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COASTAL FLOOD VULNERABILITY ASSESSMENT WITH GEOMATIC METHODS: TEST SITES OF WESTERN THAILAND, SYDNEY (AUSTRALIA) AND AEOLIAN ISLANDS (SOUTH TYRRHENIAN SEA, ITALY)

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Foreword

The work undertaken in this PhD thesis is aimed at the development and testing of an innovative methodology for the assessment of the vulnerability of coastal areas to marine catastrophic inundation (tsunami). Different approaches are used at different spatial scales and are applied to three different study areas:

1. The entire western coast of Thailand
2. Two selected coastal suburbs of Sydney – Australia
3. The Aeolian Islands, in the South Tyrrhenian Sea – Italy

I have discussed each of these cases study in at least one scientific paper: one paper about the Thailand case study (Dall'Osso et al., in review-b), three papers about the Sydney applications (Dall'Osso et al., 2009a; Dall'Osso et al., 2009b; Dall'Osso and Dominey-Howes, in review) and one last paper about the work at the Aeolian Islands (Dall'Osso et al., in review-a).

These publications represent the core of the present PhD thesis. The main topics dealt with are outlined and discussed in a general introduction while the overall conclusions are outlined in the last section.

N.B.

The following style rules have been adopted in every paper included in the present PhD thesis:

- References of each paper are reported at the end of it, after the text.
- All figures and tables are attached after the paper references.
- Figures and tables are numbered independently. In each paper the numbering of figures and tables re-starts from n. 1

SUMMARY

Introduction

The need for tools aimed at helping to reduce global risk from extreme natural events such as tsunamis has become obvious after the 2004 Indian Ocean Tsunami (2004 IOT), and further emphasized by more recent events (i.e. the 2005 Katrina Hurricane, the 2009 Samoa tsunami and the risk of a major tsunami throughout the Pacific Ocean after the 2010 Chile earthquake). The 2004 IOT was particularly catastrophic (Figure 1). It was the most lethal tsunami disaster the modern world has record of and catapulted tsunamis onto the global scientific and political stage. It has prompted an unparalleled international scientific and intergovernmental response with several foci including the development and deployment of tsunami warning systems in risk areas, detailed hazard, risk and vulnerability assessment and tsunami education and disaster planning.

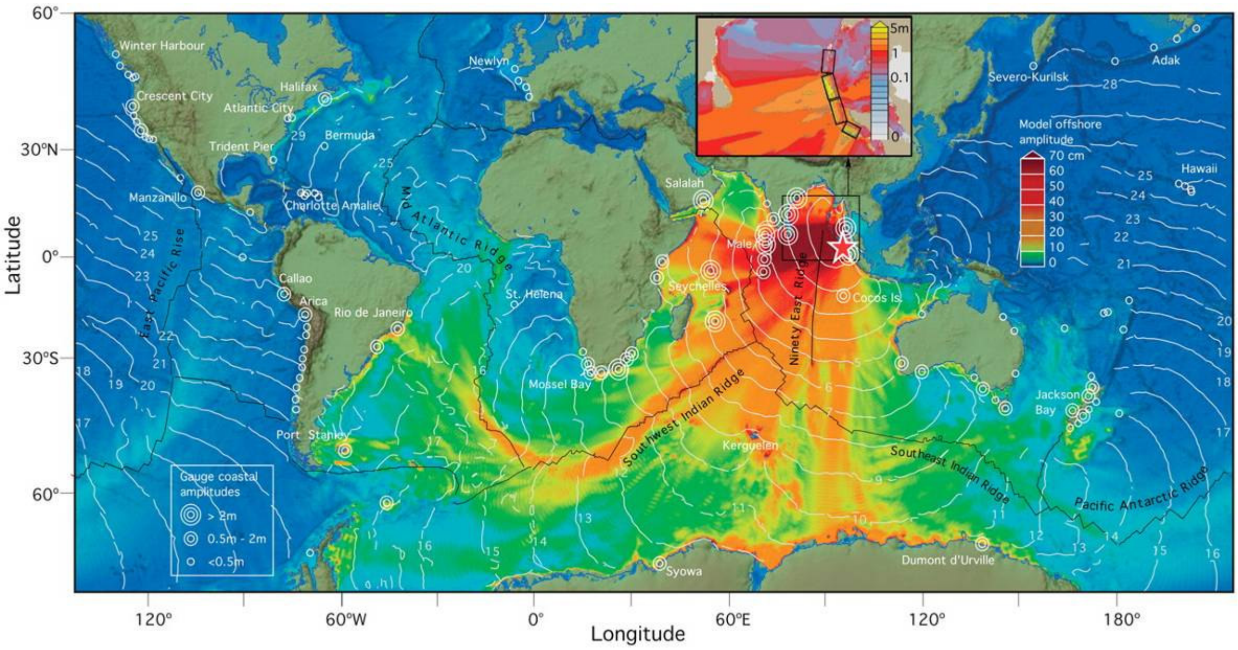

Figure 1. Global reach of the 2004 Indian Ocean tsunami (after Titov et al., 2005). White isolines are the position of the tsunami wave front in hours after the start of the event. Colours represent modelled (forecast) wave amplitudes offshore. White circles equal measured wave amplitudes (in metres) at coastal tide gauges.

The 2004 disaster was not however, unique. Similar events have occurred in the past and will happen again in the future. The most important lesson from the 2004 Indian Ocean tsunami is that we are at risk. The 2004 disaster was something of a wake up call for every country sharing a border with the sea, since prior to this event few had seriously considered the potential threat posed by tsunamis. The 2004 IOT showed that low-lying coastal areas are vulnerable to the impact of catastrophic marine floods associated with tsunami and storm surges. Furthermore, the future impacts of such floods will be worse than in the past because of climate related sea level rise and increased exposure at the coast.

As for every extreme natural event able to affect people and human properties, the tsunami threat should be managed according to international "risk management" guidelines. The three primary components of a risk management framework are: risk identification, risk reduction and disaster management. (Cardona, 2003). The definition of "risk" is thus the first step of this process.

1.1 Risk, Hazard and Vulnerability

There are many definitions of risk. In most cases it has been defined according to the aims of different science sectors in which a disaster management technique was required. Despite the high number of definitions that can be found in literature, the concept of risk as a function of "hazard" and "vulnerability" appears to be the most accepted and widely used.

According to White and Burton (1980), "risk is the product of the probability of the occurrence of a hazard and its societal consequences". Tarrant et al. (1987), as well as Ansell and Wharton (1992), simply defined the risk as the product between likelihood and consequences. At an international level, a more complete definition has been given by the United Nations (1992); The U.N. define risk as "expected losses (of lives, persons injured, property damaged and economic activity disrupted) due to a particular hazard for a given area and reference period". For the International Strategy for Disaster Reduction (ISDR), risk is "the combination of the probability of an event..." (i.e. the hazard) "...and its negative consequences" (i.e. the vulnerability).

Thus, the identification and analysis of risk involve different evaluations about both hazard and vulnerability. A large group of similar definitions can also be found for these two concepts. The United Nations (1992) define hazard as "a threatening event, or the probability of occurrence of a potentially damaging phenomenon within a given time period and area". Deyle et al. (1998) gave a definition of natural hazard, as "an extreme natural event that poses risks to human settlements". The United States Federal Emergency Management Agency or FEMA (FEMA 1997) defines it as "an event or physical condition that has the potential to cause fatalities, injuries, property damage, infrastructure damage, agricultural loss, damage to the environment, interruption of business, or other types of harm or loss".

With regard to vulnerability, there is wide agreement in defining it as the "potential for damage". Godshalk et al. (1991) described it as "the susceptibility to injury or damage from hazards", while according to Mitchell et al. (1997) vulnerability is "the potential for loss or the capacity to suffer harm from a hazard. It can generally be applied to individuals, society, or the environment". The United Nations (1992) describe vulnerability as the "degree of loss (from 0% to 100%) resulting from a potentially damaging phenomenon". ISDR defines vulnerability as "the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard."

According to such definitions of risk (and related concepts), it is obvious that risk reduction can be achieved by altering either the physical hazard or the vulnerability of the subject/system that is exposed to it. In case of tsunamis, the hazard itself is not predictable or avoidable; therefore, mitigating vulnerability is the only way in which risk can be realistically reduced. Mitigating the vulnerability level of an exposed area means to increase its ability to withstand the hazard's impact, should it occur.

The vulnerability of a coastal area includes a wide range of factors or parameters. Because of its multifaceted nature, it is difficult to quantify and there is no global consensus yet on how it should be measured (Thywissen 2006). However, according to UN guidelines (1992), vulnerability can be assessed as a percentage of the expected losses resulting from the occurrence of a given hazard. Such losses can be classified into two main groups (Coburn et al., 1994):

- direct damages: those happening during the hazard's impact or immediately after. They are also defined "tangible effects" and primarily include effects on people or physical assets (e.g. injuries and casualties, damage to buildings and infrastructure, damage to the environment, etc.);
- indirect damages: any other damage or loss arising in the hazard's aftermath, as a consequence of direct damages (e.g. economic or financial losses, damage to the social and cultural cohesion of the affected community, psychological issues, etc.).

Within the present work, vulnerability to tsunami has been defined and measured in accordance with UN (1992) guidelines. In addition, the method we developed focuses on the assessment of the potential for "direct" damages, although, as complementary results, it provides some of the data necessary to be able to undertake further assessment on the socio-economic aspects of the vulnerability.

1.2 Developing a method for tsunami vulnerability assessment

In the case of a tsunami, the affected area could include the coastal zones of a whole nation or, as tragically occurred in 2004, a whole oceanic basin. At the same time, damage caused by a tsunami is highly dependent on the physical and environmental features of the exposed areas and can be extremely heterogeneous even within the same town. Observations of the impacts of the 2004 IOT showed how variable these could be even along a few kilometres of coastline. The nearshore bathymetry is one of the key parameters (Matsuyama et al., 1999) affecting the height and intensity of the incoming waves. The topography and geomorphological characteristics of the shoreline have also a key-role in determining the extent of inundations and run-ups. Other important variables regulating the impact are given by the shielding effect provided by vegetation, especially mangrove forests (Kathiresan and Rajendran, 2006) and any artificial defence, such as coastal works or seawalls. All of these factors play a key-role in defining the height and intensity of the inundation. In addition, physical damages suffered by the urban and natural environments depend on several other parameters, such as land use, building construction standards, the degree of urban development of coastal zones, etc.

Given the potential scale of the affect of a tsunami, the high number of data needed and the extremely high spatial variability of the expected damage, local and national government agencies faced with the task of developing appropriate risk reduction strategies need appropriate tools to enable them to assess vulnerability at various scales. Furthermore, given the low frequency of tsunamis, investments (in terms of time and money) that Governments and Public Administrations normally put for prevention studies or measures are very limited, and must be prioritized.

Such observations lead me to develop a method for the assessment of the tsunami vulnerability with the following characteristics:

1. <u>Ability to work at two different scales.</u> At the smallest scale, the required detail level is lower. As a consequence, the vulnerability of large coastal areas (e.g. regional or even national) can be assessed spending relatively little time and financial resources. This must not affect the reliability of the analysis, but just its spatial resolution. At this stage, the entire coastal area exposed to the tsunami threat is covered and data on its natural and human features are coupled with the exposure to inundation. The aim of the low-scale analysis is to find out which parts of a regional or national costal area are the most vulnerable to tsunami and require further studies. The high-scale analysis can then be undertaken only in those "vulnerability hot spots" resulting from the low-scale assessment. As a consequence, the

effort typically required by high-resolution analysis will be limited to few selected coastal zones, although the whole multi-scale assessment considered a much wider area.

2. Ability to gather most of the data needed through the best available geomatic methods: the large amount of data required to undertake a reliable assessment of tsunami vulnerability is often the main limit to the correct application of international guidelines on risk management. This happens more frequently in developing countries, where national or local archives, if existing, are often incomplete or inaccessible. Paradoxically, such countries are the most vulnerable to natural hazards (ECLAC, 2003). The lack of reliable information can be partially addressed with the use of recent geomatic technologies, based on the employment of satellite surveys and remote sensing (especially the analysis of multi-spectral satellite imagery and radar surveys). With a relatively small effort in terms of time and costs, such technologies can provide a large spectrum of georeferenced information at a local or even national scale and can be applied at different resolution levels. Furthermore, the capability of such systems is increasing very quickly and recent technical progresses, especially in terms of geometrical and spectral resolution of newest sensors, suggest that the contribution of satellite surveys will quickly become indispensable to a large part of environmental or geographic studies.

3. Ability to store and manage data into Geographic Information Systems (GIS): data obtained through remote sensing are easily manageable through GIS, increasing greatly their field of application. GIS is an ideal platform for any environmental analysis organized on a geographic base. In particular, GIS tools are of great help in vulnerability assessment studies. Thanks to GIS, the hazard, the exposure and the data required to assess the vulnerability of coastal zones to tsunami impacts can be stored, organized in different graphic layers, edited or crossed with each others. Several tools for spatial and statistical analysis can also be used. Furthermore, the GIS allows to generate interactive maps, that can be consulted by different types of end–users and easily kept updated through the years, which is basic for low-frequency hazards such as tsunamis. As a result, GIS has become an indispensable tool, not only for assisting in tsunami vulnerability assessments, but for other natural hazards as well.

1.2.1 Existing approaches

At the time this work was undertaken, none of the existing methods for tsunami vulnerability assessment incorporated all the aforementioned features.

Methods working at a regional or national levels use satellite imagery or topographic data only to identify and map those areas that are exposed to or at risk from tsunami flooding (Theilen-Willige, 2008; Chandrasekar et al., 2007; Theilen-Willige, 2006). However, the vulnerability level of coastal zones depends also on their environmental and socio-economic characteristics, which are not considered by such approaches. Hence, whilst those methods are based on the use of remote sensing techniques, they do not provide a comprehensive analysis of coastal vulnerability to tsunami.

A low-scale method, which crosses exposure and land cover data, was used by Wood (2009). In that approach, land cover data are extracted by Landsat satellite images and coupled with pre-existing tsunami-hazard information. Although this approach is one of the few considering the integration of socio-economic and environmental data (i.e. the land cover), it is based on the use of a pre-existing database of tsunami hazard information, which is highly unlikely to be available elsewhere, making the application of Wood's approach problematic.

With regard to methods working at a high spatial resolution, much more information can be found in literature. Most of such approaches (Dominey-Howes, et al., in press; Garcin et al., 2008; Taubenbock et al., 2008; Aitkenhead, 2007; Dominey-Howes and Papathoma, 2007; Papathoma et al., 2003; Papathoma and Dominey-Howes, 2003; Papadopoulos and Dermentzopoulos, 1998) aim to assess the vulnerability of single buildings or infrastructure units. Required data are normally gathered through field surveys and direct census. Given the high detail of analysis, these methods must be applied to pre-selected coastal sites, on the basis of specific requests from Public Administrations, or scientific interests based on past tsunamis. Among them, the "Papathoma Tsunami Vulnerability Assessment method" (PTVAm) is one of the most widely used (Papathoma, 2003; Papathoma et al., 2003; Papathoma and Dominey-Howes, 2003).

The PTVA is a GIS-based model developed using detailed information about the impacts of historic tsunamis and the results of numerous post-tsunami surveys and building damage assessments. Papathoma (2003) identified and ranked a series of attributes (engineering and environmental) that were reported to be responsible for controlling the type and severity of tsunami damage to building structures. Such attributes include building material, building row, number of floors, building surroundings, ground floor condition, the presence of a sea defence and the width of the intertidal zone. The weighting of each attribute was determined based on the mitigating efforts that can be made to reduce its contribution to vulnerability. This required each of the attributes to be ranked in order of importance – a subjective procedure that relies heavily on the expert judgment of the authors. A review of the PTVA-1 vulnerability attributes (Dominey-Howes and Papathoma, 2007) using post-event data from the Indian Ocean Tsunami lead to the development of a revised version of the model, PTVA-2. Although this study confirms that many of the PTVA-1 attributes correlate very well with the type and severity of the damage that was observed, PTVA-2 features slight changes to the ranking and details of the attributes. A revised parameters list is published in (Dominey-Howes et al., 2009) and used to provide Probable Maximum Losses (PML) estimates for a tsunami event in Seaside, Oregan, USA. Hence, the attributes within the PTVA Model may be considered appropriate for use in assessing vulnerability and it is believed offers a robust framework to explore building vulnerability in the absence of validated engineering vulnerability assessment models. However some concern has been expressed about the subjective attribute ranking procedure (Dall'Osso et al., 2006).

1.2.2 The Proposed Methodology

The methodology developed and tested within this PhD is a multi-scale approach based on two consecutive phases, working at different spatial scales. Such phases are:

1. Assessment of tsunami vulnerability of regional or national costal zones – geographic scale of 1:150.000 – spatial resolution: 90m
2. Zoom on "vulnerability hot spots": assessment of tsunami vulnerability of single buildings, within a limited coastal tract (e.g. a costal settlement, a urban suburb, etc.) – geographic scale of 1:5000 – spatial resolution: 1m

In both phases, I maximized the percentage of data obtained through the best available geomatic and remote sensing technology (analysis of satellite imagery and radar surveys, use of the GIS).

Both in phase 1 and 2, the main attributes controlling the vulnerability of coastal zones are mapped and inserted into the GIS. Afterwards, such attributes are crossed with the exposure to tsunami inundation and, for every exposed area/object, a relative vulnerability index is calculated. Results are shown in thematic vulnerability maps, in which different coastal features and objects (land use classes, buildings, etc) are displayed with a colour code, according to their vulnerability index score. In particular, the vulnerability maps generated in phase 1 have a scale of 1:150.000, while those created in phase 2 have a scale of at least 1:5000.

Given the strong difference of the two phases - in terms of scale of analysis - each of them is carried out following a different methodology. From a technical perspective (data required, data gathering and analysis, results), phase 1 and 2 are thus completely independent. Nonetheless, as already mentioned, results of phase 1 can be used to select the "vulnerability host spots" of phase 2.

In order to be tested, methods adopted in phase 1 and 2 have been applied to three different study areas:

- the method adopted in phase-1 has been applied to assess the tsunami vulnerability of the whole western coast of Thailand (Dall'Osso et al, in review-b);
- the method adopted in phase-2 has been applied to two selected coastal suburbs of Sydney (Australia) (Dall'Osso et al., 2009a; Dall'Osso et al., 2009b; Dall'Osso and Dominey-Howes, in review) and to the Aeolian Islands, in the South Tyrrhenian Sea, Italy (Dall'Osso et al., in review-a).

1.2.2.1 Phase 1 – The small-scale assessment: overview of the method

The methodology developed for phase-1 is fully based on the use of satellite surveys and GIS. The vulnerability level of coastal zones is calculated as a function of the following input-parameters:

- land cover class (urbanized areas - high density, urbanized areas - low density, agriculture, forest, coastal vegetation, lakes and rivers)
- type of shoreline (with coastal infrastructure, beaches, pocket beaches, coastal vegetation - mangroves, high ground, low ground)
- distance from the shoreline
- topography (elevation above mean sea level)

Thanks to the small scale of the assessment, all of the required data can be obtained from ASTER imagery (Advanced Spaceborn Thermal Emission and Reflection Radiometer) and SRTM v.3 elevation model (Shuttle Radar Topography Mission – version #3), or calculated through the GIS.

ASTER images are composed by 14 overlapping spectral bands, with a geometrical resolution ranging from 15m (first three bands) to 90m (last 5 bands) (Abrams, 2000; Yamaguchi et al., 2001). Each image covers an area of 60x60 km. At the time this work was carried out, ASTER images could be purchased from the USGS (United States Geological Surveys) website at the price of 80 USD each.

The good spectral and geometrical resolution, plus the size of the area covered and the economic accessibility make ASTER images extremely suitable for environmental analysis at regional or national scale.

Data on land cover are obtained through a semi-automatic algorithm - called “supervised classification” - applied to a band subset of every ASTER image. Broadly speaking, the algorithm is able to identify, within the ASTER bands, the “spectral signature” of different land cover classes. Data on the type of shoreline are also extracted from ASTER images, trough a photo-interpretation process of first three bands, which have the best geometrical resolution.

SRTM v.3 is an interpherometric DEM (Digital Elevation Model) produced and freely distributed by NASA. It has a horizontal geometrical resolution of 90 m and a reported vertical accuracy of 10 m (root mean square error). Version 3 has been successfully used in several flood studies (Theilen-Willige B., 2006; Demirkesen et al., 2007). Within this work, SRTM v.3 is used to extract data about the topography of coastal areas.

Finally, the distance from the shoreline is calculated within the GIS, by means of a specific spatial analysis tool.

In comparison to existing methods, this approach provides a more complete vulnerability assessment, as it considers the physical attributes of coastal zones besides their exposure to inundation. Also, this method goes beyond Wood's (2009), as it exploits the flexibility and higher resolution (both spectral and geometrical) of the newer ASTER sensor and it can be applied to every coastal area, because no pre-existing tsunami-hazard database is required.

A more detailed description of this method and its application to the western coast of Thailand is provided in Paper n.1 of the present document: Dall'Osso et al. (in review-b): "A novel method for assessing tsunami vulnerability at the regional scale using ASTER imagery".

1.2.2.2 Phase 2 – The high-scale assessment: overview of the method

At this end of the spatial scale, our analysis focuses on the vulnerability of single buildings. The method adopted in phase-2 is based on the already existing PTVA Model. However, I improved the PTVA Model by introducing a multi-criteria approach to the assessment of building vulnerability. The vulnerability of every building we examined is calculated from a combination of damage that would be experienced due to the hydrodynamic forces during inundation *and* that associated with water intrusion. These two damage processes have been evaluated independently using a different set of building attributes. The vulnerability to structural damage has been assessed by considering contributions of all the original PTVA Model attributes, plus some newly-introduced elements (including foundation type and preservation condition). Also, contributions have been weighted using a new approach based on pair-wise comparisons between attributes - a method typically used in multi-criteria analysis and Analytic Hierarchy Process (Saaty, 1986). Thanks to this technique, the contribution made by separate attributes to the structural vulnerability of a building can be compared via a rigorous mathematical approach. This avoids biases and reduces to a minimum the inevitable subjective component of every decision making process. Therefore, the method we used here is an improved version of the existing PTVA-2 approach, and it has been named "PTVA-3 Model" (Papathoma Tsunami Vulnerability Assessment Model, version 3).

Due to the high spatial resolution required by the PTVA-3 Model, only a part of the data needed for the assessment can be obtained through satellite and remote sensing surveys. In particular, a subset of the required building attributes can be extracted through a photo-interpretation process of satellite or aerial images having a spatial resolution on the order of 1 m (e.g. Quickbird, Ikonos, World Wiew). Remaining building attributes need to be obtained through field surveys.

As in phase-1, the exposure to inundation is calculated from the topography of the study area. However, in order to calculate the depth of water expected to hit each building, the spatial resolution and vertical accuracy of the DEM must not exceed 1m. Currently, such performances are provided by aerial LiDAR (Light Detection And Ranging) surveys.

A detailed description of the PTVA-3 Model and its improvements with respect to previous versions is provided in Paper n.2 of the present document: Dall'Osso et al. (2009b): "A revised (PTVA) model for assessing the vulnerability of buildings to tsunami damage". The same paper includes a first test of the PTVAm-3 undertaken using building data from Maroubra beach, a coastal suburb of Sydney – Australia.

Results of a further application of the PTVAm-3 to a much larger study area (i.e. the Council of Manly – Sydney) are presented in Paper n.3: Dall'Osso et al. (2009a): "Assessing the vulnerability of buildings to tsunami in Sydney".

Implications of the PTVAm-3 output for coastal planners and risk managers are discussed in Paper n.4 of the present thesis: Dall'Osso and Dominey-Howes (in review): "'Reducing the loss' - using high-resolution vulnerability assessments to enhance tsunami risk reduction strategies ".

Finally, the PTVAm-3 has been applied and validated at the Aeolian Islands, in Italy. Results of this work are discussed in Paper n.5: Dall'Osso et al. (in review-a): "Assessing The Vulnerability Of Buildings To Tsunami Damage In The Aeolian Islands, Italy – Application And Validation Of The Ptva – 3 Model".

Paper n. 1

A novel method for assessing tsunami vulnerability at the regional scale using ASTER imagery

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A novel method for assessing tsunami vulnerability at the regional scale using ASTER imagery

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Abstract

We present here a novel method to assess coastal vulnerability to tsunami, based on GIS (*Geographical Information System*), ASTER imagery (*Advanced Spaceborn Thermal Emission and Reflection Radiometer*) and SRTM-3 elevation model (*Shuttle Radar Topography Mission-3*). We developed this method within the CRATER project (Coastal Risk Analysis for Tsunamis and Environmental Remediation) and applied it on the whole western coast of Thailand. As result, we generated a set of vectorial vulnerability maps at scale of 1:150.000. This approach provides a low-cost and quick tool to analyze extended coastal tracts, and prioritize investments for prevention measures or for further high-resolution analysis**.**

1. Introduction

The Indian Ocean Tsunami (IOT) of December 2004 clearly demonstrated that a large teletsunami can have major impacts on low lying coastal areas of those countries that surround the ocean basin. Depending on local socio-economic and environmental conditions, the vulnerability to, and impacts of a tsunami at any given location can be highly variable (UNEP, 2005).

There are many definitions of vulnerability, but at the broadest level, it is agreed as meaning "potential for damage". Godshalk et al. (1991) describe vulnerability as "the susceptibility to injury or damage from hazards", while according to Mitchell and Cutter (1997) vulnerability is "the potential for loss or the capacity to suffer harm from a hazard. It can generally be applied to individuals, society, or the environment". The United Nations (1992) describe vulnerability as the "degree of loss (from 0% to 100%) resulting from a potentially damaging phenomenon".

The 2004 IOT caused highly variable damage within the coastal zones of nine countries from South East Asia (Indonesia, Thailand, Myanmar, Bangladesh, Sri Lanka, India, Maldives) to Eastern Africa (Kenya and Somalia) more than 4500 kms from its source (Nadim and Glade, 2006; Lovholt et al., 2006; Thanawood et al., 2006; Matsutomi and Sakakyama., 2006; Titov et al., 2005).

Given the low frequency of tsunamis and the potential scale of the affects, local and national government agencies faced with the task of developing appropriate tsunami disaster risk reduction strategies need appropriate tools to enable them to assess vulnerability at various scales. National and local administrations need specific tools to analyze existing vulnerability, prioritize prevention measures and address available financial resources in most critical areas.

For a tsunami of any given magnitude, the vulnerability of exposed coastal areas may be estimated by taking into consideration all human and environmental factors that contribute to the expected level of damage. The choice of factors that can/should be analysed is dependent on the scale and the accuracy of the results required by decision makers. For example, the vulnerability of a single building may be assessed via an analysis of factors related to its physical features (e.g., construction material, number of stories etc). Conversely, assessment of the vulnerability of an entire coastal region requires other datasets at completely different scales (e.g., land cover, coastal geomorphology etc). Consequently, the types and scales of analysis influence the volumes and accuracy of data needed. Outputs from the vulnerability assessment process can be easily displayed via simple, clear thematic maps (Cutter, 2003; Williams and Alvarez, 2003).

At present, methods of tsunami vulnerability assessment are mainly undertaken at high spatial resolution (Dall'Osso et al., 2009a; Dall'Osso et al., 2009b; Dominey-Howes, et al., in press; Garcin et al., 2008; Taubenbock et al., 2008; Aitkenhead, 2007; Dominey-Howes and Papathoma, 2007; Papathoma et al., 2003; Papathoma and Dominey-Howes, 2003; Papadopoulos and Dermentzopoulos, 1998) using data at the scale of individual buildings or infrastructur units. Data are normally gathered through field surveys and direct census analysis. Due to their high resolution and the time required for data collection, these methods are well suited to the analysis of vulnerability 'hot spots' such as limited portions of urbanized areas or single villages. Those hot spots must be chosen among all exposed coastal sites, on the basis of specific LGAs requests, or scientific interests based on past tsunamis.

At the other end of the spatial scale, analysis at regional or national levels use satellite imagery or topographic data to identify and map areas that are explosed to or at risk from tsunami flooding (Theilen-Willige, 2008; Chandrasekar et al., 2007; Theilen-Willige, 2006). However, within those areas, the vulnerability level depends also on the environmental and socio-economic variability, which is not considered by most of such approaches. Land cover data were considered by Wood (2009), in a study aimed at identifying the tsunami prone land along the Oregon coast of the United States. Wood extracted land cover data from ETM Landsat satellite images and coupled these with pre-existing tsunami-hazard information. Although this approach is one of the few to consider the integration of socio-economic and environmental data, it is based on the use of a pre-existing database of tsunami hazard information which is highly unikely to be available elsewhere, making the application of Wood's approach problematic.

This paper outlines an innovative new method for undertaking rapid, regional to national scale assessments of coastal vulnerability to tsunamis that may be applied anywhere. The data needed to undertake the vulnerability analysis are easily gathered from readily available ASTER satellite images (Advanced Spaceborn Thermal Emission and Reflection Radiometer) and 3s-SRTM-v3 (3 arc-seconds Shuttle Radar Topography Mission, version 3) digital elevation models. Results of the vulnerability assessment can be displayed via GIS as a series of thematic maps at a scale of 1:150,000 and a horizontal resolution of 90 m. Our approach goes beyond that of Wood (2009) as it exploits the flexibility and higher resolution (both spectral and geometrical) of the newer ASTER sensor. It has wide applicability since it is not predicated on the need for detailed tsunami hazard or tsunami inundation zones.

We applied test our new method along the entire western coast of Thailand as part of the CRATER Phase II (Coastal Risk Analysis for Tsunamis and Environmental Remediation) project. Because of the large geographic region involved in the original CRATER project, the coast of Thailand was divided in to 12 separate mapped areas. However, here we just present a case study of Phuket Island to illustrate the capability of our approach. Readers interested in the results for the other coastal zones of Thailand zones can contact the authors and ask for the CRATER final report.

For our inundation scenario we considered a single wave (rather than wave train) generating a run-up up to 25 m a.m.s.l. (above mean sea level) inundating to a distance of 5 kms. Given the characteristics of the inundation generated by the 2004 IOT (Hori et al., 2007; Siripong, 2007; Lovholt et al., 200; Titov et al, 2005) we consider this to be the "worst credible case" for a tsunami affecting the west coast of Thailand.

2. The Developed Method

2.1 Measuring the vulnerability level: required data

Data contributing to the general vulnerability level has been chosen on the basis of the analysis scale (1:150.000), the extent of the study area, and previous post-tsunami surveys. We analyzed the vulnerability of coastal zones and inland areas using the following:

- for coastal zones: infrastructural, geomorphological and ecological features;
- for inland areas: land use, topography and distance from the shoreline.

Coastal zones: According to field surveys undertaken after the 26th of December IOT, the highest damages occurred in urbanized areas (harbors, wharfs, aquaculture plants), especially if located behind long and flat shorelines (Ghobarah, 2006; Matsutomi et al., 2006; Darlymple and Kriebel, 2005; Thanawood, 2004). In particular, beaches experienced very high changes during backwash, which eroded sediment and deposited it over coral reefs (UNEP, 2005). This scouring effect appeared to be more evident for long and wide-open beaches in flat areas, rather than in small bays with pocket beaches. Strand et al. (2005) suggested that this could be due to the higher amount of water flowing inland and back to the sea after the inundation. Coastal geomorphology was found to be an important factor controlling the tsunami effects also by Nainarpandian et al. (2007).

Another key-role of coastal ecological features was played by mangrove forests, that suffered some damages from the wave impact and the strong sedimentation rate, but also behaved as a protection for inland areas. Mangrove roots and branches reduced the flow velocity and trapped sediment and debris (Rabindra et al., 2008; Cochard, 2008; Bhalla R.S., 2007; EJF, 2006; Chang et al., 2006; UNEP, 2005).

Inland areas: the vulnerability of inland areas is strictly dependent on the overall value of each land portion that could be partially or completely damaged during the inundation. That value includes socio-economic aspects (population, buildings, economic resources) and environmental features (natural resources) (Wood, 2009). Given our scale of analysis, we considered land use as a proxy for the value of inland areas.

The inland topography (intended as elevation above mean sea level) was also considered as a basic element for understanding what will be the depth of water during inundation at any particular point within the study area.

Finally, the distance from the shoreline was also considered as a factor affecting the vulnerability of inland areas because of the dissipation of the water flow energy, caused the friction effect of soil during the inundation (Iverson and Prasad, 2006).

2.2 Data gathering and analysis: ASTER imagery and SRTM elevation model

We used a set of 15 daytime ASTER images to extract information about coastal geomorphology, land use and distance from the shoreline along the entire western coast of Thailand. Phuket Island was fully covered by a single image, taken on the 8th of February 2005 (Fig. n 1a).
The ASTER sensor has a spectral resolution of 14 bands. The first three bands are in the visible-near infrared (VNIR) and they have a spatial resolution of 15m. Six are in the shortwave infrared (SWIR) with a spatial resolution of 30 m. Five are in the thermal infrared (TIR), with a spatial resolution of 90 m (Abrams, 2000; Yamaguchi et al., 2001). Each image covers an area of 60x60 km and the repeat cycle is 16 days.
During the first phase of the work, we used the software ENVI 4.3 to plot all of the ASTER images (colour composite scheme RGB: 3N, 2, 1) and generate a mosaic. We then saved it into a geotiff file and imported into the GIS. The whole GIS database we built was georeferenced using ASTER pictures as the cartographic base of reference.
Data about topography were obtained through the use of a 3s SRTM-v3 Digital Elevation Model (DEM), version-3. SRTM is an interpherometric DEM produced by NASA (http://seamless.usgs.gov/products/srtm3arc.php#download). The SRTM DEM we used has a horizontal geometrical resolution of 90 m and a reported vertical accuracy of 10 m (root mean square error). Version 3 has been adjusted for radar speckle errors that often affect coastal flat areas. SRTM DEM have been effectively used in several flood studies (Theilen-Willige B., 2006; Demirkesen et al., 2007). Sanders (2007) compared performances of SRTM DEM with other types of on-line available DEMs (1/9 s IfSAR, 1/3 NED, 1 s NED and 1 s SRTM) and highlighted utility of SRTM data as a global source for flood modelling purposes, especially after correction for radar speckle errors. Furthermore, the SRTM vertical accuracy for relatively flat terrain was found to be better than in high relief areas, which is advantageous for coastal flood studies (Sanders, 2007).
Coastal zones: we extracted data about coastal zones via a visual photo-interpretation of the ASTER images. We digitazed the whole coastline and divided it into 6 geomorphologic classes (Fig. n 1a) expressing different vulnerability levels to tsunami. Photo-interpretation was undertaken at the maximum detail level allowed by ASTER band 1 to 3N (15 m), which is consistent with our

scale of analysis. We assigned each class a vulnerability score (CV, Coastal Vulnerability score) ranging between 1 (minimum vulnerability) and 5 (maximum vulnerability) (Tab. n 1).

Land use: ASTER images have been widely used for the supervised classification of land use type (Yuksel et al., 2008; Buhe et al., 2007; Jianwen and Bagan, 2005), in natural hazard risk analysis (Kamp et al., 2008; Hubbard et al., 2007; Liu et al., 2004), but not to study tsunami vulnerability assessment. We extracted data about land use via a combination of visual photo-interpretation of the ASTER images (within the GIS) and a supervised pixel-based classification of bands 1 to 9 with ENVI 4.3. We needed to undertake visual analysis of some of the required land use elements because the ENVI classification algorithm could not distinguish between the spectrums of agricultural fields and urban areas. We could however, identify urban areas and divide them into two sub-classes according to building density. Different density levels were identified according to all the rules of the photo-interpretation technique, based upon building colours, textures and shapes. Where present, clouds and cloud shades (where no data was recognizable) have been digitazed and added to the GIS database (Fig. n 1b).

The ENVI 4.3 classification algorithm was then applied to extract the following land use classes: (a) agricultural fields, (b) forests, (c) lakes, channels and water pools and (e) mangroves. Before running the classification algorithm, ASTER bands 4 to 9 were registered and re-sampled at the geometrical resolution of 15 m, using bands from 1 to 3N as a reference and a set of 15 ground control points over Phuket Island. We also generated a new band for the Normalized Difference Vegetation Index (NDVI), that is calculated as follows:

$$\mathrm{NDVI} = (\rho_{IR} - \rho_{R}) / (\rho_{IR} + \rho_{R})$$

Where:

- ρ_{IR} is the spectral reflectance measurement of the near infrared band (band 3N in ASTER images);
- ρ_{R} is the r is the spectral reflectance measurement of the visible red band (band no. 2 in ASTER images).

The use of NDVI allows the emphasis of the relation between spectral absorption of chlorophyll within the red spectrum and its reflectance within the near infrared one, that is a direct function of the biomass density and photosynthetic activity (Rouse et al., 1973). Visible bands, re-sampled bands from 4 to 9 and the NDVI band were then been joined into a single "metafile" used for the supervised classification process.

The Regions Of Interest (ROI), that are required for the supervised process were selected following field surveys undertaken on Phuket Island in 2005 and cross-checked using 2008 Quickbird images available on-line at Google Earth. We chose 5 to 10 ROIs for each of the four land use classes identified (water, mangroves, agriculture, forest). The exact number of ROI for each class was decided and validated following the results of the spectral separability test, based on the Jeffries-Matusita index (Richards, 1999).

Once a validated set of ROI per each land-use class was identified, we could run the classification process (we used the "maximum likelihood" algorithm). As an output, ENVI 4.3 classified every image pixel into one of the four land use classes. We verified the reliability of outputs using the confusion matrix method (Van Genderen et al., 1978). The overall classification accuracy (the ratio between the number of pixels correctly classified and the total number of pixels) was 98%. Results of the classification and photo-interpretation were joined together into a single land use map (Fig. n 1b).

A Land Use Vulnerability score (*LUV*), ranging from 1 to 5, was assigned to each land use class (Tab. n. 2). Note that low scores are given to forest and mangroves, because although they have an important natural value, the damages they would suffer have been scaled with respect to those of urbanized areas, that have been considered the most vulnerable. The class "water" includes pools for aquaculture, that together with agriculture is one of the primary economic industries for Thailand. Both aquaculture plants and agricultural crops suffered heavy damage during the 2004 tsunami (Wartnitchai et al., 2005, Mapa et al., 2005). Highest vulnerability scores are assigned to urban areas. To emphasize the difference between the vulnerability of buildings and other land use classes, we left a gap in the scores scale (none of the classes has a vulnerability score of 3).

Topography: SRTM data were downloaded in a .tiff format and converted to a vectorial dataset through ArcGIS 9.2. The whole study area was dived into cells with sides of 90 meters associated with an average topographic value expressed in meters above mean sea level (m a.m.s.l.). Since the vertical domain of analysis includes only areas lower than 25 m a.m.s.l., all of the cells up to 25 m a.m.s.l. were extracted from the DEM and displayed in a new map, after being divided into equal intervals of 5 meters. Elevation Vulnerability scores (EV) were assigned to each interval according to Table n 3 (Fig. n 2a).

Distance from the shoreline: Since the maximum wave inundation 2004 exceeded 3 kms at Khao Lak, Phang-Nga province (Siripong, 2007), we set the horizontal domain of the analysis to the 5th kilometer inland. Using the ArcGIS 9.2 "buffer" tool, we divided the first 5 kilometers of land into 5 belts, parallel to the shoreline and having each a width of 1 Km (Fig. n 2b). To each belt we gave a Distance Vulnerability score (DV) ranging from 5 (maximum vulnerability, from the shoreline until the 1st kilometre inland) to 1 (minimum vulnerability, from the 4th to the 5th kilometre inland) (Tab. n 4). Please note that the final domain of the analysis is given by a spatial intersection between the horizontal and the vertical domains, which means that we assessed the vulnerability of only those areas that fall within 5 kilometers from the shoreline AND have an elevation smaller than 25 m a.m.s.l.

2.3 Calculating the overall vulnerability level

We calculated the vulnerability of the coastline and inland areas with two different indexes.
The coastline vulnerability index scores are summarized in Table n 1.
An overall vulnerability index of inland areas (Vtot) was calculated by joining together contributions made by single vulnerability factors (land use, topography, distance from the shoreline). This index was assigned to each land portion generated through a geometrical intersection among the three factor maps. The intersection was executed though the ArcGIS 9.2 tool called "intersect". This process generated a new polygon shapefile, containing only those areas that were common to all the three factor maps. As a consequence, we calculated a Vtot value for all of the areas falling within the first 5 kilometers of the shoreline and having a topographical elevation smaller than 25 meters. Vtot scores were calculated as follows:

$$V_{tot} = 2LUV \pm EV \pm DV \qquad V_{tot} \in [4,20]$$

We gave LUV a weight of 2 because it gives information on the socio-economic and environmental value of affected areas, while EV and DV just set the domain and the entity of the inundation.

3. Results

Vulnerability scores we gave to different coastal morphologies (CV) and different type of inland areas (Vtot) have been stored into a GIS, together with all inputs and the ASTER image. We used ArcGIS 9.2 to display results in form of vulnerability maps, through a colour-coded scale. Vulnerability scores of inland areas have been divided into 5 equal intervals. That division has been made through one of the different GIS applications for graphic representation on quantitative data. ArcGIS users could display vulnerability scores in a different way without modifying the numerical information on Vtot, which is the main result of the analysis. Figure n 3 shows the geographic range of those vulnerability classes across all Phuket subdistricts (tambon). The surface extent of different vulnerability classes in every subdistrict is summarized in Table n 5.

The most vulnerable areas are located in the southern part of Phuket Island, within the subdistricts of Chalong, Wichit, Talat Nua, Talat Yai and Ratsada, where the city of Phuket is located. In that area most of the inundated zones have "High" and "Very High" vulnerability scores. Excluding the peninsula of Wichit and the mangroves in Ratsada, the coastline vulnerability index (CV) of that area ranges between 4 and 5.

On the east coast, the bays of Karon, Patong, Kamala and Choeng Tale have mainly "High" and "Very High" vulnerability scores. However, the extent of the inundated area is much smaller than at Phuket Town and CV values are average (CV=3).

The inundated areas of Sa Khu and Mai Khao have basically an "Average" Vtot, except of the Phuket International Airport, which is located at the boundary between the two subdistricts and has "High" and "Very High" scores. CV values ranges between 4 and 5, aside from a small mangroves area at north and the promontory in the southern part of Sa Khu, which would not be inundated.

On the north-western coast Vtot is mainly "Low" to "Average" although it rises to "Very High" at Pa Khlok Town. CV reaches very high (CV=5) scores at several beaches within the subdistrict of Pa Khlok, as well as at Pa Khlok Town. Within the subdistrict of Ko Kaeo Vtot and CV are "High" to "Very High".

4. Discussion and Conclusion

The method we described allows to generate tsunami vulnerability maps at the scale of 1:150.000 covering whole regional or national areas. Maps show the patterns of two different tsunami vulnerability indexes: one for coastal zones (CV) and one for inland areas (Vtot). End-users will need to consider both indexes to have a general view of the vulnerability distribution.

We showed an application on Phuket Island, Thailand. Required input have been entirely extracted from satellite products: a visual photo-interpretation of ASTER images provided data on coastal morphology, while the land use was obtained through a supervised classification of ASTER bands from 1 to 9 (plus a NDVI band); we derived topography from an SRTM DEM and calculated the distance of inland areas from the shoreline through a GIS application.

As shown by the map in Figure n 3, most vulnerable inland areas resulted to be located in highly urbanized zones close to the shoreline. However, not all urbanized areas have been judged highly vulnerable, since also topography and distance from the coast have been considered in the assessment. Most critical areas are those nearby the city of Phuket (subdistricts of Talat Yai, Talat

Nua and Chalong) and all the bays on the western coast (subdistricts of Karon, Patong, Kamala). All these areas are located right on the coast, they have a rather flat topography and an high density of buildings.

The only areas in which Vtot and CV scores could not be calculated are those covered by clouds at the moment the images were taken. However all the chosen pictures have a cloud coverage lower than the 10%.

The scenario we adopted consists in a "flat" inundation, given by a single wave hitting every point of the shoreline with the same height and able to reach inland areas located up to 25 meters a.m.s.l., within the first 5 Km from the shoreline. The choice of assuming the inundation to be "flat" and given by a single wave is an approximation that we judged to be acceptable, since at the moment this study was undertaken neither a probabilistic tsunami assessment nor a wave numerical simulation were available for such a large area. As a consequence, vulnerability maps that can be created through this approach leave aside the location of the tsunami generation site and the main direction of the tsunami propagation.

However until a probabilistic scenario is not available it will not be possible to predict accurately all of the tsunami features, but LGA's need to address such vulnerability issues now. This method may thus find many applications as a precautionary tool for supporting decision makers in long term urban planning and emergency strategies.

The use of remote sensing data allows to asses vulnerability to tsunami on very extended areas, at national or even at ocean basin scale, with a relatively small amount of time and money. To our knowledge, this is the first work aimed to the creation of a methodology for tsunami vulnerability analysis at a medium-small scale, coupling land use data from ASTER imagery and SRTM-3 topography. Most of the existing methods work at the scale of single building/infrastructure and can be applied only to pre-selected spot areas. A low scale approach like the presented one may be useful to analyze more extended coastal zones and decide whether and where further high-detail analysis should be undertaken.

Furthermore, because of world-coverage and availability of the input data required, this method can be applied anywhere and it doesn't need any pre-existing information about tsunami inundation-prone zones.

Finally, the use of GIS allows to generate interactive maps, that can be queried by different type of end –users and easily kept updated through years, which is basic for low-frequency hazards such as tsunamis.

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Figures:

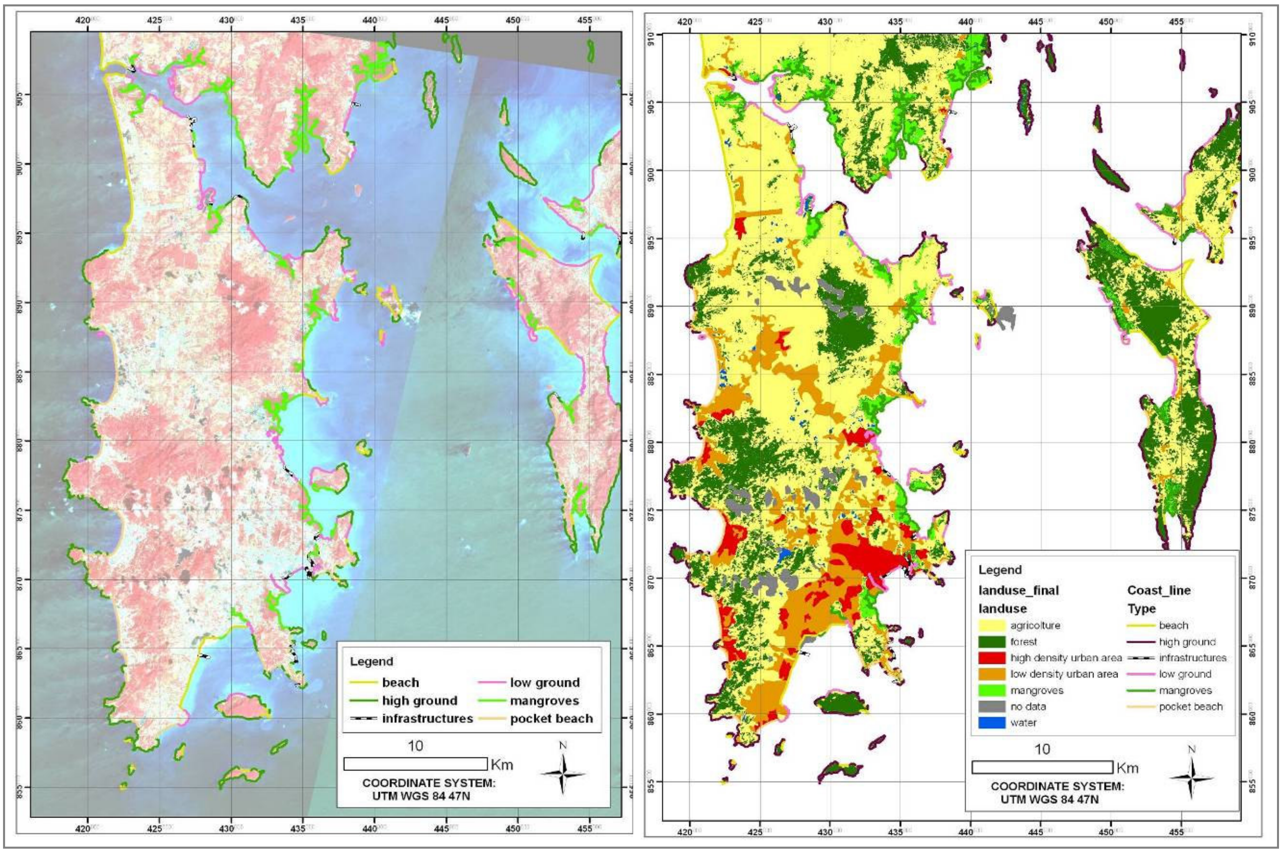

Figure 1 – (a) The ASTER image used for Phuket Island (colour composite scheme RGB: 3N, 2, 1). Results of the photo-interpretation of coastal features are shown with different colours along the shoreline. (b) Land use map of Phuket Island: the classes of "agriculture", "forest", "mangroves" and "water" have been obtained though the multispectral classification of ASTER bands 1-9 and NDVI index, while urbanized areas and clouds have been digitazed via photo-interpretation

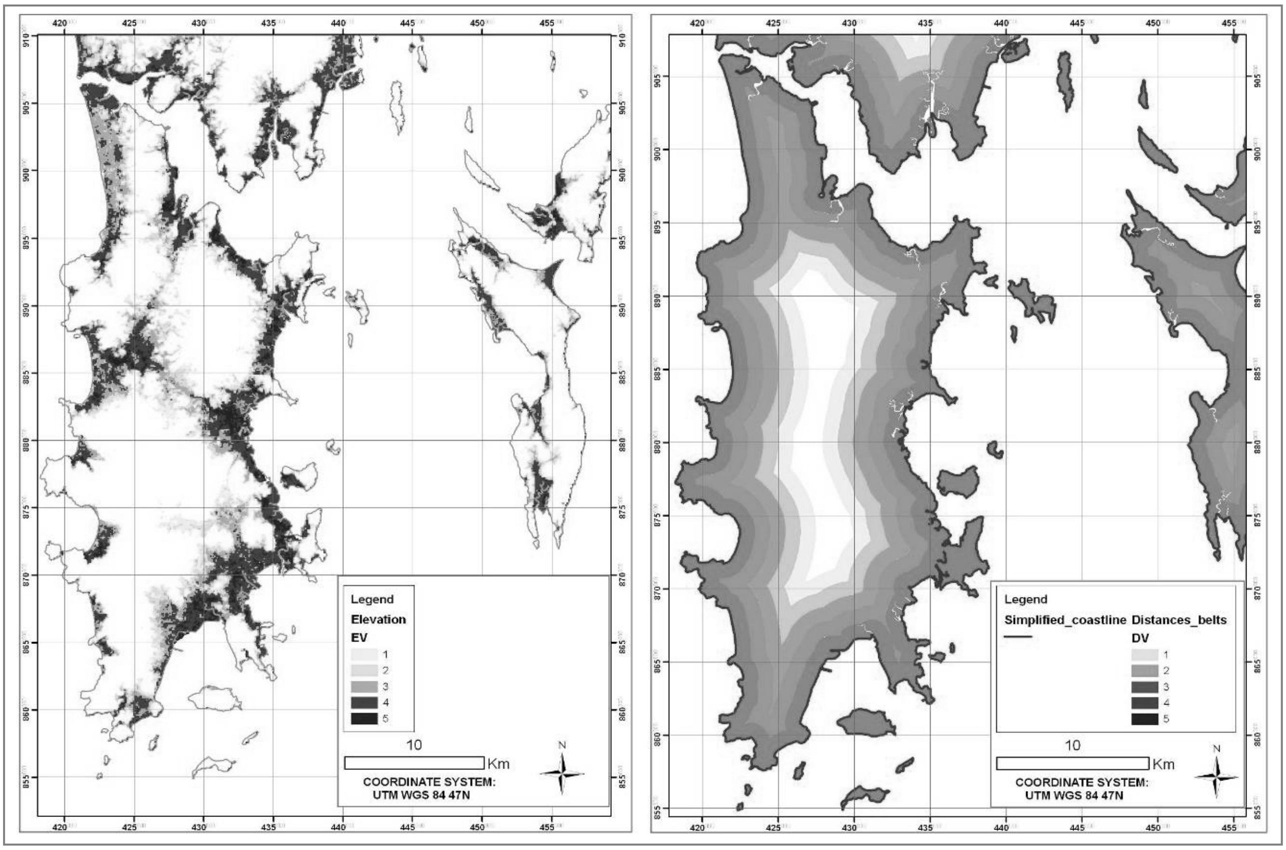

Figure 2 - (a) An "Elevation Vulnerability" score (EV) ranging between 1 and 5 has been given to all zones lower than 25 m a.m.s.l. We set EV intervals according to Table n 3. (b)We divided the first 5 kilometers from the shoreline into 5 belts, each 1-Km wide. To every belt we gave a Distance Vulnerability score (DV) ranging from 5 (from the shoreline until the 1st kilometre inland) to 1 (from the 4th to the 5th kilometre inland).

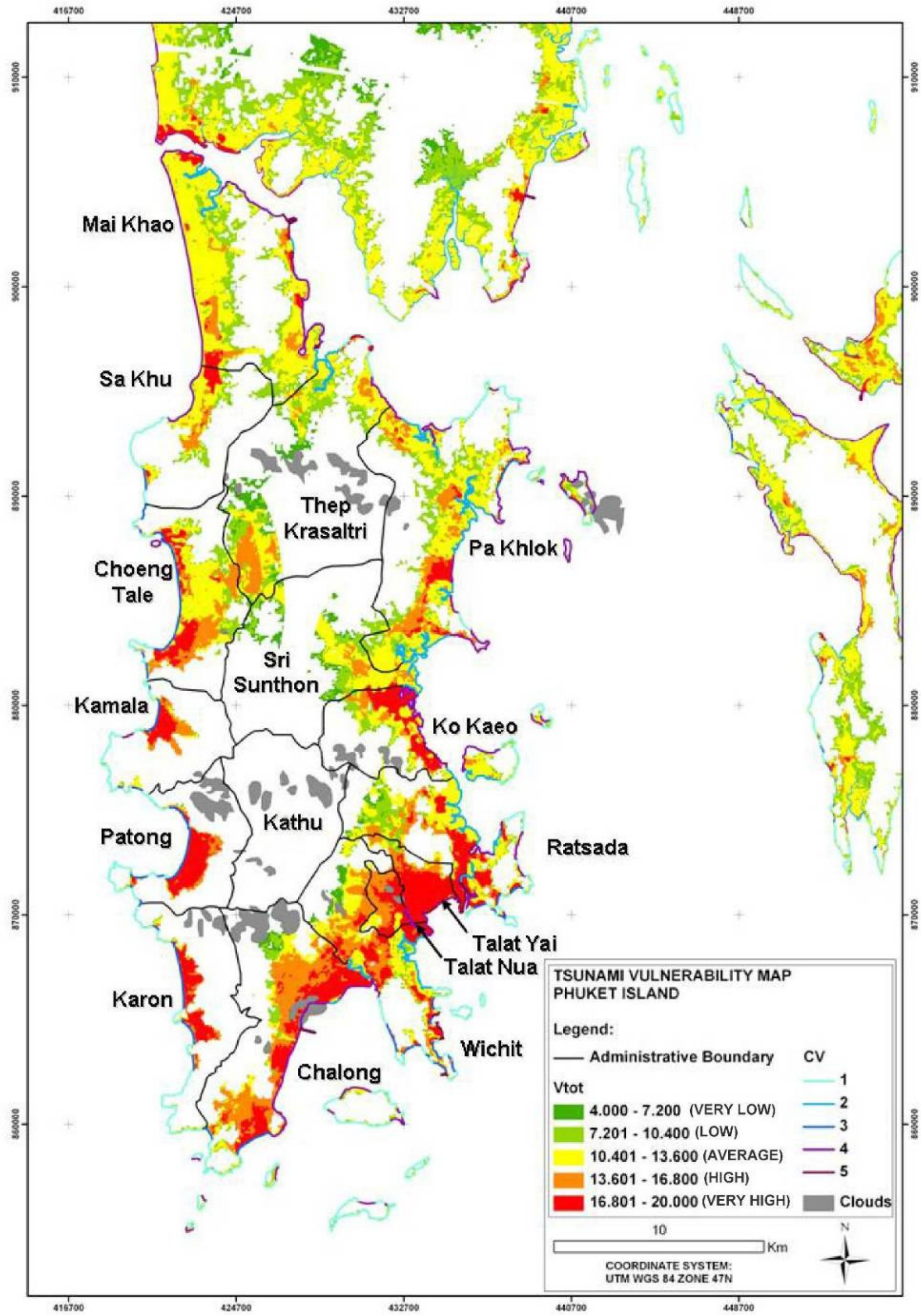

Figure 3 - Vulnerability map generated for Phuket Island, obtained as an intersection of data shown in Figures n 1b, 2a and 2b.

Tables:

Table 1 - Coastal Vulnerability scores (CV) given to each coastline class.

Coastline features:	**Infrastructure**	**Beach and Low Ground**	**Pocket Beach**	**Mangroves**	**High Ground (sea cliff)**
CV score:	5	4	3	2	1

Table 2 - Land Use Vulnerability scores (LUV) given to each land use class.

Land Use classes:	**Urbanized Areas (high density)**	**Urbanized Areas (low density)**	**Agriculture, Lakes and Freshwater**	**Forest and Mangroves**
LUV score:	5	4	2	1

Table 3 - EV scores have been given to all zones lower than 25m a.m.s.l.

Elevation (m a.m.s.l.)	**[0-5]**	**[5-10]**	**[10-15]**	**[15-20]**	**[20-25]**
EV score	5	4	3	2	1

Table 4 - Vulnerability scores (DV) given to different belts of distance from the shoreline.

Distance from the shoreline (Km)	**[0-1]**	**[1-2]**	**[2-3]**	**[3-4]**	**[4-5]**
DV score:	5	4	3	2	1

Table 5 - Surface extent of different vulnerability classes in each Phuket subdistrict.

Subdistrict	Land surface (Ha) with V_{tot} = [4-7.2] **(VERY LOW)**	Land surface (Ha) with V_{tot} = [7.2-10.4] **(LOW)**	Land surface (Ha) with V_{tot} = [10.4-13.6] **(AVERAGE)**	Land surface (Ha) with V_{tot} = [13.6-16.8] **(HIGH)**	Land surface (Ha) with V_{tot} = [16.8-20] **(VERY HIGH)**
Chalong	178.8	47.6	293.8	996.6	705.9
Choeng Tale	10.5	230.6	662.8	468.7	286.8
Kamala	0	23.3	55.8	129.9	146.3
Karon	0	26.3	54.0	108.7	274.7
Kathu	0	0	0	0	0
Ko Kareo	3.3	141.9	254.8	136.3	332.5
Mai Khao	2.3	716.4	1966.2	301.4	149.2
Pa Khlok	2.59	741.9	1521.3	569.5	193.8
Patong	0	23.1	18.1	107.4	347.9
Ratsada	49.5	318.2	715.3	281.9	418.5
Sa Khu	3.0	212.4	309.1	114.8	80.2
Sri Sunthon	188.7	313.6	502.5	118.7	16.1
Talat Nua	0	3.0	68.0	193.0	190.4
Talat Yai	0.9	32.7	48.6	120.2	466.8
Thep Krasaltri	231.3	582.4	749.1	391.9	11.1
Wichit	79.2	137.2	626.3	572.1	353.0

Paper n. 2

A revised (PTVA) model for assessing the vulnerability of buildings to tsunami damage

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A revised (PTVA) model for assessing the vulnerability of buildings to tsunami damage

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Abstract

The Papathoma Tsunami Vulnerability Assessment (PTVA) Model (Papathoma, 2003) was developed in the absence of robust, well-constructed and validated building fragility models for assessing the vulnerability of buildings to tsunami. It has proven to be a useful tool for providing assessments of building vulnerability. We present an enhanced version (PTVA-3) of the model that takes account of new understanding of the factors that influence building vulnerability and significantly, introduce the use of the Analytic Hierarchy Process (AHP) for weighting the various attributes in order to limit concerns about subjective ranking of attributes in the original model. We successfully test PTVA-3 using building data from Maroubra, Sydney, Australia.

1. Introduction

Our urban environments are susceptible to damage associated with extreme natural hazards. As populations grow and our cities expand – often in to more hazardous areas, the exposure of our built environment increases. The 2004 Indian Ocean tsunami (2004 IOT) was catastrophic. In some areas (e.g., Banda Aceh city), near complete devastation of the urban landscape occurred.

Abandoning coastal regions affected by hazards such as tsunami is simply not possible for a variety of reasons. Therefore, in order to minimise the losses that will be associated with future tsunami, assessment of building vulnerability from which estimates of probable maximum loss (PML) may be estimated are required. Estimating vulnerability (and PML) is important because they are used to determine disaster preparedness and response strategies, to develop appropriate mitigation efforts such as land-use zoning policies, and in the development and application of building codes and regulations.

Recent reports state there is a need for credible fragility models and laboratory data to understand the interaction of tsunami with the built environment (Bernard et al., 2007, Grundy et al., 2005). To our knowledge, no robust, well-constructed and validated building fragility model for assessing the vulnerability of buildings to tsunami has been developed. Whilst such models are under construction, decision makers (urban planners and emergency managers) are still in need of tools to assist them to make 'first order' assessments of the vulnerabity of structures so that they may begin to establish appropriate risk management strategies. Doing nothing whilst waiting for validated models is not an option.

1.1 The original Papathoma Tsunami Vulnerability (PTVA) Model

The Papathoma Tsunami Vulnerability Assessment (PTVA) Model was developed to provide first order assessments of building vulnerability to tsunami and the output of the model assessment is a 'Relative Vulnerability Index' (RVI) score for each building (Papathoma, 2003; Papathoma and Dominey-Howes, 2003; Papathoma et al., 2003). The 2004 IOT, although catastrophic, provided a valuable opportunity for the PTVA Model to be tested and evaluated (Dominey-Howes and Papathoma, 2007). The attribute fields within the model were well correlated with the damage to building structures experienced during the 2004 IOT (at least where the model was applied). Thus, the model performed very well during a real-life field evaluation. The attributes within the PTVA Model are considered appropriate therefore, for use in assessing vulnerability and is useful in the absence of fully validated engineering vulnerability assessment models. The model has recently been applied and tested in the United States (Dominey-Howes et al., in press).

1.2 Aim of this work

The aim of this paper is to revise the original PTVA model to take account of newly published data about attributes that affect building vulnerability (not available when the original model was developed by Papathoma) to tsunami and to introduce a mathematical mechanism (an Analytic Hierarchy Process or AHP) for weighting the various attributes in order to limit concerns about subjective ranking of attributes in the original model. These modifications will enable the development of a second generation PTVA model.

We test the new version of the model (PTVA-3) using building data collected at Maroubra, Sydney. This case is not meant to be extensive, merely indicative to determine that the model works. Dall'Osso et al., (in review) provide a comprehensive application of the model in Sydney. In our work, when we refer to PML, we are referring only to the maximum loss of 'buildings' that will be associated with our given scenario. We are fully aware that for many, PLM will also include human life, economic loss and so forth.

2 Structure of the revised model and its attributes

In this revised PTVA-3 Model, the 'Relative Vulnerability Index' (RVI) score of a building is calculated as a weighted sum of two separate elements:

i. the *vulnerability of the carrying capacity of the building structure* [by which we mean its structural vulnerability] (SV) - associated with the horizontal hydrodynamic force of water flow (the core of the original PTVA model); and

ii. the *vulnerability of building elements due to their contact with water* (WV). This is an entirely new part of the model.

It has been shown that a building with a weak structure (e.g., with a limited number of stories, weak construction material such as timber, with shallow foundations, of poor preservation condition, etc.) can experience extreme damage even though it is only partially submerged. This is because of the hydrodynamic pressure of the flowing water and/or the impact of floating objects such as cars, or boats. (Dalrymple, 2005; Warnitchai, 2005). On the other hand, a building with a very resistant structure (e.g., three or more stories, structure made of reinforced concrete, with deep pile foundations, etc.) that is totally submerged by water might loose up to 40 - 50% of its value, without sustaining any structural damage (Olivieri and Santoro, 2000).

Consequently, the RVI score of buildings using this revised PTVA-3 Model is calculated as:

$$RVI = \frac{2}{3}(SV) + \frac{1}{3}(WV) \tag{1}$$

where:

- "SV" is the standardized score for the *structural vulnerability*, and
- "WV" is the standardized score for the *vulnerability to water intrusion*.

Both "SV" and "WV" range between 1 and 5. A weighting coefficient equal to 2/3 has been assigned to SV, because heavy damage to the carrying capacity of a structure might reasonably lead to the need for expensive repair works, with costs that might be equal to, or greater than the total value of the building. We assume the contribution to vulnerability from water intrusion is equal to 1/3 and this is consistent with the findings of Olivieri and Santoro (2000).

2.1 Calculation of structural vulnerability and its attributes

The structural vulnerability "SV" of a building is determined by the:

i. *attributes of the building structure* (Bv);

ii. *depth of flood water* (Ex) at the point where the building is located; and

iii. the *degree of protection* (Prot) that is provided to that building by any barriers.

"SV" is calculated as follows:

$$SV(1, 125) = (BV) \cdot (Ex) \cdot (\text{Prot}) \tag{2}$$

where:

- "Bv" is a standardized score ranging from 1 (minimum vulnerability) to 5 (maximum vulnerability). "Bv" depends on building attributes that influence flood resistance;
- "Prot" is a standardized score for the level of protection that is provided to the building by any barriers. "Prot" ranges between 5 (no protection) and 1 (maximum protection).
- "Ex" is the standardized score for the exposure. Exposure is given by the depth of water expected at the building location. "Ex" ranges between 1 and 5 (1 = minimum water depth, 5 = maximum water depth); and

The calculated value of SV (1 - 125), after being re-scaled to the range (1-5) (Table 1), is inserted in to Eq. (1). It is important to note that in the event that a building is very well protected (with Prot = 1), its final "SV" value will be 5 times less than if no protection were present (Prot = 5). This is consistent with the degree of fragility that Reese *et al.*, (2007) calculated for 'shielded' and 'exposed' reinforced concrete buildings in Java following the 2005 tsunami.

Our inclusion of specific attributes in "Bv" and "Prot" was based on the original PTVA Model, on results from recent post-tsunami field and our expert judgment based on 2004 IOT post-event survey experience.

2.1.1 Building Vulnerability ("Bv")

The "Bv" score of each building was calculated by considering the contributions made by the following attributes (Table 2):

1. *Number of Stories (s)*: multi-storey buildings normally need to have more resistant load bearing capability than single storey buildings, because of the larger weight that must be carried by these taller structures.

2. *Building Material and Technique of Construction (m)*: typical Australian buildings have structures that are made of reinforced concrete, a double or a single layer of bricks, or timber. According to available post-tsunami field surveys, the most resistant structures were those made of reinforced concrete, followed by double or single bricks. Buildings made of timber were the most vulnerable (Reese et al., 2007; Dominey-Howes and Papathoma, 2007; Rossetto et al., 2006; Ghobarah et al., 2006; Matsutomi et al., 2006; Dalrymple and Kriebel, 2005).

3. *Ground Floor Hydrodynamics (g)*: following the 2004 Indian Ocean tsunami, building surveys in Thailand noted that buildings with an open plan ground floor and/or open-breakable accesses (such as doors, windows) decreased the wave impact, allowing the wave to pass through the ground floor. This significantly reduced structural damage (Darlymple and Kriebel, 2005).

4. *Foundations (f)*: deep foundations can resist more effectively the scouring effect of water flow and can counter the impact of a wave on building walls. During the 2004 tsunami, buildings with shallow or surface spread foundations suffered the heaviest levels of damage (Darlymple and Kriebel, 2005; Warnitchai, 2005; Reese et al., 2007).

5. *Shape and Orientation of the building footprint (so)*: after the 2004 tsunami it was clear from several field surveys that buildings having specific shapes (e.g., hexagonal, triangular, rounded, etc.) suffered lighter damage than long rectangular or "L" shaped buildings whose main wall was orientated perpendicular to the direction of flow (Warnitchai, 2005; Dominey Howes and Papathoma, 2007).
6. *Movable Objects (mo)*: during inundation, movable objects (debris, cars, boats and even trucks) will be dragged around by the flowing water and pushed against buildings, causing heavy structural damage (Darlymple and Kriebel, 2005).
7. *Preservation Condition (pc)*: buildings which are in a poor state of preservation are generally expected to suffer heavier damage, especially if there are structural failures or deformations.

"Bv" attributes must be recorded for each building and a numerical value between -1 to +1 assigned to each (Tables 1 and 2 - Bv (original)). The use of positive and negative values for Bv attributes permits the expansion of the overall Bv score of buildings to a wider range. This is in line with the approach used by Cutter et al., (2003). Using this approach, we suggest that a building with '*average'* vulnerability is one that has a 'zero' score for each attribute (and which has no protection). Once a score has been assigned to each attribute, an initial value for "Bv" (ranging between -1 to +1) (Table 2) may be calculated through a weighted sum of all the attributes:

$$BV(-1,+1) = w_{1.} \cdot s + w_2 \cdot m + w_3 \cdot g + w_4 \cdot f + w_5 \cdot so + w_6 \cdot mo + w_7 \cdot pc \tag{3}$$

Where:

"W_i" is the weighting coefficient of each attribute.

Weights were calculated using the approach described in Section 2.3 (they can range between 1 and 100). After scaling to 1 (each weight is divided by the sum of all weights, that is 423), each weight was added to give Eq.(4):

$$BV(-1,+1) = \frac{1}{423}\left(100_{.} \cdot s + 80 \cdot m + 63 \cdot g + 60 \cdot f + 51 \cdot mo + 46 \cdot so + 23 \cdot pc\right) \tag{4}$$

This relation gives as a result, a value of "Bv" ranging from -1 to +1. In order to use "Bv" in Eq. (2) it must be rescaled to a range from 1 to 5 (Table 1 – Bv (scaled)).

2.1.2 The protection factor ("Prot")

The second element of Eq. (2) is the protection factor "Prot". Factors that affect the protection of a building are shown in Table 3 and described below.

1. *The building row (Prot_br)*: post-tsunami field surveys demonstrated that buildings located in rows further inland were somewhat shielded even when buildings in front of them collapsed (Dominey-Howes and Papathoma, 2007; Reese et al., 2007).
2. *The presence of a seawall (Prot_sw):* Darlymple and Kriebel (2005) noted that building damage from the 2004 tsunami in Thailand was significantly lower in places protected by seawalls. The design of the seawall was also important. For example, at the north of Patong Beach (Phuket Island), the seawall had a sloped face that essentially created a ramp for the tsunami to run-up across and over. In this case, there appeared to be no protective effect from the seawall to the buildings located landward of the wall.
3. *Natural barriers (Prot_nb)*: natural barriers appear to both reduce velocity and trap debris and heavy floating objects that would otherwise damage buildings (Matsutomi et al., 2006, Olwig et al., 2007, Tanaka et al., 2006).
4. *Presence of a brick wall around the building (Prot_w):* individual walls located around building structures (such as garden walls) although not specifically constructed to provide protection from flooding, do offer some protection from flood inundation (Dominey-Howes and Papthoma, 2007).

In the case of "Prot", the score range is from 0 (maximum protection) to +1 (no protection), because the presence of protection can only decrease the average vulnerability of buildings. Assigned scores are shown in Table 3.

An initial numerical value of "Prot" (ranging between 0 and 1) was obtained though a weighted sum of all protection factor scores. Thus:

$$\mathrm{Prot}(0,+1) = w_1 \cdot \mathrm{Prot\_br} + w_2 \cdot \mathrm{Prot\_sw} + w_3 \cdot \mathrm{Prot\_nb} + w_4 \cdot \mathrm{Prot\_w} \tag{5}$$

Again, weights were calculated using the approach described at Section 2.3 (they can range between 1 and 100). After scaling to 1 (each weight is divided by the sum of all weights, that is 301), each weight was added to give Eq. (6):

$$\mathrm{Prot}(0,+1) = \frac{1}{301}\left[100 \cdot (\mathrm{Prot\_br}) + 73 \cdot (\mathrm{Prot\_nb}) + 73 \cdot (\mathrm{Prot\_sw}) + 55 \cdot (\mathrm{Prot\_w})\right] \tag{6}$$

This relation gives as a result a value of "Prot" ranging from 0 to 1 (Table 1 – Prot (original)). In order to use "Prot" in Eq. (2) it must be rescaled to a range from 1 to 5 (Table 1 – Prot (scaled)).

2.1.3 The Exposure ("Ex")

The third and final part of Eq. (2) is exposure "Ex" that relates to the depth of the water flow at the point where the building is located. The level of structural damage is expected to increase with water depth because the pressure applied to the building and flow velocity are direct functions of flow depth (Fritz *et al*., 2006). Scores have been given to "Ex" according to Table 1 – Ex (original) and are then rescaled (Table 1 – Ex (scaled)).

2.2 Calculation of vulnerability to water intrusion

Once the floor of a building has been inundated, all the parts of that floor that are damaged by the water (including, in some cases, the adjoining walls) will need to be repaired or replaced. Thus, the overall vulnerability of a building to contact with water is clearly dependent on the number of floors that are inundated in each building (including the basement).

Consequently, we assign to "WV" a score that indicates what percentage of the floors of a building will be inundated (Table 3 – WV (original)). Hence, for each building:

$$\mathrm{WV}(0,+1)=\frac{(number\ of\ inundated\ levels)}{(total\ number\ of\ levels)} \tag{7}$$

The value of "WV" to be inserted in Eq.(1) has been obtained by re-scaling "WV (0, 1)" to a range between 1 and 5 and is given in Table 1 – WV (scaled).

Once "SV" and "WV" are obtained, the 'Relative Vulnerability Index' (RVI) score for each building is calculated using Eq. (1). The range of RVI values is rescaled to 5 equal classes and the final description of the RVI classes is given in Table 1.

2.3 Weighting of the attributes

It is obvious that the "Bv" attributes cannot have an equal effect on the vulnerability of a building. For example, the number of stories as well as the construction material, are much more important than the preservation condition, or the shape-orientation of the building. A concern associated with the original PTVA Model of Papathoma (2003) has always been whether the ranking of the attributes was appropriate. It must be clearly understood however, that in the original model architecture, the attributes were weighted using expert judgments developed from a review of the best available published literature dealing with building damage from tsunami.

To address concerns of subject weighting of the attributes however, weights have been recalculated here via pair-wise matches between each of the attributes. Comparisons between attributes were undertaken using an evaluation matrix by means of the M-Macbeth software, a specially designed platform for multi criteria analysis and decision-making (Bana e Costa *et al.,* 2004; Bana e Costa et Chagas, 2004).

MACBETH is the acronym of "Measuring Attractiveness through a Category Based Evaluation TecHnique", which is the goal of the Analytic Hierarchy Process. Through the use of the M-Macbeth software the difference of importance between two factors can be qualitatively evaluated using the following semantic categories: "extreme", "very strong", "strong", "moderate", "weak", "very weak" and "no difference".

In the revised PTVA-3 Model, M-Macbeth has been used only for performing pair-wise comparisons between attributes affecting the structural vulnerability of buildings, as well as their level of protection. Every single attribute has been compared with all the others, both for "Bv" and "Prot". A total of 21 comparisons for "Bv" and 7 for "Prot" were undertaken.

Based upon published results of post-tsunami field surveys, personal expertise and professional judgment, we undertook pair-wise comparisons between the attributes and evaluated their difference in importance using Macbeth semantic cathegories. Every single comparison is described and discussed in Dall'Osso and Dominey-Howes (2009). While we were performing the pair-wise matches, M-Macbeth was automatically looking for inconsistent judgments. When identified, inconsistencies were removed. Once all the comparisons were completed, the software calculated the relative weight of each attribute. The same process was repeated for the protection factors. Using this approach, weights for different attributes have been calculated, and the unavoidable subjective component of the decision making process has been reduced to a minimum.

3. Testing the method at Maroubra, Sydney

In order to test the effectiveness of our revised PTVA-3 Model, we applied the vulnerability assessment tool to the area of Maroubra, SE Sydney, Australia. As the design inundation scenario we assumed a hypothetical tsunami event that achieves a run-up of +5 m asl, occuring during the peak of the maximum high tide (+2 m asl). This is a purely "deterministic" scenario, since "probabilistic" approaches for estimating tsunami inundation for the study area have not yet been developed.

We used a Geographic Information System (GIS) in which to run the model analysis and present the results in map form. In order to build the GIS and run the model, the following data were obtained:

- A recent (2008) geo-referenced and ortho-rectified aerial image of Maroubra that was used as the geographical base of the study. The aerial images were useful when it was necessary to manually digitize building vector files and for obtaining specific building features needed by the model (e.g., shape and orientation of the building footprint, building row, the presence of movable objects and protection provided by natural barriers). These images were provided by Randwick local government authority;
- A Lidar Digital Elevation Model (DEM). The DEM was used to calculate the water depth above the ground surface by subtracting the ground elevation from the horizontal flood surface at specific grid (building) points.
- Attribute data for each building. The data included all factors required by Eq. (1). These datasets were not available from Randwick council and so we undertook field surveys to collect these data building-by-building; and
- A shapefile of polygons representing building footprints. Shapefiles were manually digitized by us. Building attribute data was then entered in to the GIS database for each building file.

Figure 1 displays the area of Maroubra that would be inundated by a tsunami achieving a run-up of +5 metres above sea level (m asl), during the maximum high tide. A relatively small area of Maroubra would be inundated by the tsunami in this scenario (27 hectares). The deepest inundation is confined to the beach strip running northeast - southwest. Water would be able to penetrate inland from the south, northwards up in to the Arthur Bryne Reserve. The largest area inundated by the tsunami in this scenario lies northwest of the northern end of Maroubra Beach and includes several blocks of commercial and residential structures. Water flow depth would be no greater than 3 metres above the ground surface throughout much of this area.

A total of 96 buildings of various types would be flooded by the tsunami in this scenario. The RVI score of each building is also displayed in Figure 1. It can be seen that just four individual buildings are classified as having a "High" RVI score. No buildings are classified as "Very High".

The large building at the intersection of Mons and Fenton Avenue is the Maroubra Ambulance Station. It is one of the buildings assessed as having a "High" RVI, even though its successful operation would be crucial in the event of a real tsunami emergency. In light of this study, Randwick Council might consider options for reducing the structural vulnerability of the ambulance station and could even consider relocation it outside the inundation zone.

4. Conclusion

The original PTVA Model (Papathoma, 2003) is a useful tool for providing initial assessments of the vulnerability of buildings. We have improved the PTVA Model in two ways. First, we have introduced an entirely new set of attributes that are now known to affect the vulnerability of buildings to damage in tsunami – those related to water intrusion. Second, we introduced a multi-criteria approach to the assessment of building vulnerability. This approach based on pair-wise comparisons between attributes – is a method typically used in multi-criteria analysis and Analytic Hierarchy Process (Saaty, 1986). Thanks to this technique, the contribution made by separate attributes to the overall structural vulnerability of a building can be compared via a rigorous mathematical approach. This avoids biases and reduces to a minimum the inevitable subjective component of every decision-making process and a concern associated with the original PTVA Model.

We have tested the revised method (PTVA-3) at Maroubra, Sydney and it has provided a clear approach for assessing the vulnerability of buildings to tsunami in the absence of fully validated fragility models.

Outputs of the PTVA-3 include thematic vulnerability maps displaying the Relative Vulnerability Index of every single building. Vulnerability maps may be used by Local Government Authorities (LGAs) for future urban planning, to develop emergency plans and decide whether further prevention measures should be considered. Insurance companies may be interested in the results.

The PTVA-3 model is based on the use of GIS. GIS is a very common and easy-to-use approach to the management of spatial datasets. Once data about building attributes and the RVI of buildings are entered into a GIS, they can be retrieved, modified and kept up to date very easily. Also, GIS facilitates the display of results in many different ways, which can suit the needs of different stakeholders and decision makers (e.g., LGAs, urban planners, emergency services, insurance companies).

We recommend the application of the PTVA-3 model elsewhere, although it must be recognised that some limitationsare associated with the model. The main limitations of the model are associated with the approximation we adopted in the definition of the inundation scenario. Specifically, the presence of debris and suspended sediment is not directly considered; the flow depth was assumed to be the only forcing of the flow velocity; the flow direction was assumed to be always perpendicular to the shoreline. A more accurate scenario could be obtained following the completion of probabilistic assessment of sources. Lastly, the model in input data heavy and not all of the data required by the model will necessarily be available from LGA's. As such, considerable efforts must be invested to gathering field data on individual buildings. Future research might focus on other less intensive ways of gathering building attribute data such as via remote sensing techniques or national building databases.

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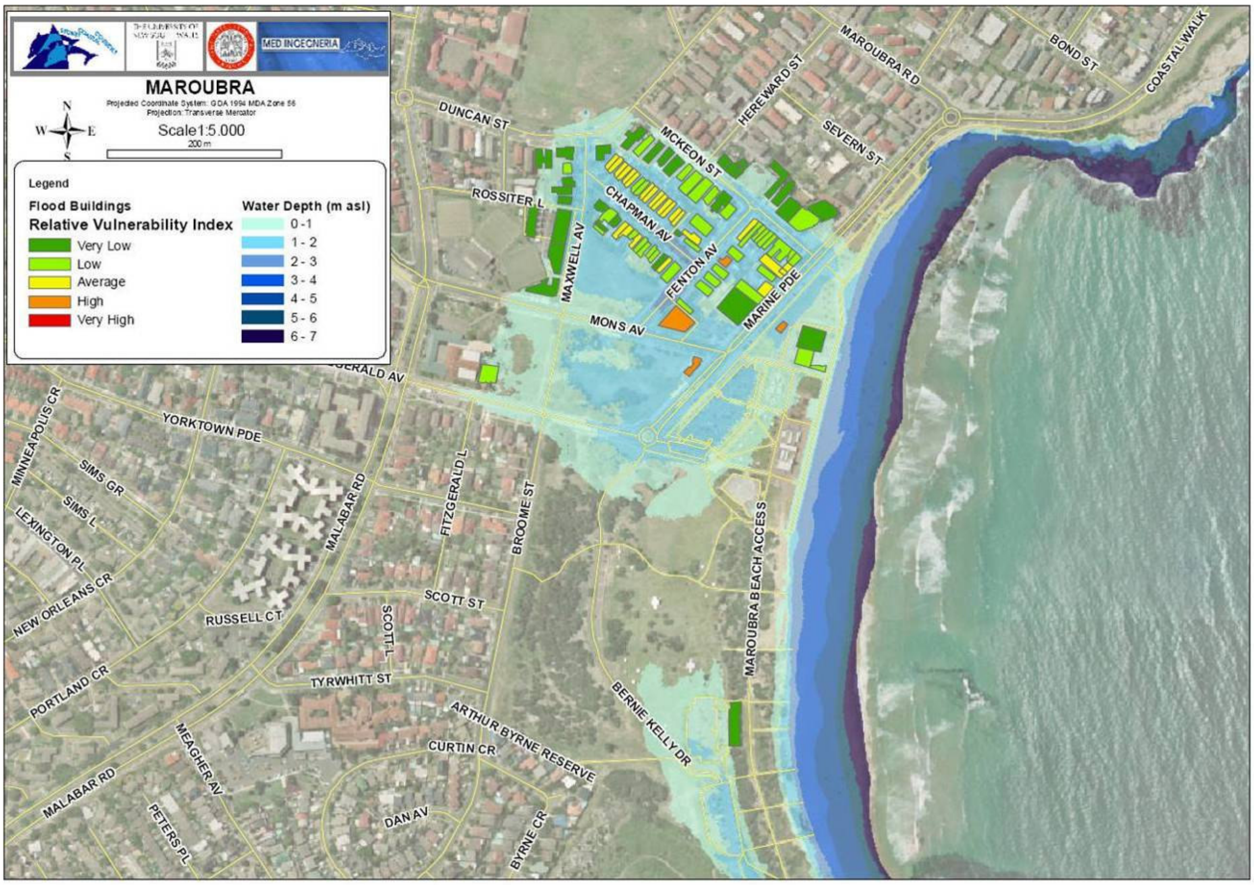

Figure. 1. Map showing the area of Maroubra, Sydney inundated by a tsunami achieving a flood run-up of +5 m asl. Also shown are the buildings that would be inundated (and damaged) by the tsunami. Specifically, the revised PTVA-3 model has been used to calculate the 'Relative Vulnerability Index' (RVI) scores for each of the buildings located within the inundation zone.

Tables:

Table 1. Original and re-scaled variables used in the calculation of the RVI scores for each building

RVI (1 – 5)	**1 – 1.8**	**1.8 – 2.6**	**2.6 – 3.4**	**3.4 – 4.2**	**4.2 - 5**
Description of relative vulnerability level	**MINOR**	**MODERATE**	**AVERAGE**	**HIGH**	**VERY HIGH**

Relative Vulnerability Index (RVI) = (2/3) x (SV) + (1/3) x (WV) [Eq. 1]

SV (original)	1 - 25	25 - 50	50 - 75	75 - 100	100 - 125
SV (scaled)	1	2	3	4	5

SV = (Bv) x (Ex) x (Prot) [Eq. 2]

Bv (original)	-1 to -0.6	-0.6 to -0.2	-0.2 to +0.2	+0.2 to +0.6	+0.6 to +1
Bv (scaled)	1	2	3	4	5
Ex (original)	0 – 1 m	1 – 2 m	2 – 3 m	3 – 4 m	> 4 m
Ex (scaled)	1	2	3	4	5
Prot (original)	0 to 0.2	0.2 to 0.4	0.4 to 0.6	0.6 to 0.8	0.8 to 1
Prot (scaled)	1	2	3	4	5

WV = (number of inundated levels) / (total number of levels) [Eq. 7]

WV (original)	0 to 0.2	0.2 to 0.4	0.4 to 0.6	0.6 to 0.8	0.8 to 1
WV (scaled)	1	2	3	4	5

Table 2. The attributes (and their values) influencing the structural vulnerability of a building "Bv". Positive values indicate an increase of the average building vulnerability given by the attribute, while negative values indicate a decrease of the average building vulnerability.

	-1	**-0.5**	**0**	**(+0.25)**	**+0.5**	**(+0.75)**	**+1**
s (number of stories)	more than 5 stories	4 stories	3 stories		2 stories		1 story
m (material)	reinforced concrete		double brick		single brick		timber
g (ground floor hydrodynamics)	open plan	open plan and windows	50% open plan		not open plan, but many windows		not open plan
f (foundation strength)	deep pile foundation		average depth foundation				shallow foundation
so (shape and orientation)	poor hydrodynamic shape		average hydrodynamic shape				high hydrodynamic shape
mo (movable objects)			minimum risk of being damaged by movable objects	moderate risk of being damaged by movable objects	average risk of being damaged by movable objects	high risk of being damaged by movable objects	extreme risk of being damaged by movable objects
pc (preservation condition)	very poor	poor	average		good		excellent

Table 3. Scores assigned to the four attributes influencing the level of protection of a building "Prot". Scores close to zero indicate a high protection level, while scores equal to 1 indicate the lowest level of protection

	0	**+0.25**	**+0.5**	**+0.75**	**+1**
Prot_br (building row)	>10th	7-8-9-10th	4-5-6th	2nd-3rd	1st
Prot_nb (natural barriers)	very high protection	high protection	average protection	moderate protection	no protection
Prot_sw (seawall height and shape)	vertical and >5m	vertical and 3 to 5m	vertical and 1,5 to 3m	vertical and 0 to 1.5m OR sloped and 1.5 to 3m	sloped and 0 to 1.5m OR no seawall
Prot_w (brick wall around building)	height of the wall is from 80% to 100% of the water depth	height of the wall is from 60% to 80% of the water depth	height of the wall is from 40% to 60% of the water depth	height of the wall is from 20% to 40% of the water depth	height of the wall is from 0% to 20% of the water depth

Paper n. 3

Assessing the vulnerability of buildings to tsunami in Sydney

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Assessing the vulnerability of buildings to tsunami in Sydney

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Abstract

Australia is vulnerable to the impacts of tsunamis and exposure along the SE coast of New South Wales is especially high. Significantly, this is the same area reported to have been affected by repeated large magnitude tsunamis during the Holocene. Efforts are under way to complete probabilistic risk assessments for the region but local government planners and emergency risk managers need information now about building vulnerability in order to develop appropriate risk management strategies. We use the newly revised PTVA-3 Model (Dall'Osso et al., 2009) to assess the relative vulnerability of buildings to damage from a 'worst case tsunami' defined by our latest understanding of regional risk – something never before undertaken in Australia. We present selected results from an investigation of building vulnerability within the local government area of Manly – an iconic coastal area of Sydney. We show that a significant proportion of buildings (in particular, residential structures) are classified as having "High" and "Very High" Relative Vulnerability Index scores. Furthermore, other important buildings (e.g., schools, nursing homes and transport structures) are also vulnerable to damage. Our results have serious implications for immediate emergency risk management, longer-term land-use zoning and development, and building design and construction standards. Based on the work undertaken here, we recommend further detailed assessment of the vulnerability of coastal buildings in at risk areas, development of

appropriate risk management strategies and a detailed program of community engagement to increase overall resilience.

1. Introduction

The 2004 Indian Ocean tsunami (2004 IOT) was an important reminder in Australia that tsunami can be devastating. Before this disaster few agencies had considered the threat that tsunamis might represent to Australia. The deployment of a fully operational Australian Tsunami Warning System (ATWS) finally occurred in mid 2009. However, efforts are still underway to understand and quantify the hazard and vulnerability to tsunami (Bird and Dominey-Howes, 2006, 2008; Hall et al., 2008). Once detailed information is available about the hazard, vulnerability and probable maximum loss for events of specific magnitudes, appropriate risk mitigation measures may be developed and decisions about the long-term sustainable development of the coast may be made.

For the coast of New South Wales (NSW) in SE Australia (Figure 1a), tide-gauge records show that historically, only small tsunamis have affected the region (Dominey-Howes, 2007). Reported geological evidence however, suggests that megatsunamis many times larger than the 2004 IOT may have occurred repeatedly during the Holocene (Bryant, 2001; Bryant *et al.*, 1992a, b; Young and Bryant, 1992; Nott, 1997, 2004; Bryant and Nott, 2001; Bryant and Young, 1996; Young and Bryant, 1992; Switzer *et al.*, 2005; Young, *et al.*, 1995; 1996) (Figure 1a). This geological work has led to the development of what has been referred to as the 'Australian Megatsunami Hypothesis' or AMH (Goff *et al.*, 2003). The evidence for the AMH is very controversial (Felton and Crook, 2003; Goff and McFadgen, 2003; Goff *et al.*, 2003; Noormets *et al.*, 2004). First, some of the proposed evidence for megatsunamis has clearly been incorrectly interpreted (Dominey-Howes *et al.*, 2006). Second, there appears to be a disjunct or miss-match between the historic record of small frequent events and the Holocene record of large infrequent tsunamis (Dominey-Howes, 2007). Last, no independent verification of the sources of these events has been undertaken – a vital component for understanding risk (Dawson, 1999). Bryant (2008) however, advocates a cosmogenic source for these events although this hypothesis also remains to be proven.

If the AMH can be independently validated, it has profound implications for the coastal vulnerability of NSW and government agencies (such as the NSW State Emergency Service (NSW SES)) are wholly unprepared for such events. For example, the proposed prehistoric megatsunamis occurred in coastal areas of NSW where more than 330,000 people now live within 1 km of the coastline and at no more than 10 metres above sea level (m asl). More than 20% of these people are over the age of 65 (Opper and Gissing, 2005). Furthermore, within the Sydney region, approximately 400,000 property addresses are located less than 3 km from the coast and about 200,000 are less than 15 m asl (Chen and McAneney, 2006). These properties have a combined value of more than $150 billion. Given this massive exposure, it is of concern that our understanding of the regional tsunami risk remains limited and unverified and that no work has been undertaken to assess the vulnerability of coastal buildings.

Although it may take some time before probabilistic assessments of tsunami return periods and maximum waves heights are available for the region, there is still a critical need to examine the vulnerability of buildings to tsunami inundation. Such assessments will be useful for developing risk management strategies and for assisting in longer-term land-use planning.

The aims of this work are to:

i. determine a 'credible worst case scenario' for tsunami generation and inundation along the coast of NSW in the region of Sydney; and

ii. to use the revised PTVA model (reported by Dall'Osso *et al.*, 2009) to determine a 'Relative Vulnerability Index' score for each building located within the expected tsunami inundation zone and display the vulnerability in a series of thematic maps at a scale of 1:5000.

This is the first time that the vulnerability of buildings to damage from tsunamis has ever been investigated in Australia.

2. Development of a credible worst case scenario and selection of case study area for building vulnerability assessment

It has recently been suggested that submarine slides down the NSW continental shelf would trigger large, locally damaging tsunamis (Glenn, 2008). New data demonstrate that the continental slope has experienced widespread sediment failure through time. Swath bathymetry has revealed the architecture of slope failures and the slip-plane geometry of a number of submarine mass failure sites including the Bulli (~20 km^3), Shovel (~7.97 km^3), Birubi (~2.3 km^3) and Yacaaba (~0.24 km^3) slides (Glenn *et al.*, 2008). These slides could have generated moderate to large local tsunamis flooding to significant heights above sea level (if they occurrec rapidly as single failure events).

Since a probabilistic tsunami hazard assessment has not yet been completed for the coast of NSW, we cannot use a probabilistic scenario as the boundary condition for our analysis. In the absence of a probabilistic scenario (event) and in view of the work of Glenn *et al*., (2008), we determine the credible worst case scenario [for this study] as follows:

- a submarine sediment slide occurs off-shore of Sydney;
- the slide occurs without an earthquake trigger (i.e., no natural warning sign);
- a tsunami arrives at shore within 10 – 15 minutes of its generation;
- the tsunami achieves a flood run-up height of +5 m asl and occurs on top of the maximum astronomical tide along the Sydney coast which is 2 m (www.maritime.nsw.gov.au). Consequently, our flood event achieves a maximum run-up of +7 m asl;
- we assume the main direction of flow of the tsunami inundation is perpendicular to the shore;
- we are only considering a single wave inundation; and
- we do not include flow velocity or entrainment of debris and sediment in the water.

It should be noted that we cannot provide any assessment of probability of occurrence for our scenario.

The selection of the Manly local government authority region (Figure 1b, c) as the case study to explore the vulnerability of buildings to the scenario was based on the need for (1) a transparent, inclusive process of consultation with local government authorities (LGA's) about the nature and purpose of the study, (2) a region where the building density at the coast is high and (3) a place of regional socio-economic importance (Dall'Osso and Dominey-Howes, 2009).

3. Method

We use the recently revised Papathoma Tsunami Vulnerabiltiy Assessment Model (PTVA-3) described by Dall'Osso *et al*., (2009) to determine a 'Relative Vulnerability Index' (RVI) score for every building in Manly struck by tsunami flood-water during the inundation described in the scenario (Figure 1c). The RVI is calculated using the PTVA-3 Model and takes account of potential damage to the building structure and to those parts of the building exposed to contact with water. Specifically, the model considers: (a) the physical characteristics of each building that are known to be associated with the degree of damage sustained by buildings to tsunamis (e.g. number of stories, building material, foundations, ground floor hydrodynamics, movable objects, etc.); (b) the degree of protection provided to each building by natural and artificial barriers; and (c) the flow depth expected to affect each building. Readers interested in further details about the PTVA-3 Model and the calculation of the RVI should refer to Dall'Osso *et al.,* (2009).

In order to build the GIS database and run the PTVA-3 Model, the following data sets were acquired:

- a geo-referenced and ortho-rectified aerial image of Manly that is used as the geographical base of the study. The aerial image was useful when it was necessary to manually digitize building vector files and for obtaining specific building features needed by the model (e.g., shape and orientation of the building footprint, building row, the presence of movable objects and protection provided by natural barriers). This image was provided by Manly LGA;
- a Digital Elevation Model (DEM) extracted from stereo aerial photos with horizontal resolution of 1 metre. The DEM was used to calculate the water depth above the ground surface by subtracting the ground elevation from the horizontal flood surface at specific grid (building) points. The DEM was also provided by Manly LGA;
- a shapefile of polygons representing all the building footprints. The shapefiles were also provided by Manly LGA. Building attribute data were then manually entered in to the GIS database for each building file; and
- attribute data for each building. The data included both building and urban environment data (e.g., seawalls etc). These datasets were not available from Manly LGA and so we undertook field surveys to collect these data building-by-building.

The data provided by Manly LGA was entered into a GIS database, and categorised according their specific formats and thematic values (Figure 1c). Topographical data were converted from a ".txt" format into a polygon shapefile. The marine flood-water depth for our scenario given by the 5 metre tsunami (plus 2 metres maximum astronomical tide = 7m AHD) were projected onto the whole study area (Figure 1c). The buildings shapefile was modified in order to be used in the vulnerability model. A total of 1141 individual building footprints were manually extracted (Figure 1c).

We ground-truthed (cross-checked) the building shapefiles created for Manly with those actually present on the ground and collected data for the attributes of the model detailed in Dall'Osso *et al.*, (2009). The area covered by the expected tsunami in Manly is large so we divided the entire area in to 18 smaller more manageable areas.

For each of these areas, we printed a map with individual building shapefiles and a standardised table for recording associated building attribute data in order to cross check the buildings present within the building shapefile (Dall'Osso and Dominey-Howes, 2009). Where the correspondence between the aerial image and field observations was poor, building shapefiles were manually corrected using the cross checked field data. The data collected during the field surveys was then entered into the attribute table of the corresponding building shapefile in the GIS. Finally, the RVI score for each building was calculated using the format described by Dall'Osso *et al.*, (2009) and appropriate maps generated.

4. Results

Different stakeholders will inevitably choose to explore the vulnerability of different types or classes of buildings depending on their own interests or responsibilities. Within the Manly LGA, we examined more than 1100 buildings of different uses. However, in organising our results, we classified the buildings into the following nine building categories:

- local government;
- health and medical services;
- education;
- utility (including water, sewerage, gas and electricity);
- transport;
- tourism;
- recreation and culture;
- commercial; and
- residential.

Using the PTVA-3 Model method to assess the relative vulnerability (RVI) of the buildings to tsunami damage, we present results as a series of thematic maps associated with each building class (e.g., local government buildings), in which the RVI score of each building is displayed using a colour code associated with that vulnerability level.

Due to the low elevation of most of Manly, it can be seen from Figure 1c that in our scenario, the tsunami would flood right across the isthmus from the ocean side of Manly through to Manly Wharf on the Harbour side. The tsunami would also be funneled through the entrance of Manly Lagoon (in the northern part of the study area) to a significant distance inland, inundating buildings in low-lying areas adjacent to the lagoon.

In our scenario, an area in excess of 169 hectares would be inundated and a total of 1133 individual buildings (plus 8 sites that were under construction at the time this study was undertaken) would be affected by tsunami flood-water. This represents total exposure. Since this is an area too large to be easily displayed on a single map, we have artificially divided our study area in to four overlapping sub-blocks (Blocks 1 to 4) (Figure 2). In our study, we actually generated some 40 different maps of building vulnerability across these four sub-blocks (one map for each of the 9 building classes in every block, plus 4 overview maps). This is far too much data to be presented here. Instead, we present selected results from Blocks 2 and 3. We choose these two sub-blocks since they are markedly different in that Block 2 is dominated by residential buildings whereas Block 3 is dominated by commercial buildings. Between these two sub-blocks however, they account for 1094 (or 95.88%) of the total building inventory of the study area. Lastly, rather than displaying maps for all nine building classes for each sub-block, we only show selected maps that in our opinion are particularly interesting in terms of the story they tell about building vulnerability.

4.1 Block 2

The area of Block 2 inundated in our scenario is shown in Figure 3. This is a large area bound to the north by the entrance to Manly Lagoon and to the east by the ocean. The depth of flood-water over the land surface is highest along the narrow coastal beach strip to the east of Block 2 and towards the northwest adjacent to Manly Lagoon, where it reaches 7 metres above mean sea level.

A large number of buildings of all types would be affected by the tsunami. This represents the total exposure to potential damage during the hypothetical tsunami. Figure 3 displays the expected water depth at, and the calculated RVI scores of, each building located within the inundation zone. A significant number of buildings are classified as having "High" and "Very High" RVI scores and most of these are located in the central and northwestern sectors.

Only a small number of buildings are associated with the utility, transport, recreation and culture, tourism and commercial classes and broadly speaking, they do not have any "Very High" or "High" RVI scores. Consequently, we do not provide separate maps for these buildings. However, we do present the RVI scores for local government, health and medical services, education and residential buildings and these are shown in Figures 4, 5, 6 and 7 respectively.

Figure 4 shows that just five buildings are the responsibility of the local government but *all* of them have been classified as having "High" and "Very High" RVI scores. Two with RVI scores of "Very High" are actually surf life saving club buildings. Figure 5 shows the calculation of the RVI scores and the spatial distribution for the health and medical services sector buildings. One building which is in fact a nursing home for elderly people, is classified as having a "Very High" RVI score whereas the others have RVI scores of 'average' or 'lower'. The education buildings are mostly clustered together in the northeast of Block 2 and have a mix of vulnerability but one has a "High" RVI score (Figure 6). The spatial distribution and calculated RVI scores of the large number of residential buildings are displayed in Figure 7. As an interesting observation, the majority of residential buildings located in the seaward sections of the study area are actually classified as having "Average", "Low" and "Very Low" RVI scores even though they are closer to the sea. Residential buildings classified as having "High" and "Very High" RVI scores are mostly clustered to the west and northwest of Block 2. This is due to two main reasons: (1) most of the structures next to the beach are new well constructed buildings with characteristics that will reduce damage from tsunamis; and (2) the calculated flow depth of water above the ground surface will actually be higher in the areas next to the lagoon.

4.2 Block 3

This sub-block (Figure 2) is centered about the administrative and commercial heart of Manly LGA. The area of Block 3 inundated by the tsunami in our scenario is shown in Figure 8. Please note that Blocks 2 and 3 overlap. Readers must be careful not to double count individual buildings shown in both Blocks 2 and 3.

Examination of Figure 8 indicates that the entire low-lying commercial heart of Manly centered around 'The Corso', would be completely submerged by flood-water. A significant number of buildings of all types would be affected by flood-water. Figure 8 displays the calculated RVI scores for these buildings. There are no significant issues associated with buildings belonging to the health and medical services, education, utility, tourism, recreation and culture, commercial or residential building classes. Consequently, we do not present vulnerability maps for these buildings. However, there are interesting results for buildings belonging to the local government and transport building classes and as such, we present the following results for these building types in Block 3 in Figures 9 and 10 respectively.

Figure 9 shows that whilst the majority of local government buildings have been assessed as having an RVI score of 'Average' or lower, one - the Manly Life Surf Club, at the southern end of Manly Beach has been assessed as having a 'Very High' RVI score. Within Block 3, only a small number of buildings are related to the transport services sector (Figure 10). The only problematic building structure is Manly Wharf that has been classified as having a "Very High" RVI score.

4.3 Total building vulnerability

Since we have been highly selective in terms of the maps of building vulnerability we have chosen to display, to assist readers with understanding the absolute number of buildings with different RVI scores by building class, Table 1 provides a summary for the whole of Manly. It is clear from Table 1 that commercial and residential structures have the highest absolute number of buildings assessed as having "High" and "Very High" RVI scores.

5. Discussion and conclusions

Assessing the vulnerability of buildings to potential tsunami damage is a vital necessity for developing appropriate risk management strategies. It is however, a complicated process. Before undertaking systematic assessments along the coast of NSW, it would be appropriate to determine the likely probability that damaging tsunami might occur and to identify their probable sources. Work is underway to independently verify the 'Australian Megatsunami Hypothesis' (AMH) since this is central to the emergency risk management approaches that might need to be implemented. At the present time, it is not possible to state whether the AMH is true or not. Further, probabilistic assessments of risk are urgently required.

In the absence of a probabilistic event that we might use as the baseline for our study, adoption of our scenario is entirely reasonable and is in fact, based on the best available evidence of likely regional sources (Glenn *et al.*, 2008). If anything, our scenario is on the conservative side of what might be expected. For example, we model only a single wave inundating Manly. In reality, several waves would flood the area. We assumed that suspended sediment and debris are evenly distributed within the water flow, but they could concentrate in different location causing heavier damages to specific buildings. Lastly, future sea level rise will increase the degree of risk for buildings located within our study area. We suggest that future modelling should try and incorporate these factors to increase confidence in the final vulnerability of structures.

We were greatly aided in our work by the provision of GIS data layers from Manly LGA. In reality though, we found many errors with the data contained within the files (which is no fault of the government authorities). Consequently, time and effort was required to cross check and correct these basic data files. Any future use of the PTVA-3 Model will also need to ensure that the base data used for assessments of building data are as reliable as possible in order to ensure vulnerability assessments are accurate and decisions made on those assessments are appropriate.

The vulnerability of Manly (that is, the potential for damage and loss) associated with the tsunami in our scenario is very large. The total surface area covered by flood-water is significant and a large number of buildings (1141) would be inundated. Water flow depth above ground surface in some areas would be as great as 7 metres. In such a situation, it is very difficult to imagine how any buildings would be left without any damage. As mentioned in Section 4, we have only included a small number of vulnerability maps by building class in this paper. Interested readers may find the entire study results in Dall'Osso and Dominey-Howes (2009).

Notwithstanding the limited data presented here, the following important observations are made:

- Most buildings within our study area (Blocks 2 and 3) belong to the commercial and residential building classes;
- Table 1 indicates that the largest number of buildings classified as having "High" and "Very High" RVI scores are in fact residential followed by commercial;
- Whilst only relatively small numbers of individual buildings are associated with the local government, health and medical services, education, recreation and culture, utilities, transport and tourism sectors, in some cases (such as in Block 2 (see Figure 4) and Block 3 (see Figure 9)) significant proportions of those buildings (e.g., those that are the responsibility of the local government) are classified as having "High" and "Very High" RVI scores. We consider this as particularly problematic because in most cases, those local government buildings with "High" and "Very High" RVI scores are also Surf Life Saving Club houses. Surf Life Savers are first responders for emergency cases on beaches and nearby water, and damage to their structures might severely affect the capacity of the Life Savers to respond. To varying degrees, Council is either directly responsible for the upkeep and condition of these buildings, or has a strong interest in those buildings being well

maintained (e.g., of medical and health service, utility or transport buildings). Therefore Council will either need to directly examine how those structures can be modified to reduce their vulnerability or work with the relevant owners of those buildings to improve their structural resilience;

- The identification of 'significant' buildings (e.g., schools and nursing homes) as having "High" and "Very High" RVI scores is worrying and again, it is likely that relevant stakeholders might wish to consider how they might address the vulnerability of these buildings to likely damage;
- With regard to the residential buildings located in Block 2, Manly (Figure 7), it is apparent that most structures closer to the sea are in fact assessed as having 'lower' RVI scores than those further inland. Though this is counter intuitive, it is because houses built closer to the coast are much newer than those located inland and have been built to newer, higher standards. Further, the depth of the tsunami flood water above the ground surface is less at the shoreline and greater closer to the lagoon;
- We acknowledge that large numbers of those residential buildings classified with "High" and "Very High" RVI scores will be privately owned and the responsibility to address such vulnerability will lie with the individual home owners. However, the emergency services may well be interested to knowing more about the demographic characteristics and any special needs of the occupants of vulnerable houses;
- Some of the residential buildings with "High" and "Very High" RVI scores will actually be 'publically' owned and managed. Those structures will be under the responsibility of local government or housing charities, who should explore the implications of the vulnerability assessment to the security of their tenants; and finally
- The Manly Wharf transport structure (see Figure 8) has been classified as having a "Very High" RVI score. Given than more than 8 million day tripper visitors per year visit Manly via the ferries that dock at this wharf and many more local people use the ferry service to get to and from the city (and that the wharf houses many private businesses), we feel that addressing the vulnerability of this structure ought to be a priority for the relevant authorities. Lastly, the car park located below ground level at the wharf would be completely inundated, worsening the damage level to the Manly transport system.

In conclusion, this is the first time that an assessment of the vulnerability of buildings to damage from a 'credible worst case tsunami' has *ever* been undertaken in Australia. We have used the recently revised PTVA-3 Model presented by Dall'Osso *et al*., (2009) to explore the spatial distribution and number of buildings of varying vulnerability in the iconic Sydney coastal region of Manly. Whilst this paper only presents selected results, it is clear that a significant proportion of buildings (in particular, residential structures) are classified as having "High" and "Very High" Relative Vulnerability Index scores. Furthermore, other important buildings (e.g., schools, nursing homes and transport sector structures) are also vulnerable to damage. Our results have potentially serious implications for immediate risk management and emergency management and longer-term land-use zoning and development and building design and construction standards.

Based on the work undertaken here, we recommend: (a) a further detailed analysis of building vulnerability, to be undertaken when a probabilistic tsunami hazard assessment and inundation models will be available for the region; (b) the development of appropriate risk management strategies, considering measures to reduce building vulnerability and possible evacuation routes; and (c) a detailed program of community engagement to increase overall resilience at Manly.

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Figures:

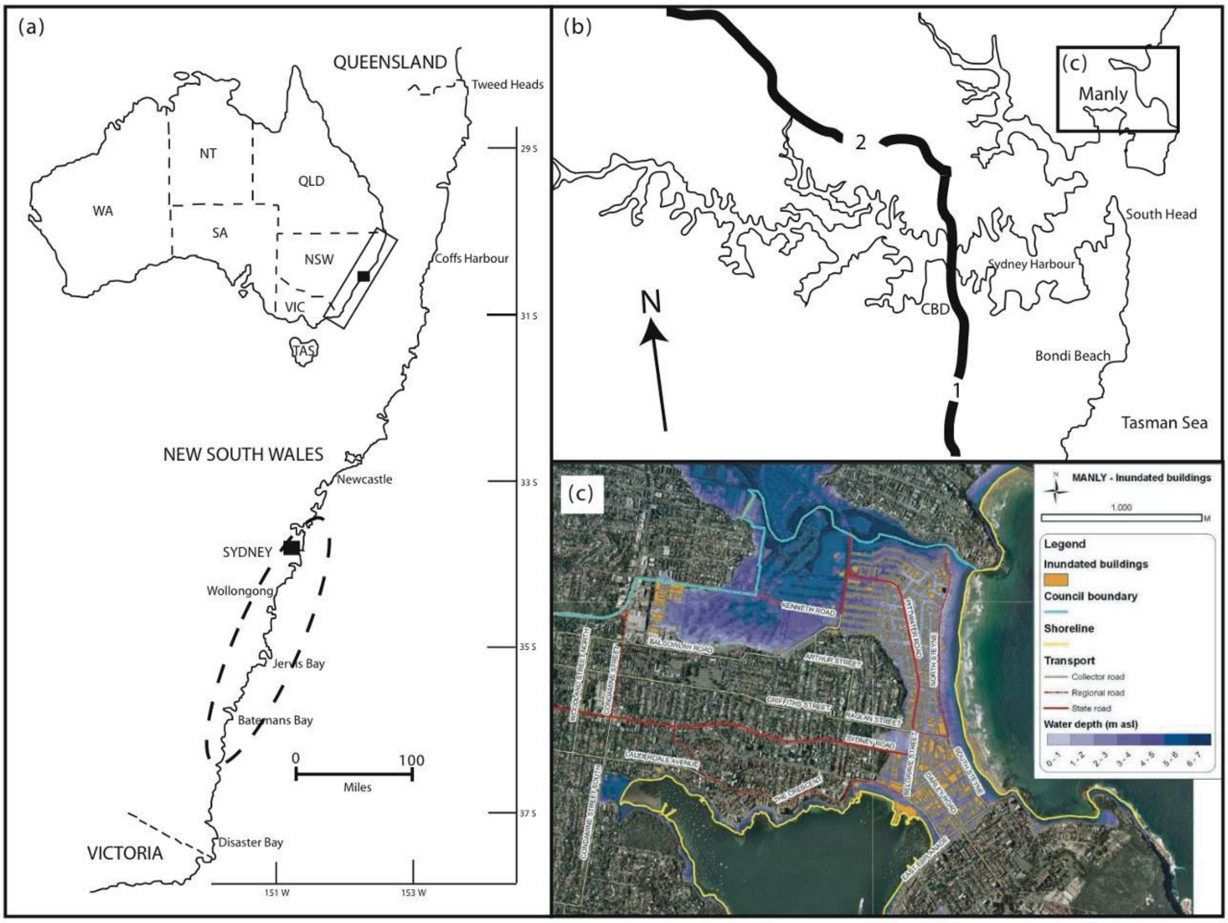

Figure 1. 1 (a) Broad location of the study region of Sydney, New South Wales (NSW), SE Australia. The hatched oval encompassing the region north of Sydney south to beyond Batemans Bay is the region reported to have been affected by Holocene megatsunami (Bryant, 2008). NSW = New South Wales, NT = Northern Territory, SA = South Australia, TAS = Tasmania, VIC = Victoria, WA = Western Australia. (b) Simplified map of the Sydney Harour region with our specific field study area of Manly located NE of the CBD. Highways 1 and 2 are shown. (c) Detailed GIS map of our study area of Manly. Area of inundation (including relative water depths above land surface) associated with our tsunami scenario are shown in blue. Principal features are high-lighted and buildings inundated by the tsunami are indicated in orange.

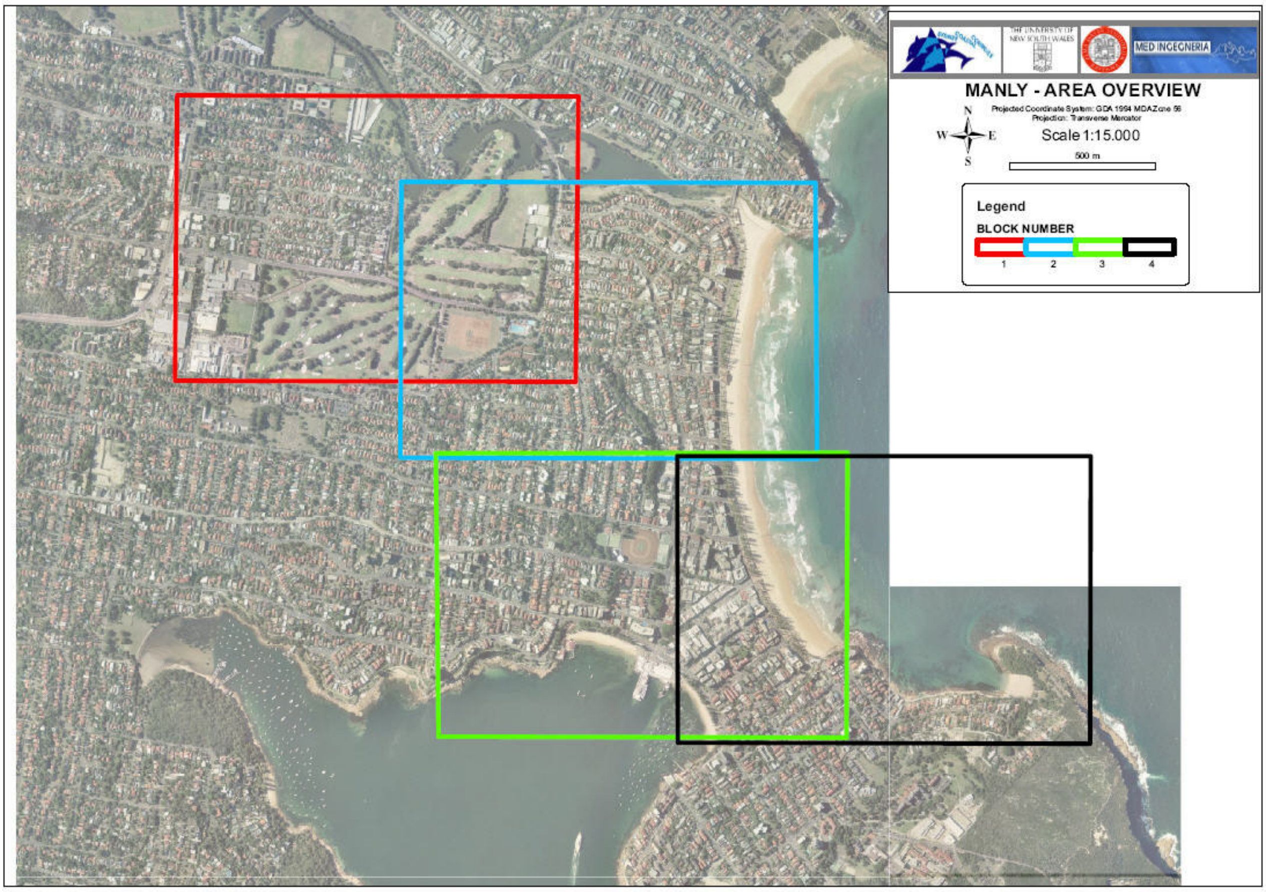

Figure 2. The Manly study area divided in to four (4) 'Blocks' for ease of results presentation. This paper just deals with Blocks 2 and 3.

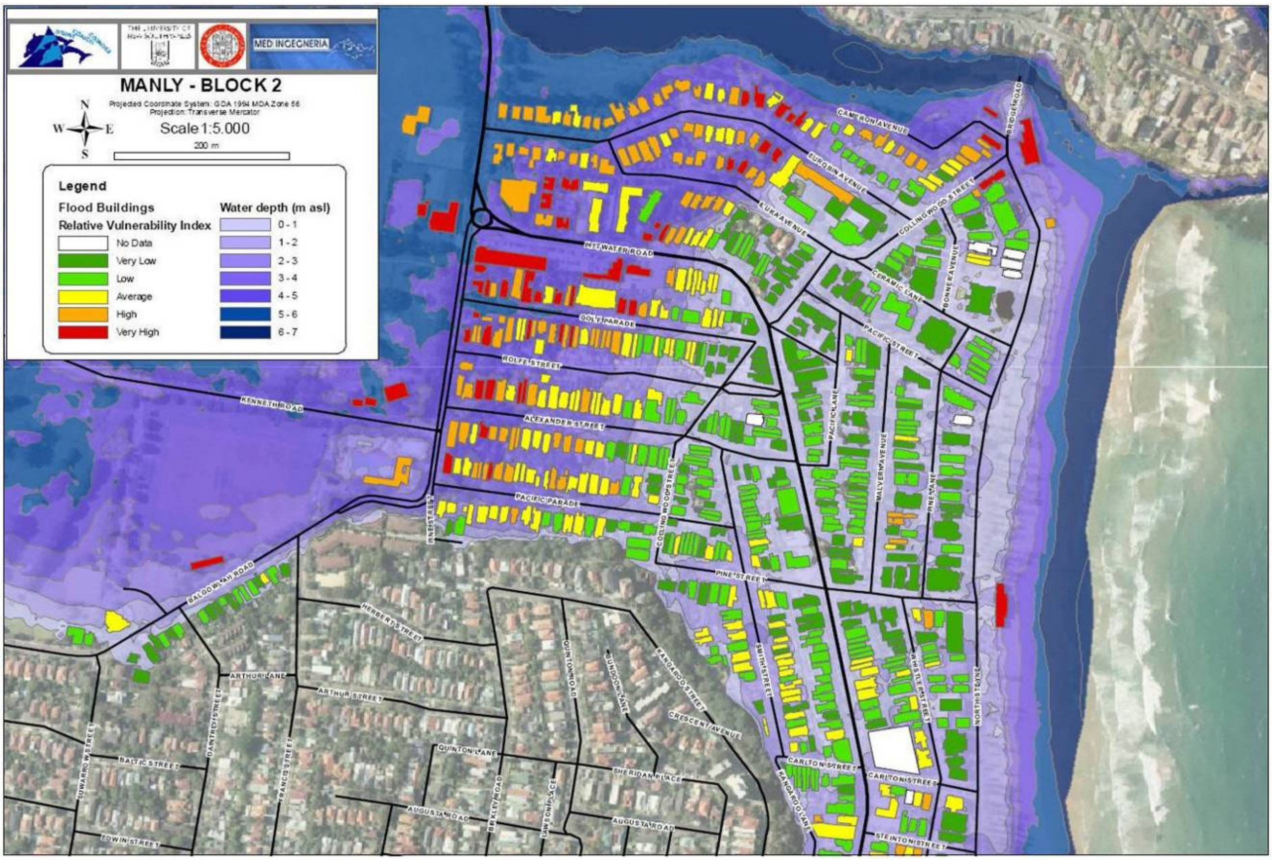

Figure 3. Tsunami inundation and water depth in Block 2, Manly. The expected water depth at, and the RVI scores of every building located within the inundation zone are shown

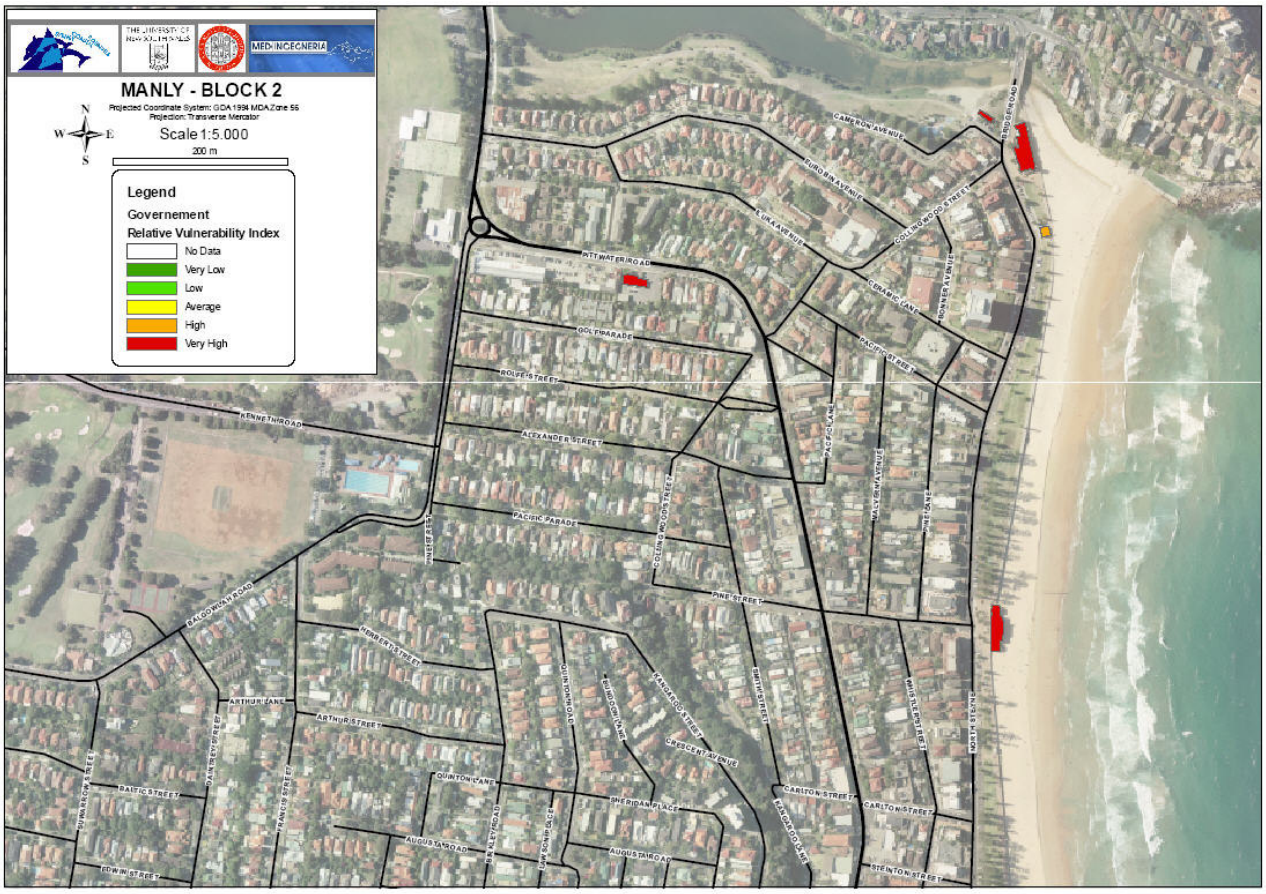

Figure 4. The spatial distribution and calculated RVI scores of all local government buildings within the tsunami inundation zone of Block 2, Manly

Figure 5. The spatial distribution and calculated RVI scores of all health and medical services buildings within the tsunami inundation zone of Block 2, Manly

Figure 6. The spatial distribution and calculated RVI scores of all education buildings within the tsunami inundation zone of Block 2, Manly

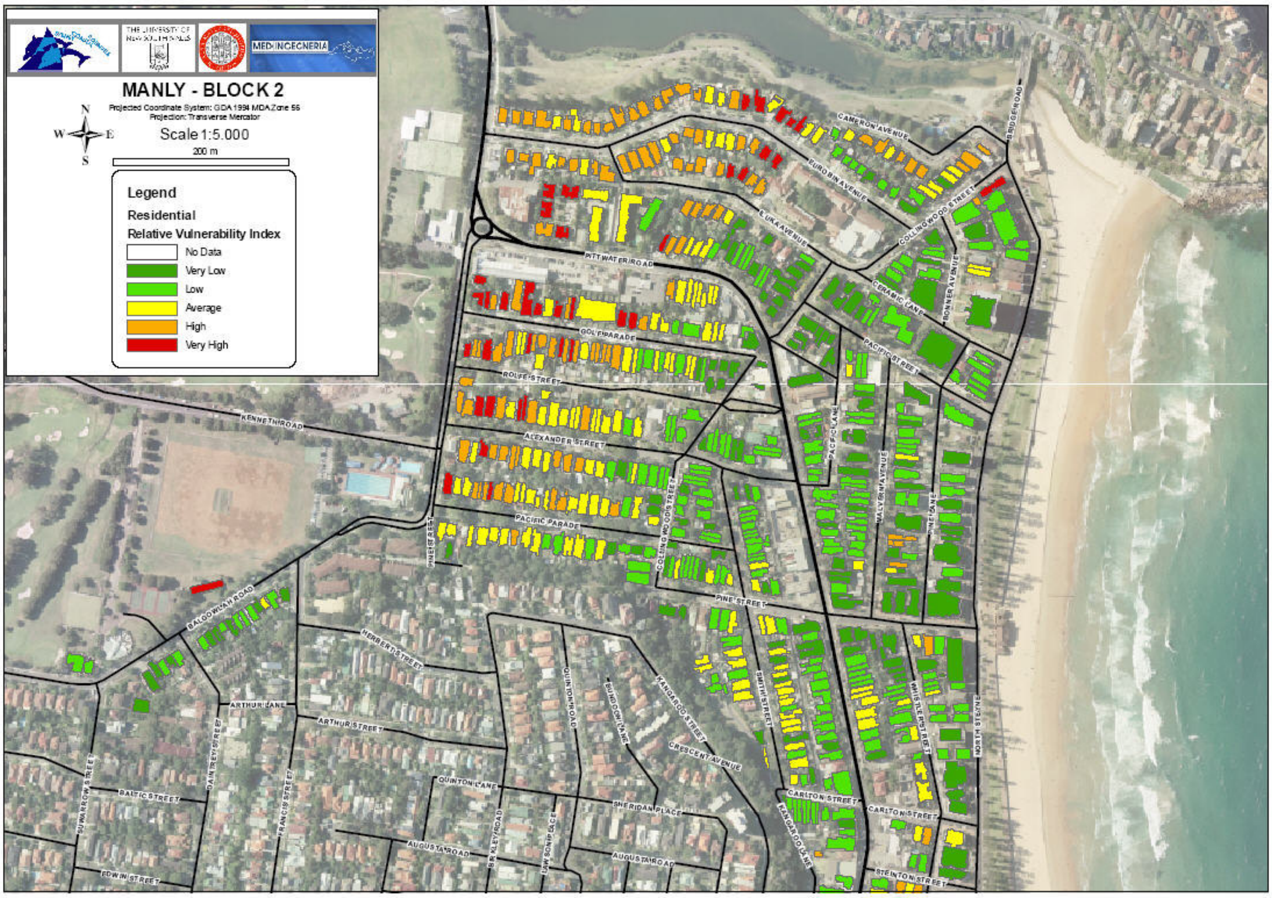

Figure 7. The spatial distribution and calculated RVI scores of all residential buildings within the tsunami inundation zone of Block 2, Manly

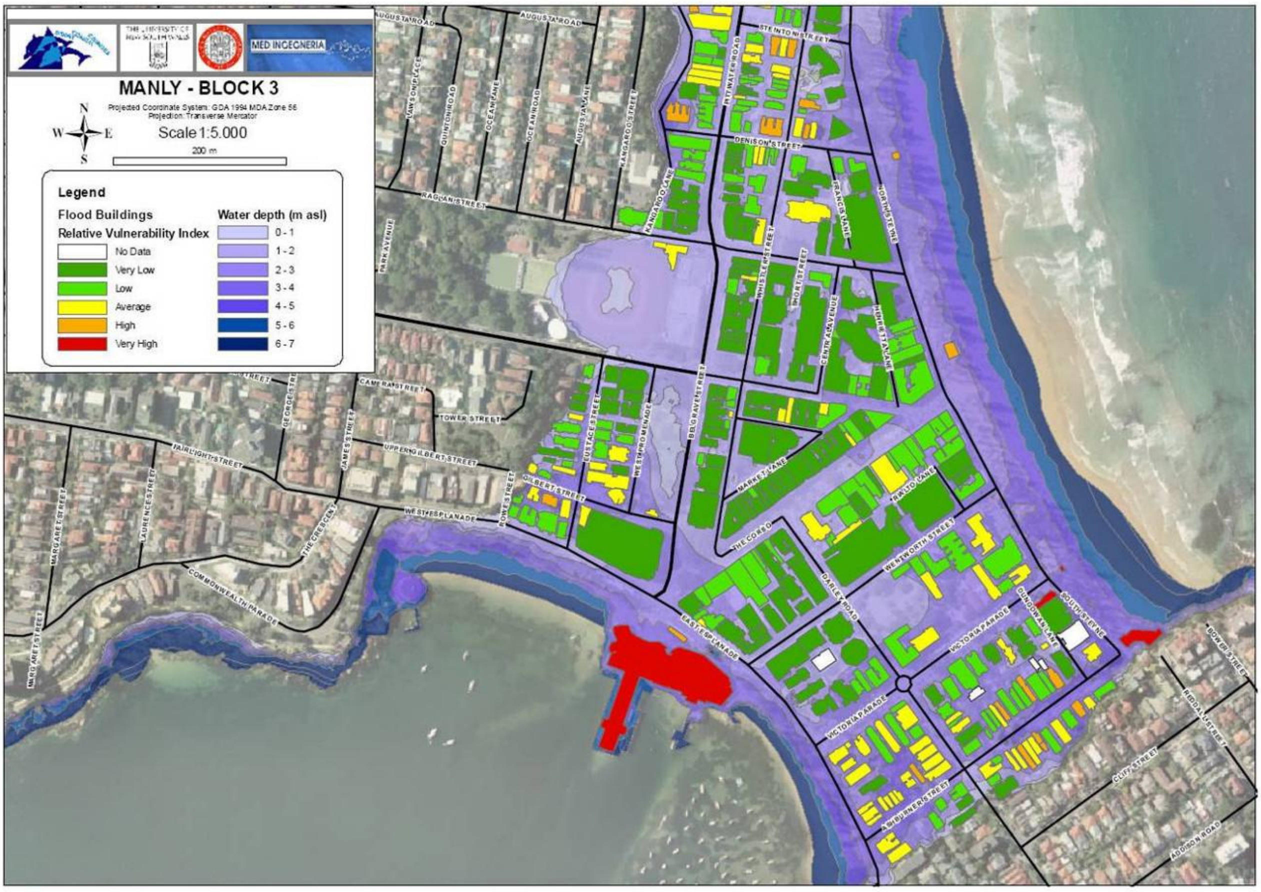

Figure 8. Tsunami inundation and water depth in Block 3, Manly. The RVI scores of every building located within the inundation zone are indicated

Figure 9. The spatial distribution and calculated RVI scores of all local government buildings within the tsunami inundation zone of Block 3, Manly

Figure 10. The spatial distribution and calculated RVI scores of all transport buildings within the tsunami inundation zone of Block 3, Manly

Tables:

Table 1. Summary of the total number of buildings by building class and the number of buildings according to their Relative Vulnerability Index (RVI) scores in Manly. Please note that each building may have more than one use and as such, the apparent total number of buildings listed in Table 1 is greater than the actual number of buildings physically located on the ground

Manly (Blocks 1 – 4)		**Relative Vulnerability Index (RVI) Scores**				
Building type	**Number of buildings**	**Buildings with "Very Low" RVI**	**Buildings with "Low" RVI**	**Buildings with "Average" RVI**	**Buildings with "High" RVI**	**Buildings with "Very High" RVI**
Local Government	**23**	**4**	**9**	**3**	**1**	**6**
Health & Medical	**19**	**10**	**5**	**3**	**0**	**1**
Education	**19**	**7**	**5**	**6**	**1**	**0**
Recreation &Culture	**22**	**5**	**7**	**5**	**2**	**3**
Utilities	**12**	**2**	**0**	**2**	**4**	**4**
Transport	**5**	**2**	**0**	**1**	**0**	**2**
Tourism	**24**	**11**	**10**	**1**	**2**	**0**
Commercial	**217**	**113**	**66**	**21**	**7**	**10**
Residential	**865**	**218**	**295**	**193**	**119**	**40**
Vacant and being redeveloped	**8**	**-**	**-**	**-**	**-**	**-**

Paper n. 4

'Reducing the loss' - using high-resolution vulnerability assessments to enhance tsunami risk reduction strategies

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'Reducing the loss' - using high-resolution vulnerability assessments to enhance tsunami risk reduction strategies

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Abstract

Australia is at risk from tsunamis and recent work has identified the need for detailed models to assess the vulnerability of buildings to damage during tsunamis. Such models will be useful for underpinning the development of land-use zoning regulations, the identification of appropriate design standards and construction codes and in outlining community relevant tsunami disaster risk reduction strategies by local emergency managers. Such strategies might include the identification of coastal areas that require evacuation, the identification of specific buildings that might be the focus of search and rescue efforts, and the demarcation of 'safe' evacuation areas and structures within expected tsunami flood zones. Dall'Osso and Dominey-Howes use the results of a very high-resolution assessment of building vulnerability to tsunami (using the PTVA -3 Model) at Manly, Sydney to illustrate how vulnerability assessments could be used to enhance tsunami risk reduction.

1. Introduction

The coasts of Australia are at risk from tsunamis. The 2004 Indian Ocean and 2006 Java tsunamis both resulted in flooding of low-lying coastal areas of NW Western Australia. More recently, the 2007 Solomon Islands and 2009 New Zealand tsunamis were both recorded on tide gauges along the eastern seaboard of Australia although there was no significant inundation associated with these events.

For the coast of New South Wales (NSW) (Figure 1a), tide-gauge records show that historically, only small tsunamis have occurred (Dominey-Howes, 2007). Reported geological evidence however, suggests that megatsunamis many times larger than the 2004 Indian Ocean event may have occurred many times during the last 10,000 years – a period in earth history called the Holocene (Bryant, 2001; Bryant et al., 1992a, b; Young and Bryant, 1992; Nott, 1997, 2004; Bryant and Nott, 2001; Bryant and Young, 1996; Switzer et al., 2005; Young, et al., 1995; 1996). This geological work has led to the development of what has been referred to as the 'Australian Megatsunami Hypothesis' or 'AMH' (Goff et al., 2003; Dominey-Howes et al., 2006). The evidence for the 'AMH' is very controversial (Felton and Crook, 2003; Goff and McFadgen, 2003; Goff et al., 2003; Noormets et al., 2004). First, some of the proposed evidence for megatsunamis has clearly been incorrectly interpreted (Dominey-Howes et al., 2006). Second, there appears to be a 'disjunct' or miss-match between the historic record of small frequent events and the Holocene record of large infrequent tsunamis (Dominey-Howes, 2007; Goff and Dominey-Howes, In press). Last, no independent verification of the sources of these events has been undertaken – a vital component for understanding risk (Dawson, 1999). Bryant (2008) however, advocates a cosmogenic source for these events although this hypothesis also remains to be proven.

If the 'AMH' can be independently validated, it has profound implications for the coastal vulnerability of NSW and government agencies (such as the NSW State Emergency Service (NSW SES)) are very likely and understandably, completely unprepared for such events. For example, the proposed Holocene megatsunamis occurred in coastal areas of NSW where more than 330,000 people now live within 1 km of the coastline and at no more than +10 metres above sea level (m asl) (Bird and Dominey-Howes, 2006; 2008). More than 20% of these people are over the age of 65 (Opper and Gissing, 2005). Furthermore, within the Sydney region, approximately 400,000 property addresses are located less than 3 km from the coast and about 200,000 are less than +15 m asl (Chen and McAneney, 2006). These properties have a combined value of more than $150 billion. Given this massive exposure, it is of concern that our understanding of the regional tsunami risk remains limited and unverified and that no work has been undertaken to assess the 'vulnerability' of coastal buildings.

Hall et al., (2008) outlined an extremely useful 'step-by-step scientific process' to gather information useful for assesing the risk to Australia's coasts from tsunamis. The first part of this process defines all likely sources of tsunamis, estimates their frequencies and then propagates tsunami waves from these sources to shallow water adajcent to the coast providing a probabilistic wave height for any particular return period of interest. The second step of the process utilises inundation modelling to examine exactly how far inland and to what elevation above normal sea level a particular tsunami might flood. At the present time, in Australia, Geoscience Australia is the lead agency that undertakes these first two steps.

The final step in the scientific process described by Hall et al., (2008) is to map the 'exposure' of (for example) buildings within the expected inundation zone and then assess the 'vulnerability' of those structures to damage associated with that event. So far though, this last step has not been undertaken by any official government agency or emergency service.

2. Assessing the vulnerability of buildings to tsunami damage using the PTVA Model

Only one model has been developed that assesses the vulnerability of buildings to damage from tsunamis. This model – the Papathoma Tsunami Vulnerability Assessment (or PTVA) Model has been described in detail in Papathoma et al., (2003) and Papathoma and Dominey-Howes (2003). It was then validated by Dominey-Howes and Papathoma-Köhle (2007) and applied to different case studies by Papathoma et al., (2003), Papathoma and Dominey-Howes (2003) and Dominey-Howes et al., (In press). Broadly speaking the model collects and integrates engineering attributes about each building together with information about the tsunami and the natural environment in order to calculate a 'Relative Vulnerability Index' (RVI) score for each building.

Recently, Dall'Osso et al., (2009a) presented a newly revised and improved version of the model – PTVA-3. Further, Dall'Osso et al., (2009b) applied the newly revised PTVA-3 model to a case study in Manly, Sydney (Figure 1b, c). They undertook an assessment of 1100+ individual buildings located within the expected flood zone associated with a particular tsunami scenario. The area of Manly inundated in their scenario is shown in Figure 1c. Since the area inundated was large, they presented their assessment of building vulnerability in four separate blocks (referred to as 'Manly, Block 1 to 4) (Figure 2).

For a full description of the results of the case study, see Dall'Osso et al., (In press b). However, their main findings are shown in Table 1. They divided the buildings in to nine classes and assessed the RVI scores of each building in each class. Table 1 indicates that of the 1100+ buildings they assessed, the majority of the building stock is residential followed by commercial. The absolute number of buildings in each class assessed as having a particular RVI score are indicated in columns 3 to 7 of Table 1. An example of the spatial distribution of all buildings in Block 2 of different classes, together with their RVI scores is shown in Figure 3. It is clear therefore, that the application of the PTVA-3 Model to individual buildings located within an expected inundation zone can provide very high-resolution information about the spatial vulnerability of buildings and by analogy, the population in that area.

3. Enhancing tsunami risk reduction strategies using high-resolution vulnerability assessments

Many different stakeholders will be interested in the management of risk associated with tsunamis. However, here we focus on Australian Local Government Authorities (LGA's) (including their Local Emergency Management Officers (LEMO's)) together with their local units of the State Emergency Service (SES) who are at the sharp end of dealing with hazardous events such as tsunamis.

Local government planners will be interested in a number of questions that include (but are not limited to):

- Which low-lying areas of coastal land are 'safe' to permit new and/or re- development?
- Are there any low-lying parcels of coastal land that are simply too 'unsafe' to permit any form of development?
- If development and/or re- development is permissible, should there be any forms of restrictions and if so, what?
- What building standards, codes and regulations should be applied to new development (and re- development) proposals to minimise the vulnerability of new structures built at the coast?
- For existing structures, what is their vulnerability and how (if at all) can that vulnerability be reduced?
- For any buildings assessed as having "High" or "Very High" RVI, what (if any) liability is faced by Local Government?

Local Government LEMO's and Emergency Service personnel will be interested in (amongst others) questions such as:

- Which areas of the coast are likely to experience flooding associated with a tsunami of a particular magnitude/return period?
- Which areas of low-lying coastal land will need to be evacuated in the event of a tsunami of a particular magnitude/return period?
- What areas can be identified as 'safe zones' to which people may be moved during an evacuation?
- What are the best routes to 'safe evacuation areas'?
- Which buildings are likely to be the most problematic or will require special attention or response (e.g., search and rescue) during a tsunami event of a particular magnitude? For example, where are the schools and nursing homes?
- In the event that it is not possible to move all people located within the expected inundation zone into 'safe' evcuation areas, which buildings provide the best options for 'vertical evacuation' above the maximum expected flood level?

We are not qualified to address these questions but it is clear that the approach we have developed and tested and which is detailed in Dall'Osso et al., (2009a, b) does provide the sort of high-resolution data needed by decision makers to tackle these important questions.

Maps displaying 'exposure' during inundation such as Figures 1c and 3, will be useful for guiding decision making processes related to land-use zoning. It is apparent that having accurate information about flow depth above ground surface will be useful for those organisations who make decisions about development proposals, building design and regulation. We are aware that prohibiting development of coastal landscape areas is neither desirable or in many cases, practical. However, data generated by models and approaches like ours certainly can help to guide decision making to ensure new, and re- developed, structures are constructed to a standard that reduces risk to an affordable minimum.

Some of the individual buildings located in Block 2 (Figure 3) are directly owned and managed by the Manly LGA. Table 1 indicates that some seven (7) LGA buildings in the whole Manly area that would be affected by a tsunami are assessed as having "High" or "Very High" RVI scores. In many ways, local taxes and environmental levies paid by residents in this LGA are used (in part) for the upkeep of buildings owned and managed by the authority. Therefore, the LGA might use the results of an assessment like that described by Dall'Osso et al., (2009b) to prioritise actions that help to reduce the vulnerability of these buildings and enhance the capacity of the LGA to recover after a tsunami event. Once again, we are not making recommendations but are pointing towards where, and how, our work might assist local decision makers.

We have used some of the results generated by Dall'Osso et al., (2009b) to explore the potential identifcation of areas that might be classified as 'safe evacuation areas' during a tsunami. Figures 4 and 5 display those areas we think could be the subject of evacuation orders. Where appropriate, in each area, we have identified individual buildings that could be used for vertical evacuation above the maximum expected flood level. In Figures 4 and 5, these individual buildings are coloured green. These buildings are identified from the PTVA-3 Model analysis carried out by Dall'Osso et al., (2009b) because they have the lowest RVI values and because their upper floors lie well above the expected maximum flood height. That is, these buildings have at least two floors above the expected maximum flood level. Once again, it should be noted that we are not making recommendations that these specific buildings should be designated 'safe evacuation structures', merely that such analysis can lead to the identification of such buildings. It is for others to determine which are most suitable.

The type of work carried out by Dall'Osso et al., (2009b) is extremely valuable. For example, Figure 4 shows that the recommended 'evacuation area' that bounds Golf Parade, Rolfe Street, Alexander Street, Pacific Parade and Pine Street does not contain a single building that would be 'safe' to evacuate in to during a tsunami associated with their scenario. That is, all buildings would be almost fully inundated and many would be severely damaged, if not completely destroyed. Therefore, people that occupy these buildings would need to fully evacuate the whole area. Having information like this means that the Emergency Services can pre-plan the best evacuation routes, implement signage at street level and develop and engage in community education and outreach programs. Conversely, the large evacuation area of Figure 4 parallel with the coast has many individual buildings we assess as useful for vertical evacuation (although the western ends of Eurobin Avenue and Iluka Avenue are some what problematic).

Figure 5 shows the mixed residential and commercial area of Manly CBD. Although the flow depth above ground surface is rather high in the tsunami scenario examined in this case, many individual buildings are assessed as being appropriate for vertical evacuation. Given that the ocean beach at Manly is a favorite with beach going visitors to the area and can be heavily populated on a sunny weekend in the summer, the close proximity of many buildings suitable for vertical evacuation, is somewhat reassuring.

4. Conclusions

As our cities expand, the exposure of our built environment to hazards such as tsunamis increases. Australia is at risk to tsunamis. The 2004 Indian Ocean tsunami was catastrophic. In some areas like Banda Aceh city, near complete devastation of the urban landscape occurred. Abandoning coastal regions affected by hazards such as tsunamis is simply not possible for a variety of reasons. Therefore, in order to enhance tsunami risk reduction strategies, high-resolution assessments of building vulnerability are required. Such assessments provide the building blocks upon which appropriate risk reduction strategies may be formulated. Recent work by Dall'Osso et al., (2009a, b) using a newly revised and improved PTVA-3 Model has been shown to be useful for providing very high-resolution assessments of the vulnerability of individual building structures to tsunamis of particular magnitudes. In this paper, we have taken the outputs from Dall'Osso et al., (2009b) and shown where and how they may be used to address important questions of relevance to local government and emergency services officers. We use a detailed case study from Manly, Sydney to explore these questions and options. We have not made specific recommendations since in our view, it is the role of responsible professional decision makers to best decide how such data might be used.

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Figures:

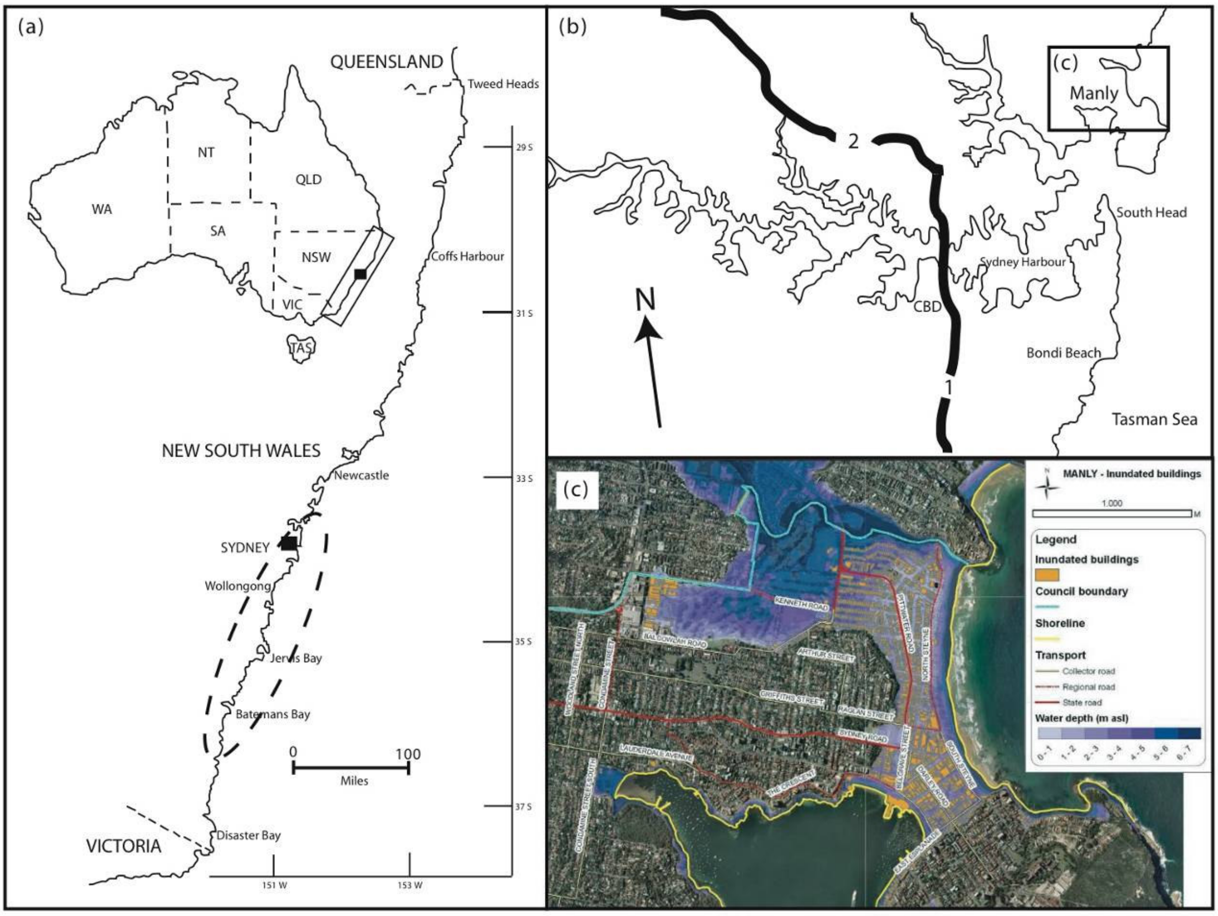

Figure 1 (a) Broad location of the study region of Sydney located in New South Wales (NSW) on the SE coast of Australia. The hatched oval encompassing the region north of Sydney south to beyond Batemans Bay is the region reported to have been affected by Holocene megatsunami (Bryant, 2008). NSW = New South Wales, NT = Northern Territory, SA = South Australia, TAS = Tasmania, VIC = Victoria, WA = Western Australia. (b) Simplified map of the Sydney Harour region with our specific field study area of Manly located NE of the CBD. Highways 1 and 2 are shown. (c) Detailed GIS map of our study area of Manly. Area of inundation (including relative water depths above land surface) associated with our tsunami scenario are shown in blue. Principal features are high-lighted and buildings inundated by the tsunami are indicated in orange.

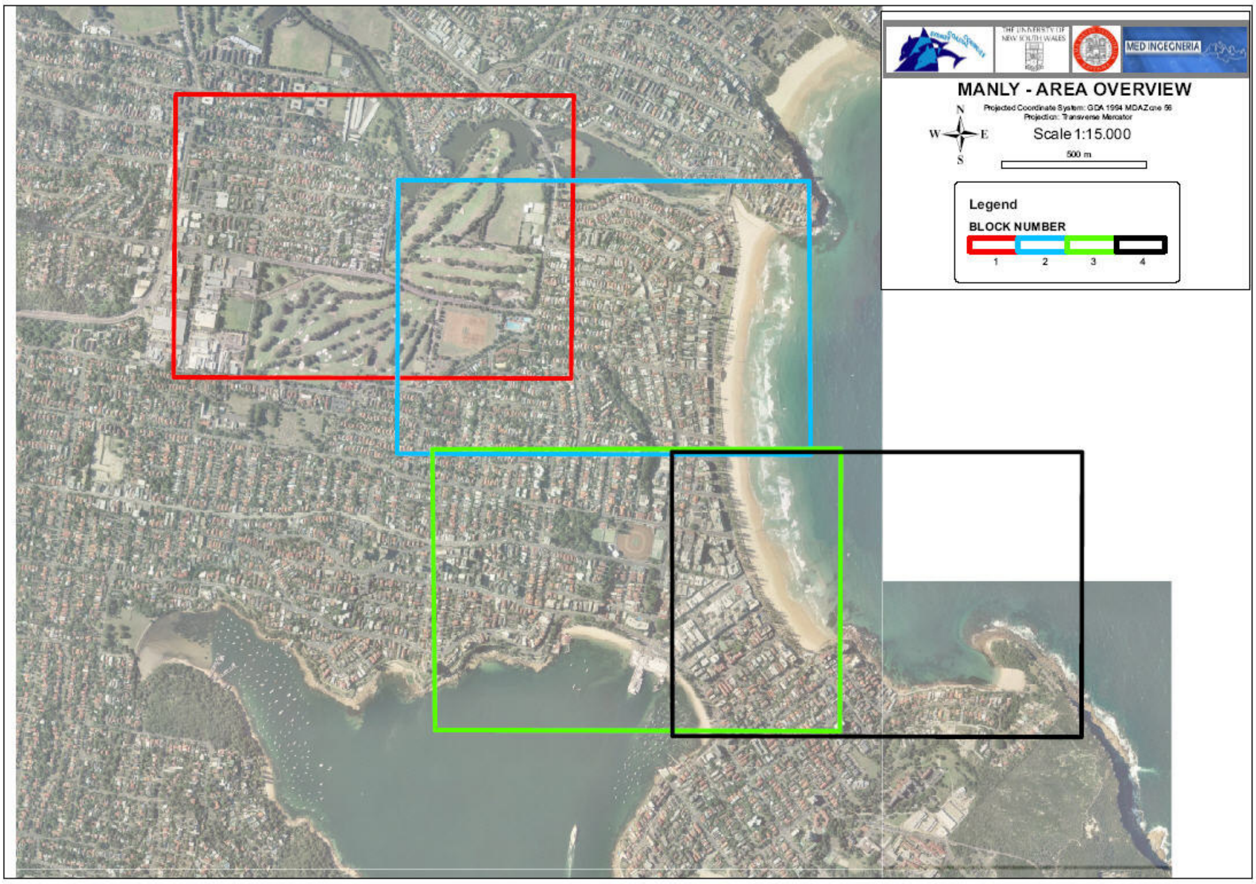

Figure 2. The Manly study area divided in to four (4) 'Blocks' for ease of results presentation. This paper just deals with Blocks 2 and 3.

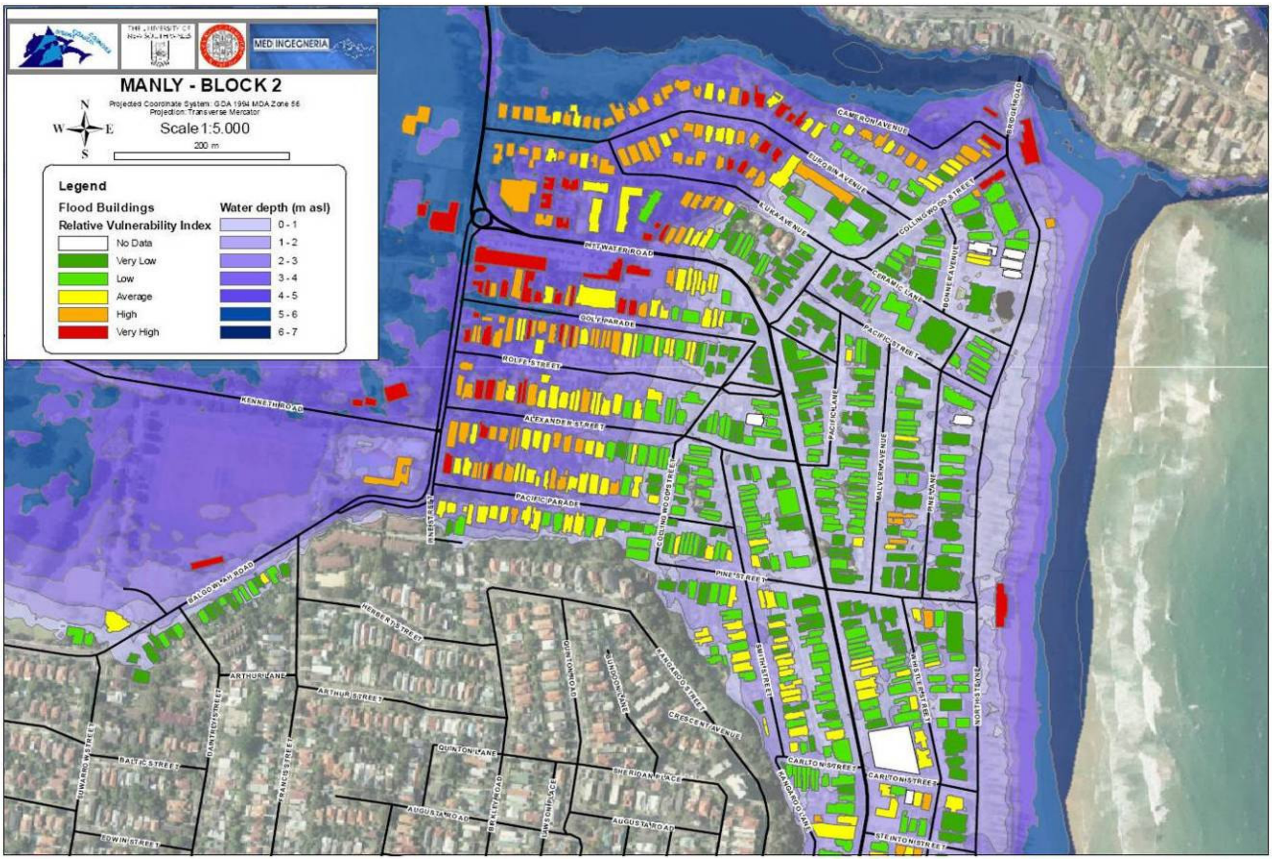

Figure 3. Tsunami inundation and water depth in Block 2, Manly. The RVI scores of every building located within the inundation zone are indicated

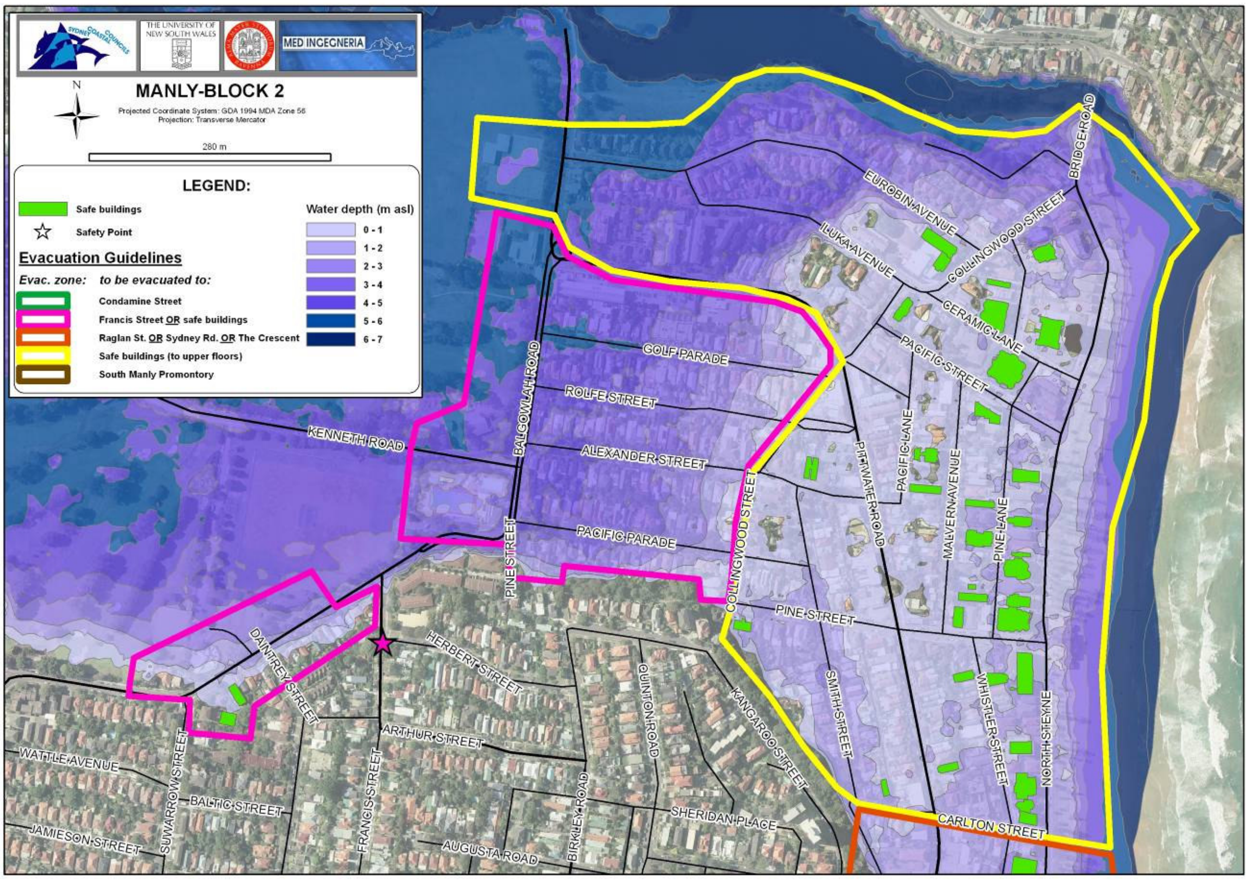

Figure 4. Evacuation areas and 'safe' buildings for evacuation, Block 2, Manly

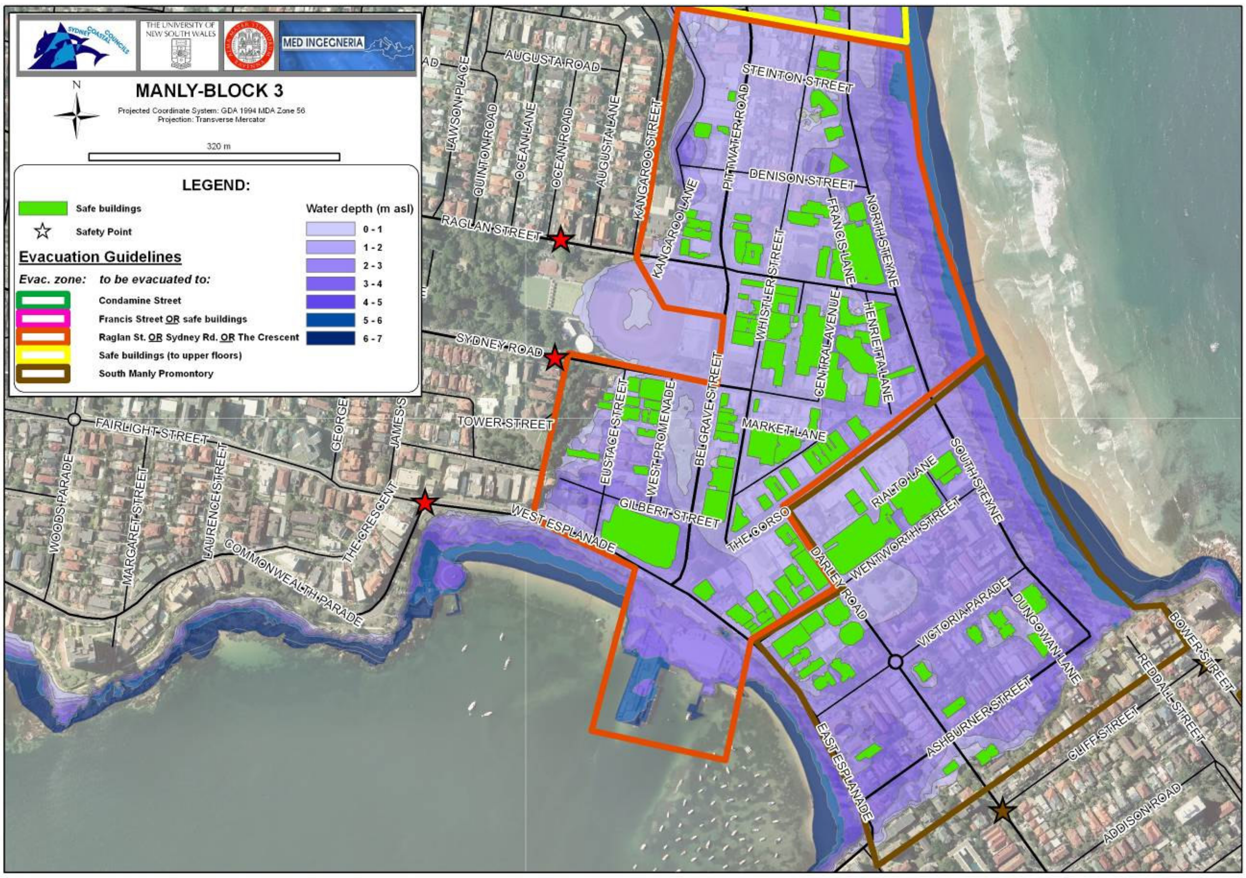

Figure 5. Evacuation areas and 'safe' buildings for evacuation, Block 3, Manly

Tables:

Table 1. Summary of the total number of buildings by building class and the number of buildings according to their Relative Vulnerability Index (RVI) scores in Manly.

Manly (Blocks 1 – 4)		**Relative Vulnerability Index (RVI) Scores**				
Building class type	**Number of buildings**	**Buildings with "Very Low" RVI**	**Buildings with "Low" RVI**	**Buildings with "Average" RVI**	**Buildings with "High" RVI**	**Buildings with "Very High" RVI**
Local Government	**23**	**4**	**9**	**3**	**1**	**6**
Health & Medical	**19**	**10**	**5**	**3**	**0**	**1**
Education	**19**	**7**	**5**	**6**	**1**	**0**
Recreation &Culture	**22**	**5**	**7**	**5**	**2**	**3**
Utilities	**12**	**2**	**0**	**2**	**4**	**4**
Transport	**5**	**2**	**0**	**1**	**0**	**2**
Tourism	**24**	**11**	**10**	**1**	**2**	**0**
Commercial	**217**	**113**	**66**	**21**	**7**	**10**
Residential	**865**	**218**	**295**	**193**	**119**	**40**
Vacant and being redeveloped	**8**	**-**	**-**	**-**	**-**	**-**

Paper n. 5

Assessing the vulnerability of buildings to tsunami damage in the Aeolian Islands, Italy – application and validation of the PTVA – 3 Model

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Assessing the vulnerability of buildings to tsunami damage in the Aeolian Islands, Italy – application and validation of the PTVA – 3 Model

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Abstract

The volcanic archipelago of the Aeolian Islands (Sicily, Italy) is included on the UNESCO World Heritage list and is visited by more than 200.000 tourists per year. Due to its geological characteristics, the risk related to volcanic and seismic activity is particularly high. Since 1916 the archipelago has been hit by eight local tsunamis (Maramai et al., 2005a). The most recent and intense of these events happened on the 30th of December 2002. It was triggered by two successive landslides along the north side of the Stromboli volcano (Sciara del Fuoco), which poured approximately 2-3 x 10^7 m^3 of rocks and debris into the Tyrrhenian Sea (Tinti et al., 2006a). The waves impacted across the whole archipelago, but most of the damage to buildings and infrastructures occurred on the island of Stromboli (maximum run-up 11 metres) and Panarea.

The aim of this study is to assess the vulnerability of buildings to damage from tsunami located within the same area inundated by the 2002 event. The assessment is carried out using the PTVA-3 Model (Papathoma Tsunami Vulnerability Assessment - version 3), recently developed and applied in Sydney by Dall'Osso et al. (2009a; 2009b). The PTVA-3 Model calculates a Relative Vulnerability Index (RVI) for every building, based on a set of selected physical and structural attributes (Papathoma et al 2003; Papathoma and Dominey-Howes, 2003). Run-up values within the area inundated by the 2002 tsunami were measured and mapped by the Istituto Italiano di Geofisica e Vulcanologia (INGV) and the University of Bologna during field surveys in January 2003. Results of the assessment show that if the same tsunami were to occur today, 54 buildings would be affected in Stromboli, and 5 in Panarea. The overall vulnerability level obtained in this analysis for Stromboli and Panarea are "average"/"low" and "very low", respectively. Nonetheless, fourteen buildings in Stromboli are classified as having an "high" or "average" vulnerability. For some buildings, we were able to validate the RVI scores calculated by the PTVA-3 Model through a qualitative comparison with photographs taken by INGV during the post-tsunami survey. With the exception of a single structure, which is partially covered by a coastal dune on the seaward side, we found a good degree of accuracy between the PTVA 3 Model forecast assessments and the actual degree of damage experienced by buildings. This validation of the model increases our confidence in its predictive capability. Given the high tsunami risk of the archipelago, our results provide a framework to prioritize investments in prevention measures and address the most relevant vulnerability issues of the built environment, particularly on the island of Stromboli.

1. Introduction

The Aeolian archipelago, located in the south Tyrrhenian Sea to the west of Calabria and to the north of Sicily, is made up of seven major islands. It is located about eleven nautical miles off the northern Sicily coast, in the province of Messina (Figure 1). The total number of residents is 13,509 and most of them live on the largest island of Lipari. The whole archipelago is listed as an UNESCO World Heritage site. The natural and geological characteristics of the Aeolian islands attract more than 200,000 tourists per year. Visits are concentrated mainly in summertime. From May to September the number of people living in the archipelago can increases fivefold.

In the frame of the geodynamical evolution of the Mediterranean basin, the collision between the African and Eurasian plates originated a marginal "fore-arc deep-basin" system of which the Aeolian Islands represent the volcanic front. All the islands were submarine volcanoes which emerged about 700ky ago and, together with the eight seamounts (Marsili, Glauco, Sisifo, Enarete, Eolo, Lamentini, Alcione, Palinuro), they constitute the Aeolian Volcanic District which extends for a total length of about 200 km along the north-western margin of the Calabria Arc and the southern limit of the Tyrrhenian Retro-Arc Basin (Barberi et al., 1973, Beccaluva et al., 1985).

The volcanism of the Aeolian Islands started during the Pleistocene, with two main periods of activity (Maramai et al., 2005a). The volcanic edifice of Panarea, the oldest in the archipelago, and the islands of Filicudi, Alicudi, part of Salina and Lipari originated during the first period in the early Pleistocene. The second phase started, after a period of dormancy, in the upper Pleistocene, with the completion of the Lipari and Salina islands and the creation of the Volcano and Stromboli islands (Maramai et al. 2005a). Stromboli is the most active volcano in the archipelago and its activity consists of almost continuous low energy explosions with ejection of magmatic scoriae from the eruptive vents located inside the crater. Significant eruptions and/or explosions happen quite frequently and they are often accompanied by earthquakes, landslides and sometimes tsunamis. The activity of the Stromboli volcano seems to be continuous from about 1,000 - 1,500 years ago (Rosi et al. 2000). The summit of the volcano reaches an elevation of 926 m, while the volcanic edifice extends below the sea level to a depth of 1,200 - 1,500 m on the east and south flanks and 1,700 - 2,200 m on the north and west flanks. One of the main features of the volcano is the deep scar located on the north-western flank, called Sciara del Fuoco, caused by several collapses that have occurred during the past 5,000 years (Pasquarè et al. 1993).

The volcanic activity of Stromboli is so peculiar that it has given rise to the term "Strombolian activity", to describe similar behaviour observed in other volcanoes around the world. (Burton et al, 2007; http://volcanoes.usgs.gov/images/pglossary/strombolian.php). This activity is characterised by rhythmic mild gas explosions, occurring at time steps of about 10-20 minutes, ejecting ash, incandescent crystal-rich scoriae and blocks (Burton et al., 2007). At Stromboli this activity is interspersed with "major explosions" which are more energetic events involving the ejection of lava bombs and blocks, that could reach distances of several hundreds meters, and also lapilli and ash that can be expelled several kilometres. Major explosions can become very energetic and last for several hours to a few days. In these cases they are called "paroxysm" and result in showers of incandescent scoriae and bombs that are violently ejected to distances of several kilometres. The paroxysms usually occur at intervals of years or decades (Barberi et al. 1993, Rosi et al. 2000) and during these phases huge amounts of erupted material can accumulate on the volcano flanks. These deposits can become unstable, collapsing into the sea triggering tsunami.

1.1 Record of tsunamis at the Aeolian Islands

The scientific community developed a systematic interest in the Aeolian volcanoes evident from the end of the 19th century and with regard to tsunamis the first reliable information of events occurred in the Aeolian islands dates back to 1916. Since then eight tsunami events, either destructive or minor, have affected the archipelago, being almost all directly or indirectly related to volcanic activity (Maramai et al., 2005a). Six of the eight tsunamis, including the strongest one, were originated by the volcanic activity of the Stromboli volcano. One occurred on Salina island and was associated with a local earthquake, and one was generated by a landslide on the volcano flank of Vulcano island.

A study of the Aeolian tsunamis was published by Maramai et al. (2005a) detailing seven historical events in the period 1916 to 1988, whereas the last and most destructive tsunami (the December 30, 2002 Stromboli event), is widely described in many papers (Pino et al., 2004; Maramai et al., 2005b; Tinti et al., 2005; 2006a, 2006b).

A summary of the Aeolian tsunamis with main tsunami parameters (time, source area, coordinates, cause, tsunami intensity, and description) is reported in Table 1 (from Maramai et al. 2005a, modified).

1.2 The tsunami of the 30th December 2002

The December 30th 2002 Stromboli tsunami is the strongest event ever reported in the Aeolian archipelago.

In the second half of 2002 the Stromboli volcano saw an increase in its explosive activity, that lasted until December the 28th, when a new effusive phase made the Sciara del Fuoco flank unstable. Two days later, on December 30th, two major landslides occurred, one submarine and the other subaerial, which triggered the generation of tsunami waves. The first slide, mainly submarine, occurred at 13:15 local time and the second one about 7-8 minutes later, with a subaerial detachment of a mass of about 7-8x10^{6} m^{3} from the Sciara del Fuoco. The total volume of transported material during the two slides was about 2-3x10^{7} m^{3} (Baldi et al, 2003; Bosman et al., 2003; Chiocci et al., 2003).

The December 30th tsunami was studied by several researchers and many post event field surveys were carried out by national and international teams in order to get a detailed picture of the effects. On the basis of eye-witness accounts, Tinti et al. (2005) established that both landslides generated a tsunami. The first sea movement, caused by the submarine slide, was a withdrawal. With regard to the second landslide, the polarity of the wave is not clear.

The first wave arrival was observed about three minutes after the landslide occurrence as the sea water flooded the beach of Ficogrande (Figure 2), and one minute later the localities of Punta Lena and Scari were inundated and severely damaged. A sea surface withdrawal was observed at the island of Panarea (Figure 1) at 13:20 (local time), about five minutes after the initial tsunami generation. Afterwards, two or three strong sea swellings inundated a part of the San Pietro harbour. In less than 20 minutes all the Aeolian islands had been struck by the tsunami and anomalous sea movements were also observed in Milazzo, in the northern Sicilian coast, about 60 km south of Stromboli (Tinti et al., 2006a; Maramai et al. 2005b).

The post-tsunami field surveys, performed according to the field procedures adopted by the international tsunami community (IOC/UNESCO, 1998), allowed researchers to describe damage and effects along the coasts of the Aeolian archipelago. In particular, the surveys were focused on the coast of Stromboli, Panarea, Lipari, Vulcano and Salina islands where major effects were expected.

The north-eastern coast of Stromboli was the most severely affected by the tsunami, with runup ranging from 3.0 to 11 meters. Severe effects were observed at Ficogrande, Piscità and Punta Lena (Figure 2) where buildings fronting the sea were heavily damaged.

At Scari (Figure 2), the tsunami effects were less severe and only some buildings on the beach were damaged. However, due to the low slope of the beach, the maximum inland inundation (135 m) was observed here.

At Panarea Island the inundation caused some damage to a few structures on the beach, particularly in the San Pietro harbour, where INGV measured the maximum runup (2.3 m) and inundation (36.5m) recorded on the island.

Tsunami effects were also observed in all the other islands of the archipelago where eyewitness reports described anomalous sea behaviour, mainly as extraordinary tides or whirlpools.

1.3 Aim of this work

The aim of this work is to assess the vulnerability of existing buildings in the Aeolian Islands to a future tsunami. The assessment is carried out using the latest version of the Papathoma Tsunami Vulnerability Assessment Model (PTVA-3 Model), recently developed by Dall'Osso et al (2009a, 2009b). The PTVA-3 Model calculates a Relative Vulnerability Index (RVI) for every inundated structure.

Since no probabilistic assessments for estimating tsunami risk are available for the study area, our approach is deterministic. The inundation scenario we adopt is the 2002 event. As a consequence, we calculate what would be the vulnerability level of buildings in case the 2002 tsunami occurred again. Accordingly, the analysis is carried out only for those structures that are currently located within the area inundated in 2002. Apart from a few newly built structures, those buildings are the same that were hit in 2002. For some of the inundated buildings, we could compare RVI values determined during our assessment with photographs of the damage suffered during the 2002 tsunami. This provides an important opportunity to 'validate' the damage forecast potential of the PTVA-3 Model against actual damage sustained during a real tsunami event.

2. Applying the Papathoma Tsunami Vulnerability Assessment Model (PTVA-3 Model)

The PTVA-3 Model (Dall'Osso et al., 2009a; Dall'Osso et al., 2009b; Dall'Osso and Dominey-Howes, in review) is a GIS based method developed to assess the vulnerability to tsunami of single buildings. The PTVA-3 is the latest version of the original PTVA Model (Papathoma and Dominey-Howes, 2003; Papathoma et al., 2003; Dominey-Howes et al., 2010), which was tested and validated during field surveys in the Maldives after the 2004 Indian Ocean Tsunami (Dominey-Howes and Papathoma, 2007). PTVA-3 takes account of recently published data about attributes that affect building vulnerability to tsunami and introduces the Analytic Hierarchy Process (AHP) for weighting the various attributes, in order to limit concerns about their subjective ranking in the original model. A similar approach, based on the AHP, was applied by Dall'Osso et al. (2006) within the CRATER project (Coastal Risk Analysis for Tsunami and Environmental Remediation), developed in partnership with INGV. The improvement of the CRATER approach and its integration within the PTVA-2 lead to the development of PTVA-3 Model.

The PTVA-3 Model calculates a Relative Vulnerability Index (RVI) for each building within the inundation zone. RVI values are then classified into five vulnerability classes, ranging from "very low" to "very high". RVIs are obtained as a mathematical function of different attributes contributing to the overall building vulnerability. The main attributes are grouped as follows:

- the physical attributes of the building that are known to be associated with the degree of damage suffered by buildings to tsunamis (e.g. number of stories, building material, foundations, ground floor hydrodynamics, movable objects etc.);
- the environment surrounding each building (e.g. degree of protection provided to the building by natural or artificial barriers)
- the depth of water expected at the building location

The PTVA-3 Model requires that all of the necessary building attributes are entered as numerical scores. Scores are given to each attribute according to its contribution to the overall building vulnerability. For example, if a building has a reinforced concrete structure the "building material" attribute will be scored lowest, given that reinforced concrete structures are the least vulnerable to tsunami impact (if all other attributes are equal). The PTVA-3 Model provides specific tables that state which score must be given to the different building attributes (e.g. for a reinforced concrete structure, the "building material" score must be -1; for a wooden structure, the "building material" score must be +1, etc.). After being entered, attribute scores are used by the model to calculate RVI scores.

Importantly, RVI scores do not depend on the economic value of buildings, nor on the value of their contents (e.g. the furniture). To the PTVA-3 Model, each building is equally important, since its value is based only on the structural-functional service it provides.

It is suggested that readers interested in further details about the PTVA-3 Model and RVI calculation refer to Dall'Osso et al. (2009a; 2009b) and Dall'Osso and Dominey Howes (2009b).

2.2 Data gathering: building the GIS

Almost all of the structures within the area inundated by the 2002 tsunami were located on the island of Stromboli, the exceptions being a few buildings at the S.Pietro harbour (Panarea). In order to apply the PTVA-3 Model, we gathered information about the following building attributes:

1. Building material
2. Number of stories
3. Hydrodynamics of the ground-floor (totally closed by walls, few small windows, high number of windows, columns and open spaces, etc.)
4. Foundation type

5. Preservation Condition
6. Number of underground levels
7. Protective structures along the shoreline (e.g. sea-walls, rocks, other fences, etc.)
8. Artificial barriers close to the building (e.g. brick wall around the garden)
9. Building use (residential, commercial, tourism, Public Administration, etc.)
10. Orientation of the building with respect to the expected or observed flow direction
11. Natural barriers between the building and the sea (e.g. vegetation, sand dunes, etc.)
12. Number of other buildings located between the considered building and the sea (to assess the shielding effect)
13. Movable objects between the building and the sea (car parks, boats, etc.)

Given the high number of required data points, we extracted spatial data from two "Worldview" satellite images. Worldview images provide a geometrical resolution of 60 cm and are suitable for the analysis of the built environment through a photo-interpretation process. We selected one image for Stromboli (Figure 2) and one for Panarea (Figure 3), using the following search filters:

- images registered after 2008;
- minimal cloud cover (all of the buildings had to be clearly recognizable);
- good brightness/contrast ratio.

Elevation data was sourced using as a reference a Digital Elevation Model (DEM) provided by INGV, with a geometrical resolution of 10 m and a vertical accuracy better than 1 m.

Once orthorectified, Worldview images and the DEM were imported into a GIS and used as geographical base of reference. We used the DEM and the tsunami inundation measures undertaken by INGV in 2003 to identify all of the exposed buildings and to calculate the depth of inundation expected to hit each of them. Buildings located within the inundation zone were manually digitized within the GIS as polygons. Afterwards, we entered the inundation depth measured after the 2002 tsunami into the attribute table of every polygon (building).

Building attributes 10 to 13 of the aforementioned attribute list (e.g. building orientation with respect to the expected flow direction, natural barriers, etc.) were obtained through a photo-interpretation process of the Worldview images. Remaining attributes (from number 1 to number 9) have been gathered building by building though field surveys.

After field surveys, all attribute data were converted into numerical scores, and manually entered into the GIS.

2.3 Adapting the PTVA-3 Model to the construction standards of Aeolian Islands

The structure of the PTVA-3 Model has been conceived to be applicable anywhere, however a few elements depend on boundary conditions (type of architecture, inundation scenario) and might need to be adapted to specific cases.

In this work, the only adaptation we introduced involves the "building material" attribute, since construction standards and typical materials used in the Aeolian Islands are different from those observed in Australia, where the PTVA-3 Model was firstly developed.

In the Aeolian Islands most of the buildings have walls made of a single layer of bricks, with a thickness between 15 and 30 cm. Some of the eldest structures have walls made of natural volcanic rocks (e.g. pumice stone), poorly cemented and degraded by atmospheric agents. Some of the newest structures are built with reinforced concrete frames and brick fillings, while few buildings are made of wood or corrugated iron.

In order to integrate those construction standards into the model, scores to the "building material (m)" attribute have been given according to Table 2.

2.4 Running the PTVA-3 Model: the "inundation vulnerability" tool for ESRI ArcGIS 9

Once attribute data have been gathered and entered into the GIS as numerical scores, the relative vulnerability of every building is automatically calculated through the application of a specific add-in developed for ESRI ArcGIS 9, called "inundation vulnerability" tool.

The "inundation vulnerability" tool was created by Dall'Osso and Dominey-Howes (2009a) during the first application of the PTVA-3 Model (Dall'Osso et al., 2009a). Once input attribute levels are entered into the GIS in the correct format, the tool is able to perform all calculations required to obtain the final RVI value of each building.

Readers interested in further details about the structure and the application of the "inundation vulnerability" tool can refer to the user's manual (Dall'Osso and Dominey Howes, 2009a).

3. Results

The results show that if the 2002 tsunami occurred again, 54 buildings would be hit in Stromboli, and 5 in Panarea. All of these buildings are currently located within the area inundated in 2002, as indicated by the INGV post-tsunami surveys.

As in previous PTVA-3 Model applications (Dall'Osso et al, 2009a; 2009b) RVI values have been grouped into the following five classes:

- RVI = "very high"
- RVI = "high"
- RVI = "average"
- RVI = "low"
- RVI = "very low "

Surveyed buildings and their RVI scores have been stored within a GIS and displayed in vulnerability maps, having a scale such that every single structure and its surroundings can be clearly indentified. The coastal area inundated by the 2002 tsunami has been fully covered by 4 different map layouts (3 for Stromboli and 1 for Panarea), corresponding to the following administrative divisions (Figure 2 and Figure 3) :

1. Stromboli island – Piscità
2. Stromboli island – Ficogrande
3. Stromboli island – Punta Lena and Scari
4. Panarea island – San Pietro harbour

In our study, we created several vulnerability maps for each division: one map displaying an overview of all affected buildings, and one for each of the building use categories observed during field surveys (i.e. residential, commercial, tourism, Public Administration and utility). For the sake of brevity, we present here just one overview-map per division, showing all types of buildings. However, Table 3 provides a summary of the total number of inundated buildings by building use and the number of buildings according to their Relative Vulnerability Index score for Stromboli Island.

3.1 Stromboli - Piscità

At Piscità the tsunami would hit 7 residential buildings (Figure 4). Two are located just behind a pocket beach and would be flooded by more than 2m of water. Their respective RVI scores are "high". The five remaining houses have "low" and "very low" RVI scores. Whilst they have similar construction characteristics, they all lay up the coastal cliff, where the maximum inundation depth would not exceed 1 metre.

3.2 Stromboli - Ficogrande

At Ficogrande the total number of inundated buildings would be 27 (Figure 5). Six out of them have a "very low" RVI score, seventeen have a "low" RVI and four have an "average" RVI value.

The main issues of concern for the area are the four residential structures located just in front of the beach, at the eastern end of the bay. These buildings are brick-made houses, with one storey, a partially closed ground-floor with few windows with no protection from the sea. According to the inundation scenario, they would experience a flow depth between 1 and 2 metres.

At the western end of the bay, most of the inundated buildings are hotel, shops and restaurants. Most of them are built according to new construction standards, with reinforced concrete structures, two or more stories and open ground-floors with large panoramic windows. The inundation depth on that side of the beach would be in the order of one metre. According to the PTVA-3 Model, the RVIs of such buildings range between "low" and "very low".

3.3 Stromboli – Punta Lena and Scari

The tsunami would hit 20 buildings in this part of the island. Two out of them are classified as having an "high" RVI score, six have as "average", nine have a "low" RVI and three have a "very low" RVI (Figure 6).

The average vulnerability in Punta Lena is higher than in Ficogrande. Although buildings here have similar construction characteristics, they are much closer to the sea and would be affected by a deeper flow. Furthermore, several sources of big movable objects have been observed along the shoreline (car and bike deposits, containers, boats, etc.). Those objects might be dragged by the tsunami against the first row of buildings, causing heavier damage.

Most of the buildings (14) in this area are residential. Two of them have an "high" RVI score. The one at the northern end has a concrete structure, but only one floor, with no openings at all. It would be hit by a wave higher than 3 metres. The southernmost one, in Scari, is built with bricks (15 cm thick walls), has two stories and the ground-floor is completely closed. Water depth impacting this building would be between 2 and 3 metres.

Residential buildings with "average " RVIs account for a further 4 of the 20 structures. They are all houses built on the shoreline, with construction characteristics similar to the previous two buildings (those having a "high" RVI), but with a lower expected water depth. Some of them have vulnerability scores reflecting better protection.

Only 4 commercial buildings would be inundated at Punta Lena and Scari. One of them, a long shaped warehouse made of corrugated iron in Scari, has an "average" RVI score.

The only "utility" building of the whole island is a public electric power station, located in the southern part of Scari (Figure 6): it would be flooded by less than 1 metre of water and its RVI score is "low".

3.4 Panarea- S. Pietro habour

At Panarea island the only area inundated by the 2002 tsunami is the San Pietro harbour. Post-tsunami surveys undertaken by INGV and the Univeristy of Bologna reported a maximum run-up of 1 metre just behind the harbour pier. The structures we analyzed are five commercial buildings (3 shops and 2 cafè). They have all very similar construction characteristics: two stories, brick-walls and a partially open ground-floor with doors and windows. Objects such as tables, chairs and boats are usually located between the buildings and the shoreline. These objects could increase the impact load in case of event; despite this, RVI scores are all "very low" (Figure 7).

4. Discussion and recommendations

The application of the PTVA-3 Model at Aeolian Islands showed that the largest part of exposed buildings is located on the island of Stromboli (54 buildings) while just 5 structures would be inundated at the San Pietro harbour, in Panarea.

In Stromboli island, nearly three quarters (74%) of all affected buildings have been classified as having a "very low" or "low" RVI score, while all of the 5 structures in Panarea have "very low" RVIs.

The most problematic buildings are 4 houses having a "high" RVI score, built only a few meters from the shoreline at Piscità and Punta Lena, and 10 buildings having an "average" RVI score. The

PTVA-3 Model did not assign the maximum RVI score (RVI – "very high") to any of the analyzed structures.

Whilst the average structural vulnerability level of built environment in Stromboli and Panarea is not critical, the tsunami would affect different types of buildings and, in some of them, cause the interruption or the delay of important socio-economic activities (e.g. tourism and commercial activities, public and emergency services, etc.). RVI scores of different types of buildings are shown in Table 3. Based on these results, the following important observations can be made:

- Most of the affected buildings are residential, although a subset of them might be rented to tourists in summertime (from May to September). During field surveys it was no possible to find out which of them are used as touristic accommodation during the summer.
- If the 2002 tsunami occurred nowadays, the impact could be noticeable in the tourist sector, even if only 10% of the inundated buildings are hotels and/or related utilities. Furthermore, if the event occurred in the high seasons, general damage and chaos could cause a negative impact on the economy related to tourism.
- Commercial activities that would be hit are mostly connected with tourism (restaurants, souvenir shops, fishing and sailing shops, etc.). Such buildings have been classified as being moderately vulnerable, and so they are not expected to suffer relevant structural damage. However, the flood would cause a partial destruction of the goods stored inside and also the interruption of commercial activities.
- Only one inundated building belongs to the "utility" class. It is the only electric power station in the island of Stromboli (division of Scari). Although its structural vulnerability is "low", damage given by a minimum inundation would be much heavier than in a "normal" building and could result in a loss of electric power throughout the whole island, which would complicate post-disaster operations. This highlights the importance of ground truthing, because the RVI score does not depend on the strategic importance of the building and its use, and this is why the PTVA-3 Model classified the power station structure as having a "very low" vulnerability.
- The Coastguard building in Scari (building #6) is another "critical" building that should be fully operational in case of a tsunami. The relevant Public Administration (PA) office might want to consider appropriate prevention measures for such a strategic building.
- Luckily, no buildings located in the inundated area belongs to the categories of "health" (i.e. hospitals, medical centres, pharmacies, etc.), "education" (i.e. schools, nurseries, etc.),

"public transport" (apart from the pier of the Stromboli and S.Pietro harbours) and "culture and recreation centres" (i.e. churches, museums, libraries, historical buildings, sport centres, etc.).

In addition to observations on different type of affected buildings, results from the PTVA-3 Model and observations during field surveys suggested a set of general prevention and mitigation measures that could help reduce further the overall vulnerability level.

In the area of Punta Lena, for example, most important issues involve buildings located a few meters from the shoreline. The development of such areas should be avoided in future urban planning, because construction will increase the risk in case of inundation and, further, would be inconsistent with most of the Integrated Coastal Zone Management (ICZM) principles.

The presence of big movable objects (e.g. cars, trucks, boats, etc.) within the inundated zones is another important issue that could be addressed with a relatively small effort from the archipelago community. Such objects can be transported by the flow and hit buildings or injure people, causing heavy damage. The presence of boats stored on land, seaside parking areas of cars and bikes for rent, garbage bins, and containers behind the beaches of Scari and Punta Lena (Stromboli) all combine to increase the RVI scores of surrounding buildings. Some of the residents interviewed during field surveys claimed that most of those boats are never used and have been abandoned on the beach.

4.1 Validating the PTVA-3 Model results

Whilst the original version of the PTVA Model has been validated during post tsunami field surveys at the Maldives (Dominey-Howes and Papathoma, 2007), we undertook a further validation to confirm the accuracy of PTVA-3, which has been recently improved with respect to previous generations of the model. For six buildings in Stromboli we could compare results forecast by the model with the damage suffered by the same buildings during the 2002 tsunami. The comparison has been carried out on a visual base, using as a reference some pictures taken by INGV during post-tsunami field surveys in December 2002 - Janaury 2003. Buildings used for the validation of the model have been numbered from #1 to #6 and marked with red symbols on the vulnerability maps of Stromboli island (Figure 4, Figure 5 and Figure 6).

Figure 8 shows the façade of building #1 after the 2002 tsunami. The footprint of same building is highlighted in the vulnerability map of Piscità (Figure 4.). Although the picture provides only a partial view, no relevant damage can be seen, except from an unhinged window at the first floor.

Building #1 is located up the coastal cliff and intersects the line of maximum horizontal water inundation. Accordingly, the water depth impacting the building was minimal and did not even flood the whole ground-floor. Damage to the interiors and to parts vulnerable to water contact was negligible. The RVI score calculated by the PTVA-3 Model for that building is "very low" and result are thus consistent with the observed damage.

Damage to Building #2, at Ficogrande (Figure 5), is shown in Figure 9. The flow broke through a door in the front wall, penetrated indoors, destroyed the interiors and one partition wall and travelled through the backdoor of the house (Tinti et al., 2006a). The overall damage level is clearly heavier than the one observed in building #1 at Piscità. The PTVA-3 Model classified building #2 as having an "average" RVI. Although such an RVI score may appear to be underestimated, Figure 9 shows that no damage occurred to the weight-bearing walls of the building. Apart from an internal partition wall, which is not designed to withstand any kind of pressure, damage involved only doors, windows, the furniture (which is not considered by the PTVA-3 Model) and the interiors, especially parts vulnerable to water (electric appliances, fixtures, paving tiles, etc.).

In Punta Lena and Scari, we could check the accuracy of the PTVA-3 Model results for four buildings (buildings #3 to #6) (Figure 6). Three of them (buildings #3 to #5) are residential houses located few metres from the sea at Punta Lena. Building #6, in Scari, is the Coastguard station.

Buildings #3, #4 and #5 have very similar construction characteristics: they are single-storey, bricks-made and have a partially open ground-floor with windows. According to INGV surveys, during the 2002 tsunami the inundation depth at buildings #3 and #5 was between 1 and 2 meters, while at building #4 the flow was shallower (about 1 metre).

Damage to building #3 (RVI = "average") is shown in Figure 10. The flow broke through doors and windows and caused total destruction to interiors. However, there is no evidence of damage to the load-bearings walls. The overall damage level is thus comparable to building #2 at Ficogrande.

Damage to building #4 (RVI = "low") is partially shown in Figure 11. The door on the front-wall has not been broken-down and suffered minor damage. However, the water penetrated indoor through the shutter openings and flooded the ground-floor, causing damage to interiors. The overall impact on the structure was lighter than for neighbouring buildings. This was due to the lower depth of the inundation and to the protection provided by the front-garden vegetation and some artificial structures between the building and the sea (a brick wall, a large concrete table in the garden and the coastal defences along the shoreline) (Figure 11b). As forecast by the PTVA-3 Model, such protection slowed down the flow and prevented a part of the floating debris from impacting the building structure.

Figure 12 shows damage to building #5 (RVI = "average"). As for building #2 and #3, window and door frames have been ripped off the wall. Building interiors have been completely destroyed and the contents dispersed widely. The impact caused a crack in the front-wall, but left undamaged the load-bearing column at its right (Figure 12b). The front-porch has been almost completely destroyed. However, the load-bearing structure of the building appears not to be severely affected.

Building #6 lays on the beach of Scari (Figure 6) and it is a Coastguard station. It has one storey, a brick-made structure and a ground-floor almost completely closed, with no openings on the seaward wall. There are no protection from the sea, apart from a high coastal dune (almost as high as the building), totally leaned against the seaward wall. The RVI score of building #6 is "average". Figure 13 shows a picture of the building taken few days after the 2002 tsunami. Whilst the picture does not provide a detailed view of the structure, it appears that the general damage level is lighter than that observed in buildings #2, #3 and #5, although they have the same RVI score. This is due to the relative position of the building and the coastal dune. The shielding effect provided by the dune was higher than predicted by the model, which is designed to consider the protection from natural fences but does not include such particular cases. However, whilst building #6 was well protected against the first impact of the tsunami, it has been inundated by more than 1 metre of water. As a consequence, some damage to interiors caused by the contact with water must have occurred, although it cannot be seen in the available picture.

From the results presented in our analysis, it is clear that the forecast capability of the PTVA-# Model matches well with actual damage sustained by buildings during a real tsunami. This high correlation increases our confidence in the power of the PTVA-3 Model as a forecast building tsunami vulnerability assessment tool.

5. Conclusion

We applied the newly developed PTVA-3 Model (Papathoma Tsunami Vulnerability Assessment Model, version 3) to assess the vulnerability to tsunami of buildings at the Aeolian Islands, in Italy. Since 1916, Aeolian Islands have been hit by 8 local tsunamis, the most recent in December 2002. Given the current unavailability of a tsunami probabilistic assessment for the study area, we adopted the 2002 inundation as a deterministic scenario.

Results show that if the 2002 tsunami happened today, 54 buildings would be hit in Stromboli and 5 in Panarea. According to PTVA-3 Model output, the overall vulnerability level of such structures is "average/low" (Table 3). However, 14 buildings have been classified as having "high" and "average" RVI scores. Those structures would be severely affected by the tsunami. Where possible, the PA should prearrange actions aimed to reduce their vulnerability. Based on the PTVA-3 Model results and observations undertaken during field surveys, some specific prevention measures have been suggested. Whilst the high tsunami risk of the Aeolian archipelago is well known, the vulnerability of buildings had never been assessed before the present work. Therefore, we believe our results can be of great help for local community and PA, as they identify main criticalities and suggest possible actions to increase the overall resilience of the built environment.

The vulnerability assessment undertaken here is entirely based on the application of the PTVA-3 Model. The PTVA-3 is the latest version of the original PTVA Model (Papathoma et al., 2003; Papathoma and Sominey-Howes, 2003) and it was recently developed and applied in Australia by Dall'Osso et al. (2009a; 2009b). Before being used in the present work, the PTVA-3 Model had to be adapted to the construction standards of Aeolian Islands. However, since every factor considered by the PTVA-3 Model can be independently modified, the required adjustments have been easily introduced, confirming the flexibility of the model.

Data required for the assessment have been extracted from two high resolution satellite images and through field surveys. Once available, data have been stored and organized within a GIS. The computation of the RVIs was automatically performed through a specific tool for ESRI ArcGIS, developed by Dall'Osso and Dominey Howes (2009a).

For some buildings we could validate the PTVA-3 Model results through a comparison with some pictures of the damage suffered by same buildings during the 2002 tsunami. Apart from the Coastguard building in Scari (Stromboli), the PTVA-3 Model assessment was found to be very accurate and in line with the observed damage. In particular, three buildings classified as having an "average" RVI score showed the same overall damage level (i.e. high damage to doors and windows, flooding of the ground-floor, destruction of interiors, damage to some partition walls but no relevant damage to the load-bearing structure). Furthermore, the model showed a very good degree of precision, as it was able to differentiate the RVIs of three houses at Punta Lena (Figure 6), whilst they have very similar construction characteristics and are located very close to each other. With regard to the Coastguard station, damage observed in the available picture appears to be lighter than those suffered by other buildings having the same RVI score. The most likely cause of that is the particular protection provided to the building by a 2 meters high coastal dune, which covers completely the seaward wall. Whilst the PTVA-3 Model considers the shielding effect from natural defences, it is not designed to provide for such particular cases, which would require a numerical simulation of the flooding.

The original version of the PTVA Model had been already validated during post tsunami field surveys at the Maldives (Dominey-Howes and Papathoma, 2007). This further validation confirmed the accuracy of version 3 of the model, which implements some important improvements based on recent publications, not available when the original PTVA was firstly developed. Future generations of the model should aim to implement a numerical simulation of the tsunami flooding, at a detail scale consistent with the size of single buildings.

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Figures:

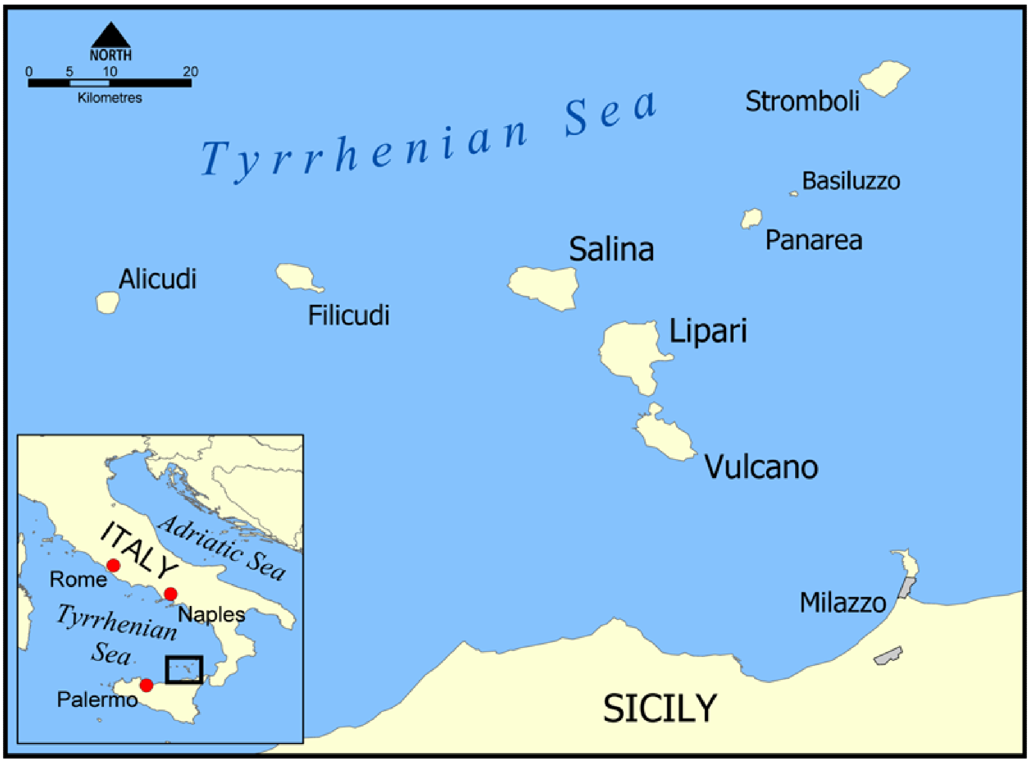

Figure 1. Geographic location of the study area. The Aeolian archipelago includes, from east to west, the islands of: Alicudi, Filicudi, Salina, Lipari, Vulcano, Panarea and Stromboli (http://whc.unesco.org)

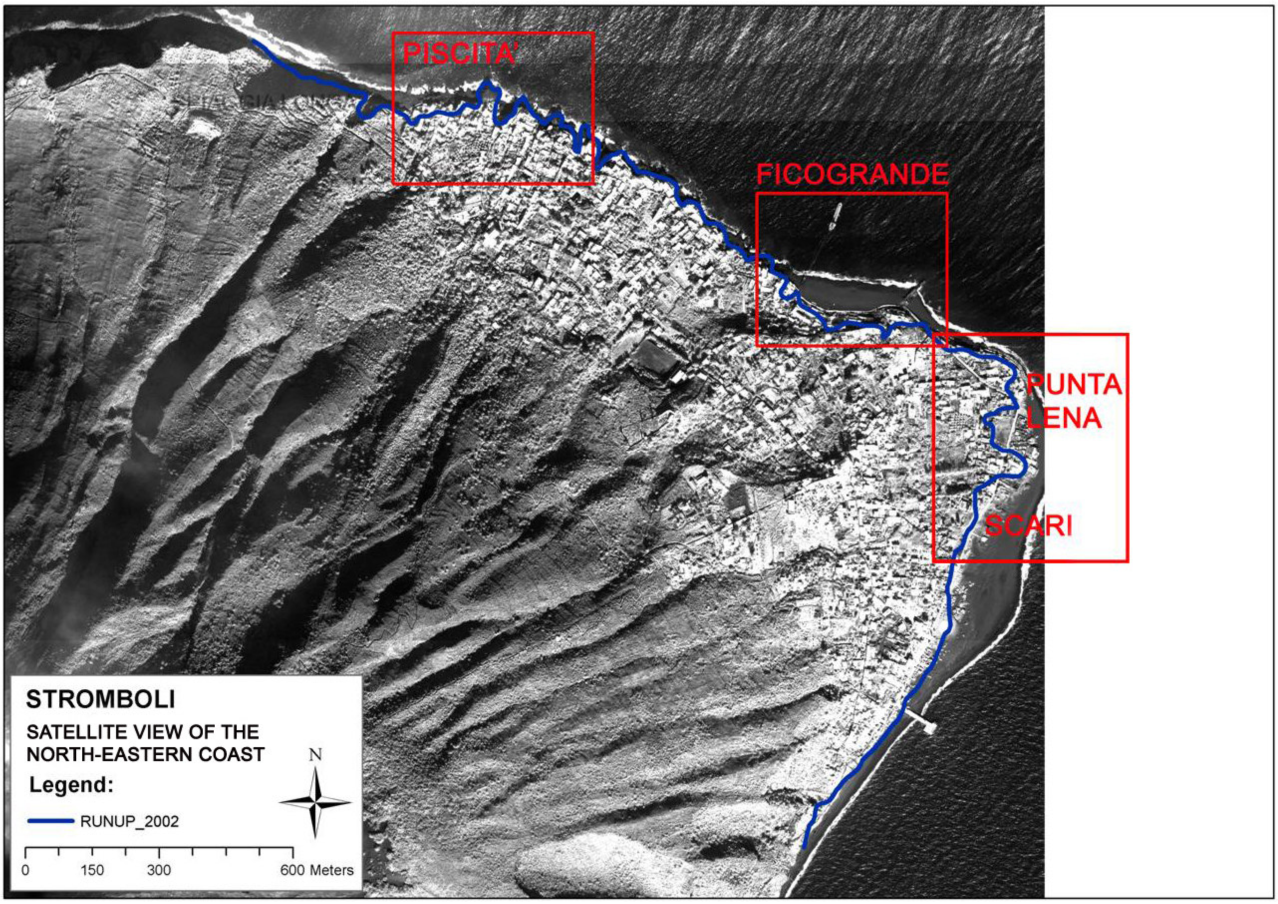

Figure 2. A "Worldview" satellite image of the north-eastern coast of Stromboli island. Main administrative divisions are highlighted with red frames. The blue line marks the limit of maximum inundation caused by the 2002 tsunami.

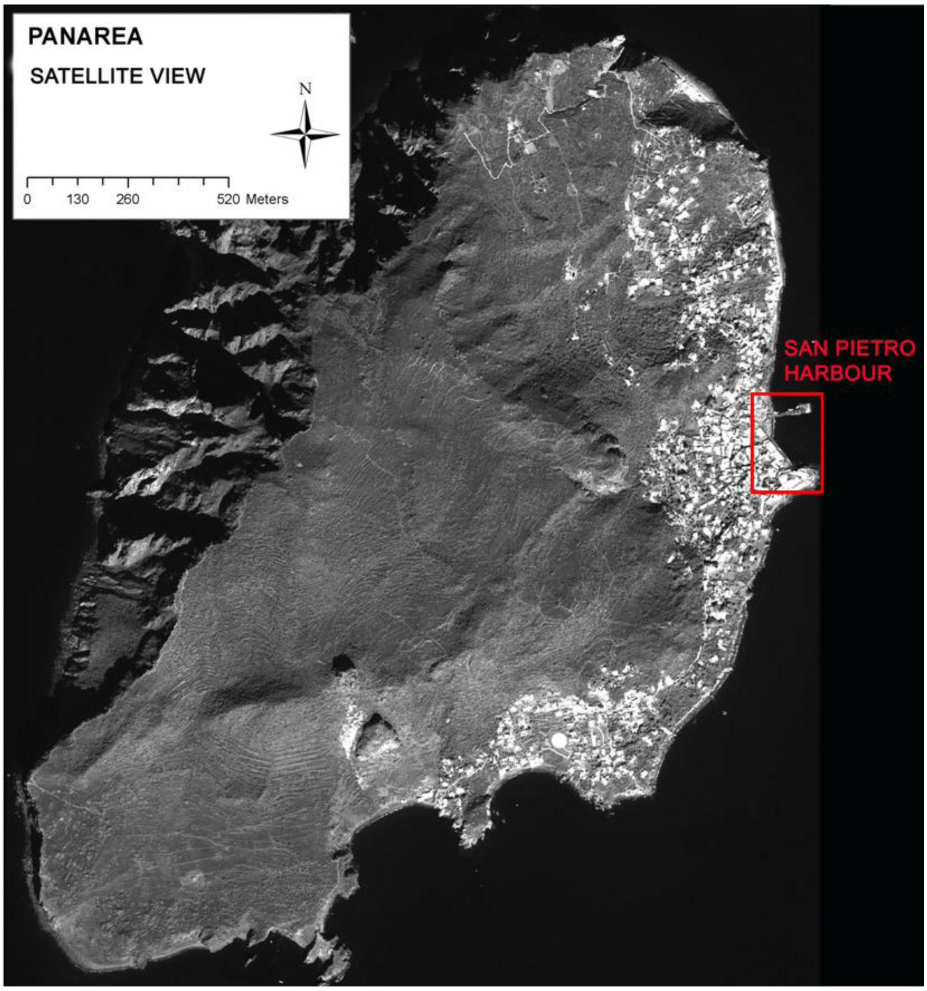

Figure 3. A "Worldview" satellite image of Panarea island. The red frame indicates the harbour of San Pietro, where five buildings were inundated during the 2002 tsunami.

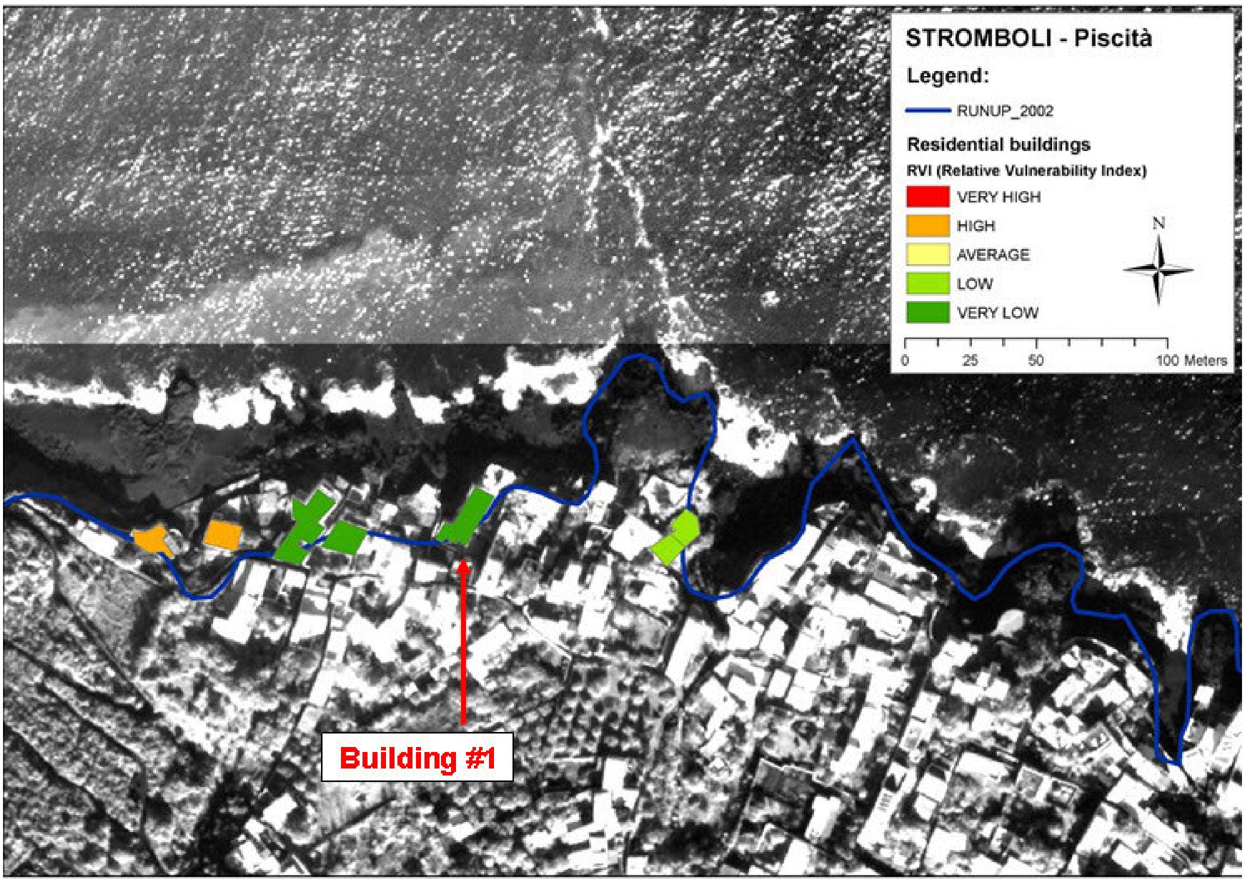

Figure 4. Vulnerability map of Piscità (Stromboli island). The map layout corresponds to the red frame in Figure 2. The blue line marks the limit of maximum inundation caused by the 2002 tsunami. Building #1 has been used to validate PTVA-3 Model results. A picture of damage suffered by building #1 during the 2002 tsunami is shown in Figure 8.

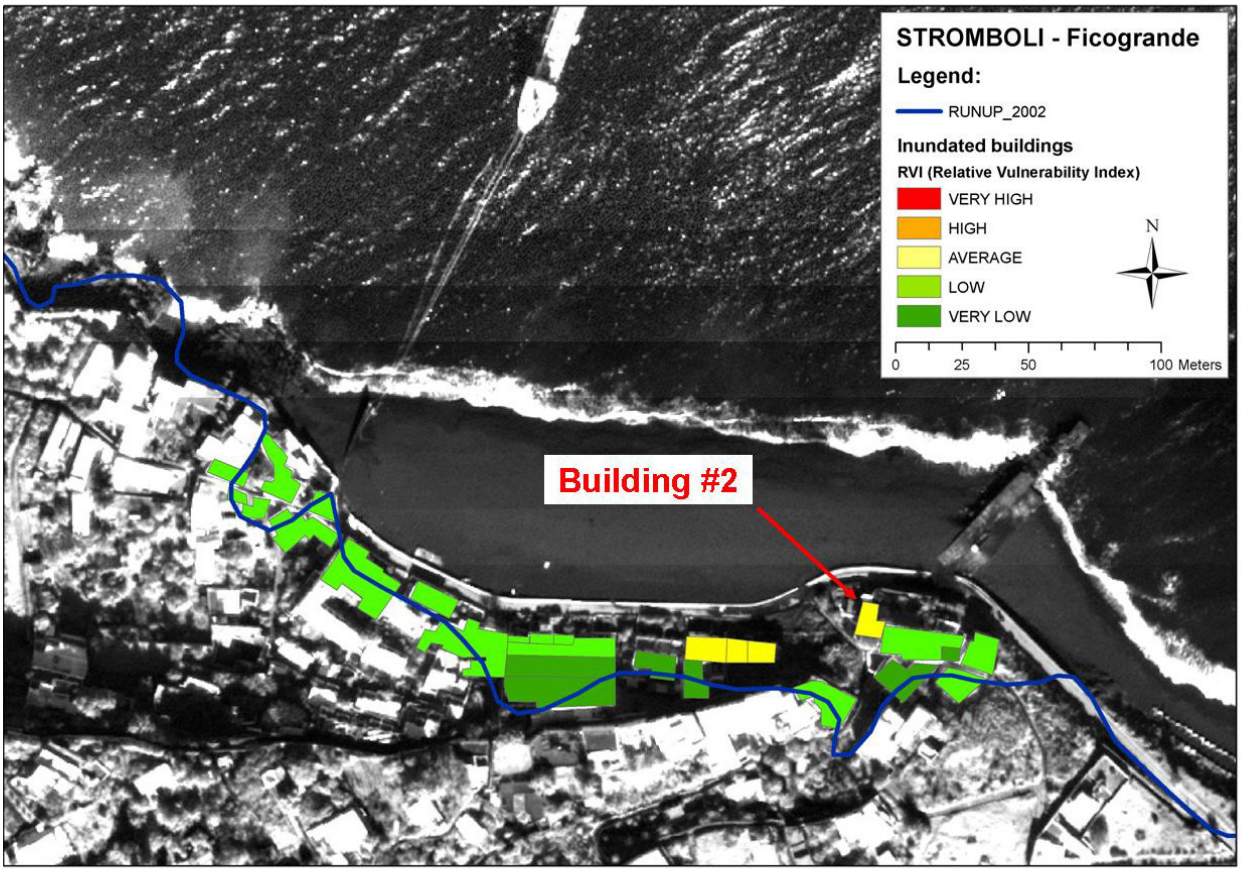

Figure 5. Vulnerability map of Ficogrande (Stromboli island). The map layout corresponds to the red frame in Figure 2. The blue line marks the limit of maximum inundation caused by the 2002 tsunami. Building #2 has been used to validate PTVA-3 Model results. Two pictures of damage suffered by building #2 during the 2002 tsunami are shown in Figure 9.

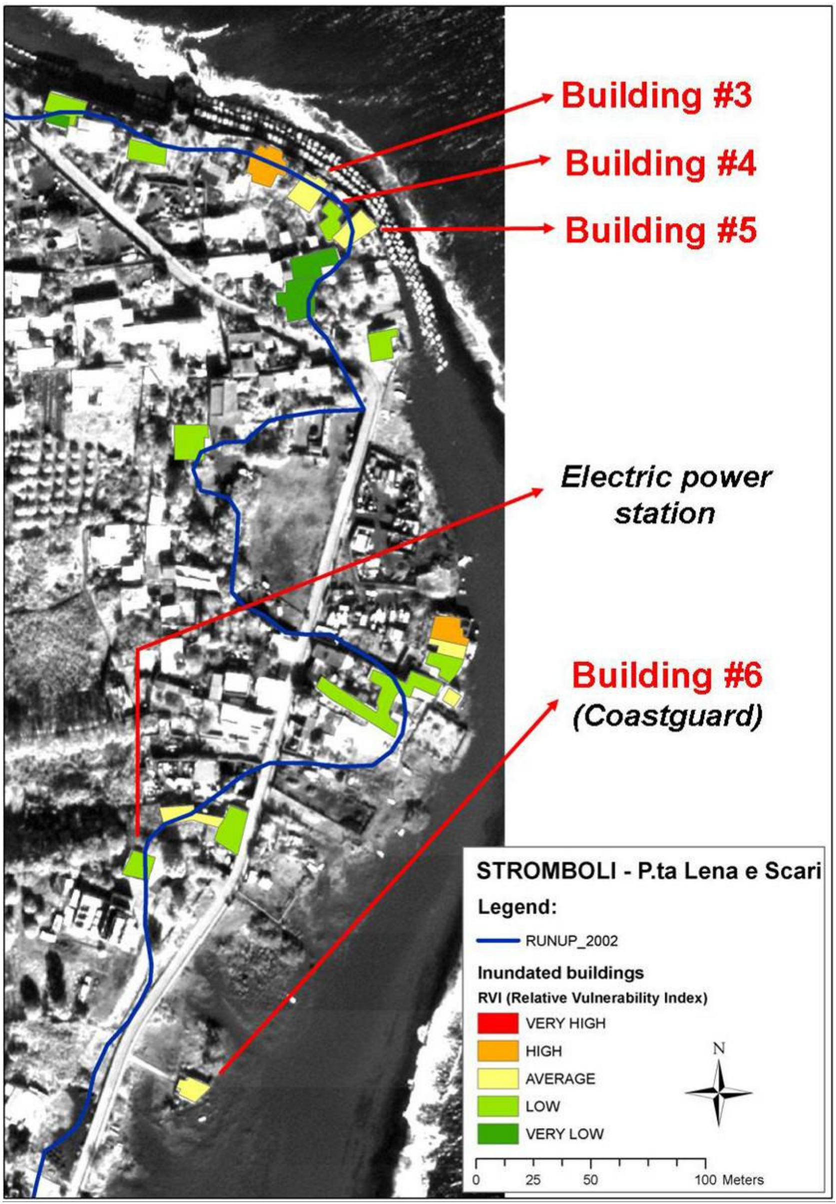

Figure 6. Vulnerability map of Punta Lena (at north) and Scari (at south)(Stromboli island). The map layout corresponds to the red frame in Figure 2. The blue line marks the limit of maximum inundation caused by the 2002 tsunami. Buildings from #3 to #6 have been used to validate the PTVA-3 Model results. Damage suffered by such buildings during the 2002 tsunami are shown in Figure 10, Figure 11, Figure 12 and Figure 13.

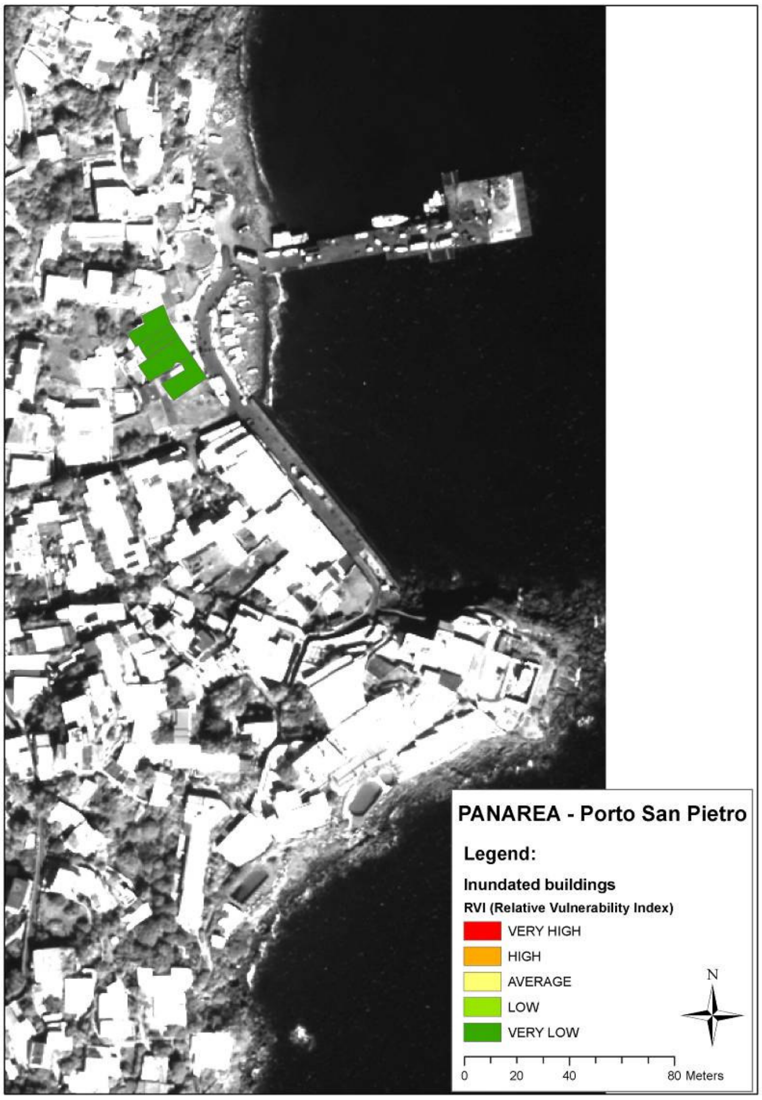

Figure 7. Vulnerability map of the San Pietro Harbour (Panarea island). The tsunami would inundate only 5 commercial buildings behind the main pier. Their RVI scores are all "very low". The flow depth in this area would not exceed 1 metre.

Figure 8. View from north-west of building #1, at Piscità (Stromboli – Figure 4). The picture was taken a few days after the 2002 tsunami. The only visible damage is an unhinged window at first floor. The PTVA-3 Model classified building #1 as having a "very low" RVI score which correlates well with the actual damage sustained by this building.

Figure 9. Pictures of building #2, at the eastern end of Ficogrande (Stromboli – Figure 5), taken after the 2002 tsunami. Figure 9(a) shows a view of the building from north-west. Figure 9(b) shows damage to the interiors. The PTVA-3 Model classified building #2 as having an "average" RVI score.

Figure 10. Two pictures of building #3 (Punta Lena, Stromboli –Figure 6) taken after the 2002 tsunami. Figure 10 (a) shows damage to interiors. Figure 10 (b) a view of the main entrance of the building, where the door have been ripped off the wall. The PTVA-3 Model assigned to building #3 an "average" RVI score.

Figure 11. Two images of building #4 (Punta Lena, Stromboli-Figure 6), taken after the 2002 tsunami. Figure 11(a) shows a door on the seaward wall of the building. The inundation did not break it down, but penetrated indoor through the shutter openings and flooded the ground-floor. The building was protected by the vegetation in the front garden (Figure 11b), some concrete works (a small wall and a table) and by the costal defences along the shoreline (concrete cubic rocks). The PTVA-3 Model classified this building as having a "low" RVI.

Figure 12. Two pictures of building #5 (Punta Lena, Stromboli – Figure 6) taken after the 2002 tsunami. The flow broke doors and windows down, penetrated indoors and dragged the building contents outside (Figure 12a). A large crack can be observed in the front side wall (Figure 12b). However, that wall does not appear to be part of the load-bearing structure of the building, as does the undamaged column at its right. The PTVA-3 Model classified building #5 as having an "average" RVI score.

Figure 13. View of the eastern side of building #6. The picture was taken few days after the 2002 tsunami. Building #6 is a Coastaguard station on the beach of Scari (Stromboli – Figure 6). As clearly shown by the picture, the seaward side of the building is totally "covered" by a coastal dune. The PTVA-3 Model attributed to building #6 an "average" RVI score.

Tables:

Table 1. Summary of the Aeolian tsunamis with main tsunami parameters: time, source area, coordinates, cause, tsunami intensity, and description (*c* = intensity of the tsunami due to the hot avalanche at Piscita`; *d* = intensity of the tsunami observed in Punta Lena and in San Vincenzo; *e* = intensity of the tsunami observed in the Sciara del Fuoco; *f* = intensity of the tsunami observed in Forgia Vecchia.).

Year	Month	Day	Source-area	Cause	Tsunami Intensity	Short description
1916	7	3	Stromboli	Speculated submarine landslide in the Sciara del Fuoco	2	Sea retreat and flooding of the beach called Spiaggia Longa in northern Stromboli
1919	5	22	Stromboli	Speculated submarine landslide in the Sciara del Fuoco	3	In Stromboli, sea retreat by 200 m and flooding of the beach. Boats carried inland in the vineyards by more than 300 m.
1926	8	17	Salina	Speculated submarine landslide associated with an earthquake	2	Initial sea retreat at Salina
1930	9	11	Stromboli	Double event: one caused by an observed hot avalanche at Piscita` and one by a speculated submarine landslide	2*c* 4*d*	A hot avalanche raised water waves that scalded and killed one man in the Eolo's grotto (northern Stromboli). Landslideinduced tsunami: sea retreat by 100 m followed by flooding of the beach of Sopra Lena by 200 m (NE Stromboli). One man killed in the beach of San Vincenzo (NE Stromboli) by 2.5-m-high waves. On the Calabrian coast, wave of 2–3 m observed.
1944	8	20	Stromboli	Double event: one caused by a speculated mass failure concomitant with an observed lava flow at Sciara del Fuoco, and one caused by an observed hot avalanche at Forgia Vecchia	2*e* 4*f*	Big waves in the Sciara del Fuoco area. Big waves in the East coast of Stromboli. One house destroyed. Beach full of fish.
1954	2	2	Stromboli	Speculated submarine landslide in SE coast	3	Initial sea retreat followed by water waves in E Stromboli. Boats carried inland.
1988	4	20	Vulcano	Observed subaerial landslide in NE flank of La Fossa	2	Water wave 1–2 m high in the source area. Wave with 0.5-m amplitude in Vulcano harbour.

2002	12	30	Stromboli	Double landslides (subaerial and submarine) in the Sciara del Fuoco flank.	5	Both landslides produced tsunami waves: the first event was characterized by a first negative sea movement, while the second produced a positive wave. A destructive tsunami, starting with an initial slow withdrawal, violently invested the northern coasts of the island with three-four big waves. Max. runup 11 metres. Severe damage to many buildings in the Stromboli island and some damage in the Panarea island. The waves propagated up to the Ustica island, the northern Sicily coast and the Campania coast.

Table 2. Scores given to the attribute "m" (building material). These scores to the have been modified with respect to the original PTVA-3 Model in order to fit with the typical construction standards used at Aeolian Islands.

Score of the attribute "m"	**- 1**	**- 0.5**	**0**	**+ 0.5**	**+1**
Construction material	reinforced concrete	bricks with thickness between 15 and 30 cm	bricks with thickness up to 15 cm	poorly cemented natural rocks	wood or corrugated iron

Table 3. Summary of the total number of buildings by building class and the number of buildings according to their Relative Vulnerability Index (RVI) scores in Stromboli island.

Stromboli island:		**Relative Vulnerability Index (RVI) Scores**				
Building class type	**Number of inundated buildings of each class type**	**Buildings with "Very Low" RVI**	**Buildings with "Low" RVI**	**Buildings with "Average" RVI**	**Buildings with "High" RVI**	**Buildings with "Very High" RVI**
Residential	**38**	9	17	8	4	-
Commercial	**10**	1	8	1	-	-
Tourism	**4**	2	2	-	-	-
Utility	**1**	-	1	-	-	-
Public Administration	**1**	-	-	1	-	-
Health	**-**	-	-	-	-	-
Education	**-**	-	-	-	-	-
Public Transport	**-**	-	-	-	-	-
Recreation and culture	**-**	-	-	-	-	-
Total	**54**	**12**	**28**	**10**	**4**	**0**

Overall conclusions

In this PhD, I successfully developed and tested a multi-scale approach for the analysis of the vulnerability of coastal areas to tsunami inundation. This approach is divided in two successive phases, working at different spatial scales. Methods adopted in each phase are completely independent. Results of the low-resolution assessment (phase 1) can be used to identify those "vulnerability hot spots" where further high-resolution analysis (phase 2) should be undertaken. The methods developed during the research work carried out in this PhD, have been applied to three different cases studiesy. In each, the percentage of input-data obtained through the most recent geomatic techniques has been maximized. Table 1 summarize the main features and applications of each phase.

Table 1- Main features of the tsunami vulnerability assessment approach developed during the PhD.

	SCALE OF THE ANALYSIS	METHOD	CASE STUDY	OUTPUTS
Phase 1	1:150.000 Spatial resolution of 90m Vulnerability assessment of entire regional and national coastal zones	Extraction of data on coastal features from satellite surveys (ASTER images and SRTM DEM). Data management and analysis through GIS. Generation of tsunami vulnerability maps at the scale of 1:150.000	1. The whole western coast of Thailand.	Dall'Osso et al., in review-b
Phase 2	1:5000 (or higher) Spatial resolution of 1m Vulnerability assessment of single buildings	The PTVA-3 Model (Papathoma Tsunami Vulnerability Assessment Model). Extraction on data on buildings features from satellite and field surveys Data management and analysis through GIS. Generation of tsunami vulnerability maps at the scale of 1:5.000	2. The coastal suburbs of Maroubra and Manly (Sydney, Australia) 3. The Aeolian Islands (South Tyrrhenian Sea, Italy)	Dall'Osso et al., 2009a; Dall'Osso et al 2009b; Dall'Osso and Dominey-Howes in review Dall'Osso et al. in review-a

Phase1 is a small-scale scale vulnerability assessment of regional or national coastal zones, which crosses data on environmental and human features of the study area with its overall exposure to tsunami inundation. All of the required data are extracted from satellite surveys and managed within a GIS. Results include vulnerability maps at a scale of 1:150.000, with a spatial resolution of 90m. Each of these maps can cover hundreds of Km of coasts, and clearly shows the location of the most relevant “vulnerability hot spots”.

I applied this method to assess the vulnerability to tsunami of the whole western coast of Thailand. The vulnerability of coastal zones has been calculated as a combination of coastal topography, geomorphology, land cover and distance from the shoreline. Data on land cover and coastal geomorphology have been extracted from ASTER satellite images, while topography was obtained from SRTM elevation models. Most of the existing methods working at this spatial scale are limited to just the analysis and mapping of exposure to inundation. Our approach provides a more complete assessment, as it includes attributes about environmental and socio economic features of coastal zones (gormorphology and land cover). A similar approach has been recently used by Wood (2009), who assessed the vulnerability to inundation of the Oregon coasts (US) as a function of land cover data (extracted from ETM Landsat images) and pre-existing tsunami-hazard information. However, our approach exploits the better spatial and spectral resolution of the new ASTER sensor, and has a wider applicability since it does not rely on any already-existing databases.

In phase2 of our approach, the scale of the assessment increases to 1:5000. At this end of the spatial scale, we focus on the vulnerability of single buildings. Assessing the vulnerability of buildings to potential tsunami damage is a fundamental necessity for developing appropriate risk management strategies. The method adopted in phase 2 is based on the already existing PTVA Model (Papathoma Tsunami Vulnerability Assessment Model). The PTVA is a GIS-based model that calculates a vulnerability index for every building exposed to inundation as a function of a selected set of building attributes that were reported to control the vulnerability of buildings to tsunami damage (e.g. construction material, number of stories, description of the ground-floor, etc.). The original version of the PTVA Model was developed by Papathoma (2003) and applied to assess the tsunami vulnerability of buildings in Greece. After the 2004 IOT, the model was upgraded to version 2 and validated using data from field surveys at the Maldives. Recently, it has been applied to a case study at Seaside, US (Dominey-Howes et al, 2010).

Within phase2 of our approach, the PTVA-2 Model has been used as a starting point. Several improvements have been introduced, particularly to the process of weighting the attributes which contributes to the overall building vulnerability. The subjectivity of such process was one of the main weaknesses of previous versions of the model and was addressed through to the introduction of the Analitic Hierarchy Process (AHP). The AHP allows to compare the contribution made by separate attributes to the structural vulnerability of a building via a rigorous mathematical approach. Such improvement, together with the introduction of some new building attributes, lead us to the development of the new version of the model, the PTVA-3, which we applied in two selected coastal suburbs of Sydney, Australia. One of the two study areas, the Manly Council, was found to be extremely exposed to a 5m-high tsunami wave, with 1133 buildings located within the inundation zone and more than 150 residential buildings were classified as having a “high” and “very high” vulnerability score. Results of our analysis have been organized within a GIS and displayed as a series of detailed vulnerability maps (at the scale of 1:5000).

Furthermore, we created an add-in for ESRI ArcGIS 9 which automatically performs all calculations required by the PTVA-3 and gives as output the Relative Vulnerability Index of every building. This tool can be used for further applications of the PTVA-3 Model to other study areas. To that purpose we also drafted a specific user’s manual, which we delivered to the relevant Sydney Authorities together with a final project report containing details about the tsunami risk in Australia, a description of the new PTVA-3 Model and the building vulnerability maps we generated for the study-areas of Maroubra (Randwick Council) and Manly (Manly Council). The project’s final report and the user’s manual are publicly available at the Sydney Coastal Council web page (http://www.sydneycoastalcouncils.com.au/). Furthermore, results of the whole project were officially presented to the relevant Sydney authorities, risk managers and other stakeholders during a meeting at the University of New South Wales (Sydney), organised in collaboration with the Sydney Coastal Councils Group. Our assessment, together with the GIS tool, has important implications for Public Administrations and risk managers. Results can be used as a baseline for the adoption of possible prevention and mitigation measures, such as land-use zoning regulations, the identification of appropriate design standards and building construction codes and emergency management strategies. Such strategies might include the identification of coastal areas that require evacuation, the identification of specific buildings that might be the focus of search and rescue efforts, and the demarcation of ‘safe’ evacuation areas and structures within expected tsunami flood zones.

Whilst the PTVA Model had been already validated after the 2004 IOT in the Maldives, a further test and validation of version 3 was carried out within the third case study developed during the present PhD: the assessment of the tsunami vulnerability of buildings in the Aeolian Islands (South Tyrrhenian Sea, Italy).

The Aeolian Islands are at high risk from tsunami inundation. Since 1916, they have been hit by eight local tsunamis. The most recent of them occurred in December 2002. Immediately after that event, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) and the University of Bologna undertook field surveys. The inundated area and maximum run-up values were measured and mapped. Some of the most damaged buildings were photographed. Within the third case study of our work, we applied the PTVA-3 Model to those buildings of the Aeolian Islands that are currently located within the area inudated by the 2002 event. Results showed that if the 2002 tsunami happened again, 55 buildings would be inundated in the island of Stromboli, and 5 in Panarea. Luckily, the average vulnerability level of such structures is just “average/low”. However, 14 buildings would be severely damaged. Some of the exposed structures are strategic service buildings that must be fully working in case of an emergency (i.e. the only electric power station of Stromboli Island and a Coastguard building). Based on the PTVA-3 Model results, a set of important recommendations for the reduction of the vulnerability of such structures has been identified. Furthermore, besides such relevant results, the application of the PTVA-3 Model to a case study in the Mediterranean Sea served to verify its capability to work in a different architectonic and environmental context.

Whilst the structure of the PTVAm-3 has been conceived to be applicable anywhere, a few elements depend on boundary conditions (type of architecture, inundation scenario) and might need to be adapted to specific cases. Typical construction materials used at the Aeolian Islands are slightly different from those identified in Australia, where the PTVA-3 Model was firstly developed. However, the PTVA-3 Model was easily adapted to the architectonic characteristics of Aeolian Islands, showing a good flexibility and increasing our confidence about its wide applicability. Finally, the PTVA-3 Model has been validated through a comparison between the photographs of buildings damaged during the 2002 tsunami and vulnerability index scores calculated for the same buildings by the model. This comparison showed a good degree of accuracy between the PTVA 3 model forecast assessments and the actual degree of damage experienced by buildings. This further validation confirmed the accuracy of version 3 of the model, which implements some important improvements based on recent publications, not available when the original PTVA was firstly developed.

At present, the main limitations of the PTVA-3 Model are the absence of a numerical simulation of the tsunami flooding and the high number of building data required. Data required by the model can be partially obtained from high-resolution satellite imagery, but a large part of them must be gathered through field surveys and direct census, which strongly impacts on the time required by the overall assessment. With regard to the numerical simulation of the flooding, it would increase further the reliability of results, as the impact of the water column on single buildings would be described with a much better accuracy.

Finally, in addition to the specific considerations that emerge from the detailed case studies undertaken in this research, the following general observations/conclusions also emerge from the research contained in this PhD thesis:

- This approach permits a multi-scale assessment of the coastal vulnerability to tsunami. Whilst methods used in phase 1 and 2 are completely independent, results of phase 1 – the small-scale (low-resolution) assessment - can be used to select those areas where phase 2 – the large-scale (high-resolution) assessment - should be carried out. This allows to concentrate the typical effort required by high-resolution analysis in few selected “vulnerability hot spots”, although the overall assessment considers a much wider area. The need for a multi-scale approach is common to many natural hazards, but we believe it is a key factor in the case of tsunamis.
- The employment of geomatic methods and tools (e.g. analysis of satellite imagery, radar DEM, aerial surveys, Geographic Information Systems, etc.) is invaluable. The assessment of the vulnerability of coastal areas and buildings require an extremely large amount of data, that is seldom found in national or regional archives – especially in developing countries. Furthermore, given the low frequency of tsunamis, financial resources and time available for prevention studies are limited and must be optimized. Geomatic methods and remote sensing can provide a wide varierty of georeferenced information with a relatively small effort in terms of time and costs. However, the contribution of such methods decreases as the scale of the analysis gets larger (and the resolution gets higher). At present, field surveys and direct census cannot be avoided when undertaking an assessment at the scale required by the PTVA-3 Model. Nonetheless, given recent technical progresses, a bigger contribution from high-resolution satellite products can reasonably be expected in the near future.
- Our assessment focuses on the vulnerability to direct damage (i.e. that happening during the tsunami impact or immediately after, such as injuries and casualties, damage to buildings and infrastructure, damage to the environment, etc.) although, as complementary results, it provides some of the data required to undertake further studies on the vulnerability to

indirect damage. In fact, at different scales, land cover data (used in phase 1) and building type classes (used by the PTVA Model) can be considered a proxy of the socio-economic aspects of vulnerability.

- The inundation scenario we adopted in each case study is not probabilistic. At the time the present PhD was undertaken no Probabilistic Tsunami Hazard Assessments (PTHA) were available for any of the selected study areas. As a consequence, the scenario we adopted is the "worst credible case" of tsunami impacting each of the study areas. This is also the main reason why we didn't carry out any hydrodynamic simulation of the tsunami flooding. However, the methodology we developed is suitable for PTHAs too - as recently shown by Dominey-Howes at al. (2010) – and should be repeated when such scenarios will be available.
- Public Administrations (PA) responsible of risk reduction strategies finance tsunami prevention studies very rarely, even if such studies are scarcely onerous. If the PA knows there is a risk, then it must do something to reduce it. However, from a political perspective, the adoption of tsunami prevention measures may be counterproductive, because they can easily generate panic among the population. As a consequence, most of the times PA prefer to know nothing about the risk, and simply hope the tsunami won't occur. This is also demonstrated by the fact that most of the investments for tsunami prevention measures have been undertaken only after big catastrophes, when they were supported by a large popular consensus.

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