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Original Research Article

Island-wide coastal vulnerability assessment of Sri Lanka reveals that sand dunes, planted trees and natural vegetation may play a role as potential barriers against ocean surges

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A B S T R A C T

Since the Indian Ocean tsunami on 26 December 2004, there have been continuous efforts to upgrade the (tsunami) early warning systems as well as their accessibility in local and regional places in South and Southeast Asia. Meanwhile, the protection offered by coastal vegetation like mangroves to the people, property and physical landscape was also recognized and prioritized by both public and private authorities at various governance levels. As more than 90% of the Sri Lankan coastline is vulnerable to water-related impacts and existing bioshields like mangroves are potentially able to protect less than one-third of it, if at all they are in good condition, an attempt was made to build knowledge on the other potential natural barriers along the coast. In this context, a *ca.* 2 km belt of the entire coast was digitized, classified and assessed for vulnerability in relation to the existing land-use/cover. First, a visually interpreted land-use/cover map comprising 16 classes was developed using Google Earth imagery (Landsat-5, 2003). Second, based on the Global Digital Elevation Model data from the ASTER satellite, the land-use/cover map was further re-classified for elevation demarcation into waterless, run-up and flooded areas. And finally, both vulnerable and less vulnerable areas were identified by taking into account the average wave heights that the 2004 tsunami reached in the country (North: 5.5 m, South: 7 m, East: 5 m and West: 3.75 m). Among the selected areas studied, Jaffna and Kaluvanchikudy-Komari are found to be vulnerable and, Trincomalee, Yala and Puttalam are less vulnerable. While vulnerability was largely associated with the conditions devoid of natural barriers, the less vulnerable areas had mangroves, *Casuarina*, dense vegetation and/or sand dunes as land cover, all of which might prove effective against ocean surges. However, these land cover types should never be considered as providing full protection against the type of threats that can be expected. As the present study provides only baseline information on island-wide vulnerability of areas to water-related impacts, further

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investigation and validation along similar research lines are needed to establish a blueprint for future preparedness.

1. Introduction

Although history has documented >2000 tsunami events since 2000 B.C. in >12,900 locations (Dunbar et al., 2008), the 26 December 2004 Indian Ocean tsunami was proven to be the most deadly in the contemporary period and created far reaching spatial and temporal impacts on terrestrial as well as marine habitats (Tang et al., 2006; Subba Rao et al., 2007; Rachmalia et al., 2011; Samarakoon et al., 2013; Andrade et al., 2014). Because of the massive death toll and property loss (e.g. IUCN, 2005a; UNEP & MENR, 2005; Chatenoux and Peduzzi, 2007; Matsumaru et al., 2012; Mishra et al., 2014), coastal communities in Southeast and central South Asia are not only fearing tsunamis but also other water-related impacts such as cyclones, sea-level rise and combinations of these, with coastal erosion as a damage-facilitating process. Although tsunami science has much progressed during the last decade, disaster mitigation remains challenging but evident from other tsunami catastrophes in the past ten years (e.g. Japan tsunami on 11 March 2011) (Oskin, 2014, 2015).

Physical structures being damaged or removed by the force of ocean surges and the debris it carries can result in the physical removal of plants and animals (Subba Rao et al., 2007; Andrade et al., 2014). In some cases this happened irrespective of the presence of coastal forests like mangrove and other land cover types (e.g. sand dunes) having the potential to act as protective buffers for coastal zone (e.g. Cochard et al., 2008; O'Connell, 2008; Das and Vincent, 2009; Tanaka et al., 2009; Mukherjee et al., 2010; Feagin et al., 2010; Zhang et al., 2012). In fact, loss and degradation of the coastal protective features due to physical infrastructure as well as agriculture and aquaculture development is still ongoing in many locations (Dahdouh-Guebas et al., 2005a; Pattanaik and Prasad, 2011; Nfotabong-Atheull et al., 2011; Satyanarayana et al., 2012; Bao et al., 2013; Dat and Yoshino, 2013; Ha et al., 2014; Santos et al., 2014; Nguyen, 2014). Therefore it could not be ascertained so far that forests like mangroves were in a healthy state adequate to fulfill their potential coastal protection function (Dahdouh-Guebas et al., 2005a,b). The current state of these ecosystems is often not well documented, raising uncertainty about their coastal protection ability and urging for a precautionary principle to reduce harmful types of exploitation or even destruction (Dahdouh-Guebas et al., 2005b). The justification in this precautionary principle also lies in the reports of other instances, in which mangroves were considered to have contributed to mitigating the effects of the 2004 tsunami on human population, physical landscape and private/government property (Williams, 2005; Dahdouh-Guebas, 2006; Dahdouh-Guebas and Koedam, 2006; Quartel et al., 2007; Ellison, 2008; Das and Vincent, 2009; Teh et al., 2009). Besides mangrove assemblages, also seagrass beds, coral reefs and sand dunes have been recognized for their functionality of reducing coastal vulnerability against ocean surges (Chatenoux and Peduzzi, 2007; O'Connell, 2008).

The coastal landforms in Sri Lanka comprise estuaries, lagoons, beaches, rocky shores, sand dunes, salt marshes and mangroves (Dahdouh-Guebas and Jayatissa, 2009), with an occasional hill or cliff right at the ocean front. The 2004 tsunami hit the entire East and Southwestern coast of the island, where its impact varied according to factors such as offshore bathymetry, beach slope, local topography, distance to the coastline, etc (Liu et al., 2005; Dahdouh-Guebas et al., 2005b; Wijetunge, 2006; Patnaik et al., 2012). Besides the loss of lives and property, coastal water bodies filled with debris, beach erosion, uprooted vegetation, and salinization of drinking water and agricultural fields, were some of the aftermath environmental consequences (IUCN, 2005b,c; UNEP & MENR, 2005). It has been postulated that different coastal plant species were affected differently. Coconut palms for instance were fairly resistant to the energy of the waves as well as to subsequent salinization, whereas *Casuarina* trees taller than 6 m were broken, yet survived (IUCN, 2005a; Mascarenhas & Jayakumar, 2008). In the case of mangroves, although frontal trees were uprooted, the back mangrove remained more or less unaffected in mangrove forests that were in a fair state (Dahdouh-Guebas et al., 2005b; UNEP & MENR, 2005). The local tsunami witnesses indeed specified that the mangrove forests protected several lives and properties located behind the vegetation (Dahdouh-Guebas et al., 2005b; Dahdouh-Guebas and Koedam, 2006; Tanaka et al., 2011; Sandilyan and Kathiresan, 2015). However, there are also studies challenging the role of mangroves in tsunami protection (e.g. Kerr et al., 2006; Kerr and Baird, 2007; Baird and Kerr, 2008; Satheeshkumar et al., 2012), whereas an overview of missing evidence was provided by Cochard et al. (2008) and Dahdouh-Guebas and Jayatissa (2009).

In Sri Lanka, more than 90% of the coastline is vulnerable to water-related impacts, while existing bioshields like mangroves could only protect less than one-third of it (Feagin et al., 2010). Hence, other potential barriers in the vicinity are to be investigated. In this study, we aim at identifying vegetation types and other physical barriers located up to 2 km inland from the coast using remote sensing and ground-truth. Subsequently, we identify vulnerable and less vulnerable areas along the coastline by using a GIS-based risk assessment incomplete yet pioneering data, which should foster the precautionary principle and draw attention to conservation and restoration of the coastal vegetation.

2. Methodology

2.1. Study area

The island area of Sri Lanka is 65,610 km^2 of which both land and inland water bodies occupy 62,705 and 2905 km^2, respectively. The total population was about 21 million, with its density highest at Colombo (3438 persons per km^2) and lowest at Mullaitivu (38 persons per km^2) in a 2011 census (DCS, 2012). The natural forest area, including 88.15 km^2 of mangroves, was estimated at 19,422.19 km^2 (DCS, 2010). The Southern half of the country is characterized by hilly and mountainous areas with an elevation reaching over 2243 (Adam's Peak) to 2524 m (Pidurutalagala). Temperature is generally high with a monthly average of 27 $^\circ$C and high humidity (70–90%) (WW & CI, 2015). Rainfall is highest during June–July (associated with the Southwest monsoon) and during October–December (associated with the Northeast monsoon) (Sirisena and Noordeen, 2014). Over the last decades, extreme weather events have become more frequent (e.g. intense rains, floods and cyclones) attributed to climate change (Cruz et al., 2007; Sivakumar and Stefanski, 2011).

2.2. Ground-truth data collection

A two-month expedition observing potential barriers against ocean surges (incl. rare tsunamis, but also the much more frequent storm surges and tidal surges) was carried out from July to August, 2010. The fieldwork was explorative, not covering the entire coastline, and established types of land-use/cover to link to the remote sensing image analysis (see section 2.3). During the fieldwork, information on the nature of vegetation or plantation (e.g. mangrove, *Casuarina*, coconut, etc.) - including morphological characteristics such as trees with trunks, presence of above-ground root systems, tree height (using MDL LaserAce®300), and distance to the coastline, was collected. Coping with the few local limitations (e.g. transportation, time, the immediate wake of the civil war), the fieldwork was conducted in select areas (Jaffna, Yala, Trincomalee, Puttalam, Galle, Colombo, Mullaitivu, Mannar and Kaluvanchikudy-Komari area). For other areas in-between, both ground knowledge (gathered randomly at the time of traveling from one place to another) as well as best professional judgement by our own research team members were considered (authors: GRo, KASK, LPJ, NK & FDG). A handheld global positioning system (Garmin, GPS III) was used to obtain geographical coordinates of the areas visited.

At each location, the existing land-use/cover categories and their boundary limits were identified on the Google Earth imagery (Landsat-5, 2003) (spatial resolution: 15 m). In total, we differentiated 16 land-use/cover classes (Table 1) using 7 image attributes (tonality, texture, structure, size, shape, shade and location) described in detail by Dahdouh-Guebas et al. (2000) and by the Canada Centre for Mapping and Earth Observation (CCMEO) of the Natural Resources Canada's Earth Science Sector (NRC, 2006). Each land-cover class was described in a fact sheet making use of all image attributes and photographs exemplary for the class, resulting in over 20 pages of 'interpretation key' which was then used in the remote sensing analysis (see section 2.3).

While mangroves were found close to estuaries and lagoons, the extent of *Casuarina* was confined mostly to the beach areas. Sand dunes were observed from few locations like Yala, Puttalam and Jaffna. The other land-use/cover categories such as aquaculture ponds, saltpans and coconut plantations were located adjacent to mangrove and beach localities. On the terrestrial side, fields used for agriculture (e.g. paddy fields, horticulture) were encountered. There were also human settlements with or without surrounding terrestrial vegetation. Any land without vegetation was considered as bare soil, with limited and short trees as sparse vegetation and, with tall and high-grown trees as dense vegetation. Along with the data on land-use/cover categories, feedback from several (local) people was gathered on the type of vegetation that contributed to protecting their lives and houses at the time of the 2004 tsunami.

2.3. Remote sensing analyses

2.3.1. Land-use/cover classification

To establish the land-use/cover map, visual interpretation based on the key attributes referred to above (together with ground knowledge) was carried out on a Landsat-5 (Google Earth) imagery. The Sri Lankan coast (up to *ca.* 2 km inland) was first digitized on-screen and then classified using GRASS GIS *v*.6.4.1 (available for download at http://grass.fbk.eu/). Altogether, 16 classes (see Fig. 1) were identified and produced a final land-use/cover coastal map. It should be noticed that any land-use/cover extending further inland from its origin within 2 km coastal boundary was also digitized for classification (i.e. sometimes reaching beyond the 2 km coastal strip). At the same time, the areas for which ground knowledge was absent or uncertainty prevailed, were ignored and left blank (i.e. considered outside our study area).

The term 'vulnerable' used in the present study denotes unsafe areas for human living (with possible ecological and economic loss) at the time of water-related hazards (cf. Løvholt et al., 2014). Since coastal vulnerability is the major focus of this study, some of the land-use/cover classes such as mangrove, sand dune and beach that could contribute similarly to wave attenuation or reduce the potential impact of ocean surges, were represented by the same colour. Sand dunes, sand beaches and even sand/mud banks are known to dissipate storm wave energy, reducing effects on landward areas (Mascarenhas & Jayakumar, 2008; O'Connell, 2008; Anthony et al., 2010; Hanley et al., 2014). Therefore, in the case of sand, both 'sand

Table 1
Ordinal (base) values attributed to each land-use/cover category of the Sri Lankan coast based on best-professional judgment and objectivated by their protection function reported by scientific literature and witness accounts. The new values are intended for sensitivity analysis. To obtain the natural numbers, the rational numbers for +5% were rounded to the upper natural number, whereas the rational numbers for −5% were rounded to the lower natural number. Since the Cost Surface Model does not support negative values, the water/aquaculture/saltpan class was considered as 0.

Land-use/cover	Source (select publications)	Base value	New value (in rational numbers)		New value (in natural numbers)	
			base value + 5%	base value −5%	base value + 5%	base value −5%
Mangrove	Barbier (2006), Chang et al. (2006), Dahdouh-Guebas (2006), Dahdouh-Guebas and Koedam (2006), Mazda et al. (2006), Quartel et al. (2007), Tanaka et al. (2007), Cochard et al. (2008), Ellison (2008), Vo-Luong and Massel (2008), Das and Vincent (2009), Mascarenhas & Jayakumar (2008), Dahdouh-Guebas and Jayatissa (2009) + 89 pre-2006 references on mangrove ability to mitigate coastal disasters therein, Mazda and Wolanski (2009), Tanaka et al. (2009), Teh et al. (2009), Mukherjee et al. (2010), Feagin et al. (2010), Horstman et al. (2012), Zhang et al. (2012), Griffin et al. (2013), Mukherjee et al. (2015), Sandilyan and Kathiresan (2015), and feedback from the local people during present investigation	10	10.50	9.50	11	9
Sand dune/beach	UNEP & MENR (2005), IUCN (2005b,c), Jayakumar et al. (2005), Dahdouh-Guebas et al. (2005b), Barbier (2006), Tanaka et al. (2006a,b; 2007), Mascarenhas & Jayakumar (2008), Cochard et al. (2008), O'Connell (2008), Mukherjee et al. (2010), Griffin et al. (2013), Hanley et al. (2014), Mishra et al. (2014)					
Casuarina	UNEP & MENR (2005), IUCN (2005a), Tanaka et al. (2006a,b; 2007), Mascarenhas & Jayakumar (2008), Cochard et al. (2008), Tanaka et al. (2009), Mukherjee et al. (2010), Tanaka et al. (2011), Griffin et al. (2013), Samarakoon et al. (2013), Mishra et al. (2014), Mukherjee et al. (2015)	6	6.30	5.70	7	5
Dense vegetation	UNEP & MENR (2005), IUCN (2005a,c), Rossetto et al. (2007), Mishra et al. (2014)					
Semi-dense settlement in dense vegetation	UNEP & MENR (2005), IUCN (2005c)					
Coconut	UNEP & MENR (2005), IUCN (2005a,b,c), Dahdouh-Guebas et al. (2005b), Tanaka et al. (2007, 2009), and information from the local people during present investigation	5	5.25	4.75	6	4
Sparse vegetation	UNEP & MENR (2005), IUCN (2005c), Tanaka et al. (2007), Cochard et al. (2008)	4	4.20	3.80	5	3
Semi-dense settlement in sparse vegetation	UNEP & MENR (2005), IUCN (2005c)					
Dense settlement (on bare soil or in sparse vegetation)	UNEP & MENR (2005), IUCN (2005c), Rossetto et al. (2007)	3	3.15	2.85	4	2
Semi-dense settlement in coconut vegetation	UNEP & MENR (2005), IUCN (2005c)					
Bare soil	IUCN (2005c), Chatenoux and Peduzzi (2007), Quartel et al. (2007), Zhang et al. (2012), Griffin et al. (2013)	1	1.05	0.95	2	0
Horticulture	IUCN (2005b,c)					
Paddy fields	IUCN (2005b,c)					
Other	IUCN (2005b,c)					
Water	UNEP & MENR (2005), IUCN (2005b,c), Tanaka et al. (2007), Rossetto et al. (2007), Zhang et al. (2012), Mishra et al. (2014), Wijetunge (2014)	0	0.50	0	1	0
Aquaculture pond/saltpan	UNEP & MENR (2005), IUCN (2005a,c), Dahdouh-Guebas et al. (2005b), Barbier (2006), Tanaka et al. (2007), Griffin et al. (2013)					

dunes' and 'sandy beaches' were represented by a single class (i.e. sand dune/beach). We emphasize that potential differences in protective capacity between sand dunes and sandy beaches are likely because of the variations in specific features such as height, and was accounted for in the elevation classification (see section 2.3.3). However, one of the caveats in our methodology is that we did not differentiate between sand dunes with and without vegetation. Most beaches were narrow and identified by smaller polygons in the digitization. Human constructions such as shrimp farms, fish ponds and saltpans were represented under the same class (i.e. aquaculture pond/saltpan) in view of their similar shapes and location, at times adjacent.

2.3.2. Application of protection scale to land-use/cover classes

To understand the extent of inundation by ocean surges, the land-use/cover classes were attributed a value on a scale from 0 to 10 on the basis of their ability to slow down waves, as justified by existing scientific literature as well as local people witness accounts (see Table 1). Areas closer to '0' (e.g. water bodies) are characterized by a lower wave dissipation capacity as compared to areas closer to '10' (e.g. mangrove forest). In this context, field-based knowledge (e.g. vegetation categories, tree morphology, etc. as mentioned previously in section 2.2) was considered to recognize the possible effect of drag force. In fact, the higher the coastal vegetation (e.g. mangroves, *Casuarina*, coconut), sand dunes and beaches, the higher the drag effect. The classification of the elevation was finally represented by three major categories: (i) 'flooded', where the elevation was smaller or equal to the wave height, (ii) 'run-up', where the elevation was smaller or equal to twice the wave height, and (iii) 'waterless', where the elevation was larger than twice the wave height.

2.3.3. Elevation classification

In order to detect vulnerable and less vulnerable areas along the coast, we used relief (i.e. elevation) of the geomorphological data acquired from the ASTER Global Digital Elevation Model (ASTER GDEM) (http://gdem.ersdac.jspacesystems.or.jp) (spatial resolution: 30 m). The kinetic energy of a wave gives itself the capacity to run-up over an elevation twice the size of its amplitude (Mader, 1990). As a result, for example, any wave with an amplitude of 3 m may theoretically produce a wave run-up of 6 m. Taking into account the average height of the 2004 tsunami waves reached along the East (5 m), West (3.75 m), North (5.5 m), and South (7 m) coasts of Sri Lanka (Wijetunge, 2006), the elevation scale in the present study (i.e. 1–3 designated for 'flooded', 'run-up' and 'waterless' areas, respectively) was reassigned with new values (Table 2) as to allow for a case-specific vulnerability assessment (with a maximum run-up of nearly 50 m; Choi et al., 2006). However, we want to emphasize that stronger, so-called "very low frequency, very high impact (mega)tsunamis", can occur, and have occurred in the past (Ramalho et al., 2015), featuring run-up heights exceeding 270 m (due to collapse of the oceanic volcano Fogo ~73,000 years ago). This would make higher elevations considered less vulnerable when taking the 2004 tsunami as a reference, extremely vulnerable, particularly when land cover does not offer a strong drag force (e.g. lakes).

Another probable caveat in the 'aquaculture pond/saltpan' land-use/cover class is the impossibility of making a meaningful differentiation of the dyke height between ponds and pans (both <3 m) in the elevation classification, due to the low vertical resolution of the GDEM. Unfortunately, at this stage, there are no GDEMs available with a higher resolution for such fine-scale differentiation.

2.3.4. Vulnerability index map

The Cost Surface Model in GRASS *v*.6.4.1 (http://grass.fbk.eu/gdp/html_grass63/r.cost.html) was used to produce the vulnerability index map denoting 'vulnerable', 'less vulnerable', and the areas in-between. In addition, the vulnerability indices at a distance of 100, 300, 500, 1000 and 2000 m from the coast were analyzed individually for selected areas (i.e. Kaluvanchikudy-Komari area, Colombo, Galle, Jaffna, Mannar, Mullaitivu, Puttalam, Trincomalee and Yala) and plotted as the stacked column charts. The latter was done using the 'select actual geographical area as the model limit' function in GRASS *v*.6.4.1.

2.3.5. Sensitivity analysis

Sensitivity analysis is to indicate how an uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input (Cruz, 1973). In the present study, initial values of the land-use/cover were subsequently modified to +5% and to −5% and the resulting percentage of vulnerable area compared with output of the standard (non-modified) run. However, it was difficult to use the same variation (+5% and −5%) for all land-use/cover variables, as negative values were not supported (Table 1). Similarly, the elevation data from ASTER GDEM cannot be changed into rational numbers, but only to natural numbers. Hence, we rounded the values to the lower natural number for the −5% sensitivity analysis and to the upper natural number for the +5% sensitivity analysis. In principle, the Cost Surface Model adds values to each cell one after one, and if any land-use or land-cover has a larger spatial extent, it shows a greater impact on the sensitivity analysis (even after the new values are assigned).

2.3.6. Validation of the model

For public and scientific utility, the SERTIT (Service Régional de Traitement d'Image et de Télédétection) (http://sertit.u-strasbg.fr/) has uploaded several satellite images (SPOT 4: spatial resolution, 20 m) showing the impact of the 2004 tsunami on Southeast Asian countries. In order to validate the model, we compared model output with affected and non-affected areas posted by the SERTIT for Sri Lanka. It should be stressed that affected and non-affected areas were detected visually by the authors and not with the aid of a numerical algorithm. Although this may imply some variation with the actual situation in the field, the interpretation of SERTIT images did allow for a reliable estimation of these classes.

2.4. Statistical analysis

The vulnerability indices (log-transformed data) obtained for locations situated 100, 300, 500, 1000 and 2000 m away from the coast were analyzed through Principal Coordinates (PCO), a routine available in the PRIMER v.6 (with PERMANOVA + add on), and portrayed the vulnerable and the less vulnerable areas in Sri Lanka.

3. Results

Our field-based observations found that the existing coastal features such as sand dunes, beaches and mangroves are irregularly distributed in relation to the local topography and the changes brought by natural and anthropogenic events. From the land-use/cover map (Fig. 1), wide-spread urban areas at Colombo and Jaffna are evident. In addition, other prominent features such as dense vegetation and sand dune/beach at the Yala National Park; aquaculture pond/saltpans at Puttalam; sand dune/beach and sparse vegetation with some paddy fields at Chenkaladi; water body/lakes at Hambantota and, plantations (e.g. coconut) and multi-species vegetation (e.g. mangrove) mixed with settlement areas at Trincomalee and Hambantota areas, could be recognized. The land-use/cover (Fig. 2a) in relation to elevation classification (Fig. 2b) and

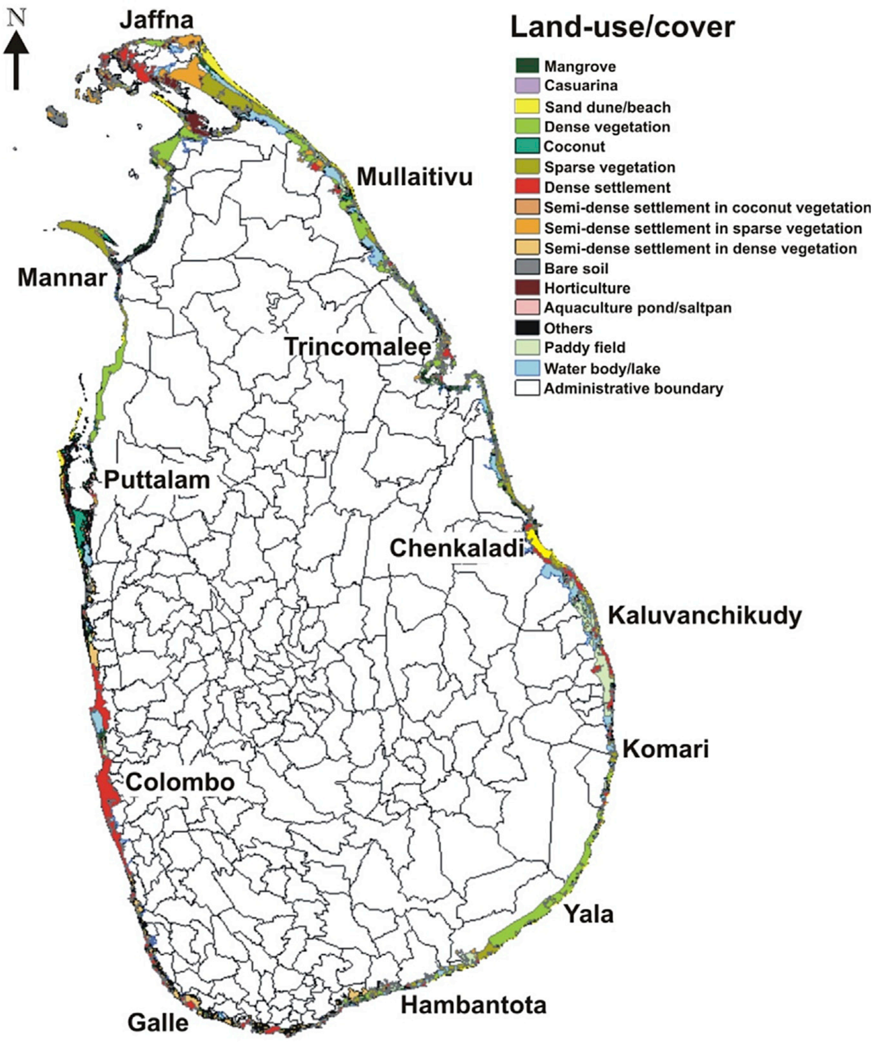

Fig. 1. Land-use/cover along the Sri Lankan coast up to 2 km inland. Polygons inside the country map represent local administrative boundaries. Representative village/city names are also mentioned.

Table 2
Re-classification of the elevation to generate a vulnerability index map for the Sri Lankan coast. X represents the wave height and 162 m is the maximum elevation found along the coast. The new values are meant for sensitivity analysis (areas close to 2 are easy to inundate and the areas close to 100 are difficult to inundate).

Elevation		Base value	New value	+1%	−1%
Class 1: Flooded area (elevation smaller or equal to the height of wave)	$0 \rightarrow X$	1	2	3	1
Class 2: Run-up area (elevation smaller or equal to twice the height of wave)	$X+1 \rightarrow 2X$	2	3	4	2
Class 3: Water-less area (elevation larger than twice the height of wave)	$2X+1 \rightarrow 162$	3	100	101	99

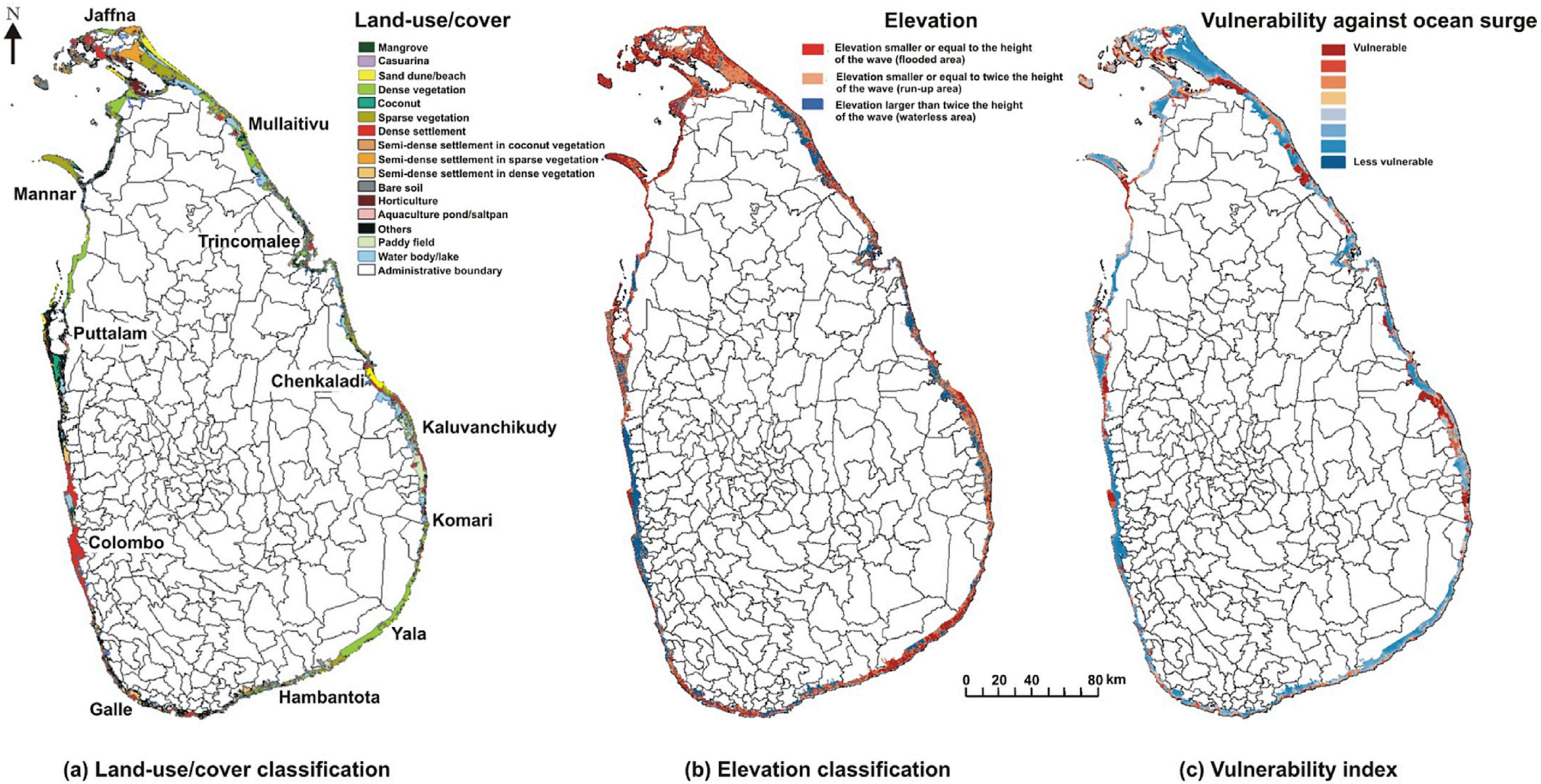

Fig. 2. Classified maps of (a) Land-use/cover, (b) Elevation and, (c) Vulnerability index, along the Sri Lankan coast up to 2 km inland. Polygons inside the country map represent local administrative boundaries. Representative village/city names are mentioned in Fig. 1a.

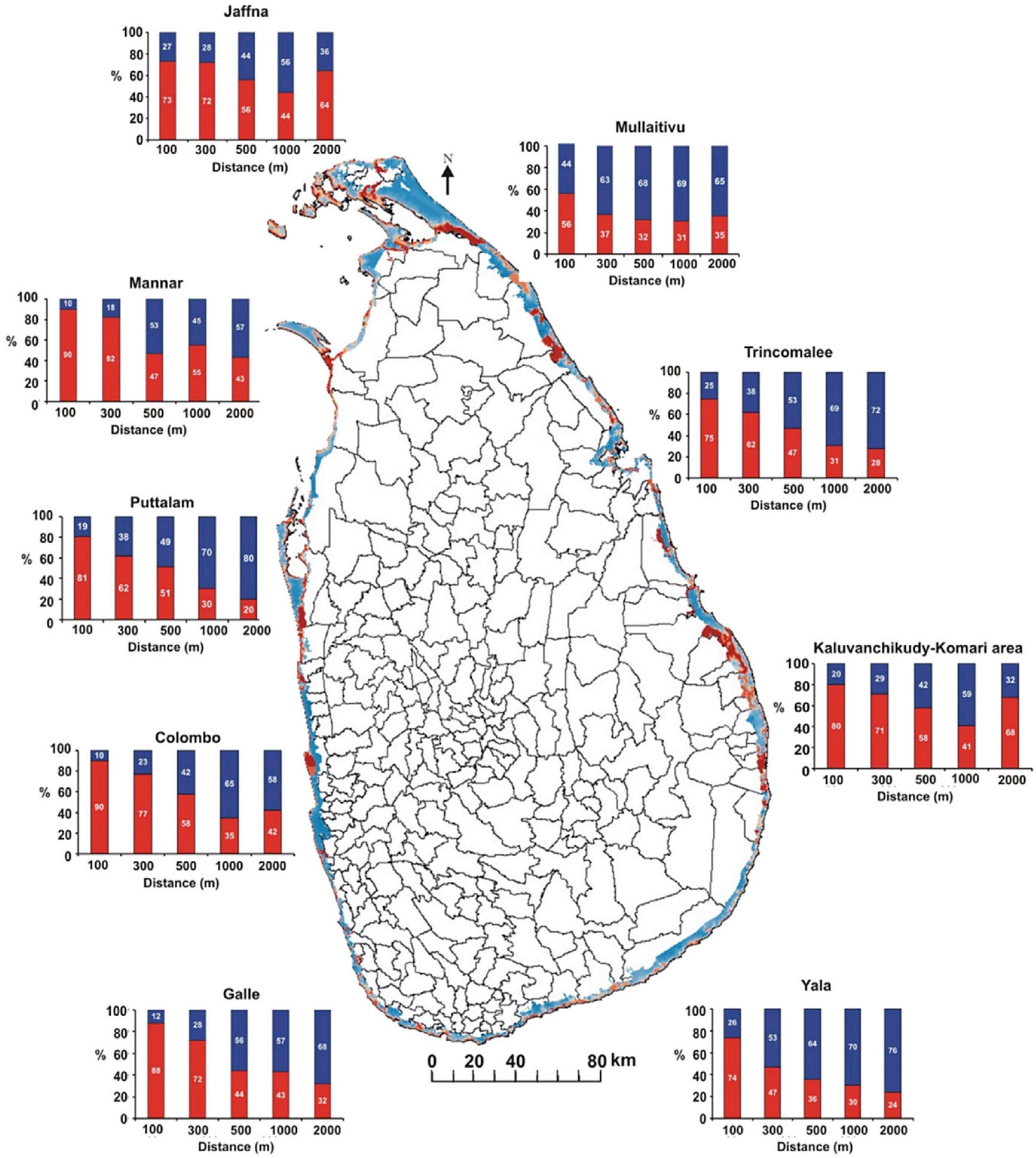

Fig. 3. Vulnerability index map showing percentage of vulnerable (red) and less vulnerable (blue) areas at different places along the Sri Lankan coast. Vulnerability is based on the distance of 100, 300, 500, 1000 and 2000 m away from the coastline. Polygons inside the country map represent local administrative boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

vulnerability index (Fig. 2c) shows that the greater part of the Sri Lankan coastline within a 2 km band is located between 'flooded' and 'run-up' areas, while most places, including the areas close to water body/lakes, are susceptible to the impact of ocean surges.

The percentage of vulnerability, at a distance of 100, 300, 500, 1000 and 2000 m from the coastline showed an expected decreasing trend with increasing distance (Fig. 3). Among the cases observed both Jaffna (on the North) and Kaluvanchikudy-Komari area (on the East) were different from others with more than 60% of vulnerability even at a distance of 2 km from the coast. The less vulnerable areas are found to be Yala, Trincomalee (on the East coast), and Puttalam (on the West coast) (with less than 30% vulnerability), followed by Galle, Colombo, Mullaitivu (30–40%), and Mannar (40–50%). These vulnerable and less vulnerable areas also coincided with the affected and the non-affected places of Sri Lanka in the SERTIT satellite images (reporting the 2004 tsunami impact) and testify the accuracy of the present results as reasonably good (accuracy assessed

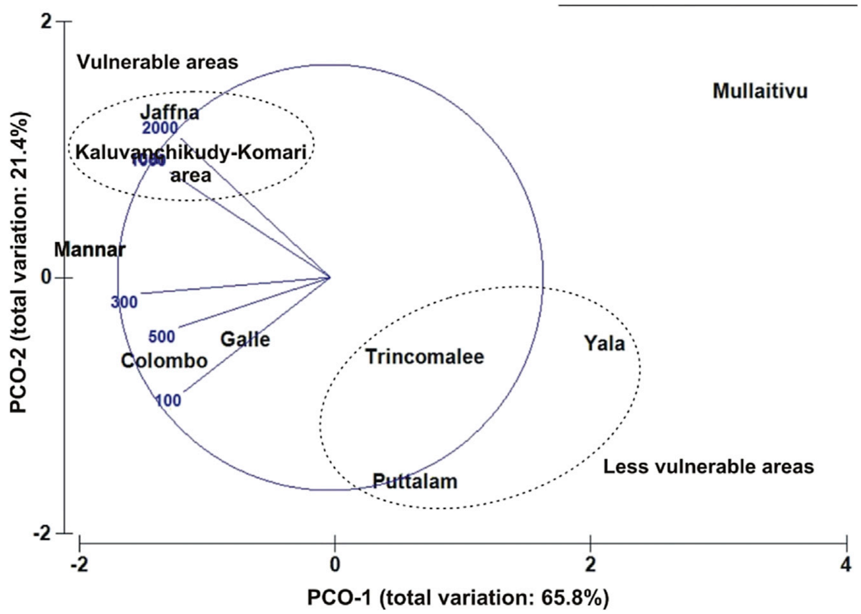

Fig. 4. Principal Coordinate (PCO) analysis showing vulnerable and less vulnerable coastal areas (dotted ellipses on the top-left and bottom-right corners) in Sri Lanka. The graph also shows the PCO correlation circle and the orientation of distance lines (i.e. 100, 300, 500, 1000 and 2000 m with their approximate relation to one another i.e., the greater the angle, the higher the separability).

Fig. 5. Selective photographs showing sand dunes with vegetation at Bundala (A) and, Panama (B–C), between Komari and Sangamankanda (photos taken by L.P. Jayatissa).

through visual comparison: ~90%). The Principal Coordinates (PCO) based analysis also showed a clear-cut separation of these areas with the total variation of 65.8% on axis-1 (cumulative variation along axes 1 and 2: 87.19%) (Fig. 4).

Area-wise land-use/cover, elevation and vulnerability index maps for Trincomalee (including the Bay), Yala, Puttalam, Kaluvanchikudy-Komari area, Jaffna, Colombo and Hambantota are also available online as supplementary material (Appendix A) with zoom-in facilities (Figs. A1-10).

4. Discussion

Evaluating coastal vulnerability is feasible but challenging at the same time, mostly due to the lack of accurate (updated) data on different vegetation and land cover types. Empirical studies and scale experiments are highly needed, but as yet largely inexistent. We refer to Dahdouh-Guebas and Jayatissa (2009) who insisted for more research on the geomorphological settings, vegetation extent, structure and composition, and combinations of different land-use/cover features to understand their coastal protection value. The present study is an assessment of potential barriers based on literature data and the Sri Lankan case-study. While assessments of the type of threat considered in this work (ocean surges) are challenging due to the spatial scale involved and the inherent complexity of (short-term) wave-landscape interactions, we believe that numerical simulations (e.g. Teo et al., 2009; Ohira et al., 2013, 2015) and GIS models as presented in this study, may help to further support and underscore current precautionary principle guidelines.

The farthest distance that the 2004 tsunami flood reached in Sri Lanka was 2 km from the coast (Rossetto et al., 2007). Since most of the coastal towns and cities are densely populated, there was a huge loss of lives and properties (UNEP & MENR, 2005). In addition, removal of intertidal forests (mangroves) have made the case severe in many countries including Sri Lanka (Dahdouh-Guebas et al., 2000, 2005b; Dahdouh-Guebas, 2006; Williams, 2005; Chang et al., 2006; Quartel et al., 2007; Cochard et al., 2008; Dahdouh-Guebas and Jayatissa, 2009). Land reclamation for agriculture and aquaculture activities, physical infrastructure developments and over-exploitation of the forest resources were some of the main causes for mangrove loss in the country (Satyanarayana et al., 2011, 2013). Satyanarayana et al. (2013) indicated that the loss of mangroves in the aftermath of the 2004 Indian Ocean tsunami must be attributed to the lack of awareness of perseverance in conservation and management strategies already implemented or proposed for the future, and suggested not to ignore different trade-offs, including local communities' priorities, while developing management policies.

The Sumatra-Andaman subduction zone is reported to be one of the world's most potential hazardous zones for triggering large tsunamis with a high population exposure (Mishra et al., 2014). In this context, Wijetunge (2012, 2014) tested different probable seismogenic tsunami scenarios numerically and found that an event, if any, similar to 2004 tsunami (magnitude: 9.0) would result again in a worst-case for Sri Lanka. Therefore, the classified maps of land-use/cover, elevation and vulnerability in the present study can visualize and provide base-line information on the island-wide vulnerable and less vulnerable areas to such ocean surges, up to 2 km inland (Figs. 1 and 2). However, further investigation and validation along similar research lines are needed to establish a blueprint for future preparedness.

Coastal vegetation together with higher elevation (89 m as reclassified) has made Trincomalee a less vulnerable area (see Appendix A, Fig. A1b-d). Yala, on the other hand is particularly protected by the presence of dense vegetation, despite its lower elevation (<10 m) and a status of flooded area (Fig. A2c-d). At Trincomalee, larger patches of mangrove and *Casuarina* (blue arrow in Fig. A1b) are expected to buffer floods and protect more landward areas (Fig. A1d), as evidenced also by studies on the wave reduction properties of mangrove stems and root complexes (Mazda et al., 1997, 2006; Quartel et al., 2007; Vo-Luong and Massel, 2008; Mazda and Wolanski, 2009; Horstman et al., 2012), as opposed to the dissipative capacity of narrow patches (black arrows in Fig. A1b). The same was also observed at Trincomalee Bay area (Fig. A3c-d). Yet it should be emphasized that the impact of ocean surges also depends largely on the direction of the main energy propagation relative to the Sri Lankan coast, which in the 2004 Indian Ocean tsunami was in north-western direction, along with wave diffraction and refraction conditions (Tomita et al., 2006). According to Lynett (2007), both wave run-up and overland flow velocity are determined by the (beach) slope at each location.

For Yala, the dense vegetation of Yala National Park is offering invaluable protection, along with sand dune/beach settings (Fig. A2b-d). Even with a widespread distribution of saltpans at Puttalam (see black arrow region in Fig. A4b), the coastal vegetation (e.g. mangrove, coconut plantation, agriculture and dense or sparse vegetation), coupled with sand dunes, makes it one of the three least vulnerable areas in Sri Lanka in our approach (Fig. 4). In fact, the most noticeable sand dunes are located close to Yala, Komari, Mannar, Batticaloa, Jaffna, Hambantota and Puttalam (personal observation and expert knowledge) (Fig. 5). However, we emphasize that vulnerability obviously increases with surges of higher magnitudes. The vulnerability close to water body/lakes and saltpans is understandable as the flood has no difficulty to cross these land-use/cover categories, due to the low drag force. Recent findings of Wijetunge (2014) and Mishra et al. (2014) also confirm a low-resistance path for the tsunami-induced surge at the water bodies. In addition, the relative tsunami damage potential map of southwest Sri Lanka produced by Wijetunge (2014) was in agreement with the vulnerability index (Fig. 2) developed for the present study (e.g. less vulnerability close to southeastern part of Galle). Nevertheless, Zhang et al. (2012) have observed a surge amplitude decreasing by 40–50 cm km^{-1} across the mangrove forest (dominated by *Rhizophora mangle* L., *Laguncularia racemosa* (L.) Gaertn.f. and *Avicennia germinans* (L.) Stearn), and 20 cm km^{-1} across the areas with a mix of mangrove and open water in a simulation-based study on the Gulf Coast. In Sri Lanka, this setting is not common and can only be found in the Trincomalee area. In contrast, the setting with mangrove forests and creeks in a coastal lagoon, often behind a sand bar blocking a river mouth, is much more common (e.g. Chilaw, Negombo, Rekawa, Kahandamodara and Kalametiya Lagoons). However, the interaction of trees with surge flow is a complicated process that depends much on the species, tree size and canopy structures (Zhang et al., 2012), as well as human infrastructure.

Another important concern raised by Tanaka et al. (2012) was the river morphology for inland wave propagation. They stated that a solitary wave like tsunami can reach far upstream, without changing its shape and speed, in a straight channel of uniform depth and width. Tanaka et al. (2012) also found that the inland embankments of water channels along the coast play a crucial role in mitigation or increase of the tsunami impact. For Sri Lanka, both Kaluvanchikudy-Komari area and Jaffna were strongly affected by our simulated ocean surge (Figs. A5 and A6). In the Kaluvanchikudy-Komari area, most of the coastline with inland water bodies and narrow beaches allowed an easy penetration of the flood in several pockets (black arrows in Fig. A5b and 5d). However, as the most inland water bodies in this region are characterized by higher elevation (Fig. A5c), higher vulnerability only accounts for exceptional ocean surges that reach more than two times the height of the 2004 Indian Ocean tsunami (cf. Ramalho et al., 2015). Although Jaffna has coastal features similar to less vulnerable areas (e.g. Puttalam), its geographic location is influenced by the Indian Ocean on all three (North, East and West) sides, rendering the location vulnerable, particularly the human settlements, water bodies, agriculture and bare soil categories in the land-use/cover map (Fig. A6b). This complex land- and seascape structure in part explains the increased vulnerability at 2 km inland due to areas affected from opposite directions or large water bodies with an easy propagation of the ocean surge. Tanaka et al. (2012) also observed a similar situation at Kitakamigawa and Abukumagawa in Japan and advises the people living in a coastal city with rivers/creeks to be more cautious - as water inundation can occur not only from the sea, but also from the rivers or creeks due to overtopping. However, one more caveat we would like to address is the fact that dense human settlements provide protection because of the built capital and its inherent physical drag, but this subjected to geographic location as well as surge intensity. Dense settlements located right at the coastline are highly vulnerable from a societal point of view, and a decreased vulnerability can be expected with distance away from the coast or with high elevations nearby. In this context, damage to cultivated areas also may have a profound socio-economic impact (Griffin et al., 2013). The analysis of the socio-economic implications of losses of lives and properties were, however, beyond the scope of this paper.

Unlike the general wind-generated waves, storm surges and tsunamis are categorically different, having exceptionally long periods and wavelengths, and hence a greater net energy (Feagin et al., 2010; Zhang et al., 2012). According to Martinez et al. (2017), nearly 189 million people are living below the one-in-a-hundred-years high storm surge level. Although coastal morphology and features like coral reefs, seagrass beds, sand dunes and beaches play an important role in protecting (at least to some extent) inland areas from ocean surges, coastal vegetation species are virtually the only barriers perceived and reported by local inhabitants having experienced such surges (Satyanarayana et al., 2013). In addition, the conservation and management of coastal vegetation is logistically easier than that of the aforementioned barriers. In Sri Lanka, next to mangroves, other coastal vegetation and landforms that can mitigate the impact of ocean surges are sand dunes, coconut plantation, *Casuarina* plantation and dense vegetation.

These findings are in agreement with the results from other researchers who have made post-tsunami environmental assessment for Sri Lanka, Thailand and India (Baird, 2006; Chang et al., 2006; Tanaka et al., 2007, 2009; Chatenoux and Peduzzi, 2007; Cochard et al., 2008; Dahdouh-Guebas and Jayatissa, 2009; Feagin et al., 2010; Patnaik et al., 2012; Samarakoon et al., 2013). Mascarenhas & Jayakumar (2008) have observed the intrinsic capacity of sand dunes and *Casuarina* in dissipating the powerful waves of the 2004 tsunami along Tamil Nadu coast, India. However, they also reported pronounced changes in the frontal strips of *Casuarina* forest (e.g. as broken, bent or stripped of green organs), and sand dunes (e.g. flattened, breached, dissected or eroded), by the wave up-rush. Along with coconut and date palm trees, *Pandanus* spp. have been recognized for their coastal protection value in several countries including Sri Lanka (e.g. IUCN, 2005a,c; Mascarenhas & Jayakumar, 2008; Samarakoon et al., 2013). In addition, the port and harbor facilities such as breakwaters and rigid houses and buildings along the coast have lessened the tsunami damage in Sri Lanka (Tomita et al., 2006).

Tanaka et al. (2006a,b) have demonstrated that the wave attenuation ability of *Pandanus* is as efficient as *Rhizophora* spp. The plantation of *P. odoratissimus* as front vegetation layer to *C. equisetifolia* forests with the open gaps (maintained at the time of plantation) was suggested by Samarakoon et al. (2013). Despite the fact that vegetation projects with a combination of species can play an effective role in mitigating the potential effects of ocean surges, the eco-socio-economic advantages and disadvantages of such projects are to be studied in detail - especially with reference to local conditions, prior to implementation (cf. Mukherjee et al., 2015). A multi-criteria evaluation of optimal vegetation composition for coastal restoration is therefore necessary (cf. Dahdouh-Guebas and Jayatissa, 2009). In addition to all of the above mentioned protection functions, we emphasize the suggestions made by Mazda and Wolanski (2009) that much more than the above- and below-ground mangrove biomass that remains standing, it is the trees themselves falling and being uprooted that may act as an effective barrier.

5. Conclusions and future perspectives

Although 'larger distance to coastline' and 'higher elevation' are the general measures of safety from any ocean surge, coastal areas have always been crowded due to industrial development, employment opportunities and therefore human settlement. Due to this sustained human pressure, potentially protective coastal features are at risk backlashing on human security. Particularly coastal forests should be treated with appropriate conservation and management guidelines in the light of their ecological (e.g. protection) and economic (e.g. livelihood) functions, goods and services. The present study provided an indication of vulnerable and less vulnerable areas along the Sri Lankan coast in the face of ocean impacts. Land-use/cover map, elevation classification and vulnerability indices are in general useful to the public as well as the decision makers for understanding the impact of ocean surges on different landscapes. Among the coastal sites, Trincomalee, Yala and Puttalam are 'less vulnerable' areas whereas the Kaluvanchikudy-Komari area and Jaffna are 'vulnerable areas', but all of them should be prioritized for conservation. For the less vulnerable areas, multi-species mangrove and dense vegetation (e.g. Yala National Park), coastal features such as sand dunes, and *Casuarina* and coconut plantations are suggested to help reducing vulnerability and corroborate findings of Tanaka et al. (2007), but are not sufficient as a measure. In view of the limited mangrove cover, the above-mentioned vegetation like the ones constituted by *Casuarina*, *Cocos*, *Pandanus*, etc., could be propagated in the coastal zone, but with a prior knowledge on the consequences, if any, in relation to the local eco-socio-economic conditions. On the other hand, true restoration of coastal vegetation as their ability to protect the coast strongly depends on the magnitude of an ocean surge. Also, sand dunes (with or without vegetation) should be a top priority for conservation and should not allow mining activity. Overall, the people in settlements lining the coastline without any seaward protection remain vulnerable. Due to the (fundamental) limitations such as incorporating fluid dynamics, treating high and low amplitude waves (as if an ocean surge entered from other sides than that of the 2004 tsunami intrusion), boundary determination and orientation of the coast, river morphology and embankments, high precision Z value of the ASTER (elevation) data, etc., in producing the maps in the present study, we recommend further research with precise data on loss of lives/property due to the 2004 Indian Ocean tsunami. We also recommend further research beyond Sri Lanka, e.g. in a wide range of countries that are recurrently or potentially affected by ocean surges, not only in the wake of a tsunami, but particularly in view of ever increasing hurricane frequency and intensity (e.g. see Caribbean hurricanes Harvey, Irma, Jose and Maria in 2017).

Author contributions

Conceived and designed the experiments: FDG & NK. Performed the experiments/fieldwork: GRa, GRo, LPJ, KASK, FDG & NK. Analyzed the data: GRa, BS, TVdS & FDG. Produced the maps: GRa & BS. Contributed reagents/materials/analysis tools: GRa, GRo, BS, TVdS & FDG. Supervised the research: FDG, LPJ & NK. Provided background data: LPJ & KASK. Provided logistical support: HML. Wrote the first draft of the paper: BS, GRa & FDG. Revised and coordinated the revisions of the subsequent drafts: BS & FDG. Provided substantial comments to improve the subsequent drafts: TVdS, LPJ & NK.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.gecco.2017.10.001.

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