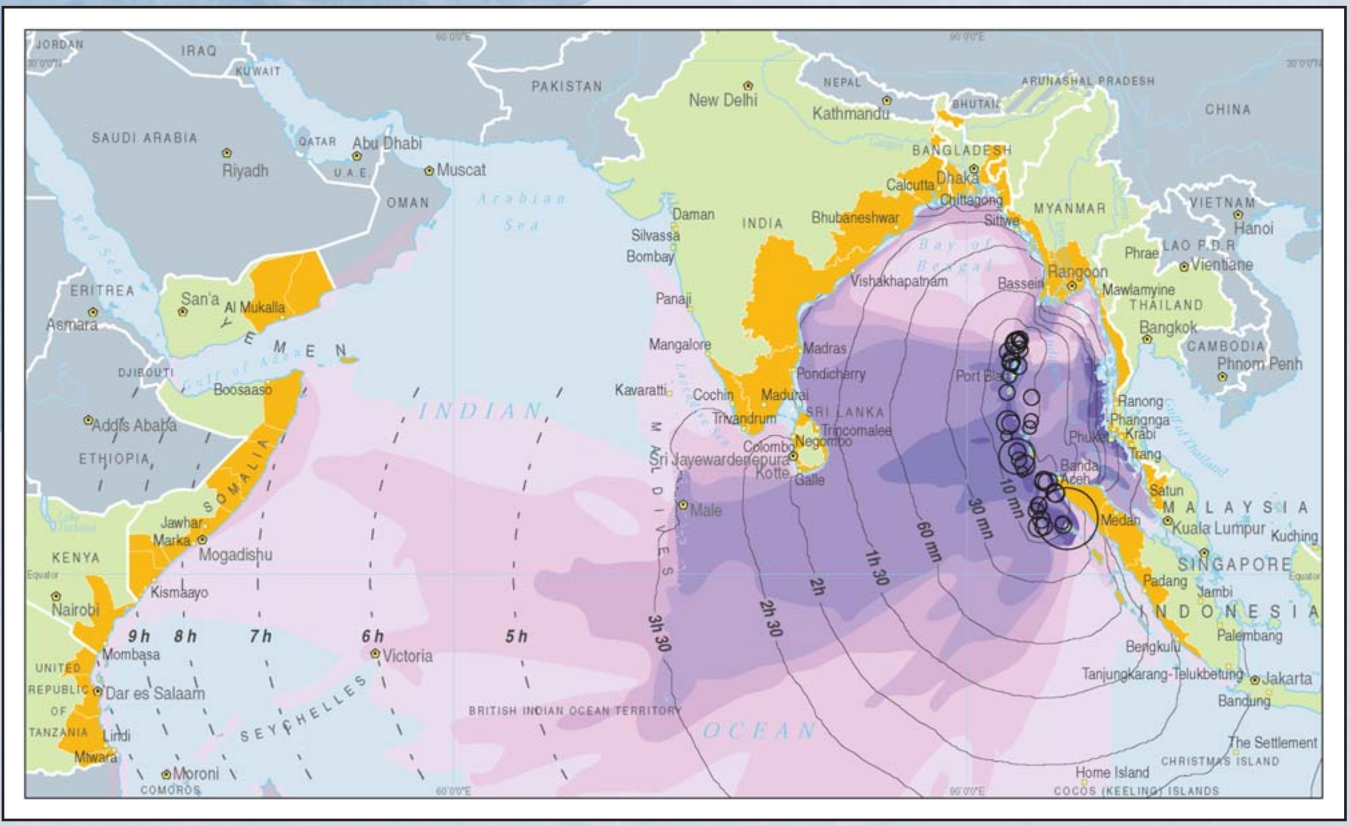
Analysis on the Role of Bathymetry and other Environmental Parameters in the Impacts from the 2004 Indian Ocean Tsunami

A Scientific Report for the UNEP Asian Tsunami Disaster Task Force



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UNEP/GRID-Europe
11, ch. Des Anémones
1219 Châtelaine
Geneva – Switzerland
Tel: +4122.917.82.94
Fax: +4122.917.80.29
Website: www.grid.unep.ch

Lead Authors
Bruno Chatenoux and Pascal Peduzzi

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Cover
Indian Ocean Tsunami Wave Propagation
Estimated timeline, offshore wave height and impact distribution

Cartography, Pascal Peduzzi,
UNEP/GRID-Europe, February 2005.
From a propagation model of Vasili Titov, NOAA

Sources: http://www.grid.unep.ch/

Abstract

Following the tsunami that wreaked havoc in North Indian Ocean coastal areas on 26 December 2004, rapid rehabilitation of infrastructure is needed to help restore the livelihoods of local populations. A thorough understanding of factors leading to higher exposure to the tsunami is essential for improving coastal management, in order to rebuild near-shore infrastructure in a safer way. To initiate such a process, a spatial and statistical analysis was performed to identify which geophysical and biological configurations were susceptible to be associated with reduced tsunami impacts. Near-shore bathymetry (water depth), the orientation and elevation of coastlines, the distance from the earthquake epicentre and other key geomorphological parameters, presence of mangroves, coral reefs and type of fringing vegetation were all extracted using GIS technologies and correlated with maximum length of inland impacts as recorded by remote sensing or ground surveys. The results clearly indicate that the scale of impact was, in the vast majority of cases, correlated with the distance to fault lines, and the steepness and length of proximal slopes. Areas covered by sea grass were less impacted, whereas areas behind coral reefs were more affected. This is surprising as coral reefs are known to protect from normal waves, and may be because tsunami wavelengths are up to a thousand times longer than other waves. Areas covered by mangroves were less impacted than other areas, probably because mangrove communities tend to be located in sheltered coastal areas. The results provided here are based on information available between February and June 2005, and the model is based on global data sets applied to the 2004 Indian Ocean tsunami. Variation in wavelength and origin contributed to diversity among the findings. A more detailed study should be carried out to allow the local-level analysis that is needed for coastal management.

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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

Foreword

The tsunami disaster of December 2004 was the first natural calamity covering such large and densely-populated areas in modern times. Inspired by the efforts of the affected countries, and by an unprecedented outpouring of international support and solidarity, the UN and other international organisations acted to meet exceptional levels of humanitarian need. As the relief operation evolved, it became clear that key natural life-support systems had been badly damaged, some by the tsunami itself and others beforehand, undermining livelihoods and increasing vulnerability to environmental shocks. While it was clear these would need rehabilitation, the scale of the task was not yet known, and environmental assessments would first be required. Following requests from affected countries, UNEP decided to join the efforts of UN colleagues to provide expertise and support to the Ministries of Environment and other partners in the affected countries.

The resulting environmental assessments involved scores of scientists from the affected countries and elsewhere. Their surveys provide a sound and credible knowledge base for restoring environments, avoiding additional environmental harm and enhancing the sustainable development of communities. They highlight the tsunami's impact on coastal ecosystems, suggest that integrated coastal zone management should be an over-arching priority, and lead to the conclusion that extensive restoration of coastal forests and other ecosystems should be undertaken.

The present study seeks to begin the process of understanding the role of biological and geological features in offering protection from tsunami waves. This could then lead to potential explanations on why areas, even close to each other, presented significant discrepancies in the extent of flooded land strip.

It should be emphasized that, although high-resolution satellite images and results from ground survey were used to assess the width of flooded land strip, the analysis on the role of features is based mostly on global-level data sets and addresses only the 2004 Indian Ocean tsunami. This study was carried out between February and June 2005; at that time, only a limited amount of information was available. Further detailed analysis should have a high priority because of the social and economic implications of attempting to use ecosystem restoration as a means of environmental hazard reduction. This report confirms that consideration of ecosystems along with other factors enriches the science of risk management.

This report was carried out by UNEP/DEWA/GRID-Europe as part of, and as co-financed by, the UNEP Asian Tsunami Disaster Task Force. The study, and more generally UNEP's environmental assistance to the tsunami-affected countries, has been generously supported by the governments of Finland, Sweden, Norway, Switzerland and the UK. UNEP continues to provide environmental assistance to the tsunami-affected countries, and to help catalyse safer and more sustainable recovery programmes, ones in which the restoration of life-supporting ecosystems has a central role.

1 INTRODUCTION

The Tsunami that wreaked havoc in the North Indian Ocean coasts on 26 December 2004, killed more than 226 thousands persons, left millions in despair and caused nearly US$ 8 billion worth of direct damage (CRED, 2005). To respond to this large-scale disaster the United Nations Environment Programme (UNEP) quickly set up a *UNEP Asian Tsunami Disaster Task Force* to assess potential environmental risk (such as pollution from impacted infrastructure) and to ensure that sound environmental practices will be implemented during the rebuilding phase. It is important not to recreate the risk and UNEP, amongst other organisations, have 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 depend on the quality of the environment: tourism, fishing and aquacultures are all economical activities requiring clean coasts and waters. UNEP wants *to extract meaningful lessons from the tsunami experience so that governments, donors and international agencies will be able to implement environmentally sound reconstruction programmes in the affected countries* (UNEP 2005).

In order to be able to improve coastal area management, and advice on how to build in safer places, a better understanding is needed on causes leading to higher impacts of Tsunami wave. The wave energy is related to the duration and amount of water moved along the fault line, but how this energy is then transformed in water height, wave velocity or blocked by barrier must be explained by near-shore parameters. For example, impacts tend to be higher closer to origin of the tsunami (NOAA 2004), or linked with shape of bathymetry (water depth). The wave's height being related to change in water depth, while entering shallower zones, wave's velocity abruptly decreased shortening the wavelength and building wave in height (Nelson 2005).

If the geomorphological role in tsunami is well studied (Kowalik 2004, Mofjeld et al. 2000), less is known about the potential protective role of environmental features. Although several press releases stated that environment components played a major role in reducing the impacts from the tsunami (Khor 2005, Friend of the Earth 2005), no scientific study could be found on the subject.

To be able to advise the affected countries and to fill the knowledge gap on the role of ecosystems in protecting the coast from tsunami waves, UNEP decided to carry our this study. The study aim was to identify which configuration of geophysical and biological parameters were leading to lower or higher exposure to tsunamis hazards. To this extent, global data sets were used to provide a first cut off as well as identifying the key parameters that are link to higher exposure to tsunami. Thus leading to potential explanations on why areas (even close to each others) presented a significant discrepancy in the width of flooded land strip.

To assess the potential protective role of Mangroves, coral reef, sea grass and coastal vegetation, it is necessary to take into account the near-shore geomorphology. To this end data on bathymetry (water depth), orientation of the coast, land cover, length of proximal slope, distance to tectonic features, presence of coral, sea grass and mangroves were extracted using GIS technologies. Then the distance of impacts was evaluated either from available ground measures or by interpreted high-resolution satellite images. This was performed for 62 sites. Then multiple regressions were performed to identify the parameters that were best explaining the distance of impacts following a method already applied in previous researches (Peduzzi *et al.* 2002).

In order to assess the distance flooded, the research uses high-resolution satellite images and results from ground surveys. Since this study was initiated in February 2005 and completed in June 2005, only a limited amount of information was available, future researches will certainly benefit from more detailed information. The analysis on the role of near-shore geomorphology (such as slopes, water depth,…) is based mostly on global-level data sets and addresses only the 2004 Indian Ocean tsunami. The results provide an overall insight, given the local complexity of each site, further detailed studies should be made undertaken. It is likely that there will be much opportunity to examine local-level data sets, and to take a comparative approach to disasters, thereby progressively building up a more comprehensive understanding through the testing of hypotheses based on findings so far. Further analysis is needed, not only about tsunami protection, but on how coastal ecosystems contribute to the livelihood of local communities and on how to use ecosystem restoration as a means of environmental hazard reduction.

2 BUILDING AN INFORMATION SYSTEM

Much of the data acquisition benefits from data collected during the response phase from the GRID-Europe database and also from UNOSAT for the satellite images and World Conservation Monitoring Centre (WCMC) for the environmental features. All the data had to be downloaded through Internet and due to the files of high-resolution satellite images, this process took several hundreds hours.

To give a rough idea of the difficulty to deal with the extraordinary extent of the area impacted by the tsunami, the imagery data set contain more than 230 satellites images (600 Go downloaded).

Choice of study area

The selection of the sites was data driven. The availability of data has lead to a restriction in the study area.

The research was initiated in March 2005 and based on information available at this time. For instance, there was little material available for Seychelles, Yemen and Somalia. And none for Burma and Andaman. Hence why the sites selected for this sample were all located between Indonesia, Thailand, continental India, Sri Lanka and Maldives.

Based on availability of satellite imagery and field survey, 62 sites could be filled with all the information. The records are spread over all the sus-mentioned countries covering wide ranges of different configurations (distance from tectonic event, bathymetry, as well as environment parameters.

The Figure 1 shows the distribution of sites through the study area which lie between

Longitude : 72°E and 100°E and
Latitude : 2°S and 24°N

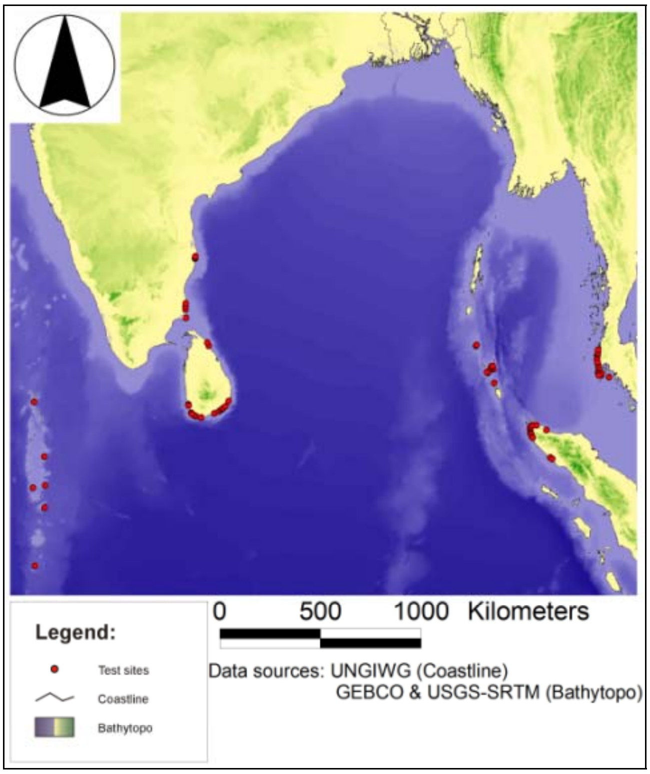

Figure 1: Test sites location

The difficulty with such a large extent in study area is aggravated by the need of precise data sets. In this respect this tsunami is the largest hazardous event ever recorded, not only from the magnitude of the human and economical impacts, but with respect to how these impacts are stretched over thousands of kilometres.

Data for assessing the distance of impact

The tsunami impact has been determined using the maximal flooded distance in a given area. This information was determined using several types of data.

Distance of impacts from remote sensing method

Interpreted images show the extension of the area flooded by the tsunami. Two kinds of interpreted images are available on-line, the first shows the potential inundated area and is based on a Digital Elevation Model (DEM) and images pre-tsunami. The second type shows the real inundated area comparing pre and post tsunami of one area.

Only interpreted images from the second type were used in this study as the focusing was on the real impacts of the tsunami. The Table 1 presents the sources used.

Table 1: Interpreted images sources

Provider	Data source
UNEP/DEWA/GRID-Europe	http://www.grid.unep.ch/activities/assessment/indianocean_crisis/index.php
UNOSAT	http://unosat.web.cern.ch/unosat/asp/charter.asp?id=55
UNEP-WCMC imaps viewer	http://tsunami.unep-wcmc.org/imaps/tsunami/viewer.htm
DLR- Centre for Satellite Based Crisis Information (ZKI)	http://www.zki.caf.dlr.de/applications/2004/indian_ocean/indian_ocean_2004_en.html
Service Regional de traitement d'image et de teledetection (SERTIT)	http://sertit.u-strasbg.fr/documents/asie/asia_en.html

In order to increase the test sites panel, pre and post tsunami satellite imagery has been downloaded from the UNOSAT and USGS websites (see Table 2). Pre-tsunami satellite images have also been downloaded from GLCF website (see Table 2) and have been used as georeferences.

Table 2: Satellite images sources

Provider	Data source
UNOSAT	http://unosat.web.cern.ch/unosat/asp/charter.asp?id=55
USGS tsunami disaster website	Restricted area
Global Land Cover Facility (GLCF) – ESDI	http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp

Distance of impacts from field survey

The impact data set was completed by field surveys reports available on-line in the Research Centre for Disaster Reduction Systems (DRS) Disaster Prevention Research Institute (DPRI) of the Kyoto University. The aim of those surveys was to evaluate the tsunami run up from clear landmark, then location available do not specifically correspond to the maximal extent of the flooded land strip.

Mixing these two types of inputs ensured a larger sample but might introduce a bias, since the maximum wave height cannot be estimated from the satellite images and the maximum distance of impacts is not necessarily reflected by the location where maximum wave height was measured. Since the information on how the distance was collected is kept, it will always be possible to see if the different sources are playing a role in the analysis.

Data for extracting potential parameters related to distance of impacts

Two approaches were followed for the selection of parameters. The first one founded on studies on the role of geomorphology on tsunami. Kowalik (2003) modelled tsunami propagation in presence or escarpment. Mofjeld et al. (2000) studied the interaction of tsunami waves with small-scale, submarine topography. It appears that *"the most important factor* (…) *is the depth of a feature compared with the depth of the surrounding region*". Consequently parameters have been chosen in order to characterise the near shore bathymetry changes.

The second approach is less documented and more empirical, it consists to collect a wide range of geographical and environmental parameters having potentially an effect on tsunami propagation.

The parameters were extracted from a wide range of sources (see Table 3). Data on location of epicentres coordinates, fault lines, level of elevation, information on coastlines, land cover, distribution of coral, mangroves and sea grass. Most of the geomorphologic parameters, however, were obtained by computation and transformation of bathymetry, thus providing information on slopes and depth.

Table 3 Data sources and providers

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	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	Joint Research Centres and related collaborators	http://www-gvm.jrc.it/glc2000
Coral distribution	UNEP World Conservation Monitoring Centre (WCMC)	http://www.unep-wcmc.org
Mangroves distribution	UNEP World Conservation Monitoring Centre (WCMC)	http://www.unep-wcmc.org
sea grass distribution	UNEP World Conservation Monitoring Centre (WCMC)	http://www.unep-wcmc.org

3 METHODOLOGY

Choice of variables

The aim of the study was to assess what parameters are leading to higher impacts from the tsunami and if environmental parameters are playing a role. Impacts from tsunami are derived from the energy from two types of characteristics: wave height and speed. Several hypotheses were made to assess what type of geomorphology of coastal zone could be best linked with distance of impacts. The distance from the event, the angle of the waves with the coastline, the shore elevation, depth at different distance (also approached by slope), the presence of coral, mangroves, sea grass and/or coastal vegetation. The data were extracted using different GIS methods as described in the following part.

Data transformation and preparation

Once all data have been downloaded, a long and bothering process has been necessary in order to integrate them in a homogeneous and robust GIS. The following chapters describe broadly the main steps of the processes applied.

Conversions to standards formats

The aim of this process was to convert in GIS standard formats the data imported from different sources in various formats as well as to convert classified data into cardinal values in order to allows their integration in the multiple regression process (see the land cover example in Table 4).

Table 4 Land cover resistance-roughness cardinal index

Legend	Resistance index
Herbaceous Cover, closed-open	1
Bare Areas	1
Water Bodies	1
Snow and Ice	1
Shrub Cover, closed-open, evergreen	2
Shrub Cover, closed-open, deciduous	2
Sparse herbaceous or sparse shrub cover	2
Regularly flooded shrub and/or herbaceous cover	2
Cultivated and managed areas	2
Mosaic: Cropland / Shrub and/or grass cover	2
Tree Cover, burnt	3
Mosaic: Cropland / Tree Cover / Other natural vegetation	3
Tree cover, regularly flooded, fresh water	4
Tree cover, regularly flooded saline water	4
Mosaic: Tree Cover / Other natural vegetation	4
Tree cover, broad-leaved, evergreen	5
Tree cover, broad-leaved, deciduous closed	5
Tree cover, broad-leaved, deciduous, open	5
Tree cover needle-leaved, evergreen	5
Tree cover needle-leaved, deciduous	5
Tree cover, mixed leaf type	5
Artificial surfaces and associated areas	6
No data	23

A significant task data preparation was to merge the SRTM DEM (digital model of the earth surface at a resolution of around 90 meter) and the GEBCO bathymetric data set (digital model of the under water topography as well as the land topography at a resolution of around 1.85 km) in order to draw profile from land into ocean. Needing a strong overlay precision as well as hole filling process (area under zero in land, or above zero in the ocean).

Data extraction

Once all data have been processed they have been clipped to the area of interest (which mean the unnecessary information has been removed). Reducing as much as possible the GIS size in order to speed the model processing as well as facilitate the GIS storage and diffusion.

As satellite imagery is usually projected and the others data are not, it was necessary to create one view per zone projected in the different Universal Transverse Mercator (UTM) projection, clip and re-project all data for each view.

Georeferencing

Another significant step of the data preparation consisted in manually geo-referencing each interpreted image using landmarks on already registered satellite images or graticules.

Field measurements done by DRS-DPRI were geo-referenced using the Ground Positioning System (GPS) coordinates available.

Several modifications were necessary to correct shift between different data sets in some areas. This requested manual intervention to guarantee the homogeneity when extracting the parameters.

Extracting Information using GIS

Identification of test sites

The test sites were determined in a first instance by the availability of interpreted images. If the interpretation of area presenting large tsunami impacts was easily carried out, area with smaller impacts request much more complex and precise interpretation, which was too time consuming to be performed during this two month analysis. Thus images availability is proportional with the impact of the tsunami, the test sites are more representatives of large impacts then small ones.

Amongst the sites available, a sample representing as many different combinations of geomorphologic and environmental parameters was chosen. However, geographic selection was done under the strong constrain of pre and post-tsunami images availability. For example it was impossible to use Andaman Islands as test site since no images were available for this area.

Extraction of the distance of impacts

Due to the coarse resolution of the bathymetric layer (1 minute or around 1.85 km in the studied area), this is the maximal flooding distance of each test site that was measured manually perpendicularly to the coast (from 15 to few kilometres). As a consequence the model will be representative of the potential maximal flooded distance should the coast be exposed. It can be seen as a vulnerability of the coast, to be completed the model should be crossed with a model of exposure.

In few sites were satellite imagery was not available, the maximal distance recorded by DRS-DPRI field team was used. But as their objective was to measure the wave maximal run up on the base of clear filed landmarks, their data have to be used cautiously in our study, as they do not systematically represent the maximal flooding distance.

Computing the distance from tectonic features

Several types of distance were extracted and tested during the multiple regression process: distance from main earthquake, distance from the area of tectonic activity (including replicas) and distance from the active subduction fault.

Data acquisition was easily performed, by creating buffers and acquiring the buffer's values on test site location.

Measuring coastline angle with tsunami wave

This parameter measures the angle between the tsunami wave energy and the coast. More specifically to indicate if the coastline was exposed directly to the wave or indirectly because on the backside of an island or a peninsula. Measurement range from 0 to 90 degrees under direct exposition, and then from 90 to 180 degrees under indirect exposition (see Figure 2).

Measurement were performed manually on screen.

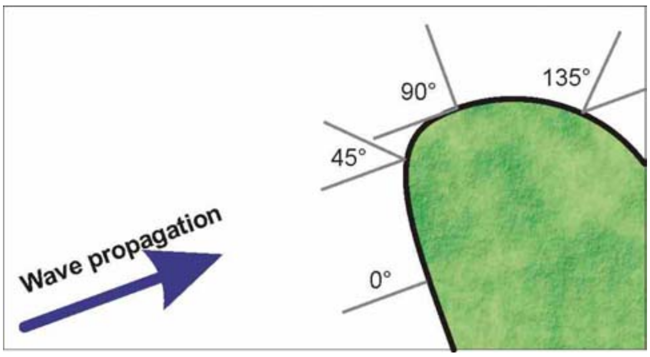

Figure 2 Coastline orientation

Measuring coastal elevation

The measures were made according to two thresholds in order to estimate average slope to an altitude of respectively 5 and 30 meters. The acquisition of data was made manually after the automatic identification of sites located at less than 5 and 30 metres elevation.

Measuring bathymetry characteristics

Many parameters were extracted from bathymetry following two principles: the depth at a given distance from the coast and the near shore morphology. It was necessary to draw in each test site a profile oriented perpendicularly to the coast and export it as Excel table.

Depth at a given distance from the coast

From the profile, the depth at several distances (500 m, 1, 2.5, 5, 10, 20, 25, 30, 40 and 50 km) from the coast has been extracted. In order to avoid local irregularities, the depth has been averaged using the neighbouring values.

Near-shore morphology

Several parameters have been extracted (see Figure 3):

- Length and slope of the proximal slope,
- Length and slope of the distal slope.

Slopes break localisation has been done visually on profiles graphs and values extracted from the Excel file.

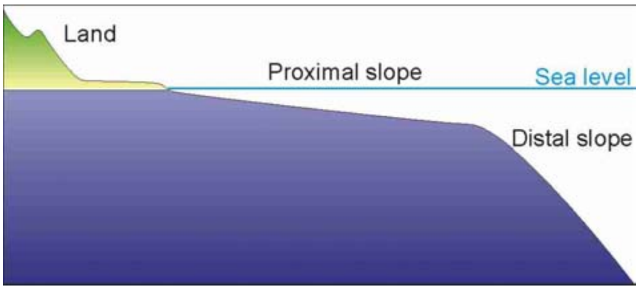

Figure 3 Relief terminology

Extracting environmental characteristics

The goal of parameters derived from environmental characteristics is to estimate the percentage of protection by a natural given barrier for each test site.

Several types of natural barriers have been used: coral reef, mangrove, sea grass.

Data extraction has been done manually following the visual rule demonstrated in Figure 4.

It as to be noticed that due to the shape and the resolution of the different data set the range of values differs depending on the data set.

For coral reef protection the values vary regularly from 0 to 100% as shape are very thin and elongated along the coast.

Concerning the Sea grass, values are mainly 0 or 100% rarely 50%, as the data set seems to have been acquired at higher resolution it is generally present or absent.

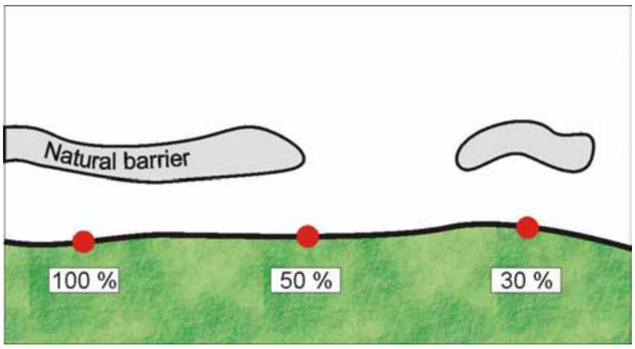

Figure 4 Natural protection estimation

For the mangrove, no patches of mangrove could be found on open sea, the reason and more details will be discussed in Chapter 4 Results & Discussion.

Land cover has also been assumed as a natural barrier (see Table 4). Data were collected using and a resistance-roughness index was associated to each type of vegetation.

Statistical analysis for Identification of Predominant Parameters

Following precedent methodology applied to other types of natural hazards in previous studies (Peduzzi *et al*. 2002, Dao & Peduzzi 2004), the 37 parameters extracted using GIS tools were introduced into a database (see Table 8 for details). The natural logarithm of the values was then computed. After studying the correlations between the variables, they were grouped in different sets for conducting multiple regressions with the *distance of impacts* as dependant variable.

Identification of parameters

Several hypotheses were made around the combination of geophysical context mixed with environmental features. After performing a multiple regression analysis, the parameters are retained when both the p-value is smaller (and preferably much smaller) than 0.05 and when the adj. R^2 is the highest.

Creating categories of impacts

Due to the use of logarithmic regressions, a significant margin of error is expected. The distance of impacts will not be expressed in metres, but by classes of expected impacts. A "*Cluster analysis*" has been performed in order to minimise intra-class distance and maximise extra-class distances. Post error estimation is performed by comparing the measured category with the modelled values.

Modelling for identification of safest coastlines

Once the statistical model identified, it can be extrapolated to other areas where distances could not be observed in order to provide insight of most to least vulnerable coast and to help prioritisation for the collection of more detailed data.

Extracting data for modelling

In order to feed the model, the coastline was converted to a succession of points spaced of 0.25 minute (approximately 450 metres in the study area). Then all retained parameters were automatically acquired for each point.

A protocol composed of seven parts was created. It mostly refers to functionality already available in the GIS software *ArcView*, or available as downloadable extension on the *ESRI* website (Dao 2004), however one functionality was specifically developed by GRID-Europe for this purpose.

The protocol can be resume as follows:

- Preparation of a coastline point layer that will receive the parameter's information,
- the depth value is collected at 10 km of the coast translating the points perpendicularly to the coast,
- then it is checked in which extent the coast is protected, using the rectangle buffer tool developed by GRID_Europe,
- using the same tool the percentage of coral protection is estimated,
- due to the big extension of the patch of sea grass and their proximity to coastline the patches are expanded of 2 pixels (around 400 meters) and the presence or absence of sea grass is recorded,
- the distance from tectonic fault (DFF) as well as the length of the proximal slope (Lengprox) are acquired simply by recording the values of their buffer,
- Finally the length of the proximal slope is detected in order to check if the point is within the domain of validity of the model. If not the point is not used in the model.

4 RESULTS & DISCUSSION

Statistical results

The regression analysis identified correlation between combinations of parameters, which in a certain configuration lead to a longer or shorter distance of impacts. The main parameters identified are linked with the distance from the tectonic origin (subduction fault line), the near-shore geomorphology “average depth at 10 km” and the length of proximal slope, but also with environmental features, as “percentage of Coral” and “percentage of Sea grass”.

The analysis was performed over 56 sites. A correlation coefficient of 0.81 was obtained with an R^2 equal to 0.655, indicating that about 65,5% of the variance is explained by the model.

This being a logarithmic regression would lead to a large error if used directly to model the expected distance. As a consequence, only classes of magnitude can be derived from such analysis.

The distribution shows several gaps, this is due to the significance of the variable “*distance from* fault line”. Countries being located at different range of distance from the fault lines (Indonesia and Andaman being the closest, Maldives the further away).

Figure 5 Distance of impacts: predicted vs. observed

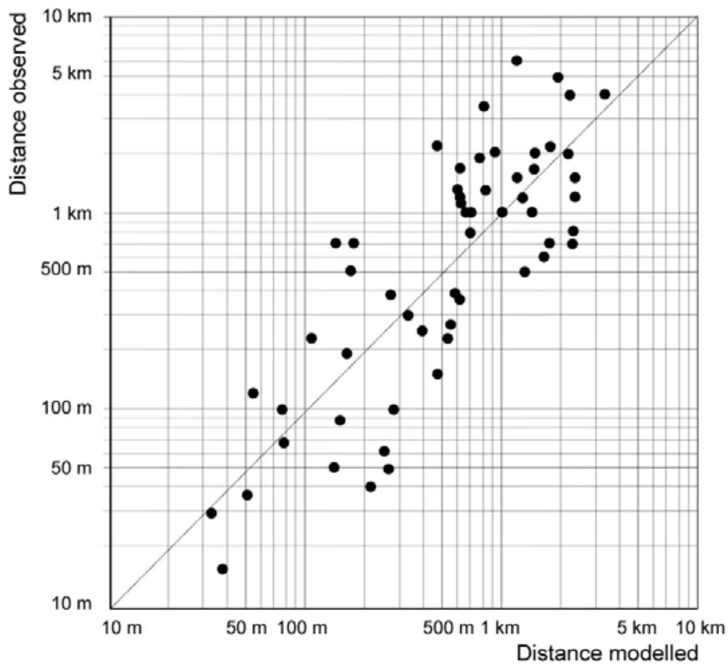

Table 5 Variables selected, weight and respective p-level.

R = 0.809, R^2 = 0.655, Adj. R^2= 0.621, N = 56 sites

Variables	B	p-level[1]
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

Where:

LnCoral = *Ln (%age of Coral*)*
LnSeag = *Ln (%age of Sea grass*)*
LnLengprox = *Ln (length of proximal slope)*
LnAv10Km = *Ln (Average depth at 10 km)*
LnDFF = *Ln (Distance from fault line)*

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

Equation 1: Model for Distance of Impacts

$$D = \exp[0.16 \cdot LnCoral - 0.13 \cdot LnSeag + 0.64 \cdot LnLengprox - 0.31 \cdot LnAv10Km - 0.83 \cdot LnDFF + 8.7]$$

Where D = expected distance of impacts should the coast be exposed to a tsunami of similar magnitude.

Outliers

The outliers are located in Maldives (1), Thailand (1) Indonesia (1) and Sri Lanka (3). These are believed to be the result from particular geomorphologic conditions that does not fit the model constrains, as well as the difference method to assess the distance.

The three under estimated sites are all located in Sri Lanka, distances assessed are all confirmed by clear landmarks (field measurement, affected airport and settlement). Particular geomorphologic conditions not taken into account in the model are probably the reason.

The three over-estimated sites had their distance assessed by satellite images (Thailand and Indonesia) and by field measure (Maldives). Both sites assessed by satellite imagery have been clearly identified as outliers in any configuration of the multiple regressions, probably due to the difficulty to visually determine distance on area with a small impact.

The last point has been taken by field team looking at clear landmarks able to attest of the water run up. As a consequence it does not represent the maximal flooding distance, but simply confirm the water reach at least this point.

Classifying safety

A cluster analysis was run on the test sites using the classificator tool (Dao 2004) and the following thresholds were identified and adapted in order to gain in understanding (see Table 6).

Table 6 Threshold of safety classes

Categories (impact)	Selected ranges [in metres]	Rounded range [in meters]
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

Applying the previous classification on the model as well as the test sites it is possible to estimate the error on categories, comparing the measured category with the categories of the surrounding modelled point.

Table 7 Error on categories

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	

The Table 7 shows the result of such comparison. Seen at regional scale, it appears that for 89 % of the tested sites the model is valid within a range of plus or minus one category. Seen at local level the model tend to underestimate the impact for all sites except for the Thailand where the impact is clearly overestimated. Likely because of the geomorphological complexity of the proximal slope which is not taken into account in the model and which probably strongly decrease the energy of the tsunami in reality.

Classes of potential impact under different exposure assumptions

Before going further, it is important to remember that the model developed during this 2 months study estimates the potential impact in case the 26th December 2004 tsunami hit a coastline of the West Indian Ocean. And to realize, that before to draw any map of risk it is imperative to combine the present study with a model of exposition, able to determine which parts of the coast are affected according to the tsunami energy propagation. Due to the short duration of the study and as it was not the main purpose, such model still remains to be developed.

The Figure 6 shows four examples of potential impact modelling in the North Indian Ocean. The same scale as well as the same legend was used in order to ease comparisons. It has to be noticed that in order to substitute the propagation model, coastline points which were clearly outside of the model validity or on obvious protected areas were not modelled. Moreover others unclear regions as for example the area located East of Phuket island and protected by it has been signalled as "*incomplete model*", study of such area should be completed integrating an exposition model.

Even if each of the presented examples is issued from the same process, each one presents some specificity that will be discussed in the following paragraphs.

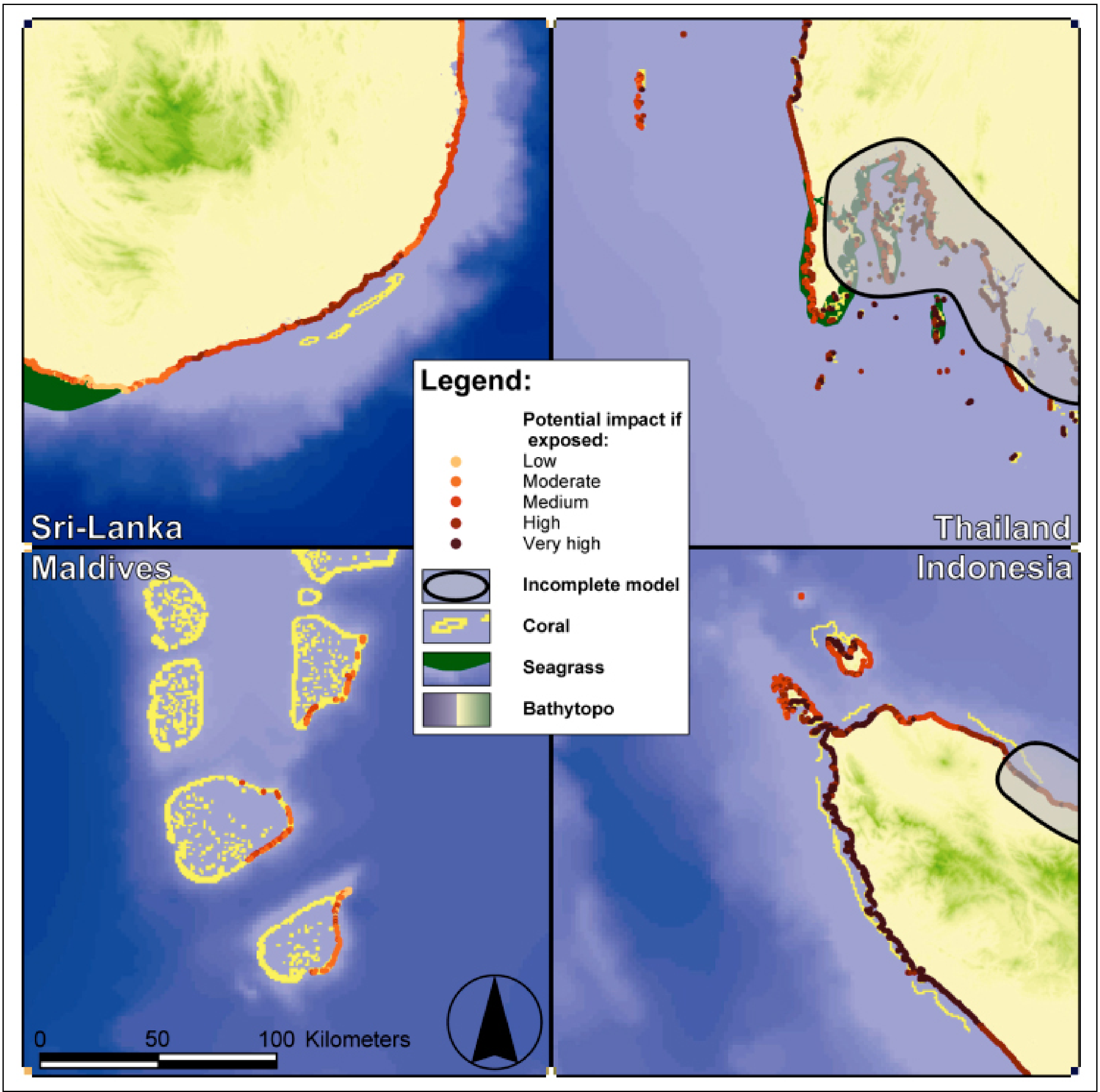

Figure 6 Examples of potential impact modelling in the North Indian Ocean

Sri-Lanka

The Sri-Lanka example is located on the south-eastern coast of the country. The regular morphology of the coastline did not present any difficulties during processing. The selected area include all levels of potential impact ranging from "low" with a short proximal slope and a coast protected by sea grass in the West, then increasing Eastern with the increasing of the length of the proximal slope. The maximal potential impact "very high" being obtained in presence of coral reef, followed by a quick decrease of the potential impact level with the end of the coral and the sharp decreasing of the proximal slope.

Maldives

The Maldives example shows the potential impact on the exposed side of the atolls of Hadhdunmathee, Kolhumadulu and Mulaku. The small size of the islands and the complex morphology of the atolls combine several difficulties during the process as well as during the validation of the model.

In fact, if the automatic acquisition of the parameters is working very well with large land bodies where the end users can visually average the potential impact of one area with the neighbouring points. Such auto-weighting is not possible on small island visualized by few points.

As numerous islands are disseminated in an area, the automatic procedure to check if a coastline is protected from the tsunami impact remains uncertain. Even more depending on the position of the island on the atoll (external / internal part, east or west) the coastline will be differently affected by the tsunami.

As a consequence only clearly affected coast (external part of the external island on the eastern side of the atolls) have been retained in the example. A better understanding of such complex context may still be difficult to achieve even combined with a regional exposition model, and may be studied as a specific case.

Indonesia

The main impact raised in the North-western part of Sumatra, where the model shows high levels of potential impact on the highly affected coastline of Banda-Aceh and Labuhan.

The North-eastern coast of the presented area has been drawn as "unexposed area ?" because the low bathymetry in the strait of Malacca between Sumatra and Malaysia does not fit the model constrains (proximal followed by a distal slope). Even more the exposition model should confirm the tsunami does not affect the area.

Thailand

The example shows the surrounding Phuket area severely hit by the tsunami, even if this area has been laborious to process and remains difficult to validate for the following reasons:

- The complex shape of the coastline prevents from determining which parts are affected by the tsunami. Such uncertainty should be resolved by the development of a propagation model. For the time being such kind of area has been draw as "*incomplete model*".
- The exceptionally long proximal slope in some areas (> 100 km) reaches the limits of the model (maximal length on test site 95 km). Moreover the complex topography of the proximal slope with mound and island just before the slope break. Make the validation of such area uncertain. This point being confirmed by the error analysis on previous chapter, were the Thailand area is the only one that tend to be overestimated.

Discussion

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, can result in drastically different wavelength. The factors identified as linked with the distance of impacts can be classified in three categories: Distance, geomorphology and environmental parameters.

Distance from the event

The negative sign before the coefficient delineate that the closer from the fault line, the longer the distance of impact. 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 2004).

Geomorphology of near-shore

The *average depth at 10 km* is related to the average slope of the water floor. A steep slope is known for blocking the energy of a tsunami, whereas a "flatter" slope is more dangerous as it helps to build a higher wave. A higher 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 then also consistent with the theory.

The positive sign preceding the coefficient relative to the *length of the proximal slope* means that a longer proximal plate is leading to a longer distance of impacts. 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 is preceding the coast.

Environmental parameters

As always the environmental components are less studied and it is difficult to find studies in the scientific literature. *Sea grass* (or sea grass substrata) have a positive role in absorbing the energy of tidal wave, the negative sign indicating that the higher the percentage of sea grass, the shorter the distance of impacts. From such statistical analysis it is impossible to differentiate if the presence of sea grass have a mechanical influence that absorb the energy of the waves or if the area that sea grass usually colonise is already protected from the wave. The result, however, was that behind areas covered by sea grass the distance of impact was in majority shorter than in other areas.

A positive sign precedes the *percentage of coral*, this is surprising and not consistent with what was expected. Usually the lagoon of an atoll protected by a coral reef, has more quiet water than outside the reef. The coral helping in breaking the waves, except in the passes, where strong and dangerous currents are recorded. As for the sea grass, it is impossible through this analysis, to differentiate if the positive coefficient is associated to the presence of coral or with the topography of area where coral is located. However, areas colonised by coral are usually shallower, it is possible that if coral are breaking the usual waves, a more significant wave might not be stopped but continue to build on such shallow area. Nothing in the literature could be found and this would request in-situ analysis or mathematical simulation. In the mean time and in absence of further research, the result tends to indicate that it would not be wise to rebuilt in coast close to coral reefs.

The case of mangroves

The mangroves were said to help reduce the impacts of the tsunami. If by common sense we can indeed conceive that a barrier of vegetation with a complex root system can offer protection, during the present study, it was impossible to find patches of mangroves located on coast on direct open sea by looking at both WCMC data set and satellite imagery. They were all present in estuary, areas sheltered by stretch of coastline or in protected bay. This was confirmed by the literature "*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*." (DIPE 2002) . In such case the only objective answer was that areas covered by mangroves were less impacted by tsunami because mangroves communities tend to be located within sheltered coastal areas.

This is not to deny positive role of mangroves: mangroves have a role in filter land run-off (Thom 1967), and reduce 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 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 has helped reduce the cost of dyke maintenance by $7.3m per year for an investment of 1.1 m (IFRC 2002).

But the true reason why mangroves should be protected in the interest of local populations, is because the area where fish are spawning, mangrove restoration provide employment to local population, protect fragile tropical coastlines and perhaps also to enhance biodiversity and fisheries productivity (Kairo et al. 2001). The livelihood of populations living in the coastal area is mostly based on fishing, tourism and aquacultures. The challenge while rebuilding after the tsunami would be to quickly restore this livelihood, while preserving these three activities. The role of mangroves in the ecosystems and in the regeneration of fish should be taken into account in the new coastal management. However, litterature suggested that mangroves planted in open sea have limited chance to take root: "*Mangroves have also died because of natural disaster*" (Jimenez 1985). "*Special attention must be paid to tidal and wave energy*" (Lewis 1992, Field 1996). "*The necessary protection to allow mangroves to grow on the exposed coastal line is usually due to favourable local current conditions or else, more often, by a barrier reef or by one or more islands protecting the coast from the ocean winds and waves*". (see http://www.specola.unifi.it/mangroves/intro/Intronew.htm).

Figure 7 depicts that location where mangroves could be found are only in sheltered areas.

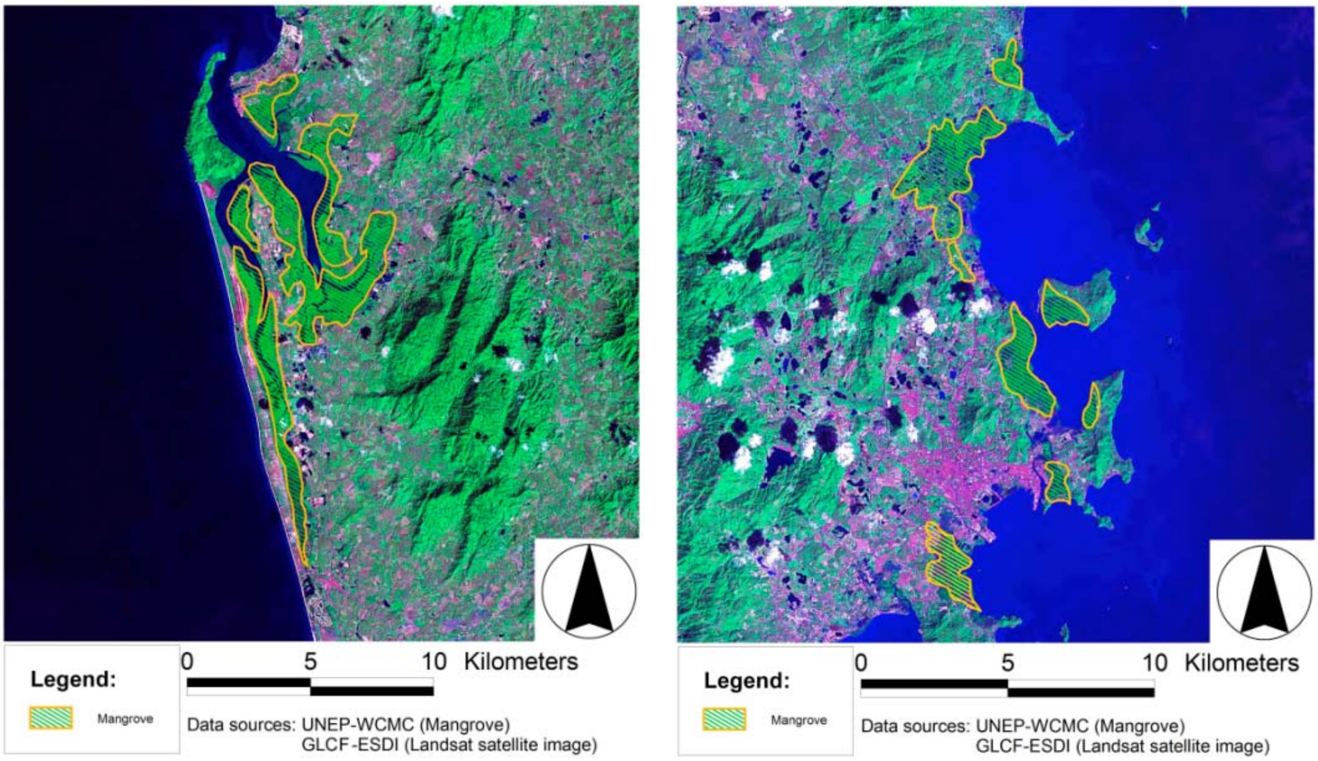

Figure 7: Mangrove location

a) Phangnga province (Thailand). b) Phuket province (Thailand).

5 CONCLUSION

The method proved successful in linking contextual parameters with recorded length of inland impacts. The model could be extrapolated to the whole area to provide five classes of exposure to the tsunami, thus easing the prioritisation of data collection during coastal management and rebuilding procedures. This method was applied to identify vulnerability of exposed coastline depending on the presence or absence of sea grass and coral, distance from event, length of proximal slope as well as depth at ten kilometres from the shore. However, the likelihood of being exposed was not part of the model. This means that the model depicts the expected level of impacts should the coast be exposed, equivalent to the vulnerability of the coast. A propagation model for identifying the exposure of the coast would also be needed.

The geomorphological parameters are consistent with theory, while the environmental parameters show more surprising results. The findings should be used with caution, as the study was done using global data sets. The coarse resolution of bathymetry data might not capture the complexity of the coastline at a detailed scale. Furthermore, this analysis was done on a single event, the tsunami of 26 December 2004. Different magnitude and origin of a future tsunami could result in a drastically different wavelength.

On the question of whether biological features offer protection from tsunami impacts, the answer varies by type of environmental features.

Remaining mangroves were only identified in sheltered areas. In the observed cases, it is therefore difficult to distinguish if the area shielded by mangroves suffered less impact because of the presence of mangroves, or because they were sheltered by the coastline or other physical factors. This is not to say that mangroves cannot protect coastlines. Literature suggests that mangroves do not survive in areas where waves are too active and thus replanting mangroves should only be done in areas suitable for mangroves. It would be interesting to conduct another analysis comparing areas previously covered by mangroves, with areas still covered by mangroves, but taking into account the bathymetry as it was done in from this study. Mangroves were found to be useful in protecting from erosion, as well as reducing the costs of dike maintenance in hurricane-prone areas.

Areas where corals grow are generally shallow waters with gentle slopes, and both these geomorphological criteria have an effect on tsunami waves. Although coral reefs are known to protect against waves in the case of tropical cyclones, storms and other windy conditions, the findings of this study suggest that this is not the case for tsunami waves. This can be explained by the fact that the wavelength of tsunami waves are about 1000 times longer than other kinds of waves, and their behaviour is very different.

The statistical model shows lesser impacts in areas located behind sea grass. This could be for two reasons: either because of the mechanical role of sea grasses in acting as a smooth filter that helps reduce the energy of the wave, or because sea grass beds are located in areas where the configuration of bathymetry is not favourable for building high waves. The reason remains unexplained, but the correlation with reduced impact is significant.

This study offers early but potentially meaningful guidance on the role of ecosystems in protecting the coastal areas, and further speaks for the sensible use of coastal areas. However, there is a need to continue the analyses, to collect more data, and to combine the analyses with modelling and field studies. Further studies would help to guide on-going restoration and rehabilitation activities in countries affected by the Indian Ocean Tsunami, while also offering concrete recommendations for preventative and risk reduction work in all areas at risk from tsunamis.

UNEP, the 20th of June 2005

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7 APPENDIXES

Table 8 List of parameters computed or extracted

Abbreviation	Description	Units
DFS	Distance from source	Kilometres
LDCOV	Land cover resistance index	Cardinal values 1 to 6
ORIENT	Orientation between the tsunami energy and a perpendicular to the coast	Degrees
COSORIEN	Cosinus of orientation	Scalar
CORAL	Percentage of protection from coral preceding the site	%age
MANG	Percentage of protection from mangroves preceding the site	%age
SEAG	Percentage of protection from Sea grass preceding the site	%age
LENGPROX	Length of proximal slope	Metres
SLPROX	Angle of Proximal slope	Degree
PCSLPROX	Angle of Proximal slope	%age
LENGDIST	Length of distal slope	Kilometres
SLDIST	Angle of Distal slope	Degree
PCSLDIST	Angle of Distal slope	%age
LDTO10M	Average slope until an inland height of 10 meters	Degree
PCLDTO10	Average slope until an inland height of 10 meters	%age
LDTO30M	Average slope until an inland height of 30 meters	Degree
PCLDTO30	Average slope until an inland height of 30 meters	%age
AV1KM	Average slope until 1 km	Degrees
PCAV1KM	Average slope until 1 km	%age
AV2_5KM	Average slope until 2.5 km	Degrees
PCAV2_5K	Average slope until 2.5 km	%age
AV5KM	Average slope until 5 km	Degrees
PCAV5KM	Average slope until 5 km	%age
AV10KM	Average slope until 10 km	Degrees
PCAV10KM	Average slope until 10 km	%age
AV20KM	Average slope until 20 km	Degrees
PCAV20KM	Average slope until 20 km	%age
AV25KM	Average slope until 25 km	Degrees
PCAV25KM	Average slope until 25 km	%age
AV30KM	Average slope until 30 km	Degrees
PCAV30KM	Average slope until 30 km	%age
AV50KM	Average slope until 50 km	Degrees
PCAV50KM	Average slope until 50 km	%age
DIST	Distance of Impacts	Metres
PCAV500M	Average slope until 5 km	%age
PCAV40KM	Average slope until 40 km	%age
DFF	Distance from subduction fault	Kilometres
DFEQ	Distance from main earthquake	Kilometres