TSUNAMI ON 26 DECEMBER 2004: SPATIAL DISTRIBUTION OF TSUNAMI HEIGHT AND THE EXTENT OF INUNDATION IN SRI LANKA

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ABSTRACT

This paper examines the impact of the massive tsunami of 26 December 2004 on Sri Lanka by tracing the tsunami height, the extent of inundation and the level of damage along the affected coastal belt. The results of an extensive field survey that was carried out in the east, south and west coasts to record the evidence of water levels left behind by the tsunami clearly indicate non-uniform spatial distribution of inundation along the affected coastline of the country. The tsunami inundation had been significantly greater for most parts of the east and the south-east coastal areas than the south, south-west and the west coasts of Sri Lanka. The results also indicate the possible influence of the coastal geomorphology on the extent of inundation. On the other hand, the measurements suggest maximum tsunami heights of 3 m – 7 m along the east coast, 3 m – 11 m on the south coast, and 1.5 m – 6 m on the west coast.

1. INTRODUCTION

The coastal belts of several Indian Ocean countries including Indonesia, Sri Lanka, India and Thailand suffered massive loss of life and damage to property due to the tsunami unleashed by the great earthquake of moment magnitude 9.3 in the Andaman–Sumatran subduction zone on 26 December 2004. In Sri Lanka, 13 of the 14 districts lying along the coastal belt were affected: the death toll was nearly 40,000 with 15,000 injured and about 89,000 housing units either completely or partially damaged leaving one million people homeless and causing massive disruption to livelihoods. The fisheries and tourism sectors were among the hardest hit with many fishing boats and beach-front hotels destroyed or damaged.

However, it was clear in the immediate aftermath of the tsunami, that the degree of damage along the coastal belt of Sri Lanka was not uniform: some areas suffered more damage, some less, and in certain other areas, often not far away, there was no damage at all. This suggests that the level of vulnerability of coastal communities for future events of tsunami exhibits considerable variation even along a short stretch of the shoreline. Such non-uniform spatial distribution of the degree of destruction and damage to lives and property may be attributed to several factors such as the coastal topography, the population density, the construction standards, the type of land use including the density of vegetation and buildings as well as the variations in the tsunami surge height and its velocity owing to the travel path of the tsunami waves, the width of the continental shelf, the energy focusing effects and the nearshore bathymetry. However, detailed studies are necessary for us to understand and determine the way in which the above factors have influenced the spatial variations in the distribution of the tsunami height, the extent of the overland flow and the degree of consequent damage along the affected coastline of Sri Lanka.

Moreover, such field information when supplemented with further inundation data from other possible scenarios of coastal flooding would help determine the level of vulnerability of the coastal communities around the country to future events of tsunamis as well as storm surges. It must be added that, storm surges, although not potentially as destructive as a major tsunami, can be comparatively more frequent, especially for the east coast of Sri Lanka. 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 has not been tested sufficiently due partly to the paucity of field data as destructive tsunamis are, fortunately, infrequent. Consequently, evidence of the extent of inundation as well as the tsunami height and the 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 and the south coasts of Sri Lanka during 4–6 January 2005 (Kawata *et al*., 2005) and 6–9 January 2005 (Shibayama *et al*., 2005), respectively. Thereafter, a team of scientists from the United States (Liu *et al*., 2005) made tsunami height measurements during 9–15 January 2005 at several locations in the east, south and south-west coasts of the country. Subsequently, a team of engineers from the Sungkyunkwan University of Korea carried out a tsunami run-up height survey during 20–26 February 2005 in collaboration with a group of engineers lead by the author from the University of Peradeniya, Sri Lanka (Choi *et al*., 2005). The study was carried out at nearly 25 locations around the country, and was focused on areas that had not been covered by the previous surveys. Thereafter, Sato *et al*. (2005) have carried out a field survey in the west and the south-west coasts during 25 February – 2 March 2005. Subsequently, Wijetunge *et al*. (2005) carried out an extensive filed survey in the east, south and west coasts of Sri Lanka to map the extent of inundation around the affected coastline as well as to estimate tsunami heights at several locations where gaps in data existed. Moreover, Sarma (2005) have also made a limited number of tsunami height measurements in the north coast from Point Pedro down to Mullaittivu under the direction of the author.

Accordingly, in the following, the present paper utilizes the data available from the above field surveys to examine the distribution of the tsunami height and the extent of inundation along the affected coastal belt of Sri Lanka due to the tsunami of 26 December 2004.

2. METHODOLOGY

The methodology adopted in carrying out the Sungkyunkwan-Peradeniya field survey reported in Choi *et al*. (2005) and the subsequent Peradeniya survey of Wijetunge *et al*. (2005) as well as in processing of data is described in the following. The above field studies covered the east coast of Sri Lanka from Nilaveli down to Trincomalee, and then from Vakaneri through Batticaloa, Kalmunai and Akkarapattu down to Potuvil and Panama; Jaffna peninsula from Thondamannar to Manalkadu; and the west and the south coasts from near Colombo through Galle, Matara and Hambantota to the Yala National Park. It must also be mentioned that this was the first time that measurements of the recent tsunami have been made in the north 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*. (2005) as well as those derived from the tidal constituents given in Admiralty Tide Tables (1999) of The United Kingdom Hydrographic Office. 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 minutes 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 hrs. by adding 15 minutes 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 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 many locations, local people could give reliable information about the maximum tsunami run-up, for example, “water came up to this step of this temple …”. The furthest limit of tsunami inundation at about 200 m – 400 m intervals along the coastal belt was obtained in this way by employing a hand-held Global Positioning System (GPS). Subsequently, *ArcInfo* software was employed to transform the GPS records of the longitude and latitude in Geographic Coordinate System with ‘WGS 1984’ as the datum to Transverse Mercator Pojection with ‘Kandawala’ as the datum. The projected coordinates of the onshore limit of inundation were then laid on 1:50,000 scale topography maps of the Survey Department of Sri Lanka to obtain the horizontal inundation distance from the zero-elevation contour line.

3. SPATIAL DISTRIBUTION OF TSUNAMI HEIGHTS

We first consider the distribution of the estimated tsunami heights in the significantly affected parts of the coastline around the country in Fig. 1. The measurements of Choi *et al*. (2005) as well as those of Kawata *et al*. (2005), Liu *et al*. (2005), Sarma (2005), Sato *et al*. (2005), Shibayama *et al*. (2005), and Wijetunge *et al*. (2005) are shown.

It must be added that, the Sungkyunkwan- Peradeniya field survey (Choi *et al*., 2005) did not cover the coastal stretch from Nilaveli down to Trincomalee as the US team (Liu *et al*., 2005) had already made measurements there, whilst 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 at that time.

The measurements of Choi *et al*. (2005) and Liu *et al*. (2005) suggest maximum tsunami heights of 3 m – 7 m along the east coast from Nilaweli (~8.66°N) through Trincomalee, Mutur, Vakaneri, Batticaloa, Kalmunai and Akkarapattu down to Potuvil, with an increasing trend towards the south.

Meanwhile, 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*. (2005) 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*. (2005) suggest tsunami heights of over 9 m at Koggala Airport (~80.32°E) and those of Shibayama *et al*. (2005) indicate a maximum water level of only 2.7 m at Polhena (~80.52°E). Moreover, the measurements of Shibayama *et al*. (2005), Liu *et al*. (2005) and Sato *et al*. (2005) 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*. (2005).

Further, Sato *et al*.'s (2005) measurements indicate tsunami heights ranging between 1.4 m – 2.9 m along the coastal reach 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 is largely sheltered from direct tsunami impact and only diffracted waves with less energy could reach there.

Moreover, the measurements of Choi *et al*. (2005) 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.

The tsunami height estimates of Sarma (2005) in the coastal stretch from Chempiyanpattu (~9.64°N) down to Nayaru (~9.08°N) suggest comparatively high wave heights of 8 – 10 m at Chempiyanpattu and Uduthurai (~9.58°N). Loss of life and damage to property was also reportedly high at Chempiyanpattu and Uduthurai as well as in the densely populated Mullaittivu city (~9.25°N). However, much less destruction to life and property has been reported at Nayaru and Vadduvakal (~9.31°N). It must be added that the tsunami height measurements of Sarma (2005) were made nearly six months after the tsunami event, and therefore, have had to rely largely on eyewitness accounts.

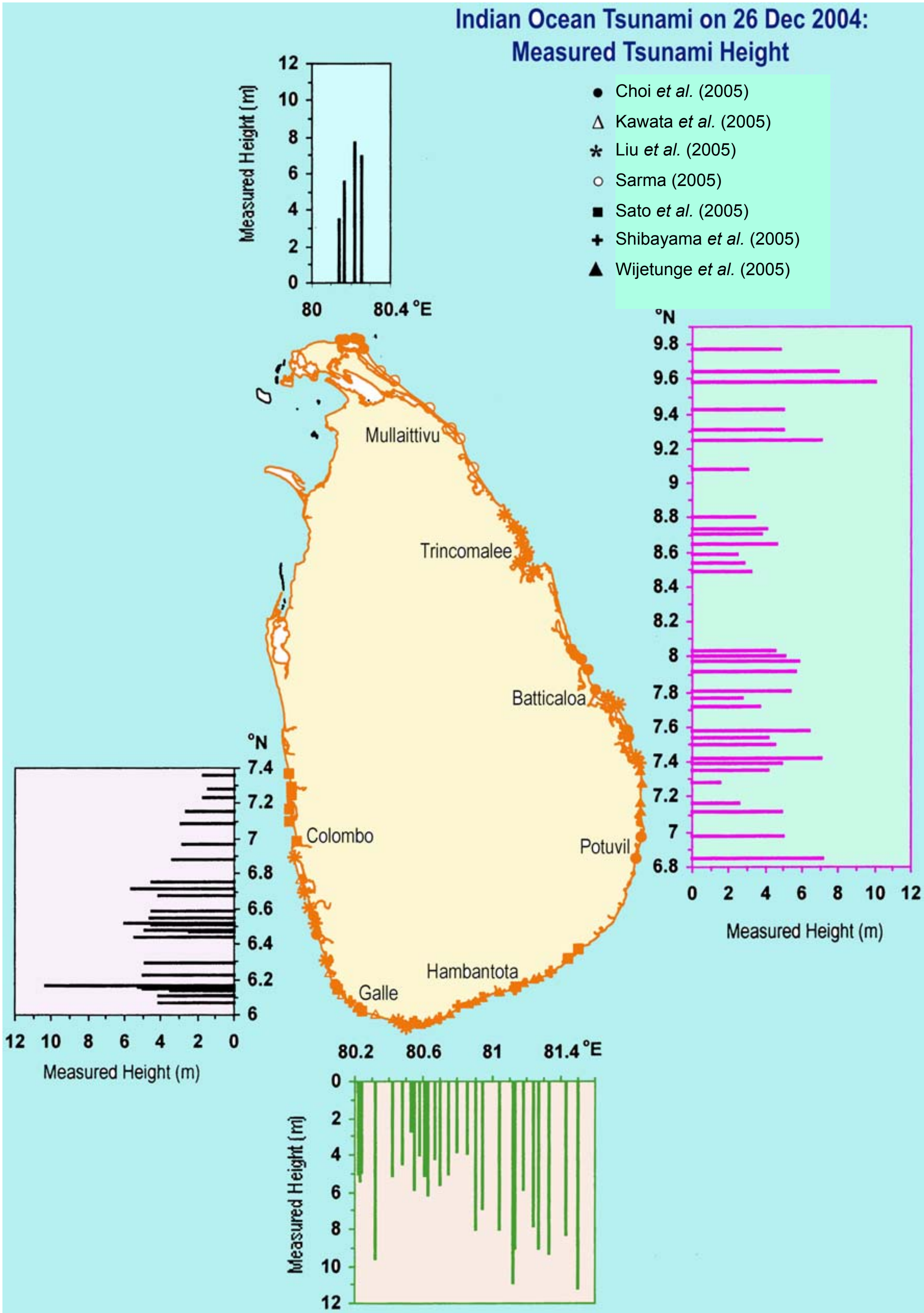

Figure 1. Distribution of tsunami height along the coastline of Sri Lanka.

Fig. 1 also 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.

4. SPATIAL DISTRIBUTION OF TSUNAMI INUNDATION

4.1 Coverage

The detailed field investigations carried out by Wijetunge *et al.* (2005) to trace the extent of inundation in Sri Lanka due to the tsunami on 26 December 2006 covered the east coast from Nilaveli through Trincomalee, Kalmunai, Akkarapattu and Potuvil down to Panama; the south coast from Galle through Matara, Tangalle and Hambantota to Yala; and the west coast from south of Colombo down to Galle as shown in Fig. 2. We consider the spatial distribution of the extent of inundation in each of the coastal sectors in the following.

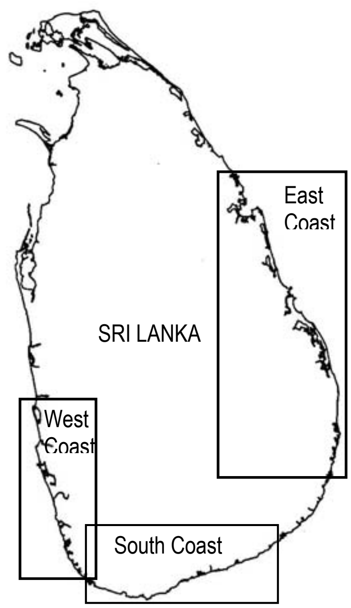

Figure 2. Coastal sectors covered in the inundation survey.

4.2 East Coast

Fig. 3 shows the tsunami inundation distances for the east coast of Sri Lanka together with the estimated tsunami heights for comparison. The two plots give (*a*) the horizontal inundation distance in metres from the shoreline (taken as 0 m MSL), and (*b*) the maximum tsunami water level near the shore in metres above the tide level at the time of tsunami attack (already presented in Fig. 1), against the Northing (N) of that part of the coastline. Note that wherever the spacing between two adjacent inundation measurements is more than 1 km, such data points are connected by a broken line.

The map of the east coast 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.

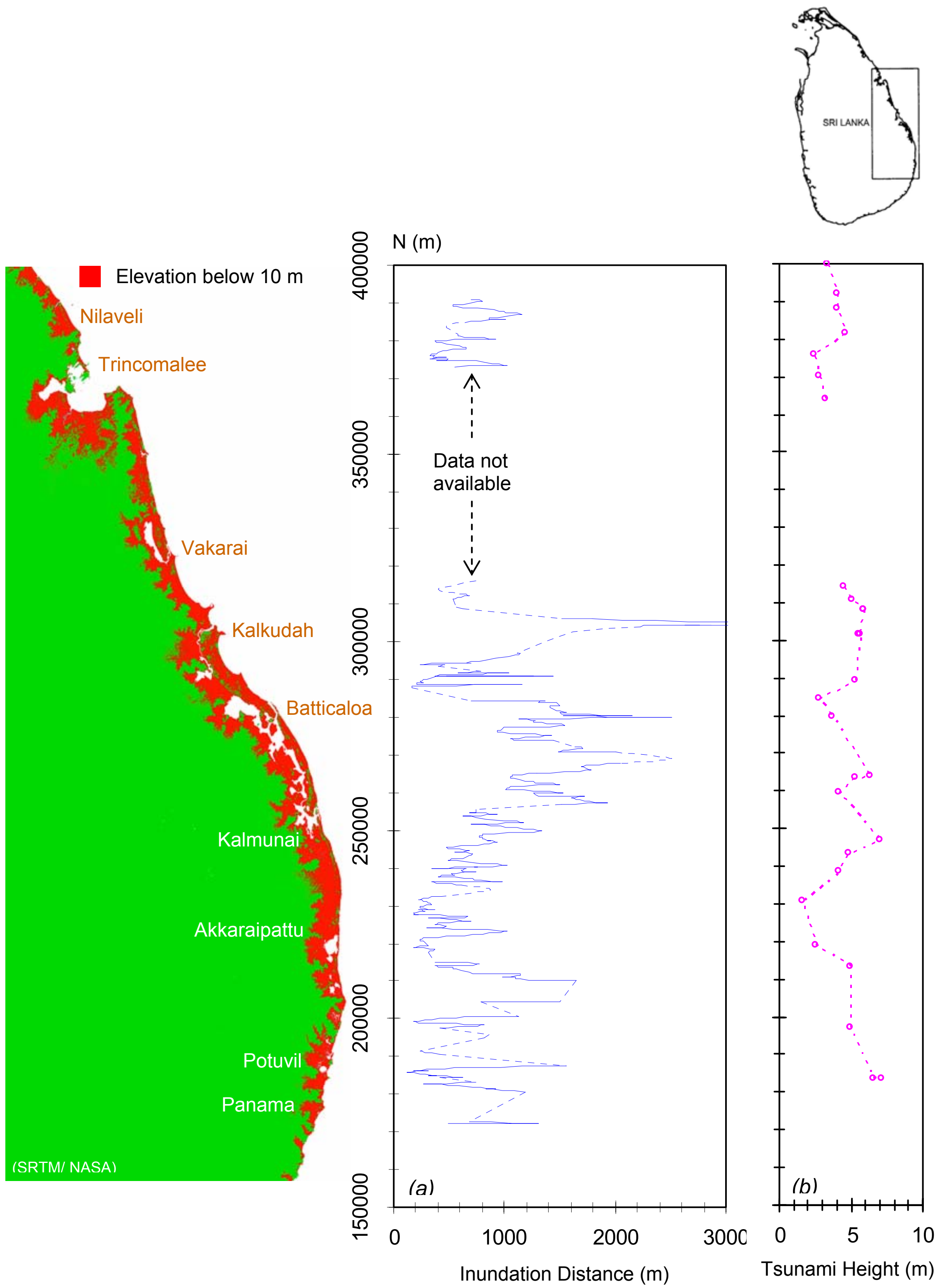

Figure 3. Spatial distribution of (*a*) inundation, and (*b*) tsunami height for the east coast of Sri Lanka.

We see that, on the whole, tsunami inundation had been quite extensive at several locations along the east coast from Nilaveli (~387 kmN) down to Panama (~172 kmN). Such significant inundation peaks, indicating inundation distances of over 2 km, can be seen at Kalkudah (~305 kmN), Batticaloa (~280 kmN), Chuddipalaiyam (~269 kmN) and Kalawanchikudi (~257 kmN). Furthermore, several other locations such as Tirukkovil (~205-210 kmN), Potuvil (~187 kmN) and Panama (~172 kmN) have recorded tsunami penetration distances of 1.5 km – 2 km. In some areas, for instance, around Batticaloa and Kalkudah, the lagoons and other water bodies have certainly helped convey the tsunami surge large distances inland. Moreover, numerous small waterways scattered in the east coast, known as 'Thona' (see Fig. 4), have also helped to carry tsunami surge into settlements interior, which would otherwise not have received tsunami flood waves over the land. In contrast, sand dunes just north of Potuvil (see Fig. 5) have protected some localities from severe flooding due to the recent tsunami.

It is also interesting to note that there is comparatively less inundation of about 200 m at Addalachchenai (~230 kmN) where the maximum tsunami height too is only about 1.5 m – 2 m.

On the whole, a comparison of the inundation peaks with elevation below 10 m areas seems to suggest a strong correlation between tsuanmi inundation and the topography of the land.

It must also be added that the stretch south of Mutur down to around Kokavillu was, unfortunately, not accessible, so inundation and tsunami height data are not available between 320 ~ 360 kmN.

Figure 4. Shore-connected small waterways commonly known as 'Thona' in the east coast.

Figure 5. Sand dunes north of Potuvil in the east coast.

The field observations of damaged boundary walls, brick-mortar type single-storey housing, and multi-storey reinforced concrete framed structures suggested three different failure modes under tsunami loading, namely, overturning, sliding and scouring, as shown in Fig. 6.

(*a*) Overturning

(*b*) Sliding

(*c*) Scouring

Figure 6. Failure modes of structures under tsunami loading in the east coast of Sri Lanka.

4.3 South Coast

Fig. 7 gives the tsunami inundation distances for the south coast of Sri Lanka from Galle to Yala National Park. The estimated tsunami heights for the south coast are also given in this Figure for comparison.

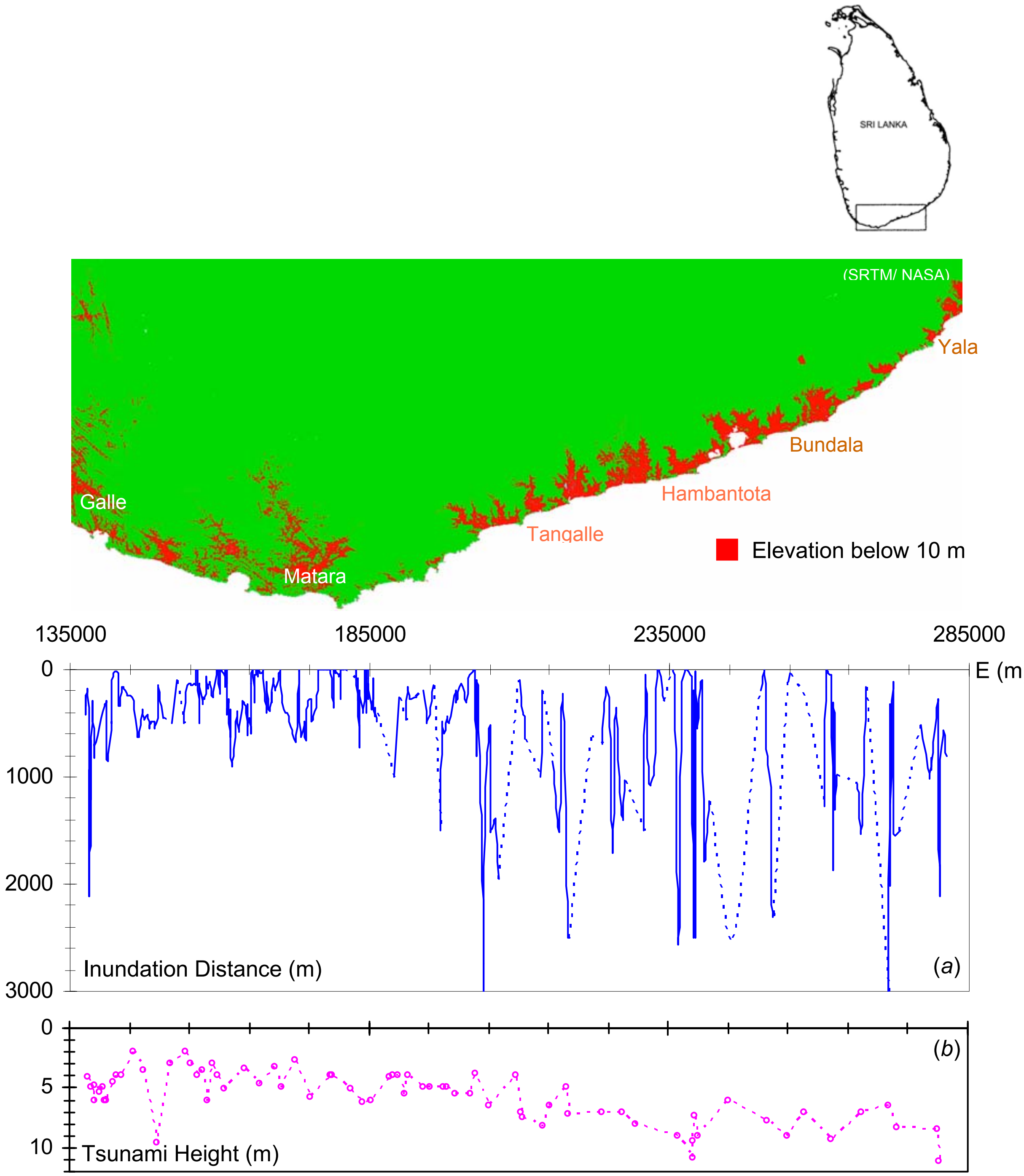

Figure 7. Spatial distribution of (*a*) inundation, and (*b*) tsunami height for the south coast of Sri Lanka.

We see that the deepest tsunami wave penetration in the south coast is at Hambantota, up to three kilometres near the salt-pans, and also near Bundala albeit with the aid of the bay. Significant inundation can also be seen further east of Hambantota, 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 175 ~ 185 kmE, to the east of Matara. 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 (see Fig. 8) and further confirmed by the topography (elevation above 10 m) map in Fig. 7.

The coastline from Galle to Matara too suffered badly with particularly deep inundation occurring along the coastal belt of Talpe–Koggala–Ahangama (~145 – 150 kmE), besides the tragic loss of life and destruction in the densely populated coastal cities of Galle and Matara.

One prominent feature of the coastal belt from Dickwella (195 kmE) to Yala (285 kmE) is the 7 – 10 m high sand dunes with thick cover of overgrowth (see Fig. 9.). The presence of such sand dunes has certainly helped reduce tsunami penetration inland. However, wherever gaps existed in the dune system, or at locations where the dune height was low or had been cut open for various activities, it appears that the tsunami surge had rushed through with enormous power causing considerable destruction. This was most evident where the popular *Yala Beach Resort* once existed; there, a section of the dune just in front of the resort hotel had been cut open to provide the occupants with a good view of the sea!

Figure 8. Comparatively steep beach fronts east of Matara on the south coast.

Figure 9. Sand dunes near Yala on the south-east coast.

4.4 West Coast

The extent of inundation as well as the measured tsunami heights for the west coast of Sri Lanka from Galle to North of Colombo are shown in Figs. 10*a* and 10*b*, respectively. On the west coast, 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 Balapitiya. Of the several peaks, the most noteworthy is the one near Peraliya where the tsunami surge overturned and submerged a Galle-bound locomotive (see Fig. 11) killing over thousand people. The railway line from Balapitiya to Galle too suffered heavy damage (see, for example, Fig. 12.).

4.5 General Comments

The spatial distribution of the extent of flooding discussed in Sections 4.2 – 4.4 indicate that the tsunami inundation had been greater for the east and south-east coasts than the south, south-west and the west coasts. 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, so part of the east and south-east coasts 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*) 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 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.

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 surveys that there was 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 including mathematical simulation of the generation, the propagation across the ocean, and more importantly, the overland run-up of hypothetical events of tsunamis are necessary for us to determine the degree of vulnerability of each locality of the coastal belt of Sri Lanka to potential coastal hazards such as tsunamis and storm surges.

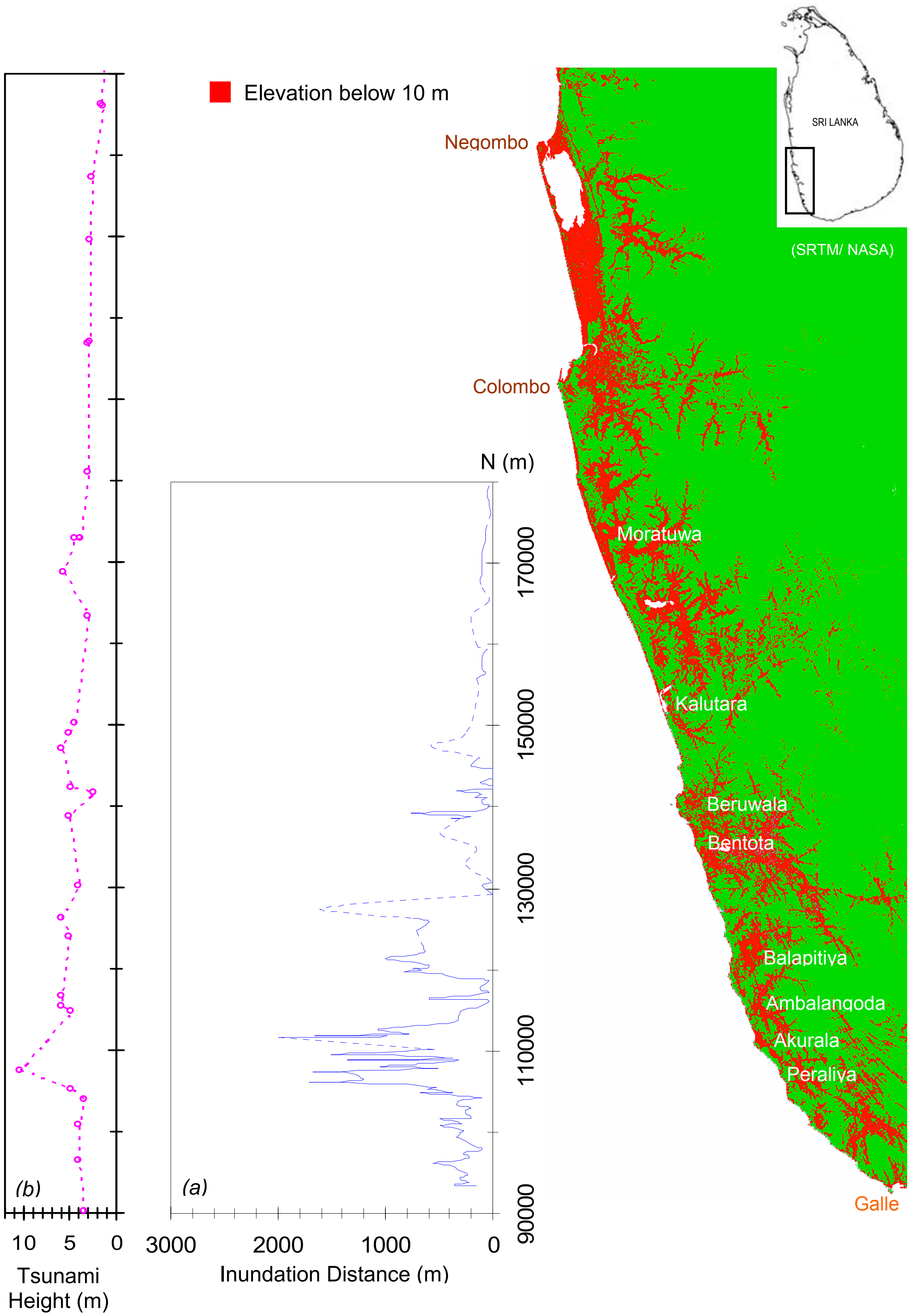

Figure 10. Spatial distribution of (*a*) inundation, and (*b*) tsunami height for the west coast of Sri Lanka.

Figure 11. Overturned rail carriages near Peraliya on the south-west coast.

Figure 12. Heavily-damaged southern railway near Akurala.

5. CONCLUSIONS

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

On the whole, the tsunami inundation had been greater for the east and south-east coasts than the south, south-west and the west coasts of Sri Lanka. The results also indicate the possible influence of the coastal geomorphology on the extent of inundation.

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. On the west coast, as one would expect, the measured tsunami heights show a decreasing trend towards the north.

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