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Impacts from the 2004 Indian Ocean Tsunami: analysing the potential protecting role of environmental features

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Abstract The tsunami that deeply impacted the North Indian Ocean shores on 26 December 2004, called for urgent rehabilitation of coastal infrastructures to restore the livelihood of local populations. A spatial and statistical analysis was performed to identify what geomorphological and biological configurations (mangroves forests, coral and other coastal vegetation) are susceptible to decrease or increase coastal vulnerability to tsunami. The results indicate that the width of flooded land strip was, in vast majority, influenced by the distance to fault lines as well as inclination and length of proximal slope. Areas covered by seagrass beds were less impacted, whereas areas behind coral reefs were more affected. The mangroves forests identified in the study were all located in sheltered areas, thus preventing to address the potential protecting role of mangroves forests.

Keywords Tsunami · Indian ocean · Impact assessment · GIS · Bathymetry · Vulnerability · Coral · Mangroves forests · Seagrass beds · Environment

Acronyms

CRED	Centre for Research on Epidemiology of Disasters
DEM	Digital Elevation Model
FAO	Food and Agriculture Organisation
GIS	Geographical Information System
IFRC	International Federation of the Red Cross
UNEP	United Nations Environment Programme
UNEP/GRID	United Nation Environment Programme, Global Resource Information Database
WCMC	World Conservation Monitoring Centre
UTM	Universal Transverse Mercator
GPS	Ground Positioning System

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Introduction

Context

The tsunami that brought havoc to the North Indian Ocean coasts on 26 December 2004, killed more than 226,000 persons, left millions in despair and caused nearly US $8 billions damage from direct impacts (CRED 2005). In order to minimise risk in the future, United Nations Environment Programme (UNEP), amongst other organisations, has called for improved coastal management and rebuilding in safer places as well as in minimising impacts on the environment. This is particularly relevant since the livelihood of the population depends on the quality of the environment: tourism, fishing and aquaculture are all economic activities requiring clean coasts and water. The scope of this study was to improve understanding of factors leading to higher coastal vulnerability to tsunami, and more specifically, to test whether environmental features could provide an efficient protection. To this end, a statistical and spatial analysis was conducted by UNEP/GRID-Europe for the UNEP Asian Tsunami Disaster Task Force (UNEP 2005a).

Tsunami impacts

Why are some areas less impacted than neighbouring ones? Is it only dependent on geomorphology, or do environmental features play a protecting role? Whereas the geomorphological role in tsunami propagation is well studied (e.g. Kowalik 2003) and the influence of small-scale submarine topography has already been modelled (Mofjeld et al. 2000), less is known about the potential protective role of environmental features. Scientific studies of the potential protective role of coral and mangroves forests are very scarce and although several press releases stated that environment components such as mangroves forests played a major role in reducing the impacts from the tsunami (Khor 2005; Friends of the Earth 2005), other more reliable sources mention the negligible role of mangroves forests since they are mainly located in estuaries (Jimenez et al. 1985; Lewis 1982; Field 1996). Experiments conducted in in-door basins demonstrated that structures with properties similar to mangroves forests decreased the height of a solitary wave in a channel (Harada et al. 2002). Hiraishi and Harada (2003) highlighted the protecting role of other coastal vegetation such as the *Hibiscus tiliaceus*, they also confirmed that mangroves forests do not grow on sandy beaches. *In situ* observations delineate the protecting role of other species such as *Scaevola sericea* and *Pemphis acidula* (UNEP 2005b).

Objective

The aim of this analysis was to assess the potential protective role of mangroves forests, coral reefs, seagrass beds and coastal vegetation, apart from the near-shore geomorphological influence. To this end, data on bathymetry (water depth), orientation of the coast, length of proximal slope, distance to tectonic features, presence of coral, seagrass beds, mangroves forests and type of land cover were extracted using GIS technologies. Then, the width of flooded land strip was evaluated either by interpreting high-resolution satellite images or from available ground measurements. Finally, multiple regressions were performed to identify the parameters that best explain the width of flooded land strip (thereafter D) following a method already applied previously (Peduzzi et al. 2002; Dao and Peduzzi 2004).

The study was based on global datasets to provide a first cut-off as well as to identify the key parameters that are linked to higher coastal vulnerability to tsunami.

Data collection

Selection of the study area

The research was initiated in March 2005, and was based on information available at that time. For instance, there was little material available for Seychelles, Yemen, Somalia, and none for Burma and Andaman Islands (India). Thus the 62 sites selected are located in Indonesia, Thailand, continental India, Sri Lanka and Maldives (Fig. 1). They cover a wide range of different configurations (distance from tectonic event, bathymetry, as well as environmental parameters).

Data on width of flooded land strip

The tsunami impact was determined using the maximal D in a given area. This information was derived using several types of data.

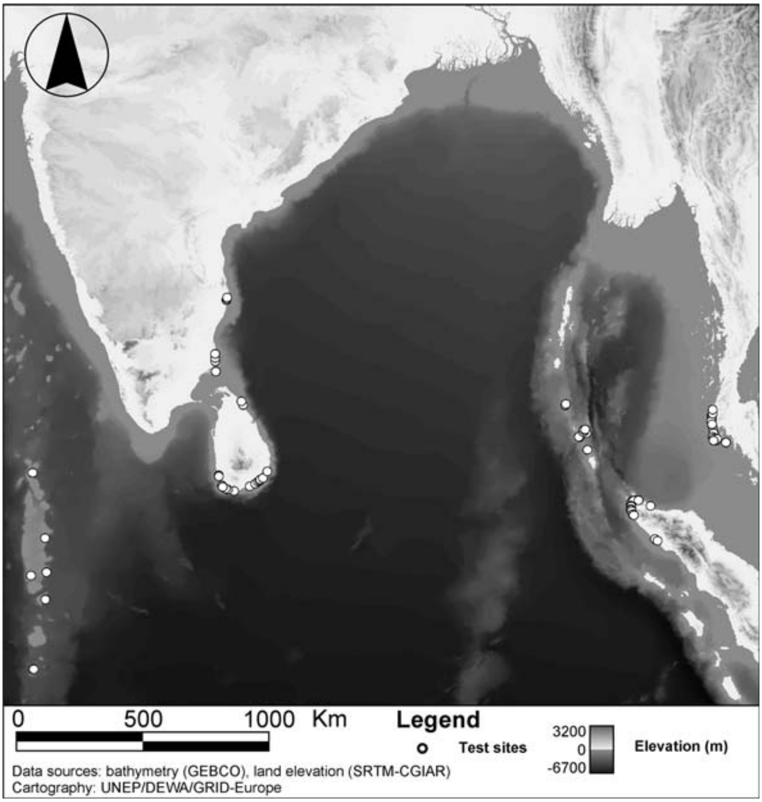

Fig. 1 Study area and selected site distribution taken perpendicularly to the coastline

The first data type consists of interpreted satellite images (sources in Table 1) that show the extent of the area flooded by the tsunami, based on an overlay and comparison of pre- and post-tsunami images. Such images are the most accurate type of data. However, coverage remains limited as it required good quality images and a long and methodical processing.

In order to increase the number of test sites, post-tsunami satellite images were visually interpreted. This was easy for large D values (several hundreds of metres), but difficult, if not impossible, for width smaller than hundred metres.

The information on flooded land was completed using field surveys from the Research Centre for Disaster Reduction Systems (DRS) and the Disaster Prevention Research Institute (DPRI) of Kyoto University. The aim of those surveys being an evaluation of the tsunami run up from clear landmark, locations available do not specifically correspond to the maximal extent of the flooded area; it only confirms that the water reached at least this distance.

Data for extracting potential parameters related to width of flooded land strip

Two sets of parameters were collected as being prone to have an influence on the width of flooded land. The first set is related on the role of near coast geomorphology. The hypothesis is based on studies such as Kowalik's (2003), which modelled tsunami propagation in presence of an escarpment and another study on interaction of tsunami waves with small-scale submarine topography revealed that ''*the most important factor (...) is the depth of a feature compared with the depth of the surrounding region*'' (Mofjeld et al. 2000). Consequently parameters were chosen in order to characterise near-shore bathymetry changes.

The second set of parameters is related to the role of environmental features. This is less documented and more empirical, hence a large panel of geographical and environmental descriptors having a potential an effect on tsunami propagation were collected.

These parameters were extracted from a wide range of sources (Table 2): location of epicentres coordinates; fault lines; elevation level; information on coastlines; land cover; distribution of coral; mangroves forests and seagrass beds. The geomorphologic parameters were obtained by computation and transformation of bathymetry or elevation (from respectively GEBCO and SRTM), thus providing information on slope and depth.

Table 1 Interpreted and other satellite images data sources

Provider	Data source
DLR – Centre for Satellite Based Crisis Information (ZKI)	http://www.zki.caf.dlr.de/applications/2004/indian_ocean/indian_ocean_2004_en.html
Global Land Cover Facility (GLCF) – ESDI	http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp
Service Regional de traitement d'image et de teledetection (SERTIT)	http://sertit.u-strasbg.fr/documents/asie/asia_en.html
UNEP/DEWA/GRID-Europe	http://www.grid.unep.ch/activities/assessment/indianocean_crisis/index.php
UNEP–WCMC imaps viewer	http://tsunami.unep-wcmc.org/imaps/tsunami/viewer.htm
UNOSAT	http://unosat.web.cern.ch/unosat/asp/charter.asp?id=55
USGS tsunami disaster website	Restricted area

Table 2 Data sources

Data	Providers	Data source
Earthquakes epicentres and replicas	Northern California Earthquake Data Centre and related contributors	http://quake.geo.berkeley.edu/cnss/catalog-search.html
Subduction fault	UNEP/DEWA/GRID-Europe	Digitised from USGS tectonic map
Digital Elevation Model (DEM)	USGS, SRTM (90 m)	http://srtm.csi.cgiar.org
Bathymetry	General Bathymetric Chart of the Oceans (GEBCO)	http://www.bodc.ac.uk/projects/gebco/index.html
Vector country border	NIMA Vmap level 0, UN Cartographic Section	http://www.mapability.com/info/vmap0_intro.html
Islands coastlines	Christian DEPRAETERE, Institut de Recherche pour le Développement (IRD) – Laboratoire d'étude des Transferts en Hydrologie et Environnement (LTHE)	Data no yet public
Global Land Cover 2000	EU/Joint Research Centre and related collaborators	http://www-gvm.jrc.it/glc2000
Coral distribution	UNEP World Conservation Monitoring Centre (WCMC)	http://www.unep-wcmc.org
Mangroves forests distribution	UNEP World Conservation Monitoring Centre (WCMC)	http://www.unep-wcmc.org
Seagrass beds distribution	UNEP World Conservation Monitoring Centre (WCMC)	http://www.unep-wcmc.org

Methodology

Theoretical model of tsunami for parameters' selection

To explain the role of environmental parameters, an *a priori* estimation and standardisation of the other parameters is needed. This can be achieved by modelling the effect of geomorphology.

During a tsunami, bathymetry has a direct link with wave height and velocity, a well known process. When the water depth decreases, the wave slows down and the wavelength decreases accordingly. This compresses the wave, which then builds up in height. The wave breaks when water depth goes down to 1.3 times the wave height (Fox 2004).

Several others parameters were extracted, assuming the bathymetry could be reduced to a model as shown in Fig. 2. Shore elevation, length and slope of the proximal and distal slope, and depth at given distances from coast were acquired for each test site using GIS techniques.

In order to also take into account the origin of the tsunami, distance from the fault line as well as the angle of the waves with the coastline were included in the dataset. Finally, the environmental parameters were integrated by estimating the percentage of coastline behind coral reef, mangroves forests and seagrass beds. The coastal vegetation was classified following an ordinal ranking in five classes of resistance (Table 3).

The table in the Appendix presents a synthesis of the variables used in the statistical analysis.

Methodology of statistical analysis

To describe the GIS processing details is beyond the scope of this paper. This chapter will summarise the statistical techniques that were applied.

In order to test the validity of the hypothesis (distance of impact dependant on bathymetry and presence/absence of natural features), all the parameters for each site were transformed so that multiple regression analysis could be applied. These transformations are necessary to obtain a normal distribution as well as a standardisation to compare different types of measures, such as percentage, angles or distances.

The variables were transformed by taking the natural logarithm (LN) of scalar or, in some cases, the LN of transformed values. Transformations already proved to be efficient in previous studies (Peduzzi et al. 2002, Dao and Peduzzi 2004). For variables ranging

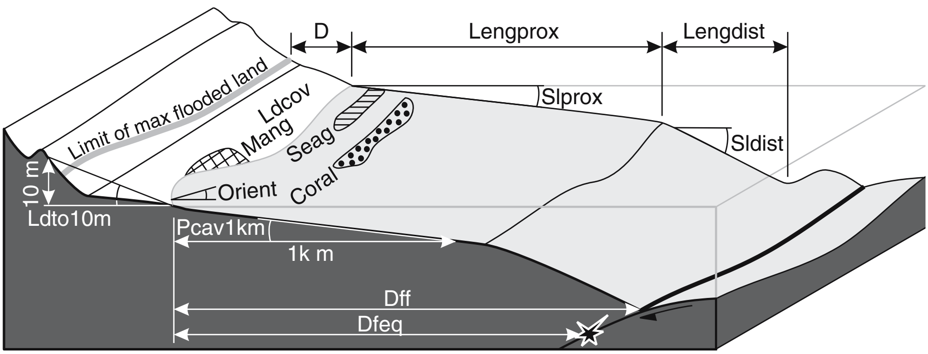

Fig. 2 Bathymetric model (not to scale); for the parameters abbreviations see Table A1

Table 3 Land cover resistance-roughness ordinal index

Legend	Resistance index
Herbaceous Cover, Bare Areas, Water Bodies	1
Shrub Cover, evergreen, deciduous, sparse shrub cover	2
Regularly flooded shrub and/or herbaceous cover, cultivated and managed areas	2
Mosaic: Cropland/Shrub and/or grass cover	2
Mosaic: Cropland/Tree Cover/Other natural vegetation	3
Mosaic: Tree Cover/Other natural vegetation, Tree cover, regularly flooded	4
Tree cover, broad-leaved, evergreen	5

between 0 and 1 (e.g. percentage) Equation 1 was applied, for transformation of angle and orientation Equation 2 was used:

Equation 1. Transformation of variables ranging between 0 and 1 (e.g. percentage)

$$\overline{V_i} = LN\left(\frac{1}{1 - V_i}\right)$$

where V_i is the variable to be transformed and $\overline{V_i}$ is the transformed value

Equation 2. Transformation of variables expressing angle/orientation

$$\overline{V_\alpha} = LN\left(\frac{\cos\alpha}{1 - \cos\alpha}\right)$$

where α is the angle or orientation to be transformed and $\overline{V_\alpha}$ is the transformed value.

A correlation matrix was computed between all the variables and was used to separate variables that are too correlated to be taken together in regression analysis. Groups of independent variables were generated, each one corresponding to a specific hypothesis, which was tested by running multiple regression analysis. The selection of the most relevant hypothesis was based on relevance (p-value < 0.05) and maximisation of R^2. This process allows the identification of combinations of parameters that best explain the LN of D and thus confirms or rejects the hypothesis on the role of the different environmental and geomorphological features.

The choice of logarithmic regression was made to reflect the interactivity between the different parameters, i.e. that they have a multiplicative effect on each other (an addition of LN being a multiplication of the exponents). This is believed to be pertinent, given the complexity of sites where one factor can mitigate or enhance another.

Results and discussion

Statistical results

The regression analysis identified correlations between combinations of parameters and the width of the flooded land strip (D) (Table 4). Several combinations were relevant, the best one consisting of the five following variables, namely: the distance from the tectonic origin (*distance from subduction fault line*); the near-shore geomorphology (through *average depth at 10 km* and *length of proximal slope*); but also with environmental features (*percentage of coral*and *percentage of seagrass beds*).

Table 4 Best parameters combination with weights (B) and respective p-levels

Variables	*B*	p-level[a]
LnDFF	−0.828	0.000014
LnAV10KM	−0.312	0.007119
LnLENGPROX	0.644	0.002405
LnSEAG	−0.133	0.000107
LnCORAL	0.158	0.000392
Intercpt	8.698	0.000000

$R = 0.809$, $R^2 = 0.655$, $N = 56$ sites

where:

LnDFF = Ln (Distance from subduction fault line); LnAv10 Km = Ln (Average depth at 10 km); LnLengprox = Ln (length of proximal slope); LnSeag = Ln (%age of seagrass beds); LnCoral = Ln (%age of coral)

[a] In broad terms, a p-value smaller than 0.05, shows the significance of the selected indicator, however this should not be used blindly

The analysis was performed on 56 sites. A correlation coefficient of 0.81 was obtained between the D and the parameters listed in Table 4, i.e., an R^2 equal to 0.655, indicating that about 65.5% of the variance is explained by the model. The very low p-values of the variables (much smaller than 0.05) attest the significance of the selection.

From Table 4 values, an equation can be derived for evaluating the theoretical D in other areas based on the values of the five selected variables (Equation 3).

Equation 3 Model for Width of flooded land strip

$$D_m = \exp\Big[0.16{\cdot}\mathrm{LnCoral} - 0.13 \cdot \mathrm{LnSeag} + 0.64 \cdot \mathrm{LnLengprox} - 0.31 \cdot \mathrm{LnAv10Km} - 0.83 \cdot \mathrm{LnDFF} + 8.70\Big]$$

where: D_m = modelled width of flooded land strip

To assess the validity of the model, the D_m plotted against the observed values D (Fig. 3). In the scatter plot, the sites distribution shows several gaps, reflecting the geographical distribution of test sites. As countries are located at different range of distance from the fault lines (Indonesia and Andaman being the closest, Maldives the further away), there is not a continuum in the width of flooded land strip distribution, the countries closer to the tectonic event origin being more impacted than those located farther away.

The model identified six outliers (white circles in Fig. 3) located in Maldives (1), Thailand (1) Indonesia (1) and Sri Lanka (3). These are believed to be the result of particular geomorphologic conditions that do not fit the model constrains, as well as the different methods used to assess the maximal flooded distance (namely remote sensing versus on-ground measurements).

The use of logarithmic regression can lead to large errors if used directly to model the expected distance on a linear scale. In order to decrease this effect, only categories of magnitude should be derived from such analysis.

A cluster analysis was run on the test sites using a classificatory tool (Dao 2004) to minimise intra-class distances and minimise inter class distances. The following thresholds of D were identified and adapted in order to gain in understanding (Table 5).

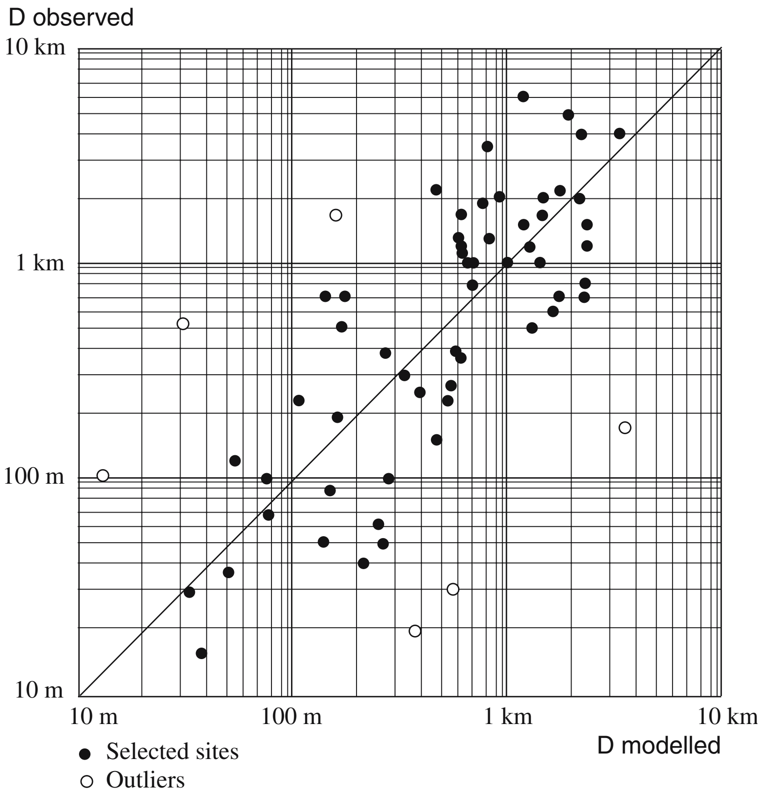

Fig. 3 Width of flooded land strip: predicted versus observed

In order to assess the confidence of the model, observed and modelled D were classified using the rounded thresholds from Table 5. Then a comparison between the classes was carried out to count when the modelled classes where similar to the observed classes and if not, what was the number of classes differences. The matrix in Table 6 provides the results with the differences of classes between observed and modelled on a region by region basis.

At the regional level, 42% of the sites correctly classify; 22% and 25% of the sites being respectively within plus or minus one class. If these percentages are added, the confidence of the model can be estimated at 89% to fall within plus or minus one class. Since there are only five classes, this might seem to be a somewhat disappointing result; however, given the fact that global data sets were used, this result was found to be surprisingly good. Seen at a national level, the model underestimates the impact, especially

Table 5 Width of flooded land strip classes

Categories (impact)	Width of flooded land strip (m)	Rounded ranges (m)
1 (low)	Less than 32.65	Lower than 30
2 (moderate)	32.65–107.35	30–100
3 (medium)	107.35–321.40	100–300
4 (high)	321.40–956.68	300–1000
5 (very high)	Longer than 956.68	1000 and up

Table 6 Differences between modelled and observed classes (with of flooded land)

Cat. Error	Nicobar	India	Indonesia	Maldives	Sri Lanka	Thailand	Total	%
−4								0
−3								0
−2	1				3		4	7
−1	4	2	1		7	1	15	25
0	2	2	11	3	3	4	25	42
1	3	2	2		3	3	13	22
2						1	1	2
3						1	1	2
4						1	1	2
Total	10	6	14	3	16	11	60	

for Sri-Lanka. In Thailand, however, the impact is overestimated. This is believed to be due to the geomorphological complexity of the proximal slope which is not taken into account in the model, and which probably strongly dampens the energy of the tsunami in reality.

Discussion

The five factors identified as having an influence on D, fall in three categories, namely: distance from the fault line; width; geomorphology and environmental parameters, described hereafter.

The negative sign before the coefficient means that the closer from the fault line, the larger the value of *D*. This is consistent with description found in the literature ''*Tsunamis typically cause the most severe damage and casualties very near their source. There the waves are highest because they have not yet lost much energy to friction or spreading*.'' (NOAA 2004b).

Geomorphology of near-shore

The average depth at 10 km is related to the average slope of the sea floor. A steep slope is known to block the energy of a tsunami, whereas a flatter slope is more dangerous as it helps build up a higher wave. A greater depth for the same distance means a steeper slope, hence less dangerous, a smaller depth being related to a flatter slope, more dangerous. The negative sign before the coefficient is consistent with the theory.

The positive sign before the coefficient relative to the length of the proximal slope means that a longer proximal slope is leading to a larger width of flooded land strip. This is also related to the slope; the longer the length the lower the angle. Together with the average depth, the two parameters indicate a higher risk configuration when a long shallow area precedes the coast.

Environmental parameters

Seagrass beds (or seagrass substrate) seems to have a positive role in absorbing the energy of tidal wave, the negative sign indicating that the higher the percentage of seagrass beds, the shorter the *D* values. From such statistical analysis, it is impossible to differentiate if the presence of seagrass beds has a mechanical influence that absorbs the energy of the waves, or if the area that seagrass usually colonise is already protected from the wave. The result, however, is that behind areas covered by seagrass, the distance of impact was in majority shorter than in other areas having similar geomorphology.

Among the results of the statistical analysis, the surprise came from coral. A positive sign preceding the coefficient suggest that the higher the percentage of coral, the larger the *D* behind. This was unexpected, as one would imagine water behind a coral reef to be somewhat sheltered.

A visual confirmation of this phenomenon was gained, using satellite images, which confirmed larger D behind corals. In Fig. 4, despite a double barrier of coral reef, the area on top of the map was more impacted than the area without reef. However, in this case, the land elevation, facing the gap of coral reef, is steeper. The first hypothesis to explain this positive correlation is that coral is mostly located in shallow areas, with a gentle slope continuing inland, hence the low-lying areas are easily flooded. Conversely areas without coral could be steeper hence would block the tsunami wave on a shorter distance in-land. This apparently logical explanation was contradicted by the statistical verification, which shows no correlation between presence/absence of coral and in-land slope, at least not with the 90 m resolution data used.

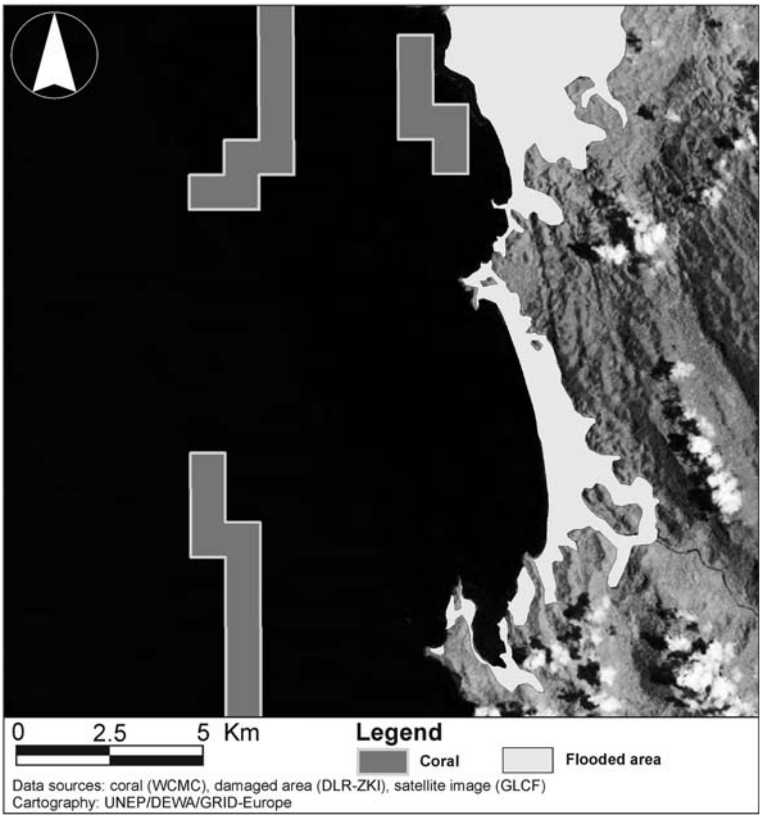

Fig. 4 Example of coral influence in Lho'Nga, Sumatra (Indonesia)

Another explanation for this phenomenon comes from the length of tsunami waves, which are about 1000 times longer than that of usual waves. If coral is offering protection for usual waves, a more significant one might not be stopped but would continue to build up on such shallow area.

This surprising result was backed up by UNEP ground assessments in Maldives and Seychelles, where the following observations were made: ''*Fringing reef crests serve a protective role against normal waves. However, in the case of the tsunami, major terrestrial and coastline damage was located in areas sheltered by fringing reefs. At these locations, damage was focused near deeper channel that allowed the waves to break closer onshore.*'' (UNEP 2005b, p. 19).

To better understand how coral, (or coral location slope) influences *D*, mathematical modelling or *in situ* observations should be performed. Pending further investigations, the results tend to indicate that it would not be wise to rebuild on coasts behind coral reefs.

The case of mangroves forests

Mangroves forests are said to help reducing the impacts from tsunamis (Khor 2005; Friend of the Earth 2005). If by common sense we can conceive that a barrier of vegetation with a complex root system can indeed offer protection, during the present study it was impossible to find patches of mangroves forests located on coast directly facing open sea. Identification of mangroves forests was made by looking at both WCMC dataset and satellite imagery. Mangroves forests were only present in estuaries, areas sheltered by stretch of coastline or in protected bay (example in Fig. 5).

This was confirmed by literature: mangroves forests do not survive in area where wave are too active (Jimenez et al. 1985; Lewis 1982, Field 1996, Hiraishi and Harada 2003). An extract of an article from DIPE (2002) states that ''*mangrove establishment requires protection from strong winds and wind generated waves, as wave action prevents seedling establishment. As a consequence, mangrove communities tend to be located within sheltered coastal areas, surrounding highly indented estuaries, embayment and offshore islands protected by reefs and shoals*''. In such case it is suspected that areas covered by mangroves forests were less impacted by tsunami just because mangroves forests communities tend to be located within sheltered coastal areas.

This is not to say that mangroves forests cannot protect coastlines, apart from their role in filtering land run-off (Thom 1967) and reducing coastal erosion (Davis 1940). In the case of tropical cyclones (one of the most devastating natural hazard in India and Bangladesh), the role of mangroves forests could be important in reducing the impact from this type of hazard (Saenger and Siddique 1993 in Kairo et al. 2003). In Vietnam, replanting mangroves forests has helped reduce the cost of dyke maintenance by \$7.3 m per year for an investment of US \$1.1 m (IFRC 2002). However, replanting mangroves forests can only be done in areas suitable for them.

Conclusion

The applied method proved to successfully link contextual parameters with recorded *D*. The model could be extrapolated to the whole area to provide five classes of exposure to tsunami, thus easing the prioritisation of collection of data during the coastal management

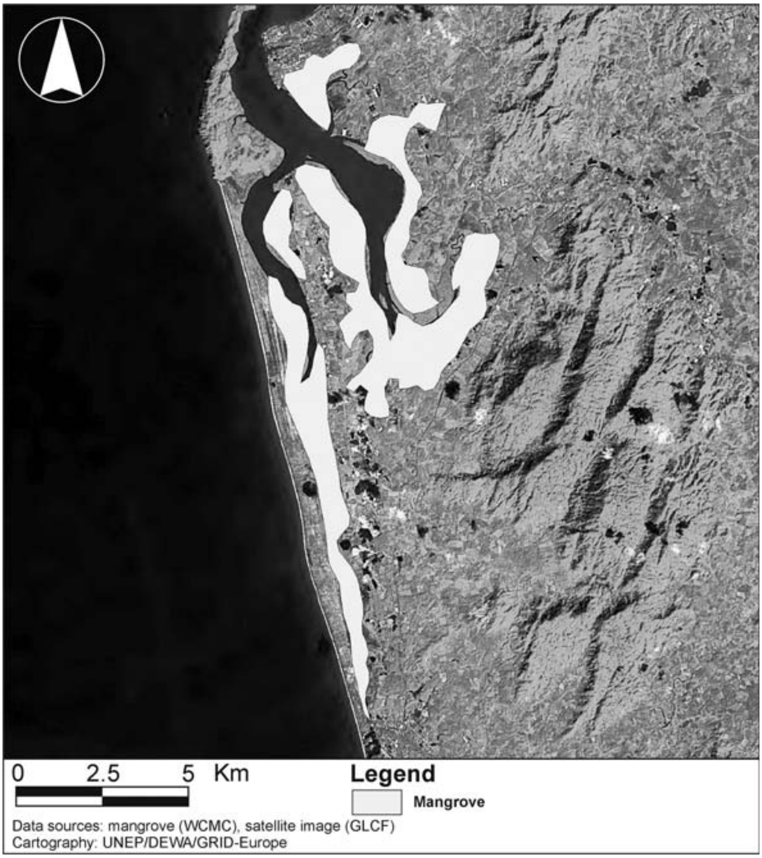

Fig. 5 Example of mangroves forests location in Phangnga province (Thailand)

rebuilding procedures. This method was applied to identify vulnerability of exposed coast depending on presence of seagrass beds, presence of coral, distance from event, length of proximal slope as well as water depth at 10 km.

Whereas the geomorphological parameters role follow theoretical knowledge, the environmental parameters were more surprising. Caution should be kept with the findings, as the study was conduced using global datasets. The coarse resolution of bathymetry data might not always capture the complexity of coastline at detailed scale.

To the question ''*are biological features a protection from tsunamis impacts?*'', the answer varies with the type of environmental features. Remaining mangroves forests being only identified in sheltered area in the observed cases, it is, therefore, difficult to distinguish whether the areas covered by mangroves forests suffered less impact because of their intrinsic nature, or because they were sheltered by coastline or other physical protection. Literature confirms that mangroves forests request calm water, but that they play a role in preventing soil erosion (Saenger and Siddique 1993 in Kairo et al. 2003) and protecting dikes (IFRC 2002).

If open sea and sandy beaches are not suitable for growing mangroves forests, other types of vegetation can be used; such as waru trees (*Hibiscus tiliaceus*). In Maldives, *Magoo* (*Scaevola sericea*) and *Kuredhi* (*Pemphis acidula*) shrubs have been reported as having dissipated much of the tsunami force (UNEP 2005b). Similar vegetation might be considered for protecting shores. To address the issue on the protecting role of mangroves forests, areas where they were removed could be compared with areas still covered by mangroves forests.

Areas where coral is growing are generally in shallow waters with small slopes, two conditions leading to higher waves. Although there are little doubts in the positive protecting role of coral from usual waves, caution should be kept while rebuilding facilities in the shore zone; the geomorphology of areas where coral usually grow might be not a safe place for tsunami protection. This was confirmed by ground observation (UNEP 2005b). Further research should be made with more detailed data as the coarse resolution of the bathymetry and coral location prevent more precise conclusions. A mathematical modelling of wave, or in situ measure could be a good solution to study the behaviour of tsunami waves in area covered by coral.

The statistical model show lower impacts in area behind seagrass beds. This could be for two reasons, the mechanical role of seagrass beds acting as a damping filter that help reducing the energy of the wave or because seagrass beds are located in areas where the configuration of bathymetry is not favourable for building high wave. The true reason remains unexplained, but the correlation with lower distance of impact is significant.

It is important to note that all this analysis was made on a single event, the tsunami of 26 December 2004. Different magnitude and origin of a tsunami could result in drastically different wavelengths thereby might induce different effects.

The identification of area most exposed to tsunami following our method can be used as a first cutoff for choosing where more detailed data should be collected, modelling the vulnerability of coast being the next logical step.

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Appendix

Table A1 List of variables computed or extracted

Abbreviation	Description	Units
AV10 KM	Average slope until 10 km	Degrees
AV1 KM	Average slope until 1 km	Degrees
AV2_5 KM	Average slope until 2.5 km	Degrees
AV20 KM	Average slope until 20 km	Degrees
AV25 KM	Average slope until 25 km	Degrees
AV30 KM	Average slope until 30 km	Degrees
AV50 KM	Average slope until 50 km	Degrees
AV5 KM	Average slope until 5 km	Degrees
CORAL	Percentage of protection from coral preceding the site	%age
COSORIEN	Cosinus of orientation	Scalar
DFEQ	Distance from main earthquake	Kilometres

Table A1 Continued

Abbreviation	Description	Units
DFF	Distance from subduction fault line	Kilometres
DFS	Distance from source	Kilometres
D	Width of flooded land strip	Metres
LDCOV	Land cover resistance index	Cardinal values 1 to 6
LDTO10M	Average slope until an inland height of 10 m	Degree
LDTO30M	Average slope until an inland height of 30 m	Degree
LENGDIST	Length of distal slope	Kilometres
LENGPROX	Length of proximal slope	Metres
MANG	Percentage of protection from mangroves preceding the site	%age
ORIENT	Orientation between the tsunami energy and a perpendicular to the coast	Degrees
PCAV10KM	Average slope until 10 km	%age
PCAV1KM	Average slope until 1 km	%age
PCAV2_5 K	Average slope until 2.5 km	%age
PCAV20KM	Average slope until 20 km	%age
PCAV25KM	Average slope until 25 km	%age
PCAV30KM	Average slope until 30 km	%age
PCAV40KM	Average slope until 40 km	%age
PCAV500M	Average slope until 5 km	%age
PCAV50KM	Average slope until 50 km	%age
PCAV5KM	Average slope until 5 km	%age
PCLDTO10	Average slope until an inland height of 10 m	%age
PCLDTO30	Average slope until an inland height of 30 m	%age
PCSLDIST	Angle of Distal slope	%age
PCSLPROX	Angle of Proximal slope	%age
SEAG	Percentage of protection from Seagrass beds preceding the site	%age
SLDIST	Angle of Distal slope	Degree
SLPROX	Angle of Proximal slope	Degree

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