Reconnaissance-level mapping of vulnerable areas in a tsunami-prone coast using shuttle radar-derived Digital Elevation Model

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The South Indian coastline experienced the most devastating tsunami on 26 December 2004, with run-up height (maximum vertical height) of 10.5 m. Possibility of a similar event in the near future is now being postulated. This work describes the run-up elevation maps prepared using SRTM (Shuttle Radar Topographic Mission) Digital Elevation Model (DEM) and geomorphic details derived from satellite images, showing the probable areas of inundation due to various wave-heights along parts of Kerala coast. These areas include the Bharathapuzha estuary, Periyar estuary, Vembanadu Lake and certain low-lying mudflats of Kuttanadu. It is also evident that the Beach ridge complexes seen in the satellite images and SRTM DEM, could act as a buffer against waves up to 10 m height. Thus, the inundation maps derived from SRTM DEM can serve as a good input for mapping vulnerable areas.

Keywords: Digital Elevation Model, inundation mapping, shuttle radar, tsunami.

DELINEATION of coastal areas vulnerable to tsunami is a difficult task as it involves intensive fieldwork to prepare physiographic maps, height details (for Digital Elevation Model, DEM), landuse and geomorphic maps. Preparation of such maps using conventional techniques is manpower intensive, expensive and depends on the terrain and weather conditions. However, these limitations can be overcome using remote sensing technique. Satellite images provide information on coastal configuration, morphology and changes, while satellite-derived DEM gives good details about topography of the coastal region. Vulnerable zones in tsunami-prone regions have been mapped using remote sensing technique[1,2]. A comprehensive study has been conducted for tsunami prediction in California using different run-up elevations[3].

The aim of this communication is to prepare a vulnerability map showing coastal areas susceptible to inundation corresponding to various wave-heights along parts of the Kerala coast.

As the tsunami travels from the deep-water, continental slope region to the near-shore region, tsunami run-up occurs. Run-up (H) is defined as the maximum height of the water observed above a reference sea-level. Parameters that may be determined from the run-up value are: (i) tsunami magnitude (m), which is defined[4] as:

$$m = \log_2 H, \tag{1}$$

and, (ii) tsunami intensity (I) which is defined[5] as:

$$I = \log_2(2^{1/2} \times H). \tag{2}$$

Tsunami may reach a run-up height of 10, 20 and even 30 m. The first wave is not likely to be the biggest. Since tsunami obeys the shallow-water wave dynamics, configuration of the ocean floor or bathymetry governs the direction of propagation. The reason why certain coasts are battered by tsunamis while the neighbouring areas are not affected, is because of the focusing and de-focusing of wave energy dictated by the bottom topography. During the recent earthquake, this phenomenon was evident when tsunami struck the Kerala coast that is on the lee side of travel direction. Some bays like the Bay of Bengal have a funneling effect. Run-up elevation details are the most important input for inundation mapping in tsunami-prone areas.

Two important inputs for inundation mapping can be obtained from remotely sensed images. The first is the elevation data of the coastal zone obtained using SRTM (Shuttle Radar Topographiic Mission) DEM. The second is information on geomorphic set-up of the coastal zone, obtained using satellite images.

DEM is a quantitative model of part of the earth's surface in digital form, in particular, elevation of a region. Typically, a DEM consists of an array of uniformly spaced elevation points in raster format. Terrain models have always appealed to military personnel, landscape architects, civil engineers as well as earth scientists. Digital terrain modelling is a process to obtain desirable models of the land surface. Satellite images like aerial photographs are potential sources for generating DEM.

Graham[2] first reported that a pair of Synthetic Aperture Radar (SAR) images of the same area taken at slightly different positions can be used to form an interferogram and phase differences recorded in the interferogram can be used to derive a topographic map of the earth's surface. This technology is called In SAR or SAR interferometry. Polidori[6] reviewed the concepts and applications of Digital Terrain Models from radar images, including SAR interferometry.

Images acquired by SAR are sensitive to terrain variation. Height information is derived using the interferogram, $\phi(x, r)$. These record the phase differences between two complex radar images with phase components $\phi_1(x, r)$ and $\phi_2(x, r)$ of the same area taken by two SARs on-board the same platform or by a single SAR revisited. According to the radio-wave propagation theory, phase delay measured by an antenna is directly proportional to the slant range from the antenna to a target point and indirectly propor-

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tional to the wavelength of the spectrum. If ϕ is the phase difference between the two complex radar images, R the slant range, and λ the wavelength of the radar signal, then

$$\phi = \frac{2\pi R}{\lambda}. \quad (3)$$

Then the interferogram $\phi(x, r)$ is given by

$$\phi = \Delta\phi = \phi_2 - \phi_1 = \frac{2 \times \pi \times Q \times \delta R}{\lambda}, \quad (4)$$

where $Q = 1$ and δR is the slant range difference when the two antennas are mounted on the same flying platform, one transmitting wave but both receiving echoes simultaneously to form a one-pass interferometry[7]; $Q = 2$ when the two SAR images are acquired at two different places by the same radar. Various missions, including SRTM have acquired SAR data over time. In this study, the SRTM DEM has been extensively used to map the topography of a part of Kerala coast to map probable areas of inundation.

The study area is a narrow strip of coastal land with a length of 225 km from Alapuzha (lat. 9°29′N and long. 76°19′E) in the south to Ponnani (lat. 10°47′N and long. 75°54′E), Kerala (Figure 1). The area is characterized by coastal lowlands, backwaters, coastal plains and lagoons. The Arabian Sea washing its shore on the west provides its distinctive physical features[9]. SRTM-derived DEM of the study area is depicted in Figure 2.

Figure 1. Study area.

The three physiographic units of the study area as identified by Soman[7] are:

(i) Coastal lowlands represented by areas within altitudinal range of 10–20 m, and consisting of floodplains, alluvial terraces, valley-fills, colluvium and sedimentary formations.

(ii) Coastal plains and lagoons, which are the low-lying areas fringing the coast and having elevations of 1–4 m amsl. Beach dunes, mudflats, barrier flats, coastal alluvial plains, floodplains, river terraces, marshes and lagoons constitute this unit.

(iii) Strand plains which are considered as the sites of significant accumulation of sediments, and lie parallel to the present shoreline. Swarms of sub-parallel beach ridges, dunes, ancient beach ridges and swales are present along most parts of the coastal stretch. These regions show an elevation between 7 and 10 m amsl.

Major rivers such as the Periyar, Bharathapuzha and Chalakudi drain the study area. The general drainage pattern

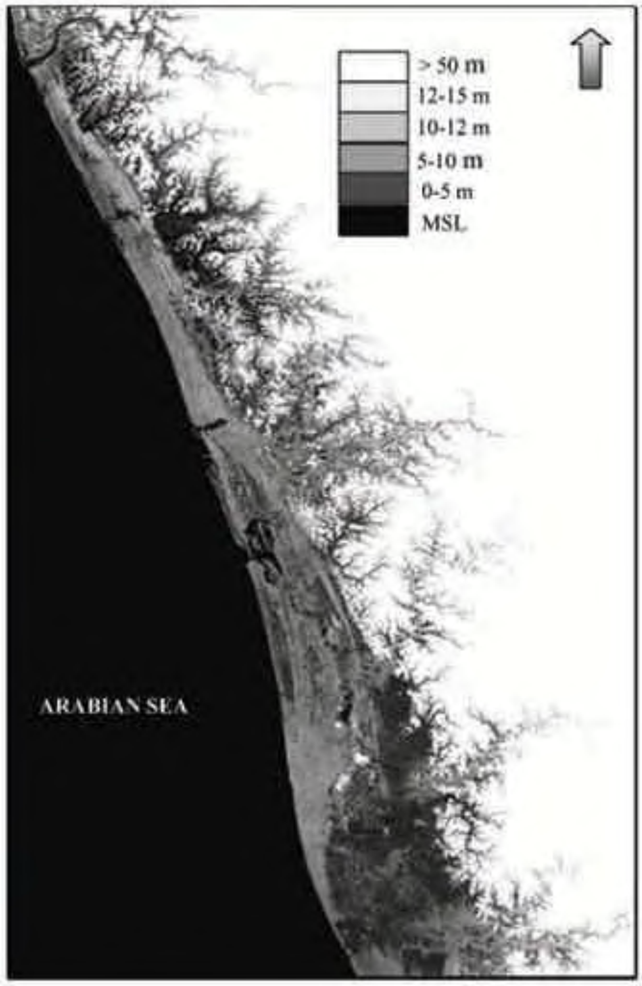

Figure 2. SRTM-derived DEM of study area.

is dendritic, although in places, trellis, sub-parallel and radial patterns are also noticeable[10]. Most river courses are straight, indicating structural control. Periyar, having a length of 240 km, is the longest river in Kerala. Since the Periyar Estuary lies in the lowland area, the river mouth and its surroundings may be affected to a large extent during a tsunami. Bharathapuzha is the second longest river in Kerala, with a length of 205 km and has a wider river mouth in the Ponnani Estuary, which lies in a lowland area. Hence, the possibility of inundation due to tsunami is high in this estuarine region. The river flows as braided form and covers a larger area, which increases the chance of inundation. Chalakudi River flows through thick forests and the channel has many waterfalls until it reaches the plains at Kanjirapally. The river has a length of 130 km.

A kayal (origin Malayalam) can be generally described as a body of brackish, marine or hypersaline water, impounded by a sandy barrier and having an inlet connecting it with the open sea. It is mostly inter-connected by natural or man-made canals. Vembanadu Lake is the largest kayal in the study area. It extends from Cochin to Alapuzha for a distance of 80 km. Its width varies from a few hundred metres to 14 km. The lake has a number of connections with the sea, which increases the chance of inundation. Bathymetry of the lake varies in different sites; the maximum depth is 10 m from mean sea-level. Considering the above factors it may be concluded that this area may also be inundated during a tsunami.

Bathymetry is defined as the water depth related to sea-level. A bathymetric map describes the ocean bottom features. Near-shore bathymetry plays an important role in inundation by tsunami. As the near-shore depth decreases, chance of inundation by the tsunami increases. For the work reported here, bathymetric details were derived from the hydrographic chart (on 1 : 150,000 scale) of the area from Alapuzha to Ponnani (Figure 3). For convenience, in this study, the area is divided into five zones as follows.

The Alapuzha zone has a gentle slope. The profile indicates that the 0–5 m stretch from the coastline is steeper than the 5–10 and 10–20 m stretches. The stretch of 20–50 m has a gentler slope compared to the above-mentioned stretches. Such an undulating shelf could result in more inundation along the coast.

The profile of bathymetric contours suggests that the Andhakaranazhi zone region has a steeper slope compared to the Alapuzha region near the shore, i.e. in the 0–5 m stretch. The slope of the region in the 5–10 and 10–20 m stretch is similar to that of the Alapuzha region. But the slope from 20 to 50 m is much less compared to the above region. This region has a creek as an inlet, thus making it vulnerable to inundation due to tsunami.

The profile suggests that the Cochin zone has the gentlest slope from the shore to a depth of 50 m. The shape of the bathymetric contours in the 10–50 m stretch depicted in the hydrographic chart is serrated, suggesting that the bottom topography in this region is undulating. The Vembanadu Lake inlet and barrier islands present in this region makes it significant in the context of tsunami studies.

The bathymetry of Kodungallur zone indicates a steeper slope for regions of 0–5 m depth and a gentler slope for those of 10–50 m depth. This region comprises the River Periyar and its tributaries that drain out into the Arabian Sea. The river mouth is much wider and bathymetry of the region is much different from that of the other four sections. This is a conduction zone for tsunami.

Bathymetry of Ponnani zone indicates a steeper slope for 5 and 10 m contours. Hence, a minimum wave-height of 3 m can inundate this region. The region witnesses the confluence of three rivers, namely Bharathapuzha, Thirur and Anniramukkupuzha. Since this region is directly connected to the sea by an estuary, it is a vulnerable zone.

Subset images of SRTM DEM were first chosen for the study area. Elevation data of the coastal areas were then compared to, and corrected with GPS-derived ground data and input from topographic maps. Since only inundation mapping of the coastal stretches was considered, the upland areas (areas or pixels with values >30 m) were masked-out and not considered for further analysis.

Density slicing is a form of selective one-dimensional classification. The continuous grey scale of an image (here elevation data) is ‘sliced’ into a series of classifications based on ranges of brightness (here elevation) values.

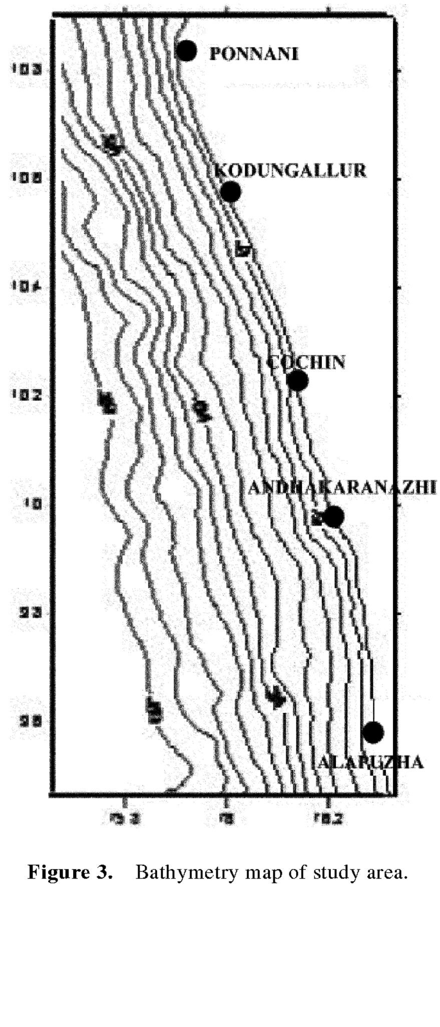

Figure 3. Bathymetry map of study area.

All pixels within a 'slice' are considered to belong to the same information class. Density slicing of SRTM DEM was carried out with minimum elevation on land as 0 m and maximum elevation as 1, 5, 10 and 20 m. The number of density slice ranges was set as 3 or 4 depending upon the minimum and maximum elevation of the area. The resulting density-sliced output image (Figure 4) reveals dependable information on the terrain model and possible inundation in the coastal area.

It is realized that coastal geomorphology plays an important role in deciding the inundation during a tsunami. LANDSAT TM image 1 : 75,000 scale, covering the segment of Alapuzha to Ponnani, Kerala was visually interpreted to delineate the coastal geomorphologic features of the study area. Interpretation has been done using the inductive and deductive analysis of various image elements like tone, texture, pattern, shape, size, association and terrain elements such as landform, drainage, erosion and landuse. A detailed coastal geomorphologic map of the study area was prepared (Figure 5) and digitized. The major geomorphic features that could act as a barrier against the tsunami include sand dunes, sand bars and barrier islands, while those that could aid in conductance of the tsunami include estuaries, creeks, kayals and mudflats.

Vulnerability mapping can be best done using an integrated approach covering SRTM DEM, coastal geomorphology and near-shore bathymetry details. Hence all data generated for the study area were integrated and the final vulnerability maps for tsunami heights of 1, 5, 10 and 20 m were generated.

The geomorphic set-up of the coastal region of Kerala is quite unique. Creeks, lagoons, estuaries, beaches, beach ridges, strandlines, dunes and slacks, mudflats and many other landforms punctuate the study area spreading over the 225 km long coastline of Kerala. The coastal area was subjected to transgression and regression of the sea[11]. This phenomenon resulted in a series of ancient beach ridges that standout today as linear to curvilinear, parallel sets of strandlines with slacks between them. Such strandlines and dune complexes are topographic highs with heights up to 10 m near the shoreline, and are well exhibited in the SRTM DEM. It is expected that the possible inundation in such areas due to tsunami run-up would be low.

Study of the geomorphic and the integrated map (Figure 6) indicates that: (i) For 1 m tsunami height, few low-lying areas and coastal stretches are likely to get affected (Figure 6 *a*), since most of these areas are directly connected to the sea through an estuary. Certain geomorphic features such as mudflats, swales and slacks may be affected. Coastal bathymetry adjacent to these areas shows steep slopes, which increases the chance for inundating

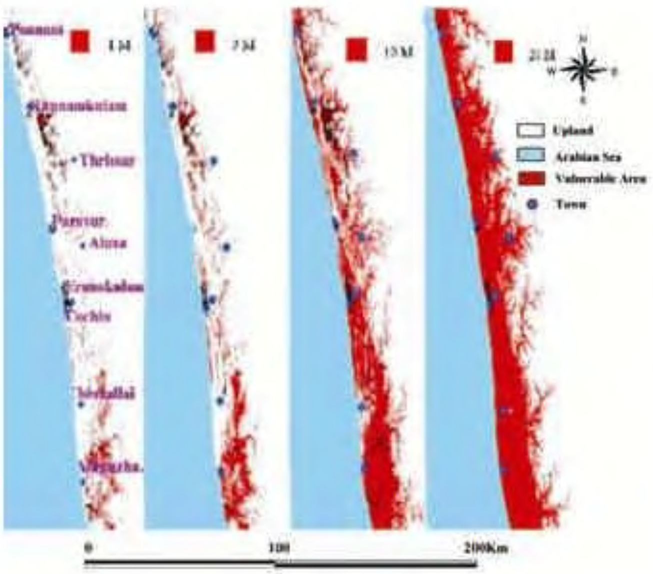

Figure 4. Density sliced tsunami run-up estimates from SRTM DEM.

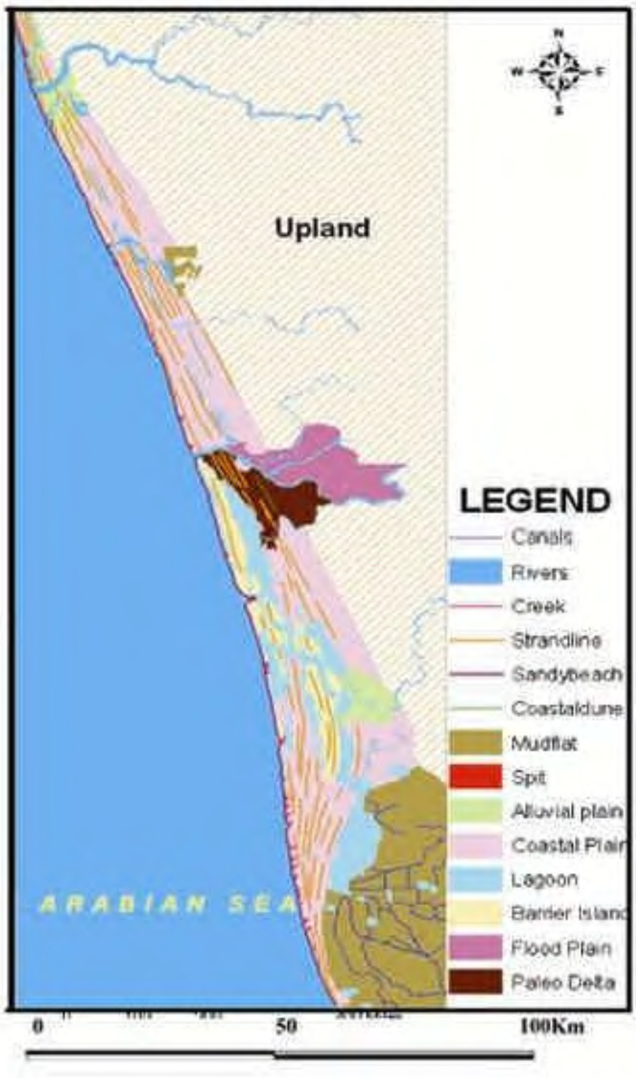

Figure 5. Coastal geomorphologic map.

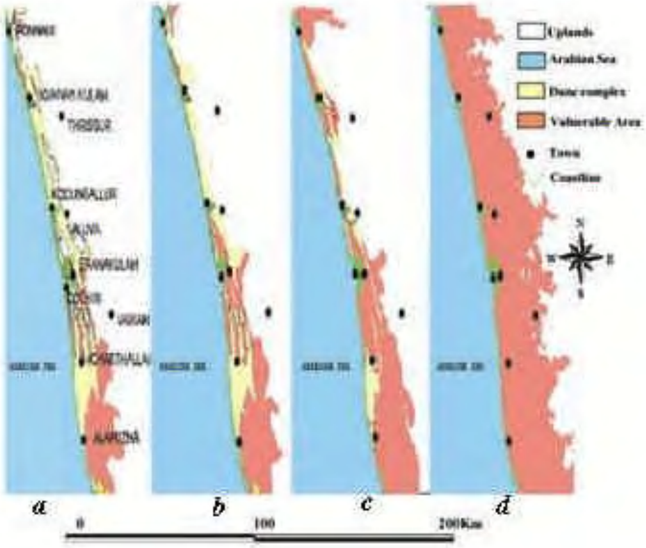

Figure 6. Final vulnerability maps.

the area by tsunami. (ii) For 5 m tsunami height, part of the coastal stretch may get affected (Figure 6 *b*). The main inundated areas are Vembanadu Lake and its surrounding region, mudflats of Kuttanadu, Periyar and Bharathapuzha estuaries and Thotapalli creek, Alapuzha district. Alapuzha zone, including Vembanadu backwaters, Andhakaranazhi zone, Cochin zone and Ponnani zone may get affected. (iii) Kodugallur may not be affected severely because of the presence of a dune complex (10 m height) in the area (Figure 6 *c*). Though bathymetry indicates that the area is under the tsunami risk zone, the dune complex acts as a buffer for waves up to 10 m. This is clearly revealed in the SRTM DEM and run-up elevation map. The 20 m height wave will severely affect all the five zones, namely Alapuzha, Andhakaranazhi, Cochin, Kodungalur and Ponnani, because the height of the dune complex is not enough to resist the upcoming wave (Figure 6 *d*). Above 10 m height, no geomorphic features control the tsunami inundation. Major towns like Alapuzha, Cherthalla, Cochin, Aluva, Kunnamkulam and Ponnani are likely to be affected. This is clearly revealed in the SRTM run-up elevation map.

The work presented so far is based on a predictive model using SRTM DEM, LANDSAT TM images and bathymetry. The inundation maps are predictive and hence the predictions need to be validated. This was done by visiting the sites in Kerala that were inundated by the recent December 2004 tsunami. About 145 inundated sites were noted. The wave height during the December 2004 tsunami was up to 3 m. The result of the field-mapping exercise also agrees with the prediction using SRTM DEM. Thus, it may be summarized that an integrated approach with SRTM DEM, geomorphology and bathymetry is best suited to identify vulnerable areas that may be classified as high, moderate and low-risk zones in the event of a future tsunami along the Kerala coast.

Geoscientists predict that another tsunami may occur in future. Preparedness by people living in the coastal areas could reduce the quantum of the disaster. Such preparedness is possible with the help of maps showing vulnerable zones of inundation. This communication demonstrates that elevation data from SRTM DEM can aid in inundation mapping at reconnaissance level. These maps provide clear details about the topography of the coastal region.

The exceptionally high coastal dune complexes of Kunnamkulam, Aluva and Alapuzha, which act as a defence against high run-ups, are clearly depicted both in satellite imagery and SRTM DEM. Similarly, the coast-parallel strandline complexes in the Alapuzha, Cherthalla, Cochin, Kodugallur and Ponnani regions, which also act as a buffer, are depicted in the DEM. The presence of creeks from Alapuzha to Andhakaranazhi region and canals makes the region vulnerable to a great extent. Field evidences collected by means of GPS surveys agree well with inundation limits indicated by the SRTM DEM, thus supporting the role of remote sensing in predicting vulnerable areas.

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