Modelling ecological and other risk factors influencing the outcome of the 2004 tsunami in Sri Lanka

A. J. Venkatachalam, J. Kaler, and A. R. G. Price

School of Life Sciences, University of Warwick, Coventry CV4 7AL United Kingdom
The School of Veterinary Medicine and Science, University of Nottingham, Sutton Bonington LE12 5RD United Kingdom
Environment Department, University of York, York YO10 5DD United Kingdom

Abstract. The 2004 Asian tsunami caused widespread devastation across the Indian Ocean. Damage from the waves was influenced by complex interplay of many factors. Using regression models incorporating different impact indicators (occurrence of inundation, inundation distance, and human deaths), we examined factors that significantly influenced tsunami damage in southern Sri Lanka. Land elevation (which is positively correlated with forest presence), sand dunes and coastal convexity (which deflects waves), were protective factors, in terms of whether the tsunami wave inundated within an arbitrary distance of 15 m inland. Water bodies, saltwells and built-up areas (e.g., roads, development) increased wave inundation distance, while beaches and sand dunes were ameliorative. Built-up areas also increased death toll. Bathymetry, a proxy for wave height and force, was the only significant factor in all three multivariable models. Coastal areas with a steeper seaward bathymetric slope gradient were less prone to inundation and human fatalities, which is consistent other tsunami research. The presence of coral reefs was highly correlated with bathymetric slope gradient, implying a potentially protective role by coral reefs. Many factors showing greatest protective effect against tsunami damage are geographical features that cannot easily be modified. However, some defence factors identified, such as sand dunes, could potentially be protected. Given the wide-ranging ecosystem services, unrelated to tsunami protection, ongoing loss/degradation of natural systems including mangroves (not a significant factor in the multivariable models), could be damaging. This might impede certain future coastal development options in post-tsunami Sri Lanka.

Key words: 2004 tsunami; coastal protection; disaster mitigation; regression models; risk factors; Sri Lanka.

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† E-mail: andrew.price@warwick.ac.uk

INTRODUCTION

The 2004 tsunami caused devastation throughout the Indian Ocean, affecting 19 countries. In Sri Lanka 13 of 14 coastal districts were impacted, death tolls exceeded 31,000 and over 443,000 people were displaced (DCS 2004, Asian Development Bank et al. 2005). Economic loss and damage was estimated at US $1 billion by the World Bank (de Silva et al. 2005). While damage resulting from the tsunami wave is well documented, many factors influenced the outcome and knowledge is still incomplete or controversial.

Much has been reported on the ability of natural systems to provide shoreline protection, both in Sri Lanka (Brown 1997, IUCN 2006a) and globally (Mazda et al. 1997, Harada et al. 2002, 2006a).
According to early eye-witness accounts and rapid assessment, natural systems, including mangroves, coral reefs and sand dunes, helped reduce damage through dissipation of wave energy, absorption of tsunami waters and by acting as physical barriers (Atapattu and Tharme 2005, Bambaradeniya et al. 2005, IUCN 2005, Kar and Kar 2005, Wabnitz et al. 2005). Post-tsunami field studies have supported these accounts, suggesting that villages behind coastal systems (i.e., mangroves, reefs and dunes) were better protected than those in more exposed locations (Danielsen et al. 2005, Kathiresan and Rajendran 2005, Chang et al. 2006, Ranasinghe and Kallesoe 2006) and that the aerial root system of mangroves increased drag force and trapped floating objects (Tanaka et al. 2007). Additionally, simulated experiments and some theoretical models have concluded a protective value for coastal forests (Harada et al. 2002, Irtem et al. 2009). Other research, however, suggests that the protective role of natural systems has been overstated, attributing variation in tsunami impact to elevation, exposure and distance inland (Dahdouh-Guebas et al. 2006, Kerr et al. 2006, Kerr and Baird 2006, Kerr and Baird 2007, Baird and Kerr 2008, Feagin et al. 2010). Studies claiming the protective role of coral reefs (Fernando and McCulley 2005) and mangroves (Dahdouh-Guebas et al. 2005) have been criticised for not including these or other potential confounding factors (Baird et al. 2005, Baird 2006, Feagin et al. 2010). Initial statistical modelling considering the effects of various risk factors on tsunami inundation distance identified bathymetric features, elevation and seagrass as important determinants of protection (Chatenoux and Peduzzi 2005), whereas coral reefs were identified as exacerbating impact. Mangroves occurred only in sheltered bays and their protective role could not be easily determined. Landscape analysis assessing the vulnerability of the Aceh coastline of Sumatra coastline provided further evidence for distance from the shore and elevation as important tsunami risk factors, but also identified vegetation type as an important factor. Developed areas sustained greater damage than forested zones (Iverson and Prasad 2007, 2008). Similarly, research between sites of comparable dimensions (considering bathymetry, coastline and exposure), but of differing vegetation, concluded that villages behind mangroves were damaged less than more exposed locations (Chang et al. 2006).

Several post-tsunami research papers have therefore recommended the implementation of bioshields (Osti et al. 2009, Tanaka et al. 2009) and projects involving restoration and plantation of mangroves with the expectation of improved shoreline protection have been implemented (IUCN 2006b). Projects have been openly opposed by local fishing communities and researchers (Rodriguez et al. 2008) due to fears that other important natural systems such as sand dunes, which may have afforded physical protection against the tsunami wave, were being used as sites for revegetation (Bhalla 2007).

Policies in Sri Lanka implemented immediately after the 2004 tsunami also promoted relocation of communities on the coast inland, in favour of a setback zone, to help safeguard critical systems (CCD 2005, Wong 2009). Although later revoked, some communities had already been relocated with severe social and economic impact (Harris 2005, Leckie 2005, Rice 2005).

This study contributes to a larger investigation into 2004 tsunami impact within Hambantota, Sri Lanka. Our initial research, involving a questionnaire survey of 500 local fishers, identified mangroves, coral reefs and sand dunes as factors perceived to be important in reducing death toll and housing damage (67–94% of respondents) (Venkatachalam et al. 2009). Using statistical models, this study further explores this and has two main aims. First, we determine the degree to which potential factors, in terms of the above and other natural systems, as well as land use/development (e.g., built-up town centres, residential housing, roads), influenced tsunami damage. This is based upon models using data on human deaths and tsunami inundation (in terms of both presence and distance). Second, we compare our findings with existing modelling studies, based upon inundation distance of the tsunami wave as the measure of impact (Adams et al. 2005, Chatenoux and Peduzzi 2005, Chang et al. 2006, Iverson and Prasad 2007).
concludes by considering the relevance of tsunami-related issues and wider environmental concerns to coastal policy setting in Sri Lanka.

**Methodology**

**The study area**

Coastal administrative district Hambantota (Fig. 1) was selected for research. Hambantota was one of the worst affected districts, with over 16,000 families displaced and over 3,000 deaths (Anputhas et al. 2005). More than 5,500 structures were damaged including 2541 houses, which resulted in significant disruption to infrastructure (DCS 2004). Hambantota is well characterised, ecologically and socioeconomically and, significantly, there is a variability of land use as the district contains both built-up/residential areas and natural ecosystems, such as forest and lagoons (Ratnayake 1989, Senaratna Sellamuttu and Milner-Gulland 2005, Senaratna 2006).

Hambantota can be further divided by political boundaries into 12 Divisional Secretariats which contain 572 Grama Niladari Divisions (GN divisions). This study focuses on the coastal GN divisions in Hambantota. This area encompasses 39 GN divisions in total within Tissamaharama, Hambantota, Ambalantota and Tangalle Divisional Secretariats.

**Tsunami impacts/outcome variables**

Tsunami impact was quantified in terms of inundation, defined as the rising or flow of tsunami waters over land. Inundation was measured and modelled as a binary measure of whether the tsunami inundated/encroached onto land (Model 1) and as the maximum distance travelled inland (Model 2). The Hambantota coastline was split, arbitrarily, into lengths of 300 m, allowing the creation of 335 units extending from the coastline to the inland boundary of each coastal GN division. All measures of inundation were extracted for the 335 units from maps provided by Sri Lanka’s Coast Conservation Department (CCD) (CCD 2008) and used to build separate models.

The death count associated with each destroyed/damaged housing unit (Model 3), was determined for each GN division (n = 39). Death toll figures were obtained from the Department of Census and Statistics, Sri Lanka, a government department which collected data on 2004 tsunami damage and impact (DCS 2004, 2007). Model 3 was restricted to a smaller sample size of 39, representing the coastal GN divisions within Hambantota as data were not available at a finer resolution. Model structure is described below followed by a description of predictor variables entered into each model.

**Model 1**

A logistic regression model (Dohoo et al. 2009) with binary outcome was used to determine factors affecting whether the tsunami inundated or not. Explanatory variables for this model were quantified within a 15 m buffer zone from the coastline as follows:

\[
\ln \left( \frac{p}{1-p} \right) = \beta_0 + \sum \beta_i X_i 
\]

where \( \ln \left( \frac{p}{1-p} \right) \) is the logit transform, \( \beta_0 \) is the intercept and \( X \) represents the series of predictor variables.

**Model 2**

Of those subunits where inundation did occur, the inundation distance was modelled. Data were normalised by log transformation and a linear regression model was used to examine univari-able and multivariable associations between inundation distance and potential explanatory variables with structure as follows:

\[
y = \beta_0 + \beta_1 X_1 + \ldots + \beta_k X_k + \varepsilon 
\]

where \( \beta_0 \) is the intercept, \( X \) represents the series of predictor variables and \( \varepsilon \) is the error (Dohoo et al. 2009).

**Model 3**

Death toll (Model 3) data were only available at the GN level, giving a total of 39 values. This small sample size made accurate count models difficult to carry out and count variables were therefore converted to binary variables, where 0 and 1 represented whether or not a GN division experienced loss of human life. Binary data were modelled using a logistic regression model with structure as described for Model 1.

**Model outputs**

In all three models, predictor variables were first tested at the univariate level and summa-
rised. However, significance at only the univariate level does not necessarily signify an effect, as there can be confounding with other factors. Hence a multivariable analysis has been conducted.

Variables showing association with the outcome variable (\( p \leq 0.05 \)) were tested in multivariable models and finalised using stepwise selection. Once multivariable models were formed, all variables regardless of significance showed association with the outcome variable were included in the models.

Table 1. Summary details of ecosystems/land uses potentially influencing tsunami impacts in the Hambantota region of Sri Lanka chosen for the models; see also Methodology.

| Predictor variable                  | Numerical values for model variables                                                                 |
|------------------------------------|-----------------------------------------------------------------------------------------------------|
| Coral reef                         | Models 1–3: (0, 1)                                                                                   |
| Mangroves                          | Models 1–3: (0, 1)                                                                                   |
| Marsh                              | Models 1–3: (0, 1)                                                                                   |
| Forest                             | Model 1: (0, 1); Model 2: 1 = 0–0.25, 2 = >0.25–0.5, 3 = >0.5–0.75, 4 = >0.75; Model 3: (0, 1)   |
| Sand dune                          | Models 1–3: (0, 1)                                                                                   |
| Salt pan                           | Models 1–3: (0, 1)                                                                                   |
| Bodies of water†                   | Model 1: (0, 1); Model 2: 1 = 0–0.1, 2 = >0.1–0.7, 3 = >0.7; Model 3: (0, 1)                      |
| Cultivated                         | Models 1–3: (0, 1)                                                                                   |
| Beach                              | Model 1: (0, 1); Model 2: (0, 1); Model 3: 1 = 0–0.1, 2 = >0.1–0.7, 3 = >0.7                          |
| Built-up                           | Model 1: (0, 1); Model 2: 1 = 0–0.1, 2 = >0.1–0.9, 3 = >0.9; Model 3: (0, 1)                        |
| Residential                        | Model 1: (0, 1); Model 2: 1 = 0–0.1, 2 = >0.1–0.75, 3 = >0.75; Model 3: (0, 1)                      |
| Proportion of natural systems to development | Model 1–2: 0–24356; Model 3: 0.001–159000000                                                    |
| Min. distance to residential and built-up areas | Models 1–2: N/A; Model 3: 0–4236 m                                                                |

† Bodies of water include lagoons, tanks and reservoirs.
were added, one by one, and tested. Where appropriate, models produced were compared with statistical performance criteria (AIC and BIC) and the best model was selected (Dohoo et al. 2009). Coefficients for Model 2 were antilogged to correct for the initial log transformation of data. In the case of odds ratios and coefficients, values $>1$ indicate an exacerbating effect of a factor on tsunami impact, while values $<1$ signify a protective effect.

**Predictor variables**

Predictor variables/potential tsunami risk factors were abstracted from both published and unpublished sources. The data extraction process and information source(s) for ecosystems/land uses (Table 1) were as follows.

- **Coral reef**: presence or absence of coral reefs offshore from each GN division within the direction of the tsunami epicentre assessed visually and recorded as a binary (0, 1) variable (Sheppard et al. 1996–1997, Spalding et al. 2001).

- **Mangroves**: presence or absence within inundation area of each GN division or subunit assessed visually from two data sources and combined (Sheppard et al. 1996–1997, Spalding et al. 1997).

- **Marsh, forest, sand dune, salt pan, bodies of water (including lagoons, tanks and reservoirs) and cultivated land, beach, built-up and residential**: areas ($m^2$) of each individual land use/biological system within the tsunami inundation area delineated and calculated using standard techniques in ArcView (ESRI Inc. 1999–2006). Areas were later converted to a proportion of the total inundation area and entered into models as categorical or binary (0, 1) variables depending on their extent. Mapping carried out by the CCD (LUP 2007, CCD 2008).

- **Proportion of natural systems to development**: land uses classified as natural or manmade. Total area for each summed and a ratio taken to indicate whether a GN division or subunit was predominately natural or developed. Data from satellite imagery and aerial photography (Sheppard et al. 1996–1997, LUP 2007, CCD 2008).

- **Minimum distance to residential and built-up areas**: calculated only for death toll and housing damage models. Minimum distance to built-up or residential areas measured for each GN division. Mapping carried out by CCD (LUP 2007, CCD 2008).

The data extraction process and information source(s) for geomorphic features potentially influencing tsunami impacts (Table 2) were as follows.

- **Bathymetry**: 200 m transects drawn for each subunit and converted to ($x$, $y$, $z$) coordinates. Coordinate values exported to Matlab and plotted. Three distinct slopes were identified for characterization: Slope A: between coastline and where profile first drops below 100 m; Slope B: between point where the profile first drops below 100 m and where it first drops below 500 m; Slope C: between the point where the profile first drops below 500 m and where it first drops below 4000 m. Lengths and gradients for each of these slopes were calculated, and values from subunits lying within GN division boundaries were averaged for Models 4 and 5. In the case of bathymetric slope gradients all three were treated as one variable representing the bathymetric profile of each GN/subunit. Data from GEBCO digital atlas (IOC et al. 2003).

- **Topography**: minimum height above sea level extracted for each subunit and GN division. All measures entered into models to ensure associations with topography were identified. SRTM (90 m) Digital Elevation Model downloaded from the CGIAR Consortium for Spatial Information (Jarvis et al. 2008).

- **Coastal shape**: determined over a 600 m and 6 km scale for subunits. Midpoint for each coastal section determined and two flanking points (300 m or 3 km away). Angle between the midpoint point and each flanking end point was calculated using standard trigonometry. These angles were then subtracted from one another to give measure of concavity or convexity. Similarly this was carried out for GN divisions but scale dependent on size of GN division. Information from maps showing the Sri Lankan coastline (LUP 2007).
Coastal angle: calculated for each subunit/GN, in relation to north, by constructing a line between the midpoints of adjacent subunits/GN divisions and calculating its angle using standard trigonometry techniques. Information from maps showing the Sri Lankan coastline (LUP 2007).

Data were used to construct a GIS map in ArcView (ESRI Inc. 1999–2006), demarcating land uses, habitats, and tsunami inundation areas within each GN division (LUP 2007) and also within each of the 335 constructed subunits. Details describing the treatment, extent and sources of ecosystem/land uses and geomorphic variables are shown in Table 1 and 2 respectively. Predictor variables which did not show linearity with model outcomes were categorised. Land uses/ecosystems which were present only in a few sampling regions (GNs/subunits), such as mangroves and coral reefs, were entered into the model as a binary rather than quantitative inputs. Significant correlations among all explanatory variables were tested and those variables significantly correlated with explanatory variables in the final model, and thus could not remain in the final model, are reported.

RESULTS

Variable distributions for each of the three tsunami outcomes are shown as frequency data (Fig. 2). Model results are described below for each model, at the univariate and multivariable level.

| Predictor variable | Extent |
|--------------------|--------|
| Bathymetry Slope A gradient: Models 1–2: 1 = −0.0023701, 2 = −0.0023701; | |
| Model 3: 1 = −0.002, 2 = −0.002 |
| Bathymetry Slope A length (m): Models 1–2: 1 = 24000–32000, 2 = 32001–48750, 3 = 487501–63950; | |
| Model 3: 1 = 26000–46200, 2 = 46601–51000, 3 = 51001–63500 |
| Bathymetry Slope B gradient: Models 1–2: 1 = −0.049, 2 = −0.049; | |
| Model 3: 1 = −0.05, 2 = −0.05 |
| Bathymetry Slope B length (m): Models 1–2: 1 = 3100–6850, 2 = 6851–9800, 3 = 9801–29250; | |
| Model 3: 1 = 26600–46200, 2 = 46601–51000, 3 = 51001–63500 |
| Bathymetry Slope C gradient: Models 1–2: 1 = −0.081314, 2 = −0.081314; | |
| Model 3: 1 = −0.08, 2 = −0.08 |
| Bathymetry Slope C length (m): Models 1–2: 1 = 22000–39000, 2 = 39001–43900, 3 = 43901–46800; | |
| Model 3: 1 = 24700–43560, 2 = 43561–44640, 3 = 44641–46640 |
| Topography Minimum height above sea level: Models 1–3: 1 = 1–4, 2 = 4–15, 3 = >15; | |
| Coastal shape Models 1–3: 1 = −15–15 (approximately straight), 2 = −15 (convex coastlines), 3 = >15 (concave coastlines) |
| Coastal angle Models 1–2: 1 = ≤0, 2 = 0–22.5, 3 = >22.5–45, 4 = >45–67.5, 5 = >67.5; | |
| Model 3: 1 = ≤50°, 2 = >50° |

Fig. 2. Plots showing distribution and range of the following model outcome variables: (a) Presence or absence of tsunami inundation within subunits (Model 1), (b) Maximal inundation distance; data have been log transformed and original data were in metres (Model 2), (c) Percentage of GN divisions within the study area where there was human fatality (Model 3).
Table 3. Variables identified with univariate logistic regression models influencing whether or not the tsunami inundated Hambantota subunits.

| Explanatory variable                  | Odds ratio | CI          |
|---------------------------------------|------------|-------------|
| Coast concavity (600 m)               |            |             |
| cat 1                                | baseline   |             |
| cat 2                                | 0.49       | 0.26, 0.94  |
| Coast concavity (600 m)               |            |             |
| cat 3                                | 0.87       | 0.46, 1.66† |
| (straight)                            | baseline   |             |
| Coast concavity (6 km)                |            |             |
| cat 2                                | 0.34       | 0.19, 0.61  |
| (convex)                              |            |             |
| Coast concavity (6 km)                |            |             |
| cat 3                                | 1.02       | 0.51, 2.05† |
| (concave)                             |            |             |
| Coral absence                         | baseline   |             |
| Coral presence                        | 0.26       | 0.15, 0.47  |
| Forest absence                        | baseline   |             |
| Forest presence                       | 0.57       | 0.34, 0.95  |
| Minimum height asl cat 1              | baseline   |             |
| Minimum height asl cat 2              | 0.29       | 0.16, 0.54  |
| Minimum height asl cat 3              | 0.23       | 0.09, 0.57  |
| Sand dune absence                     | baseline   |             |
| Sand dune presence                    | 0.25       | 0.10, 0.62  |
| Bathymetry                            |            |             |
| Slope A gradient (>−0.002)            | baseline   |             |
| Slope A gradient steeper slopes (<−0.002) | 0.45 | 0.27, 0.77 |
| Slope B gradient (>−0.049)            | baseline   |             |
| Slope B gradient steeper slopes (<−0.049) | 5.16 | 2.86, 9.32 |
| Slope C gradient (>−0.081)            | baseline   |             |
| Slope C gradient steeper slopes (<−0.081) | 0.34 | 0.20, 0.58 |
| Slope A length cat 1                  | baseline   |             |
| Slope A length cat 2                  | 4.29       | 2.23, 8.24  |
| Slope A length cat 3                  | 4.25       | 2.24, 8.06  |
| Slope B length cat 1                  | baseline   |             |
| Slope B length cat 2                  | 0.13       | 0.05, 0.36  |
| Slope B length cat 3                  | 0.08       | 0.03, 0.20  |
| Slope C length cat 1                  | baseline   |             |
| Slope C length cat 2                  | 4.62       | 2.38, 8.98  |
| Slope C length cat 3                  | 3.98       | 2.12, 7.47  |

Note: Abbreviations are: cat, category; asl, above sea level.† Within the confidence interval (CI) column indicates the variable category not significant (p > 0.05).

Model 1: factors influencing tsunami inundation
Univariate logistic model results showing variables significantly influencing whether the tsunami inundated are shown in Table 3. These include forest occurrence and coastal convexity (at the 600 m scale). Significant associations in the multivariable model are presented in Table 4. For the multivariable model, convex coastlines, minimum height above sea level and sand dune occurrence were protective factors. Minimum height above sea level was positively correlated with the presence of forest.

Bathymetric slope gradient was significantly associated with tsunami inundation. Coastal areas with a steeper bathymetric gradient between 100–500 m depth (slope B) were more likely to inundate than shallower gradients. Additionally, coastal areas with a steeper gradient between 500–4,000 m (slope C) were less likely to inundate. Slope gradients were highly correlated with both slope lengths and with the presence of coral reefs.

Multivariable model fit was tested by the Hosmer-Lemeshow (H-L) statistic, and by calculating the area under the receiver operating characteristic (ROC) curve (Hardin and Hilbe 2007). The H-L $\chi^2$ was 6.33 with p > 0.05 and the ROC curve area was 0.86. These values suggest a reasonable goodness of fit.

Table 4. Model 1 showing factors significantly associated with whether the tsunami inundated subunits at the multivariable level.

| Explanatory variable                  | Odds ratio | CI          |
|---------------------------------------|------------|-------------|
| Coast concavity (6 km)                |            |             |
| cat 1                                | baseline   |             |
| cat 2                                | 0.33       | 0.16, 0.68  |
| (straight)                            |            |             |
| Coast concavity (6 km)                |            |             |
| cat 3                                | 0.83       | 0.36, 1.95† |
| (convex)                              |            |             |
| Minimum height asl cat 1              | baseline   |             |
| Minimum height asl cat 2              | 0.31       | 0.15, 0.65  |
| Minimum height asl cat 3              | 0.18       | 0.06, 0.58  |
| Sand dune absence                     | baseline   |             |
| Sand dune presence                    | 0.03       | 0.01, 0.11  |
| Bathymetry                            |            |             |
| Slope A gradient (>−0.002)            | baseline   |             |
| Slope A gradient steeper slopes (<−0.002) | 1.39 | 0.54, 3.58† |
| Slope B gradient (>−0.049)            | baseline   |             |
| Slope B gradient steeper slopes (<−0.049) | 10.41 | 4.40, 24.63 |
| Slope C gradient (>−0.081)            | baseline   |             |
| Slope C gradient steeper slopes (<−0.081) | 0.12 | 0.04, 0.30 |

Note: Abbreviations are: cat, category; asl, above sea level.† Within the confidence interval (CI) column indicates the variable category not significant (p > 0.05).
Table 5. Coefficients and confidence intervals for tsunami impact Model 2 based on explanatory variables associated with maximum inundation distance ($p \leq 0.05$) at the univariate level.

| Explanatory variable | Coefficient | CI     |
|----------------------|-------------|--------|
| Body of water cat 1  | baseline    | ...    |
| Body of water cat 2  | 1.72        | 1.28, 2.31 |
| Body of water cat 3  | 3.24        | 2.22, 4.72 |
| Built-up cat 1       | baseline    | ...    |
| Built-up cat 2       | 1.70        | 1.27, 2.25 |
| Built-up cat 3       | 1.20        | 0.83, 1.73†|
| Beach absence        | baseline    | ...    |
| Beach presence       | 0.56        | 0.44, 0.72 |
| Coast concavity (6 km) | baseline | ... |
| cat 1 (straight)     | 0.70        | 0.56, 0.89 |
| cat 2 (convex)       | 1.11        | 0.90, 1.36†|
| Coastal concavity (6 km) | 0.70      | 0.56, 0.89 |
| Slope C gradient     | 0.66        | 0.57, 0.79 |
| Coral presence       | 0.96        | 0.71, 1.16†|
| Cultivated land absence | baseline | ... |
| Cultivated land presence | 1.72    | 1.26, 2.36 |
| Forest cat 1         | baseline    | ...    |
| Forest cat 2         | 0.97        | 0.61, 1.54†|
| Forest cat 3         | 0.53        | 0.31, 0.93 |
| Forest cat 4         | 0.68        | 0.57, 0.81 |
| Mangrove absence     | baseline    | ...    |
| Mangrove presence    | 2.16        | 1.60, 2.91 |
| Minimum height asl cat 1 baseline | 0.90 | 0.71, 1.16†|
| Minimum height asl cat 2 | 0.38 | 0.25, 0.57 |
| Residential cat 1    | baseline    | ...    |
| Residential cat 2    | 1.55        | 1.09, 2.00 |
| Residential cat 3    | 1.05        | 0.85, 1.28†|
| Rock absence         | ...         | ...    |
| Rock presence         | ...         | ...    |
| Salt pan absence     | baseline    | ...    |
| Salt pan presence    | 2.80        | 1.60, 4.90 |
| Sand dune absence    | baseline    | ...    |
| Sand dune presence   | 0.59        | 0.42, 0.85 |
| Bathymetry           |             |        |
| Slope A gradient     | baseline    | ...    |
| Slope A gradient steeper slopes (≤−0.002) | 0.70 | 0.59, 0.83 |
| Slope B gradient     | baseline    | ...    |
| Slope B gradient steeper slopes (≤−0.049) | 0.88 | 0.74, 1.05†|
| Slope C gradient     | baseline    | ...    |
| Slope C gradient steeper slopes (≤−0.081) | 0.71 | 0.60, 0.84 |
| Slope A length cat 1 | baseline    | ...    |
| Slope A length cat 2 | 1.25        | 1.08, 1.53 |
| Slope A length cat 3 | 1.73        | 1.39, 2.13 |
| Slope B length cat 1 | baseline    | ...    |
| Slope B length cat 2 | 1.62        | 1.34, 1.95 |
| Slope B length cat 3 | 0.81        | 0.66, 0.99 |
| Slope C length cat 1 | baseline    | ...    |
| Slope C length cat 2 | 1.27        | 1.02, 1.58 |
| Slope C length cat 3 | 1.69        | 1.36, 2.12 |

Note: Abbreviations are: cat, category; asl, above sea level.† Within the confidence interval (CI) column indicates the variable category not significant ($p > 0.05$).

Table 6. Model 2 showing factors associated with the maximum tsunami inundation distance within subunits at the multivariable level.

| Explanatory variable | Coefficient | CI     |
|----------------------|-------------|--------|
| Body of water cat 1  | baseline    | ...    |
| Body of water cat 2  | 1.08        | 0.84, 1.40†|
| Body of water cat 3  | 2.25        | 1.66, 3.07 |
| Built-up cat 1       | baseline    | ...    |
| Built-up cat 2       | 1.97        | 1.54, 2.51 |
| Built-up cat 3       | 1.64        | 1.24, 2.18 |
| Beach absence        | baseline    | ...    |
| Beach presence       | 0.80        | 0.64, 0.99 |
| Cultivated land absence | baseline | ... |
| Cultivated land presence | 1.47 | 1.15, 1.89 |
| Minimum height asl cat 1 baseline | 1.72 | 0.71, 2.91 |
| Minimum height asl cat 2 | 0.89 | 0.73, 1.09†|
| Minimum height asl cat 3 | 0.47 | 0.33, 0.66 |
| Salt pan absence     | baseline    | ...    |
| Salt pan presence    | 2.51        | 1.66, 3.80 |
| Sand dune absence    | baseline    | ...    |
| Sand dune presence   | 0.63        | 0.47, 0.85 |
| Slope B length cat 1 | baseline    | ...    |
| Slope B length cat 2 | 0.94        | 0.75, 1.17†|
| Slope B length cat 3 | 0.41        | 0.30, 0.55 |

Note: Abbreviations are: cat, category; asl, above sea level.† Within the confidence interval (CI) column indicates the variable category not significant ($p > 0.05$).

Water bodies, built-up areas, cultivated land and saltpans exacerbated damage while beaches, sand dunes and a greater height above sea level were protective. Additionally, a steeper slope B was also associated with a reduced inundation distance.

Deviance residuals for Model 2 were shown to be approximately normal by examination of probability plots and through the Shapiro-Wilkinson test for normality ($z = 0.968, p > 0.05$). Removal of outliers did not significantly change results (6 outliers removed in total). The link specification test and the Ramsey regression specification error test both had $p$ values $> 0.05$, indicating correct model specification.

Model 3: factors influencing death toll

Univariate associations with explanatory variables and death toll per damaged housing unit are shown in Table 7 and multivariable associations are shown in Table 8. As expected, the built-up areas variable was a key risk factor. Steeper gradients of slope C were also identified as protective. For the multivariable model the H-L...
Table 7. Odds ratios for explanatory variables associated with the presence or absence of human fatalities (Model 3) in Hambantota GN divisions at the univariate level ($p \leq 0.05$).

| Explanatory variable                        | Odds ratio | CI          |
|--------------------------------------------|------------|-------------|
| Bathymetry                                 |            |             |
| Slope A gradient ($>-0.002$)               | baseline   | ...         |
| Slope A gradient steeper slopes ($<-0.002$)| 1.3        | 0.36, 4.68† |
| Slope B gradient ($>-0.049$)               | baseline   | ...         |
| Slope B gradient steeper slopes ($<-0.049$)| 0.73       | 0.21, 2.57† |
| Slope C gradient ($>-0.081$)               | baseline   | ...         |
| Slope C gradient steeper slopes ($<-0.081$)| 0.12       | 0.23, 0.51  |
| Built-up areas absence                     | baseline   | ...         |
| Built-up areas presence                    | 6.67       | 1.47, 30.21 |
| Coast concavity cat 1 (straight)           | baseline   | ...         |
| Coast concavity cat 2 (convex)             | 3.25       | 0.66, 15.98†|
| Coast concavity cat 3 (concave)            | 19.5       | 1.99, 190.88|

Note: Abbreviation: cat, category.
† Within the confidence interval (CI) column indicates the variable category not significant ($p > 0.05$).

The only factor shown to be significant in all three multivariable models was bathymetry, although the influence of bathymetric features was not uniform. A steeper bathymetric gradient generally appears to be protective against human fatality and both occurrence and extent of tsunami inundation and. This supports earlier studies stating that gentle slopes exacerbated impact (Chatenoux and Peduzzi 2005).

Discussion

Risk factors determined from the models

Three different models form the basis of this study, which examined the role of factors that may have alleviated and exacerbated the outcome of the 2004 tsunami. Use of models is complementary to our questionnaire surveys of 500 fishers along the southern (Hambantota) coast of Sri Lanka (Venkatachalam et al. 2009). This study shows that the vulnerability of Sri Lanka’s coast to episodic events is governed by a complex interplay of factors. How tsunami impact is measured can also lead to differing results, as shown in our study, which assessed damage in three ways: inundation occurrence, inundation distance, and death toll.

The only factor shown to be significant in all three multivariable models was bathymetry, although the influence of bathymetric features was not uniform. A steeper bathymetric gradient generally appears to be protective against human fatality and both occurrence and extent of tsunami inundation and. This supports earlier studies stating that gentle slopes exacerbated impact (Chatenoux and Peduzzi 2005). Bathymetric slope length was highly correlated with bathymetric slope gradient, indicating that the length and gradient of bathymetric features may be important in all three models. Additionally, the presence of coral reefs was correlated with slope gradient, suggesting that reefs could potentially be an important factor in reducing wave energy reaching the shore. Coral reefs have a higher bottom-drag coefficient than a sandy ocean floor and have been shown in theoretical models to reduce tsunami run-up (Kunkel et al. 2006).

Other geographical features identified as influencing tsunami impact include convex coastlines and height about sea level. Compared to a straight coastline, convex coastlines were protective, perhaps by deflecting tsunami waters to adjacent areas, thereby preventing inundation. This is consistent with fisher views that concave coastlines exacerbated tsunami damage (Venkatachalam et al. 2009). The greater the minimum height above sea level for a given subunit of the Hambantota coast the more likely it was to be protected from tsunami intrusion, in terms of both inundation occurrence and distance. This finding agrees with previous studies (Chatenoux and Peduzzi 2005, Kathiresan and Rajendran 2005, Kerr et al. 2006), demonstrating, unsurprisingly, that elevation was a key factor which helped reduce tsunami impact. Forest presence was positively associated with height above sea level, indicating a potentially protective effect from tsunami inundation. Forest may have
provided a physical barrier against intrusion, as reported by previous studies (Iverson and Prasad 2007, Iverson and Prasad 2008).

Despite positive association between mangrove occurrence and tsunami inundation distance at the univariate level, mangroves were not a significant factor in final multivariable models. This could be due to the fact the mangroves were only present in 8% of our sites or perhaps indicative of a more complex role of mangroves. The result from this study differs from many existing studies, which suggest that in fact mangroves provided protection from the 2004 tsunami (Kathiresan and Rajendran 2005, Daddouh-Guebas et al. 2005, IUCN 2006).

Systems/land uses which acted as risk factors, by increasing inundation distance (Model 2), were bodies of water including tanks, reservoirs and lagoons, the presence of salt pans and built-up areas. Bodies of water were significantly associated with increased inundation distance when their area exceeded 70% of the sample area. Areas of water most likely provided an easier path for tsunami intrusion inland particularly when they were open to the coast. This is congruent with previous research, which identifies bodies of water such as rivers as exacerbating tsunami impacts (Yasuda et al. 2005). However, examination of maps indicates that the area covered in these instances predominantly constitutes the body of water itself, rather than residential or built-up areas. Salt pans are low lying surfaces which are likely to provide little frictional resistance to tsunami waters and may explain why they are a significant factor in increasing inundation. Similarly, built-up areas where there is likely to be a high percentage of paved areas and areas cleared from vegetation, would provide a reduced frictional force and absorption capacity. Death toll was also shown to be associated with built-up areas. This was an unsurprising result given that these areas are likely to have a higher population and given that built up areas were associated with greater inundation.

Additionally, inundation distance was exacerbated by the presence of cultivated land. Cultivated land, similar to salt pan, is often low lying flat expanses of land, perhaps facilitating the path for tsunami intrusion and thus increasing the distance travelled. There is qualitative evidence for this association given that many farmers relying on cultivated land suffered as a result of salt intrusion caused by the tsunami waters travelling over their crops (Kielen 2005, Chandrasekharan et al. 2008).

Although wave height was originally a risk factor intended for inclusion in the model, a comprehensive dataset encompassing values for each GN division for southern Sri Lanka was not available. Tidal gauges are infrequent and post-tsunami survey teams did not systematically visit each coastal GN division in Hambantota. However, wave height is related to bathymetry, which was a significant risk factor in the model, and the association has also been noted by other researchers (Duong et al. 2008). Seagrass was initially considered as a risk factor due to its significance in previous research (Chatenoux and Peduzzi 2005). However, there is no significant seagrass coverage within our research area (Green and Short 2007).

In previous models, distance to villages has been shown to be a significant factor (Kerr et al. 2006). Although not significant here, this may be due to built-up and residential areas giving an incomplete picture of the location of human populations. Site visits along the coast of Sri Lanka for questionnaire surveys revealed that a number of houses located in areas that are not actually heavily built-up or residential areas. These houses are also likely to be closer to the coast and may therefore have experienced a greater proportion of damage or mortality.

From a modelling perspective, it would be beneficial to obtain death toll data at the village level, allowing for smaller sampling areas and therefore a larger sample size. However, at the time of this study we were unable to obtain these data. It is also noted that death toll used in these models is per damaged and destroyed housing unit. These values may not represent the absolute death toll for each GN division (i.e., some people may have died from non-damaged houses), although the two measures are likely to be associated.

**Implications of model findings to coastal policy and management**

Several studies suggested that natural systems, including mangroves, may have reduced tsunami impact in many Indian Ocean countries (e.g.,
Bambaradeniya et al. 2005, IUCN 2005), a view shared by Hambantota fishers (Venkatachalam et al. 2009). Subsequent investment in use of bioshields and other natural barriers (e.g., IUCN 2006) was clearly influenced by these findings although, as noted, some studies have challenged the protective role of mangroves.

Although mangroves conferred no tsunami protection in our multivariable models (and were actually associated with increased inundation at the univariate level), the ecosystem was uncommon at sites modelled. Hence, any influence on tsunami outcome from our models may not be definitive. However, the role of mangroves/vegetation in coastal protection more generally, is unequivocal (IUCN 2006a). It is noted that Sri Lankan coastal areas experienced mangrove loss, which predated the Asian tsunami, as a result of many factors. Ongoing loss or degradation of mangroves and other coastal systems, could be highly risky and impede certain future coastal development options (but, arguably, create others), as noted by Venkatachalam et al. (2009). The conservation importance of wetlands is certainly implicit in national environmental and international legislation (e.g., Convention on Biological Diversity & Ramsar Convention to protect wetlands), to which Sri Lanka is party.

Our models revealed that many of the factors showing the greatest protective effect on tsunami damage were geographical features (e.g., bathymetry, height above sea level and coastal shape) that cannot easily be altered. However, there are some factors which influenced tsunami outcome that could potentially be protected. Sand dunes, for example, were shown to be protective against intrusion of tsunami waters and reduced the distance tsunami waters travelled inland. They likely acted as a physical barrier by effectively increasing the height above sea level of the coastline. The importance of dunes has been suggested in recent reports, where authors fear this role has been overlooked in favour of bioshields (Bhalla 2007). Similarly, inundation distance was also reduced in areas where beach was present along the coastline.

Tsunamis are rare, episodic events. The role of factors in our models associated with protection against the tsunami (e.g., land elevation, sand dunes and coastal convexity), and increased impact from it (e.g., built-up areas, water bodies, saltpans), should also be examined in relation to more frequent events, such as monsoon and storm damage. Additionally, the wider significance of different coastal systems and land uses, irrespective of any association with tsunami outcome, should be considered, i.e., as risk factors, prior to future development activities involving coastal modification. Post-tsunami planning has not always encompassed all these factors. For example, local communities felt unsettled and in some cases without a viable livelihood when displaced inland, from the coastal setback zone (Harris 2005, Leckie 2005, Rice 2005, Rodriguez et al. 2008, Feagin et al. 2010). Future coastal policy setting in Sri Lanka should focus on prevailing environmental concerns as well as issues relating to episodic rare events, such as tsunamis. The importance of integrated coastal management during post-tsunami reconstruction in Sri Lanka is considered further by Venkatachalam et al. (2009).

Finally, the relative merits of scientific vs intuitive/traditional ecological knowledge, in the context of tsunami studies, warrant discussion. The present modelling paper, and our earlier questionnaire study (Venkatachalam et al. 2009) directed at fishers, exemplify these two approaches. For some factors (e.g., protection afforded by sand dunes) the influence was the same in both studies. In the case of other factors, such as mangroves, >90% of fishers believed that this ecosystem helped alleviate tsunami damage in Sri Lanka, whereas multivariable models (this study) showed no significant association between mangrove occurrence and protection or impact. Similarly, a study on fisher opinions has revealed that fisheries and conservation science seriously underestimated the decline in Gulf grouper in California (Saenz-Arroyo et al. 2005). There are benefits in considering both science and opinion-based knowledge from communities closely connected to their milieu (Venkatachalam et al. 2009), and Sri Lanka would appear to be no exception to the need for an integrated approach.

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