J. Natn.Sci.Foundation Sri Lanka 2005 **33**(2): 61-68

FEATURE ARTICLE

INDIAN OCEAN TSUNAMI ON 26 DECEMBER 2004: DISTRIBUTION OF TSUNAMI HEIGHT AND INUNDATION ALONG THE COASTLINE OF SRI LANKA

JANAKA J. WIJETUNGE
Department of Civil Engineering, University of Peradeniya, Peradeniya.

Key Words: Coastal Hazards, Indian Ocean Tsunami, Tsunami Height, Inundation

INTRODUCTION

The tsunami unleashed by the great earthquake of moment magnitude 9.3 in the Andaman–Sumatran subduction zone on 26 December 2004 caused massive loss of life and damage to property along two-thirds of the coastline of Sri Lanka as well as in several other countries. However, even casual inspection of the devastation in the affected parts of the coastline around the country reveals that the extent of tsunami damage is not uniform: some areas suffered extensive damage, while damage in other areas was less and in certain other areas of the coastline there is no damage at all. Therefore, a detailed assessment of the onshore distance within which significant damage has been caused by the recent tsunami may provide some helpful guidance to identify, among other things, high-hazard as well as low-hazard site areas. This field information should be supplemented with further inundation data from mathematical simulation of other possible scenarios of coastal flooding due to tsunamis as well as storm surges. It must be noted that, storm surges, although not potentially as destructive as a major tsunami, can be comparatively more frequent. Therefore, inundation maps indicating the extent of the coastal strip that would be affected by potential events of both tsunamis and storm surges ought to be prepared, preferably for different recurrence intervals.

Such a risk assessment requires the use of mathematical models to simulate the generation, the propagation across the ocean, and eventually, the overland run-up of hypothetical events of tsunamis and storm surges. However, the reliability of the existing numerical models of tsunami have not been tested sufficiently due partly to the paucity of field data as destructive tsunamis are, fortunately, infrequent. Therefore, evidence of tsunami height and subsequent run-up left behind by the tsunami on 26 December 2004 must be traced as such data are invaluable to improve our understanding and predictive capability for tsunami hazards.

Accordingly, two Japanese teams carried out such a field survey in the south-west[1] and the south[2] coasts, respectively, during 4–6 January 2005 and 6–9 January 2005. Thereafter, a team of scientists from the United States made tsunami height measurements during 9–15 January 2005 at several locations in the east, south and south-west coasts of the country[3]. Subsequently, a team of engineers from the Department of Civil Engineering of the University of Peradeniya carried out a tsunami run-up and inundation survey during 20–26 February 2005 in collaboration with the Department of Civil and Environmental Engineering of the Sungkyunkwan University of Korea.[4] The study was carried out at nearly 25 locations around the country, and focused on areas that had not been covered by the previous surveys. More recently, Sato *et al.*[5] too have carried out a field survey in the west and the south-west coasts during 25 February – 2 March 2005.

This paper utilizes the results of the Peradeniya-Sungkyunkwan field survey as well as available data from other surveys to examine the distribution of tsunami height and the extent of inundation around the affected parts of the country due to the tsunami of 26 December 2004.

METHODOLOGY

The methodology adopted in carrying out the Peradeniya - Sungkyunkwan field survey and the subsequent processing of data is described in the following. The field study covered the east coast from north of Vakaneri through Batticaloa, Kalmunai and Akkaripattu down to Potuvil; Jaffna peninsula from Thondamannar to Manalkadu; and the west and the south coasts from Kalutara to Hambantota. It must also be mentioned that this was the first time that measurements of the recent tsunami have been made in the northern coastal sector.

The measurements at the selected locations of the affected coastline around the island included tsunami height near the shore as well as the horizontal inundation distance, i.e., how far the wall of water has travelled inland causing significant damage.

The tsunami heights were determined visually based on watermarks and damage on structures and/or trees as well as from eyewitness accounts. The heights and distances were measured using standard surveying instrumentation whilst the corresponding locations were obtained by employing a hand-held Global Positioning System (GPS).

During the survey, elevation of each tsunami watermark was measured relative to the mean swash, i.e., the sea level at the shore. Subsequently, the tide-level adjustment was made with the difference in sea levels at the time of measurement and that at the tsunami attack. The tide data used for this purpose are those given in Tsuji *et al.*[6] as well as those derived from the tidal constituents given in Admiralty Tide Tables.[7] Tide data from Point Pedro, Trincomalee, Galle and Colombo were utilized to adjust the measured tsunami heights from the north, east, south/south-west and west coastal sectors, respectively. It must, however, be added that the tide correction was often not more than ±0.2 m (i.e., less than about 2%-6% of the measured tsunami heights) owing to the comparatively small tidal range around the country.

The eyewitness accounts from the east coast indicated that the second wave was the largest and that it had arrived 10–15 min after the first wave. Therefore, the approximate arrival time of the highest wave for the east coast, required for tide correction, was taken as 9.30 h. by adding 15 min to the estimated arrival time of the first wave. The arrival times of the highest wave for the other coastal sectors were also estimated similarly.

The other important parameter in connection with the tsunami overland flow is the extent of inundation. The extent of significant tsunami inundation too 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. At several locations, local people could give reliable information about the maximum tsunami run-up, for example, "water came up to this step of this temple ...". As it is practically very difficult to make such inundation measurements at each and every kilometre along the coastline, one primary objective of the field survey was to verify the reliability of the tsunami inundation data that could be obtained from satellite images, for example, ESRI[8] vector data, taken after the tsunami. Fortunately, the inundation measurements at most of the selected locations were found to give good agreement with those derived from the ESRI data. Therefore, it appears that the inundation and damage shown on ESRI satellite images are sufficiently reliable to prepare a preliminary tsunami inundation map for the country.

RESULTS AND DISCUSSION

We first consider the distribution of the estimated tsunami heights in the significantly affected parts of the coastline around the country in Figure 1. The measurements of Wijetunge *et al.*[4] as well as those of Kawata *et al.*[1], Shibayama *et al.*[2], Liu *et al.*[3] and Sato *et al.*[5] are shown.

It must be added that, the Peradeniya field survey[4] did not cover the coastal stretch from Nilaveli down to Trincomalee as the US team[3] had already made measurements there. Most parts of the coastline north of Nilaveli towards Mullaittivu and beyond as well as the stretch south of Mutur down to around Kokavillu were, unfortunately, not accessible.

The measurements of Wijetunge *et al.*[4] and Liu *et al.*[3] suggest maximum tsunami heights of 3 m – 7 m along the east coast from Nilaweli through Trincomalee, Mutur, Vakaneri, Batticaloa, Kalmunai and Akkaripattu down to Potuvil, with an increasing trend towards the south.

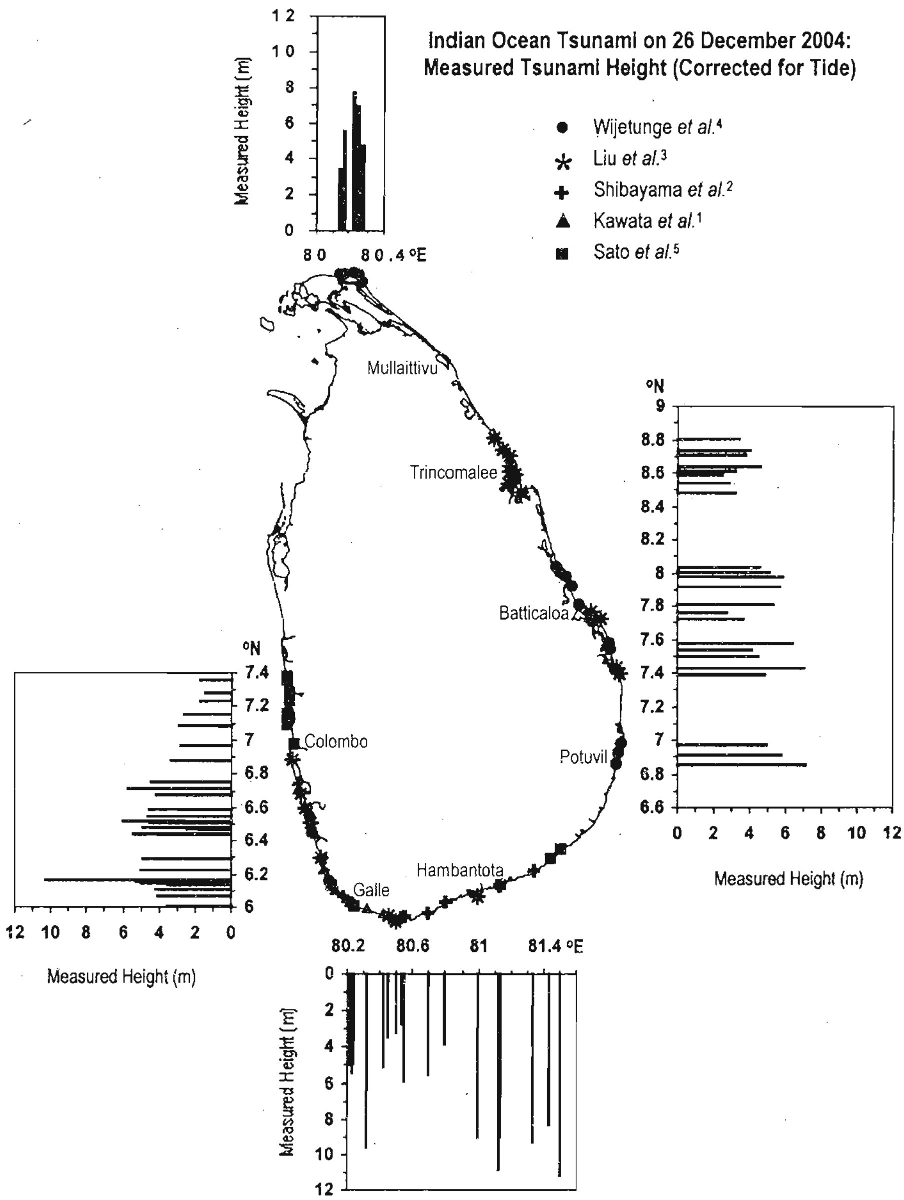

Figure 1: Distribution of tsunami height along the coastline of Sri Lanka.

On the south coast, there appears to be considerable variation in the tsunami height with values ranging from less than 3 m to as high as over 11 m. Kawata *et al.*[1] have made tsunami height measurements at five locations at the city of Galle (~80.22°E), and we see in Fig. 1 that the average tsunami height there is about 4.5 m – 5 m. The measured tsunami heights in the coastal stretch from Galle to Tangalle are about 4 m – 6 m except at two locations; the measurements of Kawata *et al.*[1] suggest tsunami heights of over 9 m at Koggala Airport (~80.32°E) and those of Shibayama *et al.*[2] indicate a maximum water level of only 2.7 m at Polhena (~80.52°E). Moreover, the measurements of Shibayama *et al.*[2], Liu *et al.*[3] and Sato *et al.*[5] clearly indicate considerably high tsunami heights of about 9 m – 11 m at Hambantota, Kirinda as well as in Mahaseelawa and Patanangala beach areas of the Yala National Park (coastal stretch from ~81.0°E – 81.5°E).

On the south-west and the west coasts, the measured tsunami heights show a decreasing trend towards the north. The recorded tsunami heights in the Dodanduwa–Beruwala stretch (~6.1°N–6.5°N) is about 4 m – 5 m barring one location at Kahawa (~6.16°N) where the estimated water elevation is over 10 m according to Kawata *et al.*[1]

Further, Sato *et al.*'s[5] measurements indicate tsunami heights ranging between 1.4 m – 2.9 m along the coastal stretch from Mattakkuliya in the north of Colombo to the Lansigama beach in Marawila (~6.9°N–7.4°N). The comparatively low tsunami heights in the west coast is not surprising as this part of the coast was largely sheltered from direct tsunami impact and only diffracted waves with less energy could reach there.

The measurements of Wijetunge *et al.*[4] in the accessible parts of the coastline of the Jaffna peninsula indicate tsunami heights ranging from about 3.4 m to 7.6 m. It is interesting to note that Point Pedro at the north-east corner of the peninsula has recorded wave heights of over 7 m whilst that at Manalkadu on the east coast of the peninsula is less than 5 m.

Figure 1 shows that, on the whole, the distribution of the tsunami height along the affected coastline around the country is not uniform. In general, such non-uniform distribution of tsunami height could be attributed to many factors including the travel path of the tsunami waves, the width of the continental shelf, the energy focusing effects, the shape of the coastline and the nearshore bathymetry.

It is interesting to note that, Yeh *et al.*'s[9] measurements along a 350 km stretch from Pulicat down to Vedaranniyam on the south-east coast of India appear to show a correlation between the tsunami heights and the width of the continental shelf. A similar comparison was made for the tsunami-affected coastline of Sri Lanka, and the results are shown in Figure 2 for the south and the east coasts. Note that, the 100 m and 200 m depth contour lines have been used in Figure 2 to represent the edge of the continental shelf.

We see in Figure 2*a* that, along the south coast, the widest point of the continental shelf (about 35 km) lies off the coast of Hambantota, and the narrowest (about 5 km) off Matara. Although, not entirely consistent, Figure 2*a* for the south coast appears to show smaller tsunami heights associated with the narrow continental shelf off Matara (~80.4°E–80.7°E), whilst comparatively larger tsunami heights are associated with the wider shelf off Hambantota-Yala (~81.0°E–81.5°E). However, a correlation between the tsunami heights and the breadth of the continental shelf is not at once discernible from Figure 2*b* for the east coast.

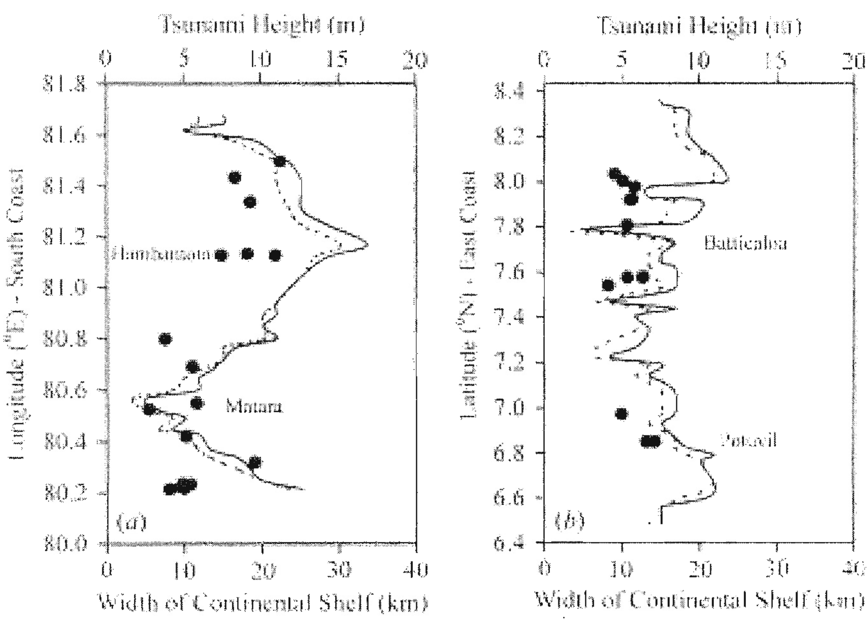

Figure 2: Tsunami heights and the width of the continental shelf along the south and east coast of Sri Lanka.

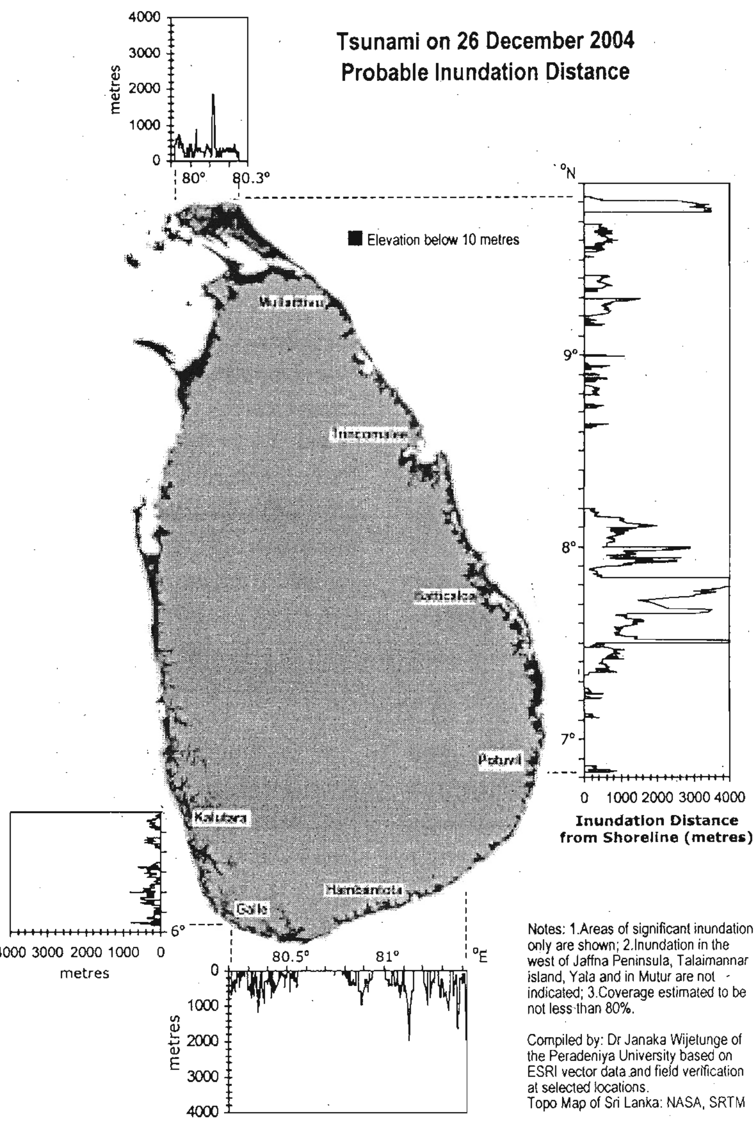

Figure 3: Distribution of probable inundation along the coastline of Sri Lanka.

Figure 3 shows the probable tsunami inundation distances that were obtained as described in Section 2 for the south and the south-west coasts as well as for the north and the east coasts (modified after Wijetunge[10]). Each of the four plots gives the probable horizontal inundation distance in metres from the shoreline against the latitude (°N) or the longitude (°E) of that part of the coastline. The map of Sri Lanka also shows the coastal areas with elevation below 10 m MSL. The digital elevation data used in this image are those that were acquired by the Shuttle Radar Topography Mission (SRTM) of the United States National Aeronautics and Space Administration (NASA) in February 2000. The SRTM used Synthetic Aperture Radar (SAR) technique to capture the land topography, so the actual elevation in some areas could probably be around 7 m – 10 m owing to the possible presence of land cover.

The tsunami inundation had been greater for the east coast than the south, south-west and the west coasts, barring a few locations like the area around Hambantota. This was because: (*a*) the earthquake that created the tsunami occurred just about 1000 kilometres east to south-east of Sri Lanka along the Andaman–Nicobar-Northern Sumatra line, and the east coast had the tsunami waves propagating almost head-on compared to most parts of the south-west and the west coasts which only had diffracted and/ or refracted tsunami waves laterally dispersing into the shadow zone, (*b*) the tsunami waves crashed almost head-on onto the east coast, the velocity and hence the momentum of the tsunami induced surge flow could have been higher resulting in greater penetration along the east coast than the south-west and the west coasts, and, (*c*) the north and the east coasts generally consist of low-lying, wide stretches of flat coastal lands compared to the rest of the country's coastal belt.

On the north and the east coasts, tsunami inundation had been quite extensive at several locations along the coastline from Vakarai (~8.15°N) down to Batticaloa-Kalmunai (~7.42°N), and along an eight-kilometre stretch south of Point Pedro from Tumpalai, Vallipuram down to Kudattanai (~9.81°N–9.75°N), as well as around Mullaittivu (~9.2°N–9.3°N). In some areas, for instance, around Batticaloa (~7.75°N), the lagoons have certainly helped convey the tsunami surge large distances inland.

In the Jaffna peninsula, we see particularly greater inundation, reaching a maximum of nearly 1800 m onshore, in the vicinity of the lagoon entrance at Tondamannar (~80.14°E). This, however, is not surprising owing to the presence of the lagoon as well as low-lying (elevation below 10 m) coastal lands in and around Tondamannar. We also see that the tsunami inundation is only about 300 m–400 m deep on either side of the peak at Tondamannar, i.e., along the coastal stretches from 79.08°E–80.09°E and 80.17°E–80.25°E, approximately. This is because, in these areas, there are patches of high ground immediately onshore of the comparatively narrow, low-lying beach-fronts of breadth 0.5 km – 1 km and 0.5 km – 2 km, respectively, to the east and the west of Tondamannar. On the other hand, there is an extensive strip of low-lying coastal lands from Point Pedro down to Chundikkulam (~9.8°N–9.6°N) and we see that these areas are clearly associated with large inundation distances.

The deepest tsunami wave penetration in the south coast is at Hambantota (~81.13°E), over two kilometres near the salt-pans. Significant inundation can also be seen further east of Hambantota in the Kirinda–Uyangoda–Palatupana stretch (~81.2°E–81.45°E), particularly around the smaller lagoons and bays. Hungama-Tangalle beach to the west of Hambantota too has recorded notable inundation, especially where tsunami surge waves had been conveyed inland through water bodies opening to the sea such as lagoons and lakes.

The inundation plot for the south coast shows a stretch of the shoreline without significant tsunami damage between 80.55°E to 80.75°E, to the west of Dickwella. This was not because the tsunami wave heights were low, but because the coastal lands there are at a comparatively higher elevation with steep beach slopes, as observed during the field survey and further confirmed by the topography map in Figure 3.

The coastline from Galle to Matara (~80.22°E–80.52°E) too suffered badly with particularly deep inundation occurring along the coastal belt of Talpe–Koggala–Ahangama

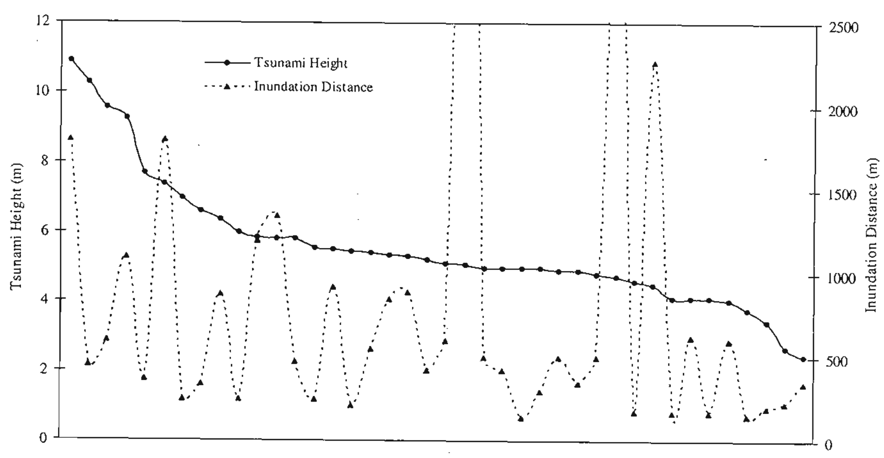

Figure 4: Tsunami heights and inundation distances.

(~80.3°E–80.4°E), besides the tragic loss of life and destruction in the densely populated coastal cities of Galle and Matara.

On the south-west and west coasts, we see a lessening of tsunami inundation, albeit with intermittent peaks, as we go from Galle to Kalutara and further up. Predominant inundation peaks on this stretch of the coast appear near Paraliya-Telwatte, Akurala, and Ahungalla Points.

Finally, the measured tsunami heights together with the corresponding inundation distances are shown in Figure 4. Clearly, the results shown in Figure 4 do not suggest any strong correlation between the tsunami heights and the extent of inundation. This, however, is not entirely surprising as the extent of inundation depends upon several factors other than the tsunami height, such as the land topography, the surface roughness and the momentum of the tsunami surge flow.

It must be added that, what we have discussed above is the larger, overall picture of the tsunami height as well as the resulting inundation and damage for the whole country. However, it was clear during the field survey that there is considerable local variation of inundation and consequent damage even along a short stretch of the coastline in many parts of the country. In general, such non-uniform tsunami inundation could be attributed to many factors including the nearshore tsunami height, land topography and surface roughness. However, further detailed studies are necessary for us to understand and determine the way in which the above factors have influenced the tsunami overland flow and the consequent damage at a given location.

CONCLUSION

The evidence of tsunami height and subsequent run-up left behind by the tsunami on 26 December 2004 has been mapped around the country as such data are invaluable to improve our understanding and predictive capability for tsunami hazards.

The measurements suggest maximum tsunami heights of 3 m – 7 m along the east coast with an increasing trend towards the south. On the south coast, there appears to be considerable variation in the tsunami height with values ranging from less than 3 m at Polhena, about 5 m at Galle and Matara to as high as over 11 m near Hambantota, Kirinda and Yala. The distribution of tsunami height around Jaffna Peninsula too seems to be highly non-uniform, with values ranging from about 3 m – 8 m. On the south-west and west coasts the measured tsunami heights show a decreasing trend towards the north.

On the whole, the tsunami inundation had been greater for the east coast than the south, south-west and the west coasts, barring a few locations like the area around Hambantota. The results also indicate the possible influence of the coastal geomorphology on the extent of inundation.

References

1 Kawata Y., Imamura F., Tomita T., Arikawa T. & Yasuda T. (2005). The December 26, 2004 Sumatra earthquake tsunami: field survey around Galle, Sri Lanka. *http://www.drs.dpri.kyoto-u.ac.jp/sumatra/srilanka/galle_survey_e.html.*

2 Shibayama T., Okayasu A., Wijayaratna N., Sasaki J., Suzuki T. & Jayaratna R. (2005). The December 26, 2004 Sumatra earthquake tsunami: field survey around southern part of Sri Lanka. *http://www.cvg.ynu.ac.jp/G2/srilanka_survey_ynu_e.html.*

3 Liu P., Lynett P., Fernando J., Jaffe B., Fritz H., Higman B., Synolakis C., Morton R. & Goff J. (2005). South Asia tsunami, Sri Lanka field survey. *http://ceeserver.cee.cornell.edu/pll-group/tsunamis_data.htm.*

4 Wijetunge J. J., Choi B. H., Hong S. J. & Sampath D. M. R. (2005). Indian ocean tsunami on 26 December 2004: post-tsunami run-up height survey in Sri Lanka. *http://www.civil.pdn.ac.lk/academic staff/tsunami/tsunami.htm.*

5 Sato S., Koibuchi Y., Honda T., Welhena T. & Ranasinghe S. (2005). Tsunami on 26 December 2004: field investigations carried out along the west and south coasts of Sri Lanka. *http://www.drs.dpri.kyoto-u.ac.jp/sumatra/srilanka-ut/SriLanka_UTeng.html.*

6 Tsuji Y., Namegaya Y. & Ito N. (2005). Astronomical tide levels along the coasts of the

Indian ocean. Earthquake Research Institute, The University of Tokyo. *http://www.eri.u-tokyo.ac.jp/namegaya/sumatera/tide/srilanka.htm.*

7 The United Kingdom Hydrographic Office (1999). Tidal constituents for the Indian ocean and South China sea. *Admiralty Tide Tables*, Vol. 3, The Hydrographic Office, Somerset, UK.

8 Environmental Systems Research Institute (ESRI), California, USA. *http://www.esri.com/data.*

9 Yeh H., Petersen C., Chada R.K., Latha G. & Katada T. (2005). Preliminary Report on the 2004 great Indian ocean tsunami: tsunami survey along the South-East Indian coast. *http://tsunami.oregonstate.edu/Dec2004/eeri/India-Survey2.pdf.*

10 Wijetunge J. J. (2005). How far inland? *The Sunday Times*, 20 March 2005, Wijeya Newspapers Ltd., Colombo.