ASSESSING THE VULNERABILITY OF BUILDINGS TO TSUNAMI – A SYDNEY CASE STUDY

Dall'Osso, F[1,4] Gonella. M[4] Gabbianelli, G[1] Withycombe, G[3] Goff, J[2] and Dominey-Howes, D[2]

[1] Department of Environmental Science, University of Bologna, Italy
[2] Australian Tsunami Research Centre, University of New South Wales, NSW 2052
[3] Sydney Coastal Councils Group Inc., Sydney, NSW 2001
[4] MED Ingegneria S.r.l., Italy

Introduction

Our urban environments are susceptible to damage associated with extreme natural hazards. As populations grow and our cities expand – often in to more hazardous areas, the exposure of our built environment increases. The 2004 Indian Ocean tsunami (2004 IOT) was catastrophic and was an important reminder in Australia of the damage that can be caused by tsunamis. In some areas (e.g., Banda Aceh city), near complete devastation of the urban landscape occurred. In order to minimise the losses that will be associated with future tsunamis, decision makers (urban planners and emergency managers) require tools to assist them to make 'first order' assessments of the vulnerability of structures so that they may begin to establish appropriate risk management strategies. Estimating vulnerability (and PML) is important because such estimates are used to determine disaster preparedness and response strategies, to develop appropriate mitigation efforts such as land-use zoning policies, and in the development and application of building codes and regulations.

For the coast of New South Wales (NSW) (Figure 1a), historically, only small tsunamis have occurred (Dominey-Howes, 2007). Geological evidence however, suggests that megatsunamis many times larger than the 2004 IOT may have occurred repeatedly during the last 10,000 years (Bryant, 2008) (Figure 1a). This hypothesis has profound implications for the coastal vulnerability of NSW and we are entirely unprepared for such events. For example, 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 (Bird and Dominey-Howes, 2006; 2008). 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 (Goff and Dominey-Howes, In press) and that no work has been undertaken to assess the '*vulnerability*' of coastal buildings.

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

The final step in the scientific process described by Hall *et al*., (2008) is to map the '*exposure*' of (for example) buildings within the expected inundation zone and then assess the '*vulnerability*' of those structures to damage associated with that event.

So far though, this last step has not been undertaken by any official government agency or emergency service.

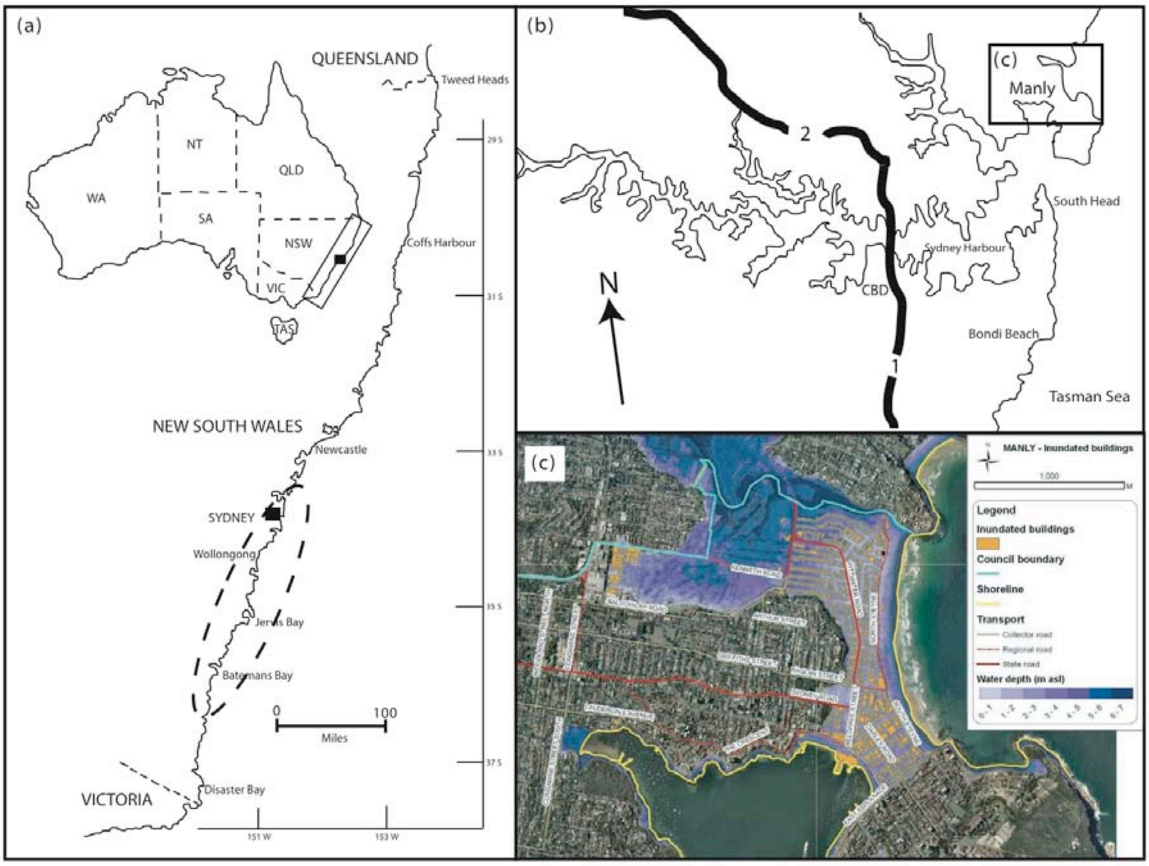

Figure 1: (a) Broad location of the study region of Sydney located in New South Wales. The hatched oval encompassing the region north of Sydney south to beyond Batemans Bay is the region reported to have been affected by megatsunamis. NSW = New South Wales, NT = Northern Territory, SA = South Australia,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

A model for assessing the vulnerability of buildings to tsunami

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

Recently, Dall’Osso *et al*., (2009) presented a newly revised and improved version of the model – PTVA-3. The RVI score of a building is calculated as a weighted sum of two separate elements:

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

2. the vulnerability of building elements due to their contact with water (*WV*).

For further information about the model, its structure and the method for assessing vulnerability, see Dall’Osso and Dominey-Howes (2009) and Dall’Osso *et al*., (2009). We used a Geographic Information System (GIS) in which to run the model analysis and present the results in map form. Dall’Osso *et al*., (In press) applied the newly revised PTVA-3 model to a detailed case study of Manly, Sydney (Figure 1b, c). The aims of this paper are to provide a ‘snap-shot’ synthesis of the study of Dall’Osso and Dominey-Howes (2009) and Dall’Osso *et al*., (In press) and to explore the emergency risk management and land use/building implications of their assessments of individual building vulnerability.

Results

For a full description of the results of the case study, see Dall’Osso and Dominey-Howes (2009) and Dall’Osso *et al*., (In press). Since the area inundated in this study was large, we originally presented our assessment of building vulnerability in four separate blocks (referred to as ‘Manly, Block 1 to 4) (Figure 2).

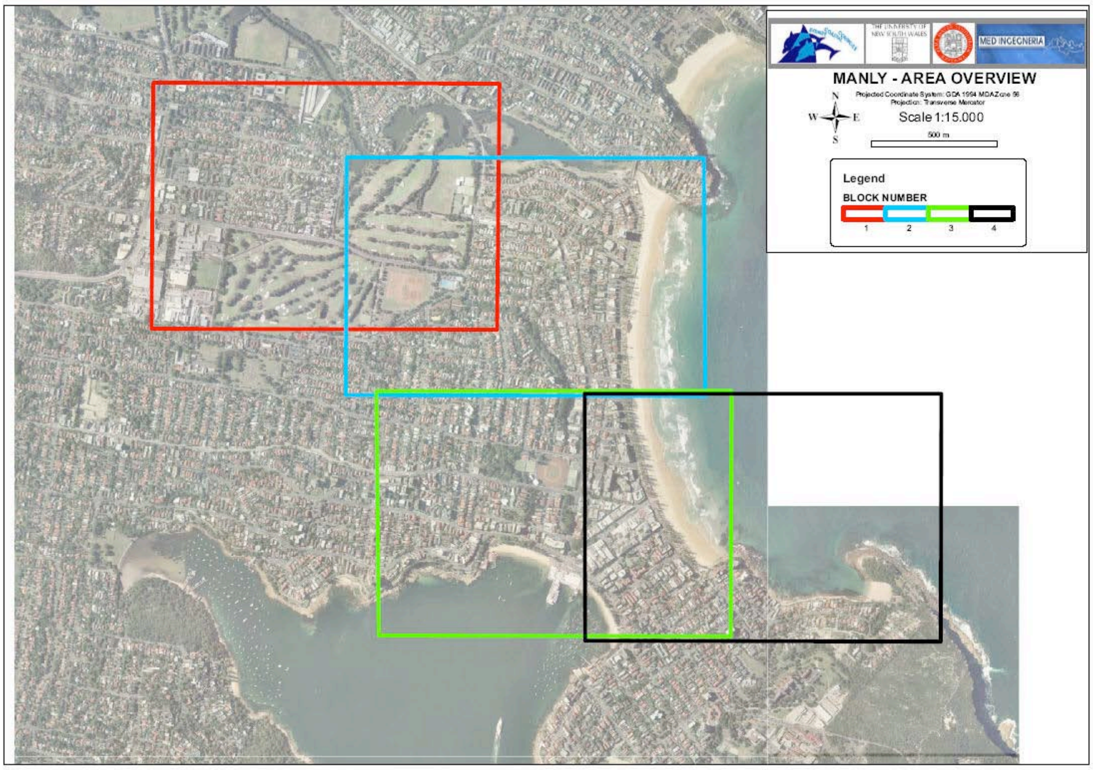

Figure 2 The Manly study area divided in to four (4) 'Blocks' for ease of results presentation. This paper just deals with Block 2

Different stakeholders will inevitably choose to explore the vulnerability of different types or 'classes' of buildings depending on their own interests or responsibilities. We classified the buildings in to the following nine building categories:

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

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

An area in excess of 169 hectares would be inundated and a total of 1133 individual buildings (plus 8 sites that were under construction at the time this study was undertaken) would be 'touched' by tsunami flood-water (Figure 1c). This represents total 'exposure'. In our study, we actually generated some 40 different 'maps of building vulnerability' across the study area (and relating to Blocks 1 to 4) but here we only focus on a few selected results for illustrative purposes only.

The main findings of Dall'Osso and Dominey-Howes (2009) and Dall'Osso *et al.*, (In press) are summarised in Table 1. Table 1 indicates that of the 1100+ buildings assessed, the majority of the building stock is residential followed by commercial. An example of the spatial distribution of all buildings in Block 2 of different classes, together with their RVI scores is shown in Figure 3. The absolute number of buildings in each class assessed as having a particular RVI score are indicated in columns 3 to 7 of Table 1. It is clear therefore, that the application of the PTVA-3 Model to individual buildings located within an expected inundation zone can provide very high-resolution information about the spatial vulnerability of buildings and by analogy, the population in that area. The 'take home message' from Table 1 is that commercial and residential structures have the highest absolute number of buildings assessed as having "High" and "Very High" RVI scores.

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	-	-	-	-	-

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

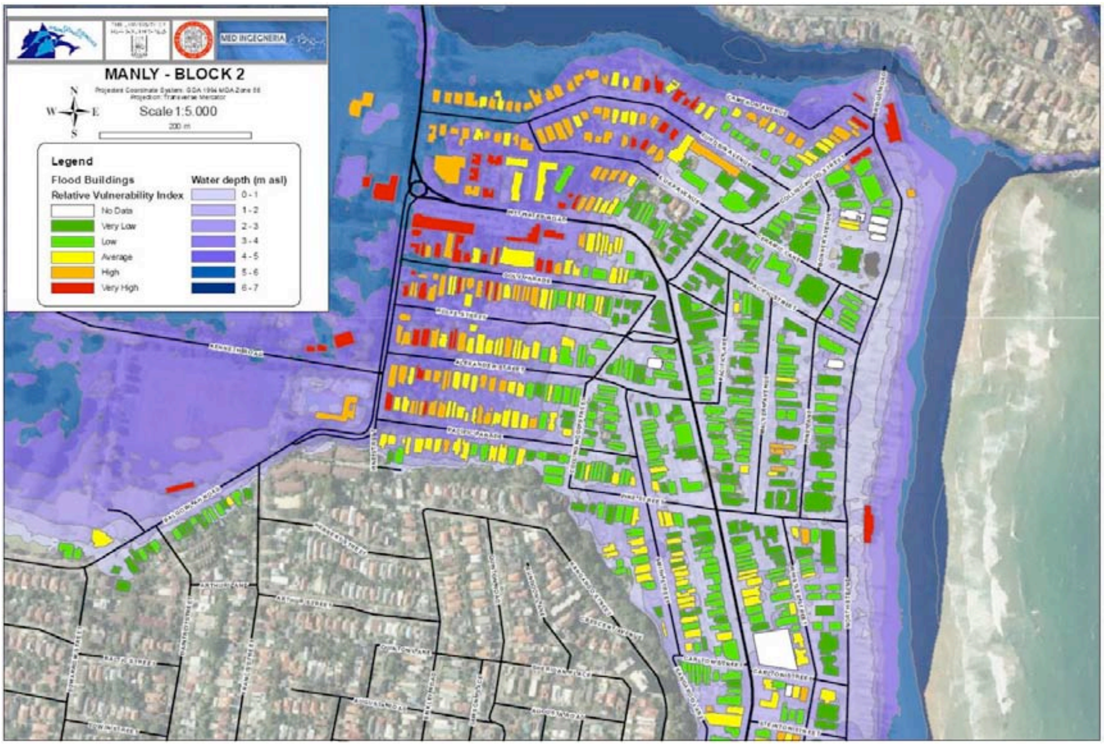

Figure 3 Tsunami inundation and water depth in Block 2 (Figure 2), Manly. The RVI scores of every building of all classes located within the inundation zone are indicated. Depth of flood water (in metres) above ground surface is shown

The area of Block 2 inundated in our scenario is indicated in Figure 3. 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. The depth of flood-water over the land surface is highest along the narrow coastal beach strip to the east of Block 2 and towards the northwest adjacent to Manly Lagoon.

A large number of buildings of all types would be 'touched' by the tsunami. This represents the total 'exposure' to potential damage during the hypothetical tsunami and it is clearly high. Figure 3 displays the calculated RVI scores of each building 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 sectors.

Discussion and conclusions

Assessing the vulnerability of buildings to potential tsunami damage is a vital necessity for developing appropriate risk management strategies.

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

The *risk* to Manly (that is, the probability for damage and loss) associated with the tsunami in our scenario is very large. The total surface area covered by flood-water is significant and a large number of buildings (1141) would be inundated. Water flow depth above ground surface in some areas would be as great as 7 metres. In such a situation, it is very difficult to imagine how any buildings would escape some degree of damage.

Not-with-standing the limited data presented here, the following important observations are made:

- Most buildings within our study area belong to the commercial and residential building classes;
- Table 1 indicates that the largest number of buildings classified as having “High” and “Very High” RVI scores are in fact, residential followed by commercial;
- Whilst only relatively small numbers of individual buildings are associated with the local government, health and medical services, education, recreation and culture, utilities, transport and tourism sectors, in some cases (such as in Block 2 (see Figure 3), significant proportions of those buildings (e.g., those that are the responsibility of the local government) are classified as having “High” and “Very High” RVI scores. This we believe is particularly problematic because in most cases, those local government buildings with “High” and “Very High” RVI scores are also Surf Life Saving Club houses. Surf Life Savers are first responders for beach goers in the event of an emergency and damage to these structures might severely affect the capacity of the Life Savers to respond. Furthermore, ultimately, the local community will have to cover the cost of reconstruction of such structures via local taxes. To varying 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 relevant owners of those buildings to improve resilience;
- The identification of ‘significant’ buildings (e.g., schools and nursing homes) as having “High” and “Very High” RVI scores is worrying and again, it is likely that relevant stakeholders might wish to consider how they might address the vulnerability of these buildings to likely damage;
- With regard to the residential buildings located in Manly (Figure 3), 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. Further, the depth of the tsunami flood water above the ground surface is less closer to the sea and greater closer to the lagoon;
- Some of the residential buildings with “High” and “Very High” RVI scores will actually be ‘publically’ owned and managed and will be under the responsibility of local government or housing charities. 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 tenants.

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

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

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

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

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

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

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

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

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

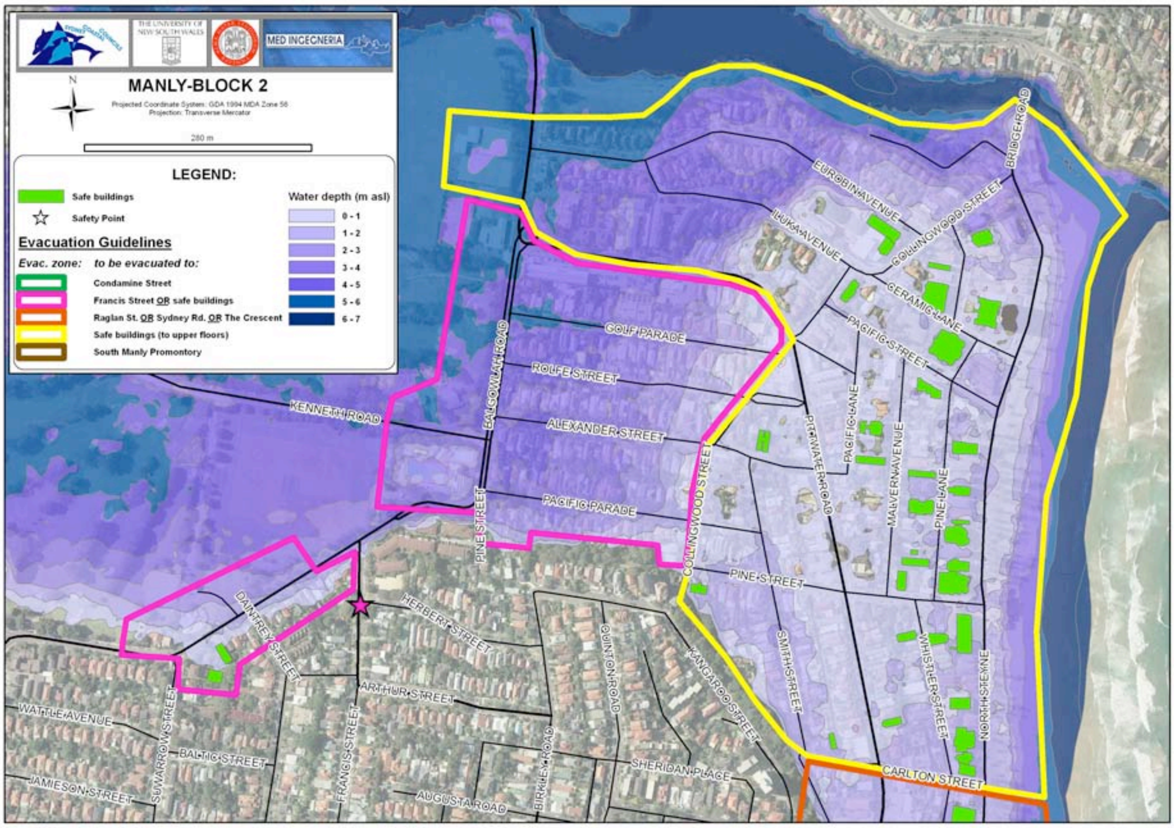

Figure 4 Evacuation areas and 'safe' buildings for evacuation, Block 2, Manly

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

Conclusion

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

References

Bird, D. and Dominey-Howes, D. (2008). Testing the use of a ‘questionnaire survey instrument’ to investigate public perceptions of tsunami hazard and risk in Sydney, Australia. *Natural Hazards*, 45, 99-122.

Bird, D. and Dominey-Howes, D. (2006). Tsunami risk mitigation and the issue of public awareness. *The Australian Journal of Emergency Management*, 21 (4), 29-35.

Bryant, E. 2008: Tsunami: The underrated hazard (2nd ed.): Chichester, Springer Praxis Publishing, 342 p.

Dall’Osso, F. and Dominey-Howes, D. 2009. A method for assessing the vulnerability of buildings to catastrophic (tsunami) marine flooding. Unpublished report. Pp139 Report available at http://www.sydneycoastalcouncsilsgroup.com.au

Dall’Osso, F., Gonella, M., Gabbianelli, G., Withycombe, G. and Dominey-Howes, D. (2009). A revised (PTVA) model for assessing the vulnerability of buildings to tsunami damage. *Natural Hazards and Earth System Sciences*, 9, 1557-1565.

Dall’Osso, F., Gonella, M., Gabbianelli, G., Withycombe, G. and Dominey-Howes, D. (In press). The vulnerability of buildings to tsunami in Sydney. *Natural Hazards and Earth System Sciences*.

Dominey-Howes, D. (2007). Geological and historical records of Australian tsunami. *Marine Geology*, 239, 99-123.

Dominey-Howes, D. and Papathoma, M. (2007). Validating a Tsunami Vulnerability Assessment Model (the PTVA Model) Using Field Data from the 2004 Indian Ocean Tsunami. *Natural Hazards*, 40, 113-136.

Dominey-Howes, D., Dunbar, P., Vernar, J. and Papathoma-Köhle, M. (In press). Estimating probable maximum loss from a Cascadia tsunami. *Natural Hazards*.

Goff, J. and Dominey-Howes, D. (In press). Australasian palaeotsunamis – do Australia and New Zealand have a shared trans-Tasman prehistory? *Earth Science Reviews*.

Hall, G., Stevens, R. and Sexton, J. (2008). Tsunami planning and preparation in Western Australia: application of scientific modelling and community engagement. *The Australian Journal of Emeregency Management*, 23 (4), 30-36.

Papathoma, M., and Dominey-Howes, D. (2003). Tsunami vulnerability assessment and its implications for coastal hazard analysis and disaster management planning, Gulf of Corinth, Greece. *Natural Hazards and Earth System Sciences*, 3, 733–747.

Papathoma, M., Dominey-Howes, D., Zong, Y., and Smith, D. (2003). Assessing Tsunami vulnerability, an example from Herakleio, Crete. *Natural Hazards and Earth System Sciences*, 3, 377-389.