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RESEARCH ARTICLE

Delineation of relative tsunami risk for the coastlines of Eastern and Southern Provinces of Sri Lanka[**]

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Abstract: This paper presents a preliminary assessment of the spatial distribution of tsunami risk for the Eastern and Southern Provinces of Sri Lanka. In the absence of probabilistic tsunami hazard assessments and detailed information on the vulnerability of coastal communities, field observations and numerical simulations of the 2004 tsunami were utilized to obtain the distribution of three parameters (the incident tsunami height, the horizontal inundation distance and the degree of damage to housing) that quantify the tsunami impact in the above two provinces. The incident tsunami height is reflective of the level of hazard, whereas both the inundation distance and damage to property partially reflect the vulnerability of each locality. Accordingly, in the present assessment, the distribution of relative tsunami risk is computed by factoring the influence of each of these parameters normalized with the respective mean value for the entire coastal sector. Two separate curves depicting the variation of the relative risk are compiled in this way for the Eastern and Southern Provinces. The results suggest that the several submarine canyons that are present in the eastern seaboard have a significant effect on the incident tsunami amplitudes, and consequently, on the risk distribution along the east coast. Moreover, the computed curve for the Southern Province indicates the influence of coastal geomorphology and onshore topography on tsunami risk. The high risk areas delineated in this study may be given priority in formulating mitigatory measures for tsunami threat.

Keywords: Indian Ocean Tsunami, inundation distance, risk assessment, tsunami hazard.

INTRODUCTION

The impact of the 2004 tsunami along the coastline of Sri Lanka was not uniform: there was considerable destruction in some localities whilst little or no destruction in certain other areas in the proximity (Wijetunge, 2005). For instance, the tsunami impact on Addalachchenai in the Eastern Province was minimal although there was considerable destruction in the neighbouring cities to the north and the south: statistics on the number of people affected and the number of housing units damaged (Department of Census and Statistics, 2005a,b) clearly confirm this (Figure 1). Such observations reveal that the level of tsunami risk for coastal communities exhibits considerable variation even along a short stretch of the shoreline. Also, the high cost and the scarcity of coastal lands in many areas demand an accurate assessment of the tsunami risk rather than arbitrary conservative zonation (Carayannis, 1988). Moreover, information relating to the spatial distribution of the tsunami risk is essential in formulating post-tsunami coastal land use plans as well as in planning of evacuation of people during tsunami warnings.

However, neither comprehensive probabilistic assessments of the tsunami hazard nor the detailed information pertaining to the vulnerability of coastal communities are available at present for Sri Lanka. Consequently, the methodology adopted in the present paper is to use field observations and numerical simulations of the 2004 tsunami, which may be considered a worst-case scenario, in order to obtain the variation along the coastline of three parameters that quantify the tsunami impact. These three parameters are the tsunami height, the horizontal inundation distance and the degree of damage to housing as a result of the 2004 tsunami.

The relative risk is computed by factoring the influence of each of these three parameters normalized with the respective mean value for the entire length of the coastal sector concerned. Two separate curves depicting the spatial variation of the relative risk are compiled

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in this way for the Eastern and Southern Provinces as the geomorphology of these two coastal sectors are essentially different.

METHODS AND MATERIALS

Study area**:** Of the five provinces affected by the 2004 tsunami disaster, the Eastern Province suffered the most in terms of the number of lives lost as well as the destruction to property with 47% of the death toll and 53% of the housing units completely or partially damaged (Department of Census and Statistics, 2005a,b). The Southern Province was the second most affected with 33% of the death toll and 25% of the housing units completely or partially damaged (Department of Census and Statistics, 2005a,b). The present study is limited to the Eastern and Southern Provinces owing to non-availability of sufficiently detailed data for the rest of the coastal belt.

The coastline of the Eastern Province stretches from Kumana (81.71°E, 6.51°N) to Pulmoddai (80.96°E, 8.99°N) across three administrative districts, namely, Ampara, Batticaloa and Trincomalee (Figure 2). The east coast is generally flat and low-lying with wide expanses of depositional, sandy beaches. The coastal belt of the Southern Province extends from Bentota (80.00°E, 6.43°N) to Kumana (81.71°E, 6.51°N) along the administrative districts of Galle, Matara and Hambantota (Figure 2). The southern coastline is dominated by bays and rocky headlands as well as barrier beaches and spits (Swan, 1983). Narrow tidal inlets that are maintained by bays or lagoons and associated upland drainages also compartmentalise many stretches of the south coast. The coastline of the Hambantota District has well-developed dune systems, which typically rise up to about 8 – 10 m in several successive levels and are usually stabilised with vegetation cover.

Selection of parameters**:** The tsunami risk for a given locality is determined by the combined influence of the level of hazard and the degree of vulnerability. The tsunami height, which depends on factors such as the source characteristics and the wave processes, is reflective of the level of tsunami hazard along a coastline. The impact of a tsunami on a given locality also depends on factors such as the ground elevation above the sea level, the population density and the construction standards, all of which represent the vulnerability of the area concerned. However, in the absence of detailed studies of the physical vulnerability of the coastal belt for tsunami threat, the spatial variation of two parameters gathered during the field measurements carried out in the aftermath of the 2004 tsunami, i.e. the extent of inundation and the degree of damage to housing units may be considered, at least partially, to reflect the vulnerability of each locality. This is because the inundation distance depends, for example, on the ground slope (Wijetunge, 2009a), and the level of damage to housing units depends on factors such as the type and construction standard of such dwellings. Accordingly, the methodology adopted in the present study is to utilize available spatial data relating to the tsunami height (i.e. maximum water levels near the coastline), the horizontal inundation distance, and the degree of damage to housing as a result of the 2004 tsunami, to delineate the tsunami risk for the coastal belts of the Eastern and Southern Provinces.

It must be added that none of the parameters selected for the present study reflect social and economic vulnerability of coastal communities. Unfortunately, paucity of data relating to social and economic vulnerability indicators or proxies such as household income, adult literacy and unemployment, at the desired spatial resolution does not allow incorporation of the same in the present risk analysis. However, the present study could be extended and further refined to also incorporate social and economic aspects of vulnerability once such data at sufficiently high spatial resolution become available for the coastlines concerned.

Tsunami height**:** The spatial resolution of the tsunami heights available from the field measurements of the 2004 tsunami is not adequate for the present purpose. Therefore, the tsunami heights at a resolution of 250 m along the coastline of the Eastern and Southern provinces were computed by employing a previously validated numerical model based on shallow-water equations. A five-segment fault plane model corresponding to an earthquake of moment magnitude $M_w = 9.1$ (Wang & Liu, 2006) in the Northern Sumatra-Andaman subduction zone was adopted for these simulations. The maximum water levels nearest the shoreline, i.e. at each offshore wet point ahead of the first land point encountered by the tsunami waves, were extracted from the inner-most grid of the dynamically coupled nested system of grids employed to cover the seaboard of the Eastern and Southern Provinces as well as the fault plane.

Inundation distance**:**

Inundation distance is the maximum horizontal penetration of tsunami flooding in the direction normal to the shoreline. The distribution of inundation distances in the east and south coasts are available from the field surveys carried out by the author (Wijetunge, 2006, 2009a, b) in the aftermath of the 2004 tsunami. The extent

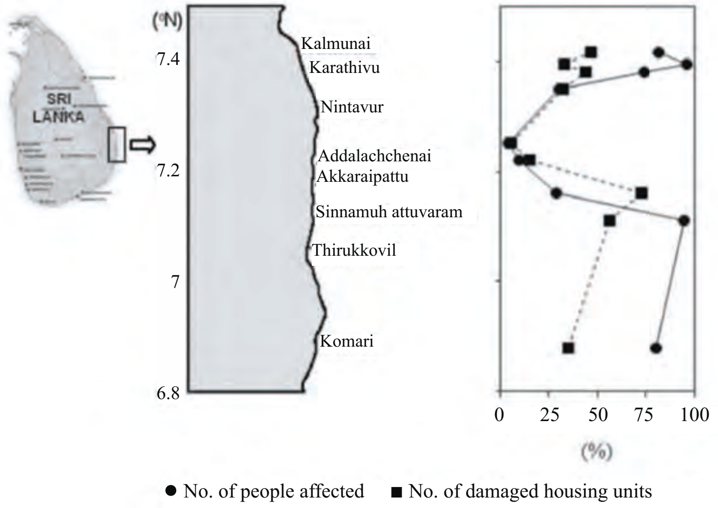

Figure 1: Spatial variation of statistics on the number of people affected and the number of housing units completely or partially damaged by the 2004 tsunami in the coastal stretch between Kalmunai and Komari in the Eastern Province.

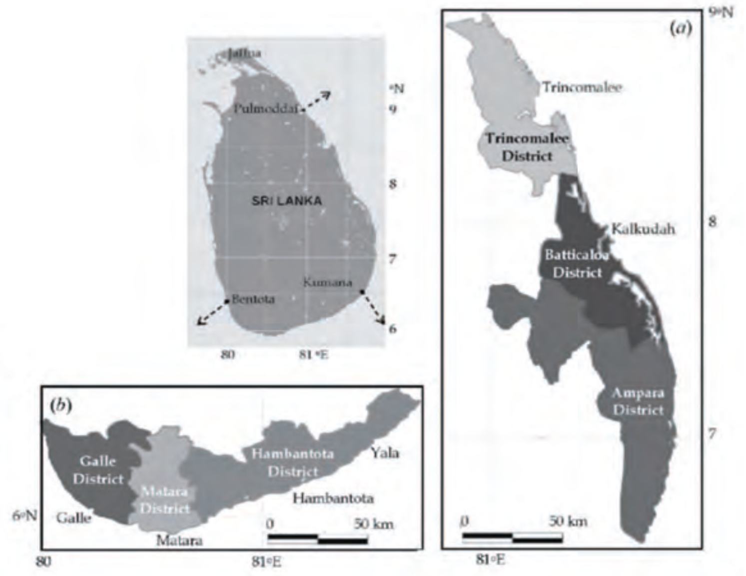

Figure 2: Study area: (a) Eastern Province and (b) Southern Province, of Sri Lanka.

of significant tsunami inundation was determined based on damage to structures and/ or trees and vegetation, lines of debris and location of wreckage as well as eyewitness accounts of overland flow. It must be added that, although it was possible to make use of the traces left behind by the tsunami to detect the inundation limit in the first few weeks after the disaster, subsequently, eyewitness accounts were extensively made use of as perishable physical evidence disappeared with time. The furthest penetration of tsunami inundation, in general, at about 200-400 m intervals along the coastal belt, was obtained in this way by employing a hand-held *Magellan*

GPS receiver with a horizontal positional accuracy within 7 m. Subsequently, Global Mapper v8.03 software was employed to overlay the GPS records of onshore limit of inundation on digital topographic data from the Survey Department of Sri Lanka to obtain the horizontal inundation distance normal to the zero-elevation contour, which was taken as the shoreline.

***Damage to housing*:** Extensive data gathered after the 2004 tsunami relating to the number of housing units that were either completely damaged or partially damaged but unusable have been published by the Department of Census and Statistics of the Government of Sri Lanka (Department of Census and Statistics, 2005a). In this survey, a place of dwelling of human beings separated from other places of dwelling and with a separate entrance is termed a 'housing unit'. These data were utilized to obtain the percentage of the number of housing units that were completely or partially damaged in the Divisional Secretariats (DS) with a coastal boundary in each administrative district of the Eastern and Southern Provinces. Detailed descriptions of the damage caused by the 2004 tsunami to housing and other buildings in the Eastern and Southern Provinces can be found in Dias *et al*. (2006) and Rossetto *et al*. (2007).

***Computation of relative risk*:** Computed tsunami heights were available at 1,100 and 750 locations along the east and south coasts, respectively. Accordingly, data pertaining to the inundation distance and the percentage of housing units damaged were linearly interpolated to obtain the corresponding values at the locations where the computed tsunami heights were available.

The following formula was used to factor the spatial data relating to the computed tsunami height (H), the inundation distance (d) and the percentage of damaged housing units (D) to quantify the relative tsunami risk (RTR) for each coastline:

$$(RTR)_i = \left(\frac{H_i}{H_m}\right) \cdot \left(\frac{d_i}{d_m}\right) \cdot \left(\frac{D_i}{D_m}\right) \qquad \text{... (1)}$$

where, the index i represents the grid location along the shoreline and m denotes the mean value of each parameter for the entire length of the respective coastline. The mean values of H, d and D used in the computations are given in Table 1. Note that all three parameters are given the same weight in the present analysis.

Table 1: Mean values of each parameter used in the calculation of relative risk

Province	Mean value		
	H_m (m)	d_m (m)	D_m (%)
Eastern	5.7	710	39
Southern	4.9	252	21

RESULTS AND DISCUSSION

Figure 3 shows the spatial variation of the following parameters for the Eastern Province: (*a*) computed tsunami heights nearest the shoreline, (*b*) measured inundation distances, and (*c*) the percentage number of housing units damaged. The corresponding data for the Southern Province is shown in Figure 4. Clearly all three parameters show considerable spatial variation along the coast of both provinces. The computed tsunami heights for the Eastern Province range from 2.2 – 11.4 m with a mean value of 5.7 m, whilst in the Southern Province, the corresponding range is 2.1 – 11.6 m with a mean value of 4.9 m. The tsunami heights recorded by several field survey teams in the immediate aftermath of the 2004 tsunami (Choi *et al*., 2005; Liu *et al*., 2005; Sato *et al*., 2005; Goff *et al*., 2006; Shibayama *et al*., 2006; Tomita *et al*., 2007) are also shown in these figures.

The extent of tsunami inundation in the Eastern Province is considerably larger than that in the Southern Province. For instance, the median value of measured inundation distances in the Eastern Province is 600 m (maximum = 2500 m), whilst in the Southern Province, the respective values are 180 m and 1300 m. This is primarily because the coastal areas of the Eastern Province mostly has low-lying, wide stretches of flat coastal lands in contrast to the Southern Province. Secondly, as the tsunami waves crashed almost head-on onto the east and south-east coasts, the velocity and hence the momentum of the tsunami induced flood flow could have been higher resulting in greater penetration in the east coast than in the south and the south-west (Wijetunge, 2006). The inundation distances that have been influenced by the presence of coastal waterways and water bodies such as rivers, canals, lakes and lagoons are not included in the present analysis. It must also be mentioned that inundation measurements are not available for that part of the coast between Kokavillu and Mutur (8.1~8.6°N) and between Nilaveli (~8.73°N) and Pulmoddai (~8.99°N) in the Eastern Province (Figure 3) as these areas were not accessible owing to the security situation prevailing at the time. The stretch of coastline between Kumana (6.5°N) and Savalai (6.83°N) was also not accessible due to lack of passable roads and presence of dense forest cover. Further discontinuities in the measurements also exist across shorter stretches of the coastlines of both the Eastern and Southern Provinces owing to difficulties in accessing interior areas at some locations.

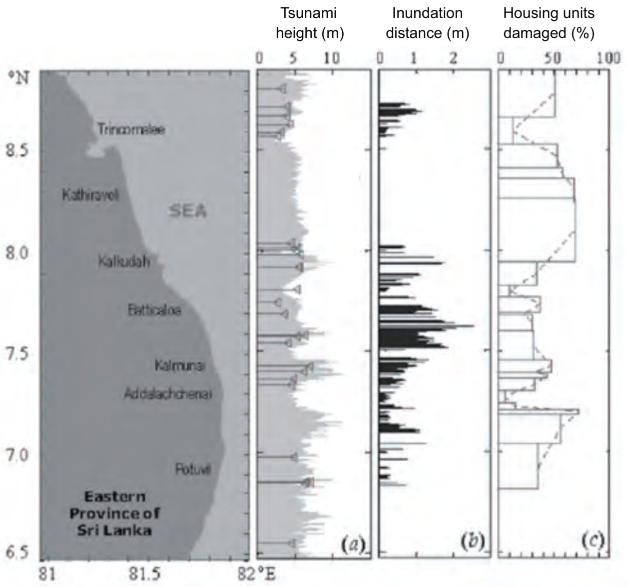

Figure 3: Spatial variation off the east coast of: (a) computed maximum water levels adjacent to the shoreline (in grey); field measurements of maximum water levels (inverted triangles) (Choi *et al*., 2005; Liu *et al*., 2005; Sato *et al*., 2005; Goff *et al*., 2006; Shibayama *et al*., 2006 & Tomita *et al*., 2007), (b) measured inundation distances, and (c) the percentage of housing units completely or partially damaged in each Divisional Secretariat (DS). (modified after Wijetunge, 2009a)

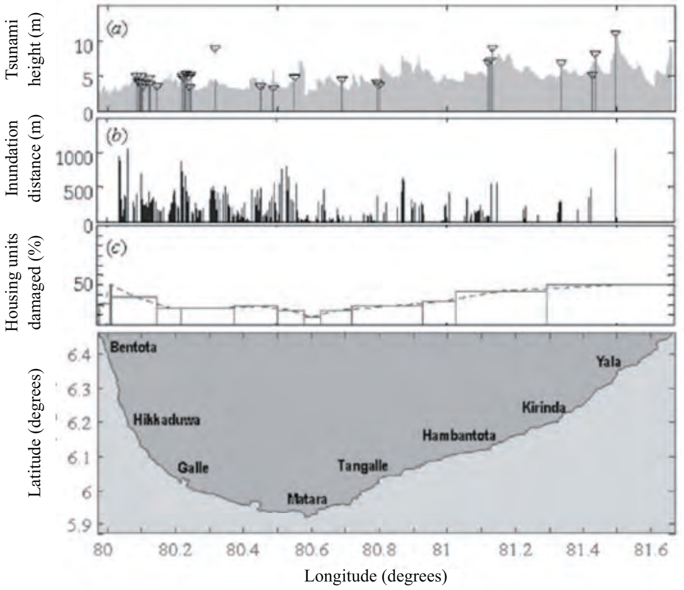

Figure 4: Spatial variation off the south coast of: (a) computed maximum water levels adjacent to the shoreline (in grey); field measurements of maximum water levels (inverted triangles) (Choi *et al*., 2005; Liu *et al*., 2005; Sato *et al*., 2005; Goff *et al*., 2006; Shibayama *et al*., 2006 & Tomita *et al*., 2007), (b) measured inundation distances, and (c) the percentage of housing units completely or partially damaged in each Divisional Secretariat (DS). (modified after Wijetunge, 2009b)

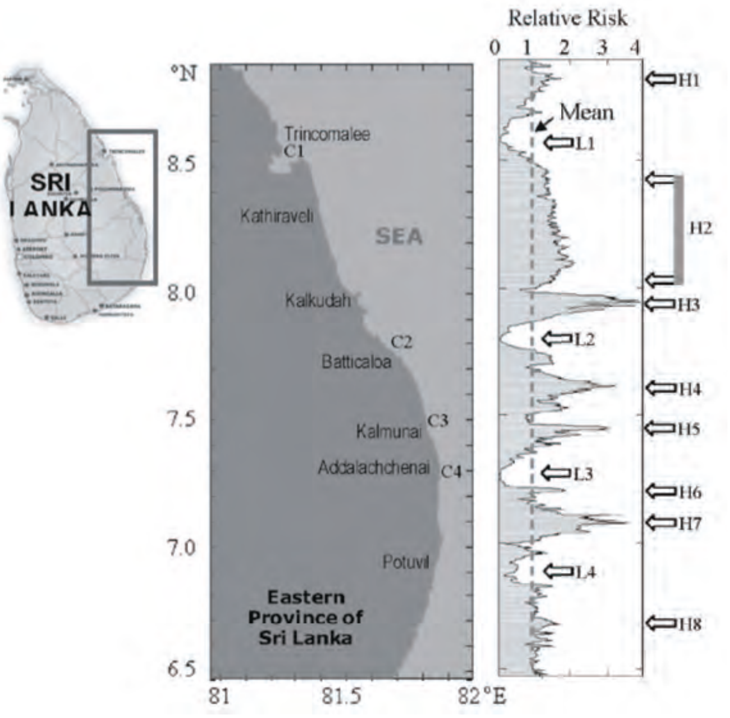

Figure 5: Variation of relative tsunami risk for the Eastern Province. The broken line shows the mean value for the entire coastline. Arrows H1-H8 and L1-L5, respectively denote relatively high risk and low risk localities. C1-C4 marked on the left panel show the locations of the valleys of submarine canyons.

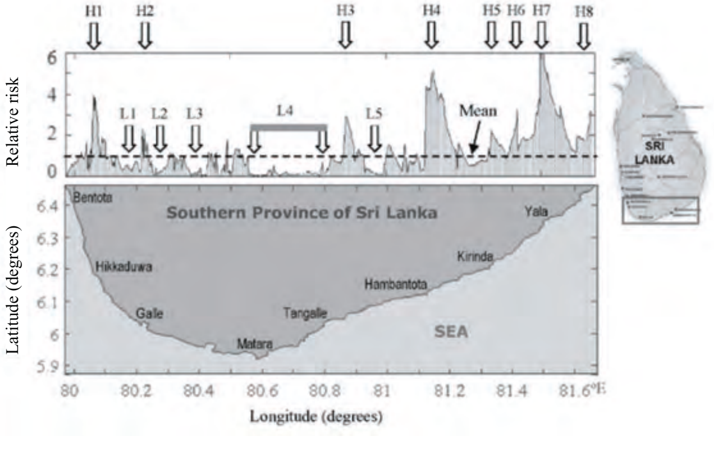

Figure 6: Variation of relative tsunami risk for the Southern Province. The broken line shows the mean value for the entire coastline. Arrows H1-H8 and L1-L5, respectively denote relatively high risk and low risk localities.

The statistics on damage to housing units also reflect the relatively more severe impact of the 2004 tsunami on the Eastern Province. The percentage of housing units damaged in the Southern Province range from 7 - 40 % with a mean value of 22 %; the corresponding figures for the Eastern Province are 5 - 73 % with a mean value of 39 %.

The way in which the relative tsunami risk (*RTR*, equation 1) varies along the coastline of the Eastern and Southern Provinces is shown in Figures 5 and 6, respectively. Note that these relative risk curves indicate whether the risk is lower or higher at a given location compared to the mean for the entire coastline. Therefore, the average level of risk for the coastline concerned is also shown in these figures by a broken horizontal line passing through *RTR* = 1.

For the east coast (Figure 5), the tsunami risk appears to be lower in the vicinity of L1 (8.6°N), L2 (7.80°N), L3 (7.27°N), and L4 (6.9°N), whereas the peaks indicating higher risk can be seen near H1 (8.85°N), H2 (8.05~8.45°N), H3 (7.95°N), H4 (7.62°N), H5 (7.45°N), H6 (7.2°N), H7 (7.1°N), and H8 (6.68°N). Some of these prominent peaks and troughs in the relative risk curve are related to the influence of four submarine canyons in the eastern seaboard (C1-C4 marked on the left panel of Figure 5). For example, the troughs L1-L4 are largely due to the lower tsunami heights, and consequently, lower inundation distances and damage levels, as a result of energy defocusing caused by the valleys of the respective canyons. On the other hand, focusing of tsunami energy caused by the ridges of the canyons is primarily responsible for most of the notable peaks in the risk curve: for example, peak H5 is clearly due to focusing of wave energy by the ridges of the canyons at C3 and C4, and peak H3 is mainly due to wave energy focusing by the northern ridge of the canyon at C2 further aided by the bathymetry to the north. Furthermore, the peaks H4 and H7 are also due to wave energy convergence caused by both the northern ridge of the canyon at C3 and the southern ridge of the canyon at C4, respectively. Besides the incident tsunami height, factors such as the coastal geomorphology and the onshore topography are also responsible for the spatial variation depicted in the risk curves at some localities.

The tsunami risk for the south coast (Figure 6) appears to be comparatively lower at: L1 (80.16~80.19°E), L2 (80.26°E), L3 (80.38~80.42°E), L4 (80.58~80.79°E), and L5 (80.96~80.99°E). On the other hand, notable peaks for the Southern Province can be seen near: H1 (80.05°E), H2 (80.23°E), H3 (80.87°E), H4 (81.15°E), H5 (81.35°E), H6 (81.42°E), H7 (81.5°E), and H8 (81.65°E). Peaks H4 and H7 are primarily consequent to the direct exposure of that part of the coast to tsunami waves due to source directivity (Ben-Menahem & Rosenman, 1972) as well as strong energy focusing by the offshore bathymetry. The peak in relative risk at H1 (Akurala-Peraliya) is where the tsunami surge overturned and submerged an intercity train killing over thousand people. The tsunami risk is mostly below-average from 80.26°E to 80.85°E, and in particular, the risk is very low in the stretch L4 owing to the presence of comparatively high elevation ground with steep beach slopes.

The high risk areas identified above may be given priority in emergency planning and in formulating mitigatory measures. A strategic approach that could be adopted to mitigate tsunami impact is discussed by Hettiarachchi and Samarawickrama (2006).

It is emphasized that the present study delineates the relative tsunami risk on a larger scale, based primarily on the field evidence of the impact of the 2004 tsunami owing to the lack of probabilistic tsunami hazard assessments and detailed information relating to all aspects of vulnerability for the coastal belt of Sri Lanka. Although some aspects of the physical vulnerability of the coastline are factored through the use of field measurements of the extent of inundation and damage to property, social and economic vulnerability of coastal communities have not been considered in the present risk assessment. Moreover, potential tsunami hazard from other seismic zones around the Indian Ocean (Gunatilaka, 2005) is also not considered in the present analysis; however, numerical simulations carried out by Okal and Synolakis (2008) appear to suggest that the 2004 tsunami could still be the worst-case for the east and the south coasts of Sri Lanka.

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