# A METHOD FOR ASSESSING THE VULNERABILITY OF BUILDINGS TO CATASTROPHIC (TSUNAMI) MARINE FLOODING

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**Filippo Dall'Osso**
**and**
**Dale Dominey-Howes**

This report "A method for assessing the vulnerability of buildings to catastrophic (tsunami) marine flooding" was prepared for the Sydney Coastal Councils Group Incorporated by:

**Filippo Dall'Osso** [1]
**Dale Dominey-Howes** [2]

1 CIRSA, Department of Environmental Sciences, University of Bologna, Italy and
MEDINGEGNERIA S.r.l, Hydraulic and Coastal Engineering, Italy

2 Australian Tsunami Research Centre and Natural Hazards Research Laboratory, University of New South Wales, Sydney

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**Enquirie**s should be addressed to:

Associate Professor Dale Dominey-Howes, Australian Tsunami Research Centre and Natural Hazards Research Laboratory, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW 2050, Australia.
Phone: +61 2 9385 4830
Fax: +61 2 9385 1558

Email: dale.dh@unsw.edu.au or fillipodallosso@gmail.com

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## EXECUTIVE SUMMARY

This report represents the main outcome of a partnership between the Sydney Coastal Council Group (SCCG) and the University of New South Wales (UNSW), whose aim was to apply and test a newly developed and highly novel GIS tool to assess the vulnerability of coastal infrastructure to catastrophic marine floods (tsunami).

The project was coordinated by Geoff Withycombe from the SCCG and Associate Professor Dale Dominey-Howes from the Australian Tsunami Research Centre, UNSW. The Project Officer who undertook the research is Mr Filippo Dall'Osso, a coastal hazards and GIS expert from the University of Bologna, Italy. Mr Dall'Osso is currently doing a PhD on tsunami vulnerability assessment at the University of Bologna and he is working as a consultant for MEDINGEGNERIA Srl, one of the premier Italian engineering company's working on Integrated Coastal Zone Management and Hydraulics.

Sydney's low-lying coastal infrastructure is vulnerable to the impact of catastrophic marine floods associated with tsunami and storm surges. 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. Coastal planners and risk managers need innovative tools to undertake assessment of the vulnerability of buildings and infrastructure and likely *probable maximum loss* located within their areas of responsibility. Such assessments will enable risk mitigation measures to be developed and challenges of long-term sustainability to be addressed.

The aim of this project is to apply a newly developed GIS vulnerability assessment tool to selected coastal suburbs of Sydney, evaluate and quantify the vulnerability of buildings at those locations to a hypothetical tsunami (or storm surge) flood based on the latest scientific understanding, produce maps to display the spatial distribution of vulnerable structures at a scale of 1:5000 and to make recommendations about possible risk management strategies at those locations.

The GIS model was applied at two study areas within the Sydney Coastal Council Group area: Maroubra Beach (Randwick Council) and Manly Ocean Beach (Manly Council). The inundation scenario we adopted is a locally generated submarine landslide tsunami achieving a run-up of +5 metres above maximum tide level (+2m asl). Such tsunami are the most likely to occur in the Sydney region.

The model calculated a Relative Vulnerability Index (RVI) score for every building that would be touched by the water. RVI scores were calculated combining buildings physical features (number of stories, construction material, hydrodynamics and orientation of the ground floor, type of foundation, preservation condition), building surroundings (movable objects that could hit the structures and possible protection offered by other buildings or natural and artificial fences) and exposure to inundation (the expected water depth at the points where buildings are located). An innovative approach based on the

Analytic Hierarchy Process was used to weight all the different contributions to the final value of RVI.

Results are displayed using a series of thematic vulnerability maps, in which different types of buildings are displayed using a colour code that gives information about their RVI score.

The maps show two very different situations for Maroubra and Manly. Because of its higher average topographical elevation, the inundation at Maroubra would cover only 27 Ha, while 169 Ha would be flooded in Manly. As a consequence, only 96 structures would be touched by the water in Maroubra, with a maximum water depth of 3 metres. None of these 96 structures was found to have a “Very High” RVI score.

At Manly, a total of 1133 buildings would be inundated, and water depth could reach a maximum of 7 metres in the lagoon area. In the southern part of our study area the water would be able to flow through the Corso and reach the Manly Wharf on the harbour side. RVI scores show that a large number of residential and commercial structures are highly vulnerable to damage and most of them are located in the area next to Manly Lagoon. Also, a number of Local Government and transport sector structures are classified as being very vulnerable.

Lastly, we provide a series of recommendations to assist LGA’s and the emergency services to think about ways in which they might mange tsunami risk in the future. These include land-use zoning, buildings standards and codes and emergency and evacuation planning.

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# 1 INTRODUCTION, BACKGROUND and AIMS

**SECTION SUMMARY - In this section we note that the devastating 2004 Indian Ocean tsunami has resulted in significant efforts to reduce the effects of similar events in the future. We acknowledge that local government authorities and emergency service agencies need detailed information to be able to develop appropriate tsunami risk mitigation strategies. We ask whether the coast of New South Wales is at risk from tsunamis before outlining the aims of this study**

The Indian Ocean tsunami of December 26th 2004 (Figure 1) was catastrophic. It was the most lethal tsunami disaster the modern world has known and catapulted tsunamis on to 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 at risk areas, detailed hazard, risk and vulnerability assessment and tsunami education and disaster planning.

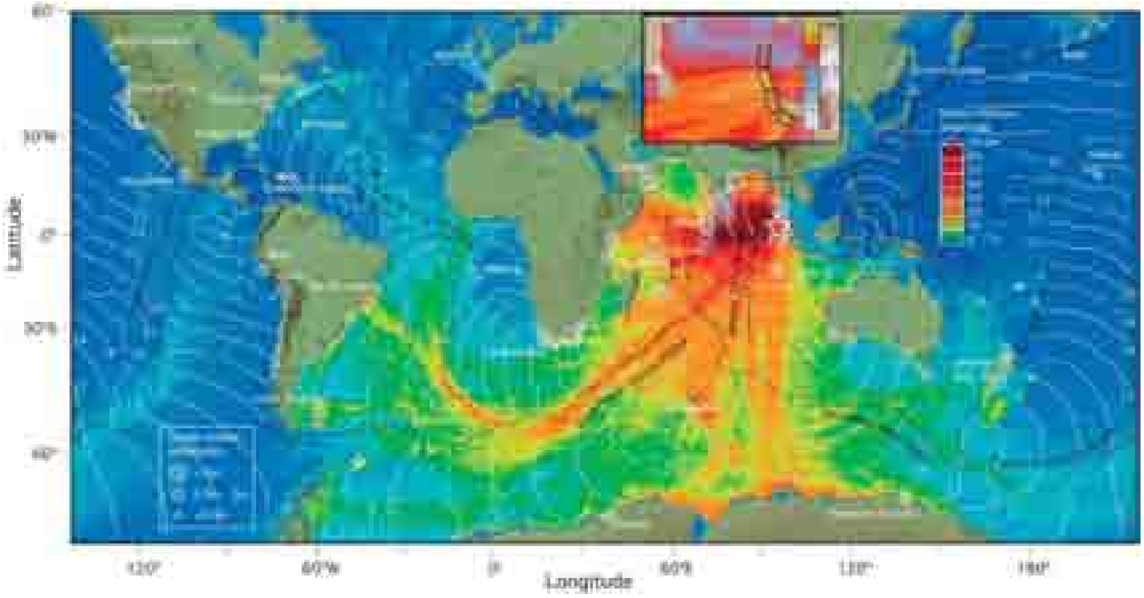

**Figure 1. Global reach of the 2004 Indian Ocean tsunami (after Titov *et al.*, 2005). White isolines are the position of the tsunami wave front in hours after the start of the event. Colours represent modelled (forecast) wave amplitudes offshore. White circles equal measured wave amplitudes (in metres) 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 for Australia, is that we *are* at risk. The 2004 disaster was something of a wake up call for Australia since prior to this event few had seriously considered the possible threat that tsunamis might pose to the country.

Our understanding of how often large, widely destructive tsunamis may occur and what areas they may impact is still very limited – especially in Australia. Together with the establishment of an Australian Tsunami Warning System (ATWS) (Geoscience Australia, 2005)[1], there is now a clear and urgent need to fully understand and quantify the hazard and community vulnerability to tsunami (Bird and Dominey-Howes, 2006, 2008).

Once detailed information is available about the hazard, vulnerability and probable maximum loss, appropriate risk mitigation measures may be developed that aid with long-term sustainable development of coastal areas. This is vital to local government authorities (LGA's) with coastal and estuarine foreshore areas and local units of the State Emergency Service (SES) who will be at the sharp end of post-tsunami disaster response and recovery.

## *1.1 Is the coast of New South Wales at risk from tsunami flooding?*

Tide gauge records show that historically, only *small* tsunamis have affected the coast of New South Wales (NSW) (Dominey-Howes, 2007).[2] Geological evidence however, has been reported which suggests that massive tsunamis many times larger than the 2004 Indian Ocean event may have occurred repeatedly during the last 10,000 years (the period of earth history called the Holocene) along the coast of NSW (Bryant, 2001; Bryant *et al.*, 1992a, b, c; Young, *et al.*, 1996; Nott, 1997, 2004; Bryant and Nott, 2001; Bryant and Young, 1996; Young and Bryant, 1992; 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).

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 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, whilst geological data suggests that the coast of NSW has been repeatedly impacted by prehistoric megatsunamis, it is not yet possible to identify the sources of these events – a vital component of understanding risk (Dawson, 1999).

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[1] See Appendix 1 for information about the Australian Tsunami Warning System

[2] See Appendix 2 for a list of New South Wales tsunami events

If the ‘AMH’ can be independently validated, it has profound implications for the coastal vulnerability of NSW and government agencies are wholly unprepared to safeguard us from 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 (SES, 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 building infrastructure.

It is not the purpose of this report to provide a critique of the reported geological records of prehistoric tsunamis along the coast of NSW. For such a review see Dominey-Howes (2007) and Dominey-Howes *et al*., (2006).

Since the 2004 Indian Ocean tsunami disaster, significant local, state and federal government activity and university based research has started that is aimed at:

1. understanding the hazard and risk to New South Wales (and Australia);
2. identifying dominant source regions for tsunamis capable of affecting NSW;
3. estimating return periods and probable maximum wave heights along the coast;
4. identifying geological records of prehistoric tsunamis and written records of post-European events; and
5. understanding tsunami propagation, inundation and run-up through numerical modelling and simulation.

In line with these studies, decisions have been made about the development and deployment of the Australian Tsunami Warning System (ATWS), the location and deployment of deep water tsunami detection equipment and appropriate state level emergency service action including risk assessment, emergency planning and public education. This work is on-going and will take some time to complete. Therefore, the key questions of *‘how often’* and *‘how big’* tsunamis are along the coast of NSW are not possible to answer at this moment in time. Work is underway to complete a probabilistic tsunami hazard assessment for the coast of NSW and results will be provided by the NSW State Government and the NSW State Emergency Service in due course.

Although it may be some time before a probabilistic assessment of tsunami return periods and maximum waves heights from which inundation modeling may be derived is available, there is still a critical need to examine the vulnerability of building infrastructure along the coast to possible tsunami inundation. This is because local governments and the emergency services need information in order to begin to make decisions about land-use zoning, building regulation and emergency planning and response.

## 1.2 Aims

Based on the introduction, the aims of this report are to:

1. determine a 'credible worse case scenario' for tsunami generation and inundation along the coast of NSW in the region of Sydney;
2. work with the Sydney Coastal Councils Group Inc. (SCCG) and specific local government authorities (LGA's) to identify two contrasting case study local government areas to explore building vulnerability to tsunami damage;
3. select and modify as appropriate, a tsunami vulnerability assessment tool;
4. work with the SCCG and LGA's to obtain appropriate building data to undertake vulnerability assessment;
5. apply the selected tsunami vulnerability assessment tool to the building data collected;
6. determine a 'Relative Vulnerability Index' score for each building located within the tsunami inundation zone for the scenario chosen;
7. display the tsunami building vulnerability in a series of thematic maps at a scale of 1:5000;
8. discuss the findings of the study and consider the implications for LGA's and the emergency services; and
9. to use these results to make a series of recommendations.

# 2 RESEARCH APPROACH and METHOD

**SECTION SUMMARY - In this section we outline the various steps undertaken during this project. We explain the development of a 'credible worse case scenario', selection of case study sites, manipulation of a suitable tsunami vulnerability assessment tool and calculation of relative vulnerabilities for individual building structures**

In order to complete this project, we undertook the following steps:

## 2.1 Step 1 – development of a credible worse case scenario

In Section 1.1, it was noted that there is an apparent disjunct or miss-match between the frequent historic occurrence of small tsunamis along the coast of NSW and the reported occurrence of less frequent megatsunamis during recent geological time. Bryant (2001) suggests that the megatsunamis may have been generated by asteroid strikes in to the Tasman Sea. This hypothesis remains to be tested and like the proposed evidence for the megatsunamis themselves, is very controversial.

Recently, there has been some suggestion that underwater sediment slides or slumps down the NSW continental shelf could trigger large, locally damaging tsunamis. In order to investigate this possibility, Geoscience Australia undertook a 15 day marine cruise during which they surveyed the NSW continental shelf (Glenn *et al.*, 2008). This survey was designed to provide a much better understanding of the morphology and history of the continental shelf and any associated underwater sediment slides. The survey by Glenn *et al.*, (2008) focused on the region between Jervis Bay and Forster. The survey gathered baseline data that will help Geoscience Australia assess the probability, and implications, of localised underwater sediment slides.

Geoscience Australia's survey data reveal that the continental slope of NSW has experienced widespread underwater sediment slide failure through time even though the rate of sedimentation on the continental shelf is very low. Swath bathymetry has revealed the architecture of slope failures and the slip-plane geometry of a number of submarine mass failure sites. Sites that have failed include the Bulli (~20 $km^3$), Shovel (~7.97 $km^3$), Birubi (~2.3 $km^3$) and Yacaaba (~0.24 $km^3$) slides (Figure 2) (Glenn *et al.*, 2008).

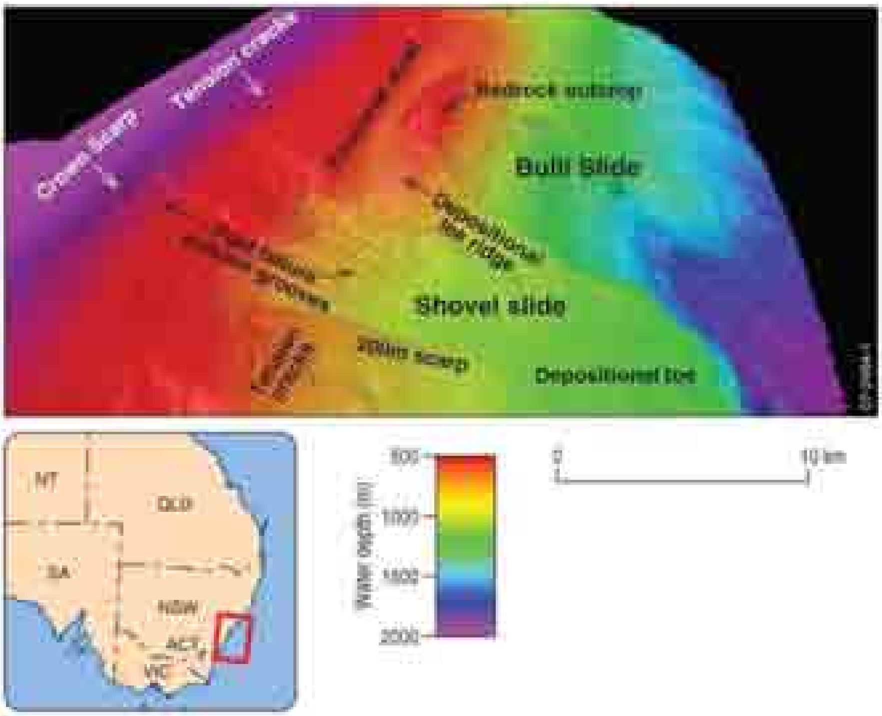


**Figure 2. The slope failure architecture and slip-plane geometry of the Shovel Slide. Location of the large Bulli Slide is also indicated. Insert – the area of the NSW coast surveyed by Geoscience Australia (Glenn, 2008)**

The importance of the work of Geoscience Australia lies in the confirmation of the existence of suspected underwater sediment slides along the continental shelf and the identification of new large slide events not previously known. These slides could have been capable of generating large local tsunamis flooding to significant heights above sea level – perhaps explaining the megatsunami deposits reported by Bryant (2001) and others.

In view of the recent work of Geoscience Australia, we define the credible worse case scenario for this project as follows:

- an underwater sediment slide occurs off-shore of Sydney;
- the sediment slide occurs without an earthquake trigger;
- a tsunami arrives at shore within 10 – 15 minutes of its generation;
- the tsunami achieves a flood run-up height of +5 metres above sea level (m asl) and occurs on top of the maximum astronomical tide along the Sydney oceanic coast which is approximately 2 m (www.maritime.nsw.gov.au). Consequently, our flood event achieves a maximum run-up of +7 m asl;
- we assume the tsunami inundates parallel 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 is clear therefore, that our scenario is ‘deterministic’. That is, it is not associated with a *specific* event and as such is not a probabilistic forecast. Since probabilistic tsunami hazard assessment has not yet been undertaken for the coast of NSW, we cannot use a probabilistic scenario.

Since we are not assessing the likely impact of the tsunami on people or socio-economic systems, we are not concerned with the time or day of the year in which the tsunami occurs.

## 2.2 Step 2 – identification and selection of case study sites

We worked in partnership with the Executive Officers of the Sydney Coastal Councils Group Inc. (SCCG) to identify appropriate case study sites. Selection of case study sites was based on the following process:

- a transparent, inclusive process of consultation with local government authorities (LGA’s) about the nature and purpose of the study;
- consent and involvement of LGA’s and specific, nominated professional officers at council;
- ability to access appropriate datasets held by local government in a ‘Geographic Information System’ (GIS) format;
- inclusion of sites where project results would be useful for local government and State Emergency Service planning purposes;
- inclusion of at least one site where building density (and exposure) is high;
- inclusion of a LGA area that had not previously been subject to significant research projects initiated by the SCCG Inc.; and
- inclusion of at least one iconic location to help raise awareness of the project and its capacity to deliver useful results.

Based on this process, it was decided that this project would focus on the **Maroubra Beach** area within the local government authority of Randwick Council and the **Manly Ocean Beach** area of Manly Council. Both councils are located within the metropolitan area of Sydney and are member councils of the SCCG Inc.

## 2.3 Step 3 – selection and modification of an appropriate tool

Once a hazard such as tsunami has been recognised, it is desirable to begin to estimate likely *probable maximum losses* (or PML’s) for events of specific magnitudes. This is helpful since PML’s are often 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.

To estimate PML’s, it is necessary to have information about the extent and severity of the *hazard* (in this case tsunami inundation distance and flow depth), asset *exposure* (for example, buildings located within the expected flood zone), the *vulnerability* of those buildings to damage and their *value* (or replacement cost).

Previous research developed a vulnerability assessment ‘framework’ or approach using a Geographic Information System (GIS) that may be used to identify local areas that should be the focus of further analyses (Wood, 2002; Wood *et al.*, 2002a, b; Wood and Good, 2004). This GIS framework is valuable in helping to identify (1) areas likely to experience the occurrence of hazardous processes such as tsunami inundation; and (2) the exposure of community assets within hazardous zones. When such data are combined, it is possible to identify what Wood and Good (2004) describe as *‘relative vulnerability hotspots’* – the intersection of hazard and exposure.

As valuable as the framework of Wood and Good (2004) is, they point out that their tool is an ‘issues identification tool’ and is not designed to provide a quantification of *probable maximum loss* (or PML) for a community during a tsunami (Wood and Good, 2004; p. 265). They state that communities interested in identifying, characterising and quantifying the vulnerability of their assets to tsunami damage and loss will need to apply an “objective scientific weighting scheme” to the rankings of specific vulnerability attributes at the local level. Such objective analysis of, for instance, residential building vulnerability, should be carried out by technical experts and engineers at high-resolution scales as assessment tools and appropriate data become available. To our knowledge, no robust, well constructed and validated building fragility curve model for tsunami impact has been developed although Geoscience Australia is working on the development of such a model (Dale, personal communication 2007, 2008). Recent reports have found that there is still a need for credible fragility models and laboratory data to understand the interaction of tsunamis with the built environment (Bernard *et al.*, 2007, Grundy *et al.*, 2005).

The Papathoma Tsunami Vulnerability Assessment (or PTVA) Model was developed using detailed information about the impacts of historic tsunamis and the results of numerous post-tsunami surveys and building damage assessments (Papathoma, 2003; Papathoma and Dominey-Howes, 2003; Papathoma *et al.*, 2003). Papathoma (2003) identified and ranked in descending order of importance, 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. The 2004 Indian Ocean event, 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 extremely well correlated with the type and severity of damage to building structures experienced during the Indian Ocean tsunami (at least where the PTVA Model was applied). Thus, the PTVA Model performed very well during a real-life field evaluation. 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.

The transferability and value of the PTVA Model was recently tested by the United States Federal Government as part of its National Tsunami Hazard Mitigation Program administered by the National Oceanic and Atmospheric Administration (NOAA). The testing occurred during a tsunami building vulnerability assessment project focused on the coastal community of Seaside, Oregon (Dominey-Howes *et al.*, in press).

The PTVA model is a dynamic model in that the building attribute data contained within the primary GIS database may be modified and updated allowing investigation of vulnerability both spatially and temporally. The PTVA Model is organised and presented within a GIS framework, allowing rapid data entry and visualisation and characterisation of changing vulnerability.

Thus, in the absence of fully developed and validated tsunami building fragility-damage assessment tools, the PTVA Model provides a framework potentially capable of providing first order assessments of building vulnerability and PML and provides the technical detail missing from the vulnerability assessment framework of Wood and Good (2004).

We used the PTVA Model as the starting point in this study. However, we 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 because of the hydrodynamic forces during inundation AND from that associated with water intrusion. These two damage processes have been evaluated independently using a different set of sub-factors. The vulnerability to structural damage has been assessed by considering contributions of all the 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 within this project may be considered as an improved version of the existing PTVA Model approach.

The outputs will be used to determine whether: (1) the [revised] PTVA Model is useful in helping to understand the vulnerability of building structures to damage from tsunami; (2) for estimating likely PML's; (3) might be applicable to similar assessments across Australia and elsewhere; and (4) may be useful in helping local government authorities make decisions about future data collection needs, land-use zoning, building regulations and community education.

The definition of vulnerability used in this project is *"the susceptibility to injury or damage from hazards"* (Mitchell, 1987). Thus, in this study we estimate the 'relative' vulnerability of every building structure between the shoreline and +7 m asl (that is equivalent to the +5 m asl inundation combined with the highest astronomical tide of 2 metres).

### 2.3.1 Conceptual basis of the revised PTVA Model: the Relative Vulnerability Index

According to the definition of vulnerability used by us, the **'Relative Vulnerability Index'** (RVI) score of each building is estimated as a weighted sum of two different components:

1. the vulnerability of the carrying capacity of the building structure - hit by the horizontal hydrodynamic force associated with water flow; and
2. the vulnerability of different building components due to their prolonged contact with water (the internal and external plaster, the fixtures, the paving tiles, the floors and electric appliances etc).

It has been estimated that a building totally submerged by water might loose up to 40 - 50% of its total economic value, without reporting any structural damage (Olivieri and Santoro, 2000). Conversely, the structure of a building which is only partially submerged by water, may still be seriously damaged by the hydrodynamic pressure of the flowing water or by the impact of heavy movable objects such as cars, trucks, boats and other debris. For example, a two story building made of wood might suffer extreme structural damage even if only a part of its first floor was inundated (Dalrymple, 2005; Warnitchai, 2005). Alternatively, very strong building structures (e.g., reinforced concrete, deep pile foundations) could be totally submerged by water without suffering any structural damage. In light of these possibilities, the RVI score of every building in this study has been calculated using the following equation:

$$\textbf{Relative Vulnerability Index (RVI)} = (2/3) \times (SV) + (1/3) \times (WV) \qquad \text{(Eq. 1)}$$

where:

**SV** is the standardized score (from 1 to 5) for the **structural vulnerability**, and
**WV** is the standardized score (from 1 to 5) for the **vulnerability to water intrusion**

Both SV and WV range between 1 (minimum contribution to vulnerability) and 5 (maximum contribution to vulnerability). 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. In the event that a building is not structurally damaged but does come in to contact with tsunami flood water, we assume the contribution made by contact with water is be equal to 1/3 of the maximum vulnerability level of the structure. This is consistent with the findings of Olivieri and Santoro (2000).

### 2.3.1.1 Calculating the Structural Vulnerability (SV) component

The Structural Vulnerability (SV) of a building is dependent on:

1. the characteristics of the building structure (such as the number of stories, building material, foundations etc);
2. the depth of flood water at the point where the building is located; and
3. the degree of protection that is provided to that building by natural and artificial barriers (such as coastal vegetation, sand dunes, seawalls, presence of other buildings between it and the shoreline etc).

Thus, an initial value for SV, ranging between 1 and 125, was calculated as follows:

$$\mathbf{SV\ (1,\ 125) = (Bv) \times (Ex) \times (Prot)} \qquad \text{(Eq. 2)}$$

where:

**Bv** is a standardized score ranging from 1 (minimum vulnerability) to 5 (maximum vulnerability) for the structural vulnerability of the building itself. “Bv” depends on the physical characteristics of the building that influence its resistance to a flood (see “Calculating the “BV” factor” below);
**Prot** is a standardized score for the level of protection that is provided to the building by its surroundings. “Prot” ranges between 5 (no protection) and 1 (maximum protection) (see “Calculating the “PROT” factor” below);
**Ex** is the standardized score for the exposure. The exposure is given by the water depth that is expected to occur at the point where the building is located. “Ex” ranges between 1 and 5 (1 = minimum water depth, 5 = maximum water depth) (See “Calculating the “EX” factor” below).

Once “SV (1, 125)” was obtained, it was re-scaled to a range between 1 (minimum level of structural vulnerability) to 5 (very high level of structural vulnerability). This scale range is shown in Table 1.

**Table 1. Rescaled structural vulnerability (SV) classes**

| SV (1, 125) | [1, 25[ | [25,50[ | [50,75[ | [75,100[ | [100,125] |
|---|---|---|---|---|---|
| **SV (1, 5)** | **1** | **2** | **3** | **4** | **5** |

The values of SV (1, 5) are then 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 smaller than what it would be if no protection were present (Prot = 5). This is consistent with the degree of fragility that Reese *et al*., (2007) calculated for shielded and totally exposed reinforced concrete buildings in Java following the 2005 tsunami.

##### 2.3.1.1.1 *Calculating the Building Vulnerability "Bv" factor*

The selection of factors considered in the assessment of "Bv" was based on (1) the PTVA Model, (2) results from post-tsunami field surveys (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; UNEP, 2005; Warnitchai, 2005; UNDP and BCPR, 2004; ECLAC, 2003; Papathoma and Dominey-Howes, 2003) and, (3) the expert judgment of project team members who have undertaken post tsunami field surveys following the 2004 Indian Ocean tsunami in the Maldives (Dominey-Howes) and in Thailand (Dall'Osso).

The factors chosen are:

**Number of Stories (SV_s)**: multi-storey buildings have good structural resilience to the impact of tsunami. This is because these 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. In particular, the structures of multistory buildings are stronger at the ground floor level where the impact of the wave is expected to be maximum (Sarà, 1993).

**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, timber buildings have always suffered higher structural damage than buildings made of bricks or reinforced concrete (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). During the 2005 tsunami in Java, 70% of single storey buildings made of wood were destroyed by a wave with a flow depth of just 1.5 metres. All buildings collapsed when flow depth exceeded 2 metres. Single brick buildings (with one story) faired slightly better when the water depth was greater than 2 metres. Multistory concrete buildings were resistant to damage even when water flow depth reached 4 metres (Reese *et al.,* 2007).

**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).

**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).

Unfortunately, no data about the foundations of the buildings we examined in this project were available. However, according to the approach of Terzaghi (1943) which is widely used in civil engineering for foundation analysis, the foundation strength can be inferred as a direct function of the load of the building and the type of soil. If we assume that all the building structures we examined are 'engineered' structures, and that the type of soil is constant, the foundation strength becomes a direct function of the building load and load is correlated with the number of stories. In order to obtain the "best available estimate" for the foundation factor, we considered this approximation to be acceptable.

**Shape and Orientation of the building footprint (so):** this factor is considered as a proxy for horizontal hydrodynamic force applied to buildings. 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 orinentated perpendicular to the direction of flow (Warnitchai, 2005; Dominey Howes and Papathoma, 2007).

**Movable Objects (mo):** during inundation, movable objects will be dragged around by the flowing water. During the 2004 tsunami, debris, cars, boats and even trucks were pushed against buildings, causing heavy structural damage. Buildings close to car parks, or to crossroads, are more likely to be damaged by this secondary flood effect (Darlymple and Kriebel, 2005).

**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.

Each of the seven factors listed above was observed and recorded for every building located within our study areas and a numerical value ranging between -1 to +1 was assigned to each factor. When the factor was thought to increase the average vulnerability level of a building, a positive score was recorded. When the factor decreased the average vulnerability level, a negative score was recorded. This approach is similar to that used by Cutter *et al.* (2003). For example, if the building had a reinforced concrete structure, then SV_m = -1. However, where it was made of timber, then SV_m = +1.

Using this approach, we suggest that a building with an '*average*' vulnerability is one that has a score of 'zero' for each of the seven factors and which has no protection. All the values assigned to the seven factors are shown in Table 2.

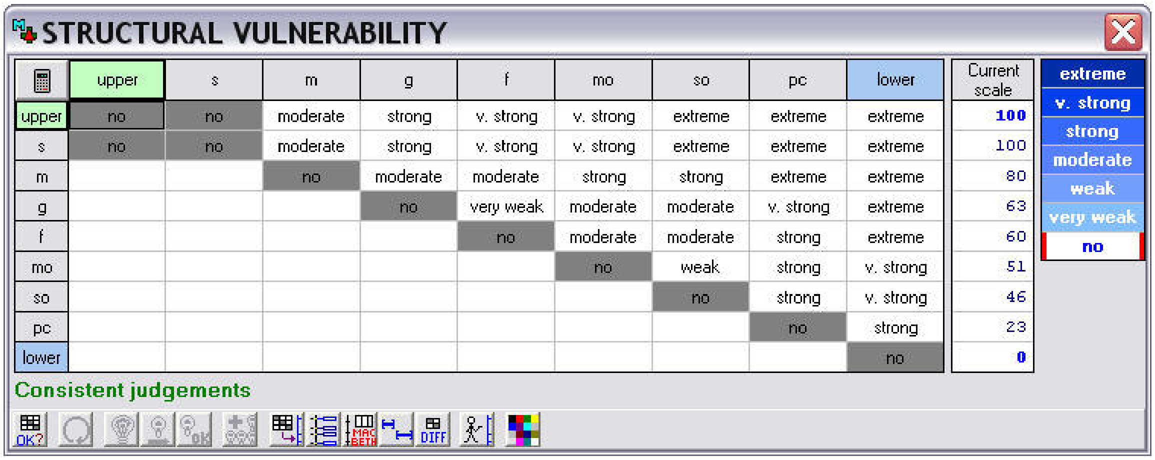
Once we have assigned a score to every factor, an initial value for "Bv" (ranging between -1 to +1) may be calculated through a weighted sum of all the factors:

$$\mathbf{Bv\ (-1,+1) = (W_1 \times s) + (W_2 \times m) + (W_3 \times g) + (W_4 \times f) + (W_5 \times so) + (W_6 \times mo) + (W_7 \times pc)} \qquad \text{(Eq. 3)}$$

Where:

"$W_i$" is the weighting coefficient of each factor.

It should be noted that not each of the seven factors has the same influence on the vulnerability of a building ("Bv"). Therefore, before being summed, the contribution of each factor must be weighted. For example, the number of stories and the construction material, are much more important than the preservation condition, or the shape-orientation of the building. Weights have been calculated via pair-wise matches between each of the factors. Comparisons between factors were undertaken using an evaluation matrix by means of the M-Macbeth[3] software, a specifically designed platform for multi criteria analysis and decision making processes (Bana e Costa *et al.,* 2004; Bana e Costa et Chagas, 2004). The evaluation matrix, together with the pair-wise match results are shown in Figure 3.



STRUCTURAL VULNERABILITY

| | upper | s | m | g | f | mo | so | pc | lower | Current scale |
|---|---|---|---|---|---|---|---|---|---|---|
| upper | no | no | moderate | strong | v. strong | v. strong | extreme | extreme | extreme | 100 |
| s | no | no | moderate | strong | v. strong | v. strong | extreme | extreme | extreme | 100 |
| m | | | no | moderate | moderate | strong | strong | extreme | extreme | 80 |
| g | | | | no | very weak | moderate | moderate | v. strong | extreme | 63 |
| f | | | | | no | moderate | moderate | strong | extreme | 60 |
| mo | | | | | | no | weak | strong | v. strong | 51 |
| so | | | | | | | no | strong | v. strong | 46 |
| pc | | | | | | | | no | strong | 23 |
| lower | | | | | | | | | no | 0 |

Consistent judgements

**Figure 3. Evaluation matrix for pair-wise matches between structural vulnerability factors. The matrix was built using "M-Macbeth" (see text for explanation).**

---

[3] The M-Macbeth is a software program designed to support multi-criteria analysis (Bana e Costa *et al.,* 2004; Bana e Costa et Chagas, 2004). MACBETH is the acronym of "**M**easuring **A**ttractiveness through a **C**ategory **B**ased **E**valuation **T**ec**H**nique", which is the goal of the Analytic Hierarchy Process. The key distinction between Macbeth and other multi-criteria approaches is that it needs only qualitative judgments about the difference of attractiveness between two factors at a time in order to generate numerical scores for the options (factors) in each criterion, and weight the criteria. The seven Macbeth semantic categories are: "extreme", "very strong", "strong", "moderate", "weak", "very weak" and "no difference". As the judgments expressed by the evaluator are entered in the M-Macbeth, their consistency is automatically verified and suggestions are offered to resolve inconsistencies if they arise. In this study, the M-Macbeth has been used only for performing pair-wise comparisons between factors affecting the structural vulnerability of buildings, as well as their level of protection. Thanks to this approach, weights of different factors have been calculated, and the unavoidable subjective component of the decision making process has been reduced to its minimum. An evaluation version of M-Macbeth can be downloaded for free from www.m-macbeth.com

Pair-wise comparisons between different factors were undertaken by us based upon published results of post-tsunami field surveys and our personal expertise and professional judgment. However, results of pair-wise comparisons may not be the same if they are performed by other researchers. This kind of subjectivity can not be avoided, and is typical of every decision making process. Nonetheless, every single comparison is described and discussed in Appendix 3.

From a technical point of view, the evaluation matrix was completed by undertaking the following steps. Each factor in a row was compared with one in a column. When the factor in the row was judged to be more important than the one in the column, their difference was expressed qualitatively in the corresponding cell. The difference between the importance of the two factors was chosen from the following range of possibilities: “extreme”, “very strong”, “strong”, “moderate”, “weak”, “very weak” and “no difference”. Lower and upper factors have been introduced as fictitious references. The upper one has the same importance as the most important factor (number of stories), while the lower factor does not give any contribution to the structural vulnerability level.

While we were performing all the pair-wise matches, the software 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 factor (Figure 4).

**Table 2. Values assigned to the seven factors influencing the structural vulnerability of a building ("Bv"). Positive values indicate an increase of the average building vulnerability given by the factor, while negative values indicate a decrease of the average building vulnerability**

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

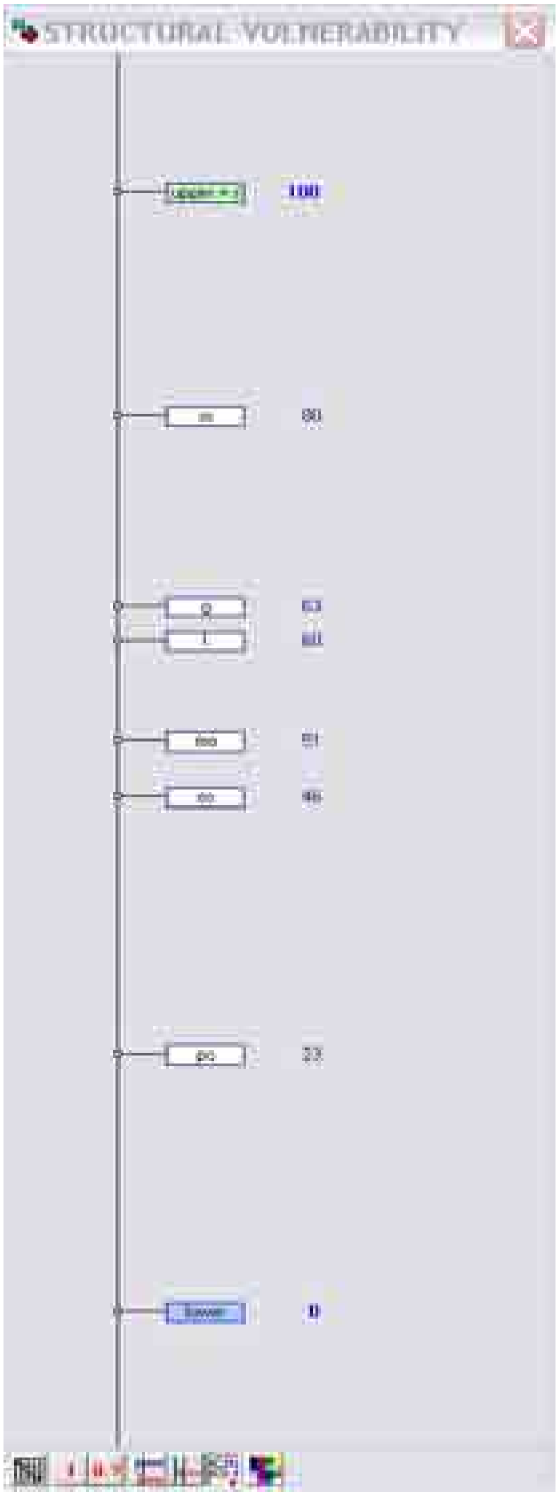


**Figure 4. The relative weights of the structural vulnerability factors derived from pair-wise comparisons between various factors**

After scaling to 1 (each weight is divided by the sum of all weights, that is 423), each weight was added to Eq. 3 to give Eq. 4:

$$\mathbf{Bv\ (-1, +1) = (1/423) \times [100 \times (s) + 80 \times (m) + 63 \times (g) + 60 \times (f) + 51 \times (mo) + 46 \times (so) + 23 \times (pc)]} \quad \text{(Eq. 4)}$$

As said, this relation gives as a result a value of Bv ranging between -1 to +1. In order to use Bv in (Eq.2) it has been scaled to a range from 1 to 5 (Table 3).

**Table 3. Values calculated for Bv have been scaled to a range from 1 to 5**

| Bv<br>(-1,+1) | [-1, -0.6[ | [-0.6, -0.2[ | [-0.2, +0.2[ | [+0.2, +0.6[ | [+0.6, +1] |
|---|---|---|---|---|---|
| **Bv**<br>**( 1, 5 )** | **1** | **2** | **3** | **4** | **5** |

### 2.3.1.1.2 *Calculating the Protection "Prot" factor*

The protection factor "Prot" was calculated as a weighted sum of different contributions in the same way as "Bv" was calculated. Factors that affect the protection level of a building are:

**The building row (Prot_br)**: one of the most important factors that can provide protection from the impact forces of a tsunami is the number of other structures located between a particular building and the coastline. 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).

**The presence of a seawall (Prot_sw):** vertical seawalls, normally built to protect against high tides and storm surges, can also provide protection during a tsunami. Darlymple and Kriebel (2005) noted that building damage from the 2004 tsunami in Thailand was significantly lower in places protected by seawalls. They also noted that in places where no sea wall existed (for example, to allow pedestrian access to the beach), damage to buildings was higher. 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.

**Natural barriers (Prot_nb):** the presence of natural barriers such as coastal forests, can significantly reduce the level of structural damage to buildings located landward of these natural barrier features (Matsutomi *et al.,* 2006, Olwig *et al.,* 2007). Natural barriers appear to both reduce velocity and trap debris and heavy floating objects that would otherwise damage buildings (Tanaka *et al.,* 2006).

**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 this study, wherever present, we noted and allowed for the protection offered by walls to buildings. Walls ranged in height from 0.5 to 2 metres.

Data about these factors was obtained for every building in our study areas during field surveys and visual interpretation of aerial images. For each building we assigned a score to every protection factor. In this case, 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 4.

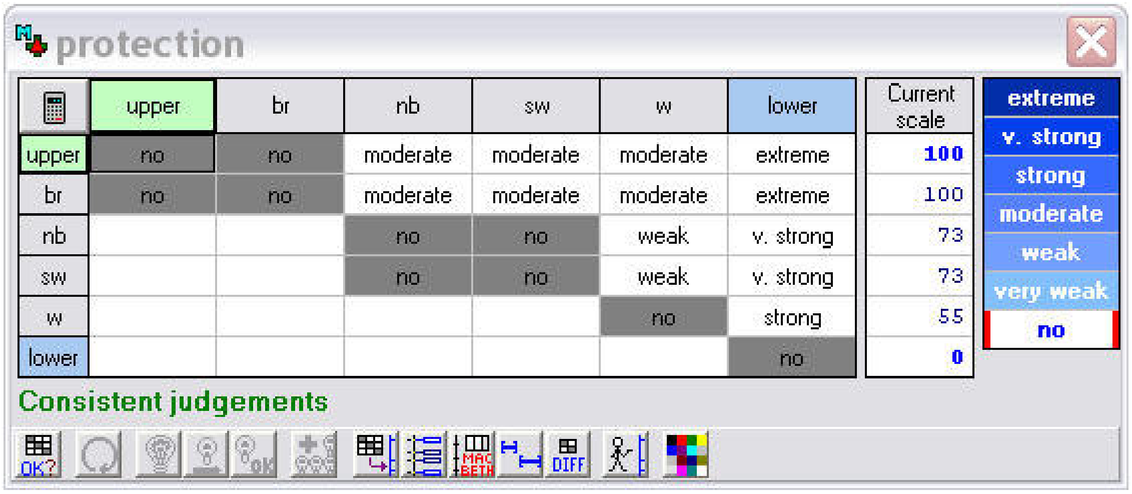
**Table 4. Scores assigned to the four factors influencing the level of protection of a building ("Prot"). Scores close to zero indicate a high protection level, while scores equal to 1 indicate the lowest level of protection**

| | **0** | **0.25** | **0.5** | **0.75** | **1** |
|---|---|---|---|---|---|
| **Prot_br**<br>**(building row)** | >10th | 7-8-9-10th | 4-5-6th | 2nd-3rd | 1st |
| **Prot_nb**<br>**(natural barriers)** | very high protection | high protection | average protection | moderate protection | no protection |
| **Prot_sw**<br>**(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<br>sloped and 1.5 to 3m | sloped and 0 to 1,5m OR<br>no seawall |
| **Prot_w**<br>**(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 |

As in the case of “Bv”, a first numerical value of “Prot” (ranging between 0 and 1) was obtained though a weighted sum of all protection factor scores. Thus:

$$\mathbf{Prot\ (0, 1) = (}\boldsymbol{W_1}\mathbf{\ x\ Prot\_br) + (}\boldsymbol{W_2}\mathbf{\ x\ Prot\_sw) + (}\boldsymbol{W_3}\mathbf{\ x\ Prot\_nb) + (}\boldsymbol{W_4}\mathbf{\ x\ Prot\_w)} \qquad \text{(Eq. 5)}$$

Again, weights have been calculated via pair-wise matches using the M-Macbeth software. Results are shown in Figure 5 and Figure 6 while a more detailed description of comparisons may be found in Appendix 4.



| | upper | br | nb | sw | w | lower | Current scale |
|---|---|---|---|---|---|---|---|
| upper | no | no | moderate | moderate | moderate | extreme | 100 |
| br | no | no | moderate | moderate | moderate | extreme | 100 |
| nb | | | no | no | weak | v. strong | 73 |
| sw | | | no | no | weak | v. strong | 73 |
| w | | | | | no | strong | 55 |
| lower | | | | | | no | 0 |

Consistent judgements

**Figure 5. Evaluation matrix for pair-wise comparisons between different protection factors**

**Figure 6. The relative weights of the protection factors**

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:

$$\mathrm{Prot}\ (0, 1) = (1/301) \times [100 \times (\mathrm{Prot\_br}) + 73 \times (\mathrm{Prot\_nb}) + 73 \times (\mathrm{Prot\_sw}) + 55 \times (\mathrm{Prot\_w})] \quad \text{(Eq. 6)}$$

As said, this relation gives as a result a value of "Prot" ranging between 0 to +1. In order to use "Prot" in (Eq.2) it has been scaled to a range from 1 to 5 using Table 5.

**Table 5. Values obtained for "Prot" have been scaled to a range from 1 to 5**

| Prot (0, 1) | [0, 0.2[ | [0.2, 0.4[ | [0.4, 0.6[ | [0.6, 0.8[ | [0.8, 1] |
|---|---|---|---|---|---|
| **Prot ( 1, 5 )** | **1** | **2** | **3** | **4** | **5** |

### 2.3.1.1.3 *Calculating the Exposure "Ex" factor*

The third and last element of (Eq. 2) is exposure "Ex" - a score ranging from 1 to 5 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 the flow velocity are direct functions of flow depth (Fritz *et al.*, 2006). Scores have been given to "Ex" according to Table 6.

**Table 6. Scores ranging from 1 to 5 have been given to "Ex" according to the water depth**

| Water Depth | 0 to 1 m | 1 to 2 m | 2 to 3 m | 3 to 4 m | > 4 m |
|---|---|---|---|---|---|
| **"Ex"** | **1** | **2** | **3** | **4** | **5** |

### 2.3.1.2 Vulnerability associated with Water Intrusion (“WV”)

Once the floor of a building has been inundated, all the parts of that floor which are damaged by the water 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 (which includes the basement).

Consequently, we assign to ‘WV’ a score that indicates what percentage of the floors of a building will be inundated. Hence, for each building:

**WV (0, 1) = (number of inundated levels) / (total number of levels)**

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 7.

**Table 7. Values obtained for “WV” have been scaled to a range from 1 to 5**

| WV (0, 1) | [0, 0.2[ | [0.2, 0.4[ | [0.4, 0.6[ | [0.6, 0.8[ | [0.8, 1] |
|---|---|---|---|---|---|
| **WV (1, 5)** | **1** | **2** | **3** | **4** | **5** |

## 2.3.2 Calculating the Relative Vulnerability Index

Once “SV” and “WV” are obtained, the **‘Relative Vulnerability Index’** (RVI) score for each building may be calculated using Eq.1. The range of RVI values was then divided in to 5 equal intervals (Table 8).

**Table 8. Final Relative Vulnerability Index (RVI) scores for buildings in our study areas**

| RVI (1, 5) | [1 - 1.8[ | [1.8 - 2.6[ | [2.6 - 3.4[ | [3.4 - 4.2[ | [4.2 - 5] |
|---|---|---|---|---|---|
| **Relative Vulnerability Index** | **MINOR** | **MODERATE** | **AVERAGE** | **HIGH** | **VERY HIGH** |

In the final analysis and presentation of results in map form, we adopt a colour coding scheme (Table 8) to represent the various vulnerability values since such an approach is common in other hazard assessment types and is easy for the user to understand.

## 2.4 Step 4 – Model applications at Maroubra Beach and Manly

***To obtain appropriate data sets, run the vulnerability assessment model to calculate the Relative Vulnerability Index scores for individual buildings and produce vulnerability maps***

This project used a Geographic Information System (GIS) in which to run the model analysis and present the results in map form. The GIS software we used was ArcGIS Desktop 9.2 available from ESRI. The main advantage of using GIS is the complete flexibility of the system, which allows each end-user to obtain dedicated and specific data. GIS software also allows end-users to keep updating the primary database through time. This is critical since it facilitates the production of up-to-date and reliable vulnerability maps which are extremely valuable when dealing with low frequency hazard processes like tsunamis and storm surges. The coordinate system chosen for the whole project is the Transverse of Mercator projection, GDA 1994 MDA datum, zone 56.

The data collected and used in this project, together with the results, were stored in a GIS database, following a hierarchic framework made up of groups of sub-directories. Data are initially divided in to two directories according to their digital format (vectorial and raster). Further sub-divisions are then made according to file typology and semantic areas.

### 2.4.1 Data needed: building the GIS

In order to build the GIS and run the model, the following data were obtained:

- A recent geo-referenced and ortho-rectified aerial image of each study area which is 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 Manly and Randwick councils;

- A Digital Elevation Model (DEM) with the best horizontal resolution and vertical accuracy. 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's were also provided by council;

- A shapefile of polygons representing all the building footprints. The shapefiles were alo provided by Manly council but were manually digitized by us for Maroubra. Building attribute data was then manually entered in to the GIS database for each building file; and

- Attribute data for each building. The specific attributes were listed at sections 2.3.1.1.1 and 2.3.1.1.2. The data included both building and urban environment data (e.g., seawalls etc). These datasets were not available from council and so we undertook field surveys to collect these data building-by-building.

The data provided by Manly and Randwick Councils were entered into a GIS database, and categorised according their format and different thematic areas (Figure 7).

**Figure 7. The construction of the GIS database for Manly**

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 8).

**Figure 8. Inundation map for Manly**

In the case of Manly, the combined 'Buildings' shapefile was modified in order to be used in the vulnerability model. A total of 1141 individual building footprints were manually extracted (Figure 9). For Maroubra, inundated buildings were manually digitalized.

Figure 9. Building footprints have been manually extracted and plotted on to the Manly map

### 2.4.2 Field surveys and data recording

We needed to undertake ground-truthing of the building shapefiles created for Manly and Maroubra and collect building data for the various attributes of the model. The area covered by the expected tsunami flood water is large in Manly. Therefore, we divided the whole study area in to 18 smaller more manageable blocks (Figure 10)

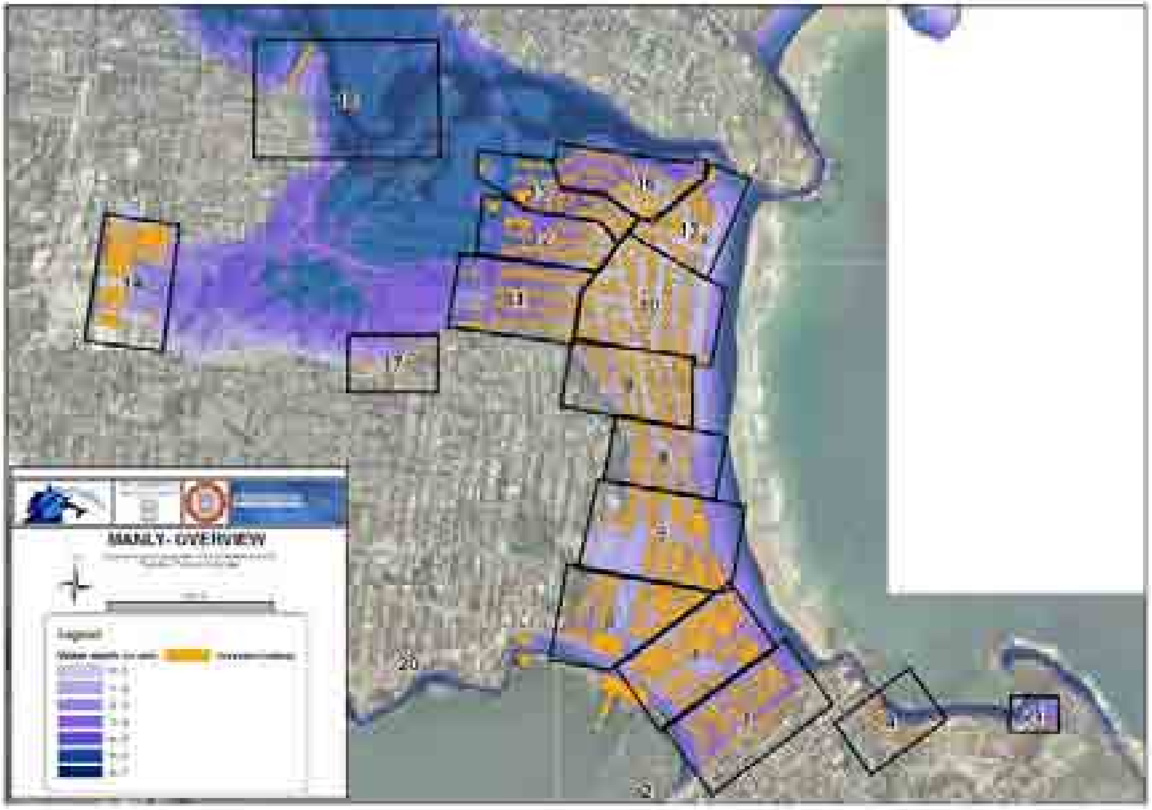
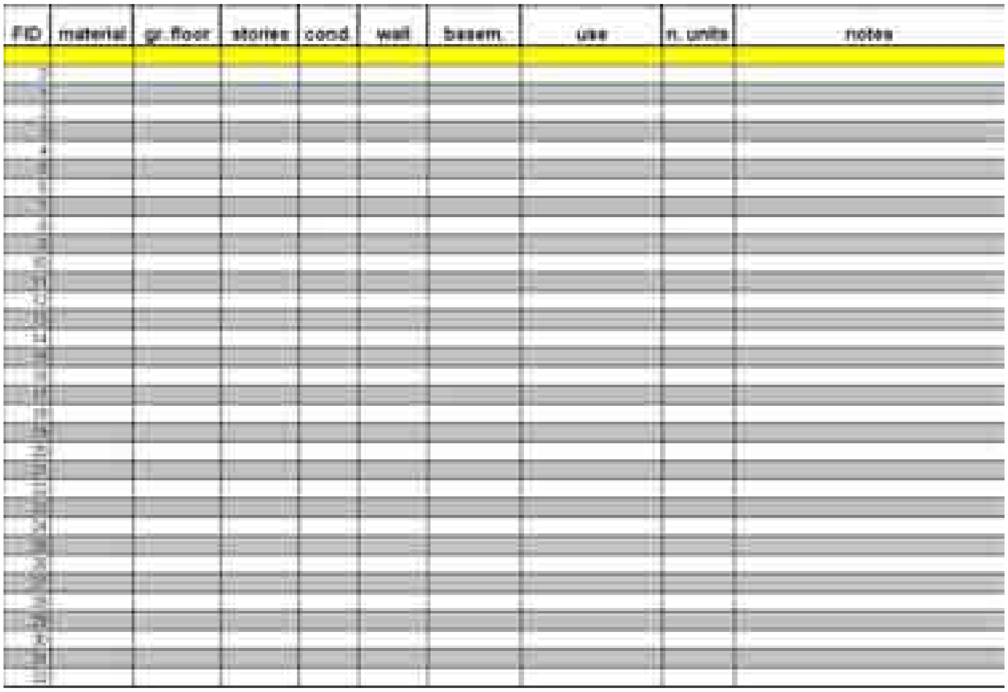


**Figure 10. For field surveys, buildings in Manly have been divided into 18 manageable sized blocks**

For each of the 18 block areas, we prepared a master sheet with individual building shapefiles (Figure 11) in order to ground-truth these buildings and record building attribute data for each confirmed building structure according to a standardised data sheet (Figure 12). Preparation of separate block areas was not necessary for Maroubra because a significantly smaller area and number of buildings were affected.

**Figure 11. Example of a master map with individual building shapefile used during field surveys**



| FID | material | gr. floor | stories | cond. | wall | basem. | use | n. units | notes |
|---|---|---|---|---|---|---|---|---|---|

**Figure 12. Example of the 'building and attribute' table to be completed during field surveys**

The rows of the table shown in Figure 12 include a building identification number, while all the factors to be observed and recorded were listed in the columns.

Where the correspondence between aerial images and field observations was not good, building shapefiles were manually corrected using the ground-truth data.

The data collected during the field surveys was entered into the attribute table of the corresponding building shapefiles in the GIS. Finally, the Relative Vulnerability Index score for each building was calculated and maps produced for each study areas (see Section 3 – Results).

# 3 Results

**SECTION SUMMARY - This section of the report displays the exposure of buildings to tsunami flood damage for the scenario used in this project in Maroubra and Manly. It also shows the results of the calculation of the 'Relative Vulnerability Index' (RVI) score for every building located within the tsunami inundation zone. We show that only a small number of buildings would be inundated at Maroubra and most have low 'Relative Vulnerability Index' scores. Conversely, a large number of buildings in Manly would be inundated by a tsunami and many building structures have a high to very high 'Relative Vulnerability Index' score**

## *3.1 Introduction*

The results are divided in to two sections – assessment of building vulnerability in (1) Maroubra and (2) Manly. In this study, we have chosen to present the results as a series of thematic maps that relate to specific 'classes' (or types) of buildings. The classes have been chosen by us and are:

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

For each class of building, the maps are provided at a scale of 1:5000. We chose these classes because they represent a common sense approach and because specific stakeholder groups would be interested in these various classes of buildings. Further, in many cases, large numbers of buildings are present within particular areas and it is useful to be able to view specific classes or types of buildings in a single map. Clearly, any particular user could choose to display the buildings in different classes appropriate to their own needs.

## 3.2 Maroubra

### 3.2.1 Inundation and exposure

Figure 13 shows the area of Maroubra that would be inundated by a tsunami achieving a run-up of +5 metres above sea level (m asl).

Figure 13. Inundation at Maroubra

Examination of Figure 13 indicates that a relatively small area of Maroubra would be inundated by the tsunami in our scenario (27.4 ha). The deepest inundation is confined to the beach strip running northeast - southwest. Tsunami flood waters 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 as far east as Mckeon Street, as far north as Duncan Street and southward towards Fitzgerald Avenue. Water flow depth would be no greater than 3 metres above the ground surface throughout much of this area.

### 3.2.2 Vulnerability of all buildings exposed at Maroubra

A total of just 96 buildings (of all building class types) would be ‘touched’ by tsunami flood water in our scenario (Figure 14). We then calculated the ‘Relative Vulnerability Index’ (RVI) score of every building located within the inundation zone using the approach outlined in Section 2.3. The results are also shown in Figure 14.

Figure 14. The Relative Vulnerability Index scores of all exposed buildings in Maroubra

From Figure 14, 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 four buildings classified with a “High” RVI score are located in areas where water depth would exceed 1 metre.

### 3.2.3 Vulnerability of local government buildings

Figure 15 shows the RVI scores of those buildings in Maroubra that are the responsibility of local government. The RVI scores of these structures are “Very Low” and “Low” and there are only four such buildings in the area. It is fortunate that the RVI scores are low since each of these buildings is located close to the shoreline and well within the deep inundation zone (Figure 13).

**Figure 15. The Relative Vulnerability Index scores of local government buildings**

### 3.2.4 Vulnerability of buildings related to health and medical services

Figure 16 shows the calculated RVI scores of those buildings in Maroubra that are related to health and medical services. Such facilities would be critical to emergency response and recovery after a tsunami impact. Fortunately, only two buildings fall in to this classification but one of them – the ambulance station located at the intersection of Mons Avenue and Fenton Avenue has been classified as having a RVI score of “High”.

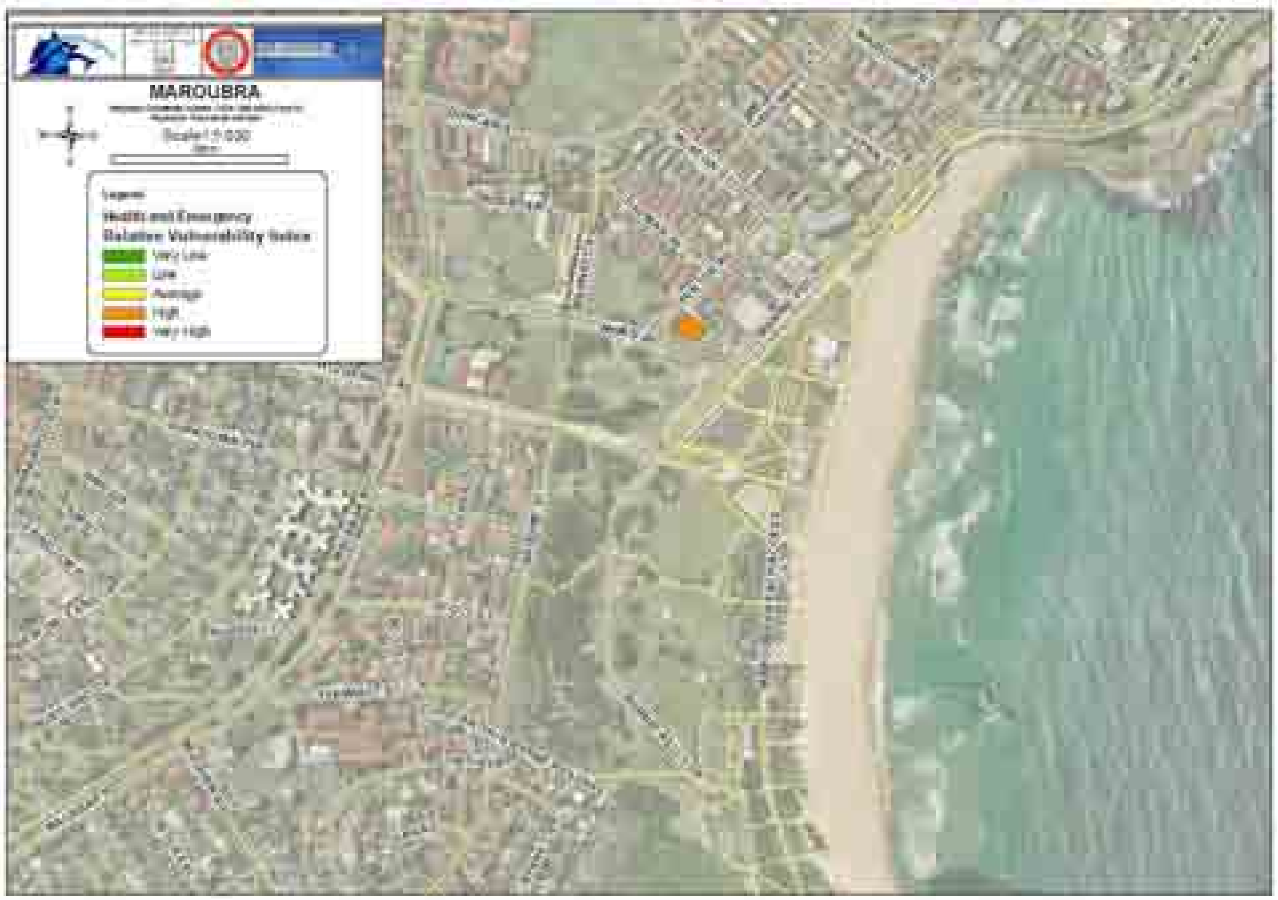


**Figure 16. The Relative Vulnerability Index scores for health and medical services buildings in Maroubra**

### 3.2.5 Vulnerability of buildings related to recreation and culture

Figure 17 shows the calculated RVI scores of those buildings in Maroubra that are related to recreation and culture. There are just two buildings of this type and they have RVI scores of “Very Low” and “Low”.

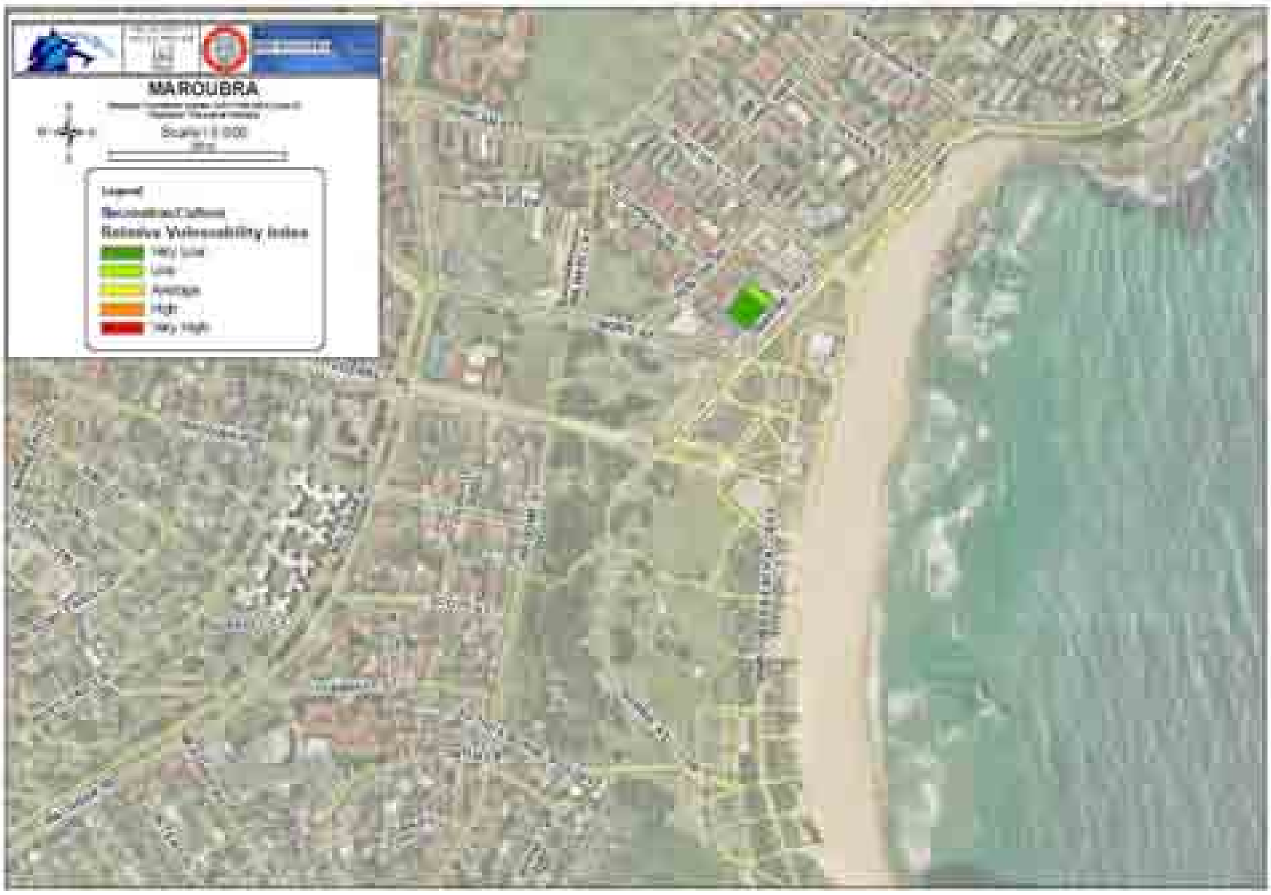


Figure 17. The Relative Vulnerability Index scores for recreation and culture buildings in Maroubra

### 3.2.6 Vulnerability of transport system buildings

There are just two transport related buildings within the tsunami inundation zone of Maroubra. Figure 18 shows the location of these buildings and the RVI scores. Both have RVI scores of “High”.

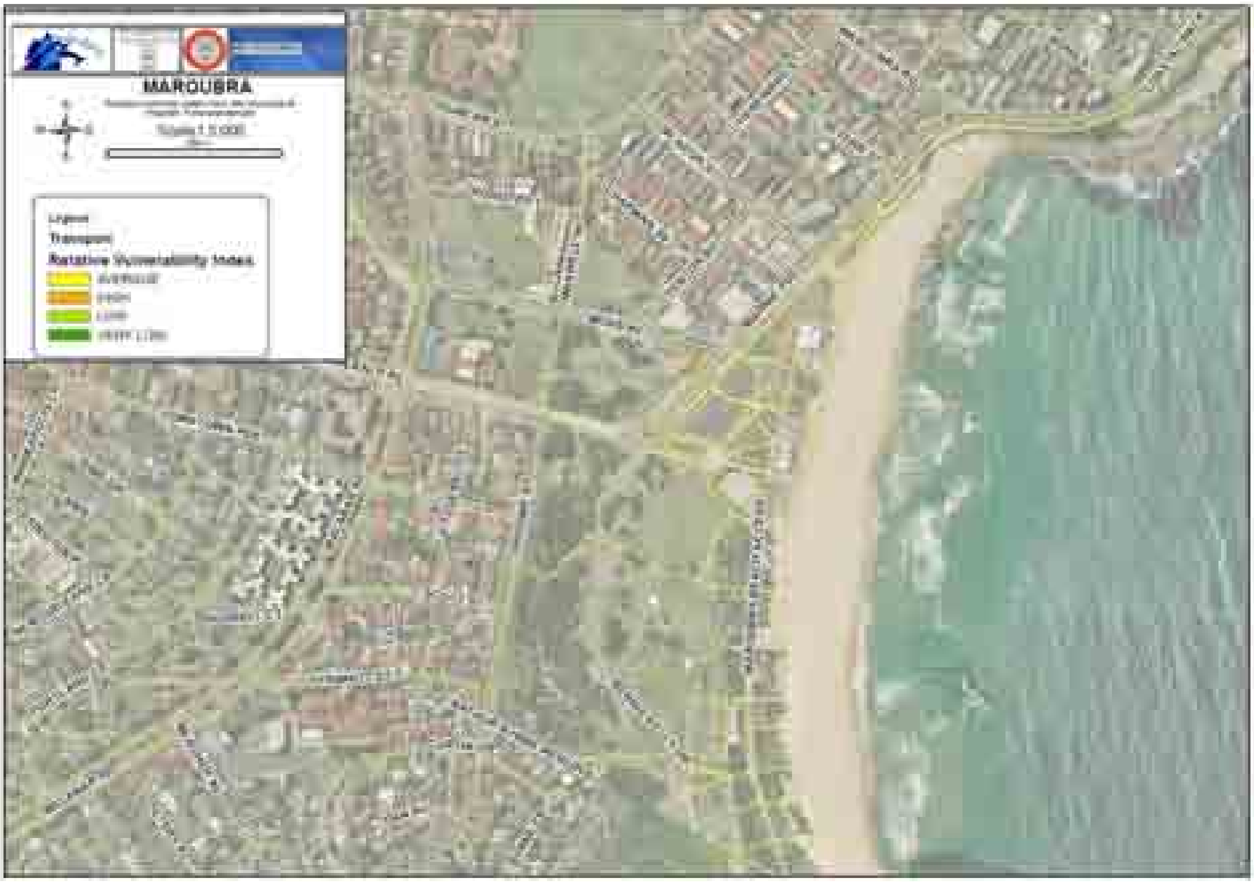


**Figure 18. The Relative Vulnerability Index scores of transport system buildings**

### 3.2.7 Vulnerability of tourism buildings

There are just two tourism related buildings within the tsunami inundation zone of Maroubra. Figure 19 shows the RVI scores of each of these and fortunately, the buildings have scores of “Very Low” and “Low”.

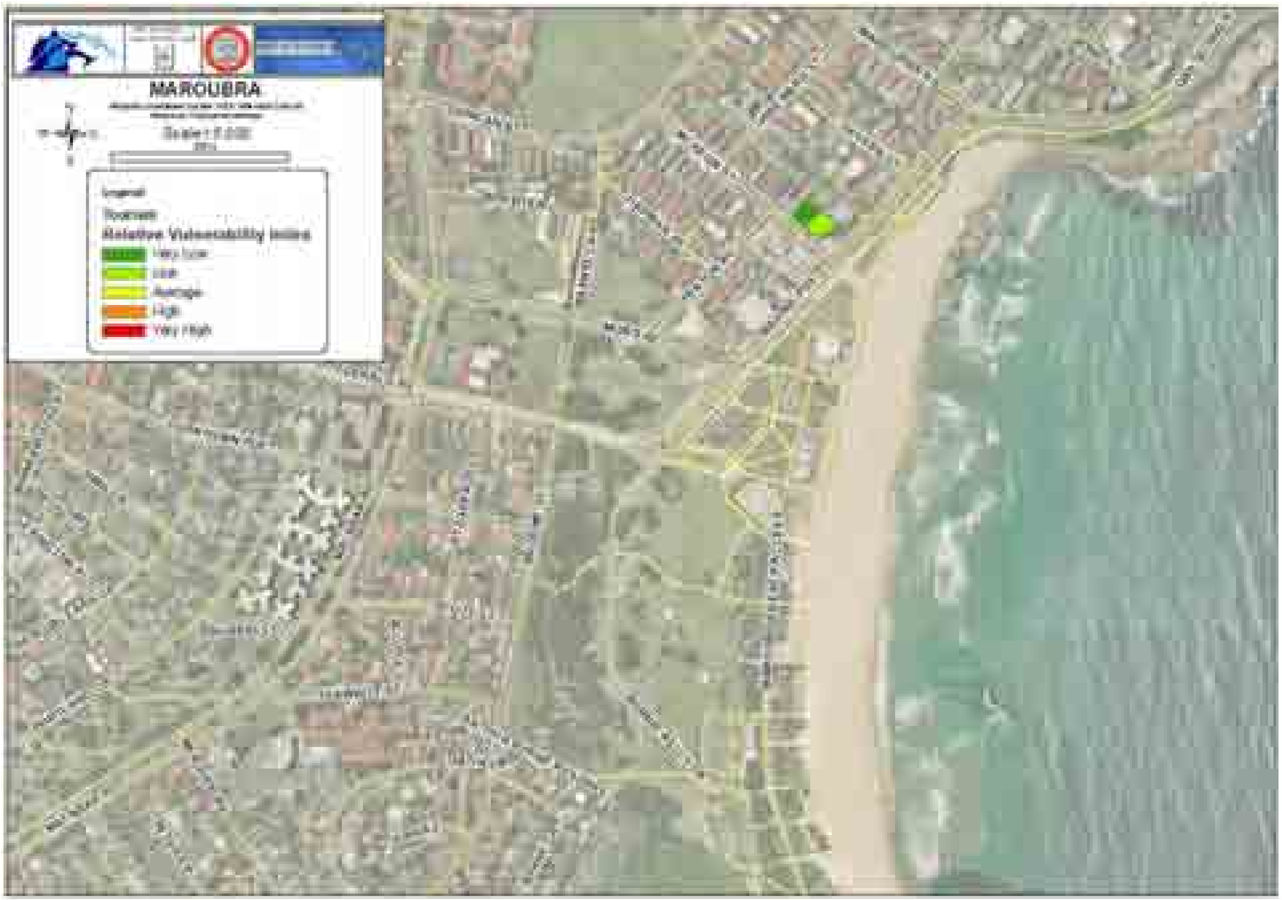


Figure 19. The Relative Vulnerability Index scores of tourism buildings in Maroubra

### 3.2.8 Vulnerability of commercial buildings

There are a total of 18 commercial building structures within the tsunami inundation zone of Maroubra. Figure 20 shows the RVI scores of each of these buildings. These commercial buildings are classified as having “Very Low”, “Low” or “Average” vulnerability”. None of them have a “High” or “Very High” RVI score.

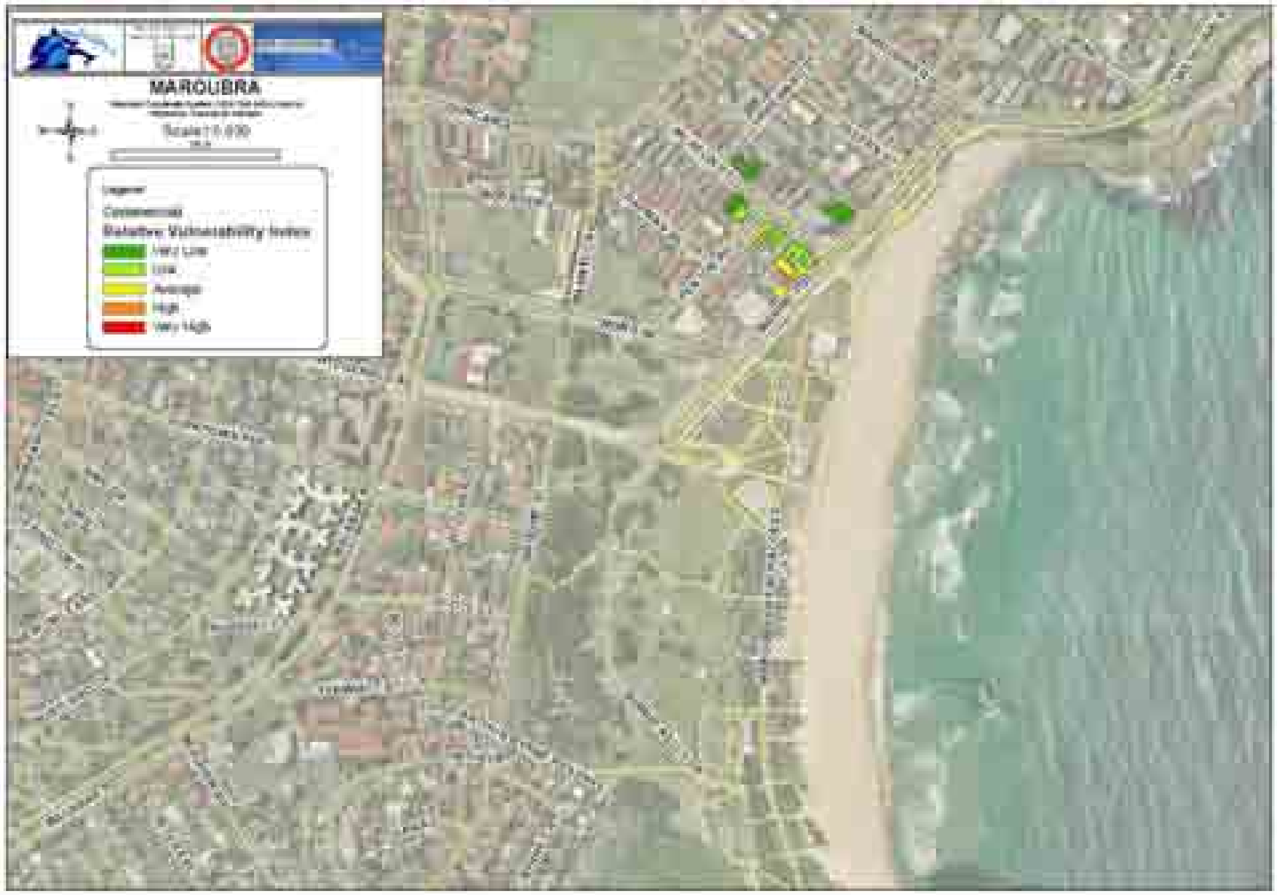


Figure 20. The Relative Vulnerability Index scores of commercial buildings in Maroubra

### 3.2.9 Vulnerability of residential buildings

There are a total of 67 residential buildings within the tsunami inundation zone of Maroubra. Figure 21 shows the RVI scores of each of these buildings. The vast majority of residential structures are classified as having “Very Low”, “Low” or “Average” vulnerability. Only one residential building is classified as having “High” vulnerability.

Figure 21. The Relative Vulnerability Index scores for residential buildings in Maroubra

### 3.2.10 Vulnerability of education and utility buildings

None of the 96 buildings shown in Figure 14 and inundated by the tsunami in our scenario are associated with the education or utility sectors. We have therefore, not provided any maps as they would evidently be blank.

### 3.2.11 Overall observations

The following general observations are made about building exposure and vulnerability for the area of Maroubra:

- Generally speaking, only a very few building structures are located within the tsunami inundation zone associated with our scenario. Therefore, the overall ‘exposure’ is in fact, rather low;
- Overall, the majority of building structures touched by tsunami flood water in this scenario have an “Average” or lower ‘Relative Vulnerability Index’ score;
- Only a very small number of individual building structures have a “High” Relative Vulnerability Index score and one of these is an ambulance station;
- The Maroubra and South Maroubra Surf Life Saving Clubs located on the esplanade behind the beach have a “Low” RVI score in this scenario; and
- Large areas of low lying foreshore area behind the Maroubra beach including Broadarrow Reserve and Arthur Bryne Reserve are currently not developed and should probably remain so.
- The Randwich LGA does not need to worry about the vulnerability of any buildings for which it is responsible;
- Buildings belonging to the transport system and its operators have been assessed as having “High” RVI scores. The relevant owners/operators should consider measures to address the vulnerability of these structures.

## 3.3 Manly

Manly is a much more complex situation than Maroubra with a significantly larger area of land inundated in our scenario (169.5 ha) (Figure 22).

**Figure 22. Area of Manly local government covered by tsunami flood water in our scenario**

Due to the low-lying character of the coastal region of Manly, it can be seen that the tsunami would flood fully down the Corso from the ocean side of Manly through to the Manly Wharf on the Harbour side. The tsunami would also be funneled through the entrance of Manly Lagoon to a significant distance inland inundating buildings in low lying areas on the south side of the lagoon. The tsunami would be able to inundate farther inland than shown by Figure 22 but we are only concerned with the impacts of the tsunami in the Manly local government area and so we have not explored the effects of the tsunami in neighbouring local government areas.

A total of 1133 buildings (plus 8 sites that were under construction at the time this study was undertaken) are touched by tsunami flood water in our scenario. This is far too large an area to easily display on a single map. Therefore, for graphical reasons, we have divided the Manly area affected by inundation in to four smaller blocks shown in Figure

23. In the remainder of this Section of the report, we will sequentially deal with Manly Blocks 1, 2, 3 and 4. In Section 3.2, we described the absolute number of buildings of each class in the inundation zone of Maroubra. We do not do this for the Manly case study since the four sub-blocks over lap. If we were to provide absolute building numbers as a sum of the buildings in each block, we would overestimate their actual number (1141), because buildings located in the overlapping areas of the blocks would be double-counted. Nonetheless the absolute number of buildings of each class, for the whole inundated area in Manly, is shown in Table 9.

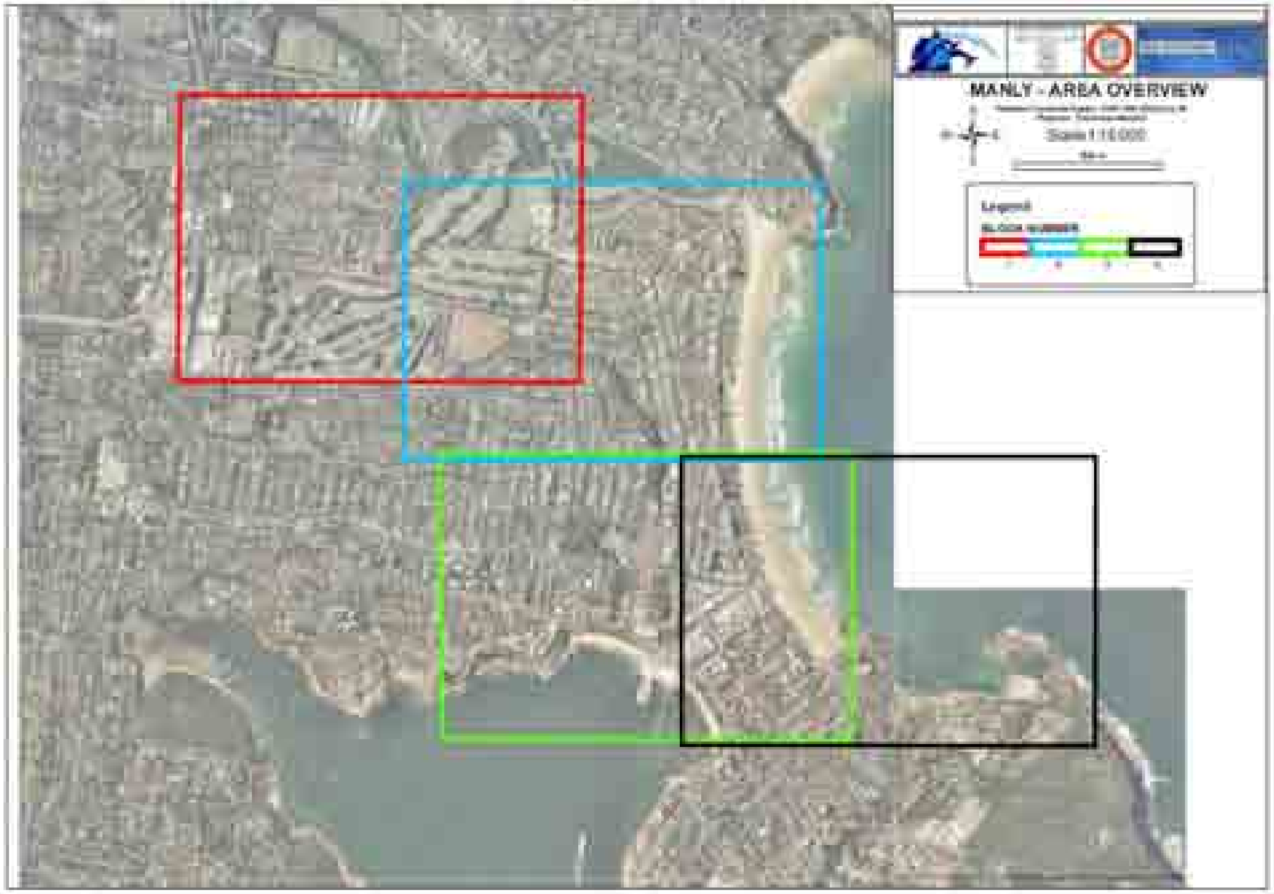


**Figure 23. The four "blocks" used to divide manly in manageable areas for display purposes**

## 3.3.1 Manly Block 1

### 3.3.1.1 Inundation and exposure

The area of Manly Block 1 inundated by the tsunami in our scenario is indicated in Figure 24.

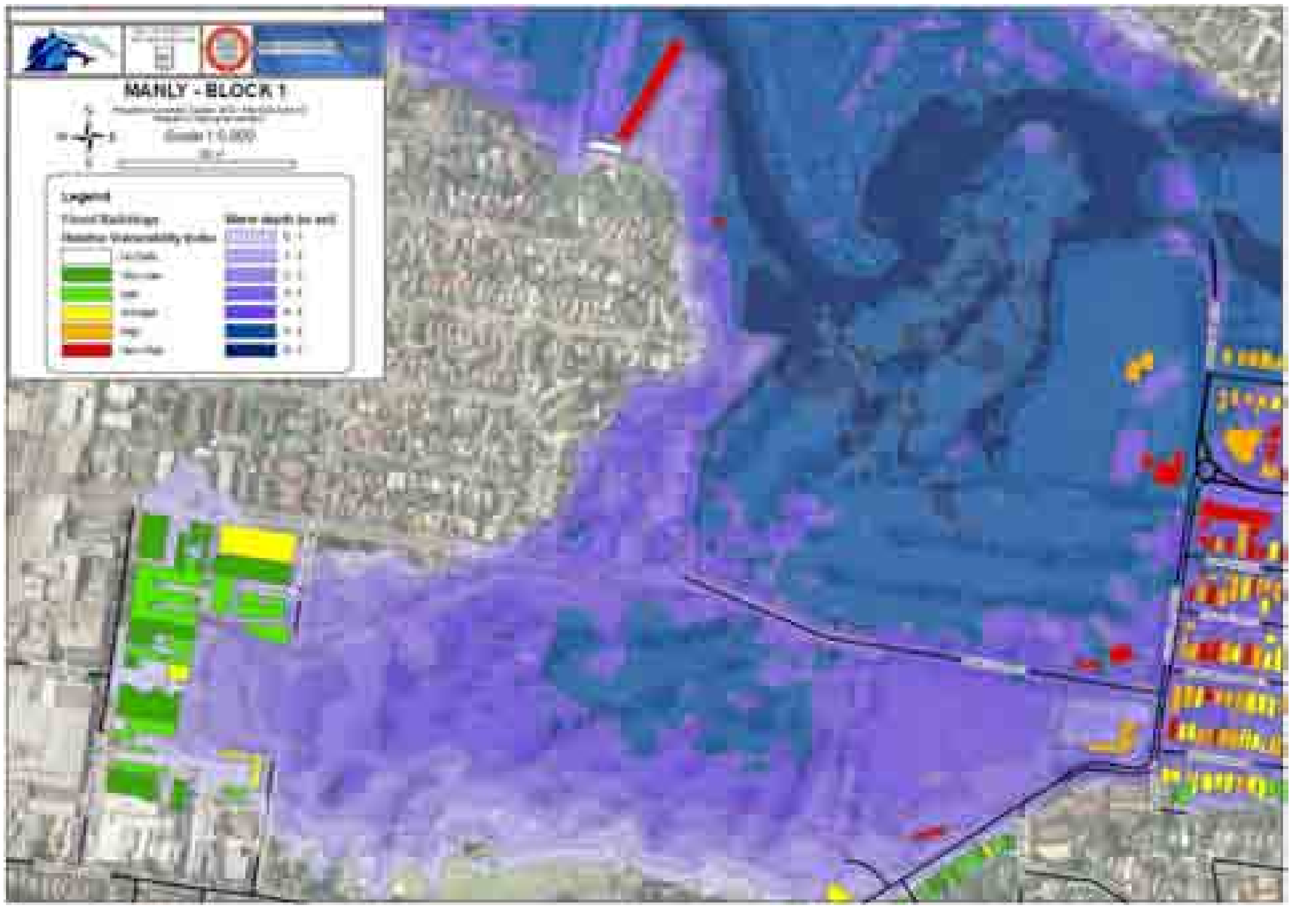


**Figure 24. Inundation of Block 1, Manly by the tsunami in our scenario**

Examination of Figure 24 indicates that a relatively large area of Block 1 would be inundated. Most of the area however, is covered by the Manly Golf Course. A large number of buildings of all types would be ‘touched’ by flood water during the tsunami in our scenario. This represents the total ‘exposure’ to potential damage during the hypothetical tsunami. Figure 24 also displays the calculated ‘Relative Vulnerability Index’ (RVI) scores of each of the buildings located within the inundation zone. It can be clearly seen that a significant percentage of buildings are classified as having “High” and “Very High” RVI scores.

### 3.3.1.2 Vulnerability of local government buildings

Figure 25 shows the RVI scores of those buildings in Manly Block 1 that are the responsibility of the local government. Only a small number of buildings fall within this class and fortunately, all buildings are classified as “Average” or lower in terms of their RVI. Furthermore, these buildings are all located at the most landward (western) extent of the inundation zone in the region of Quirk Road and Roseberry Street.

**Figure 25. Distribution and final vulnerability classification of government owned-managed buildings in Manly Block 1**

### 3.3.1.3 Vulnerability of buildings related to health and medical services

Figure 26 shows the RVI score of the one building in Block 1 that relates to health and medical services. This building is classified as having a “High” RVI score and is the Senior Citizen Centre at the edge of the Manly Golf Course off Pittwater Road.

**Figure 26. The vulnerability of the health and medical services building, Block 1, Manly**

### 3.3.1.4 Vulnerability of buildings related to education

Figure 27 shows the calculated RVI score of those buildings in Block 1 that relate to the education sector. These building are classified as having an “Average” RVI score.

**Figure 27. The vulnerability of the education buildings in the Manly Block 1 area**

### 3.3.1.5 Vulnerability of recreational and cultural buildings

Figure 28 shows the RVI scores of the recreational and cultural buildings in Manly Block 1 located within the tsunami inundation zone. These buildings are characterized by a mix of “Very High”, “High” and “Low” RVI scores.

Figure 28. The vulnerability of recreational and cultural buildings in Manly Block 1

### 3.3.1.6 Vulnerability of utility buildings

Figure 29 indicates that only a very small number of individual buildings classified as utility buildings are located in this area. However, their RVI scores are “High” and “Very High”.

**Figure 29. The vulnerability of utility buildings in Block 1, Manly**

### 3.3.1.7 Vulnerability of commercial buildings

Figure 30 shows the calculated RVI scores of the commercial buildings in Block 1 located within the tsunami inundation zone. A relatively small number of commercial buildings are located within the inundation zone and most have RVI scores of “Average” or lower.

Figure 30. The vulnerability of commercial buildings in Block 1, Manly

### 3.3.1.8 Vulnerability of residential buildings

Figure 31 shows the RVI scores of residential buildings located within the tsunami inundation zone of Block 1. A relatively large number of residences would be inundated. The majority of residential buildings have an RVI score of “Average” and higher.

Figure 31. The RVI scores of residential buildings in Block 1, Manly

### 3.3.1.9 Vulnerability of buildings associated with the transport and tourism sectors

No buildings within the Manly Block 1 area are associated with the transport or tourism sectors. Therefore, no exposure exists.

### 3.3.1.10 Overall observations

With regard to Manly Block 1, we make the following general observations:

- Large areas of Block 1 – currently the Manly Golf Course are undeveloped and as such, the building exposure is not as high as it might otherwise be;
- A large number of residential structures are however, vulnerable to damage, and of these, a significant percentage have been classified as having "High" and "Very High" RVI scores;
- The small number of utility sector buildings located within the inundation zone of Manly Block 1 are all classified as having high vulnerability. This is potentially highly problematic in terms of impacting upon the capacity to recover and these buildings should be the subject of efforts to reduce their vulnerability;
- Finally, the one health and medical services building within the Block 1 inundation zone (a nursing home) has an RVI score of "High" and as such, requires effort to reduce its vulnerability (and/or improve emergency response efforts in the event of a tsunami).
- Those buildings that are the responsibility of the Manly LGA have "Average" of lower RVI scores. Therefore, nothing to worry about for the local government. Similary for education buildings.

## 3.3.2 Manly Block 2

### 3.3.2.1 Inundation and exposure

The area of Manly Block 2 inundated by the tsunami in our scenario is indicated in Figure 32.[4] This is a large area bounded to the north by the entrance to Manly Lagoon and to the east by the ocean. It extends as far south as Steinton Street and to the west to Pittwater and Balgowah Roads.

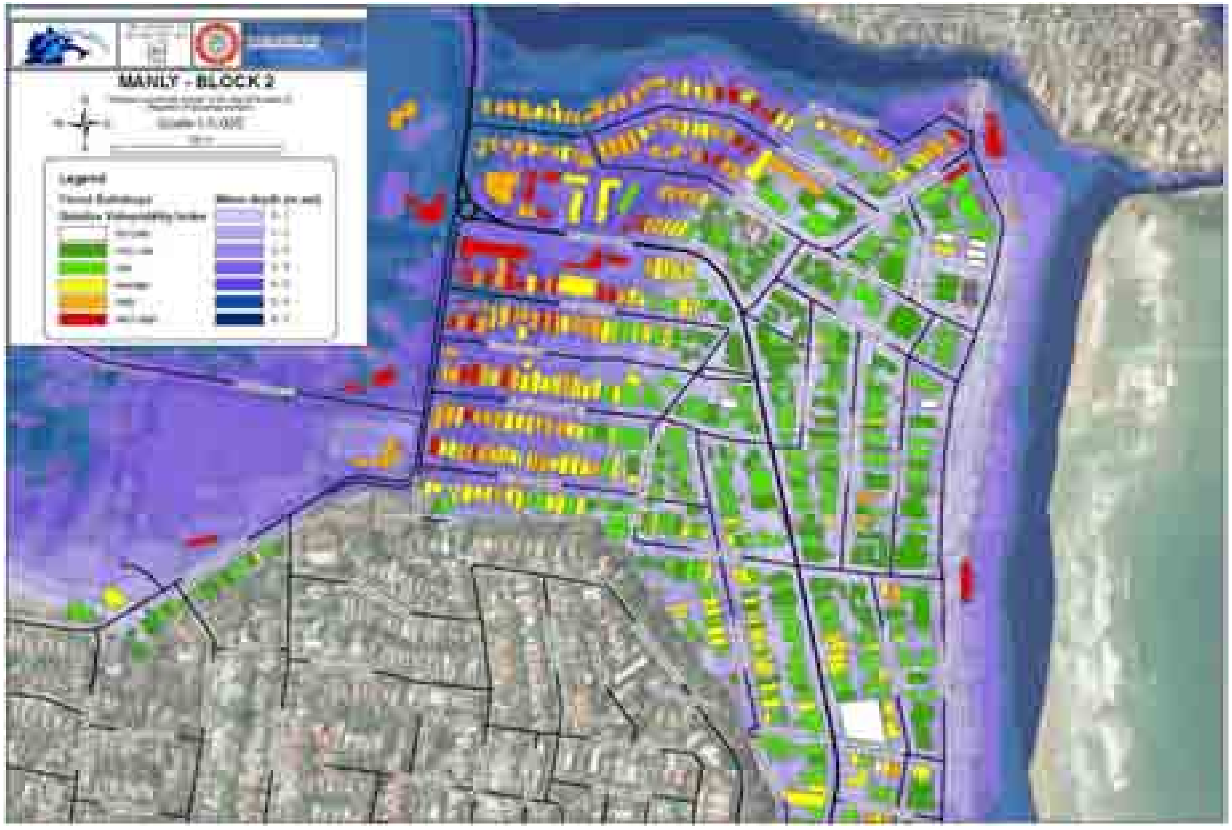


Figure 32. Inundation by the tsunami and the RVI scores in Block 2, Manly

Examination of Figure 32 shows that a relatively large area of Block 2 would be inundated in our scenario. A large number of buildings of all types would be 'touched' by the flood water. This represents the total 'exposure' to potential damage during the

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[4] Please note that Blocks 1 and 2 overlap and as such, a number of individual buildings appear in both Block 1 and 2 maps. Users of this Report should be careful not to double count individual buildings if the data is used beyond the descriptions given in this Report.

hypothetical tsunami and it is clearly high. Figure 32 also displays the calculated RVI scores of each of the buildings located within the inundation zone. It can be clearly seen that a significant percentage of buildings are classified as having "High" and "Very High" RVI scores and most of these are located in the central and northwestern portions of Block 2.

### 3.3.2.2 Vulnerability of local government buildings

Figure 33 displays the calculated RVI scores of those few buildings in Block 2 that are the responsibility of the local government. Just 5 individual buildings are the responsibility of local government. It can be seen that all these buildings have been classified as having "High" and "Very High" RVI scores.

**Figure 33. The distribution and final vulnerability classification of government owned-managed buildings in Block 2, Manly**

### 3.3.2.3 Vulnerability of buildings related to health and medical services

Figure 34 shows the calculation of the RVI scores and the spatial distribution of those buildings in Block 2 that relate to the health and medical services sector. One building is classified as having a "Very High" RVI whereas the others have an average or lower RVI score.

Figure 34. The vulnerability of health and medical services buildings in Block 2, Manly

### 3.3.2.4 Vulnerability of buildings related to education

Figure 35 shows the RVI scores of the small number of education buildings located within the inundation area of Block 2. These buildings have a mix of vulnerability but one, (which is a school) has a “High” RVI score.

Figure 35. The vulnerability of education buildings in Block 2, Manly

### 3.3.2.5 Vulnerability of recreational and cultural buildings

Figure 36 displays the calculated RVI scores of the recreational and cultural buildings in Bock 2. As can be seen, the majority of these buildings have been assessed as having “High” and “Very High” RVI scores.

Figure 36. The vulnerability of recreational and cultural buildings in Block 2, Manly

### 3.3.2.6 Vulnerability of utility buildings

Figure 37 displays the calculated RVI scores of buildings belonging to the utilities of water, gas and electricity services in Block 2 located within the tsunami inundation zone. They have all been assessed as having “High” and “Very High” RVI scores in spite of being located some distance from the shore.

Figure 37. The vulnerability of utility buildings in Block 2, Manly

### 3.3.2.7 Vulnerability of transport system buildings

Figure 38 shows the calculated RVI score of the only transport system building located within the tsunami inundation zone of Block 2 (the RTA motor registry). It is classified as having a "Very High" RVI score.

Figure 38. The vulnerability of the transport system building, Block 2, Manly

### 3.3.2.8 Vulnerability of tourism buildings

Figure 39 shows the calculated RVI scores for and spatial distribution of those buildings associated with the tourism sector within Block 2. Of these, just one has been classified as having a “High” RVI score.

**Figure 39. The vulnerability of tourism buildings in Block 2, Manly**

### 3.3.2.9 Vulnerability of commercial buildings

Figure 40 displays the spatial distribution and calculated RVI scores for the commercial buildings located within the tsunami inundation zone of Block 2. Most buildings have been assessed as having either “Low” or “Very Low” RVI scores. However, a few buildings have been assessed as having “Average”, “High” or “Very High” RVI scores.

**Figure 40. The final RVI scores of the commercial buildings Block 2, Manly**

### 3.3.2.10 Vulnerability of residential buildings

Located within the tsunami inundation zone of Block 2, Manly are a large number of residential structures. Their spatial distribution and calculated RVI scores are displayed in Figure 41. 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 and initial point of inundation.

Figure 41. The RVI scores of residential buildings in Block 2, Manly

### 3.3.2.11 Overall observations

With regard to Manly Block 2, we make the following general observations:

- The central and seaward sections of Block 2 at Manly are very densely developed with buildings of mixed building class types. However, the vast majority of the buildings are private residences;
- At present, the western portion of Block 2 is not very developed and this area is occupied by the Manly Golf Course;
- All the LGA buildings presented in this area have been classified as “High” and “Very High” RVI. It is highly likely that Manly Council will wish to address the vulnerability of these structures;
- At present, all of the utility services, health and medical services, recreation and culture, transport and tourism buildings located within the inundation zone have also been calculated as having “High” and “Very High” RVI; and
- A relatively large number of residential structures are present within the inundation zone and many of these have been classified as having “High” and “Very High” RVI scores. It is not clear from our work if any of these residential properties are associated with public housing or if they are all privately owned.

## 3.3.3 Manly Block 3

This block is centered around the administrative and commercial heart of the Manly local government area.

### 3.3.3.1 Inundation and exposure

The area of Manly Block 3 inundated by the tsunami in our scenario is shown in Figure 42[5].

**Figure 42. Tsunami inundation and RVI scores in Block 3, Manly**

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[5] Again, 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 42 indicates that a relatively large area of Block 3 would be inundated in our scenario. Significantly, 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 'touched' by flood water. This represents the total 'exposure' to potential damage in our scenario. Figure 42 also displays the calculated RVI scores for each of the buildings located within the inundation zone.

### 3.3.3.2 Vulnerability of local government buildings

Figure 43 shows the calculated RVI scores and the spatial distribution of those local government buildings present within Block 3, Manly. Of these, just two are classified as having "Very High" RVI scores. One is the South Manly Surf Life Saving Club, and the other is a public seating structure on the promenade.

Figure 43. The distribution and final RVI scores of government buildings in Block 3, Manly

### 3.3.3.3 Vulnerability of buildings related to health and medical services

Figure 44 displays the spatial distribution and calculated RVI scores of the health and medical services buildings located within the Block 3 area. Just one building has been classified as having an “Average” RVI score. The others have “Low” and “Very Low” RVI scores.

**Figure 44. The RVI scores of health and medical services buildings in Block 3, Manly**

### 3.3.3.4 Vulnerability of buildings related to education

Within the Block 3 area of Manly, just a handful of buildings are associated with the education sector. Figure 45 shows the calculated RVI scores for these buildings and their locations. It can be seen that three of them have been classified as having “Average” RVI scores.

**Figure 45. The RVI scores of health and medical services buildings in Block 3, Manly**

### 3.3.3.5 Vulnerability of recreational and cultural buildings

Within the Block 3 area of Manly, a relatively small number of buildings are associated with recreation and cultural activities. Figure 46 shows the calculated RVI scores of each of these buildings and their locations. One third of these buildings have been assessed as having "Average" RVI scores and the rest are classified as "Low" and "Very Low" RVI.

**Figure 46. The vulnerability (RVI) scores of recreational and cultural buildings in Block 3, Manly**

### 3.3.3.6 Vulnerability of utility buildings

A very small number of individual buildings belonging to the utilities sector are present within the tsunami inundation zone of Block 3. The locations and RVI scores of these buildings are displayed in Figure 47. Of these, one building is classified as having a “High” RVI score. The remaining buildings have all been assessed as having lower RVI scores.

**Figure 47. The RVI values of the utility buildings in Block 3, Manly**

### 3.3.3.7 Vulnerability of transport system buildings

Within the Block 3 study area of Manly, only a small number of buildings are related to the transport services sector. Of these, the most significant is Manly Wharf located on the harbour side of the inundation zone. Figure 48 displays the calculated RVI scores of these buildings and their exact locations. The only problematic building structure is Manly Wharf which has been classified as having a “Very High” RVI score.

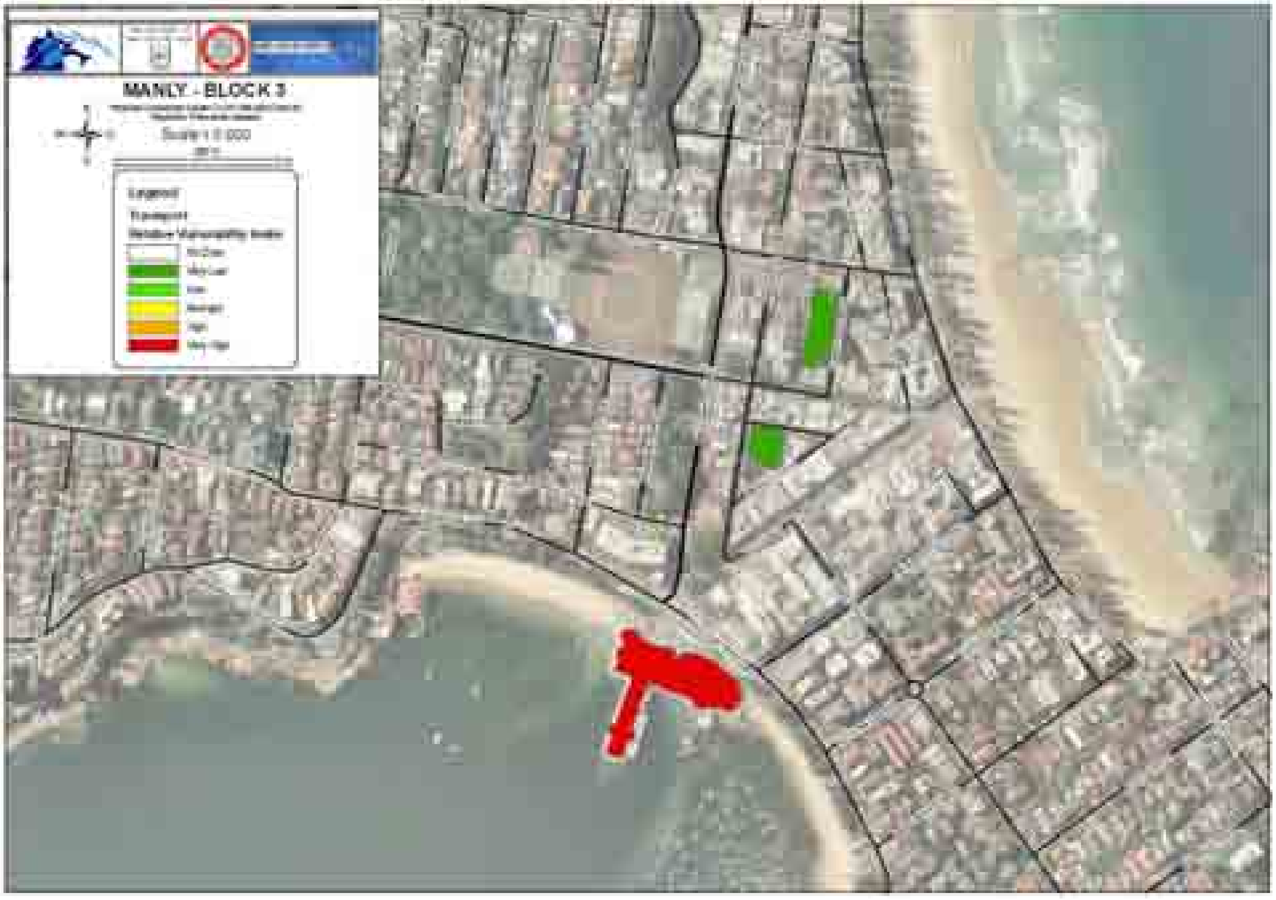

Figure 48. The vulnerability (RVI) scores of transport system buildings in Manly Block 3

### 3.3.3.8 Vulnerability of tourism buildings

Manly is an iconic Australian tourism destination and this importance is reflected in the relatively large number of tourism related buildings located within the Block 3 area of Manly (Figure 49). Of these, just one (the Tourism Information Office outside Manly Wharf) has been classified as having a “High” RVI score. The remaining buildings have all been classified as having “Average” or lower RVI scores.

**Figure 49. The RVI values for the tourism buildings located within Block 3, Manly**

### 3.3.3.9 Vulnerability of commercial buildings

Since Block 3 incorporates the commercial heart of Manly, it has the highest number of commercial building structures of any part of this study. Their distribution and calculated RVI scores are shown in Figure 50. It should be noted that Manly Wharf appears under this classification as well as the transport sector since individual commercial business operators are located within the wharf structure. These individual business operators have been joined together as a ‘single’ business within our analysis. Of all of the commercial buildings present in Block 3, just three have been classified as having “Very High” RVI scores and just one was classified as having a “High” RVI score. The remaining buildings have been assessed as having RVI scores of “Average” or lower.

**Figure 50. The vulnerability of commercial buildings in Manly Block 3 according to their RVI scores**

### 3.3.3.10 Vulnerability of residential buildings

There are a moderately large number of residential buildings within Block 3. Due to the nature and character of Manly, most residential structures in Block 3 are actually multi-dwelling, multi-story buildings rather than separate houses. The exact location and calculated RVI scores for each of these residential buildings is shown in Figure 51. The vast majority of these residential structures have been assessed as having “Average”, “Low” and “Very Low” RVI scores. Only a small number of buildings are assessed as having “High” RVI scores.

Figure 51. The RVI scores of residential buildings in Manly Block 3

### 3.3.3.11 Overall observations

In regard to Manly Block 3, we make the following general observations:

- The entire commercial heart of Manly would be inundated by the tsunami associated with this scenario;
- The South Manly Surf Life Saving Club building has been assessed as having a “Very High” RVI score and given its importance as a community building, this should potentially be addressed;
- A relatively large number of commercial structures are vulnerable to one degree or another;
- The Manly Wharf structure is highly vulnerable to tsunami damage and as the most significant transport structure, should probably be the focus of appropriate risk mitigation activities;
- We are uncertain whether those residential structures classified as “High” and “Very High” RVI are public housing or private residences.
- There are no problems with buildings associated with health and medical services and education
- Some attention needed to the sectors of utility, transport and tourism

### 3.3.4 Manly Block 4

Block 4 overlaps with the southern part of Block 3 and extends eastwards incorporating low-lying building structures clustered around Bower Lane and Shelly Beach in the Cabbage Tree Bay area.

#### 3.3.4.1 Inundation and exposure

The total area of Block 4 inundated in our scenario is indicated in Figure 52.

Figure 52. The inundation of Block 4, Manly

Examination of Fig 52 indicates that a relatively large area of Block 4 would be inundated during our scenario – mostly towards the commercial centre of Manly (which was presented in Section 3.3.3). A moderately large number of buildings of all types would be ‘touched’ by flood water during this event. This represents the total ‘exposure’ to potential damage. Figure 52 also displays the calculated RVI scores of each of the buildings located within the inundation zone.

### 3.3.4.2 Vulnerability of local government buildings

Figure 53 shows the calculated RVI scores of the small number of buildings in Manly Block 4 that are the responsibility of local government. Two of these buildings has been classified as having “Very High” RVI scores – the Manly Surf Life Saving Club (both dealt with by the analysis of Block 3 structures) at the southern end of Manly Beach and a shelter structure on the main South Steyne Promenade.

**Figure 53. The distribution and final RVI scores of local government buildings in Manly Block 4**

### 3.3.4.3 Vulnerability of buildings related to the health and medical services

Figure 54 displays the distribution and calculated RVI scores of those buildings in Block 4 that relate to the health and medical services. One structure is classified as having an "Average" RVI score whilst the others have lower RVI scores.

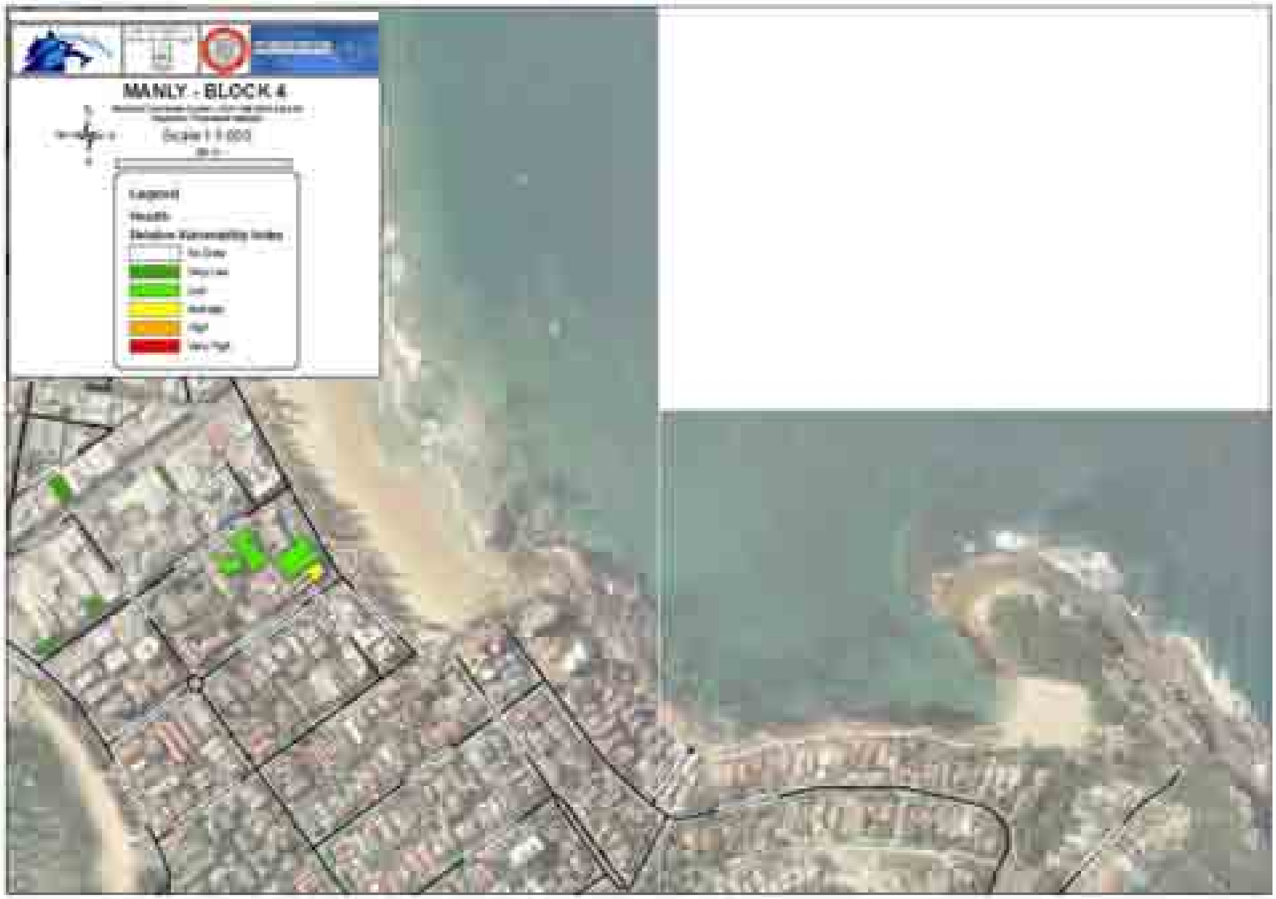

**Figure 54. The RVI scores for health and medical services buildings in the Manly Block 4 area**

### 3.3.4.4 Vulnerability of buildings related to education

Figure 55 displays the distribution and calculated RVI scores of the small number of buildings within Block 4 that relate to the education sector. Three of these are classified as having “Average” RVI scores.

**Figure 55. The vulnerability of the education buildings in the Manly Block 4 area**

### 3.3.4.5 Vulnerability of recreational and cultural buildings

Figure 56 displays the calculated RVI scores and spatial distribution of the small number of recreational and cultural buildings in Manly Block 4. Of these, two are classified as having “Average” RVI scores.

Figure 56. The vulnerability of recreational and cultural buildings in Manly Block 4

### 3.3.4.6 Vulnerability of utility buildings

Figure 57 indicates that only a very small number of individual buildings associated with the utilities sector are located within the Manly Block 4 area (5 of them fall below the legend, but they are visible in Block 3,Figure 47). The visible building is an electric station and it has been classified as having an "Average" RVI score.

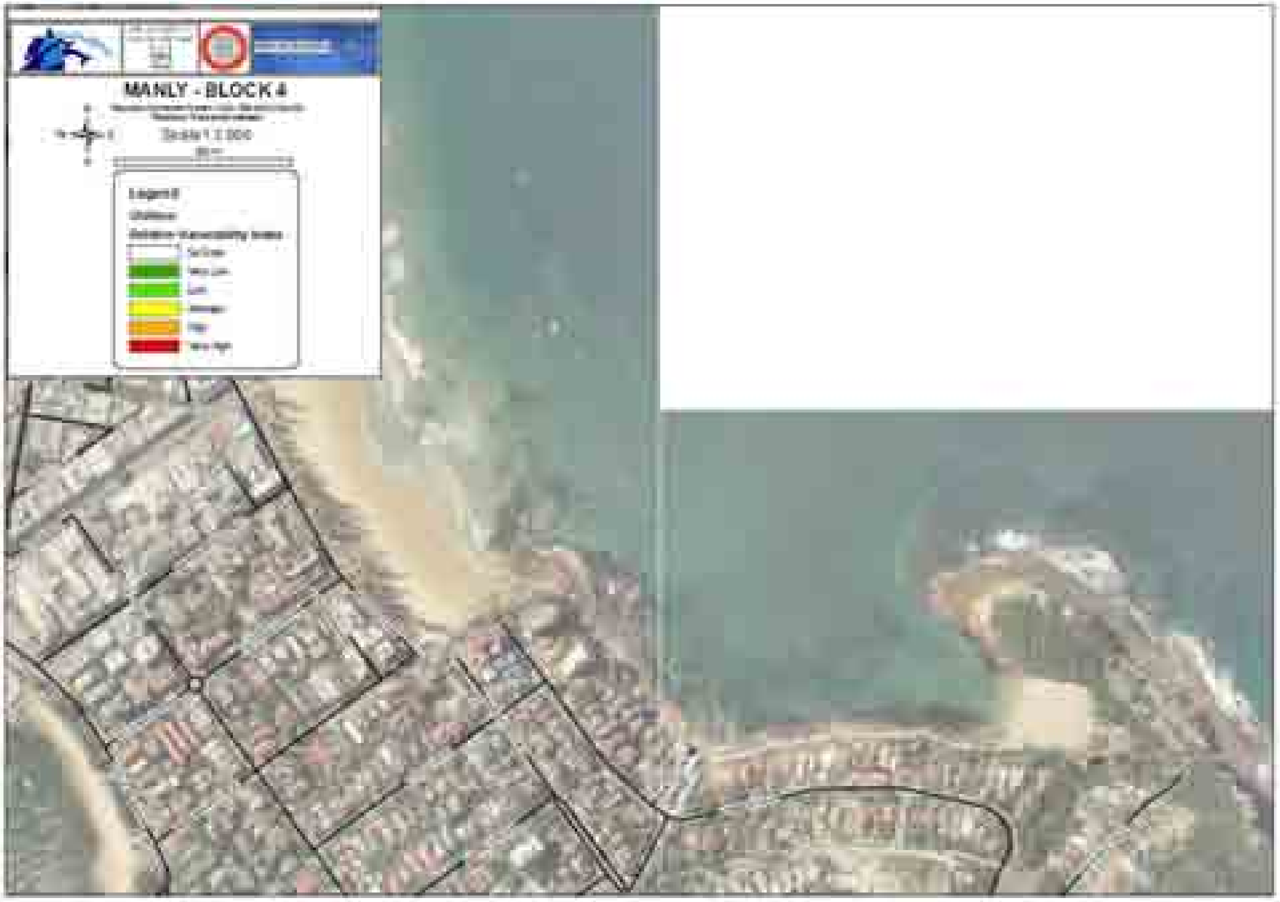

Figure 57. The vulnerability of utility buildings in Manly Block 4

### 3.3.4.7 Vulnerability of transport system buildings

Figure 58 shows the calculated RVI scores and spatial distribution of the extremely small number of transport related building structures located within the Block 4 area of Manly. One of them is located behind the legend, but it can be seen in Block 3, Figure 48). Just one building - Manly Wharf has been assessed as having a “Very High” RVI score.

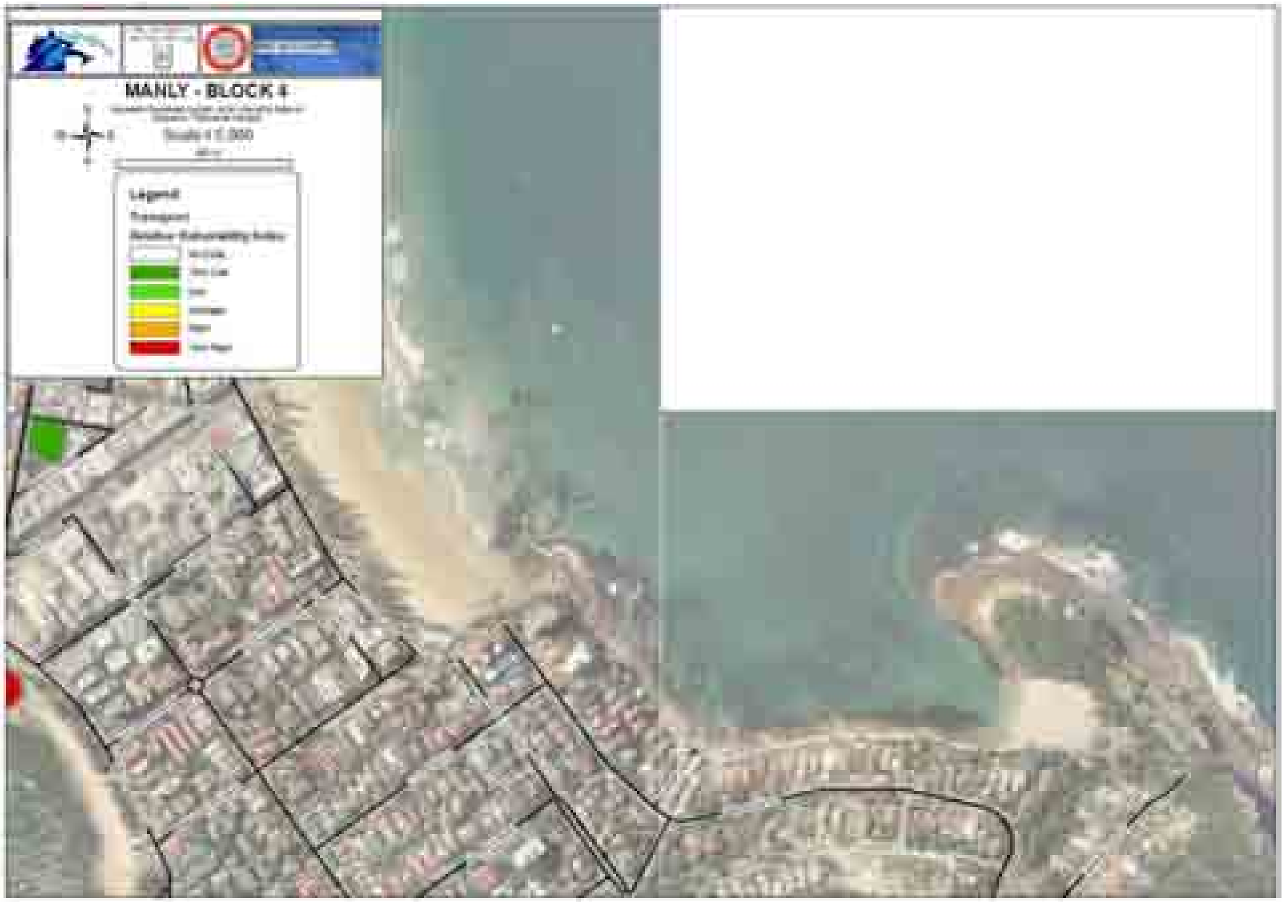

**Figure 58. The vulnerability of transport system buildings in Manly block 4.**

### 3.3.4.8 Vulnerability of tourism buildings

Figure 59 displays the spatial distribution and calculated RVI scores for the relatively small number of tourism related buildings located within the tsunami inundation zone of Manly Block 4. They have all been assessed as having “Average”, “Low” and “Very Low” RVI scores**.**

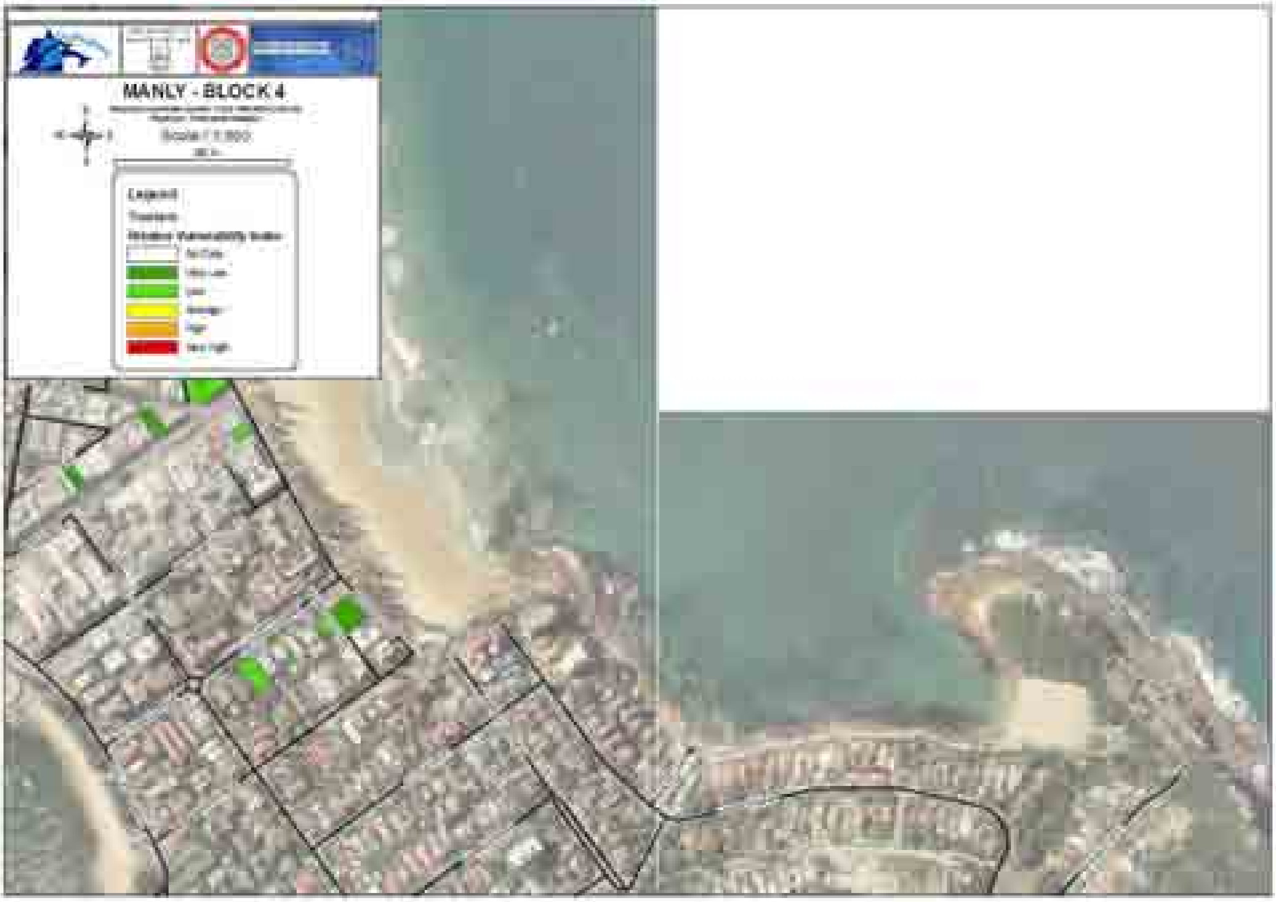

**Figure 59. The vulnerability of tourism buildings in Manly Block 4**

### 3.3.4.9 Vulnerability of commercial buildings

Figure 60 displays the calculated RVI scores and spatial distribution of the moderately large number of commercial buildings in Manly Block 4 located within the tsunami inundation zone. Only 7 of them have been assessed as having “High” and “Very High” RVI scores.

Figure 60. The distribution and RVI scores of commercial buildings in Manly Block 4

### 3.3.4.10 Vulnerability of residential buildings

Figure 61 shows the spatial distribution and calculated RVI scores for the relatively large number of residential buildings located within the Manly Block 4 tsunami inundation zone. The vast majority of residential structures are classified as having “Average”, “Low” or “Very Low” RVI scores.

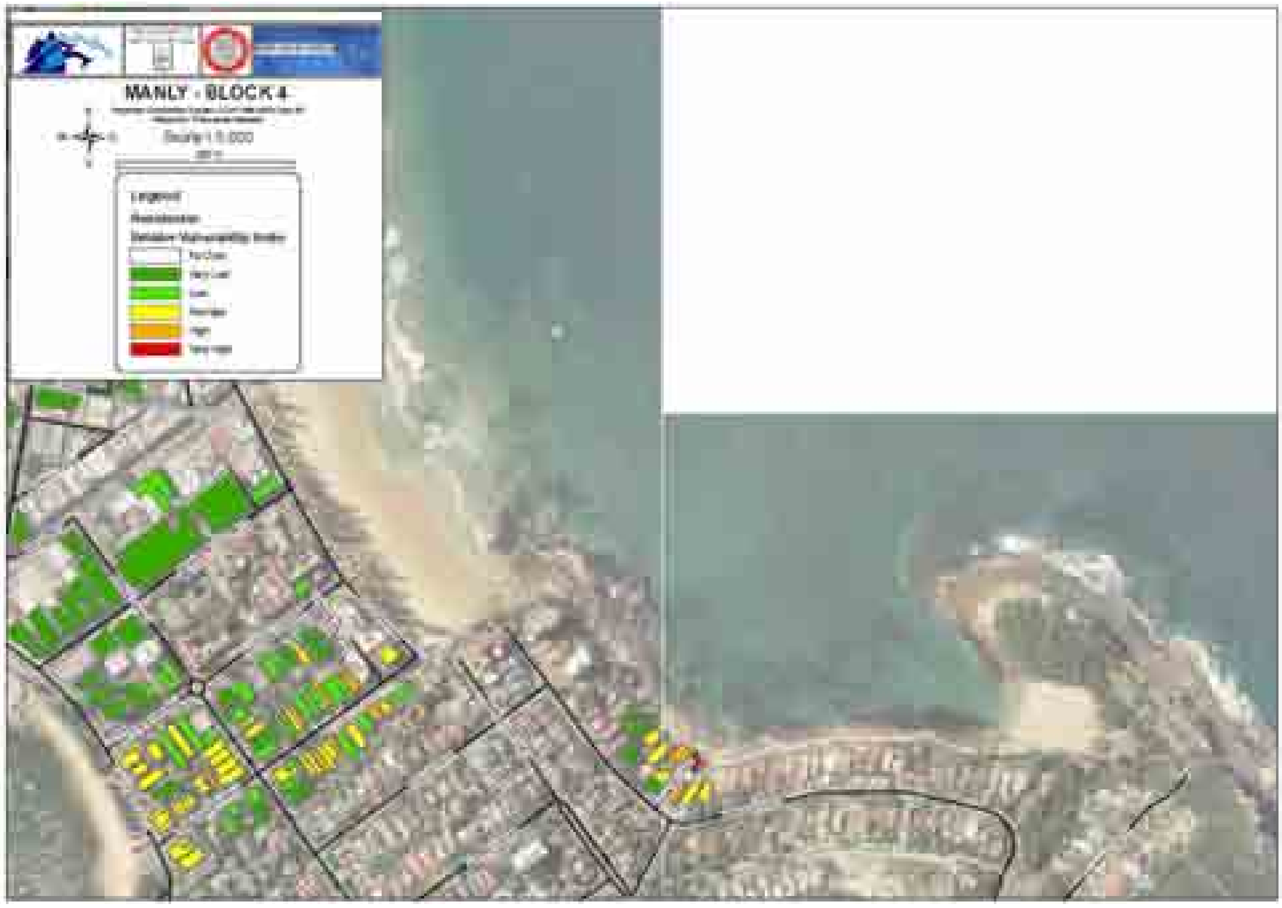

**Figure 61. The distribution and calculated RVI scores of residential buildings in Manly Block 4**

#### 3.3.4.11 Overall observations

With regard to Manly Block 4 we make the following general observations:

- A relatively large area of Manly Block 4 would be inundated by a tsunami associated with our scenario (although only a modest number of buildings would be inundated and most of these overlap with those at the southern end of Block 3 and have as such, already been considered).

### 3.3.5 Summary of Relative Vulnerability Index scores for Manly

To assist readers with understanding the absolute number of buildings with different RVI scores by building class type, Table 9 provides a quick look summary. The "take home message" from Table 9 is that commercial and residential structures have the highest absolute number of buildings assessed as having "High" and "Very High" RVI scores.

**Table 9. Summary of the total number of buildings by building class type and the number of buildings according to their Relative Vulnerability Index score in Manly. Please note that each building may have more than one use**

| 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 | - | - | - | - | - |

# 4 DISCUSSION and RECOMMENDATIONS

**SECTION SUMMARY – In this section we discuss our fundamental understanding of the risk to the coast of New South Wales from tsunamis and re-examine the scenario we have used. We discuss in general terms the method we have applied and its associated challenges, specific issues arising from each case study location and more general issues common to both study sites. We acknowledge the limitations of this work before making a series of recommendations**

## *4.1 The foundations of the study*

We begin the Discussion by returning to the foundations of this study – namely, the actual risk to the coast of New South Wales (NSW) and the scenario we have developed and used.

The historic record of tsunami impacting NSW (Appendix 2) clearly shows that numerous small tsunamis have occurred since European occupation of the region. Consequently, some *hazard* associated with tsunamis exists. The disjunct between the known historic record and the proposed geological evidence for much larger palaeotsunamis during the last 10,000 years however, is not easy to explain. Further plaeotsunami research work is an imperative to resolve this disjunct and test the validity for the claims of palaeo- megatsunamis. Given the absence of any published probabilistic assessments of tsunami risk for the coast of NSW, it is currently not possible to state with any degree of confidence, what the actual *risk* is to the region of Sydney considered in this study.

We are aware that at the time of writing, probabilistic tsunami hazard assessments (PTHA) of tsunami are being undertaken for NSW and when available, the estimates of tsunami amplitude in shallow water close to shore, or ideally, the inundation forecast onshore, should be taken in to consideration when thinking about the likely effects on coastal infrastructure, buildings and people.

Not-with-standing the difficulty with the reported geological evidence for past tsunamis and the absence of PTHA's, the recent marine survey work of Geoscience Australia (Glenn *et al*., 2008) provides the most compelling evidence for potential sources of locally generated tsunamis that could impact the coast of NSW. That said and as Glenn *et al*., (2008) acknowledge in their report, further work needs to be undertaken to better constrain the ages and sizes of these submarine sediment slides off the continental shelf. Such work will increase our confidence in assessing the potential of such events for generating local tsunamis.

If it is assumed that the work of Glenn *et al.,* (2008) is reasonable (which it certainly appears to be), then submarine sediment slides are the most likely cuase of local tsunamis. Therefore, our scenario for this study remains valid and probably lies at the 'conservative' end of what could be expected for a local tsunami. For example, if a large low-pressure cyclonic system were centred over Sydney at the time of the tsunami, that coincided with a king tide – the maximum run-up might well be much higher than used in our scenario. Further, in our scenario we assume present mean sea-level. If the scenario event were to occur 50, 100, 150 years in the future, sea-level associated with climate change would be higher – compounding the maximum expected run-up. Lastly, in our scenario, we assume the tsunami wave strikes the coast parallel to the shore and that only a single wave inundates the coast. In reality, it is much more likely that two or more individual tsunami waves would impact the coast and, as you move away from the point source of the event, so the tsunami would strike the coast at different angles. Our scenario also fails to consider the likely impacts of tsunami back-wash as the wave runs back out to sea. Clearly, such a wave would be full of building debris, cars and other objects that are capable of causing further damage to buildings. Our model and approach does not take in to account any of these possibilities.

We have worked hard to make improvements to the PTVA Model of Papathoma (2003) (see Dall'Osso *et al.,* in review). We have been able to introduce several important new elements to the PTVA Model based on recently published results of investigations of the impacts and effects of the 2004 Indian Ocean tsunami on urban environments across the Indian Ocean region. These improvements increase our confidence that the PTVA Model is an appropriate framework for providing first order assessments of the vulnerability of buildings in the absence of fully validated building fragility (damage) curves.

Whilst we have been able to up-grade the PTVA Model, the PTVA Model still does not include a sediment/debris entrainment component that would reasonably be expected to affect the degree of vulnerability of buildings. However, we integrated in the model a more accurate description of protection that is provided to each building by other structures and natural barriers, which were proven to be very effective in trapping debris and sediment. Further, we made the assumption the flow velocity is a direct function of the water depth, based on Fritz *et al.* (2004), but a much more accurate knowledge of the pressure applied on each building surface could arise from an hydrodynamic simulation of the inundation of the study area. Also, we assumed the direction of the flow to be perpendicular with respect to the shoreline, which is a model limit, especially where the ground slope and topography are very heterogeneous and there are obstacles that can deviate the flow. Again, this limitation could be overcome with a numerical simulation of the flooding.

In Section 2.4, we provided details about how we integrated different datasets to construct and run the model assessments. It is clear that this model is data 'hungry'. Information (values) for many different building and environmental attributes are needed in order to make a realistic assessment of the vulnerability of a building structure. If any of these attribute (values) are missing, then the quality of the final assessment will be reduced. In fact, some values are critical (e.g., flow depth above the ground surface) and without them the model cannot be run.

The two biggest challenges we faced were: (1) to obtain an accurate data about building footprinst from available information at the Council's GIS office; and (2) how to collect building attribute data not available from local government?

We know it is very uncommon to find all the data we needed in a LGA GIS office, because our datasets had been specifically designed for tsunami risk analysis. However, most of the essential elements, such as aerial photographs and Digital Elevation Models (DEM) were available at both Councils offices. Moreover, the Council of Manly provided us a DEM derived shapefile of all the building roofs. This file let us save a lot of time, even if it needed to be significantly modified to be converted into buildings footprints.

With regard to building attributes, none of the required data was available at Manly and Maroubra Coucils. We extracted from the aerial photos a little part of the data we needed, but we had to go on the field to get the largest part of them (such as the construction material, number of stories, the type of groundfloor, etc.).
We undertook a labour intensive, time consuming building-by-building surveys. This was difficult, but we needed such data to be able to undertake our assessment. In this project, this was achievable since in the worse case of Manly, we were only dealing with some 1100+ buildings and we could draw upon a large natural hazards research group (at UNSW) to assist. We acknowledge that such efforts will not be possible in all circumstances where the approach used by us is to be employed.

The results of this study clearly show two very different vulnerability conditions for Manly and Maroubra. Since the average topographic elevation in Manly is much lower, the inundated area is significantly larger than in Maroubra by a factor of 6 (169.47 ha at Manly versus 27.4 ha in Maroubra). As a consequence, the number of inundated buildings in Manly exceeds 1100, while in Maroubra just 96 buildings would be flooded.
.

## 4.2 Maroubra

Our analysis for the Randwick LGA only covered a small area of coastal foreshore and exposure was very low. This gives the impression that the risk is very low – which it is (relatively speaking) in the area we examined in this study. If our approach was applied elsewhere in the Randwick LGA or when building development (and exposure) had changed, the results of an assessment like ours might be considerably different.

To our mind, the only problematic structure in the Maroubra study area is the ambulance station at the corner of Mons Avenue and Fenton Avenue (Figure 14). Given the current day-to-day, and the potential future importance of the station to responding during a tsunami event, the fact that the station building has been assessed as having a “High” RVI score should be regarded as an issue worth addressing.

The ‘take home message’ for the Maroubra are of the Randwick Council is that the undeveloped area behind the present ocean beach should remain so. At the moment, that area is zoned as “open space for public recreation”. There probably are, and certainly will be in the future, pressures to develop this area for uses requiring permanent occupation (i.e. residential or commercial structures). These pressures should be resisted (as far as possible). Further, if minor development consent is given, it would be preferable to build an amenity block and great care should be taken to the zoning and building codes/standards and materials of the buildings approved for construction in order to ensure they are constructed with the minimum vulnerability possible.

## 4.3 Manly

The *risk* to Manly (that is, the probability for damage and loss) associated with the tsunami in our scenarion is very large indeed. The total surface area covered by floodwater would be large and a significant number of buildings 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 escape some degree of damage.

With regard to the residential buildings located in Block 2, Manly (Figure 41), it is apparent that most structures closer to the sea are in fact, assessed as having 'lower' RVI scores than those further inland. For many this will be counter intuitive but the lower vulnerability of these structures is because generally speaking, they are much newer than those located farther away from the shoreline, are in better condition and have been built to newer, higher standards and specifications.

Manly Wharf is a critical piece of (transport) infrastructure that is intensely used by large numbers of people both travelling in to and out of Manly and by people utilising the commercial businesses located at the wharf. Our feeling is that some considerable effort should be given to considering how to deal with large numbers of people using the wharf during an emergency event given its "Very High" RVI score.

Manly Council might wish to consider what (if anything) it can or should do in partnership with commercial business operators and owners of residential property assessed as having "High" and "Very High" RVI scores for their buildings. Council may find it prudent to explore its legal responsibilities in relation to risk and tsunami and how (if at all) that risk is communicated to business and property owners

## 4.4 General issues common to both Maroubra and Manly

As in most situations, avoiding a problem in the first place is always better that dealing with the consequences. In light of this generality, we advocate that wherever possible, both Manly and Randwick Council's should avoid unnecessary further development of open spaces that are currently not built upon – e.g., Manly Golf course or the Arthur Bryne Reserve. As exposure increases, inevitably, so too will losses when (if) an event occurs in the future.

We are aware that it is unrealistic to expect local government authorities to prevent future development (and redevelopment) of coastal areas. However, wherever possible keeping such development to a minimum will help. Very large damaging tsunamis are 'difficult' to forsee along the coast of NSW based on historic events and the proposed but controversial geological evidence. However, with climate change a reality, future sea-level rise, increasingly intense storms and coastal floods will only increase the vulnerability of and risk to coastal infrastructure regardless. Therefore, exercising a precautionary principle in relation to tsunami risk – coupled with risk associated with climate change seems appropriate.

Where permissions for development in low-lying coastal areas that could be affected by tsunamis are granted, council should consider the latest available information in relation to building codes and standards. Generic guidelines for structures in terms of floor layouts, heights of builbings, numbers of floors, material, orientation and so forth are available. We are not qualified to make judgements or recommendations about such design guidelines but we draw the attention of relevant decision makers to such codes and standards. We could however, participate as part of an "Expert Advisory Group" to oversee the development of guidelines for Council. As a minimum however, we would suggest that for residential structures to be located in the lowest lying areas close to the coast – single story buildings made of wood or fibro such be completely avoided.

There is some confusion about the value of protection offered to building structures by natural vegetation at the coast. However, as a rule of thumb, vegetation and natural features such as sand dunes do act as 'buffers' against the hyraulic forces of inundation. As such, wherever possible, we encourage local councils to protect and enhance their existing natural coastal features and vegetation. A coincidential advantage of improving such 'natural' features is that they contribute to a wide range of ecosystem goods and functions (services) upon which human and non-human communities are dependent.

Both local government areas we examined in this study have buildings that have been assessed as having "High" and "Very High" RVI scores - Manly in particular. To verying degrees, Council is either directly responsible for the upkeep and condition of these buildings, or in an indirect way, has a vested interest in those buildings being well maintained (e.g., of medical and health service, utility or transport buildings). Therefore, in some instances, Council will either need to directly examine how, if at all, those structures can be modified to reduce their vulnerability or work with the relvant owners of those buildings to improve resilience.

We are especially concerned to see 'critical' buildings such as schools, ambulance stations, surf life saving clubs, utility and government buildings assessed as having "High" and "Very High" vulnerability. The operations undertaken inside such structures are vital to the regular functioning of communities and business of council. For the priotection of occupants and for ensuring business continuity for critical functions, emergency plans should be developed that identify how normal ioperations would continue if the building in question was severely damaged or destroyed.

We recognise that most residential structures are in fact privately owned buildings. That said, some will be public housing. We do not know however, which 'residential' properties are owned and operated for the public housing sector and as such are unable to offer help or advise about these structures. From a risk management perspective however, those responsible for public housing may need to explore the implications of the vulnerability assessment to the security of their tennants.

Local council is not directly responsible for private residential property. However, the local unit of the State Emergency Service may be interested in knowing the vulnerability of these residential structures and working with local community to reduce the vulnerability of those structures if possible.

For residential buildings we know nothing about who the occupants are. For example, are they young or old? Is the first language of the people who live at home English? Will they understand emergency instructions given to them? Are they able bodied or is anyone at the home in need of particular assistance in the event of an emergency? Such questions were not explored in this study but other work (Bird and Dominey-Howes, 2006; 2008; Dominey-Howes, 2007) suggests that such issues are also critical in terms of reducing 'community vulnerability' to tsunami.

For buildings classified as tourism, recreaction and culture that are visited and used by a very wide variety of people (with different first languages and who may or may not know the areas they are in well), we have no idea if staff and guests to these buildings would know what to do in an emergency situation? Staff working within such buildings might need special training for preparation and assistance in responding to a developing event (Dominey-Howes, 2007b).

## *4.5 Limitations of this study*

We are aware of a number of limitations that affect this study. These include:

1. We have worked in a deterministic way. We have not used an actual probabilisitic event as the base line for the study. It could be argued that a determinsitic event is unrealistic. Whilst we acknowledeg this, we note that in the absence of a probabilistic tsunami hazard assessment from which we may select a probable event, our approach represents the best that can be done at the present time.

2. Our scenario is not the result of a numerical simulation of the flooding. The inundated area boundaries are given only by their topographical elevation. Also, we assumed that the flow velocity is a direct function of water depth and that flow direction is perpendicular to the shoreline, which are both approximations. A numerical simulation of the inundation could provide a more accurate scenario, and it is highly recommended once a probabilistic scenario will be available.

3. Our scenario is perhaps on the conservative side and in reality the 'event' would be much worse than described. Impacts would be complicated (made worse?) by sediment and debris entrainment in the flowing water and by debris-rich backwash flow. Each of these possibilities could make the vulnerability of buildings worse than assessed by us.

4. We have only worked with two case studies and one covers a very small area. This does not enable us to assess the likely affects of such an event on the Sydney metropolitan region as a whole.

5. Our research has focused on the vulnerability of building structures. It has not sought to explore the vulnerability of community, the local economy or the natural environment. As such, it only provides a small ‘window’in to the likely effects of a tsunami and perhaps arguably, avoids the most important element – people.

6. Since an individual building structure can have more than one use (e.g., on the ground floor it may be one or more businesses and on the upper floors it may contain residential apartments), it is not immediately easy to separate out and quantify the cost of a tsunami impact on different classes of building use. However, where buildings had more than one use, that was specified into the GIS dataset.

## 4.6 Recommendations

Based on the Results presented in Section 3 of this report and the preceding Discussion, we make the following recommendations.

***Recommendations for further research:***

**Recommendation 1** - Independent geological study of reported palaeo- megatsunamis should be undertaken to determine the validity of the Australian Megatsunami Hypothesis and better constrain the local tsunami hazard.

**Recommendation 2** - Probabilistic Tsunami Hazard Assessments (PTHAs) should be expidited. Further, they should be linked to inundation modelling to ensure forecase estimates of wave amplitudes are not given for water depth off-shore. Wave amplitudes MUST be brought on-shore to be meaningful.

**Recommendation 3** - Tsunami inundation modelling should be undertaken as a matter of urgency for selected key coastal locations of NSW including Sydney. These inundation models need to take account of the best available modelling science and datasets.

**Recommendation 4** - We advocate the need for the acquistion of detailed, high-resolution baythemtry to compliment available LIDAR datasests to permit appropriate tsunami modelling. Incidentially, such datasets will also be critical for storm surge modelling and sea-level rise forecasts and assessments.

***General recommendations:***

**Recommendation 5** - Local government authorities should work with relevant State and Federal government departments and agencies to enhance the quality, accuracy and coverage of their building inventory databases. High quality datasets are useful not just for tsuanmi risk assessment but also for a multitude of other development and planning applications and for the assesement of risk associated with other natural hazard processes such as storm surge, sea-level rise, coastal erosion and landslide and bushfire (amongst others).

**Recommendation 6** - We suggest the development of an "Expert Advisory Group" to explore and develop principles for land use zoning, building design codes and standards for the redevelopment/extensions in these already developed areas recognizing that management is the key issue for these existing areas..

**Recommendation 7** – This study and the method adopted by us should be 'rolled-out' across all LGA members of the SCCG Inc. and metropolitan region of Sydney – and other coastal LGA's in NSW and Australia as the need arises.

**Recommendation 8** – Surveys of the 'social vulnerability' of the community that lives, works and visits the study areas should be undertaken to compliment and extend our engineering focused work.

**Recommendation 9** – Both Manly and Randwick LGA's in partnership with their local units of the State Emergency Service should consider identifying and establishing evacuation routes and safe zones for evacuaees to meet. Such efforts should be part of a wider tsunami risk management plan for each local government area.

**Recommendation 10** – Local governments should resist wherever possible, applications for new development of undeveloped low-lying coastal areas.

***Precautionary Risk Management Recommendations for Maroubra:***

**Recommendation 11** - The ambulance station located at the corner of Mons Avenue and Fenton Avenue should be examined in order to identify ways of increasing its resilience. Such actions might include relocation out of the low-lying flood zone, improving building integrity and enhancing emergency plans for the building.

**Recommendation 12** - Large areas of low-lying foreshore area behind the Maroubra Beach including Broadarrow Reserve and Arthur Bryne Reserve are currently not developed and should remain so.

**Recommendation 13** - The Maroubra Surf and Life Saving Club on the beach would be inundated by one metre of water maximum. Even if damages are not expected to be very high, the inundation might put out of order the emergency equipment. Thus a part of it should be kept safe at the first floor, together with other important gear or documentation.

**Recommendation 14** – Until an appropriate Tsunami Emergency Plan is developed and agreed upon that includes suggestions for the best evacuation routes, we recommend that people living in Chapman, Mons and North Maxwell Avenues should evacuate westward, towards Malabar Road; those living in Fenton Avenue, McKeon Street and along the Marine Parade should evacuate northward towards Duncan and Hereward Streets and the roundabout at the north end of Marine Parade.

***Precautionary Risk Management Recommendations for Manly:***

**Recommendation 15 –** Manly Council should consider ways to engage with the owners of private residences to see how they can increase the resilience of their properties. This is especially so with private residential properties in Blocks 1 and 2 close to the northern end of our study area.

**Recommendation 16** - Until an appropriate Tsunami Emergency Plan is developed and agreed upon that includes suggestions for the best evacuation routes, we recommend that:

*Block 1:* people living in the buildings on Roseberry Street and Bangowlah Road are very close to the boundary of the inundation zone, so they should just walk towards the hill.

*Block 2:* evacuation of buildings located in Block 2 is much more complex because of the extent and depth of inundation and the distance from higher and safe areas. Buildings located inland close to the area of Bangowlah Road, would be affected by an inundation depth up to 5-6 metres, while those closer to the beach would be affected by only 1-2 metres. Therefore, people living inland and closer to the hills should evacuate on to the more elevated areas. People living closer to the lagoon would probably be too far from the hill to reach it safely. Also, the bridge connecting Manly to Warringah would not be available, because it would be flooded. As a consequence, the only safe points of evacuation for people living close to the lagoon would be the highest and least vulnerable buildings close to the beach and in the area behind it. Figure 62 shows all buildings in Block 2 that can be considered as a safe point for evacuation (that is, they have an RVI score of "Very Low" and at least two floors of each of these buildings would be ABOVE the expected maximum flood height.

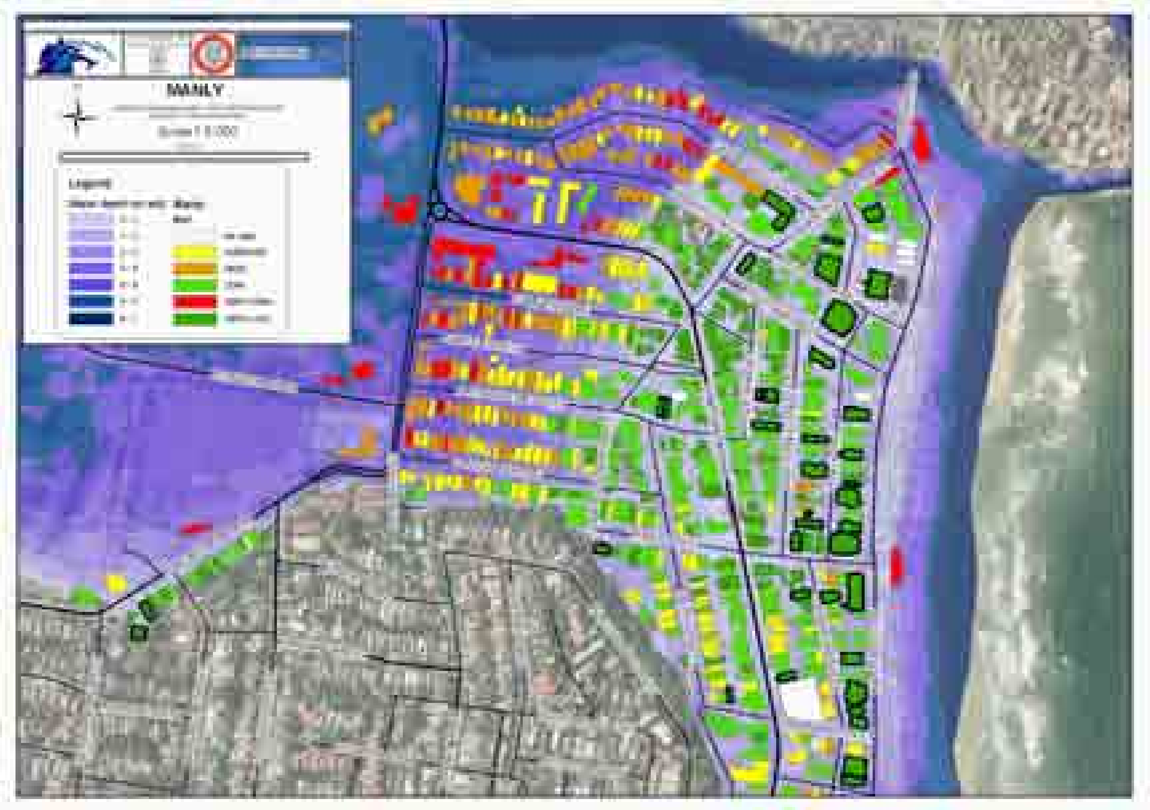

**Figure 62. Buildings in Block 2 that are considered safe for evacuation are circled with black. They are considered safe because they have an assessed RVI score of "Very Low" and at least two of their floors would be above the expected flood level**

*Block 3:* The proximity of Block 3 to higher (topographically elevated) areas makes evacuation much easier. We suggest that people living, working or visiting the north of the Corso evacuate on the northern hill along Sydney Road, while those to the south-east of the Corso should evacuate on to the South Manly promontory. Figure 63 also displays those buildings that we consider to be safe for evacuating to since they have been assessed as having "Very Low" RVI and at least two floors would be above the expected maximum flood level.

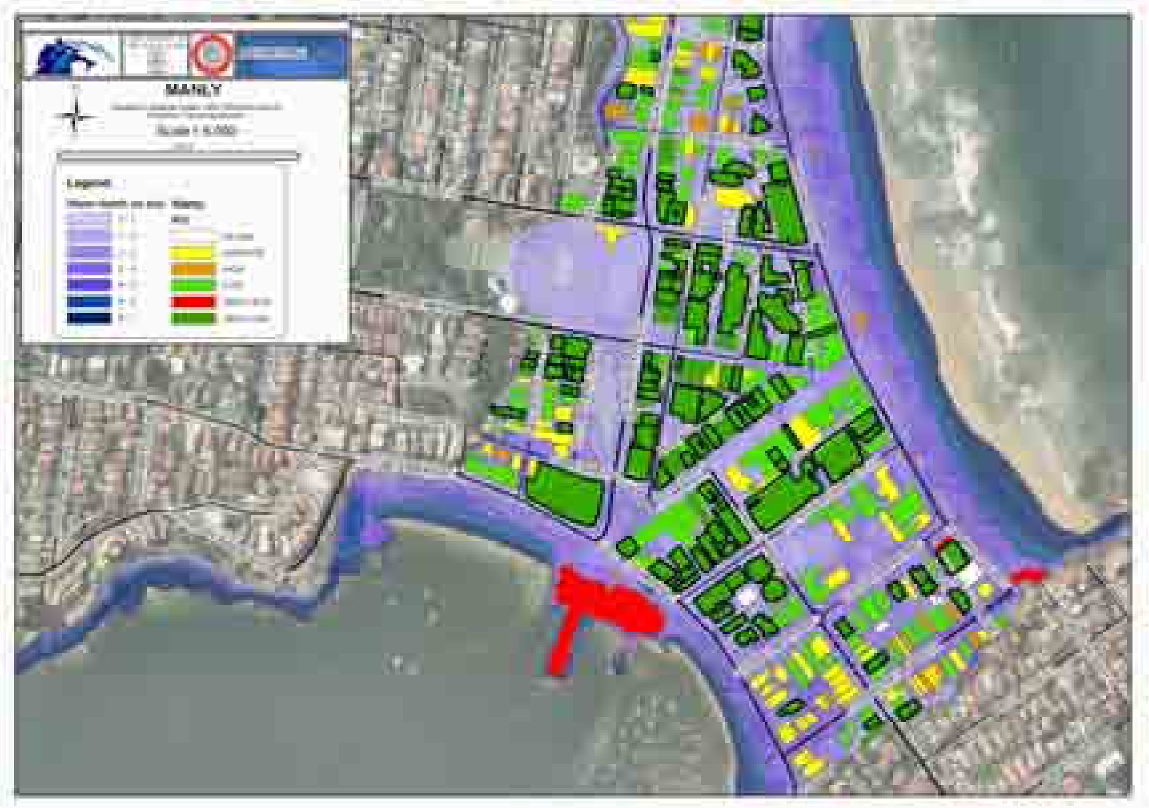

**Figure 63. Buildings in Block 3 that are considered safe for evacuation are circled with black. They are considered safe because they have an assessed RVI score of "Very Low" and at least two of their floors would be above the expected flood level.**

*Block 4*: Only a very small number of buildings are affected by tsunami inundation in the region of Bower Street and Shelly Beach in Block 4. It would be extremely easy for residents, shoppers and other visitors to the area to evacuate to higher ground near by.

# 5 CONCLUSIONS

**SECTION SUMMARY – In this section we go back to the study aims and verify that they have been achieved. We also discuss the reliability of the applied model, which to our knowledge, is the best available technique for assessing the vulnerability of buildings to tsunami.**

In light of the project undertaken by us and described herein, we draw the following general conclusions as they relate to the specific project aims listed on page 16:

1. We have been able to determine a credible worse case tsunami scenario to which we might explore the vulnerability of buildings. As such, we have achieved Aim 1;

2. We have worked successfully with the Sydney Coastal Councils Group Inc (SCCG) and Manly and Randwick LGA's to identify appropriate contrasting case stuies (Maroubra Beach and Manly Ocean Beach) for assessment. This fulfils Aim 2 of the study.

3. We have selected and improved an appropriate tsunami buildings vulnerability assessment tool. The PTVA-3 Model approach is based on the previously tested PTVA Method. The Papathoma Tsunami Vulnerability Assessment (or PTVA) Model was developed using detailed information about the impacts of historic tsunamis and the results of numerous post-tsunami surveys and building damage assessments (Papathoma, 2003; Papathoma and Dominey-Howes, 2003; Papathoma *et al.*, 2003). Also, after the catastrophic event of December 2004, the PTVA was validated using field surveys (Dominey-Howes and Papathoma, 2007). The attribute fields within the model were extremely well correlated with the type and severity of damage to building structures experienced during the Indian Ocean tsunami (at least where the PTVA Model was applied). Thus, the PTVA Model performed very well during a real-life field evaluation.

4. Our PTVA-3 Model was developed from the original PTVA Model and has been upgraded 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 because of the hydrodynamic forces during inundation AND from that associated with water intrusion. These two damage processes have been evaluated independently using a different set of sub-factors. The vulnerability to structural damage has been assessed by considering contributions of all the 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. PTVA-3 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 RVI are entered into a GIS, they can be retrieved, modified and kept up to date very easily. Also, GIS allows us to display results in many different ways, which will suit the needs of different types of stakeholders and decision makers. Together, points 3 and 4 mean we have achieved Aim 3.

5. Our partnership with the Manly and Randwick LGA's meant that with their help, we were able to collect the building data we needed to undertake the assessment of building vulnerability to tsunami. We therefore achieved Aims 4 and 5.

6. Using our revised PTVA-3 Model, we have been able to calculate a 'Relative Vulnerabiliuty Index' (RVI) score for every building located within the inundation zones for our scenario. The spatial distribution of the RVI scores of buildings has been displayed in a series of 1:5000 vulnerability maps. This addresses Aims 6 and 7.

7. At Maroubra, only 27 Ha of low-lying land would be inundated, with a maximum water depth of 3 metres. A total of 96 buildings would be touched by the water and none of these were found to have "Very High" RVI scores. However, a few of them are estimated to be highly vulnerable – including the ambulance station.

8. At Manly a total of 169 Ha of low-lying land would be inundated, and the water depth would reach a maximum of 7 metres in the area next to the lagoon. 1133 buildings would be flooded. In the southern end of our study area, the water would be able to flow through the Corso and reach the Manly Wharf on the harbour side. RVI scores showed that a large number of residential and commercial structures are highly vulnerable to damage and most of them are located in the lagoon area. Also, a number of Local Government and transport sector structures (such as the Manly Wharf) are assessed as being very vulnerable to damage.

9. In the absence of a fully validated fragility assessment model, the PTVA-3 was found to be very useful in helping to understand the vulnerability of building structures to damage from tsunami and in estimating PML's.

10. The main limitations of our approach include the approximation we adopted in the definition of the inundation scenario. Further, assumptions/limitations associated with the model include: the presence of debris and suspended sediment is not directly considered; we only consider flow depth and not velocity; the flow direction was assumed to be perpendicular to the shoreline.

11. We have been able to make a series of recommendations for further research work and for enhancing emergency risk management.

12. We recommend the application of the PTVA-3 for similar assessments across Australia and elsewhere and we suggest a repeat of our analysis in Sydney when a probabilistic tsunami assessment (complete with a more realistic inundation) becomes available.

# Appendix 1

## The Australian Tsunami Warning System (ATWS)

Following the devastating 2004 Indian Ocean tsunami, the Australian Federal Government decided to develop and deploy an operational Australian Tsunami Warning System (ATWS).

The Australian Federal Government committed $68.9M over four years to establish an Australian Tsunami Warning System to be fully operational by June 2009. This will include:

- Establishment of an Australian Tsunami Warning Centre (AusTWC) with 24/7 monitoring and analysis capacity for Australia;
- The upgrade and expansion of sea-level and seismic monitoring networks around Australia and in the Indian and South West Pacific Oceans;
- Implementation of national education and training programs about tsunami;
- Assistance to the intergovernmental Oceanographic Commission (IOC) in developing the existing Pacific Tsunami Warning & Mitigation System (PTWS) and establishing an Indian Ocean Tsunami Warning & Mitigation System (IOTWS); and
- Technical assistance to help build the capacity of scientists, technicians, and emergency managers in the South West Pacific and Indian Oceans.

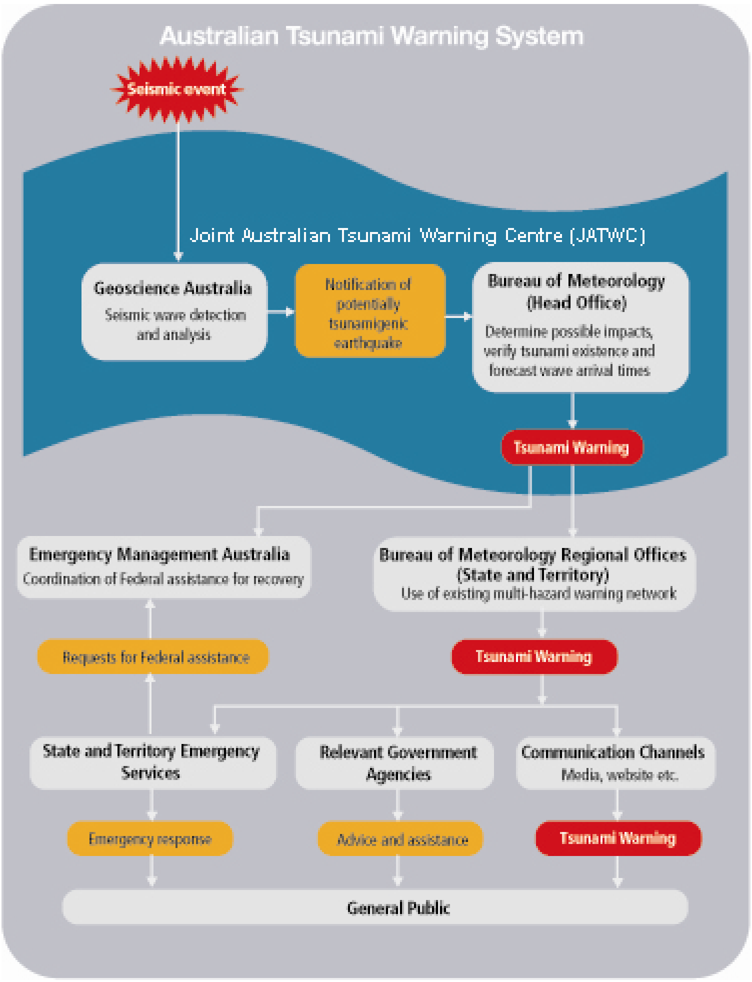

Figure A1.1 Organisational structure of the Australian Tsunami Warning System (Source: Geoscience Australia).

**How will the new ATWS work?**

Geoscience Australia will operate an enhanced network of seismic stations nationally and have access to data from international monitoring networks. It will advise the Bureau of Meteorology and Emergency Management Australia of the size, location and characteristics of a seismic event, which has the potential to generate a tsunami.

Based on this seismic information from Geoscience Australia, as well as advisories from the Pacific Tsunami Warning Centre (PTWC) in Hawaii and from neighbouring countries with tsunami detection capacity, the Bureau will run a tsunami model to generate a first estimate of the tsunami size, arrival time and potential impact locations. The Bureau will verify the existence of a tsunami using information from an enhanced sea-level monitoring network.

The Bureau will then promulgate advice and warnings on any possible tsunami threat to State emergency management services and the Public through its National Office in the first instance, and subsequently through its network of Regional Offices once a tsunami is verified. Emergency management agencies will then use this information to estimate coastal inundation using pre-generated inundation models prepared by Geoscience Australia.

Emergency Management Australia will liaise with the operations centres of affected State and Territory emergency management organisations and coordinate Federal assistance as required.

Emergency Management Australia also has responsibility for improving public awareness and preparedness for tsunami in Australia.

# Appendix 2

### Tsunami reported to have affected/impacted the coast of New South Wales (after Allport and Blong, 1995; Dominey-Howes, 2007)

| Event Number | Date | | | Source region D – Distant R – Regional L - Local | Cause & source of tsunami | Locations of impact in NSW | Max (*H*) (run-up); maximum wave height where recorded on a tide gauge; maximum water height given; distance of inundation | Comments and descriptions | TI | Rel | Information sources / references |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Year | M | D | | | | | | | | |
| **Palaeotsunami events (i.e., those occurring prior to European occupation of Australia in AD1788)** | | | | | | | | | | | |
| 1 | 105,000 years ago | | | D - Hawai'i | Submarine landslide (off of volcano) | Tura Head, NSW (150$^{o}$ 00" E, 36$^{o}$ 50" S) | *c.* 15 – 25 (?) m asl | Tsunami thought to have been generated by submarine sediment slides off Lanai, Hawai'i; last interglacial sand barriers almost completely destroyed……. Traces of erosional features observed on ramps | XII | 2 | Bryant (2001); Bryant and Nott (2001); Young *et al.*, (1992, 1993, 1996) |
| 2 | ~8,700 – 9,000 years before present | | | Unknown | Unknown | Kiola, NSW (150$^{o}$ 30" E, 35$^{o}$ 50" S); Tuross Head, NSW (150$^{o}$ 10" E, 36$^{o}$ 00" S); Steamers Beach, Jervis Bay, NSW) (150$^{o}$ 75" E, 35$^{o}$ 20" S) | Run-up at Steamers Beach reported at elevation of at least +100 m asl | "[at Kiola] Estuarine sandy mud buried under 2.3m of coarse beach sand and pebbles, which in turn is buried by 2.5m of dune sand", "[at Tuross Head] a train of large boulders which rises to an elevation of +8 m asl, ends in an extensive deposit of sand that is morphologically and pedologically distinct from the modern beach sand", "[at Streamers Beach] this deposit of sand and shell hash is undoubtedly of marine origin because is contains scattered pebbles and muddy lenses, and has numerous" sequences of flat bedding <2 m thick" | XII | 2 | Bryant (2001); Young et al (1996, 1997); |
| 3 | ~6,500 years before present | | | Unknown | Unknown | Bellambi, NSW (150$^{o}$ 90" E, 34$^{o}$ 35" S); Callala, NSW (150$^{o}$ 70" E, 35$^{o}$ 00" S) | Inundation up to 10 km inland at Shoalhaven Delta | "[at Bellambi] exposed grey sandy clay, containing estuarine shells, buried under a layer of orange , humate-rich sand, and a layer of grey sand. The orange sand contains boulders up to 40 cm in diametre, and a layer of cobble sized pumice clasts", "[at Callala] sand ridge overlying estuarine deposit" | XII | 2 | Bryant (2001); Young et al (1993, 1997) |
| 4 | ~3,000 years before present | | | Unknown | Unknown | Cullendulla, NSW (150$^{o}$ 10" E, 35$^{o}$ 70" S) | Run-up *c.* +1.5m asl, inundation approximately 1.5 km inland | "innermost sand ridges….. The shells in this deposit are from very mixed origins, including estuarine, rocky shoreline, open beach and continental shelf environments" | ? | 2 | Bryant (2001); Bryant and Nott (2001)<br>Bryant *et al* (1992); Young *et al* (1997) |
| 5 | ~1,600 – 1,900 years before present | | | Unknown | Unknown | Mystery Bay, NSW (150$^{o}$ 10" E, 36$^{o}$ 10" S); Cullendulla, NSW (150$^{o}$ 10" E, 35$^{o}$ 70" S); Cape St. George, Jervis Bay, NSW (150$^{o}$ 75" E, 35$^{o}$ 20" S); Sandon Point, NSW (151$^{o}$ 00" E, 34$^{o}$ 30" S) | Minimum run-up for this event is +5.7m asl; deposits located along 240 km stretch of coastline | "[at Mystery Bay] mound of cobble and shell….. eroded remnant of another, almost identical deposit….. also consists of cobbles and shell, but the cobbles are significantly larger….", "[at Cullendulla] the sixth sand and shell ridge at this location which rises to elevation of 4m asl and is 500 metres inland…. Probably formed by a tsunami", "[at Cape St. George] very large boulders have been carried northwards through a wide channel cut across the shore platform surface at an elevation of about 5m asl", "[at Sandon Point] deposit containing sand, shell and boulders" | ? | 2 | Bryant (2001); Bryant *et al* (1992a); Young *et al* (1997) |
| 6 | ~500 - 900 years before present | | | Unknown | Unknown | Cullendulla, NSW (150$^{o}$ 10" E, 35$^{o}$ 70" S); Shelly Point, Kioloa, NSW (150$^{o}$ 30" E, 35$^{o}$ 50" S); Mermaids Inlet, NSW (151$^{o}$ 00" E, 35$^{o}$ 00" S); | Run-up to >40 m asl at Atcheson Rock; deposits located along 120 km stretch of coastline | "[at Cullendulla] ridges of sand containing shell overlying estuarine sediments", "[at Shelly Point] <2m of shell, sand and well-rounded cobbles and pebbles…. obvious interbedding…… large number of unbroken shells", "[at Mermaids Inlet] extremely large pile of massive boulders…. boulders up to +4 m asl", "[at Atcheson Rock] depositing sand, shells, rounded cobbles and regolith…. deposit at least 1.5m thick", "[at Crookhaven Head] series of large boulders carried onto the rock platform", "[at Narwallee] large sandstone block flanked by a train of very | ? | 2 | Bryant (2001); Bryant *et al* (1992); Young *et al* (1997) |

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| | | | | | | Atcheson Rock, NSW (151° 00” E, 34° 60” S); Crookhaven Head, NSW (150° 80” E, 34° 90” S); Narawallee, NSW (150° 50” E, 35° 30” S) | | large boulders” | | | |
| 7 | ~200/250 years before present | | | Unknown | Unknown | Haycock Point, NSW (150° 00” E, 37° 10” S); Mystery Bay, NSW (150° 10” E, 36° 10” S); Bass Point, NSW (151° 00” E, 34° 60” S); Short Point, NSW (150° 00” E, 35° 37” S); Greenfields Beach, Jervis Bay, NSW (150° 80” E, 35° 05” S); North Beach, Port Kembla, NSW (151° 50” E, 34° 50” S); Little Bay, Sydney, NSW (151° 10” E, 34° 00” S) | *c.* +5 m asl | “[at Haycock Point] blocks plucked from shore platform and deposited up to +5 m asl” , “[at Mystery Bay] deposit of cobble, gravel and unbroken shell forms a very well defined ridge at 3.2m asl… ridge contains no sand”, “[at Bass Point] strongly imbricated boulders”, “[at Short Point] plucked boulders…. aligned boulders” , “[at Greenfields Beach] pile of large angular boulders transported up to +8m asl” , “[at North Beach] deposit of sand, clay and shells rises to <2m above the modern beach” , “[at Little Bay] eroded bedrock channel contained scattered boulders” | ? | 2 | Bryant (2001); Bryant *et* al (1992); Young *et al* (1997) |
| | | | | | | **Historic tsunami events (i.e., those occurring after European occupation of Australia in AD1788)** | | | | | |
| 8 | 1866 | 8 | 9 | Tasman Sea | Unknown | Sydney, NSW (151° 12” E, 33° 51” S) | Maximum ‘wave height’ = 0.0 m (given by Rynn, 1994) | According to Rynn (1994), “tsunami was registered on the “tide gauge”. However, there is no report of unusual tidal fluctuations at the Fort Denison Tidal Register<br>NOAA (2007) has an event entry but no runup entry for this event | II | 0 | NOAA (2007), Rynn (1994) |
| 9 | 1866 | 8 | 15th - 21st | Tasman Sea | Unknown | Sydney, NSW (151° 12” E, 33° 51” S) | Maximum ‘wave height’ = 0.0 m (given by Rynn, 1994) | According to Rynn (1994), “tsunami was registered on the “tide gauge”. However, there is no report of unusual tidal fluctuations at the Fort Denison Tidal Register<br>NOAA (2007) has an event entry but no runup entry for this event | II | 0 | NOAA (2007), Rynn (1994) |
| 10 | 1867 | 8 | 5th - 13th | Tasman Sea | Unknown | Sydney, NSW (151° 12” E, 33° 51” S) | Maximum ‘wave height’ = 0.0 m (given by Rynn, 1994) | According to Rynn (1994), “tsunami was registered on the “tide gauge”. However, there is no report of unusual tidal fluctuations at the Fort Denison Tidal Register<br>NOAA (2007) has an event entry but no runup entry for this event | II | 0 | NOAA (2007), Rynn (1994) |
| 11 | 1868 | 8 | 15 | D - North Chile | Earthquake in Chile on 13/8/1868, 21:30. Tsunami arrived two days later in Australia in the morning | Sydney, NSW (151° 12” E, 33° 51” S); Newcastle, NSW (151° 47” E, 32° 55” S); Wollongong, NSW (150° 54” E, 34° 25” S); Jervis Bay, NSW | Runup of 1.2 metres in Sydney (NOAA) | “A remarkable phenomenon was observed in Sydney Harbour on the 15th August. It was high water about 5 o’clock on that morning, and the tide was ebbing at a constant velocity about 8 am, when it suddenly turned, and the waters, as if impelled by some extraordinary influence, returned up the harbour with great force….. at Darling Harbour, and particularly in Johnstons Bay the effects were very marked. In some places, the water seemed as if in a boil, in others whirlpool eddies were formed, while at one time a tidal wave swept up Johnstons Bay snapping thee warps of one of the steam ferries at Balmain, and completely stopping another while on her passage across the harbour “, and; “in some parts of Port Jackson the | V | 4 | SMH (17/8, 18/8, 19/8, 20/8, 21/8/1868); SMH (22/8, 24/8,31/8, 2/9, 5/9, 7/9, 9/9/1868); SMH (5/11/1868); Fort Denison Tidal Register, May 1866 - December 1882; NOAA/NGDC (2006); Rynn (1994) |

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| | | | | | Magnitude = 8.5 located at: 71$^{o}$ 00” W, 18$^{o}$ 60” S | (150$^{o}$ 75” E, 35$^{o}$ 00” S) | | [tidal] effects were more noticeable during the afternoon….. On rounding the spit at 3 pm, a large whirlpool was observed to form suddenly ahead of the Vesta steamer completely diverting her from her course, and almost driving her ashore…..”, and; “an extraordinary tidal disturbance has been experienced here [Newcastle] this morning since about half past 6 o’clock, - the vessels at the coal shoots broke from their moorings, one nearly loosing her masts; the sandbank was suddenly uncovered to the extend of a foot, and was rapidly covered again”, and; “the extraordinary phenomenon that took place this morning, and continues, is termed by nautical men, a volcanic wave. At 8.30, the vessels in the harbour were thrown in to great confusion. The Alexander broke from her moorings and had to anchor in the stream. The Planter was shaken so much by the action of the tides that the captain expected his masts to fall. The ship, Lucibelle, 1000 tons, was swung round four times, although a strong ebb tide was running; and vessels in harbour were swung round in all directions. The tide ran down sometimes at a rate of 12 knots, the same as if there was a strong fresh in the river. At 11.30, the extraordinarily sudden rise and fall of the tide was between four and five feet which caused great consternation among shipping. The steam tugs Warhawk and Rapid were left stranded in the Blind Channel by the retreating of the water. The action was experienced the same at Port Waratah. The sandbanks in the channel were left quite dry at times, and as suddenly covered. Mr Keene, Government Examiner in Coal Fields, was watching a gauge at the time of low water, shortly before 12 o’clock, and he witnessed a rise and fall of two feet and four inches in fifteen minutes”, and; “a very singular phenomenon in connection with the tide at Wollongong took place on Saturday last….. The water suddenly receded from the harbour, falling within eight or ten minutes not less than three or four feet. So sudden was the fall, that numbers of lobsters were left high and dry, and became easy prey to those who happened to be present. For some time the water was at least three feet lower than it usually is at deep low water”, and; “we have been credibly informed that on last Saturday morning, at ebb tide, the water rushed up Currimbene Creek, Jervis Bay, with unusual force and velocity, and increased volume; some time after it raced back in a similar manner, sweeping away a large portion of sand that had impeded the navigation”, and; “on Saturday a very unusual phenomenon was observed in Moreton Bay by the residents of Sandgate…. There were five tides in the day….. the waves came in like the ordinary tide, but rose somewhat above the level of the highest springs. They came in rapidly and almost immediately receded”, and; “Mr Todd of South Australia, had given the local report made at Port Adelaide and Port Victor, where it seemed the wave was noticed at 7 am, 10 am and again at 4 pm”, and; “on the morning of the 15th instant, at 8 o’clock, Albany Harbour, King Georges Sound, was visited by what appeared to be a great sea wave. The sea suddenly rose three feet, lighters were turned round, and old hulks that lay embedded in the sand for years were removed from their places and carried further up on to the beach. This occurrence appears to have been somewhat similar to what took place in Sydney Harbour on the same day”, and; “early on the morning of Saturday a tidal wave was seen approaching the shore at Newtown [Hobart], near the residence of Captain Bailey; there was a vast body of water that spread over a large area of hitherto dry land. This phenomenon was repeated at intervals throughout the entire day”, and; “there was a very high tide in the river on Saturday afternoon; at Risdon [Hobart] the water overflowed the road, and, receding suddenly, left a number of fish high and dry, which were easily captured by those in the neighbourhood”, and: “The master of the schooner Marie Louise, from Oyster Cove [Hobart], reports that the unusual disturbance of the waters was observed at Oyster Cove on Saturday and Sunday last; | | | |

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| | | | | | | | | especially on Saturday, when the waves, at intervals of half an hour or so, rose to the extent of three feet and rushed up the cove, and then receded an equal distance, making the rise and fall equal to six feet from the highest to the lowest reach of the sea on the beach, during the continuance of the extraordinary wash of the sea”<br>This event #911 in Allport and Blong (1995) appears to be the same as event #912 in Allporta nd Blong (1995). | | | |
| 12 | 1868 | 10 | 16 | D - Central Chile | Earthquake | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S) | Allport and Blong (1995) records ‘maximum run-up of 0.0 m” | “disturbances were observed at this location”, and; “there were five tides during the day and there was erratic water movement”<br>Allport and Blong (1995) cites the SMH 19/10/1868 as the source for this event but this original source has not been relocated | III | 3 | SMH (19/10/1868); Allport and Blong (1995) |
| 13 | 1869 | 8 | 11 | Unknown | Unknown | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S) | Allport and Blong (1995) records ‘maximum run-up of 0.0 m” | According to Rynn (1994), “tsunami was registered on the “tide gauge”. However, there is no report of unusual tidal fluctuations at the Fort Denison Tidal Register | I | 0 | Allport and Blong (1995); Rynn (1994) |
| 14 | 1870 | 8 | 12 | Unknown | Unknown | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S) | 0.0 m asl | According to Rynn (1994), “tsunami was registered on the “tide gauge”. However, there is no report of unusual tidal fluctuations at the Fort Denison Tidal Register | I | 0 | Allport and Blong (1995) (1995); Rynn (1994) |
| 15 | 1877 | 5 | 10 | D - North Chile | Earthquake on 10th May. Tsunami takes day to reach Australia<br>Magnitude = 8.3 located at: 70$^{o}$ 20” W, 19$^{o}$ 60” S | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S); Newcastle, NSW (151$^{o}$ 47” E, 32$^{o}$ 55” S); Ballina, NSW (153$^{o}$ 34” E, 28$^{o}$ 52” S) | Maximum ‘wave height’ of 0.8 m reported | “the first indication in Sydney occurred on Friday at 5.20 am, when the tide gauge at Fort Denison recorded the first series of waves, which went on in short intervals during the day, reaching a maximum at 2 pm of three feet six inches. The Boomerang steamer was being taken on to slip at noon, when one of the waves came in and lifted her suddenly off her cradle, and then receding left her high and dry”, and; “ a singular phenomenon occurred in the harbour [Newcastle] this morning in the shape of a tidal wave. At about half past five, during the flood tide, the ships in the harbour were observed swinging about in a strange manner, and the cause was immediately manifested by the motion of the water in the harbour, which rose and fell in short intervals, with great rapidity. At 11.30 this morning [11th May], when the tide was at ebb, the gauge on the wharf showed a sudden fall in the tide of thirty-one inches in the space of four minutes, followed immediately by a sudden rise. In the afternoon when the flood tide set in, there was also a fall of two feet in five minutes. These were the most remarkable instances noticed, but throughout the day the waters of the harbour were very unsettled”, and; “an extraordinary tidal phenomenon was observed in the harbour [Newcastle] today at 11.30 am. There was a rapid fall in the tide of about thirty-one inches and at 2 pm, there was a rise of twenty-two inches”, and; “At Ballina, similar phenomenon [to that at Newcastle] were observed all day, the greatest rise being eighteen inches” | V | 4 | Maitland Mercury (15/5/1877); Allport and Blong (1995); SMH (12/5, 15/5/1877); NOAA/NGDC (2006); Rynn (1994); Journal of Assistant Harbour Master of Newcastle, 26 June 1873 - 28 January 1881 |
| 16 | 1879 | 5 | 15 | Unknown | Unknown | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S) | ‘Wave height on tide gauge’ of 0.05 m | “on the afternoon of May 15th, the tide gauge at Fort Denison recorded a series of periodic waves usually called tidal waves; they were smaller than usual, the largest being only two inches from crest to trough, but so marked in ‘period’ that it seems worthwhile to mention them. Between 8.30 pm on the 15th and 3.30 am on the 16th, they were best marked by the gauge, and recurred at an average interval of 26 minutes” | II | 4 | Allport and Blong (1995); SMH (20/5/1879) |
| 17 | 1880 | 9 | 21 | D - Chile | Earthquake | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S) | ‘Wave height on tide gauge’ of 0.0 m | Fort Denison Tidal Register states “tide oscillating several inches”. Rynn (1994) states that the event was registered on "tide gauge". Rynn (1994) is the only source for this otherwise unknown event.<br>The original source (tide gauge record) for this event has not been located. | II | 2 | Fort Denison Tidal Register May 1866 – December 1882; Allport and Blong (1995); Rynn (1994) |
| 18 | 1883 | 8 | 28 | R - South Java Sea - Krakatoa | Volcanic eruption | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S); Newcastle, NSW (151$^{o}$ 47” E, 32$^{o}$ | Wave height ‘estimated’ by eyewitnesses at 1.5 m | “Krakatoa tsunami waves recorded from 28/8/1883 until 31/8/1883. At 4.30 pm on August 28th, the tide in Sydney harbour rose suddenly and unexpectedly by 10 cm and receded just as dramatically. An hour later, it again rose by 10cm only to fall by 38 cm. And that is how the tide level continued to fluctuate throughout the following day”, and; “ a rather | V | 4 | NOAA/NGDC (2006); Allport and Blong (1995); Rynn (1994); Hunt (1929); Berninghausen (1966, 1969); Fort Denison Tidal Register January 1883 – December 1892; Journal of |

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|  |  |  |  |  |  | 55” S) |  | strange phenomenon was observed on the tide sheets [at Newcastle] yesterday and today. A tide track on the sheet showed a run of eleven or twelve inches whereas the sea to all appearances was perfectly smooth”, and; “the most amazing phenomenon occurred at Newcastle at 6.30 am on August 29th. At that time the tide was about to peak, then suddenly, the disbelieving harbour pilots saw all the ships at anchor swing right around as though the tide was retreating with speed. The vessels remained in this position for a short time – and then swung back to their original and normal positions”, and; “an extraordinary tide [at Ashburton] set in at 12 pm on the 27th, the tide rose nearly five feet then ebbed rapidly”, and; “ a succession of tidal waves [at Carnarvon] from three to four feet high occurred, causing a rise and fall of the tide three times in one and a half hours” |  |  | the Assistant Harbour Master, Newcastle 28 May 1883 - 31 December 1885; Daily Mirror (12/7/1977) |
| 19 | 1895 | 2 | 2 | Unknown | Unknown | Newcastle, NSW (151° 47” E, 32° 55” S) | ‘Wave height on gauge’ of 0.33 m | “At 5.10 pm on the 2nd at Newcastle, there was a tidal wave of thirteen inches on the sheet causing ships in the harbour to drag their anchors.”<br>The original source (tide gauge record) for this event has not been located. | IV | 3 | Fort Denison Tidal Register December 1892 – December 1898; Allport and Blong (1995) |
| 20 | 1922 | 11 | 11 | D - North Chile | Earthquake<br>Magnitude = 8.5 located at: 70° 00” W, 28° 50” S | Sydney, NSW (151° 12” E, 33° 51” S); Newcastle, NSW (151° 47” E, 32° 55” S) | ‘Wave height on tide gauge’ of 0.2 m | “Erratic operation of tidal gauge pen at Fort Denison was that of an earthquake in Chile”, and; “first shock recorded at Sydney at 2.51 pm on the 11th November”, and; “in the case of the Chilean quake there were two repetitions at about 33 hour intervals after the arrival of the direct waves”, and; “The steamship Grelisle was crossing over the Newcastle bar on Saturday last, when a huge wave swept down upon her. At the time the Grelisle had four feet seven inches of water under her, but as her bow rose with the sea her stern crashed onto the bar, giving the vessel and her crew a very severe shaking. The wave, which is considered tidal, was experienced at Newcastle at 1.30 pm….. It is also reported that big vessels in port at Newcastle carried away their moorings as the wave swirled up the harbour, causing much confusion”, and; “it was an abnormal sheet and no weather was experienced either before or after to cause such readings; therefore, in my opinion, something of an extraordinary nature must have happened.”<br>The original source (tide gauge record) for this event has not been located. | IV | 4 | NOAA/NGDC (2006); Rynn (1994); Hart (1931); Port of Sydney Journal (1946); Daily Mail (18/11/1922); Acting Deputy Superintendant Department of Navigation, Newcastle (1922) |
| 21 | 1924 | 6 | 26 | R - Macquarie Island | Earthquake<br>Magnitude = 7.8 located at: 157° 50” E, 56° 00” S | Sydney, NSW (151° 12” E, 33° 51” S) | Allport and Blong (1995) states ‘maximum run-up’ is 0.0 m asl | “Macquarie Island Earthquake 26th June 1924…..first tidal effect [at Fort Denison Tidal Register, Sydney] at 3.30 pm on 26 June….. tidal wave appears 464 mph” | II | 4 | Allport and Blong (1995); Rynn (1994); Fort Denison Tidal Register, December 1922 - February 1928 |
| 22 | 1929 | 6 | 17 | R - New Zealand | Earthquake | Sydney, NSW (151° 12” E, 33° 51” S) | NOAA (2007) lists max water height of 0.1m at Fort Denison<br>Allport and Blong (1995) states ‘maximum run-up’ is 0.0 m asl | “New Zealand earthquake (Sydney time 08.52) 1st tidal effects felt at Fort Denison”, and; “first shock of earthquake recorded at Sydney at 8.52 am” | II | 4 | Hart (1931); Allport and Blong (1995); Rynn (1994); Fort Denison Tidal Register, March 1928 - May 1933 |
| 23 | 1931 | 2 | 3 | R - New Zealand | Earthquake | Sydney, NSW (151° 12” E, 33° 51” S) | Allport and Blong (1995) states ‘maximum run-up’ is 0.0 m asl | Rynn (1994) states " observation registered on tide gauge" although there are no references to anomalous tidal movements at Fort Denison Tidal Register<br>The vertical axis of the tide gauge record provided by Hart (1931) does not include units of measurement so it is impossible to read | I | 0 | Allport and Blong (1995); Rynn (1994) |
| 24 | 1931 | 2 | 13 | R - New Zealand | Earthquake | Sydney, NSW (151° 12” E, 33° 51” S) | ‘Wave height recorded on tide gauge’ of 0.0 m | "reported tsunami attributed to earthquake in New Zealand", and, "first shock recorded at Sydney at 11.32 am on the 13th" | II | 4 | Hart (1931); NOAA/NGDC (2006); Allport and Blong (1995) (1995); Rynn (1994) |
| 25 | 1933 | 3 | 2 | D - Japan | Earthquake | Sydney, NSW (151° 12” E, 33° | Allport and Blong (1995) states ‘maximum run-up’ | "the full effect of the catastrophe did not manifest itself on the tide register at Sydney until some 54 hours afterwards" | II | 4 | NOAA/NGDC (2006); Port of Sydney Journal (1946); Allport and |

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| | | | | | Magnitude = 8.4 located at: 147$^{o}$ 70” E, 39$^{o}$ 10” N | 51” S) | is 0.0 m asl | | | | Blong (1995) |
| 26 | 1946 | 4 | 2 | D - Aleutian Islands | Earthquake on 1st April. Tsunami takes day to reach Australia<br>Magnitude = 8.1 located at: 163$^{o}$ 20” W, 53$^{o}$ 30” N | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S) | ‘Wave height recorded on tide gauge’ of 0.08 m | "after a shock in the same area (Aleutian Islands) on April 1st 1946, a tidal wave of three inches high reached Sydney in 46 hours", and, "1$^{st}$ , 2nd and 3rd movements of the Aleutian Islands tidal waves recorded" | II | 4 | Allport and Blong (1995) (1995); SMH (12/3/1957); Fort Denison Tidal Register, July 1944 - August 1950 |
| 27 | 1948 | 9 | 9 | R - Tonga Trench | Earthquake<br>Magnitude = 7.8 located at: 174$^{o}$ 00” E, 21$^{o}$ 00” N | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S) | ‘Wave height recorded on tide gauge’ of 0.0 m | "Niaufu tidal wave recorded" | II | 4 | Allport and Blong (1995); Fort Denison Tidal Register, July 1944 - August 1950 |
| 28 | 1951 | 8 | 24 | D - Formosa, Taiwan | Earthquake (?) | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S) | ‘Wave height recorded on tide gauge’ of 0.0 m | "disturbance indicated on tide trace reckoned to be the results of earthquake in Formosa" | II | 3 | Fort Denison Tidal Register, September 1950 - July 1956; Allport and Blong (1995) |
| 29 | 1952 | 11 | 4 | D - Kamchatka, Russia | Earthquake<br>Magnitude = 9.0 located at: 159$^{o}$ 50” E, 52$^{o}$ 75” N | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S) | ‘Wave height recorded on tide gauge’ of 0.0 m | "effects of an earthquake in far north Pacific noted on gauge" | II | 4 | Fort Denison Tidal Register, September 1950 - July 1956; Allport and Blong (1995) |
| 30 | 1953 | 11 | 4 | R - Solomon Islands | Earthquake | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S) | ‘Wave height recorded on tide gauge’ of 0.0 m | "severe earthquake near the Solomon’s. Recorded at 4pm EST 26 hours after earthquake at Fort Denison on gauge" | II | 4 | Fort Denison Tidal Register, September 1950 - July 1956; Allport and Blong (1995) (1995) |
| 31 | 1957 | 3 | 10 | D - Central Aleutians | Earthquake<br>Magnitude = 9.1 located at: 148$^{o}$ 55” E, 44$^{o}$ 53” N | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S) | ‘Wave height recorded on tide gauge’ of 0.0 m | “In Sydney, the effect of the tidal wave was felt on Sunday afternoon [11/3/1957] when it raised the normal tide two to three inches. The first wave that reached Sydney was thirty miles wide, according to the Maritime Services Board Chief Surveyor, Mr G. Hart. This was followed by a trough, then smaller waves about fifteen miles across. The waves, he said, must have travelled at more than 350 miles an hour to Australia”, and; “shock waves from Aleutian Islands [at Fort Denison Tidal Register] recorded between 1715 hrs and 2300 11/3/1957”, and; “shock waves from Aleutian Islands recorded [at Camp Cove Tidal Register] at 1715 hrs. 11/3/1957 shock waves recorded until 2300 hrs” | IV | 4 | SMH (11/3, 12/3/1957); Fort Denison Tidal Register, August 1956 - October 1962; Camp Cove Tidal Register, June 1954 – August 1960; Allport and Blong (1995) |
| 32 | 1958 | 11 | 8 | D - South Kuril Islands | Earthquake<br>Magnitude = 8.3 located at: 148$^{o}$ 55” E, 44$^{o}$ 53” N | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S) | ‘Wave height recorded on tide gauge’ of 0.0 m | “Main shockwave from severe earthquake off Japanese coast recorded at [Fort Denison] tide gauge at 11.45 pm 39 hours after initial disturbance”, and; “severe earthquake off Japanese coast….. main shockwave recorded on [Camp Cove] tide gauge at 11.45pm” | II | 4 | NOAA/NGDC (2006); Fort Denison Tidal Register, August 1956 - October 1962; Camp Cove Tidal Register, June 1954 - August 1960; Allport and Blong (1995) |
| 33 | 1960 | 5 | 23 | D - Central Chile | Earthquake on 22$^{nd}$. Tsunami takes day to reach Australia | Sydney, NSW (151$^{o}$ 12” E, 33$^{o}$ 51” S); Ballina, NSW (153$^{o}$ 34” E, 28$^{o}$ 52” S); Coffs Harbour, NSW (153$^{o}$ 08” E, 30$^{o}$ | Allport and Blong (1995) states that ‘maximum run-up’ of 1.723 m asl was recorded at Eden, NSW and cite NOAA as their source of measurement. NOAA (2007) provides | “First Chilean shockwaves recorded at Riverview at 8.15 pm on 21/5/1960….. first seismic ocean waves recorded by tide gauge [at Fort Denison] at 9.35 pm on 23/5….. severe seismic ocean waves recorded cessation at 3.15 am 28/5”, and; “first seismic ocean waves recorded by tide gauge [at Camp Cove] at 9.50 pm”, and; “freak currents tore away moored boats and upset shipping. The huge tide tore from their moorings about 30 launches and craft and two barges at the Spit, swirled the barges | V | 4 | NOAA/NGDC (2007); Rynn (1994); Courier Mail (25/5/1960); Fort Denison Tidal Register, August 1956 - October 1962; Camp Cove Tidal Register, June 1954 - August 1960; Allport and Blong (1995) |

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|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | Magnitude = 9.5 located at: 74$^o$ 50” W, 39$^o$ 50” S | 18” S); Eden, NSW (149$^o$ 54” E, 28$^o$ 52” S); Newcastle, NSW (151$^o$ 47” E, 32$^o$ 55” S) | the following: ‘maximum water height of 0.90m at Eden” | in among drifting launches, overturning several of them and damaging others. Smashed one of the barges in to Spit Bridge. Set adrift 800 logs from moorings at Balmain shipping yard, which were then swept down the Parramatta River. Swept away a strip about 100 yards by 60 yards from ark and exposed a high tension submarine cable”, and; “fishing boasts were removed from their moorings in Brisbane and Sydney and went aground and were damaged at Evens Head and Newcastle”, and; “in one tense moment a 30 foot fishing trawler sank in Throsby Creek near Newcastle. Eight launches were ripped from their moorings in Throsby Creek and swept half a mile into Newcastle Harbour”, and; “fishing boats were removed from their moorings in Brisbane and Sydney”, and; “tidal waves following the Chilean earthquake moved boats from their moorings at Cabbage Tree Creek, Shorncliffe yesterday. The boats dragged their anchors for 100 yards. The tidal waves gave Moreton Bay suburbs up to five high tides in two hours and played havoc with Brisbane’s post office tide gauge at Edward Street. The gauge showed 16 river rises between 2.15 am and 3 pm. The biggest was nine inches. Pile light officer Mr W. Devonshire said, ‘At 4 am a two foot rise in the tide swept right over the bank’…… at Brighton residents saw about five high tides sweep in between 8.45 am and 10.45 am”, and; “activity commenced [in Cairns] at 1500 GMT on the 23rd May”, and; “activity commenced [in Townsville] at 1500 GMT on the 23rd May. The periods of the first few waves seem to be about 1.5 hours, with maximum amplitudes of about a foot”, and; “initial signs of abnormal fluctuations in the tide level [in Mackay] appeared at 1600 GMT on the 23rd May, (0200 EST 24th) the first few waves having a period of about an hour and reaching a maximum peak to peak amplitude of just less than 1 foot at 1830 GMT”, and; “a salmon-spotting pilot yesterday saw three mile beach, Wilsons Promontory, ‘disappear’ while he was flying over it. Reporting on this effect of the Pacific tidal waves the pilot, Dick Ritchie said: ‘in a minute and a half, while I flew over it, the water rushed out 200 yards”.<br>The original source (tide gauge record) for this event has not been located. |  |  |  |
| 34 | 1964 | 3 | 29 | D - Alaska | Earthquake on 28th March. Tsunami takes day to reach Australia<br>Magnitude = 9.2 located at: 147$^o$ 50” W, 61$^o$ 10” N | Sydney, NSW (151$^o$ 12” E, 33$^o$ 51” S); Bobbin Head, NSW (151$^o$ 09” E, 33 09 S); Coffs Harbour, NSW (153$^o$ 08” E, 30$^o$ 18” S) | Allport and Blong (1995) states ‘ maximum run-up [at Bobbin Head]’ of 1.0 m asl.<br>NOAA (2007) states ‘maximum water height’ at 0.2m | “drastic alterations in the motion of the tides were noted”, and “…..the tide gauge at Fort Denison recorded small variations. …..the maximum change was a sudden fluctuation of about eight inches at 8.45am”, and “the tide changed five times at Bobbin Head”. | I | 4 | Braddock (1969); Allport and Blong (1995); SMH (30/3/1964) |
| 35 | 1971 | 7 | 26 | R - Bismark Sea, New Guinea | Earthquake<br>Magnitude = 7.9 located at: 153$^o$ 20” E, 4$^o$ 90” S | Sydney, NSW (151$^o$ 12” E, 33$^o$ 51” S) | Allport and Blong (1995) states ‘maximum run-up’ at 0.0 m asl | Hatori (1982) indicates that this tsunami was observed in NE and SE Australia | I | 3 | Hatori (1982); Allport and Blong (1995); SMH (27/7 and 28/7/1971) |
| 36 | 1975 | 7 | 21 | R - Solomon Islands | Earthquake | Sydney, NSW (151$^o$ 12” E, 33$^o$ | Allport and Blong (1995) states ‘maximum run-up’ | “tsunami wave recorded on Camp Cove tide gauge” | II | 4 | NOAA/NGDC (2006); Camp Cove Tidal Register, March 1973- |

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|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Magnitude = 7.8 located at: 155° 00” E, 6° 60” S | 51” S) | at 0.0 m asl | The original source (tide gauge record) for this event has not been located. | | | December 1979; Allport and Blong (1995); SMH (22/7/1975) |
| 37 | 1976 | 1 | 14 | D - Kermadec Islands | Earthquake<br>Magnitude = 8.0 located at: 177° 60” E, 28° 20” S | Sydney, NSW (151° 12” E, 33° 51” S); Lord Howe Island, NSW (159° 04” E, 31° 31” S) | Allport and Blong (1995) states ‘maximum run-up’ at 0.0 m asl. However, NOAA (2007) state that ‘maximum water height is at 0.3m’ | Fort Denison Tidal Register states that "Earthquake - Pacific Ocean….. First tidal effects at 7.47 EST, 14th January" and, Rynn (1994) states that "observations of the tsunami were made" | II | 4 | NOAA (2007); Allport and Blong (1995); Rynn (1994); Fort Denison Tidal Register, March 1975 - November 1981; Allport and Blong (1995) (1995) |
| 38 | 1977 | 4 | 20 | R - Solomon Islands | Earthquake<br>Magnitude = 6.8 located at: 163° 30” E, 9° 80” S | Sydney, NSW (151° 12” E, 33° 51” S) | Allport and Blong (1995) states ‘maximum run-up’ at 0.0 m asl | Fort Denison Tidal Register states "Solomon earthquake effects recorded in Sydney" | II | 4 | Allport and Blong (1995); SMH (22/4/1977); Fort Denison Tidal Register, March 1975 - November 1981 |
| 39 | 1986 | 5 | 8 | D - Aleutian Islands | Earthquake on 7th. Tsunami takes day to reach Australia<br>Magnitude = 8.0 located at: 174° 70” E, 51° 20” N | Sydney, NSW (151° 12” E, 33° 51” S) | Allport and Blong (1995) states ‘maximum run-up’ at 0.0 m asl | Fort Denison Tidal Register notes observation of seismic ocean waves on 8/5/1986 | II | 4 | Fort Denison Tidal Register 1982 – 1994; Allport and Blong (1995) |
| 40 | 1989 | 5 | 23 | R - Macquarie Island | Earthquake<br>Magnitude = 8.1 located at: 160° 60” E, 52° 34” S | Sydney, NSW (151° 12” E, 33° 51” S); Eden, NSW (149° 54” E, 28° 52” S) | Allport and Blong (1995) states ‘maximum run-up’ at 0.3 m asl and quotes NOAA as its source of reference. However, NOAA (2007) states ‘maximum water height at 0.2m’ | Fort Denison Tidal Register notes observation of tidal disturbances following Macquarie Island earthquake. NOAA indicates run-up of 0.3 m asl on the SE coast of Australia | II | 4 | NOAA (2007): Allport and Blong (1995); Rynn (1994); Fort Denison Tidal Register 1982 - 1994 |
| 41 | 1989 | 10 | 19 | D - California, USA | Earthquake on 18th. Tsunami takes day to reach Australia<br>Magnitude = 7.1 located at: 128° 80” W, 37° 00” N | Sydney, NSW (151° 12” E, 33° 51” S) | Allport and Blong (1995) (1995) states ‘maximum run-up’ is 0.0 m asl | Fort Denison Tidal Register observes tidal disturbances following San Francisco earthquake on 18/10/1989.<br>The original source (tide gauge record) for this event has not been located. | II | 4 | Fort Denison Tidal Register 1982 – 1994; Allport and Blong (1995) |
| 42 | 1995 | 5 | 16 | R - Loyalty Islands, New Caledonia | Earthquake | Camp Cove, Sydney, NSW (151° 12” E, 33° 51” S); Tweed Heads, NSW | Allport and Blong (1995) (1995) states ‘maximum run-up’ is 0.0 m asl | "observed on tide gauge"<br>Allport and Blong (1995) list the date of this event at Sydney as occurring on the 15/05/1995. However, NOAA (2007) lists the date of this event as the 16/05/1995 (which was the actual date of the earthquake trigger event) | II | 4 | National Tidal Facility / Bureau of Meteorology; Allport and Blong (1995) |

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|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | (153$^o$ 32” E, 28$^o$ 10” S); Crowdy Head, NSW (152$^o$ 41” E, 31$^o$ 52” S), Ballina, NSW (153$^o$ 34” E, 28$^o$ 52” S); Norfolk Island, NSW (167$^o$ 55” E, 29$^o$ 03” S) | | The original source (tide gauge record) for this event has not been located. | | | |
| 43 | 2004 | 12 | 26 | R - Sumatra, Indonesia | Earthquake<br>Magnitude = 9.0 located at: 95$^o$ 90” E, 3$^o$ 30” N | Port Kembla, NSW (150$^o$ 55” E, 34$^o$ 29” S) | NOAA/NGDC (2007) sates that ‘maximum water height was 0.5m’ at Port Kembla | “observed on tide gauges” | III | 4 | National Tidal Facility / Bureau of Meteorology; NOAA/NGDC (2007) |
| 44 | 2006 | 5 | 3 | R - Tonga | Earthquake<br>Magnitude = 8.0 located at: 174$^o$ 20” E, 20$^o$ 20” S | Port Kembla, NSW (150$^o$ 55” E, 34$^o$ 29” S) | Wave height recorded on tide gauge of 0.2 m | “observed on tide gauges” | I | 4 | National Tidal Facility / Bureau of Meteorology |
| 45 | 2007 | 4 | 1 | R - Solomon Islands | Earthquake<br>Magnitude = 7.1 located at: 157$^o$ 00” E, 8$^o$ 50” S | Port Kembla, NSW (150$^o$ 55” E, 34$^o$ 29” S); Lord Howe Island, NSW (159$^o$ 04” E, 31$^o$ 31” S) | Wave height at Lord Howe Island tide gauge was 1.7m and wave height on tide gauge at Port Kembla was 0.35m | “observed on tide gauges”; NSW Bureau of Meteorology issued a Tsunami Warning; at Coffs Harbour, unusual oceanic behaviour and strong currents were observed | II | 4 | National Tidal Facility / Bureau of Meteorology; Manly Hydraulics Laboratory |

For each event, the catalogue supplies: the corresponding ID (event) number, the date of occurrence (year, month (M), day (D)), the source region of the tsunami, the cause, the region of impact in Australia, the maximum (max (*H*)) wave run-up (metres above sea level) and / or inundation data, a comments description, an indication of the tsunami intensity (TI) of each event based upon the 12 point (I – XII) tsunami intensity scale of Papadopoulos and Imamura (2001) TI I = not felt, II = scarcely felt, III = weak, IV = largely observed, V = strong, VI = slightly damaging, VII = damaging, VIII = heavily damaging, IX = destructive, X = very destructive, XI = devastating and, XII = completely devastating and an indication of the Reliability (Rel) of the tsunami event (based upon the NOAA NGDC Tsunami Database classification): 0 = erroneously listed event, 1 = very doubtful tsunami, 2 = questionable tsunami, 3 = probable tsunami, 4 = definite tsunami)

# Appendix 3

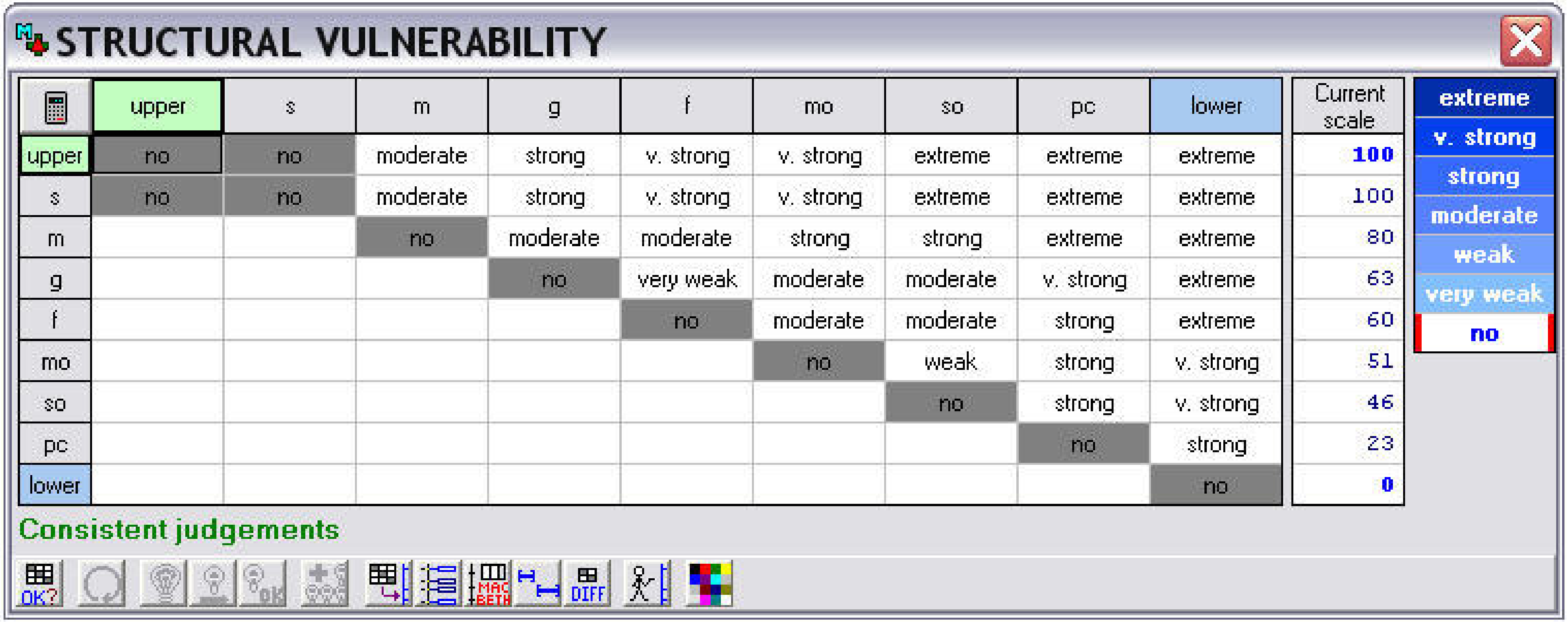
## Pair-wise comparisons between structural vulnerability factors

In this appendix, choices made during pair-wise matches between structural vulnerability factors are shown and discussed.

Structural vulnerability factors to be weighted are:

1. **Number of Stories (s)**
2. **Building Material and Technique of Construction (m)**
3. **Ground Floor Hydrodynamics (g)**
4. **Foundations (f):**
5. **Shape and Orientation (so)**
6. **Movable Objects (mo)**
7. **Preservation Condition (pc)**

In order to discuss every single comparison amongst them, the evaluation matrix is reported below. Since the matrix is symmetrical, only comparisons in the upper right part will be discussed. Also, to decide the result of each match, we compared a building having the best score in the first factor and the worst in the second, with a building having the worst score in the first factor and the best one in the second (and the same score in all the remaining factors). The only exception is given by the "movable objects" factor (since its worst score is 0, it has been compared with other factors considering as their worst score the characteristics they have in the "0" column). "Lower" and "upper" factors have been introduced as fictitious references. The upper factor has the same importance as the most influential factor (number of stories), while the lower factor makes no contribution to the structural vulnerability.



| | upper | s | m | g | f | mo | so | pc | lower | Current scale |
|---|---|---|---|---|---|---|---|---|---|---|
| upper | no | no | moderate | strong | v. strong | v. strong | extreme | extreme | extreme | 100 |
| s | no | no | moderate | strong | v. strong | v. strong | extreme | extreme | extreme | 100 |
| m | | | no | moderate | moderate | strong | strong | extreme | extreme | 80 |
| g | | | | no | very weak | moderate | moderate | v. strong | extreme | 63 |
| f | | | | | no | moderate | moderate | strong | extreme | 60 |
| mo | | | | | | no | weak | strong | v. strong | 51 |
| so | | | | | | | no | strong | v. strong | 46 |
| pc | | | | | | | | no | strong | 23 |
| lower | | | | | | | | | no | 0 |

Consistent judgements

**Figure A3.1. Evaluation matrix for pair-wise matches between structural vulnerability factors. The matrix was built using “M-Macbeth”, a software program designed for multi-criteria analysis and decision making processes. Each factor in the row is compared with each factor in the column. When the factor in the row is judged to be more important than the one in the column, the difference is qualitatively expressed in the crossing cell. “Lower” and “upper” factors have been introduced as fictitious references. The upper factor has the same importance as the most influential factor (number of stories), while the lower factor makes no contribution to structural vulnerability.**

1. **Number of Stories (s) versus Building Material (m) = moderate.** The number of stories is considered moderately more influential than the building material. A building made of timber with 5 or more stories is thus considered to have a structure moderately less vulnerable than a building made of concrete, but with only one storey. The structure of the first building must be strong enough to carry the load of at least 5 stories, irrespective of the type of material used. For the same reason, the second building (one storey, made of concrete) does not require such a strong (resistant) structure.

2. **Number of Stories (s) versus Hydrodynamics of the Ground floor (g) = strong.** The number of stories is considered strongly more influent than the hydrodynamics of the ground floor. A building with 5 or more stories and a totally closed ground floor is thus considered to have a structure strongly less vulnerable than a building having 1 storey and an open ground floor. Even if post tsunami field surveys emphasized the importance of having an open ground floor, it was clear that most of the buildings having only one storey suffered heavier damages than multistoried ones (Reese et al., 2007; Rossetto et al., 2006; Ghobarah et al., 2006; Matsutomi et al., 2006).

3. **Number of Stories (s) versus type of Foundations (f) = very strong.** The number of stories is considered more influent than the type of foundations. Their difference is “very strong”. In engineered buildings, these two factors are strictly connected. Higher buildings must have strongest foundations. In non engineered building, the number of stories has been considered more important than the foundation type, because of the strongest structure it needs to carry. Moreover, after the 2005 tsunami in Java, many building having 1 floor but with concrete foundations were swept away by the water flow, even if the concrete ground floor remained undamaged (Reese et al., 2007).

4. **Number of Stories (s) versus Movable Objects (mo) = very strong.** The number of stories is considered more influent than the presence of movable objects. Their difference is “very strong”. A building with 3 stories located behind a car park is considered to be much less vulnerable than a building with 1 storey located far from potential sources of movable objects. The main reason is that even if movable objects can cause severe damages also to the strongest structures, it is not possible to predict exactly where movable objects will be dragged by the flow (Warnitchai, 2005).

5. **Number of Stories (s) versus Shape and Orientation (so) = extreme.** The number of stories is considered extremely more influent than the shape and orientation of a building. The reason is similar to the previous comparison: the direction of the flow is not exactly predictable.

6. **Number of Stories (s) versus preservation Condition (pc) = extreme.** The number of stories is considered extremely more influent than the preservation condition. A 5 stories building in very poor condition is considered much less vulnerable than a 1 storey building in excellent conditions. The reason is that, in our opinion, the structure of a 5 stories building cannot ever be in so bad conditions (if the building is standing and safe) to be considered less resistant than the structure of a well preserved 1 storey building.

7. **Building Material (m) versus Hydrodynamics of the Ground floor (g) = moderate.** The building material is considered moderately more influent than the hydrodynamics of the ground floor. This means that a building having a reinforced concrete structure but closed ground floor is moderately less vulnerable than one having wooden structure but a totally open ground floor. In most of the observed cases, reinforced concrete buildings with closed ground floor had brick infill walls. Where the water depth was higher than 2 m, some infill walls were broken, but the concrete structure resisted (Ghobarah et al., 2006) On the other hand, wooden buildings on strong piles

behaved better than normal wooden ones, but they resisted water depths higher than 2 metres only in few cases (Reese et al., 2007).

**8. Building Material (m) versus Foundations (f) = moderate.** The building material is considered moderately more influent than the foundation type. A building having a reinforced concrete structure but shallow foundations is thus moderately less vulnerable than a timber building with deep pile foundations. The typical technique of construction used in Australia for timber residential buildings is based on the use of multiple thin wooden joists, which can be easily damaged by a water flow deeper the 2 m. In case the foundations were very strong, only the ground floor would resist (Reese et al., 2007). Reinforced concrete buildings are assumed to be well anchored to their foundations, even if they are shallow. On the other hand, they could experience severe damages given by the scouring action of the water flow, but this kind of effect was found to be minimum with water depth smaller than 8m (Ghobarah et al., 2006).

**9. Building Material (m) versus Movable Objects (mo) = strong.** The building material is considered strongly more influent than the presence of movable objects, because, as said, it is not possible to predict exactly where the flow will drag cars and debris.

**10. Building Material (m) versus Shape and Orientation (so) = strong.** The building material is considered strongly more influent than the shape and orientation of the building. A reinforced concrete building having a long rectangular shape, with the main side parallel to the shoreline, is considered to be much more resistant than a wooden building having a more hydrodynamic shape.

**11. Building Material (m) versus Preservation Condition (pc) = extreme.** The building material is considered extremely more influent than the preservation condition. This means that a reinforced concrete building in very poor conditions is considered still much less vulnerable than a wooden building in excellent condition.

**12. Hydrodynamics of the Ground floor (g) versus Foundations (f) = very weak.** The ground floor characteristics are considered slightly more influent than the type of foundations. Thus, a building with shallow foundations and totally open ground floor is considered slightly less vulnerable than one with deep pile foundations, but ground floor completely closed. Even if the first building is not well anchored to the ground, the pressure on its structure will be much smaller than the one applied on the second building, because the water flow will be able to pass through it. On the other hand, the scouring effect will be stronger for the first building, because of the higher flow velocity. However, damages given by the scouring effect were found to be minimum when the flow depth was smaller than 8m (Ghobarah et al., 2006).

**13. . Hydrodynamics of the Ground floor (g) versus Movable Objects (mo) = moderate.** The ground floor characteristics are considered moderately more influent than the presence of movable objects around the building. This means that a building having the at least 50% of its ground floor open, located behind a car park is moderately less vulnerable than a building having the ground floor totally closed, but far from sources of movable objects. Since we cannot assume that the cars will hit the building located at the back of the car park, then a we decided to give more importance to the ground floor characteristics.

**14. Hydrodynamics of the Ground floor (g) versus Shape and Orientation (so). = moderate.** The ground floor characteristics are considered moderately more influent than the shape and orientation. A building with open ground floor but with a poorly hydrodynamic shape is thus moderately less vulnerable than one having a highly hydrodynamic shape but a totally closed ground floor. In the first case, since the water will be able to pass through the building, its shape doesn't appear to be very relevant.

**15. Hydrodynamic of the Ground floor (g) versus Preservation Conditions (pc) = very strong.** The ground floor characteristics are considered strongly more influent than preservation conditions. A building in a very poor preservation state, having a totally open ground floor is thus considered much more resistant than one with a completely closed ground floor, but in excellent conditions. In fact, the second one will be exposed to a pressure much higher than the first one.

**16. Foundations (f) versus Movable Objects (mo) = moderate.** The foundation strength is considered moderately more influent than the presence of movable objects in front of a building. A building with average foundation strength, located at the back of a car park, is considered to be moderately less vulnerable than a building with shallow foundations, located far from car parks. The main reason is that there is a high degree of uncertainty about the point where movable objects will be dragged by the water.

**17. Foundations (f) versus Shape and Orientation (so) = moderate.** foundation strength is considered moderately more influent than the shape and orientation of the building. This means that a building with deep pile foundations and a poorly hydrodynamic shape is considered to be moderately less vulnerable than a building with shallow foundations and a highly hydrodynamic shape. The reason is still partially related to the uncertainty about the flow direction. Also, we assume that the higher pressure on walls of the first building would be balanced by its foundations.

**18. Foundations (f) versus Preservation Conditions (pc) = strong.** The foundation type is considered strongly more influent than preservation conditions. This means that a building with deep pile foundations in a very poor preservation state was judged to be strongly less vulnerable than a very well preserved one, but with shallow foundations. The preservation condition of the building structure was never found to be so bad to put the building stability at serious risk. The strength of the foundations is thus much more important.

**19. Movable Objects (mo) versus Shape and Orientation (so) = weak.** The presence of movable objects is considered slightly more influent than the shape and orientation. Even if they both depend on the direction of the water flow, which is not known, movable objects were judged to be more dangerous than the hydrodynamics of the building shape, because of the relevant number of structural damages they caused in past tsunamis (Dominey-Howes and Papathoma, 2007; Ghobarah et al., 2006; Darlymple and Kriebel, 2005), when they hit also buildings having a good shape/orientation.

**20. Movable Objects (mo) versus Preservation Conditions (pc) = strong.** The presence of movable objects has been considered strongly more influent than preservation conditions. This means that an average preserved building located behind a car park has been considered more vulnerable than a poorly preserved one, even if it is located far from potential sources of movable objects. In the worst case, observed preservation conditions were not enough bad to be considered more influent than movable objects.

**21. Shape and Orientation (so) versus Preservation Conditions (pc) = strong.** The shape and orientation of a building has been considered strongly more influent than its preservation condition. Thus, a well preserved building having a very low hydrodynamic shape has been judged to be more vulnerable than one with a very good shape (triangular, or round), but in very poor conditions. In the worst case, observed preservation conditions were not enough bad to be considered more influent than movable objects.

**22. Preservation Conditions (pc) versus Lower Factor = strong.** As stated, the “lower” is a fictitious factor, used as the lowest reference. It must be considered as a factor which does not have any influence on the structural vulnerability of a building. So, with respect to zero, the influence of preservation conditions has been considered strong. This means that even if “pc” is the least important among the real factors, it still gives a contribution to the final vulnerability level.

# Appendix 4

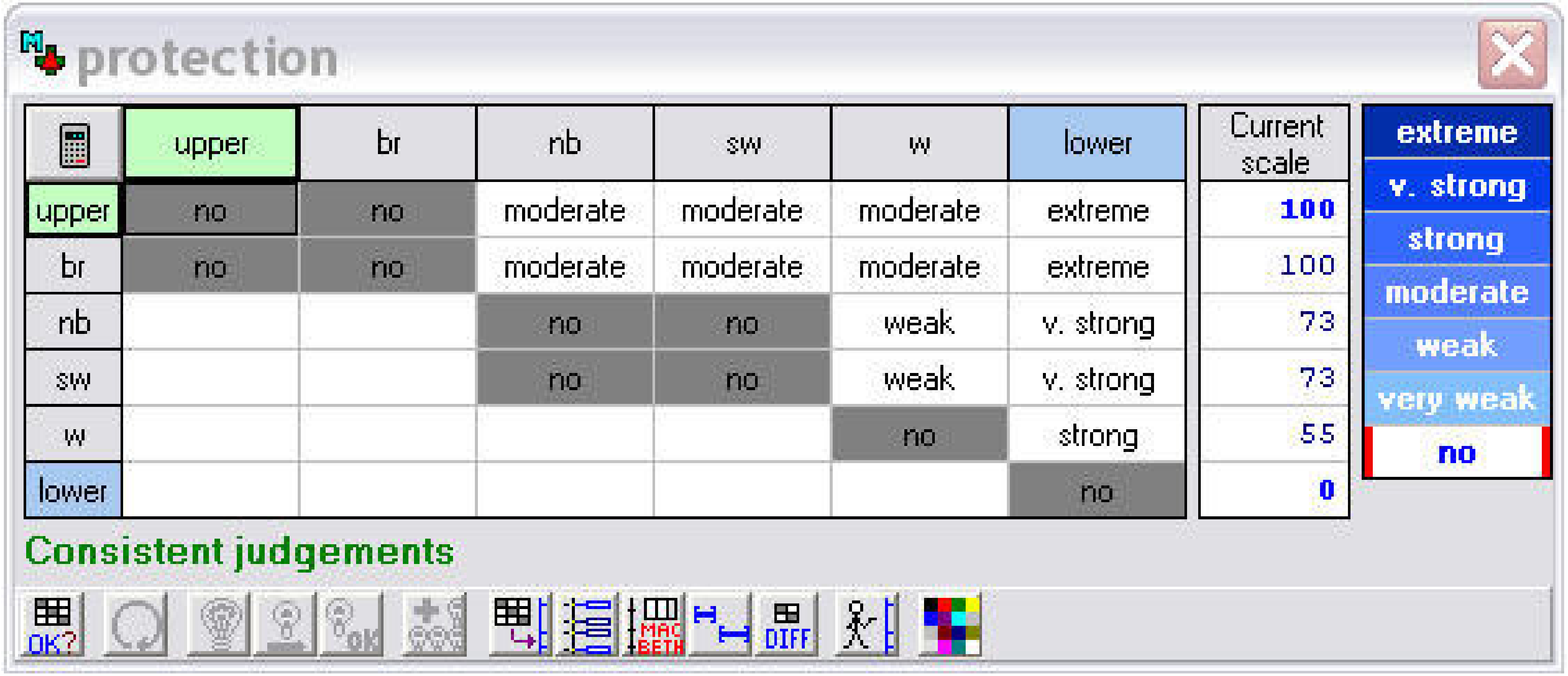
**Pair-wise comparisons between protection factors**

In this appendix, choices made during pair-wise matches amongst protection factors will be shown and discussed.

Protection factors to be weighted are:

1. **The Building Row (Prot_br)**
2. **The presence of a Seawall (Prot_sw)**
3. **Natural Barriers (Prot_nb)**
4. **Presence of a Brick Wall around the building (Prot_w)**

In order to discuss every single comparison amongst them, the evaluation matrix is reported below. Since the matrix is symmetrical, only comparisons in the its upper right part will be discussed. In order decide the result of each match, we compared a building having the best score in the fist factor and the worst in the second, with a building but having the worst score in the first factor and the best one in the second (and the same score in all the remaining factors).



| | upper | br | nb | sw | w | lower | Current scale |
|---|---|---|---|---|---|---|---|
| upper | no | no | moderate | moderate | moderate | extreme | 100 |
| br | no | no | moderate | moderate | moderate | extreme | 100 |
| nb | | | no | no | weak | v. strong | 73 |
| sw | | | no | no | weak | v. strong | 73 |
| w | | | | | no | strong | 55 |
| lower | | | | | | no | 0 |

Consistent judgements

**Figure A4.1. Evaluation matrix for pair-wise matches amongst protection factors. The matrix was built through "M-Macbeth", a software designed for multi-criteria analysis and decision making processes. Each factor in the row is compared with each one in the column. When the factor in the row is judged to be more important than the one in the column, their difference is qualitatively expressed in the crossing cell. "Lower" and "upper" factors have been introduced as fictitious references: the upper factor has the same importance of the most influent factor (the building row), while the lower factor doesn't give any contribution to the structural vulnerability**

1. **Building row (Prot_br) versus Natural Barriers (Prot_nb) = moderate.** The "building row" protection factor has been considered moderately more important than the presence of "natural barriers". This means that a building located behind the 10th row, without any natural barrier, has been considered more protected than a building in the first row, but well shielded by coastal vegetation (ex. within a coastal forest). . Even if both factors are very important, several post tsunami field surveys (Reese et al., 2007; Dominey Howes and Papathoma, 2007; Darlymple and Kriebel., 2005, ) emphasized the protection function performed by many rows of buildings.

2. **Building row (Prot_br) versus Seawall (Prot_sw) = moderate.** The "building row" protection factor has been considered moderately more important than the presence of a seawall. This means that a building located behind the 10th row, without any seawall along the beach, has been considered more protected than a building in the first row, but shielded by a seawall as high as the incoming wave. Even if a seawall is normally designed to withstand the largest storm waves, the cumulative effect of more than 10 building walls, together with the increasing distance from the shoreline, has been judged more influent in the reduction of the flow velocity.

3. **Building row (Prot_br) versus Brick Wall around the building (Prot_w) = moderate.** The "building row" protection factor has been considered moderately more important than the presence of a brick wall around the building. This means that a building located behind the 10th row, without any brick wall around, has been considered less vulnerable than a building on the first row, but protected by a brick wall higher (or as high as) the water flow. The main reason is that a brick wall is not designed to withstand an high hydrodynamic pressure, and its effect will be smaller than the one of 10 rows of building walls (even if they might not offer a complete shielding, because of the presence of streets, gardens and other empty spaces among them).

4. **Natural Barriers (Prot_nb) versus Seawall (Prot_sw) = no difference.** Protection offered by natural barriers and seawall have been considered equally important. During past tsunamis, both factors played a very important role in protecting buildings from the water flow. According to Matsutomi et al. (2006) and Darlymple and Kriebel (2005), during the 2004 tsunami at Patong Beach (Phuket - Thailand) single storey brick buildings partially withstand a 5 m wave, because of the presence of a seawall (even if it was much smaller than 5m). A similar thing happened to some other single-storey brick buildings in the Khao Lak area: since they were locate within a coastal forest, they resisted to a more than 4 metres inundation depth (Matsutomi et al., 2006). It must be noticed that this kind of building, if not protected, is expected to be almost totally destroyed by a 2 m deep water flow (Reese et al., 2007; Rossetto et al., 2006).

5. **Natural Barriers (Prot_nb) versus Brick Wall around the building (Prot_w) = weak.** Protection offered by natural barriers has been considered slightly more important than the presence of a brick wall around the building. This means that a building without a wall, but well shielded by coastal vegetation, is slightly more resistant than one without any natural barrier, but with a brick wall higher (or as high as) the water flow. . The main reason is that a brick wall is not designed to withstand a high

hydrodynamic pressure, and its effect will be smaller than the friction exerted by costal forests or other natural barriers.

**6. Seawall (Prot_sw) versus Brick Wall around the building (Prot_w) = weak.** Protection offered by a seawall has been judged to be slightly more influent than the one of a brick wall. The main reason is that the seawall is designed to withstand heavier pressures.

**7. Brick Wall around the building (Prot_w) versus Lower Factor = strong.** As stated, the "lower" is a fictitious factor, used as the lowest reference. It must be considered as a factor which does not have any influence on the protection level offered to a building. So, with respect to zero, the influence of a brick wall has been considered strong.

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