations. It depicts wave amplitudes in the Sri Lanka coast as well as the Nagapattinam region. This shows many locations along the coast of India and other regions in the Indian ocean.

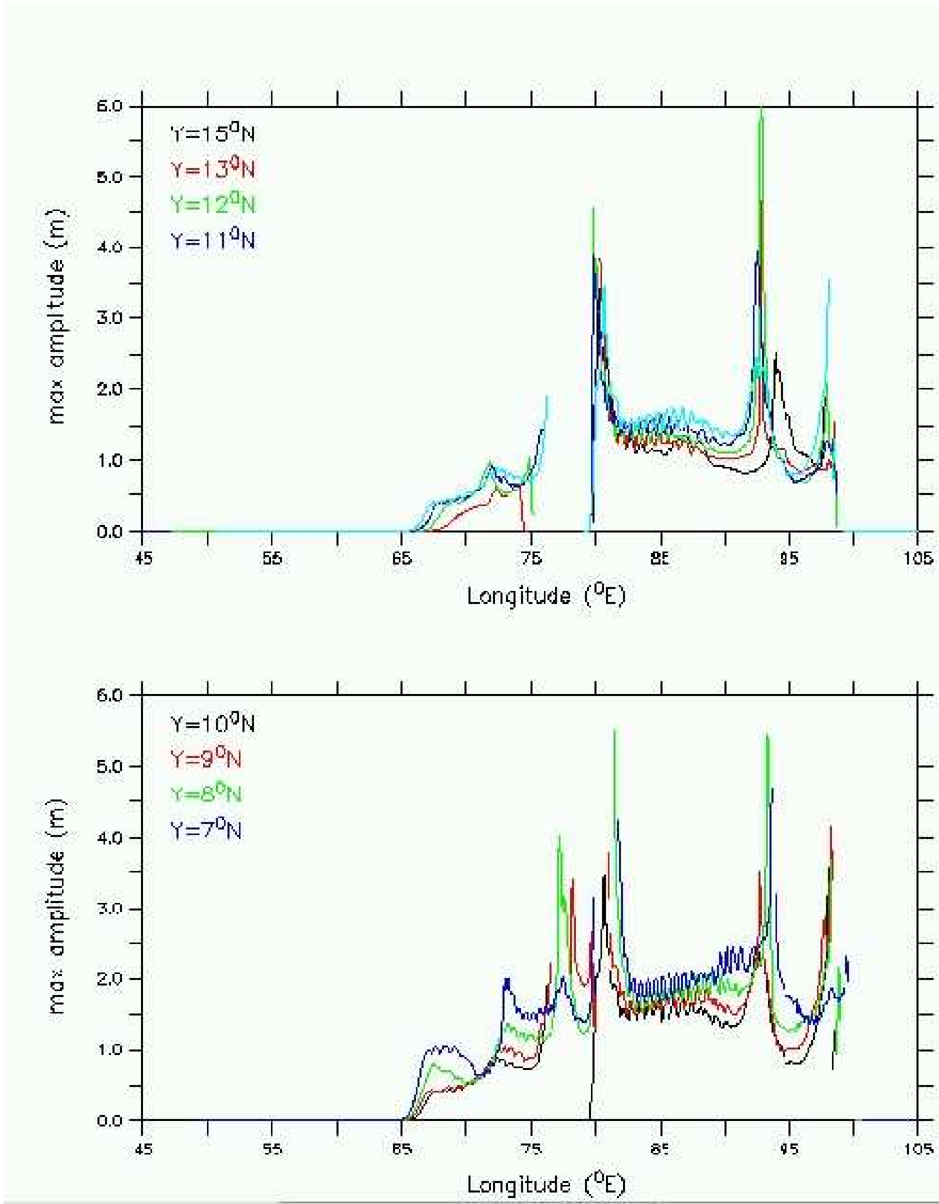


Figure 25: Maximum amplitude curves for various locations

5.9. Validation of the model results

The Tunami N2 model is used for the generation, propagation and amplification of tsunami waves. The results obtained from the model are compared with the tide gauge measurements. Because of the lack of detailed bathymetry/topography data in the model, the qualitative agreement between the two results should not be expected. With ETOPO –5 bathymetry data, the comparison does holds good as it implies that with better bathymetry data, the results will be more accurate in terms of their qualitative agreement. The amplification of tsunami waves for the event shows good agreement with the actual event.

Table 12: Comparison of model results with Tide gauge Measurement at various locations

Station	Latitude	Longitude	Tide Gauge Measurement Wave amplitude (m)	Model derived Wave amplitude (m)
Chennai	13.09°N	80.27°E	1.14	2.008
Nagapattinam	10° 46.0' N	79° 51.0' E	3.58	4.21
Andaman	11º 40N	92º 44E	4.09	5.88
Vishakhapatnam	17º 42’ N	83º18’ E	2.47	3.407
Tuticorin	8º 45’ N	78º 13’ E	1.90	2.289
Kochi	9º 15’ N	76º 07’ E	1.61	2.007

The above table shows the tide gauge measurements and the model results in terms of amplitude for various locations. It can be seen that the amplitude at the Andaman area is showing a higher value. This can be attributed to the location of Andaman region. It lies very close to the location of epicentre in the Sumatra region. With the incorporation of near-shore bathymetry for the coast of Nagapattinam, the model results show amplitude at the coast to be of the order of 4.21 m. Better results can be expected with detailed bathymetry and topographic data. Even the creation of the fault geometry has bearing with the final results of the simulation. The arrival time of the tsunami waves at the south-eastern coast of India is in agreement with the real event. In the actual event, the tsunami waves reached the coast of India in 180 minutes which holds good for the model simulation results for the arrival time at the Indian coast. The result of the amplification of tsunami waves at different locations shows good agreement with the real event where the height of the tsunami waves was in the range of 8 – 30 m. The model validation is done with respect to the tide gauge measurements for some locations and results were compared with the amplification of the tsunami waves using Tunami N2 model. Though there are differences in the values that are to be compared, but with ETOPO 5 bathymetry and creation of the fault geometry considering the simplest case of a half-ellipsoid model, deviation from tide gauge measurements for amplification of sea waves are on expected lines.

5.10. Limitations of the model

There are certain limitations to the Tunami N2 model that is employed for the generation, propagation and amplification of tsunami waves for the event of December 26, 2004. These have affect on the overall result on the numerical modeling. The fault geometry of the model is created with the half-ellipsoidal structure on the fault rupture. This is a simplistic case for the generation of tsunami waves. The earthquake that generated the tsunami has rather complex fault geometry. This simplistic assumption affects the overall result of the simulation. The model employs ETOPO 5 bathymetry instead of a detailed bathymetry that affects the model results. With the use of ETOPO 2, the model is expected to perform better. The model incorporates the near-shore bathymetry from National Hydrographic Chart for a small coastal area. Since, the simulation is done for the south-eastern coast of India, it would be better to incorporate the near-shore bathymetry for the entire coast. The model employs the 2D-coordinate system in the model. Detailed topography is not incorporated in the model simulation that could be beneficial in future research on estimating run-up and inundation extent.

6. Conclusion and Recommendation

6.1. Conclusion

The Indian Ocean Tsunami is the most destructive experienced by humanity since antiquity. The tsunami event of 26 December 2004 had varied implications on the psychology, social life, scientific considerations and understanding of hazards and priorities of mitigation measures. Moreover, it had affected the roots of political establishments and strategies of non-governmental organizations in their efforts to mitigate natural hazards. In a global perspective, this event will remain as the top priority in the agenda of assessment of natural hazards in the long run. The present work has fulfilled all its objectives and corresponding research questions in the broad framework of the thesis formulation.

The tsunami project in the coastal area of Nagapattinam had three objectives. The first two pertains to the mapping of the extent of inundation for the study region and subsequently, the damage to various landcover classes in the Nagapattinam area due to tsunami inundation. The IRS P6 LISS III satellite image is used to map the extent of inundation. This showed variations in the extent of inundation along the coast. Nagapattinam is a low-lying area and some places have higher inundation extent as compared to other regions because of their low-lying presence. Presence of creeks like Vedaranyam also helped in the intrusion of seawater. The landcover map is prepared from pre-tsunami IRS P6 LISS III satellite image. The damage to various landcover classes shows the various classes and the effect of tsunami inundation on them.

The third objective dealt with the numerical modeling of tsunami waves and the propagation state of the waves at various interval of time. The vital parameters required for numerical modeling of the tsunami waves are the initialising conditions and the bathymetry. Fault geometry is created to depict the initialisation of the waves based on the fault parameter. A simplistic method is used to create the fault geometry of the model with a half-ellipsoidal shape to the rupture area. This fault geometry is the basis for the initialisation of tsunami waves. Bathymetry data is an essential prerequisite for ocean wave modeling. In this scenario, the model is run with ETOPO 5 bathymetry data with a resolution of 9 km. Moreover, the incorporation of the near shore bathymetry data gave better information regarding the propagation state and amplification of the waves near the coast.

It can thus, be concluded that there are variations in the extent of inundation in the Nagapattinam area due to various topographic as well as man-made causes. The damage to various landcover classes due to inundation of seawater has made the plight of the people miserable in the area. Fieldwork carried out during the month of August gave a realistic impression of the tsunami event unprecedented in the history of natural disasters in India. The aftermath was vivid and the tragic stories of the event from the local coastal community gave an idea of the enormity of the damage to life and property in the region. Numerical modeling of the event is an attempt to understand the event from scratch and suggest awareness for rare but catastrophic events like tsunami.

6.2. Present Needs and Future Perspectives

Tsunami carried in its gamut various issues that need to be given appropriate consideration. One of the salient features in such a scenario is the mapping and impact assessment taking into consideration the ecological as well as human perspective. Risk and Vulnerability maps are essential requirements for effective policy-making in case of such a rare event as tsunami. Improvement in the simulation of the tsunami event may be achieved basically in two ways: by providing more accurate input data and by enhancing the numerical codes, which in turn implies identifying better models to describe complex processes and improving numerical techniques to solve the governing equations.

6.3. Improvements in data for numerical simulation

Tsunami propagation calculations are dependent on the input ocean depth. Accurate bathymetry data sets are required, as well as access to the data has to be ensured Shallow-water and Boussinesq approximation models are sufficient to carry out tsunami numerical simulations induced by earthquakes, but could be inappropriate for other sources such as landslides where other parameters like velocity, horizontal and vertical sea displacements may play a role. Techniques such as domain decomposition and nesting should be further developed for accurate computation of tsunami propagation from the source region to the coastal areas.

Improvements of tsunami calculations should be focused on the following aspects.

- Shallow-water or Boussinesq equations: suitability and limitations of the various models to deal with different processes like propagation, variations in bathymetry etc.
- Run-up, Overtopping, run-down, backwash.
- Interaction with structures and vegetation
- Bottom friction parameters in the coastal zone
- Development of interactive software techniques and procedures to perform tsunami forecast.
- Sensitivity of the result to each parameter (e.g. bathymetry, topography, bottom friction)

In numerical modeling of Tsunami event, accuracy and performance of the simulation are key aspects of consideration. Thus, near-accurate data is an important criteria for carrying numerical modeling of events like tsunami. Geological, Seismological and Geodetic parameters are required to characterise the sources. Bathymetry, topography, bottom friction data on coastal zone, potential for morphological changes in the near-shore region and in-filed data are essential requirements to carry out numerical modeling of tsunami. It is strongly recommended that data access and more importantly, real-time access are needed to run real-time simulation models. It has to be emphasized that comparison of tsunami simulation results and of observations can be used to improve modeling techniques. Tsunami numerical models can be used in the framework of inversion approaches to better characterise the source (e.g. size and fault dislocation for earthquakes).

6.3.1. Validation of the model

Validation of the model is an important consideration that has to be addressed in the framework of the comparison to physical models data, testing the validity of approximations against numerical models, comparison with observational data and assessment of the efficiency and accuracy through benchmarks of numerical methods.

6.3.2. Sensitivity analysis

Sensitivity analysis should be carried out to determine the influence of each source parameter in the tsunami generation and the basin feature like bathymetry and topography that play a vital role in the tsunami initial phase. There is the need to carry out global events, sine they are potentially the most destructive.

6.3.3. Tsunami Scenarios

In recent times, using scenarios has been a technique that has been widely used to make risk assessment and is based on numerical simulation. These scenarios should be based on tsunami catalogues and on the sesimotectonic knowledge of the region. As tsunamis are rare events, the event is difficult to reproduce, especially for lack of understanding of the generation mechanism. Methodology on sensitivity analysis and reliability analysis holds a lot of importance in case of generating tsunami scenarios. Reliable scenarios can help coastal zone management strategies, providing inputs for local authorities, and can increase the safety perception of the coastal community. (Tinti 2005)

It is stressed that current emergency plans do not cater to the challenges posed by an event like tsunami in the Indian Ocean.

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Appendix 1 : Field Pictures

The field survey was carried out from 6th August 2005 till 11th August 2005 from the Nagapattinam coastline to Point Calimere. Though 8 months had elapsed since the destructive tsunami came and created havoc with coastal communities, the damage could still be seen near the entire coastal stretch. Here are some photographs that would reveal the extent of damage. Few selected photographs are shown here which were taken during the field visit to Nagapattinam district. There had been extensive damage due to tsunami. In the villages adjoining the coast, watermarks as high as 5 ft could be seen. The interviews were also conducted with the local fisherman, residents of coastal villages and eyewitnesses to the tsunami of December 26, 2004. The general response of the people suggested that people who were near the shore heard sounds as if a helicopter is approaching them while people in the villages were caught unaware with the tsunami waves. The time difference between the first and the second wave was approximately 30-40 minutes.

Damage in Samunthanpete village. Huge blocks of construction materials are shown in rubbles.

Damage in Pattenacheri village

Damage at Periyakuttahai village

Erosion at Periyakuttahai village

The above two pictures show the remains of the lighthouse constructed during the Chola reign. This tall structure had been damaged due to tsunami waves. The enormity of the damage and destruction can be gauged from the fact that the other half of the lighthouse was taken away to a distance of around 300 meters from the original position. The picture below (left) shows the coastal area of Tharangampadi that suffered extensive loss due to tsunami, while the military bridge at Karaikal that was badly damaged disrupted the day-to-day traffic and a temporary bridge is constructed to re-establish the links.

Coastal village of Tharangambadi.

Military bridge at Karaikal

The house shown above in the coastal village of Tharangampadi is around 200 meters from the shore and a lot of fishing activities are carried out in this area. As interviews with local fisherman suggested that on the day when tsunami happened, most of the fisherman were on their way and some were preparing their boats and fishing accessories for their day-to-day activities. The people tried to run away from the incoming waves but with houses and other constructions in the place, some were trapped and could not find a safe passage. Moreover, the material carried with these incoming waves hit the people who were running for the safety of their family and themselves.

Temporary shelters at Tharangangampadi village

An Infant burial site

After the destruction due to the tsunami of December 26, 2004 many temporary shelters have been created for the affected people. These have been done with the help and support from Government of India, Tamil Nadu state government and a lot of work is done by private non-governmental organizations. The infant burial site shown in the picture above (right) shows the enormity of the destruction. This mass gravesite stands testimony to the fact that around 300 children were buried on this piece of land. The pictures below show casuarinas plantations that were damaged due to the tsunami waters but they acted as natural barriers to prevent inundation. The picture on the right gives glimpses of hope for people who are living in temporary shelters to be getting permanent houses.

Reconstruction Activities

Casuarina plantations

Appendix 2: Questionnaire

Questionnaire for the Field visit to Nagapattinam

I. Basic Information

Q1. Interviewee's name, date of Interview, gender, age, profession, place and where was the interviewee during the tsunami event?

II. Earthquake Information

Q2. What was the main damage from the earthquake (s)?

Q3. His personal account of the event?

Q4. Were any precursors to earthquake noticed?

III. Tsunami Information

Q5. What was the situation before the Tsunami (meteorological, sea level, light conditions, sounds or noise?

Q6. How much was the approximate time between main earthquake shock and wave arrival?

Q7. What was the behaviour of the water?

Q8. How high were the waves?

Q9. From what direction did the water come? And in which direction did it go?

Q10. How did people escape and were there obstacles?

Space for additional comments

Appendix 3: Tsunami Damage

The table below shows the damage in the states of Andhra Pradesh, Kerala, Tamil Nadu, and Pondicherry.

Tsunami damage in India					
Factor	**Andhra Pradesh**	**Kerala**	**Tamil Nadu**	**Pondicherry**	**Total**
Population affected	211,000	2,470,000	691,000	43,000	3,415,000
Area affected (Ha)	790	Unknown	2,487	790	4,067
Length of coast affected (Km)	985	250	1,000	25	2,260
Extent of penetration (Km)	0.5 - 2.0	1 - 2	1 - 1.5	0.30 - 3.0	-
Reported height of tsunami (m)	5	3-5	7-10	10	-
Villages affected	301	187	362	26	876
Dwelling units	1,557	11,832	91,037	6,403	110,829
Cattle lost	195	Unknown	5,476	3,445	9,116

Source URL: http://www.tsunamiquake.org

Appendix 4: Temporary Shelter Details

TEMPORARY SHELTERS DETAILS in NAGAPATTINAM

Sl. No.	Name of the Location	No. of families
1	Akkaraipettai	768
2	Keechankuppam	960
3	North Pogainallur	44
4	Nambiar Nagar	630
5	Ariyanattu Theru	800
6	Vedaranyam Chetti Theru	400
7	Nagathoppu, Warehouse area	50
8	Palpanaichery, MGR Nagar, Nallianthottam	200
9	Nagathoppu, Cooks Road	220
10	Keelapattinacheri	100
11	Manalmedu	62
12	Silladi Nagar, Keelapattinacheri, Rly.Backyard, Melapattinacheri, Pandagasalai	624
13	Samanthanpettai	340
14	Mela Pattinachery, Pandagasalai.	200
15	Keela Pattinacheri, Vadakudi Road & others	500
16	Velankanni Konarthottam	200
17	Velankanni Konarthottam	202
18	Velankanni Konarthottam	172
19	Velankanni Konarthottam	90
20	Ariyanattu Theru	23
21	Mahilchi Matha koil street	137
22	Kallar – Meenavar street	128
23	Kallar – Uzhavar street	44
24	Serudur	272
25	Kameswsaram	72
26	Vilunthamavadi South	127
27	Vilunthamavadi North	30
28	Vellapallam	262
29	Vanan Mahadevi	263
30	Pushpavanam	275
31	Periyakuthagai	52

32	Arcottuthurai	183
33	Thirumullaivasal	575
34	Thoduvai	305
35	Koolaiyar	120
36	Poompuhar	365
37	Pudukuppam	143
38	Vanagiri	430
39	Melamoovarkarai	64
40	Keelamoovarkarai	155
41	Palayar	621
42	Madavamedu	95
43	Kottaimedu	100
44	Ola Kottaimedu	60
45	Chinnankudi	160
46	Chinnamedu	70
47	Thalampettai	44
48	Pudhupettai	240
49	Perumalpettai	181
50	Pillai Theru	7
51	Chinna Manickampangu	23
52	Chinnurpettai	40
53	Chandrapadi	221
54	Tharangambadi	708
55	Karantheru	20
56	Kesavanpalayam	80
57	Kuttiyandiyur	215
58	Vellakoil	84
	TOTAL	**13556**

These are data sets collected from the Collectorate in Nagapattinam that shows the temporary shelters provided to the coastal community affected by the tsunami that happened on 26th December 2004.These are efforts from government and non-governmental organisations.

Appendix 5: GPS survey list

Here is a list of places where GPS survey was carried out during the fieldwork in the month of August.

S. No.	Latitude/Longitude	Location	Remarks
1	10°45′21″N, 79°50′26″E	Temporary railway bridge (Devanadi river)	River. Temporary bridge was constructed to restore transportation.
2	10°50′58.8″N, 79°51′54.4″E	Periyakuttahai village (mosque)	Erosion of some landmass is shown in the picture.
3	10°23′23.3″N, 79°52′11.4″E	Arukkatuthurai village (Fisherman's area)	
4	10°23′48″N, 79°51′0″E	Thopputhurai area	Settlement area
5	10°20′6.2″N, 79°50′40.5″E	Vedaranyam Agasthyanpalli	Salt pan area
6	10°19′49.2″N, 79°50′37.5″E	Vedaranyam forest cover	Salt pan area where tsunami water penetrated and caused extensive damage
7	10°16′59.9″N, 79°50′25″E	Grassland and shrub area	Shrub area
8	10°16′36.3″N, 79°50′36.3″E	Kodaikanal coast	Mud flat region
9	10°54′35.7″N, 79°50′13.3″E	Military Bridge, Madhuvadi, Karaikal	Military bridge damage (Picture included)
10	11°01′25.8″N, 78°51′27.8″E	Tharangampadi Church	Damage to this area but no damage to the Portugese museum nearby.
11	11°01′21.6″N, 79°51′25.7″E	Thanjore Museum, Tarangampadi	Tsunami water broke the main gate and gushed inside the museum. This was a Danish Museum sold to East India Company
12	11°01′51.6″N, 79°51′24.3″E	Tharangampadi coast	This area had the largest extent of house damage. The type of houses present were mainly masonry walls