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# CLASSIFICATION OF TSUNAMI HAZARD ALONG THE SOUTHERN COAST OF INDIA: AN INITIATIVE TO SAFEGUARD THE COASTAL ENVIRONMENT FROM SIMILAR DEBACLE

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## Abstract

Prevention of natural disasters is not feasible but the destruction it conveys could be minimized at least to some extent by the postulation of reliable hazard management system and consistent implementation of it. With that motive, the beaches along the study area have been classified into various zones of liability based upon their response to the tsunami surge of 26 December 2004. Thereby, the beaches which are brutally affected has been identified and the beaches which are least. Based on the seawater inundation with relative to their coastal geomorphic features, we have classified the tsunami impact along the coast and the probability of the behaviour of the beaches in case of similar havoc in future. The maximum seawater inundation recorded in the study area is 750 m as in the case of Colachel and the minimum is 100 m as in the case of Kadiapatanam, Mandakadu and Vaniakudy. Beaches like Chinnamuttom, Kanyakumari, Manakudy, Pallam and Colachel are under high risk in case of similar disaster in future and the beaches like Ovari, Perumanal, Navaladi, Rajakkamangalam, Kadiapatanam, Mandakadu, Vaniakudy, Inayam and Taingapatnam are under least viability.

## 1. Introduction

A Tsunami is a killer wave that brings great havoc in the coastal environment. On 26th December 2004, tectonic disturbances happened in the Java Sumatra islands with an intensity of around 9.3 in the Richter scale extend to the Southern Indian Ocean basin. One such region is south west part of India facing the Bay of Bengal and Arabian Sea. Detection of Tsunami is possible only in nearshore zone where the shoaling effect can be observed. The major destructions in this area are due to the run-up height of 3m-4m leading to erosion activities changes in the beach slope variation. The first visible indication of an approaching Tsunami is a recession of water by the through preceding an advancing wave. A rise in water level is amounted to one half the amplitude of the decreasing water level. The wave moved to shore as above with churning front. In the shallow water of bay and breaker has initiated the seizing.

26th December 2004 havoc induced more damage in the southwest coast compared to southeast coast of India. It did raise the concern of scientists and emergency planners about the impact of larger earthquake/tsunami from the Java Sumatra coast. With increased awareness of the tsunami hazard, there has been confusion about areas at risk and areas of safety. Some areas of high hazard have no evacuation planning or tsunami awareness. The hazard maps produced by this study is to improve awareness of tsunami hazards and to encourage responsible emergency planning efforts by illustrating the range of possible tsunami events based on the best currently available information.

The coastal area has been subjected to tsunami which had wrought a major impact on nearshore morphology forming a risk to any vulnerable coastline. This vulnerability leads to a long term environmental impact along the shore. The tsunamis hit the obstacles that come along their path with great ferocity and the east coast (islands) was the first obstacle which the huge tidal waves encountered, causing destruction all along. All the areas remained like deserted battlefields with broken buildings, dead bodies, carcasses of animals, uprooted trees and deserted and lone houses and huts. With increased awareness of the tsunami hazard, there has been confusion about areas at risk and areas of safety. Some areas of high hazard have no evacuation planning or tsunami education efforts. Unnecessary evacuation increases exposure to other earthquake hazards. The hazard maps produced in this paper is intended for educational purposes, to improve awareness of tsunami hazards and to encourage responsible emergency planning efforts by illustrating the range of possible tsunami events based on the best currently available information.

## 2. Study Area

The study area (Figure. 1) lies between Latitude of N $8^0$ 04' to N $8^0$ 17' and Longitude of E $77^0$ 32' to $77^0$ 54' E at southern and western part of the Tamilnadu State, India. It encompasses the districts of Kanyakumari and Tirunelveli. The study area is bounded by Indian Ocean in the south, Arabian Sea in the west and Bay of Bengal in the east but the main part of the coast faces the Arabian Sea with mountains and undulating valleys in the north. The study area is manifested with marine terrace, sand dunes, beach ridges, estuaries, floodplains, beaches, mangroves, peneplains, uplands, sea cliff, etc., Apart from the perennial river Thamirabharani, streams like Nambiyar, Hanuman, Palaiyar, Panniyar and Valliyar forms the major drainage system along the study area with several other creeks and brooks. Most of the beaches are erosional in nature and are enriched with workable deposits of placer minerals (Angusamy and Rajamanickam, 2000). Most of the beaches are devoid of dune and habitually espouse a steep gradient in the beach face. Coconut plantation encircles most the beaches beyond the dune. Rich growth of mangrove and salt marshes has been developed in the beaches near estuary especially in Manakudy. The continental shelf along the study area extends, generally, far away from the shoreline.

## 3. Materials and Methods

Beach profile survey has been performed using levelling and surveying equipments following Stack and Horizon Method speculated by La Fond and Prasada Rao (1954) which was later simplified by Emery (1961). Intense field survey has been carried out to decipher the inundation extent.

The inundation distance of the seawater has been decoded by its signature in the coastal settings and from the local people's information. Digital Elevation Model (DEM) has been projected for the study area using Surfer package.

Tsunami hazard maps has been prepared using Geographic Information System (GIS) technique – ArcGIS (9.1) based on the inundation distance with respect to the nature of the coast to show the inland extend of flooding and topography of the area.

The beaches of the study area have been classified into different zones based on their relative geomorphic features and thereby the vulnerability could be decoded based on the inundation extent with respect to the coastal geomorphic features which in turn would develop a criteria to delineate the hazard area boundaries. Accordingly, the beaches of the study area have been divided into different zones based on their geomorphic features as below

Open Coast Zone

This zone is a low-lying zone in which the coast is relatively in the lower position with reference to the MSL (Mean Sea Level), say for example, submergent coast, sandy beach, etc.,

Estuary Zone

This zone includes the coasts neighbouring a river mouth/ tidal inlet/ creek and similar other coastal features.

Upland Zone

This zone includes the coasts which are comparatively elevated well above the MSL, say for example, emergent coast, rocky coast, etc.,

Tsunami hazard area boundaries are initially defined for each zone above based on elevation and inundation distance.

We emphasize numerous sources of uncertainty in hazard delineation. The size and character of faulting in a specific event may also amplify or reduce the size of the resulting tsunami. Only recently has the impact of tsunami has been recognize in contributing to tsunami hazards. The maps are intended to improve awareness of tsunami hazards.

## 4. Results and Discussion

The extent of inundation has also been determined by the angle of incidence of the tsunami surge as well as its velocity. Due to the presence of Sri Lanka (Figure. 2), most of the beaches along the east coast had experienced the ‘shadow waves’ but the beaches along the west coast starting from Kanyakumari had experienced the refracted waves of comparatively high rapidity. Hence, the beaches along the east coast are under least viability to any such similar hazards in future whereas high vulnerability prevails along the west coast beaches as they are devoid of any natural blockade (Narayana et al, 2005; Raval, 2005).

Figure. 3. and Table. 1. shows the coverage of the inundated seawater during the havoc along the study area. Seawater inundation had occurred to the maximum of around 750 m in Colachel and in the beaches of Kadiapatanam, Mandakadu and Vaniakudy the inundation had not exceeded 100 m. It has been inferred that maximum inundation has occurred in the coast where there is a river mouth or an estuary as in the case of Manakudy and Colachel. The inundation proved to be ineffective along the coast where rock exposures are present as in the case of Muttom and Kadiapatanam. Though there are numerous river mouths in the east coast, inundation has not claimed vast inland because of the fact that the approached waves are of low intensity due to the obstruction rendered by Sri Lanka. Despite of the fact that the west coast beaches have experienced, comparatively, high intensity tsunami surge, the fact that most of the coastal regions beyond the backshore are well vegetated with coconut plantations and other similar coastal plant life which would have discouraged the inundation to a considerable degree as attested by the beaches of Mandakadu, Taingapatnam, etc., (Barbara Keating et al, 2004; Glenda Besana et al, 2004; Koji Minoura et al, 1994)

The inundation of seawater encouraged by the tsunami waves could not proceed for longer distance in the beaches which are elevated, comparatively, from the mean sea level (MSL) as attested by the beaches of Muttom, Kadiapatanam and Mandakadu (Chandrasekar, 2005) whereas inundation has happened to its utmost coverage in the beaches where the coast is, relatively, lower than the MSL as evident from the beaches of Manakudy and Colachel (Figure. 4. a & 4.b)

The hazard map provides the bird's eye view of the impact of the tsunami surge along the study area and it has been prepared by considering the proper procedures (Chandrasekar and Loveson Immanuel, 2005; Fumihiko Imamura, 2004; Joel Bandibas et al, 2003; Timothy Walsh et al, 2000)It is well evident from Figure. 5 and Figure. 6 that west coast beaches have been brutally affected when compared with the east coast beaches. To be specific, the north eastern beaches were least affected and so is the north western beaches which may be attributed to the fact that the impact of the tsunami surge could not dominate in those coastal regions due to the variation in the intensity of the approached tsunami surge. It has been inferred that the impact of the tsunami surge was high in the southern most part of the study area as most of the high vulnerable beaches falls on that region like Chinnamuttom, Kanyakumari, Manakudy and Pallam since they are awfully very much exposed to the refracted and diverted waves from Sri Lanka.

Colachel was the only beach to suffer maximum destruction in the northwestern coast as the inundation has been encouraged by the river mouth. There were manyother beaches neighbouring river mouth but were not much affected as Colachel and Manakudy which might be due to the fact that the bathymetry of Colachel and Manakudy and their coastal configuration along with their coastal geomorphic features have favoured much inundation there. Manakudy, due to its awful location in the southern tip of the continent facing the direction of the refracted waves from Sri Lanka along with a negative feature of estuary to facilitate the inundation had suffered utmost catastrophe. The presence of a notable promontory at Muttom had been found to acted as a safeguarding feature in screening the tsunami surge diverted and refracted from Sri Lanka and then from Kanyakumari, to the beaches northwest of Muttom.

It has been inferred that the geomorphic features had also played a vital role in the partiallity in destruction (Nobuo Shuto, 2001) and hence, the geomorphic features of the beaches were also taken into account in differentiating the tsunami hazard classification along the study area (Table 2 and 3). Based on the inundation extent with relative geomorphic features, the tsunami hazard classification map has been prepared for the study area (Figure. 5, Figure. 6 and Table.4)

This paper recognizes the complexity of tsunami hazards. Despite of the fact that tsunami could strike the coast at high velocity, the fluctuating surges of water would cause infilling and draw down bays and send volume of water miles inland along large coastal rivers. The nature of the hazard and the likely inundation impact will differ in the different types of area present along the study region.

## Conclusion

From the above investigation it has been inferred that the tsunami impact is more in the beaches of low lying flat topography as in the case of Manakudy, Colachel, etc., Based upon the elevation of the coast the inundation of the seawater influenced by the tsunami had varied from few meters as in the case of Mandakadu, Kadiapatanam, Vaniakudy, Inayam, Ovari etc., to around 750 meters inland as in the case of Colachel. The High lying undulating topography have less impact during the tsunami as in the case of Muttom, Kadiapatanam, etc., Furthermore, the coastal vegetation have been found to be a reliable feature in checking the seawater inundation and they had really served as a initial line of defence in controlling the inundation as in the case of Mandakadu, Taingapatanam, etc.,

It is well evident from the field observation that the river mouths and estuaries may facilitate the inundation of seawater under certain critical circumstances as attested by the beaches of Manakudy and Colachel.

The hazard map thus prepared bestow a panoramic view of the impact induced by the tsunami surge and the response of the respective beaches to the unexpected hazard. It exposes the beaches which are severely affected, thereby providing some probable clues for their destruction. The hazard map urges the need of proper coastal hazard management programme and would definitely serve as a guide to initiate the hazard management system as it shows clearly the beaches where immediate action should be taken and the beaches which need consistent disaster management measures.

**Acknowledgement**

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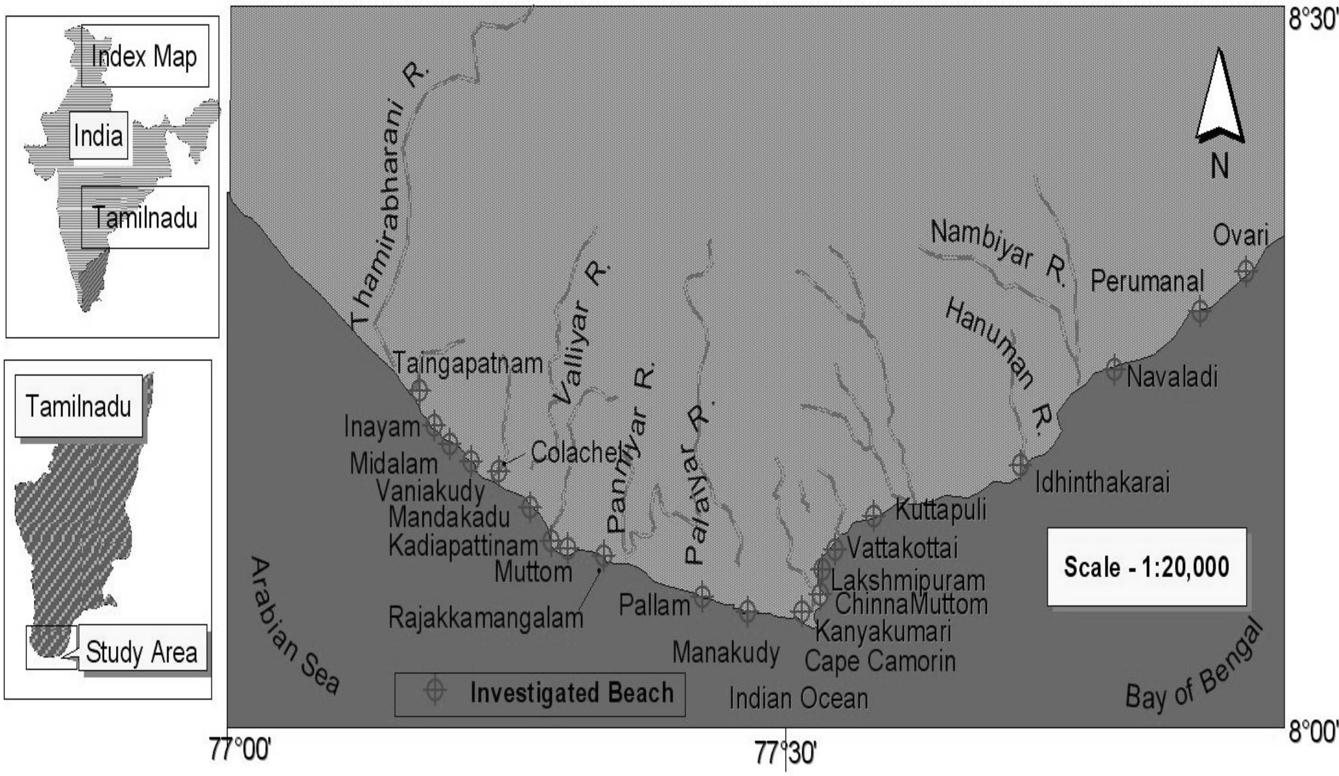


**Figure. 1. Location map of the study area**

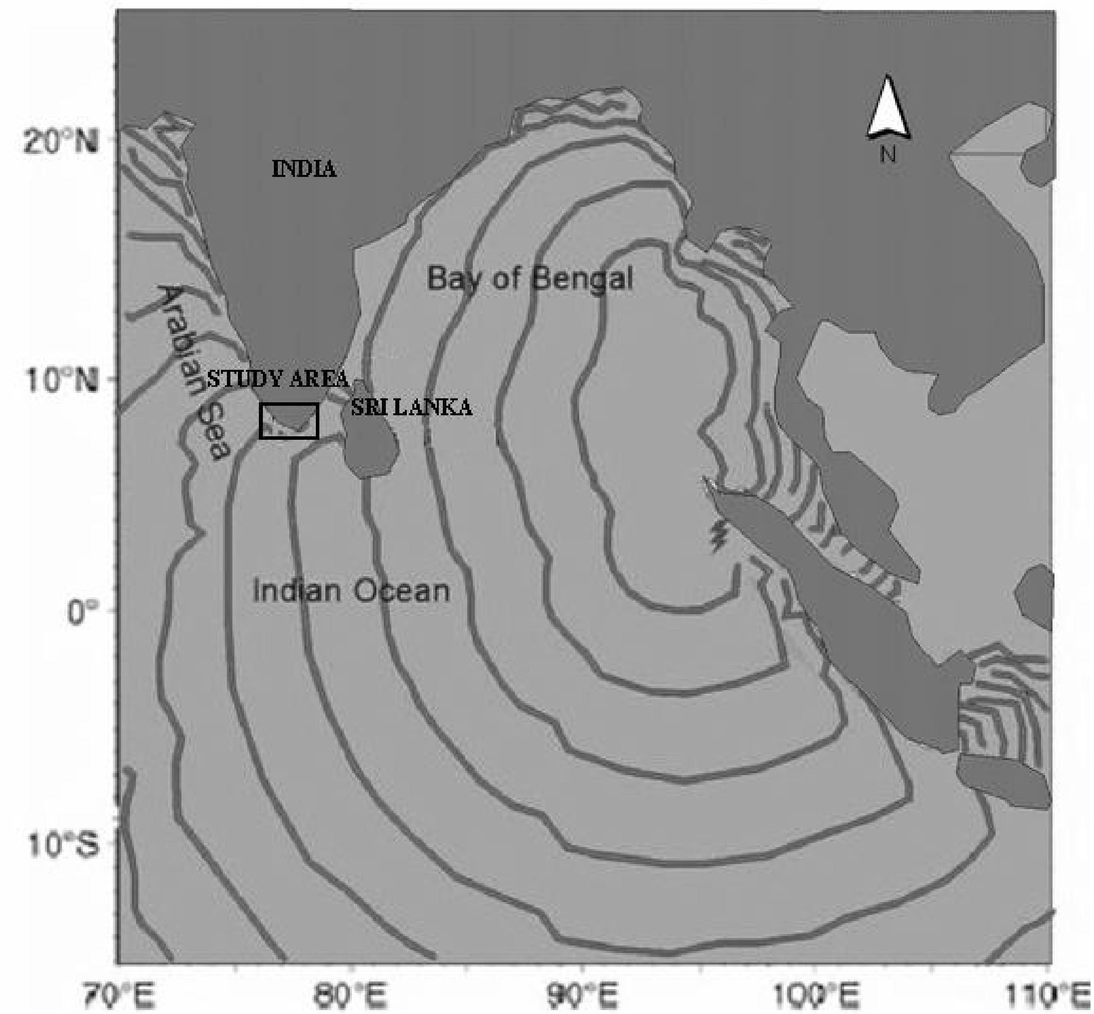


**Figure. 2. Nature and Angle of Incidence of the Tsunami Surge Approached the Study Area**

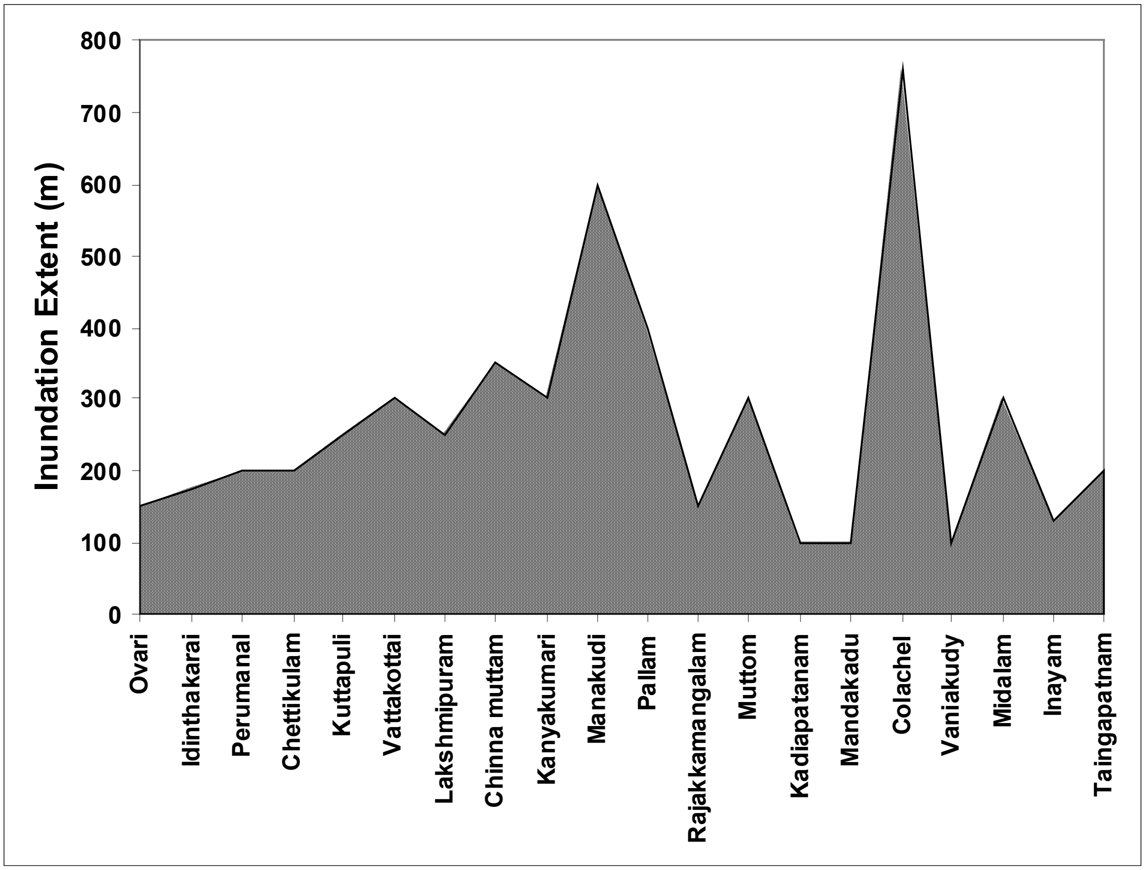


**Figure. 3. Inundation Distance Limit along the Study Area**

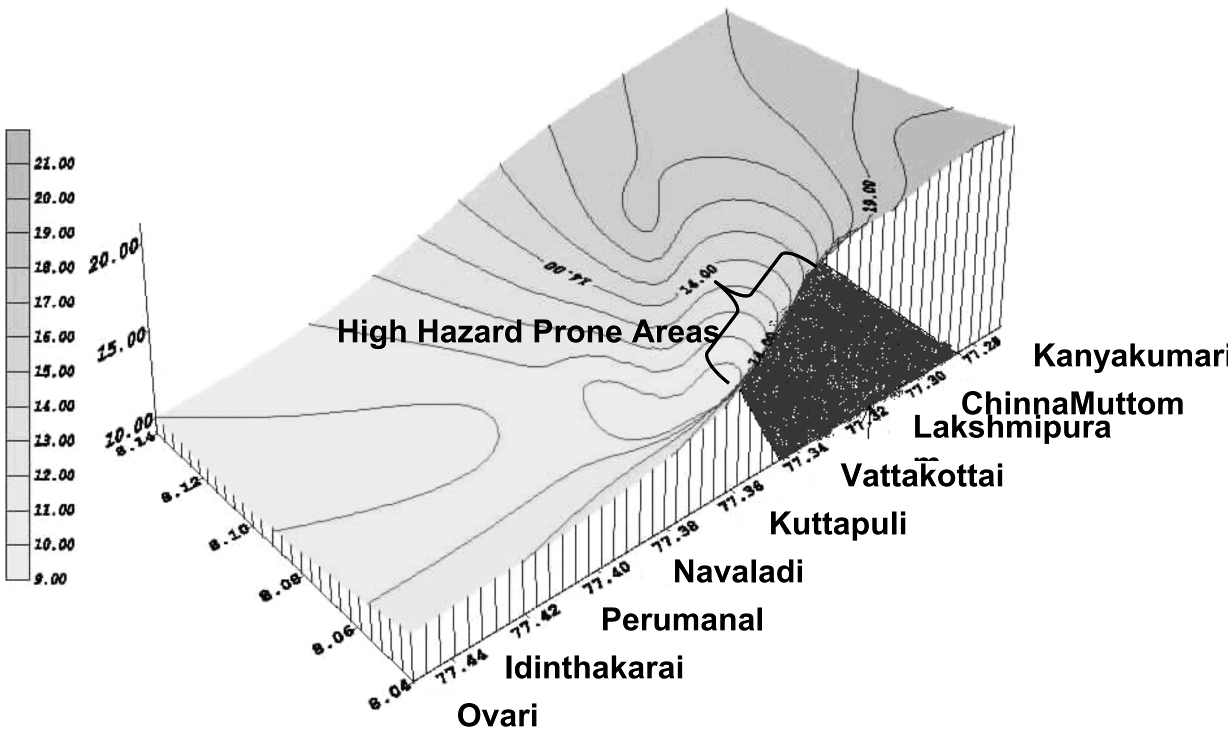


**Figure. 4. a. Digital Elevation Model (DEM) from Ovari to Kanyakumari**

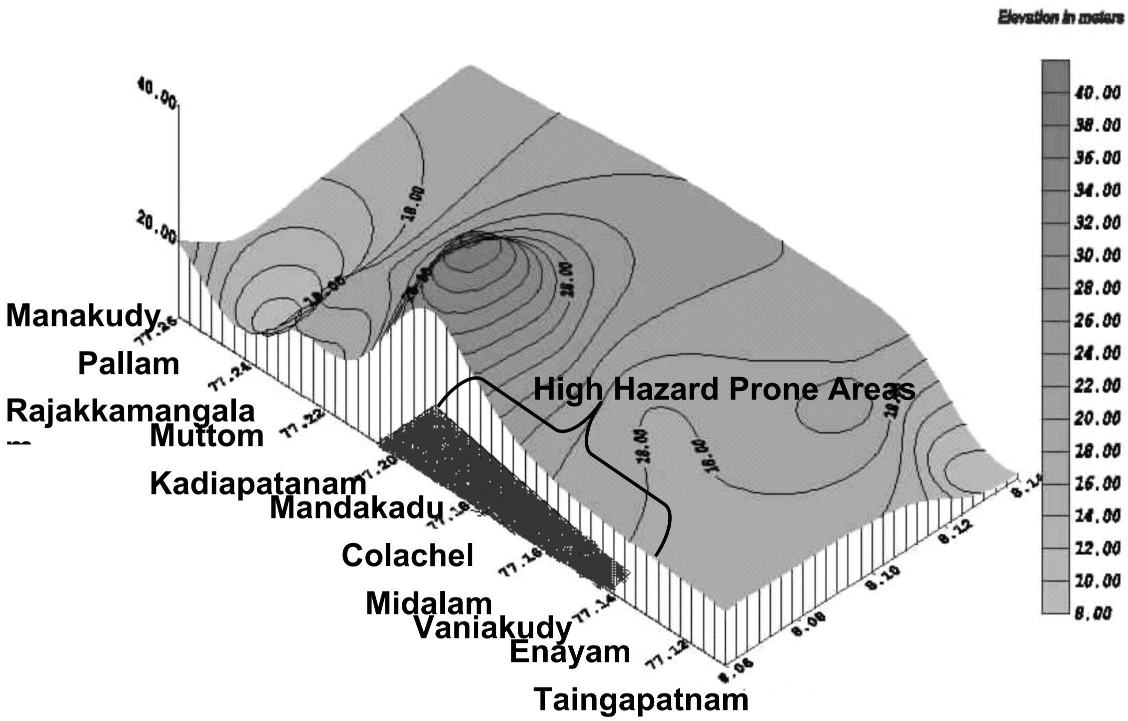


**Figure. 4. b. Digital Elevation Model (DEM) from Manakudy to Taingapatnam**

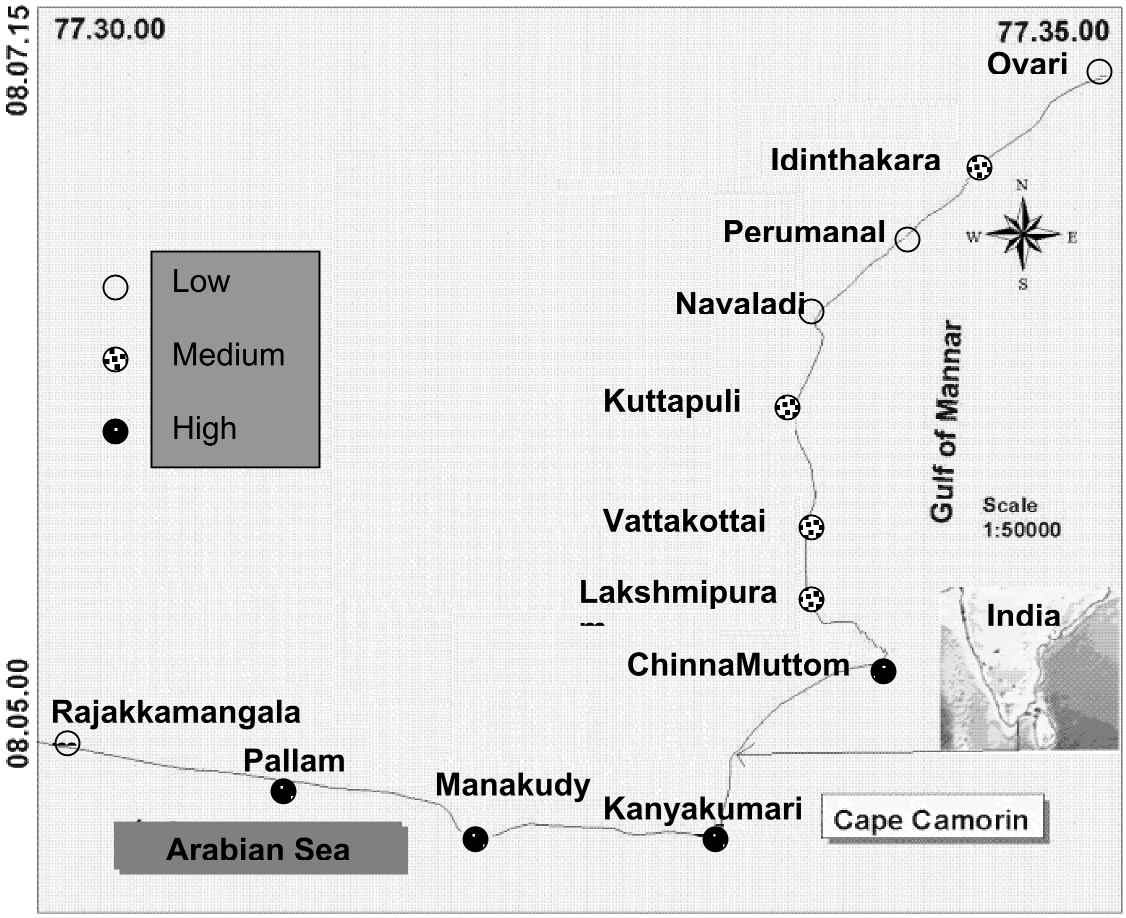


**Figure.5.a. Tsunami Hazard Classification Map for Ovari to Rajakkamangalam**

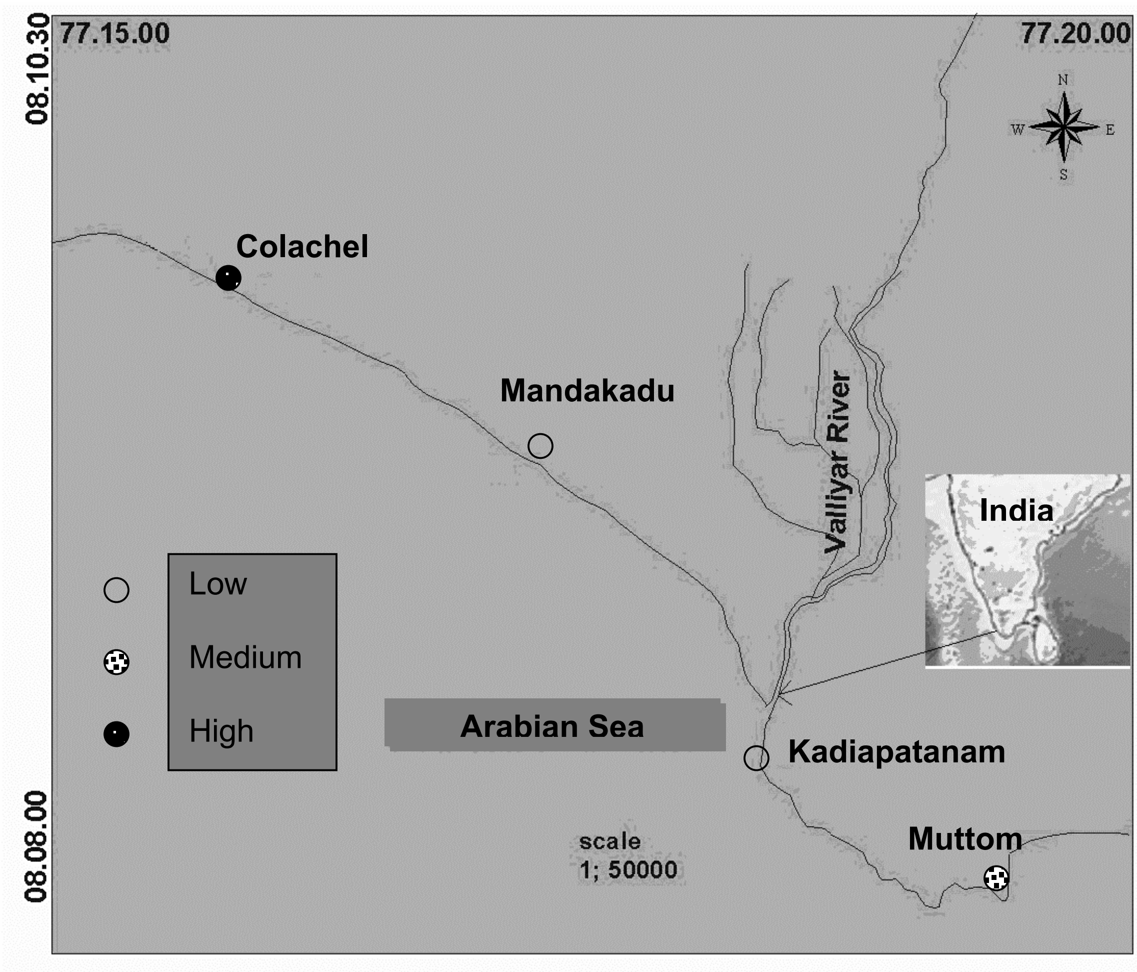


**Figure.5.b. Tsunami Hazard Classification Map for Muttom to Colachel**

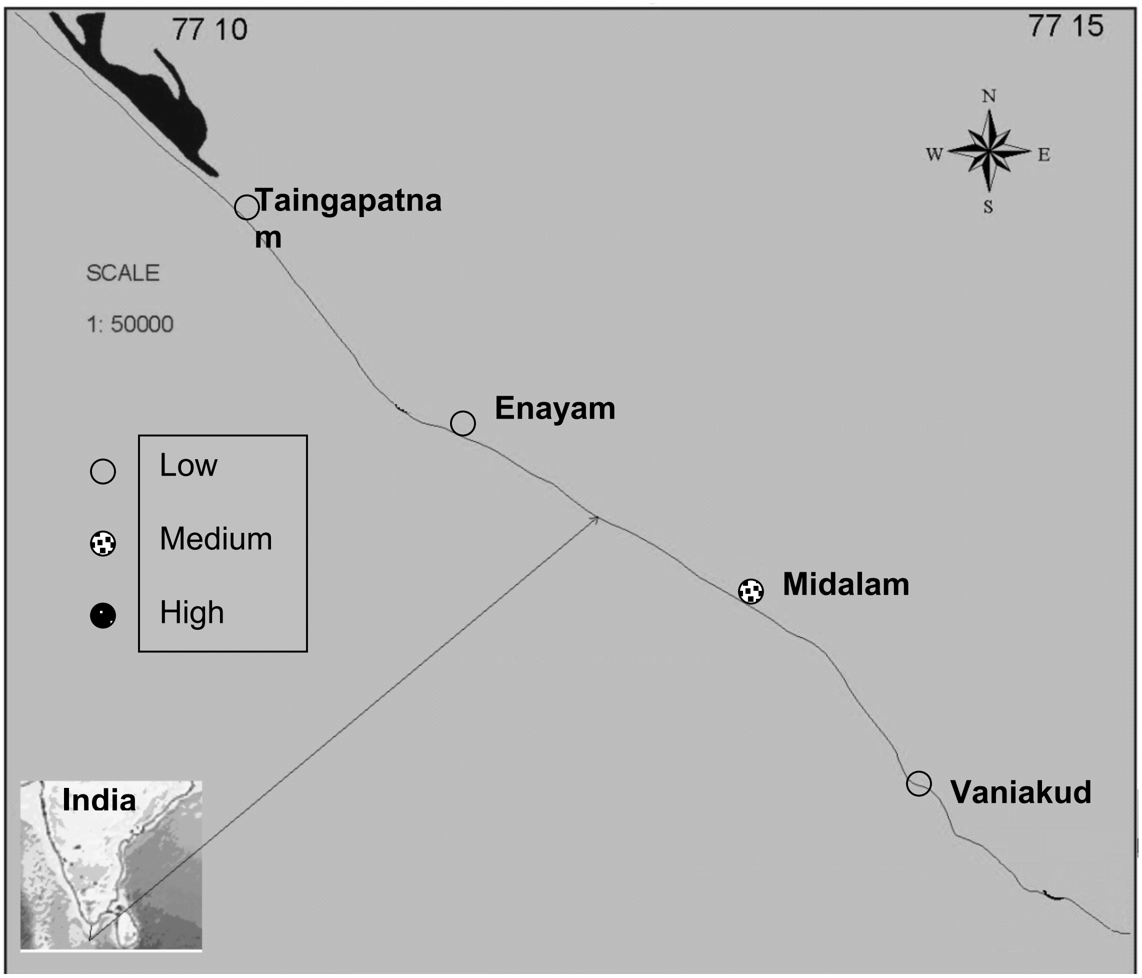


**Figure.5. c. Tsunami Hazard Classification Map for Vaniakudy to Taingapatnam**

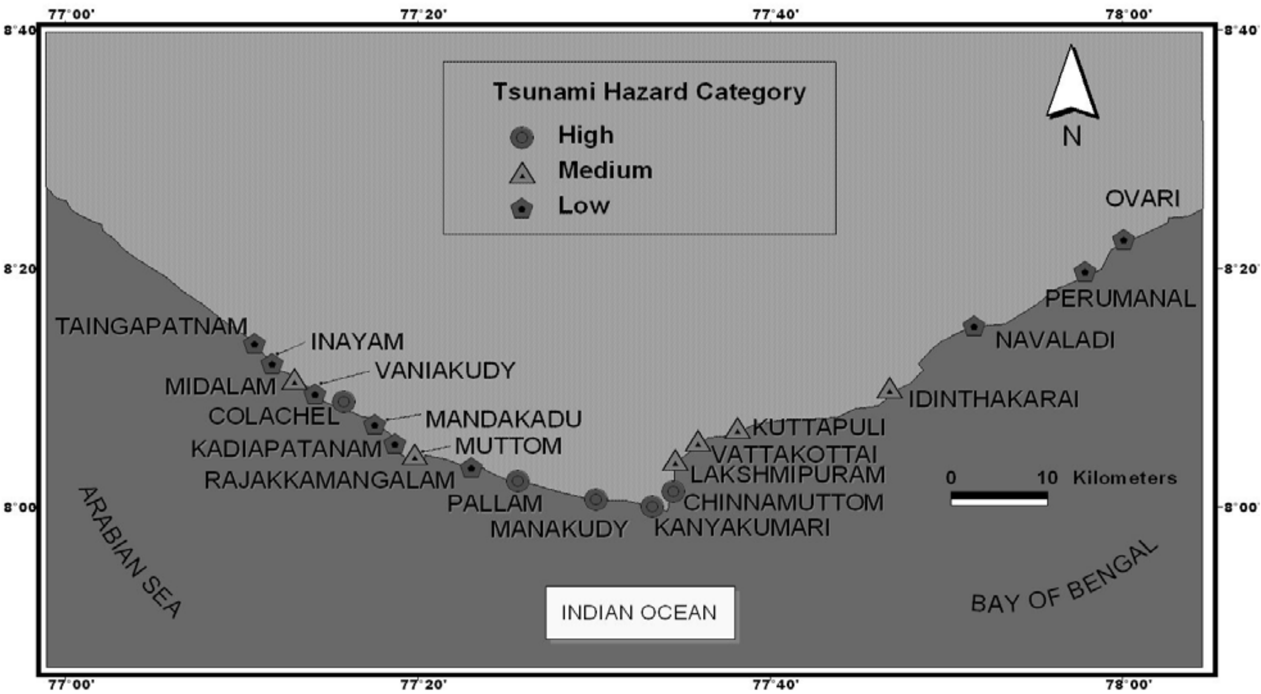


**Figure.6. Integrated Tsunami Hazard Classification Map of the Study Area**

**Table 1. Inundation Distance Extent along the Study area**

| Location | Longitude | Latitude | Elevation (m) | Inundation distance (m) |
|---|---|---|---|---|
| Ovari | 77.49 | 8.17 | 19 | 150 |
| Idinthakarai | 77.45 | 8.14 | 18 | 175 |
| Perumanal | 77.39 | 8.09 | 17 | 200 |
| Navaladi | 77.37 | 8.08 | 16 | 200 |
| Kuttapuli | 77.36 | 8.08 | 16 | 250 |
| Vattakottai | 77.34 | 8.07 | 15 | 300 |
| Lakshmipuram | 77.34 | 8.07 | 16 | 250 |
| Chinna muttam | 77.34 | 8.06 | 17 | 350 |
| Kanyakumari | 77.33 | 8.04 | 21 | 300 |
| Keelamanakudi | 77.29 | 8.05 | 09 | 600 |
| Pallam | 77.25 | 8.05 | 14 | 400 |
| Rajakkamangalam | 77. 22 | 8.06 | 16 | 150 |
| Muttom | 77.19 | 8.07 | 11 | 200 |
| Kadiapatanam | 77.18 | 8.08 | 14 | 100 |
| Mandakadu | 77.16 | 8.09 | 16 | 100 |
| Colachel | 77.15 | 8.1 | 12 | 750 |
| Vaniakudy | 77.14 | 8.11 | 16 | 100 |
| Midalam | 77.12 | 8.12 | 17 | 300 |
| Enayam | 77.09 | 8.13 | 15 | 130 |
| Taingapatnam | 77.1 | 8.14 | 14 | 200 |

**Table. 2. Description of Beaches based on their Geomorphic features**

| Description | Beach |
|---|---|
| Upland Zone | Chinna Muttom, Kanyakumari, Muttom. |
| Open Coast Zone | Ovari, Idinthakarai, Kuttapuli, Vattakottai Lakshimipuram, Pallam, Mandaikadu, Vaniakudy, Midalam, Enayam. |
| Estuary zone | Perumanal, Manakudy, Rajakkamangalam, Kadiapattinam, Colachel, Taingapatnam, |

**Table. 3. Criteria of Tsunami Hazard Classification**

| Classification of Coast | Description of the Coast | Tsunami Hazard Category (Based on Inundation Extent (in M)) | | |
|---|---|---|---|---|
| | | High | Medium | Low |
| Open Coast Zone | Relatively in the lower position with reference to the MSL | 301 – 400 | 201 – 300 | 0 – 200 |

| | | | | |
|---|---|---|---|---|
| Estuary Zone | Coasts neighbouring a river mouth/ tidal inlet/ creek and similar other coastal features | 501 – 750 | 251 – 500 | 0 - 250 |
| Upland Zone | Coasts which are comparatively elevated well above the MSL | 201 – 300 | 101 - 200 | 0 - 100 |

**Table. 4. Tsunami Hazard Classification of the Study Area**

| Sl. No. | Tsunami Hazard Category | Beach Coinciding with the Respective Category |
|---|---|---|
| 1. | Low | Ovari, Perumanal, Navaladi, Rajakkamangalam, Kadiapatanam, Mandakadu, Vaniakudy, Enayam, Taingapatnam |
| 2 | Medium | Idinthakarai, Kuttapuli, Vattakottai, Lakshmipuram, ChinnaMuttom, Midalam |
| 3 | High | Kanyakumari, Manakudy, Muttom, Pallam, Colachel |

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# TSUNAMI IMPACTS ON MORPHOLOGY OF BEACHES ALONG SOUTH KERALA COAST, WEST COAST OF INDIA

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## ABSTRACT

The present study is based on the post tsunami survey conducted in January 2005 along the southwest coast of India. Although tsunami affected the whole coastline of Kerala, it devastated the low-lying coastal areas of Kollam, Alleppey and Ernakulam districts leading to the loss of life and property. This paper illustrates the variation of tsunami intensity along the coasts of these districts and the consequent morphological changes occurred in the coastal area during tsunami. Topographic survey data showed that the coastal inundation was rampant along the worst affected regions where the coastal areas are like a narrow strip of land of width 100-400m, lying between the Arabian Sea and the backwaters and the down slope of the coastal area increases towards the backwater side. The data on run-up height showed a variation of 1.9 – 5 m along the study area. Post tsunami beach profiles showed erosion of the foreshore and backshore and landward transport of beach material during the run-up of waves at Puthu-Vypeen. The erosion of the backshore (berm) in several places along the coast was quite evident in the study. This has caused reduction in the elevation which may make these areas more vulnerable to breaching by the high waves, particularly during the monsoon and also during certain spring tides which is a matter of serious concern.

## INTRODUCTION

On 26th December 2004, Indian subcontinent experienced the most devastating tsunami in its recorded history. The phenomenon was triggered by a submarine earthquake located at 3.4° N, 95.7° E off the coast of Sumatra (Indonesia) with an intensity of 9RSU.

Even though tsunami is a common phenomenon in the Pacific region, some destructive tsunamis have also occurred in the Indian and Atlantic Oceans (Altinok, 2000). Oceanic waves caused by the (27th August) 1883 Krakatoa volcanic explosion in Indonesia, was the earliest record of tsunami attack in India (Murty and Bapat 1999). The earthquake of magnitude 8.25 RSU occurred on 28$^{th}$ November 1945 near Karachi created large waves of height 11 to 11.5m in Kutch region (Pendse 1945). Most of the tsunamis are generated by the earthquake-initiated seabed displacements. Landslides (including underwater landslides), volcanic eruptions, impact of large objects (such as meteors) into the open ocean (Hills and Goda, 1998) and underwater explosions are also some triggering mechanisms for the generation of tsunami. The coastal features can determine the size and impact of tsunami waves. Kishi and Saeki (1966) identified the effect of coastal terrain roughness on wave run-up.

While tsunami approaches coast, it undergoes shallow water transformation (Synolakis, 1987). Tunami, imperceptible at deep sea, may grow to several meters when it approaches the land (Mirchina and E.N. Pelinovsky, 1982). Its speed decreases as the water depth decreases but the kinetic energy transported by the tsunami, which is dependent on both its wave speed and wave height, must remain constant. Gedik et al., (2005) carried out laboratory investigations of tsunami run-up and erosion on permeable slope beaches. Tsunamis may affect coastal areas differently, causing great damage and loss of life in one area but little in another. The destructive nature of the waves themselves act as a main cause of damage. Secondary effects include the debris which will act as projectiles and run into other objects. Just like other water waves, tsunami begins to loose energy as it rushes into the land. Some energy may get reflected and part of its energy may dissipate on the bottom.

## MATERIALS AND METHODS

State of Kerala has a coastline length of 560 km and undergoes seasonal changes in the near shore processes. For the present study, the southwest coast of Kerala between Neendakara (latitude 9° 01' 17.87") and Munambam (Latitude 10° 10' 37.55") is selected (Fig. 1). The coastal plain between Cochin and Kollam consists of a series of parallel sand ridges. The coastal area is backed by Vembanad estuary, extending from Munambam to Alleppey and the large brackish water system in Kerala opens into the sea near to Valiazheekkal and heavy mineral deposits can be seen north of the Kayamkulam inlet. The Cochin port is situated at the mouth of Vembanad Lake at 9° 58' 18".

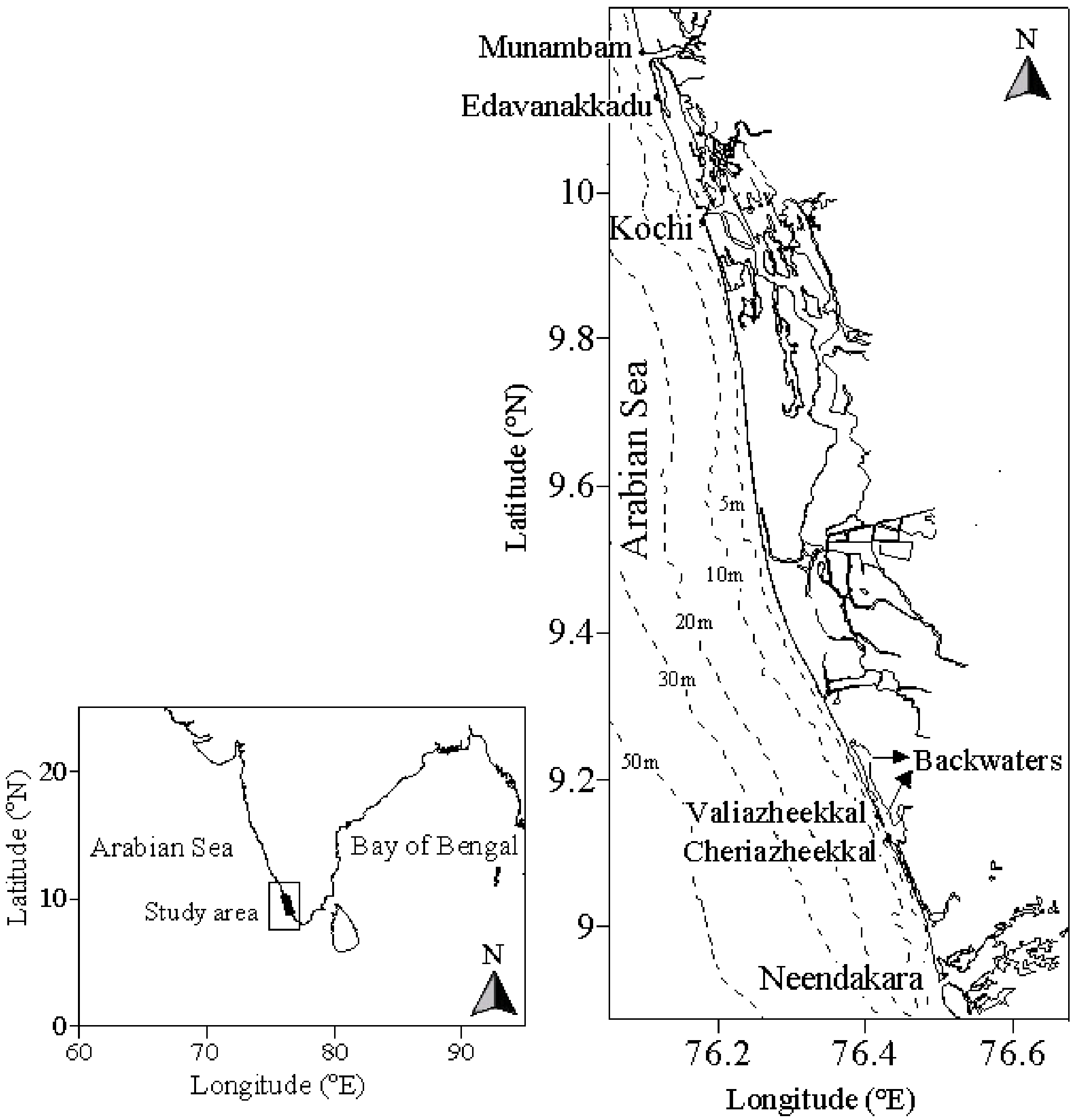


**Fig.1**: Study area

An extensive field survey was conducted using Differential global positioning system (DGPS), Theodolite, Dumpy level, GPS, directional compass etc., to study the impact of tsunami waves on the South west coast of India. Measurements were made of land elevation, beach slope, tsunami flow direction and distance, maximum run-up height and duration of inundation, shoreline position and status of beach vegetation. In all places, the phenomenon was also documented through systematic interviews of eyewitnesses. The Post Tsunami Survey guidelines of the Intergovernmental Oceanographic Commission (IOC, 1998) were strictly followed during the observation. The primary measurements in the field surveys were the estimation of height reached by the seawater as well as for its horizontal penetration. Information on run-up height and inundation limit are important to analyze the phenomenon (Curtis, 1982).

## RESULTS AND DISCUSSION

Tsunami inundation and damage was not uniform along the coast. This may be due to the geographical orientation of the coast, geomorphology of the landmass, shallow water bathymetry and orientation of approaching waves etc. Traces left by the tsunami such as watermarks on buildings, trees and debris lines along the coast or vegetation damaged by seawater were used to identify the run up and inundation limit.

Field investigation shows variation of tsunami intensity along the study area. Maximum intensity of the tsunami was observed in Kollam district followed by Alleppey and Ernakulam. The sectors adjacent to the Kayamkulam inlet between Kollam and Alleppey districts, recorded the maximum run-up height during the flood. The run-up level recorded at the northern side of inlet (Valiazheekkal) was 4.4m. There was a drastic increase in the run-up level at Cheriazheekkal (southern side of inlet) and reached up to 5m. Figure 2 shows the post tsunami beach profile at Cheriazheekkal, where the coastal area experienced maximum inundation and run-up (zero value in the X-axis indicates the position of benchmark used for conducting the topographic survey). Here the down slope of the narrow coastal belt increases towards the backwater side. This coastal feature allows seawater to enter in to the land during high tide and strong waves which trigger panic situation among the coastal community. The devastation was quite extensive at Valiazheekkal where the width of the narrow coastal belt varies from 100m to 400m and is running parallel to the shoreline (Fig. 3). The down slope of this low-lying region increases towards the backwater side. The run up level on the coastal area between Alleppey and Cochin varied from 1.9-2.8 m. On the northern side of Cochin barmouth, the waves got intensified and maximum run up height was observed at Edavanakkadu (Fig. 4), a narrow down sloping barrier beach (Fig. 5), backed by water bodies (aquaculture farms) connected to the Cochin backwaters.

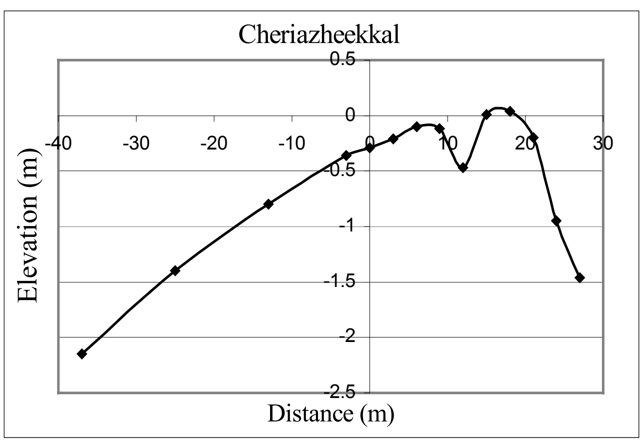


**Fig. 2:**
Post Tsunami beach profile at Cheriazheekkal (Kollam district)

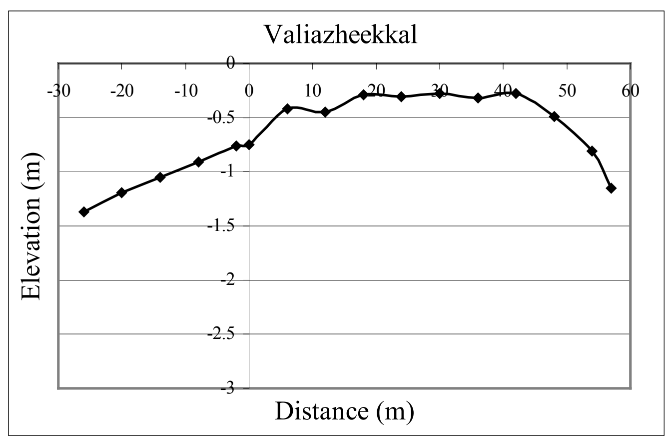


**Fig. 3:**
Post Tsunami beach profile at Valiazheekkal (Alleppey district)

**Fig. 4:**
A photograph shows the run-up height of tsunami at Edavanakkadu.

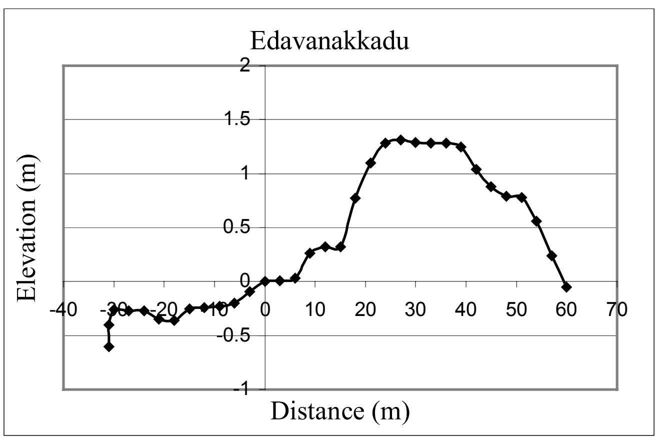


**Fig. 5:**
Post tsunami beach profile at Edavanakkadu (Ernakulam district)

The northern side of Cochin inlet (Puthu-Vypeen) beach is wide and having an average elevation of 1.5-2.0m. Monthly beach profile measurements have been carried out in this region as a part of an ongoing programme. Maximum inundation occurred here at 13:28 on 26th December 2004 as recorded by the digital camera from the shoreline, and covered up to 600m towards the land (Fig. 6). The post tsunami beach profiles of four stations at distance of 1km apart (Fig. 7) show the changes in beach elevation and erosion that have taken place near the seaward end. It is evident from the observation that the eroded sediments from the seaward side have been carried further inland and got deposited near the benchmark. The presence of vegetation on the beach appears to have helped to reduce the intensity and thereby decreased the erosional characteristics of the incoming waves. Most of the vegetation is seen already were wiped off during the run-up of waves, or being destroyed due to high saline conditions in the soil.

**Fig. 6:**
A photograph showing the tsunami inundation at Puthu-Vypeen

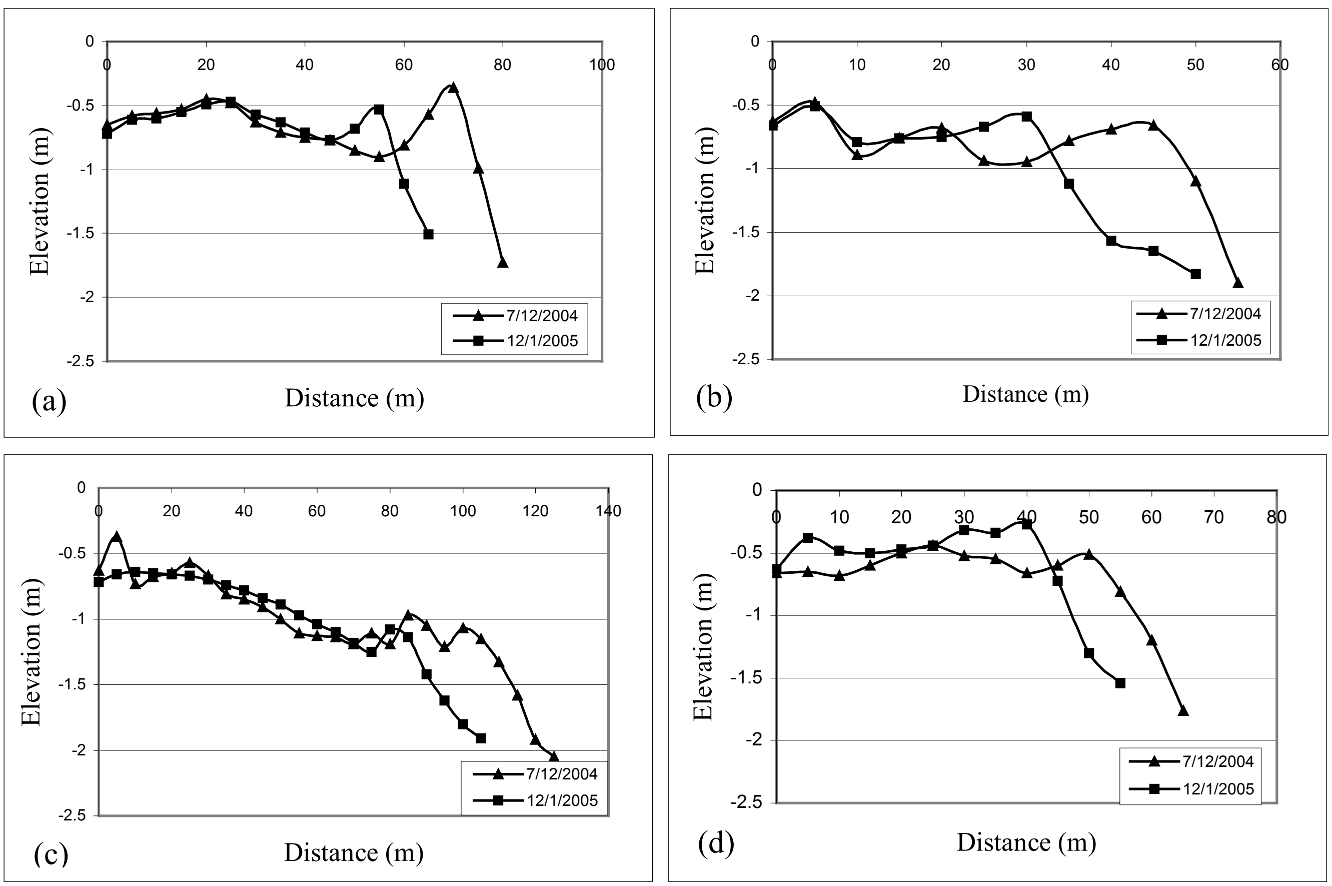


**Fig. 7:** Pre and post tsunami beach profiles at Puthu-Vypeen

The run-up measurements show a variation in height from 1.9 –5 m along the study area. The run-up heights and inundation limits are listed in table 1.The maximum run-up height was at Cheriazheekkal (5m) where the loss of life and property were severe.

The post tsunami beach profiles at Cheriazheekkal (Fig. 2), Valiazheekkal (Fig. 3) and Edavanakkadu (Fig. 5) reveal some basic similarities among these regions. The coastal areas are lying below the mean waterline due to its down sloping characteristic (Fig. 8). Moreover, the back water system is generally running parallel to the shoreline and the coastal areas are like a narrow strip of land (barrier Beach) lying between the backwater and sea. The inundated water had flooded into the backwaters and the force of wave has damaged most of the physical structures along the coast. It is evident that presence of seawall has played an important role in reducing the intensity of the waves along the coast, but the affected areas were not having any effective coastal defense structures (because the traditional fishermen use these places as fish landing centres). The tsunami floods at some places even destroyed the rubble-mound seawalls which got scattered along the coastline (Fig. 9).

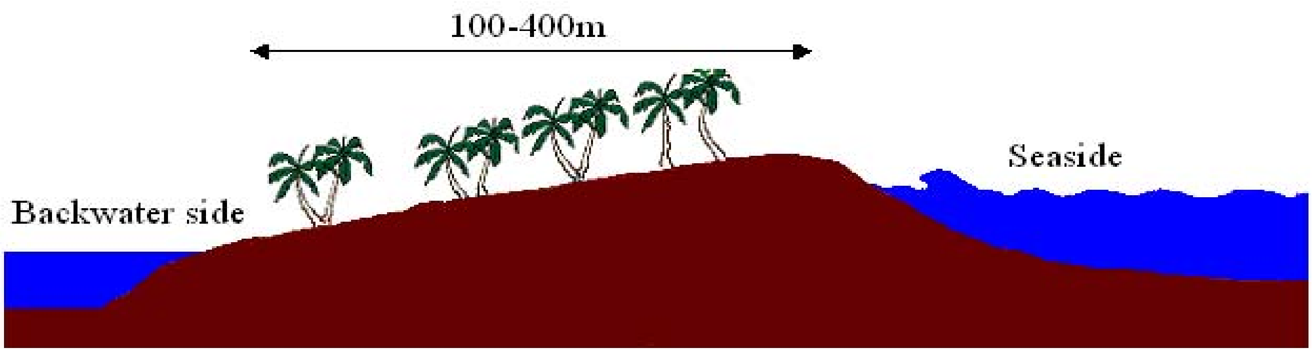


**Fig. 8**: Schemataic representation of the low-lying barrier beach


**Fig. 9:**
The destroyed and scattered seawall at Edavanakkadu

Tide gauge data provide vital information on severity of tsunami. The sea level data collected by Cochin port trust at Cochin and the hydrographic department, Government of Kerala at Neendakara provided important information on the intensity and time of occurrence of tsunami at respective places (Fig. 10). The alongshore separation between the two stations is approximately 100 km. The first hit of the tsunami took place at Neendakara at approximately 1045 hrs on 26$^{th}$ December, 2004 whereas in the case of Cochin, it was at 1115 hrs, suggesting a speed of 200km/hr. The sudden increase in water level at Cochin was approximately 0.65 m in 9 minutes, at the first hit. Subsequently, there were dramatic rise and drops in the water levels. In the case of Neendakara, The sudden increase in water level was approximately 0.83 m in 15 minutes. As observed in the case of Cochin, here also there were dramatic rise and drops in the sea level. The overall range of water level variability was quite high at Neendakara, as compared to Cochin. Normally, the tidal ranges are less at Neendakara as compared to Cochin, as seen in the figure. The tidal records showed the occurrence of tsunami continued till 30$^{th}$

December 2004 at different intervals with varying amplitudes and diminishing progressively from 26th December.

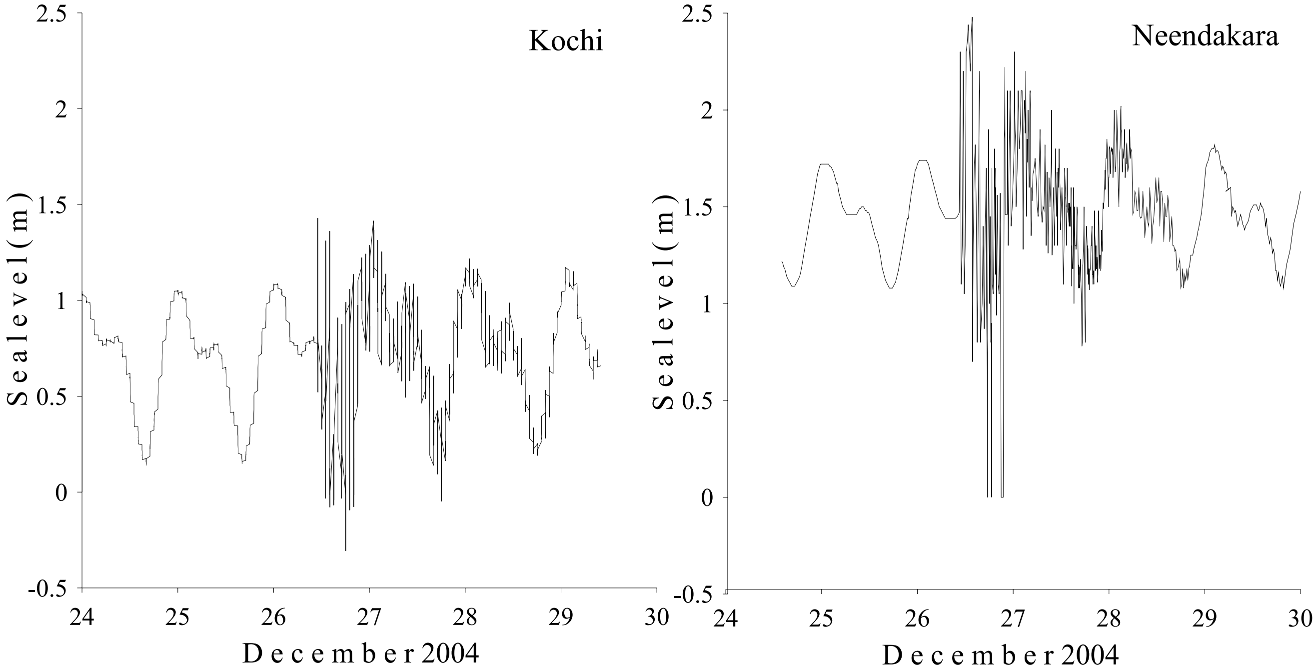


**Fig. 10**: Sea level variations at Cochin and Neendakara during Tsunami

Table 1. Survey results of Tsunami height

| Sl No | District | Location | Latitude (°N) | Longitude (°E) | Height Measured (m) | Direction of approach (Degrees) | Inundation distance (m) | Inundation time | Maximum Inundation |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Kollam | Neendakara | 08°55' 54.1" | 76°32’23.2" | 2.40 | 220 | 240 | 1010<br>1210 | 1210 |
| | | Panikkar Kadavu | 09° 02'4.5’’ | 76°30° 8.05" | 3.20 | 230 | 100<br>Up to Kayal | 1130<br>1200 | 1200 |
| | | Cheriazheekkal | 09°030'5.5" | 76°30'8.3" | 5.00 | 230-250 | 400<br>Up to Kayal | 1100<br>1130<br>1200 | 1200 |
| 2 | Alleppey | Valiazheekkal | 09°08'20.3" | 76°27’43.1" | 4.40 | 220-240 | 600<br>Up to Kayal | 1030<br>1100<br>1145<br>1230 | |
| | | Thrikkunnappuzha | 09°15'29.1" | 76°24'25.6" | 2.77 | | 60 | | |
| | | Ambalappuzha | 09°15' 30.1" | 76°24' 26.6" | 1.90 | 230-250 | 160 | 1005<br>1045-1100<br>1330-1400 | |
| | | Alleppey Beach | 09°29'32.1" | 76°19'04.3" | 2.80 | 200 | 95 | 1030<br>1430 | |
| 3 | Ernakulam | Puthu-Vypeen | 09°59'53.7" | 76° 13' 06.0" | 2.30 | 250 | 600 | | 13:28 |
| | | Edavanakkadu | 10°05' 6.1" | 76°11'36.6" | 2.45 | 230-240 | 90<br>Up to Kayal | | |

## CONCLUSION

Variation in run-up observed along the coastline depends on the topography of the coastline, near-shore bathymetry, beach slope, coastal orientation, direction of the arriving wave etc. Variations in the near shore bathymetry and bottom topography have to be studied in detail to understand the relationship with the amplification of the tsunami height. The Tsunami waves have penetrated inland with a greater force in areas where coastal defense structures were absent. The low-lying coastal areas with narrow strip of land between the sea and backwater at Cheriazheekkal, Valiazheekkal and Edavanakkadu, amplified the effect of waves and caused severe damage and loss of life. On the other hand, the wider beach at Puthu-Vypeen reduced the impact/damage of tsunami on life and property.

## ACKNOWLEDGEMENT

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# TSUNAMI RISK SITE DETECTION IN GREECE BASED ON REMOTE SENSING AND GIS METHODS

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## ABSTRACT

Based on LANDSAT ETM and Digital Elevation Model (DEM) data derived by the Shuttle Radar Topography Mission (SRTM) of the coastal areas of Greece were investigated in order to detect traces of earlier tsunami events. Digital image processing methods used to produce hillshade, slope, minimum and maximum curvature maps based on the SRTM DEM data contribute to the detection of morphologic traces that might be related to catastrophic tsunami events. These maps combined with LANDSAT ETM and seismotectonic data in a GIS environment allow the delineation of coastal regions with potential tsunami risk. The evaluations of LANDSAT ETM imageries merged with digitally processed and enhanced SRTM data clearly show areas that must have been flooded in earlier times. In some cases morphologic traces of waves as curvilinear scarps open to the sea-side are clearly visible.

## 1. INTRODUCTION

This study is considering tsunami risk mapping for coastal areas where no severe tsunami has occurred recently, but the geomorphologic and topographic features and characteristics are similar to areas hit by recent catastrophic tsunamis as Sumatra. A tsunami hazard map of such an area that predicts the potential location of future tsunami occurrences is required. In the case of a catastrophic event it can provide rescue teams with the map of the areas where the tsunami energy is expected to be destructively large and damage is most severe. Around the Mediterranean Sea there is a high potential for generation of large tsunamis, and in addition, for the generation of tsunamis produced in the near-shore zone that could have catastrophic effects on a local scale (BOSCHI et al., 2005, YALÇINER et al., 2001, 2004). Parts of the Mediterranean coastline have suffered from disastrous marine waves many times in history. Historical earthquakes and associated tsunamis for the whole Mediterranean basin are identified from verified catalogues. In addition to historical and geologic information, or distribution of fault zones, volcanoes, and other probable tsunamigenic sea bottom structures, there are numerous source areas which may be considered responsible for severe tsunamis. One of the important source areas of tsunamis in the Mediterranean are the normal fault zones of Greece and the subduction in the Tyrrhenian sea. The tsunami waves caused severe damage and flooded low lands in many segments of the coast.

## 2. APPROACH

This contribution considers the support provided by remote sensing data and a GIS based spatial databases for the delineation of potential risk sites in Greece. On a regional scale the areas of potential tsunami risk will be determined by an integration of remote sensing data, geologic, seismotectonic and topographic data.
LANDSAT ETM and DEM data were used for generating an image based GIS and combined with ESRI data and other thematic maps, see Fig.1 b. These include an inventory of seismic

records, large-scale geomorphologic analysis, digital elevation data and high-resolution remote sensing data. As one of the procedures to generate a tsunami hazard map a comparison between the geomorphologic/ topographic settings of the areas previously hit by tragic tsunamis in recent times (as in Sumatra) and the potential risk sites in Greece is proposed. There are typical geomorphologic features found in areas prone to catastrophic tsunami events as fan shaped flat areas, fan-shape like arranged drainage patterns, arc-shaped (seawards opened) walls and scarps, often running parallel to the coast, Remnants of tsunami floods are irregular swamps, ponds and lagoons near the coast. The evaluation of digital topographic data is of great importance as it contributes to the detection of the specific geomorphologic/ topographic settings of tsunami prone areas. For the objectives of this study the following digital elevation data have been evaluated: **S**huttle **R**adar **T**opography **M**ission - SRTM, 90 m resolution) data provided by the University of Maryland, Global Land Cover Facility (http://glcfapp.umiacs. umd.edu:8080/esdi/) and GTOPO30 data provided by USGS (http://www.diva-gis.org/Data.htm, 1 km resolution) were used as base maps. Height values for the SRTM dataset are referenced to GTOPO 30 global digital elevation model. SRTMT data offer a useful and numerous advantages for tsunami research.

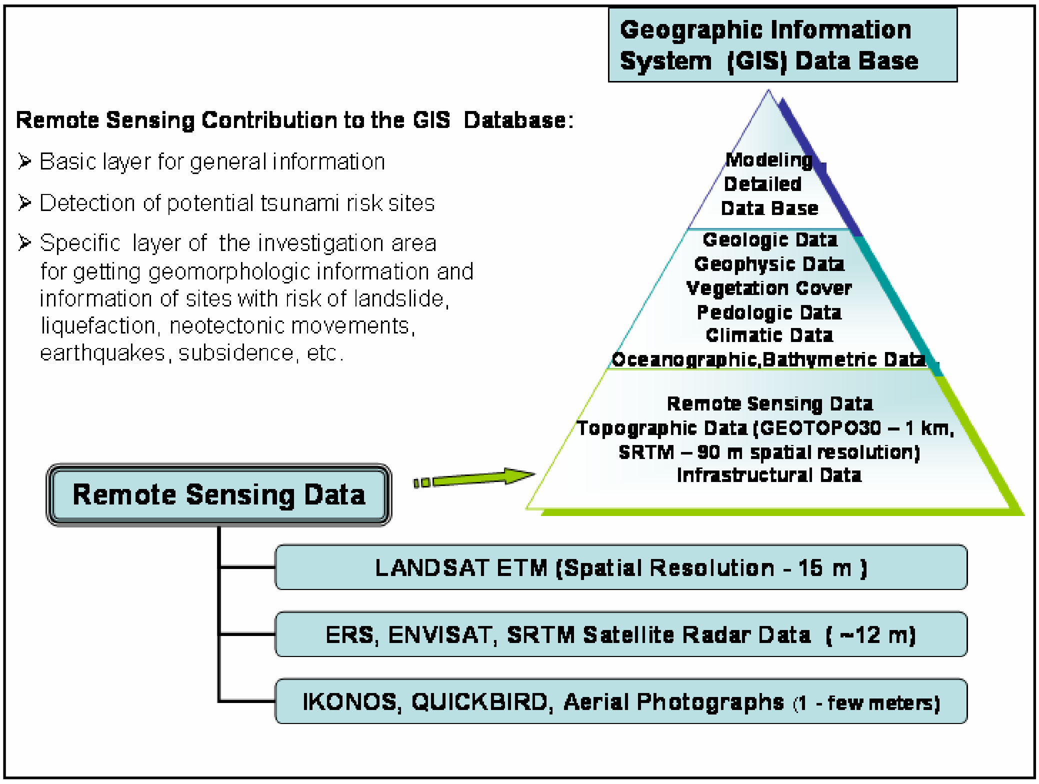


Figure 1 : Remote Sensing Contribution to a Tsunami Hazard Information System

The digital topographic data were merged and overlain with LANDSAT ETM data (Band 8: 15 m resolution). For enhancing the LANDSAT ETM data digital image processing procedures have been carried out. Various image tools delivered by ENVI Software/ CREASO were tested. Effective cartographic displays are achieved when DEMs are combined with landcover information derived from satellite imagery. Other geodata as provided by ESRI ArcIMS GIS were included, so earthquake data or bathymetric maps. With digital image processing techniques maps can be generated to meet specific requirements considering risk mapping: For getting a geomorphologic overview SRTM data terrain parameters were extracted from a DEM as shaded relief, aspect and slope degree, minimum and maximum curvature or plan convexity maps using ENVI and ArcMap software (Fig.2).

Geomorphometric parameters as slope degree, minimum or maximum curvature provide information of the terrain morphology indicating geomorphologic features that might be related to tsunami events. These SRTM derived, morphometric parameters correspond to groups of 0, 1st and 2nd order differentials, where the 1st and 2nd order functions have components in the XY and orthogonal planes.

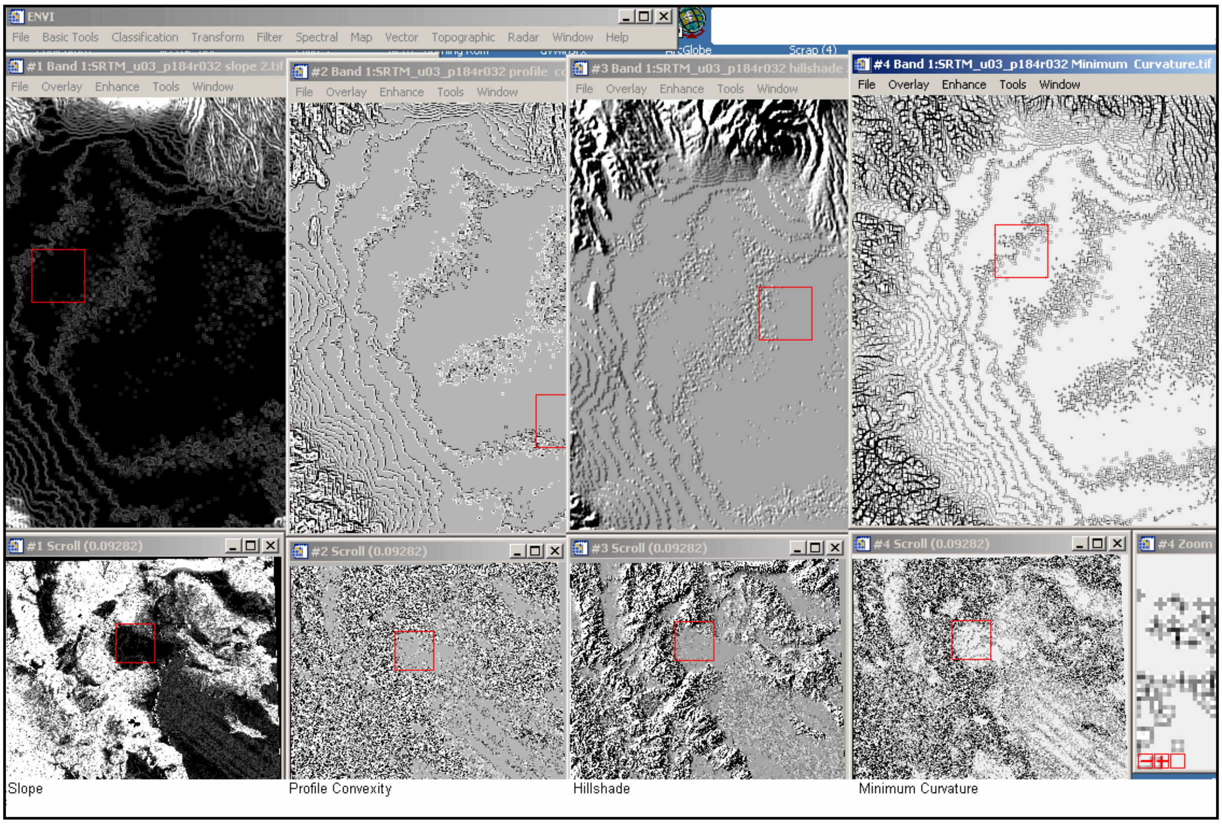


Figure 2 : SRTM based maps from the area of Thessaloniki

The various data sets as LANDSAT ETM data, topographic, geological and geophysical data from the studied areas were integrated as layers into GIS using the software ArcView GIS 3.3 with the extensions Spatial Analyst und 3D-Analyst and ArcGIS 9.0 of ESRI. As a complementary tool Google Earth Software was used in order to benefit from the 3D imageries of the various investigation areas (http://earth.google.com/).
A systematic GIS approach is recommended as described in Figs.3 and 4 extracting geo-morphometric parameters based on the SRTM DEM data as part of a Tsunami Information System.

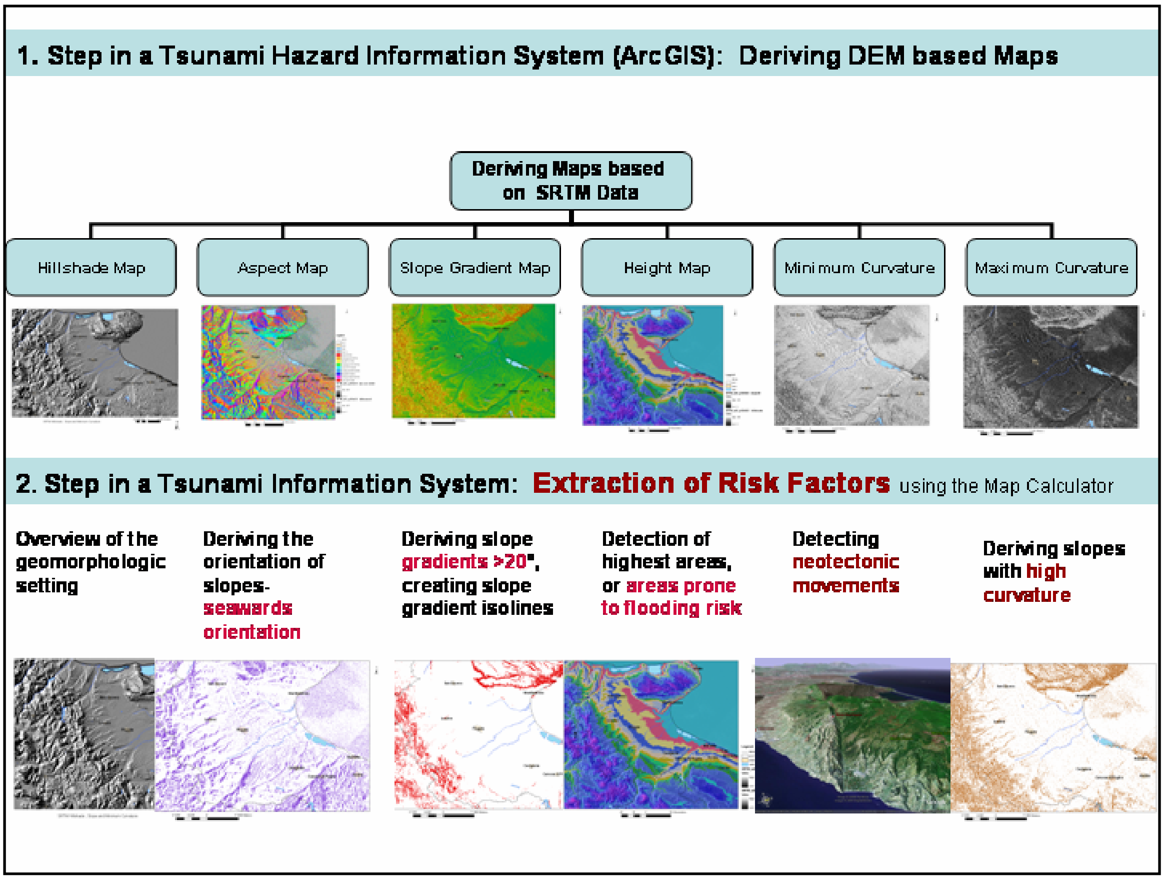


Figure 3: Workflow in a Tsunami Hazard Information System

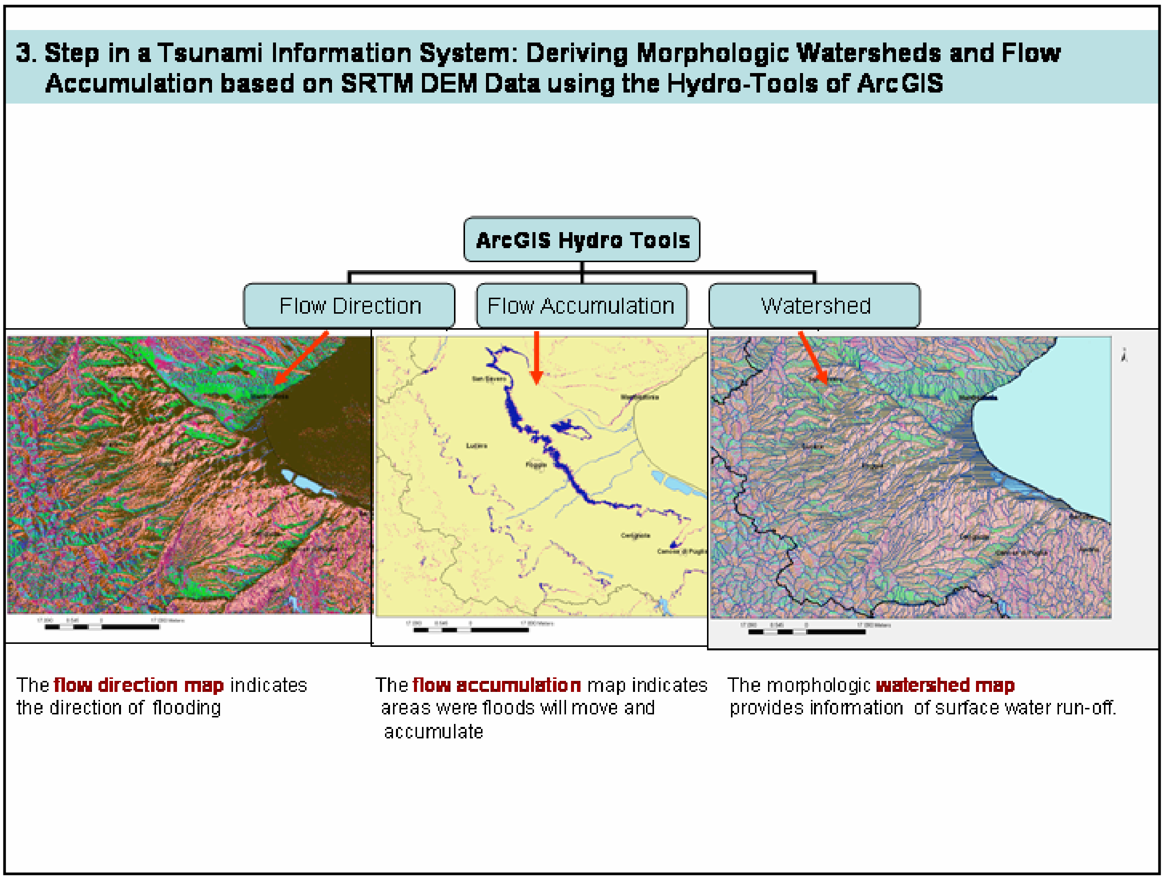


Figure 4: Deriving hydro-morphometric parameters

## 3. EVALUATION OF SRTM AND LANDSAT ETM DATA FROM COASTAL AREAS OF GREECE

Potential risk sites for hazardous tsunami waves were identified by analyzing areas in Greece showing heights below 20 m above sea level (Fig.5). These areas below 20 m height were studied then more detailed.

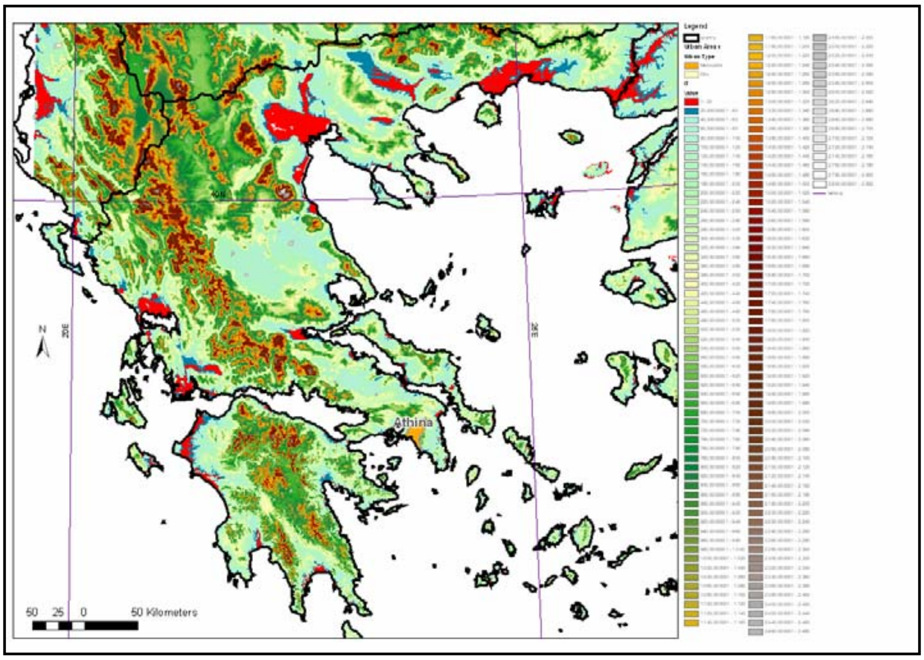


Figure 5: Height map of Greece indicating areas below 20m height above sea level.

As first example the Bay of Thessaloniki is presented. Figs.6 - 9 show the results of SRTM data based map products. Potential traces of flood waves as parallel, arc-shaped walls can be inferred by minimum curvature maps as presented in Fig.6 as well as by color coding the DEM map (Fig.7). Potential traces of run-up can be detected considering the parallel, sea-wards opened curvatures. By far the most common method of displaying raster data in a GIS is to use a 2-dimensional colour coding where each elevation value is assigned a colour value. By colour coding the DEM map of the study area flat regions and different height levels become visible. Estuary plains and broader river beds were probably prone more to tsunami wave propagation risk than the higher environment. River mouths represented a large entrance for tsunami waves. Especially the Axios, Aliakmonas, Galikos and Loudias rivers would be prone to flooding.

Provided that the morphologic properties of the Thessaloniki Bay area are related to tsunami events it can be assumed that the morphology is the result of abrasion due to catastrophic tsunami floods. This assumption is confirmed by the hillshade map (Fig.8). The flooding tsunami waves obviously came by South.

According to the characteristic morphologic properties visible on the hillshade, the aspect, minimum curvature and slope map the run-up heights along the south-facing, flat shorelines are estimated at least of about +/- 30 km.

Submarine mass movements as slumps, turbidity currents and landslides presumably triggered by earthquakes might be an explanation for the intensity of waves and floods forming the coast-near landscape in the Bay of Thessaloniki.

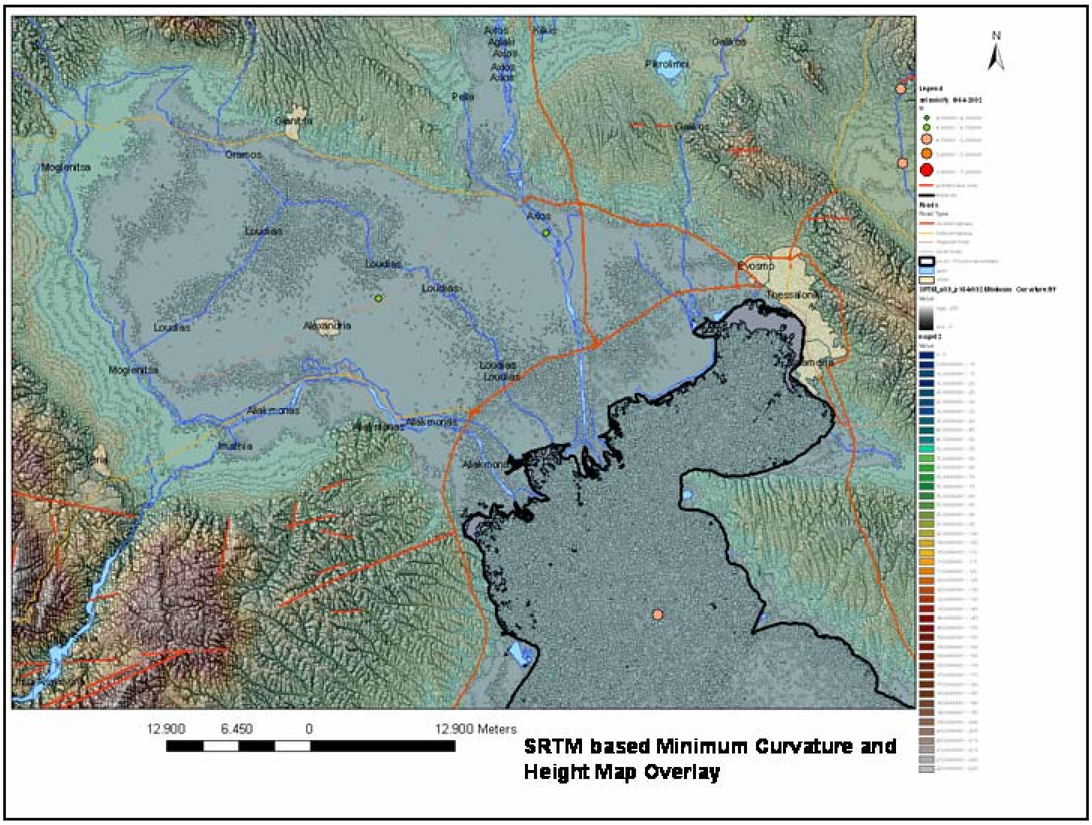


Figure 6: SRTM based shaded relief and minimum curvature map of the Bay of Thessaloniki

The minimum curvature map illustrates the seawards orientation of the terrain and enhances as well smaller walls, ridges and terraces with seawards opened, arc-shaped contours.

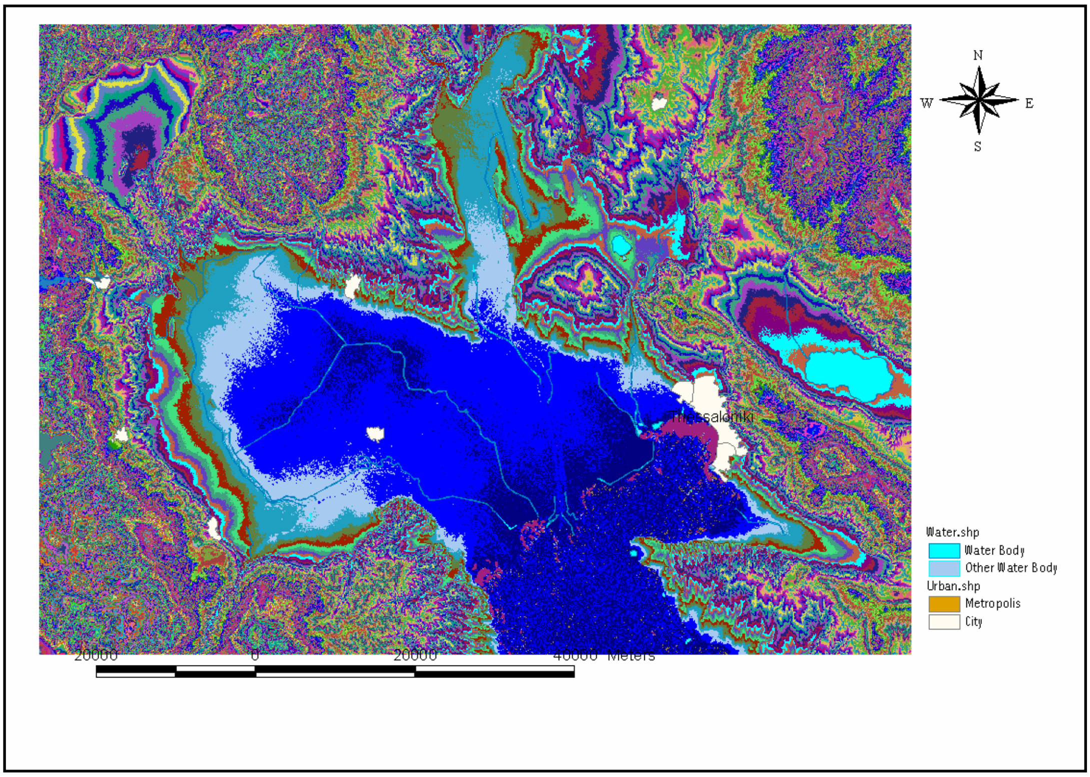


Figure 7: Height map based on SRTM DEM data using ArcView GIS

The map clearly shows the different levels in the basin probably formed by floods. It seems that tsunami waves "intruded" along existing river beds. Therefore run up and inundation distance of the floods along riverbeds was probably more extended than in the adjacent areas.

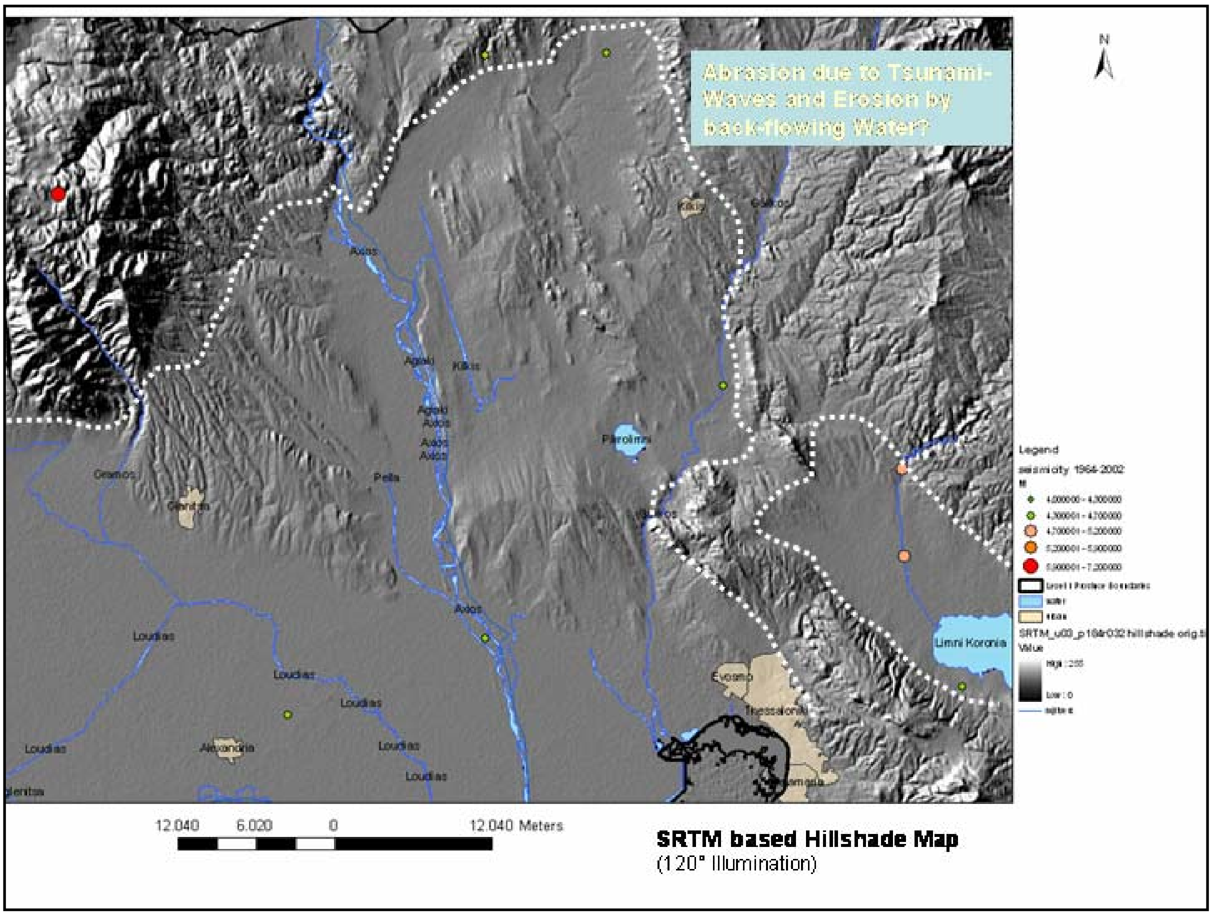


Figure 8 : SRTM based Hillshade map of the northern Thessaloniki area
The dashed line illustrates the area assumed as flooded by probably catastrophic tsunami events according to the geomorphologic properties of the area. The surfaces seem to be "smoothened" by abrasion and erosion. There is a distinct morphologic difference to the surrounding area.

Fig.9 presents the minimum curvature map of the airport area south of Thessaloniki enhancing walls and terraces opened to the sea, obviously related to floods and varying sea levels, including sea level changes caused by earthquakes and aseismic movements (uplift and subsidence).
Digital image processing of LANDSAT ETM data provides information of water streaming and current mechanisms in the Bay of Thessaloniki as indicated in Fig.10. Due to the coastal morphology and shape of the shore line the main stream can be observed at the southern part of the bay near the airport. The shape of the bay influences the intensity of currents focusing the energy especially in the eastern part of the bay.
Thus, LANDSAT ETM imageries contribute to a better understanding of streaming mechanisms that might be of importance for potential tsunami waves and their interactions with the contour of the shore line..
Several case studies of tsunami risk levels are presented in Fig.11.

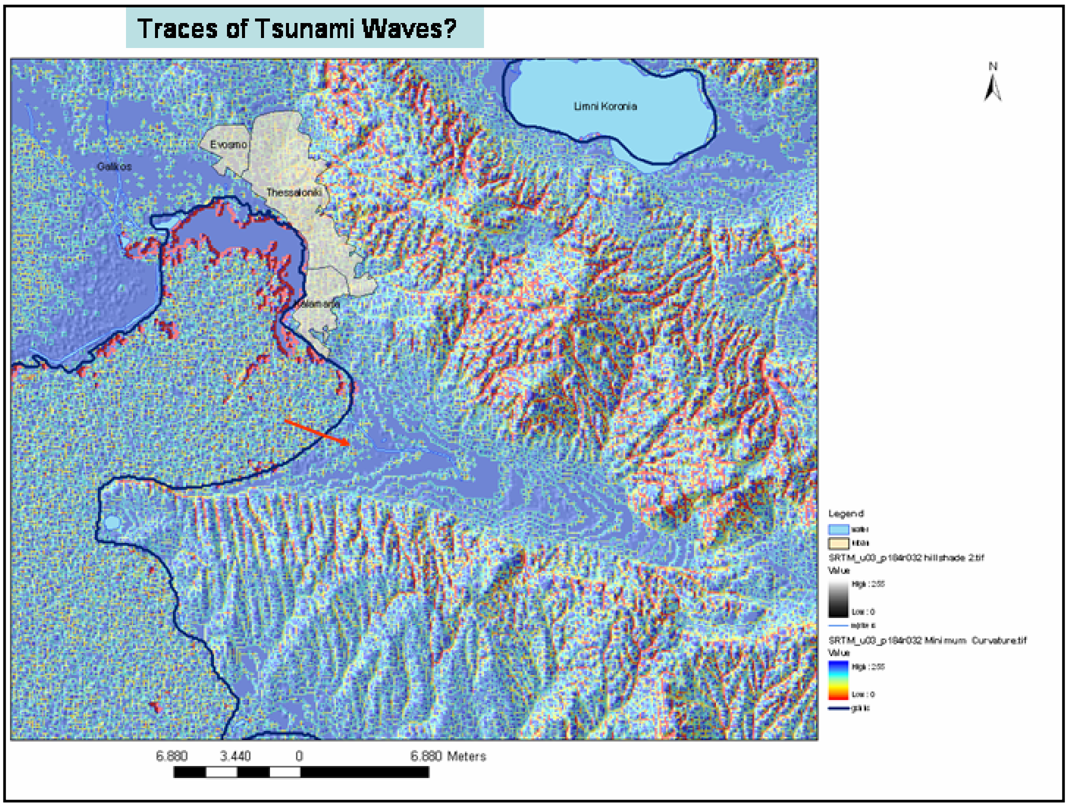


Figure 9: Color coded  Minimum Curvature Map based on SRTM DEM of the Bay of Thessaloniki

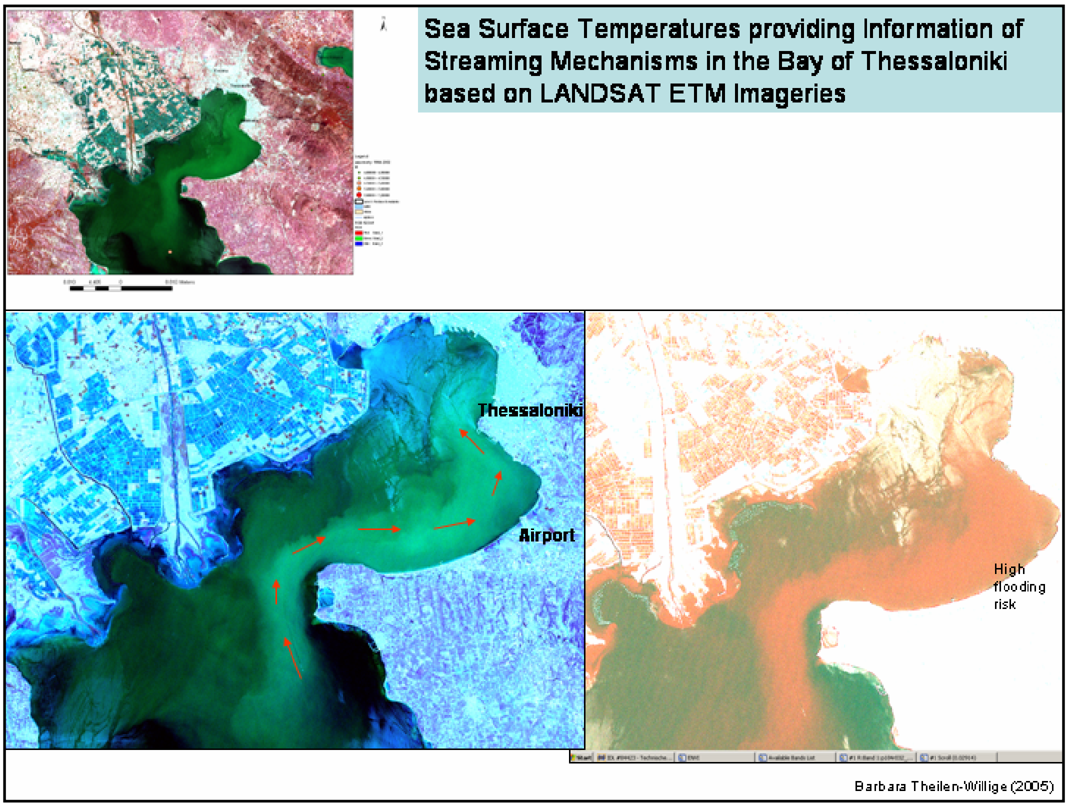


Figure 10: Digital image processing of LANDSAT ETM data for enhancing water currents

The **R**ed, **G**reen, **B**lue - RGB-Principle is reviewed briefly: Three images from the different LANDSAT bands to be used as end-members in a triplet are projected, one image through one primary colour each, i.e. one image is coded in blue, the second in green and the third in red. In this way, each image is given a particular false colour (GUPTA,1991 and 2003).

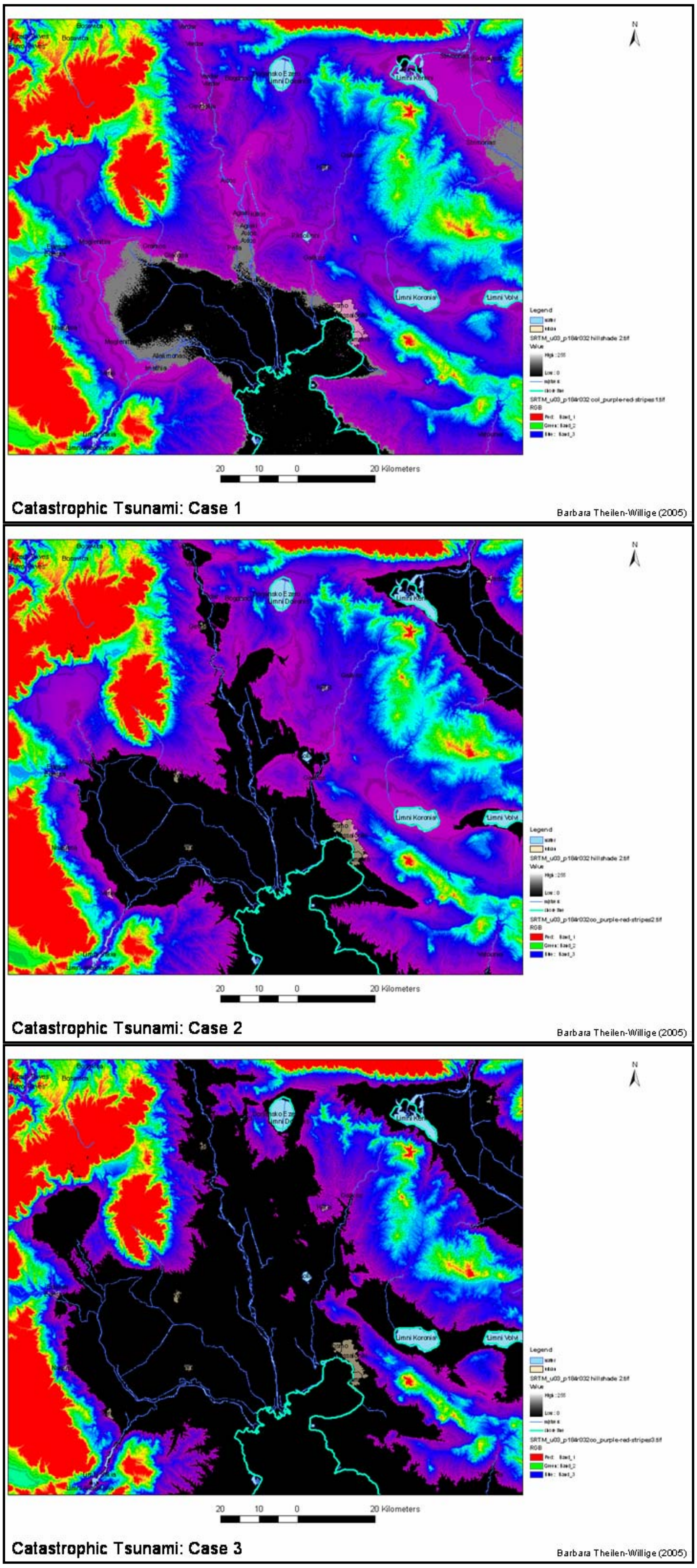


Figure 11: Tsunami risk sites (black colour) in case of different levels of catastrophic tsunami events

Another example of a potential tsunami risk site is shown in the Figures 12 a-c from Northeast Greece. The Bay of Lagos is investigated considering its potential tsunami risk based on SRTM DEM derived morphometric maps.

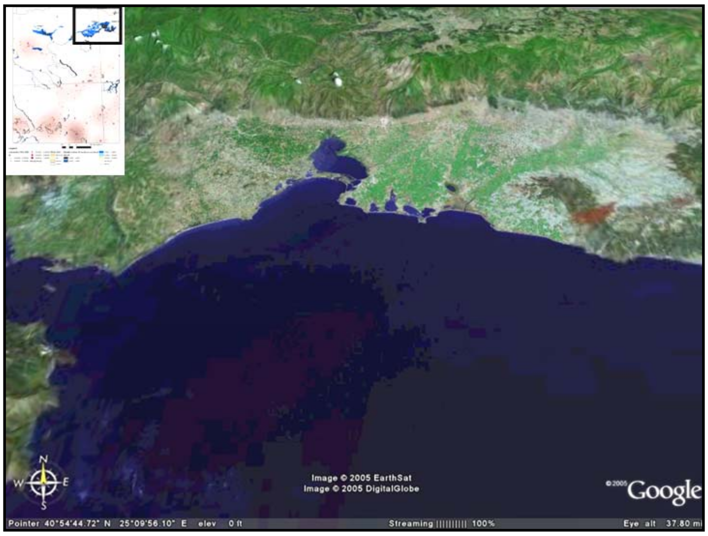


Figure12 a: Test site in NE Greece

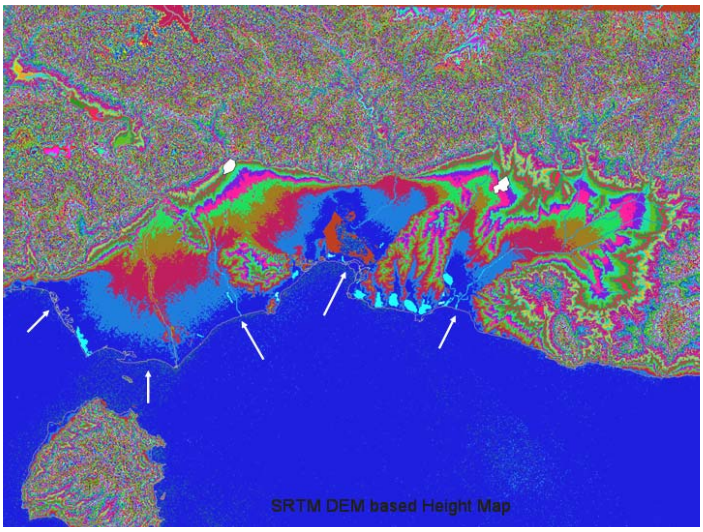


Figure 12 b: Colour coded DEM indicating the potential tsunami risk sites (blue)

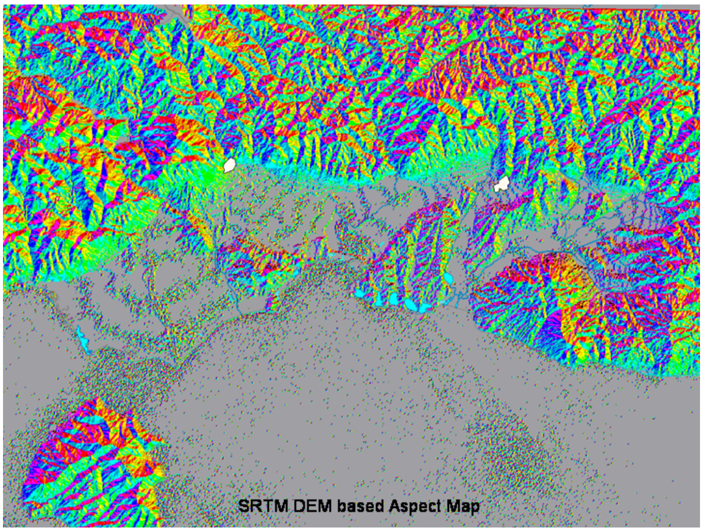


Figure12 c: Aspect map showing the seawards orientation of the slopes near the coast

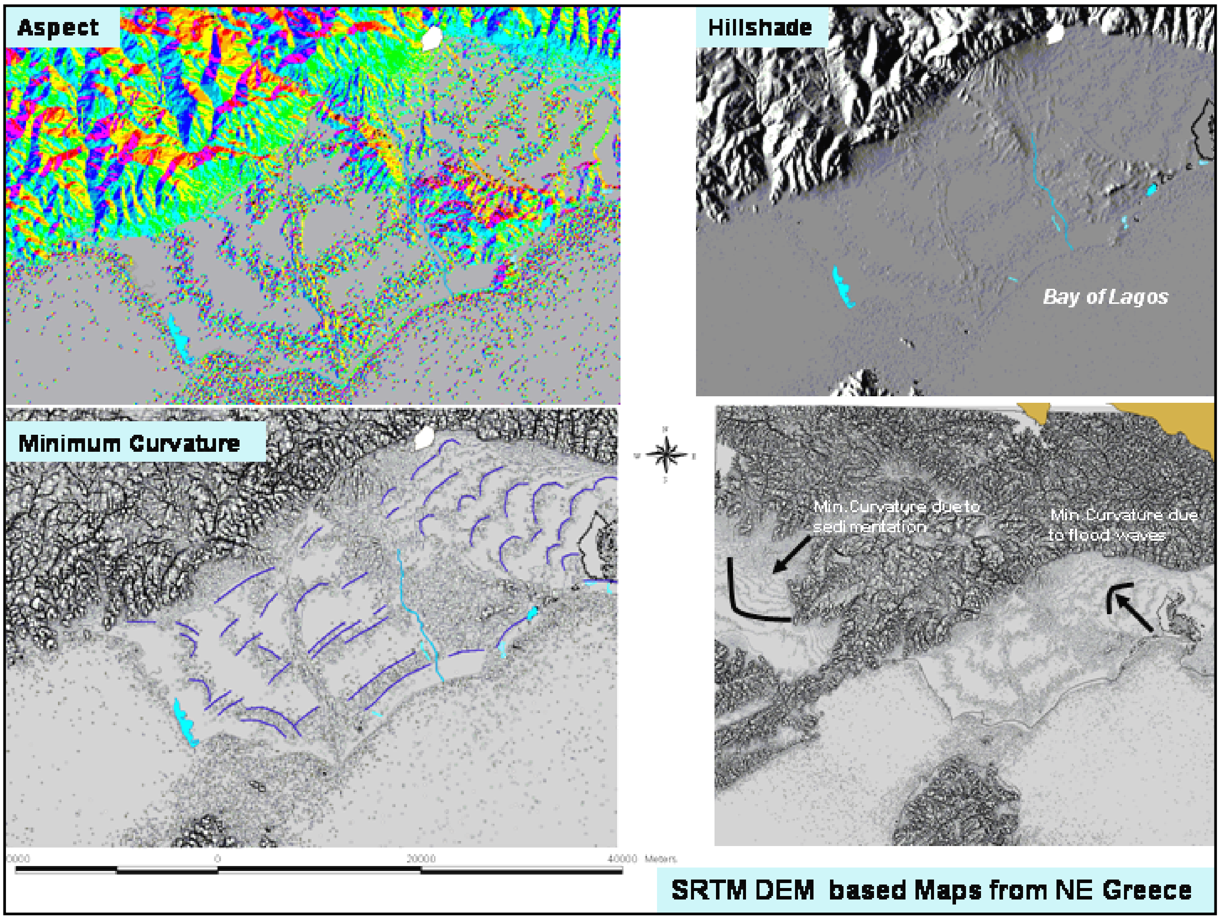


Figure12 d: Evaluation of the morphometric maps
By analyzing the morphometric maps it seem to obvious that the subtle geomorphologic features near the coast were formed by flood waves from the sea.

## 4. CONCLUSIONS

The evaluation of digital processed and enhanced LANDSAT ETM data merged with SRTM derived map products as hillshade, slope gradient, minimum and maximum curvature in a GIS environment can contribute to the detection of traces of past tsunami events and future potential tsunami sites. In sum, several geomorphologic evidences of tsunami events can be found in Greece:

- fan shaped, flat areas near the coast
- irregular lagoons, ponds and lakes
- arc-shaped (seawards opened) small walls, ridges and scarps parallel to the coast
- seawards orientation of the slopes
- fan-shape like arranged drainage pattern.

Considering such tsunami characteristic features and traces several the sites exposed to tsunami risk can be detected in the coastal areas of Greece.
Using Earth observation data it is possible to detect traces of past tsunami events, to compare different tsunami prone areas and to analyse recently affected areas. The interpretation of remote sensing data from ancient tsunami prone areas will help to a better recognition of hazardous sites and, thus, being one basic layer for a tsunami alert system. Remote sensing technology embedded in a GIS information database can be used as a complementary tool for existing tsunami hazard studies offering an independent and complementary approach providing a base for further field research..

By providing up-to-date information and integrating the results with traditional tsunami hazard assessment studies, coherent and reliable information is provided. By these means the information can be used for early-warning, for decision support in disaster management. However, a lot of work still needs to be done in order to take the appropriate actions for the mitigation of the tsunami catastrophic effects on Circum Mediterranean countries.

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# THE ORPHAN TSUNAMI OF 1700

By:

**Brian F. Atwater, Musumi-Rokkaku Satoko, Satake Kenji, Tsuji Yoshinobu, Ueda Kazue and David K. Yamaguchi , ISBN 0-295-98535-6, U.S. Geological Survery, UW Press (2005)**

## A REVIEW

**By:**

**George Pararas-Carayannis**

## REVIEW SUMMARY

"Orphan Tsunami of 1700" is a beautifully illustrated book which - in addition to very useful reference material - provides a wealth of diverse geologic data as evidence that mega thrust earthquakes of magnitude 8 or 9 in the Cascadia region may have generated major tsunamis along the Pacific Northwest and possibly elsewhere in the Pacific Ocean.

A section of the book summarizes and interprets the significance of extensive geological findings and purported paleotsunami deposits (sand layers covering peaty soils) found by geological investigations along the shores of northern California, Oregon, Washington and British Columbia, as evidence that tsunamigenic earthquakes have occurred throughout geologic time along the Cascade Subduction Zone. Based on the stratigraphic layering of the deposits, their extensive geographical distribution, and their dendrochronological and radiocarbon dating - as previously reported in the literature - the authors establish a relative chronology of at least three mega thrust events for the Cascadia region – the latest about 300 years ago (AD 1710 +/- 10 years). Lore of early natives pertaining to cataclysmic flooding and other unusual phenomena in the Pacific Northwest is provided as additional forensic evidence.

Subsequent sections of the book provide a comprehensive historical account of a destructive tsunami of unknown origin that struck Japan on January 26, 1700, and the results of a numerical modeling study of the tsunami, postulating the latest Cascadia mega thrust earthquake as its source - since it occurred around the same time.

Based on the dating of the ostensible paleotsunami deposits, the numerical tsunami simulation, the native accounts, and by a process of "elimination" - since no other great earthquakes occurred that year - the authors conclude that the missing parent source of "The Orphan Tsunami of 1700" observed in Japan (but nowhere else in the Pacific), must have been the megathrust earthquake in the Cascade region. To this earthquake an estimated moment magnitude range of 8.7 to 9.2 is assigned (which is almost as great as the December 26, 2004 tsunamigenic earthquake along the Great Sunda Trench), and a rupture zone of more than 1,000 Km (600 miles) – thus suggesting a continuous break of all fault segments along the entire length of the Cascadia subduction zone on the eastern side of both the Juan De Fuca and Gorda tectonic plates. Furthermore, based on the tsunami travel time to Japan as determined by the numerical simulation, the authors refine the radioactive carbon dating of the Cascade megathrust event as having occurred around 9 PM on January 26, 1700.

In summary, the book represents a dissection of the two disasters on opposite sides of the Pacific and is jam-packed with beautiful graphics and interesting views as to the Pacific Northwest's earthquake and tsunami vulnerability. However, no conclusive evidence is presented that moment magnitude 8 and 9 earthquakes can indeed occur along the Cascadia mega thrust, or that the earthquake of 1700 had such a high magnitude (8.7 to 9.2), or that it was indeed the source of the tsunami observed in Japan. Connecting the two events is an interesting scenario that is plausible, but the forensic geologic evidence on which it is based is largely circumstantial.

Although the book does not provide all the answers, nonetheless it is a valuable contribution that helps understand better the vulnerability of the Pacific Northwest and offers a strange sort of comfort in the knowledge that if a major or great earthquake occurs in the future, there will be additional vigilance and tsunami preparedness in the region. Thus, the purpose of the book to provide an overview of potential future risk factors for disaster assessment and mitigation is partially achieved. However, as the chosen title connotes, "The Orphan Tsunami of 1700" in Japan, may still remain a partial mystery, at least until additional geologic or tsunami run-up evidence elsewhere in the Pacific, ties it together conclusively to an earthquake in the Cascadia region.

## DETAILED REVIEW OF THE ORPHAN TSUNAMI OF 1700

### PART 1

In summary, Part 1 of the book, titled "Unearthed earthquakes", provides a cursory review of past historical earthquakes in the Cascadia region, speculates on their magnitudes and tsunamigenic potential on the basis of recently found paleotsunami deposits, makes comparisons with other known seismically active subduction regions of the world where large megathrust tsunamigenic earthquakes have occurred – claiming that they are analogous - and concludes that great earthquakes of magnitude 8 or 9 can occur also along the Cascadia Subduction Zone (CSZ).

More specifically, this section addresses the potential of tsunami generation in the region from megathrust earthquakes, and presents excerpts from diaries of early explorers which elicit lore of native tribes about flooding from the sea and recessions – one lasting for as much as four days - but not associated with any earth shaking motions.

Subsequently presented is an overview of the effects of extensive subsidence along Cascadia's Pacific coast, which has resulted in ghost forests inside areas that are now tidal marshes. Analogies are drawn from the 1964 Alaska earthquake, which caused extensive land subsidence, tidal incursions and depositions of sand and silt, thus burying preexisting surface soils. Examples are given of tree ring analysis as clues that the shoreline subsidence was sudden, following earthquake events on the megathrust. Associated geological evidence is presented that tsunamis must have overran the subsided areas, since sand sheets were found on top of previous soil surfaces – as with tsunami action in Chile, Japan and Alaska. Additional geologic evidence is provided that earthquake-induced subsidence was the cause of destruction of native campsites along the coast of Washington State. Also, examples are given which illustrate that strong shaking from earthquakes must have caused the filling of cracks and of other geological intrusions and the geomorphologic features found during surveys of shorelines along the Pacific Northwest.

Finally, based on this geologic evidence, this section of the book poses the question on whether the Cascadia region has the potential for earthquakes of moment magnitude 9, admitting to an existing impasse in reaching scientific consensus on this matter. However, claims are made that the geologic deposits and the dead trees that are separated by great distances - but linked as concurrent in time by radiocarbon dating and dendrochronology - indicate that the Cascadia earthquake of AD 1700 had a great rupture. On the basis of the purported long rupture of 1,000 Km or more, a final claim is presented that the earthquake had moment magnitude that could have ranged from 8.7 to 9.2.

**Comments for Part 1**

Although brief, the discussion in Part one of the book is informative and well presented but leaves a number of questions unanswered while raising new ones. The discussion does not extent to the specific seismogenic parts of the Cascadia megathrust – an analysis of which could improve the understanding of the mechanics of this important fault zone or why and how it could be considered analogous to other subduction zones where large earthquakes have occurred and destructive tsunamis have been generated. For example, there is no discussion of the state or origin of the N-S compressive stress field along the Cascadia Subduction Zone (CSZ). Is the stress field really analogous to that of other subduction zones and can the region indeed generate earthquakes with an upper range moment magnitude of as much as 9.2? Furthermore, is such large magnitude possible along the CSZ in view of the fact that there have been few, if any, earthquakes recorded instrumentally?

An earthquake of such magnitude would require a continuous rupture from the Mendocino fracture zone in the south to the Queen Charlotte Fault in the north. We know from recent geophysical and geological investigations that the rupture-zone geometry of the CSZ has potential constrains that could prevent such long crustal fracturing. Therefore, how can the unusual aspects of this region be mechanically similar to other major plate boundary faults around the world, given the additional fact that the seismogenic part of the Cascadia megathrust appears to be located offshore and west of the CSZ? Two major earthquakes with magnitudes of 7.2 in June 14, 2005 and in November 8, 1980 occurred west of the CSZ and did not generate tsunamis. The April 25, 1992, Cape Mendocino earthquake (M=7.2), at the southernmost part of the subduction zone, generated a relatively small tsunami. Maximum tsunami wave height (peak-to-trough) was 1.1 meters at Crescent City, and 0.2 meters at Point Arena, California, and only 0.1 meters in the Hawaiian Islands.

**PART 2**

The more extensive Part 2 of the book provides a great historical account of a destructive tsunami of unknown origin - “The Orphan Tsunami of 1700” - that struck nearly 1,000 km of the Pacific coast of Japan, in the evening of January 27/28, 1700.

The primary sources of the historical information are listed and beautifully illustrated with copies of original accounts and old maps of ports and coastlines of Honshu and Hokkaido Islands. According to the old Japanese government manuscripts, tsunami waves as high as 15 feet inundated several coastal towns and villages along a 500-mile stretch of the Island of Honshu in northern Japan. Waves up to 10 feet high damaged 20 homes in the town of Miyako and further south rice paddies and storehouses were flooded.

Additional information is provided on even earlier destructive historical tsunamis and further correlated with Samurai scribes and records. Specific tsunami amplification factors for certain regions of Japan are discussed and the heights of the 1700 tsunami are estimated – for some areas - based on recorded losses of human lives. The chronology of recorded events in the Japanese calendar is then correlated and converted to times and dates in the Gregorian calendar, in an effort to link in time a possible distant origin source for "the orphan tsunami". Subsequently presented are the results of a numerical simulation study that postulates the tsunami's source to be a large megathrust earthquake off the Pacific Northwest. Based on the tsunami travel time from the Pacific Northwest to Japan, it is subsequently deduced that the Cascadia earthquake must have occurred at about 9 p.m. on January 26, 1700.

**Comments for Part 2**

The entire part 2 section of the book is an outstanding work of scholarship with the usual perfection and thoroughness that characterizes Japanese record keeping and their pioneering tsunami research work. The numerical study is valid but it should be pointed out that the earthquake source parameters are primarily based on conjecture. However, the exactness of the dating of the Cascadia event and the reconciliation of chronologies and calendars are addressed in the commentary for Part 3.

## PART 3

The third part of the Book entitled "The orphan's parent" is an effort to further document a dogmatic opinion originally expressed at the 1996 meeting of the Trans-Pacific Reunion that the "parent" event that caused the tsunami in Japan was the postulated magnitude 9 Cascadia megathrust earthquake. On the basis of subsequent geologic findings and through a process of "elimination" – since no other great earthquake occurred elsewhere in the Pacific - this section refocuses on a Cascadia source earthquake. Correlation to the Cascadia "parent" event is further advocated on the basis of earlier work on tree-ring tests and dendrochronology, which placed the approximate window of time for the megathrust earthquake to be - for a certain area only - in the range of August 1699 and May 1700. From this evidence, and radiocarbon dating of "paleotsunami" deposits that give a time range of about 1700 -1710 (+/- 10 years), a conclusion is provided that large earthquakes had struck the Pacific Northwest repeatedly in the past several thousand years and - as previously stated - the latest Cascade megathrust event purportedly occurred in the evening (9 P.M) of January 26, 1700.

Subsequently, based on the geographical spread of the observations, this section reiterates that the rupture of the Cascadia megathrust earthquake was at least 1,000 km long and, thus, the moment magnitude in the range of 8.7 to 9.2 – as much or even more than that of other great tsunamigenic earthquakes in other subduction zones. Furthermore, in an attempt to establish a recurrence frequency of megathrust earthquakes, the subsequent section presents data and illustrations identifying episodes of subsidence along the Pacific Northwest. These episodes are then correlated to megathrust earthquakes, the relative chronology of occurrences is established and an estimate of 10% probability of recurrence in the next 50 years is assigned to the next great Cascadia earthquake.

The final section of Part 3 concludes with some useful information on preparedness and disaster mitigation measures. It includes a cursory discussion of disaster preparedness issues from a repeat of the great Cascadia earthquake and tsunami and provides some general guidelines for hazard zones and safe areas – as obtained from tsunami hazard modeling studies.

**Comments on Part 3**

The conclusions of Part 3 of the book linking the "orphan" tsunami in Japan to the purportedly contemporaneous, great Cascadia megathrust earthquake of 1700 are based on postulations which appear to be reasonable but which, however, lack definitive confirmation. They are based on conjecture and are somewhat contradicted by current geological and geophysical findings. The analysis and conclusions linking the two events together in Part 3 raise questions as pointed previously, but also invoke the need for additional commentary.

Although the origin of the "orphan" tsunami may have been unknown since there was no earthquakes recorded in Japan, Kamtchatka, Alaska, or South America that year (A.D. 1700), it is possible that a different source - such as a landslide or an unreported or unfelt earthquake - may have caused it. The 1992 earthquake in Nicaragua is an example of such a silent offshore earthquake. None of the people in Central America felt any strong earthquake motions before the tsunami struck. Therefore, it is possible that the "orphan" tsunami in Japan may have had a similar unknown local or distant origin source – and not necessarily from the Cascadia region. No paleotsunami deposits have been found in Hawaii or elsewhere in the Pacific that would support the generation of a Pacific-wide tsunami from a Cascadia earthquake. Furthermore, tsunamis from major earthquakes in Northern Japan in 1963 and 1994, or the great Kamchatka earthquake of 1952 – which had similar energy path orientation but from the opposite side of the Pacific – were not significant in the Pacific Northwest. Therefore, why should we assume that a Cascadia earthquake was the parent source event of the "orphan" tsunami in Japan, when the well-documented and more recent data for other events does not support major azimuthal focusing of tsunami energy?

Additionally, the postulated chronology of events on both sides of the Pacific could be incorrect given the differences of calendars, the limits of error in radiocarbon dating techniques (+/- 10 years), or the seasonal time window of dendrochronology. Even if we assume that all corrections reconciling calendars (Japanese, Julian and Gregorian) were made correctly – which is doubtful - to deduce that the Cascadia earthquake occurred at about 9 P.M. on January 26, 1700 based on the 10 hour tsunami travel time to Japan, as determined by the numerical modeling study which postulated such a source, is a self fulfilling prophesy. It is unwarranted accuracy based on compounded conjecture.

Even if we assume that the chronology is correct, can we really conclude that all of the purported paleotsunami sediments found over a large expanse of the Pacific Northwest were deposited by a single tsunami generated by a single Cascadia earthquake? Could there have been more than one event, perhaps closely spaced in time? Many subduction zones produce large earthquakes within days or weeks apart. The subduction zones in Japan and the Solomon islands have produced major or great earthquakes, days or weeks apart, as one segment of a fault stress loads another. The recent earthquake of December 26, 2004 in Sumatra is another example. Stress load transfer caused the great Nias island earthquake of March 28, 2005 in the adjacent southern segment of the Great Sunda Subduction Zone, three months later.

Additionally, could it be that some of the purported paleotsunami sediments and sand layering found in the Pacific Northwest were actually deposited by storm surge action, flash flooding, or some other rapid depositional mechanism that could also account for the random mix of sediment particle sizes?

Furthermore, can we reasonably conclude that one single megathrust earthquake in the Cascadia region in 1700 had a rupture of 1,000 or more km and a moment magnitude of as much as 9.2, based only on the presumption of widely scattered sediment layers believed to have been deposited by a single tsunami? Is such a long rupture possible on the CSZ given the fact that the Cascadia zone has not produced any earthquakes with magnitudes greater than 6 during the past 70 years? This fact alone has convinced many scientists that the region is relatively inactive – not necessarily because of locking - but because sediments from the Columbia River must constantly ``lubricate" the downward-thrusting oceanic plates so they never build up significant strain – thus believing that earthquakes with moment magnitude 9 are highly unlikely to occur in the future.

Unfortunately, the book "The Orphan Tsunami' had already been written when the 7.2 magnitude earthquake of June 14, 2005 occurred off the coast of Northern California. An analysis of this event, if included in the book, would have been useful in the assessment of potential megathrust tsunamigenic earthquakes near the Cascadia Subduction Zone. Only a sensitive tide gauge recorded a 3 cm tsunami. This latest earthquake occurred inside the highly deformed southernmost portion of the Juan de Fuca plate, known as the Gorda plate. In spite of the earthquake's proximity to the subduction zone, its crustal displacements resulted from slip on a NE striking, left-lateral, strike-slip fault on the seismogenic portion of the Gorda plate - which we know to be highly deformed. In fact the epicenter of this quake was about 67 miles west of the epicenter of the November 8, 1980, where a 7.2M earthquake, which had been even closer to the CSZ, but did not generate a tsunami.

This latest earthquake event of June 14, 2005, raises several additional questions that create doubt as to some of the conclusions provided in the "Orphan Tsunami". The length of the rupture has been previously addressed but must be questioned again. Could all segments of the CSZ from the Mendocino fracture boundary plate to the Queen Charlotte fault break in sequence for a length of 1,000 km to generate a 9.2 earthquake? Where would the rupture originate? Would it originate near the Nootka fracture zone of the central Juan de Fuca plate, which separates it from the northern Explorer segment, and, if so, how could it be 1,000 km long? Would it originate near the Blanco Fracture Zone close to the northern boundary of the Gorda plate and extend north? Or would perhaps originate at the southeastern most corner of the Gorda plate near the triple junction where the CSZ joins the Mendocino Fracture Zone and the San Andreas fault? The 7.2 magnitude Cape Mendocino earthquake in 1992 occurred near the triple junction but no great rupture occurred. The tsunami was relatively small in Crescent City and elsewhere. There was no significant tsunami along the Pacific Northwest.

Also, additional questions arise from the conclusions of “The Orphan Tsunami” about Cascade earthquakes with moment magnitude 9 - given the complexity of Cascadia’s stress provinces. For example, both the Pacific Northwest Province and the Cascade Convergence Province have compressive stresses but one has a N-S orientation while the other has a NNE-SSW orientation. This could be a limiting factor in rupturing. Therefore, are the apparently different types of compression geometry and segmentation along the CSZ, limiting factors as to the size of earthquakes that can occur and the length of potential ruptures? Should we perhaps accept that the CSZ has different geometry and stresses than the subduction zone along the Great Sunda Trench? Can we reasonably categorize the two regions and their tectonics as being analogous? Would a segmentation and fragmentation analysis of the Juan de Fuca or Gorda plates show that such a long break might not be possible? Shall we perhaps reexamine the tectonic plate motions in the entire Pacific Northwest? We have divergence on the western boundary of the Juan De Fuca tectonic plate and convergence along the eastern boundary. We have rotation along the southern boundary. Could perhaps large earthquakes in Cascadia involve blocks with maximum rupture lengths of only 200 – 250 km as those along the Japanese subduction zone? Finally, can indeed tsunamis be generated in the Cascadia region that can have destructive far field effects as far away as Hawaii or Japan? Finally, shall we perhaps look somewhere else for the parent event of the “Orphan Tsunami” rather than in the Cascade region?

## CONCLUSIONS

“The Orphan Tsunami” is a great book with very useful information in assessing the tsunami risk of the Pacific Northwest, but does not provide all the answers. The authors do a magnificent job of documenting the historical information of the tsunami in Japan and in outlining potential tsunami risks of the Pacific Northwest from major earthquakes that can indeed occur along the Cascadia Subduction zone – although potential magnitudes may have been overstated. The major conclusion linking the “orphan” tsunami in Japan to a Cascade megathrust, magnitude 9 earthquake is based primarily on conjecture and peripheral circumstantial evidence. Thus, the title “The Orphan Tsunami” was properly chosen for the book, which, in spite of its wealth of data, elaborate detective work, and seemingly persuasive arguments – still leaves us with the uncertainty of what really was the parent event that resulted in the destructive tsunami of 1700 in Japan. What is presented in the book is a possible scenario but not necessarily what actually happened. However, this should not detract from the value of the book as an outstanding work of scholarship and documentation, even in the absence of adequate historical or geological data to work with and sufficiently link the two disaster events.

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