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Assessing the vulnerability of buildings to tsunami in Sydney

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

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1 Introduction

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

For the coast of New South Wales (NSW) in SE Australia (Fig. 1a), tide-gauge records show that historically, only small tsunamis have affected the region (Dominey-Howes, 2007). Reported geological evidence however, suggests that megatsunamis many times larger than the 2004 IOT may have occurred repeatedly during the Holocene (Bryant, 2001; Bryant et al., 1992a, b; Young and Bryant, 1992; Nott, 1997, 2004; Bryant and Nott, 2001; Bryant and Young, 1996; Switzer et al., 2005; Young, et al., 1995, 1996) (Fig. 1a). This geological work has led to the development of what has been referred to as the "Australian Megatsunami Hypothesis" or AMH (Goff et al., 2003). The evidence for the AMH is very controversial (Felton and Crook, 2003; Goff and McFadgen, 2003; Goff et al., 2003; Noormets et al., 2004). First, some of the proposed evidence for megatsunamis has clearly been incorrectly interpreted (Dominey-Howes et al., 2006). Second, there appears to be a disjunct or miss-match between

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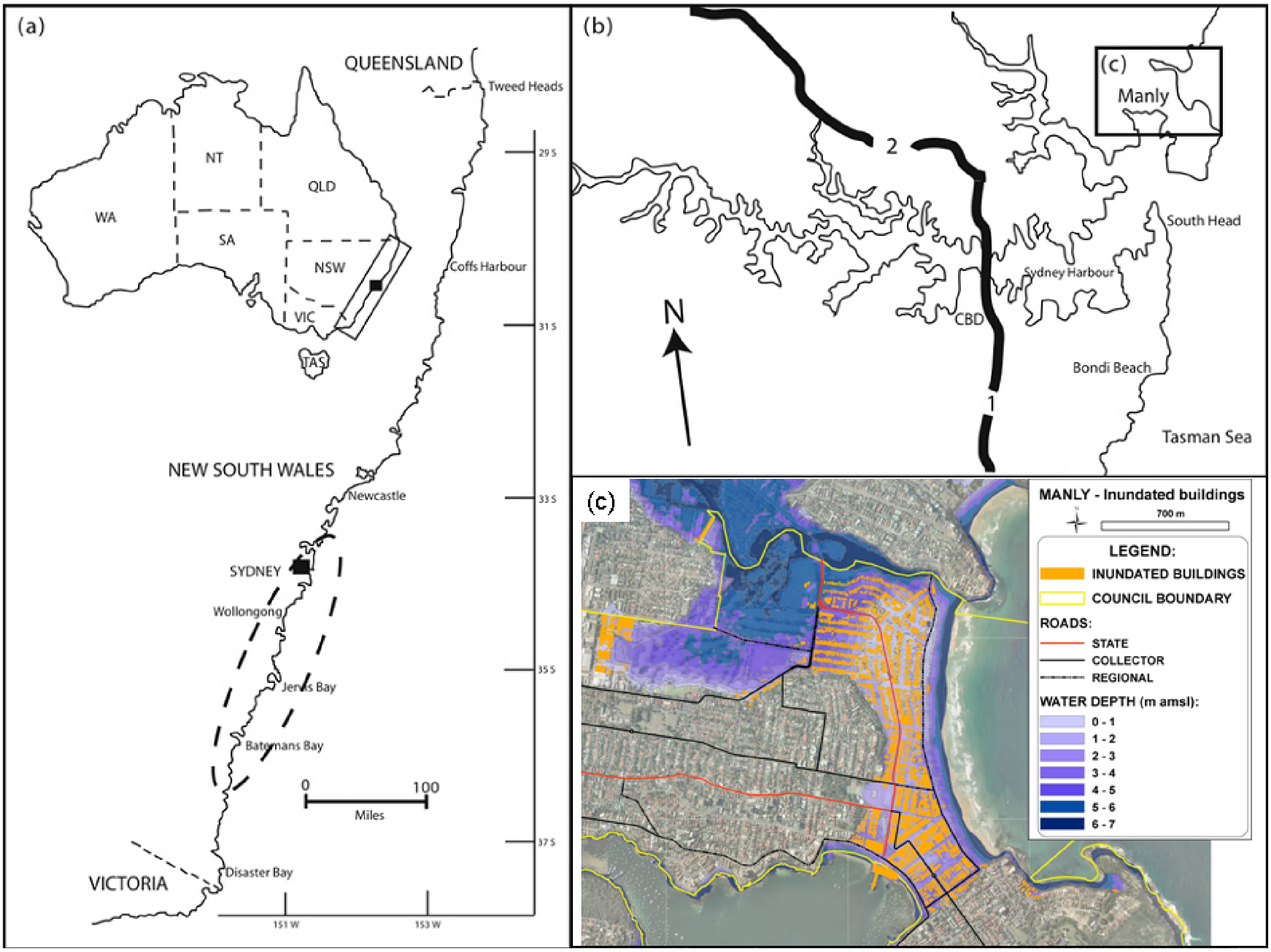

Fig. 1. **(a)** Broad location of the study region of Sydney, New South Wales (NSW), SE Australia. The hatched oval encompassing the region north of Sydney south to beyond Batemans Bay is the region reported to have been affected by Holocene megatsunami (Bryant, 2008). NSW = New South Wales, NT = Northern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

the historic record of small frequent events and the Holocene record of large infrequent tsunamis (Dominey-Howes, 2007). Last, no independent verification of the sources of these events has been undertaken – a vital component for understanding risk (Dawson, 1999). Bryant (2008) however, advocates a cosmogenic source for these events although this hypothesis also remains to be proven.

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

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

The aims of this work are to:

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

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

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

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

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

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

- a submarine sediment slide occurs off-shore of Sydney;

- the slide occurs without an earthquake trigger (i.e., no natural warning sign);

- a tsunami arrives at shore within 10–15 min of its generation;

- the tsunami achieves a flood run-up height of +5 m a.s.l. and occurs on top of the maximum astronomical tide along the Sydney coast which is 2 m (www.maritime.nsw.gov.au). Consequently, our flood event achieves a maximum run-up of +7 m a.m.s.l.;

- we assume the main direction of flow of the tsunami inundation is perpendicular to the shore;

- we are only considering a single wave inundation; and

- we do not include flow velocity or entrainment of debris and sediment in the water.

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

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

3 Method

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

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

- a geo-referenced and ortho-rectified aerial image of Manly that is used as the geographical base of the study. The aerial image was useful when it was necessary to manually digitize building vector files and for obtaining specific building features needed by the model (e.g., shape and orientation of the building footprint, building row, the presence of movable objects and protection provided by natural barriers). This image was provided by Manly LGA;

- a Digital Elevation Model (DEM) extracted from stereo aerial photos with horizontal resolution of 1 m. The DEM was used to calculate the water depth above the ground surface by subtracting the ground elevation from the horizontal flood surface at specific grid (building) points. The DEM was also provided by Manly LGA;

- a shapefile of polygons representing all the building footprints. The shapefiles were also provided by Manly LGA. Building attribute data were then manually entered in to the GIS database for each building file; and
- attribute data for each building. The data included both building and urban environment data (e.g., seawalls, etc.). These datasets were not available from Manly LGA and so we undertook field surveys to collect these data building-by-building.

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

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

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

4 Results

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

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

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

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

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

4.1 Block 2

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

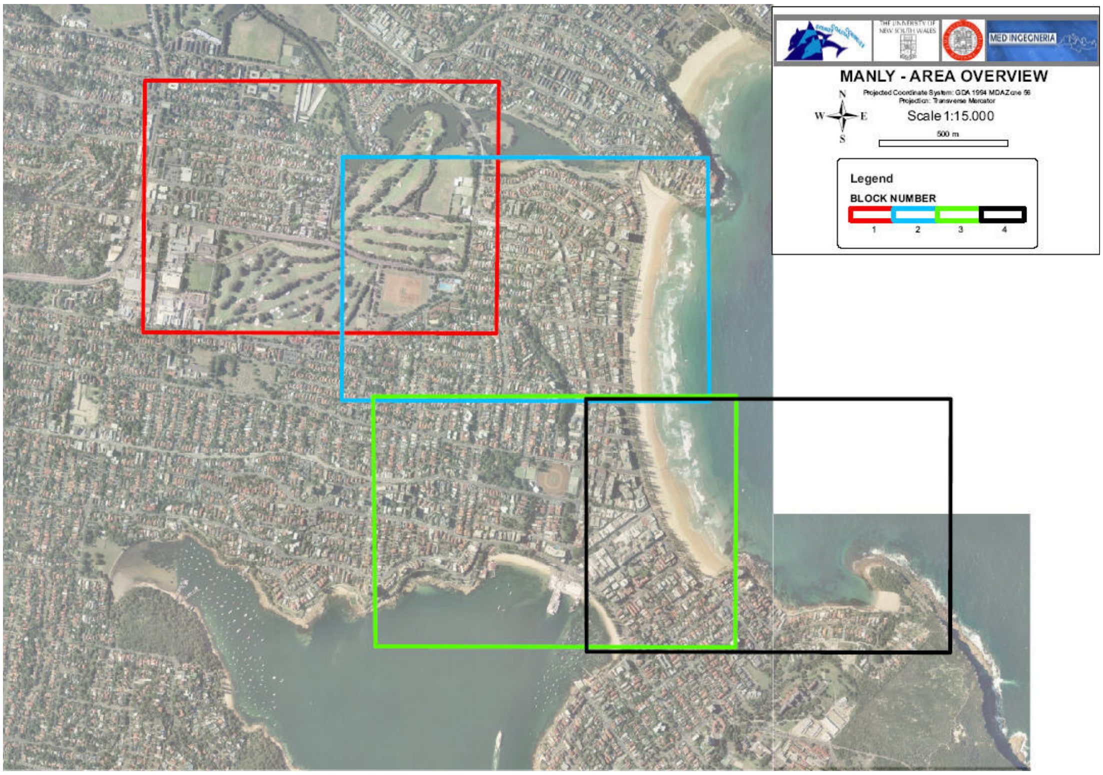

Fig. 2. The Manly study area divided into four (4) "Blocks" for ease of results presentation. This paper just deals with Blocks 2 and 3.

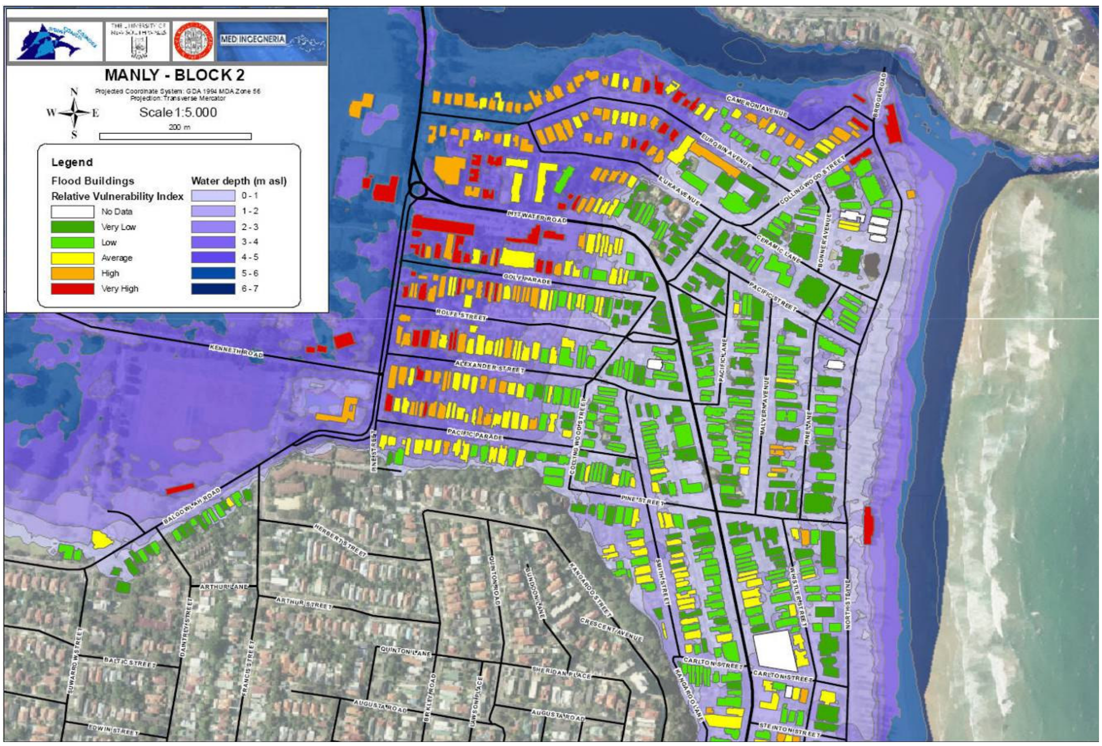

Fig. 3. Tsunami inundation and water depth in Block 2, Manly. The expected water depth at, and the RVI scores of, every building located within the inundation zone are shown.

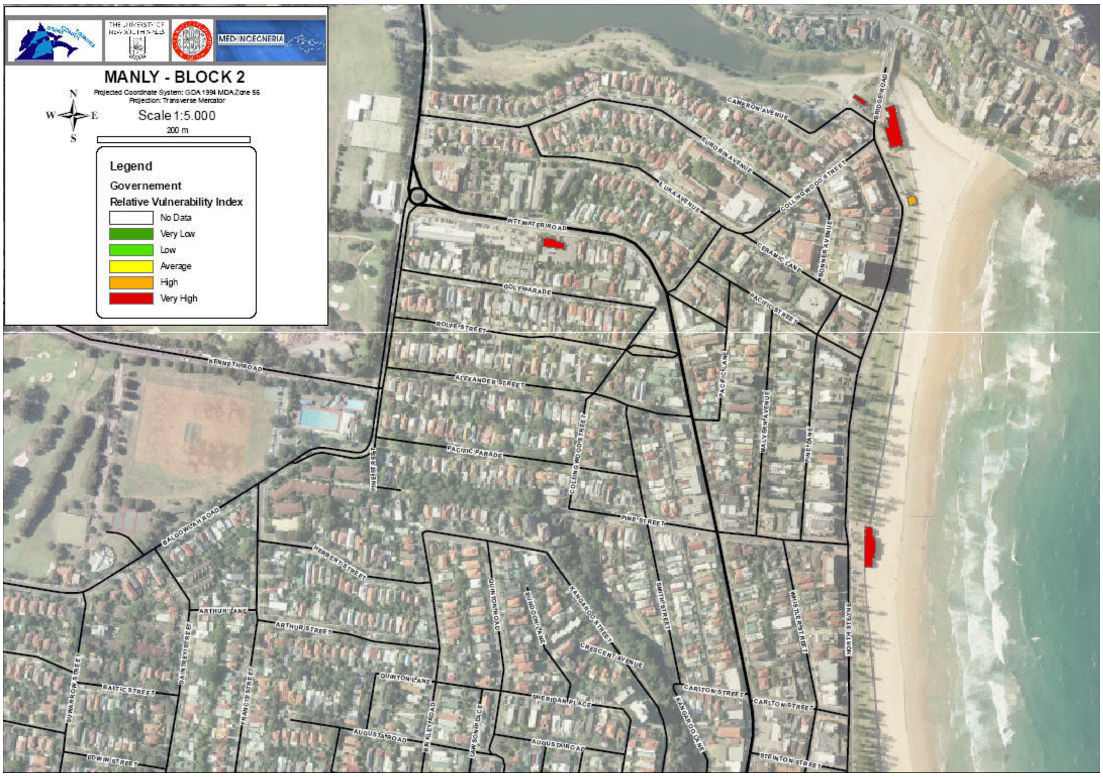

Fig. 4. The spatial distribution and calculated RVI scores of all local government buildings within the tsunami inundation zone of Block 2, Manly.

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

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

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

4.2 Block 3

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

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

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

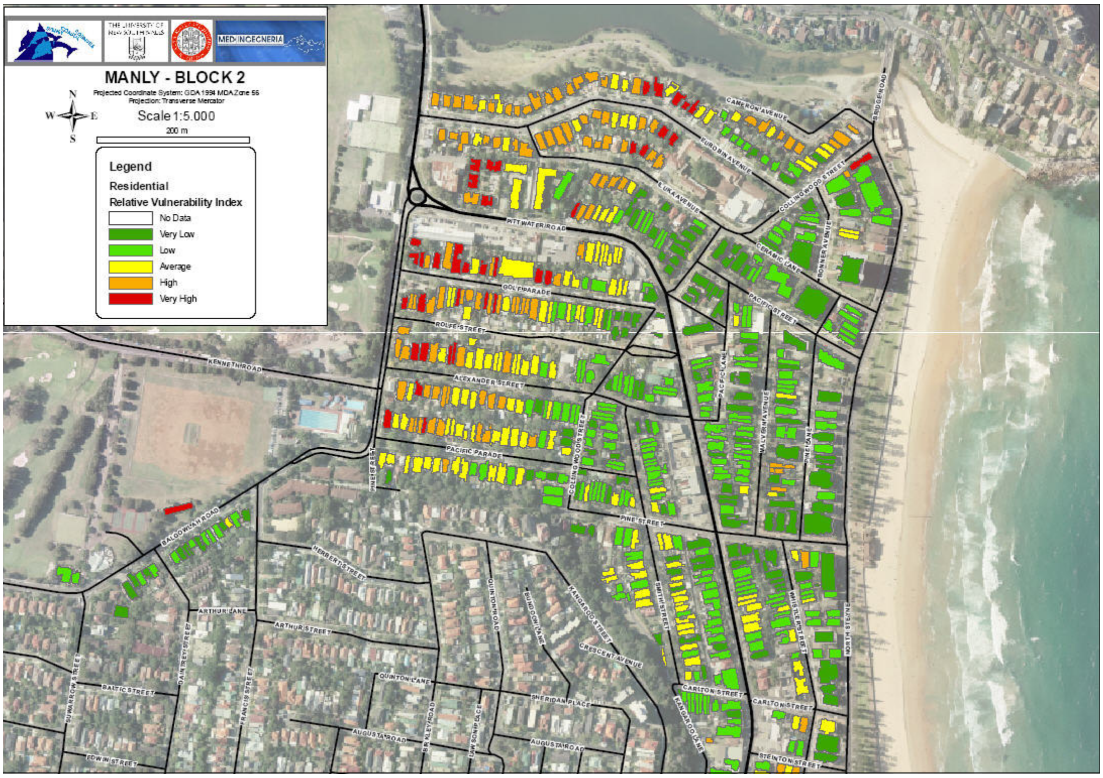

Fig. 7. The spatial distribution and calculated RVI scores of all residential buildings within the tsunami inundation zone of Block 2, Manly.

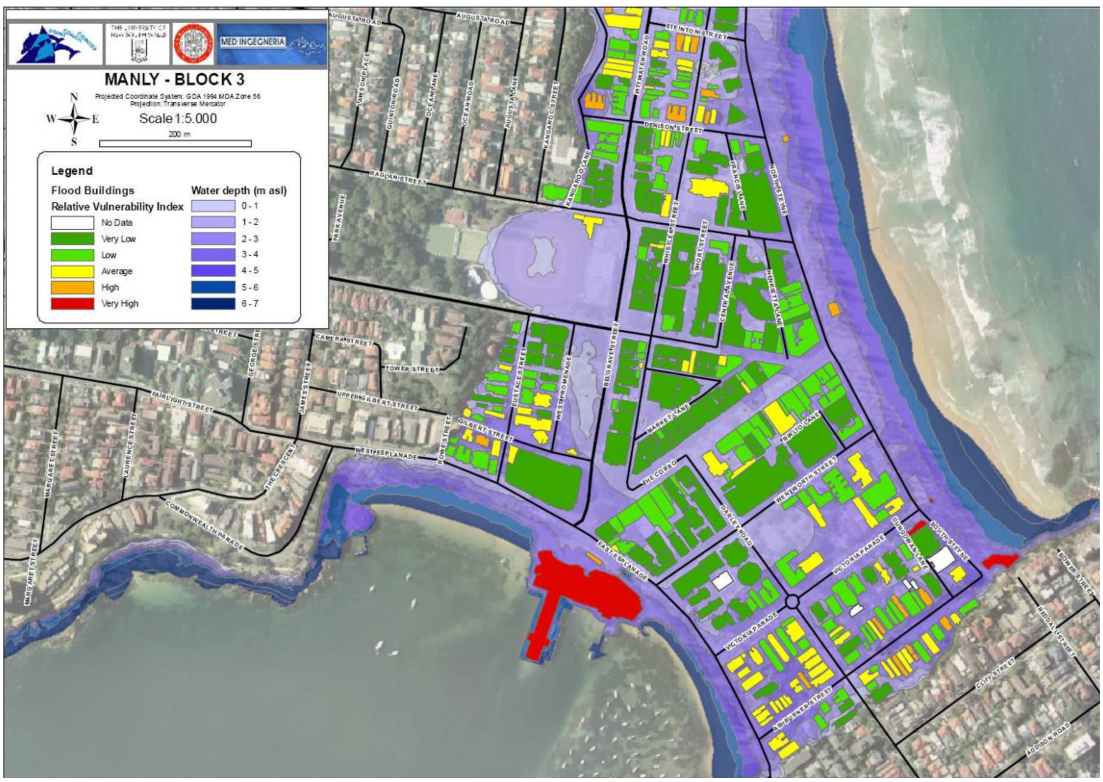

Fig. 8. Tsunami inundation and water depth in Block 3, Manly. The RVI scores of every building located within the inundation zone are indicated.

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

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

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

4.3 Total building vulnerability

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

5 Discussion and conclusions

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

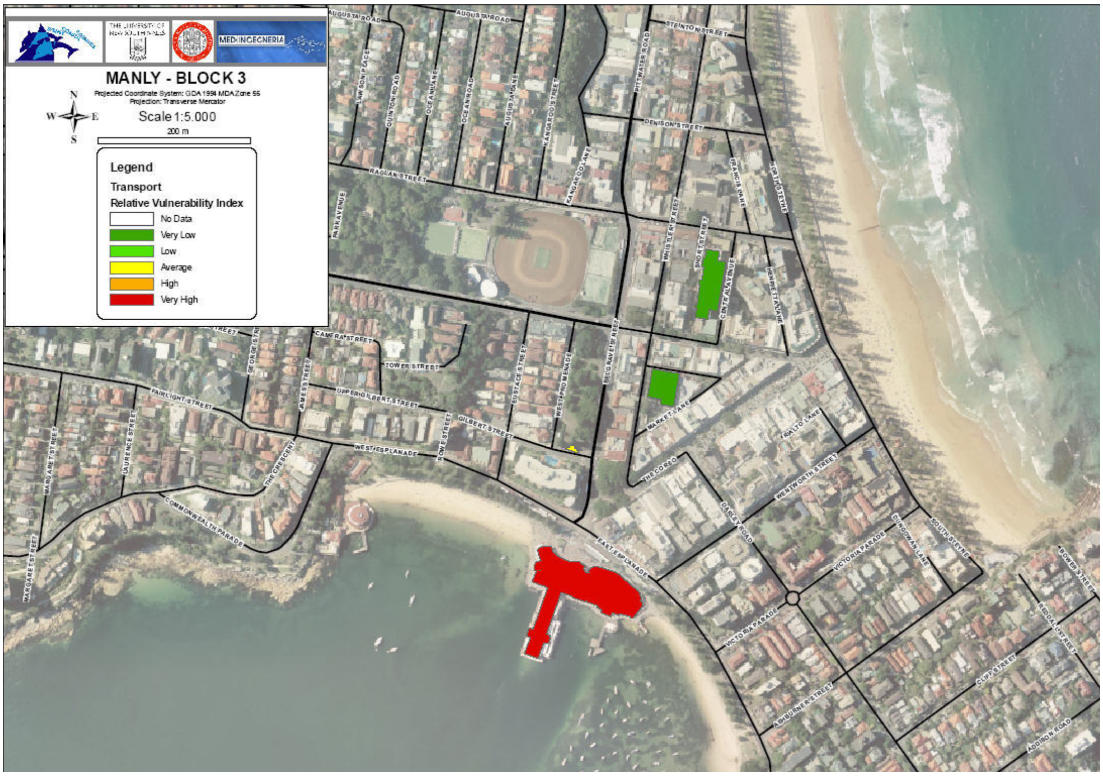

Fig. 10. The spatial distribution and calculated RVI scores of all transport buildings within the tsunami inundation zone of Block 3, Manly.

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

Manly (Blocks 1–4)		Relative Vulnerability Index (RVI) Scores				
Building type	Number of buildings	Buildings with "Very Low" RVI	Buildings with "Low" RVI	Buildings with "Average" RVI	Buildings with "High" RVI	Buildings with "Very High" RVI
Local Government	23	4	9	3	1	6
Health and Medical	19	10	5	3	0	1
Education	19	7	5	6	1	0
Recreation and 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	–	–	–	–	–

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

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

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

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

- most buildings within our study area (Blocks 2 and 3) belong to the commercial and residential building classes;

- Table 1 indicates that the largest number of buildings classified as having "High" and "Very High" RVI scores are in fact residential followed by commercial;

- whilst only relatively small numbers of individual buildings are associated with the local government, health and medical services, education, recreation and culture, utilities, transport and tourism sectors, in some cases (such as in Block 2, see Fig. 4, and Block 3, see Fig. 9) significant proportions of those buildings (e.g., those that are the responsibility of the local government) are classified as having "High" and "Very High" RVI scores. We consider this as particularly problematic because in most cases, those local government buildings with "High" and "Very High" RVI scores are also Surf Life Saving Club houses. Surf Life Savers are first responders for emergency cases on beaches and nearby water, and damage to their structures might severely affect the capacity of the Life Savers to respond. To varying degrees, Council is either directly responsible for the upkeep and condition of these buildings, or has a strong interest in those buildings being well maintained (e.g., of medical and health service, utility or transport buildings). Therefore Council will either need to directly examine how those structures can be modified to reduce their vulnerability or work with the relevant owners of those buildings to improve their structural resilience;

- the identification of 'significant' buildings (e.g., schools and nursing homes) as having "High" and "Very High" RVI scores is worrying and again, it is likely that relevant stakeholders might wish to consider how they might address the vulnerability of these buildings to likely damage;

- with regard to the residential buildings located in Block 2, Manly (Fig. 7), it is apparent that most structures closer to the sea are in fact assessed as having "lower" RVI scores than those further inland. Though this is counter intuitive, it is because houses built closer to the coast are much newer than those located inland and have been built to newer, higher standards. Further, the depth of the tsunami flood water above the ground surface is less at the shoreline and greater closer to the lagoon;

- we acknowledge that large numbers of those residential buildings classified with "High" and "Very High" RVI scores will be privately owned and the responsibility to address such vulnerability will lie with the individual home owners. However, the emergency services may well be interested to knowing more about the demographic characteristics and any special needs of the occupants of vulnerable houses;

- some of the residential buildings with "High" and "Very High" RVI scores will actually be "publically" owned and managed. Those structures will be under the responsibility of local government or housing charities, who should explore the implications of the vulnerability assessment to the security of their tenants; and finally

- the Manly Wharf transport structure (see Fig. 8) has been classified as having a "Very High" RVI score. Given than more than 8 million day tripper visitors per year visit Manly via the ferries that dock at this wharf and many more local people use the ferry service to get to and from the city (and that the wharf houses many private businesses), we feel that addressing the vulnerability of this structure ought to be a priority for the relevant authorities. Lastly, the car park located below ground level at the wharf would be completely inundated, worsening the damage level to the Manly transport system.

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

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

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