Progress towards an understanding of tsunami risk in NSW.

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Abstract

Tsunamis pose considerable risk to coastal communities around the globe and understanding this risk is a key aspect of emergency management and risk reduction. This paper explores the nature and extent of tsunami hazard to NSW coastal communities and informs tsunami emergency planning and management.

We outline the results of recent risk scoping which has examined sources of tsunami hazard, and tsunami history together with results of inundation studies for selected sites and then discuss the level of tsunami risk to NSW communities. We also outline how the results have complemented research by the Australian Bureau of Meteorology in confirming tsunami warning thresholds for NSW.

Work undertaken to date indicates that the coast of NSW has a moderate tsunami hazard level. Whilst historical impact of tsunami inundation in NSW has been relatively minor, and generally restricted to marine based events, the modelling of selected earthquake generated events indicates the potential for land inundation, particularly at high (rare) return periods. Low lying populated communities around estuary foreshores are particularly at risk, although results also indicate there is potential for inundation of open coast sites at very high (very rare) return periods.

The results confirm the need for and support the ongoing collaborative development of emergency management arrangements for tsunami.

Introduction

Considerable advances have been made in the management of tsunami risk in Australia over the last decade. This includes the introduction of the Australian Tsunami Warning System (Bureau of Meteorology 2013a), which included the establishment of the Joint Australian Tsunami Warning Centre, the upgrade and expansion of sea-level and seismic monitoring networks as well as the implementation of national education and training programmes; along with considerable work on offshore probabilistic tsunami hazard definition (Geoscience Australia 2013, Burbidge et al., 2008).

Within NSW the release of the NSW Tsunami Emergency Sub Plan (NSW SES 2006, 2008) a sub plan of the then NSW Disaster Plan (Displan), now NSW Emergency Management Plan (EMPlan) marked a major step forward in the prevention, preparedness, response and recovery from tsunami. The sub-plan outlines responsibilities and arrangements for emergency management of tsunami in NSW; however it also highlighted the lack of knowledge of tsunami hazard levels threatening NSW and the need for more detail to inform emergency planning and management (Gissing et al., 2008)

Work on hazards has included a state-wide risk scoping study (Somerville et al., 2009), which summarised knowledge on tsunami sources, tsunami history and provided a general assessment of tsunami risk on the NSW coast, along with a ranking of sites for inundation modelling. This study identified NSW as having moderate tsunami hazard level and suggested sites for future inundation modelling based on a broad-based risk assessment methodology incorporating offshore hazard levels (Thio and Summerville 2006), coastline shape (Baldock et al., 2007, 2008) and elevation based address data. Other work has also been undertaken on incorporating building type into vulnerability assessment (Dall'Osso et al., 2009).

In this paper we summarise the results of tsunami inundation modelling at five NSW coastal sites to provide for an improved understanding of the tsunami risk. This provides some information to begin to consider tsunami impacts in coastal zone management and planning, as well as assisting in the development of tsunami emergency planning, response and community education.

The study involves the modelling of tsunami resulting from earthquakes of a range of magnitudes, and from a variety of global source locations. Tsunamigenic databases developed by the Bureau of Meteorology and Geoscience Australia were utilised and scenarios from these were used as boundary conditions for shelf scale inundation models.

Background

Historical records of tsunami impacting the NSW coast include 40 events between 1866 and 2007 (Allport and Blong 1995, Dominey-Howes 2007). Since 2007 a further four tsunami events have been observed including tsunamis originating from earthquakes off the Solomon Islands, New Zealand, Chile and Japan (Bureau of Meteorology 2013b). The maximum run-up for a historical event is +1.7 m above sea level recorded at Eden on the 23rd May 1960 (Dominey-Howes 2007) although there are some reports that exceed this in isolated locations (Beccari, 2009). This tsunami was generated by the Chile earthquake event on the 22nd May. This event is also the most widely reported tsunami (>20 observations) (Beccari, 2009). Many of these records include observations of strong currents and rapidly oscillating water levels within bays and harbours. Several events have resulted in damage or grounding of boats and minor inundation of foreshores.

Geological studies also suggest tsunami impact along the NSW coast with seven events documented in the review by Dominey-Howes (2007). The oldest event is dated at 105 ka BP and is reported to have been generated by submarine sediment slides off Lanai, Hawai'i (Young et al., 1992, 1993, 1996). The six youngest palaeo-tsunami events all occurred during the Holocene. The causes of these other six events are unknown. The maximum run-up for a palaeo-tsunami is reported at possibly as much as +130 m above sea level at Steamers Beach, Jervis Bay, while another event is reported to have inundated the coast to distances of 10 km inland. (e.g. Bryant (2001); Bryant and Nott (2001); Bryant and Young (1996); Bryant et al., (1992a, b); Kelletat and Scheffers (2003); Nott (1997; 2003a, b); Switzer et al., (2005); Young and Bryant (1992) and Young, et al., (1995; 1996)). Some authors have however begun to question the evidence reported for these events (Felton and Crook, 2003; Goff and McFadgen, 2003; Goff et al., 2003; Noormets et al., 2004; Dominey-Howes et al., 2006). Most recently, Dominey-Howes et al., (2006) re-examined one of the key sites for a palaeo-megatsunami deposit (Minnamurra Point, Kiama), finding that the proposed tsunami deposited sediments were an in-situ soil horizon. Further work is required to examine the palaeo-tsunami record in order to check the accuracy of the palaeo-tsunami record (Dominey-Howes, 2007, Somerville et al., 2009).

Tsunamis are known to be generated by submarine earthquakes, volcanic eruptions, landslides, asteroids and meteorologic phenomena (Geoscience Australia 2013).

The majority of tsunamis are caused by earthquake-induced displacement of the seafloor typically along subduction interface plate boundaries (Burbidge et al., 2008). This includes the world's largest tsunami, including the Mw 9.5 1960 Chile earthquake, the Mw 9.2 1964 Alaska earthquake and the Mw 9.1 Sumatra–Andaman Islands earthquake of 26 December 2004 and the Mw 9.0 Japan earthquake of 11 March 2011 (USGS 2013). Smaller earthquakes can cause significant tsunamis as well, however their impact tends to be more localised.

At return periods of above 500 years Burbidge et al. (2008) and Thio and Somerville (2006) indicate only a few potential earthquake sources contribute to the tsunami hazard in NSW. These sources include the regional plate boundaries of the New Hebrides (Vanuatu), Kermadec and Puysegur trenches. This is because only a few sources can generate tsunamis having a large near shore wave amplitude. At a return period of less than 100 years (more frequent), however, many potential sources contribute to the tsunami hazard in NSW. These include both regional and distant plate boundaries and include the regional subduction zones off New Hebrides (Vanuatu), Kermadec and Puysegur, as well as distant sources off Peru, Chile and Indonesia.

There are at least five active volcanoes capable of generating a tsunami that could affect Australia (Rynn & Davidson 1999, Burbidge and Cummins, 2007) however, the Krakatau eruption of 26–27 August 1883 is the only documented eruption to have generated a tsunami that affected Australia (Gregson and Van Reeken, 1998) and is recorded in the NSW record (Dominey-Howes 2007). It caused 36 000 deaths in Indonesia and generated a tsunami in the Indian Ocean that was more extensive than the 2004 Indian Ocean tsunami.

Submarine slides are also a source for tsunami (Satake, 2001; Watts, 2004) although their effects tend to be more localised. It is worth noting however, that major submarine slides (e.g. in Hawaii, Satake, 2001) can generate giant tsunami that could devastate coastal regions thousands of miles away. Off the NSW coast numerous submarine slide scars can be seen on the continental slope, with several significant ones lying adjacent to Sydney (Jenkins & Keene, 1992, Glenn et al., 2008). One of the largest slides occurred off Bulli and was 10km wide and 20km long and is considered large enough to have generated a significant local tsunami (Somerville et al., 2009). Slope stability models based on measured sediment shear-strengths indicate that the upper slope sediments should be stable however, multibeam sonar data reveal that submarine land sliding is a common (geologically) process (Clark et al., 2012) thought to be related to earthquake occurrence (Hubble et al., 2012.). Clark et al. (2014) undertook morphologic characterisation of five distinct, eastern Australian upper continental slope submarine slides and modelling of their tsunami hazard. Their analysis suggests that the reoccurrence of submarine slides with similar characteristics to those shed from the margin in the geologically recent past would be expected to generate tsunami with maximum flow depths between 5 and 10 m at the coastline, run-up of up to 5 m and inundation distances of up to 1 km.

Tsunami can also be generated by asteroid strike impact on the ocean, and although there are no known examples during human history, there is geological evidence of ocean impacts from asteroid-tsunami. For example, there is evidence to suggest that a 1 km or larger object, the Eltanin asteroid, impacted the Southern Ocean circa 2.15 Ma (Gersonde et al., 1997).

Probabilistic modelling by Ward and Asphaug (2000) extrapolated to NSW indicates the return period for an asteroid generated tsunami with a wave amplitude of 1 metre at a water depth of 15 metres is approximately one thousand years. However, several other recent studies suggest this may be too frequent and a return interval for an event this size may be more likely to be around 10,000 years (Somerville et al., 2009).

In the current assessment we focus on earthquake related tsunami as the major contributor to the hazard, but note that other sources also need to be considered.

Study Sites

In the current study five coastal locations were selected for detailed inundation modelling based on work undertaken in the initial risk scoping study (Somerville et al., 2009). These study areas, shown in Figure 1, were identified in Stage 1 of the tsunami risk assessment as being potentially vulnerable to tsunami inundation. The five coastal locations were:-

- Swansea/Lake Macquarie
- Manly
- Botany Bay/Kurnell
- Wollongong/Port Kembla
- Merimbula

The extent of each study area was defined by local geomorphic features, such as headlands and embayments, and as far landward so as to define the full extent of expected tsunami inundation. This was nominally defined as the area up to the 15m AHD contour.

Methodology

Inundation models covering each of the study sites were established using the Delft3D software package. The Delft3D numerical scheme has been adopted in many tsunami studies worldwide and has been compared to world standard benchmark verifications with good agreement (Garber et al., 2011). For tsunami propagation and transformation Delft3D solves the non-linear shallow water equations, which have been shown to provide a good description of tsunami behaviour (e.g. Titov and Synolakis 1998).

For each site a digital elevation model was established using available terrain data. The DEM was developed from a range of sources including available hydrographic survey data (see MHL 2009), LiDAR data and the 250m Digital Terrain Model of Australia/NZ (Whiteway, 2009).

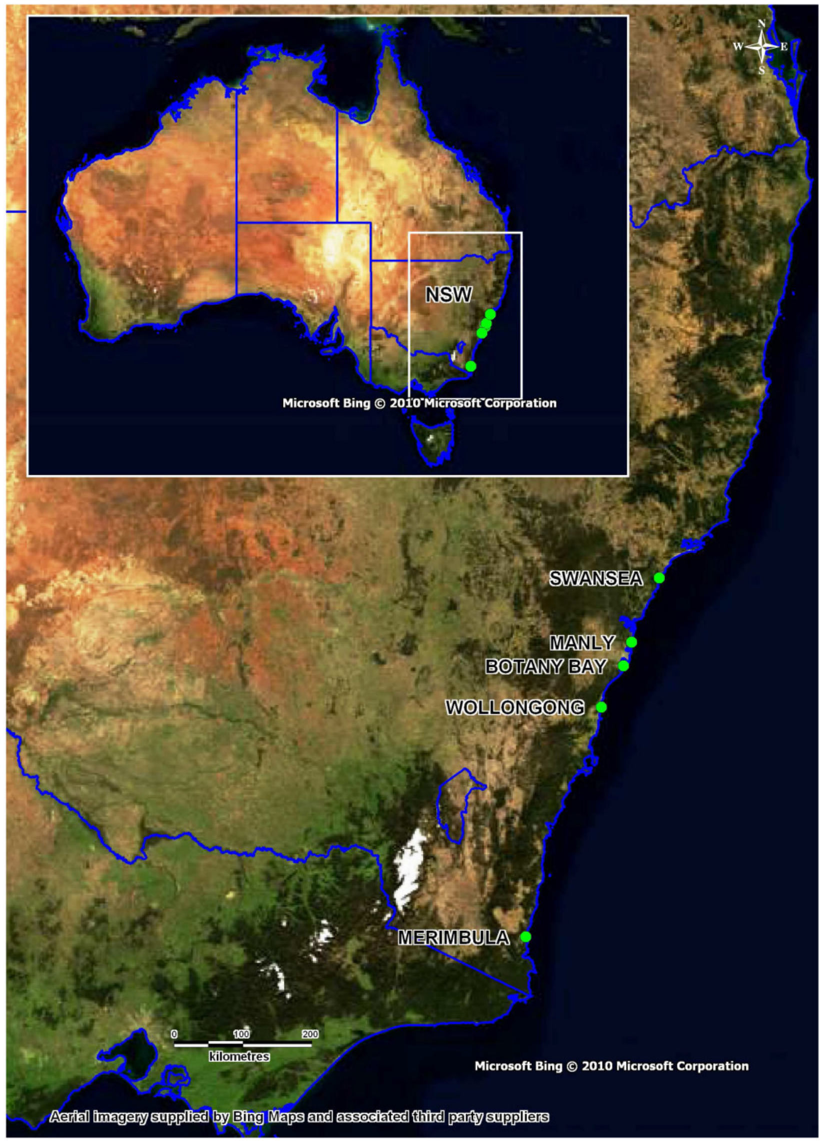

Figure 1 Study sites

Multi-domain model systems were established for each study site, with the extent and size of the individual study area grids varying depending on site specific features. Model setups at each site typically consisted of three to five nested grids extending around 50km north and south of each specific study area and out beyond the 3000m depth contour (50-100km offshore), beyond (east of) the continental shelf. This practice ensured that issues associated with high frequency boundary reflections were avoided at the offshore boundary. The offshore regional grids had resolution of 500m while on land 10m grids were extended up to the 15m AHD contour. Model setup incorporated spatially variable roughness allowing for variability in surface characteristics.

For tsunami event selection and the subsequent inundation modelling the Geoscience Australia Tsu-dat probabilistic database (Geoscience Australia, 2010) and the Bureau of Meteorology's Enhanced Tsunami Scenario Database: T2 (Greenslade et al., 2009) were utilised. For each site 24 events were selected to be representative of a range of different annual return periods (ARI)(200 year, 500 year, 1,000 year, 2,000 year, 5,000 year and 10,000 year) and to cover a range of potential source zones so that different sensitivities to approaching directions and alignments could be investigated (Table 1). Recurrence interval estimates are based on the recurrence intervals presented in Tsu-dat and are based on wave heights in 100m water depth associated with earthquake generated tsunamis. It should be noted that these may not necessarily lead to the equivalent ARI inundation extent and thus should be considered a best estimate only. Earthquake magnitudes associated with these return periods varied from around

8.6Mw to 9.3Mw. Model runs were initiated with a dynamic tidal condition with maximum tsunami wave amplitude coinciding with HAT or mean sea level (MSL).

Scenario No.	ARI (years)	Source Zone *	Water Level ^
S1	200	KER	HAT
S2	200	NHB	HAT
S3	200	PUY	HAT
S4	200	SCH	HAT
S5	200	TGA	HAT
S6	500	KER	HAT
S7	500	NHB	HAT
S8	500	PUY	HAT
S9	500	TGA	HAT
S10	1000	KER	HAT
S11	1000	NHB	HAT
S12	1000	PUY	HAT
S13	2000	KER	HAT
S14	2000	NHB	HAT
S15	2000	PUY	HAT
S16	2000	KER	MSL
S17	2000	NHB	MSL
S18	2000	PUY	MSL
S19	5000	NHB	HAT
S20	5000	PUY	HAT
S21	5000	NHB	MSL
S22	5000	PUY	MSL
S23	10000	NHB	HAT
S24	10000	PUY	HAT

Table 1: Summary List of Modelled Tsunami Scenarios at Each Location

* KER = Kermadec, NHB = New Hebrides, PUY = Puysegur, SCH = South Chile, TGA = Tonga ^ HAT = Highest Astronomical Tide, MSL = Mean Sea Level

The modelling was validated using the 1993 Okushiri Island (northern Japan) 'benchmark verification' case as well as tide gauge measurements for recent tsunami events along the NSW coast (for details see Garber et al., 2011).

Results

Mapped inundation extents for the indicative return periods are shown in Figure 2. The results of this inundation modelling show that the five sites are exposed to tsunami hazard with land inundation becoming significant particularly at the 1,000 to 2,000-year ARI level and above, although the results also indicate some potential inundation even at the lowest return intervals examined, particularly at Swansea. In general, overtopping of the open coast dunes is restricted to the rarest scenarios assessed with low lying estuary foreshores being more exposed at more frequent return periods.

The maximum runup heights above Australian Height Datum (AHD) at each site are shown in Figure 3. At the 200 year ARI level maximum runup heights vary between 2.3m AHD at Merimbula to 3.2m at Manly. At the 1,000 year ARI level maximum runup heights increase to between 3.64 m AHD in Botany Bay 4.80 m AHD at Manly. While at the 10,000 year ARI level maximum runup heights increase to between 4.87m AHD in Botany Bay 8.26m AHD at Swansea. The lower runup heights within Botany Bay are thought to be due to the relatively small entrance that restricts penetration of the tsunami into the Bay.

Discussion

NSW has had limited historical experience of inundation associated with tsunami, with most events being relatively small and impacts limited to marine based infrastructure associated with strong currents and minor foreshore inundation (Gissing et al., 2008, Beccari 2009). The results of the inundation modelling undertaken for this study, however, confirm that the NSW coast is subject to risk from land inundation associated with tsunami. The results show that on the open coast the frontal dunes generally provide some protection from tsunami with inundation becoming significant above the 5000 year ARI level, and particularly where dunes are lower. At lower return periods inundation of low lying areas along estuary foreshores is an issue. At many coastal towns in NSW there is considerable development adjacent to estuarine foreshores that is low lying and is more likely to be at risk from inundation associated with tsunamis at lower (more frequent) return periods.

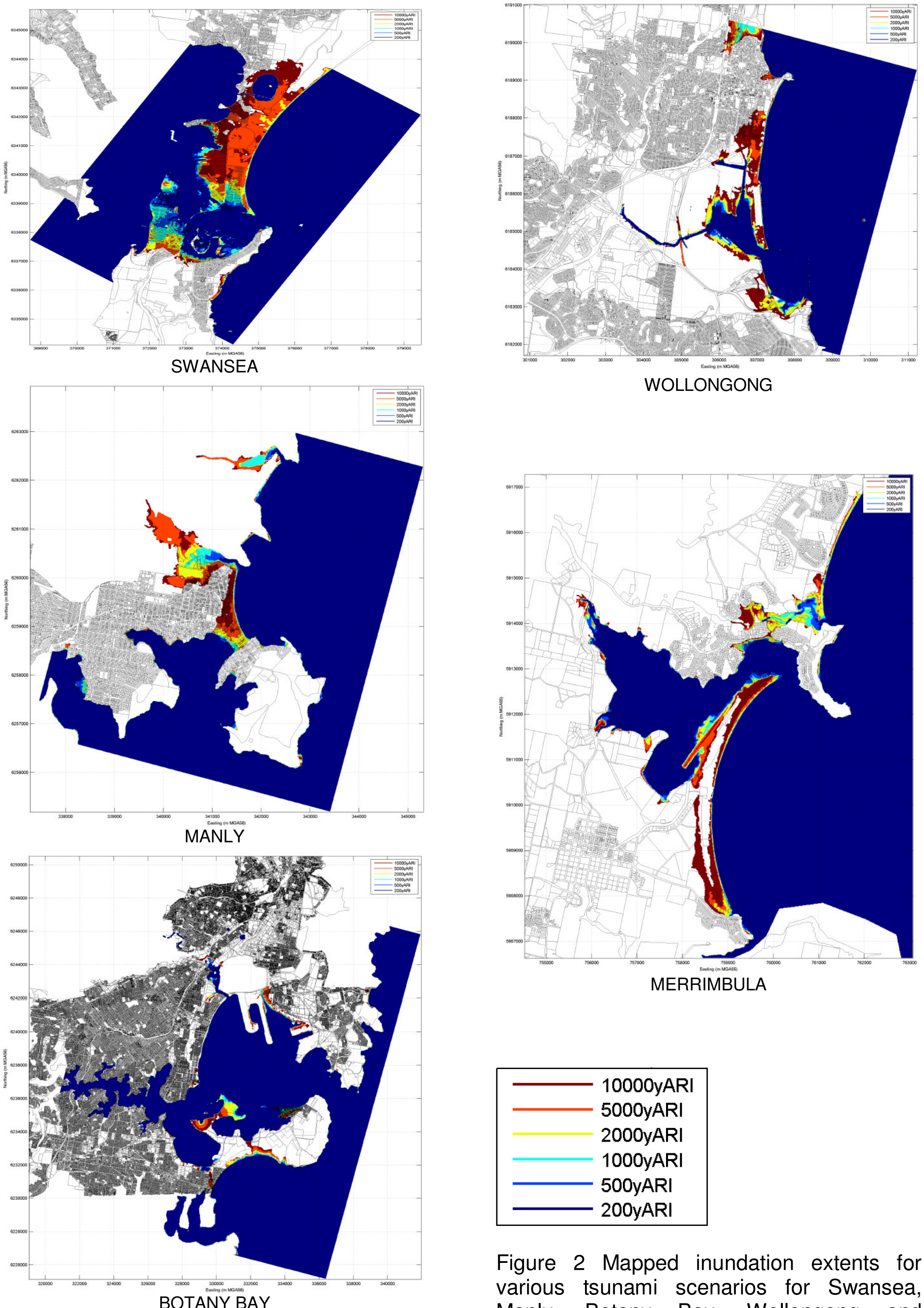

Figure 2 Mapped inundation extents for various tsunami scenarios for Swansea, Manly, Botany Bay, Wollongong and Merimbula.

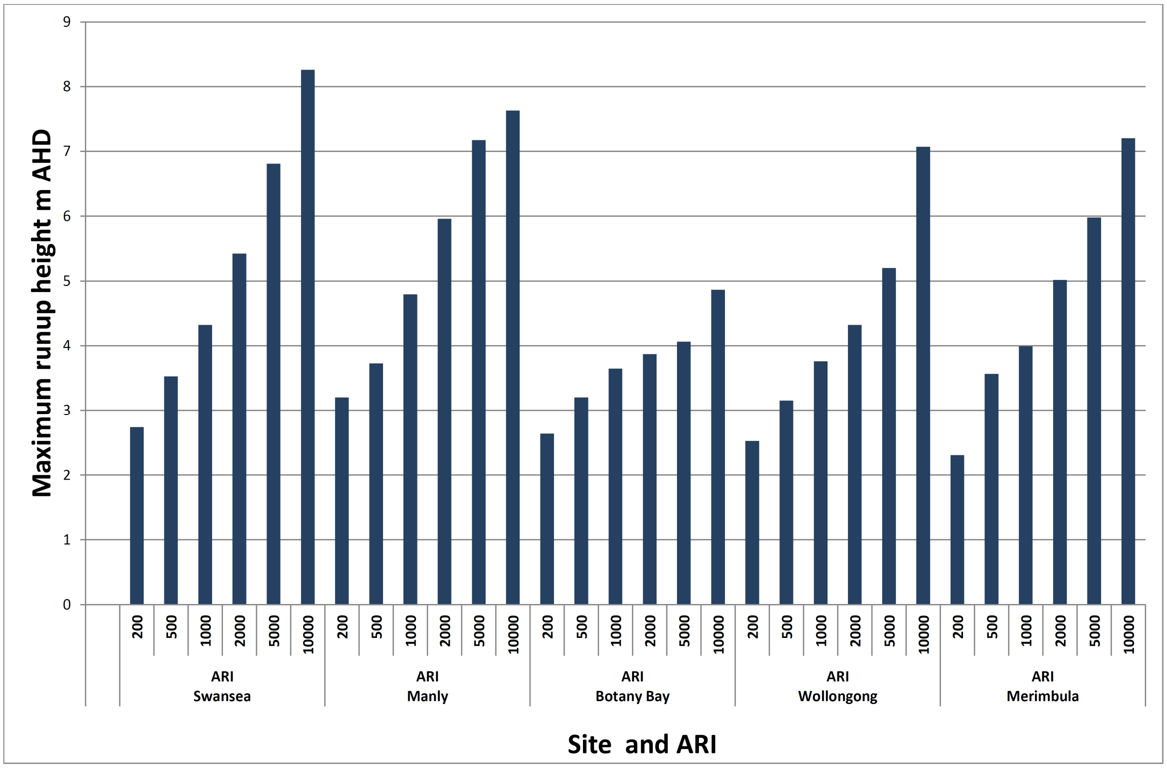

Figure 3 Maximum runup heights for each site and ARI level

In general inundation becomes significant, particularly at the 1,000 to 2,000-year ARI level and above, although the results show some inundation even at the lowest return intervals examined. For the lower (more frequent) return period events, some caution needs to exercised in the interpretation of the results, as the real probability of occurrence for these scenarios would need to consider the joint coincidence between the tsunami event and the tidal or water level condition at the time, which in the results presented, is set at HAT.

Within estuaries maximum wave height decreases as a result of refraction and diffraction as the tsunami propagates along the estuary/coastal river however localised resonant responses resulting in higher wave heights within small embayment's are also observed making generalisation difficult.

Uslu and Greenslade (2013) compare potential tsunami warnings issued by the Joint Australian Tsunami Warning Centre (JATWC) against the inundation modelling results reported here, with particular focus on the JATWC's pre-defined warning threshold levels. The results have indicated that the thresholds used by the JATWC warning scheme are in general set conservatively and they should not be modified on the basis of these results. Uslu and Greenslade (2013) also discuss the potential for improving the JATWC warnings by developing "tailored" threshold levels for each coastal zone, or by incorporating real-time inundation modelling in the forecast system.

NSW SES are using the inundation modelling results reported here to review and update evacuation area mapping particularly to address low lying development near estuaries. One issue that this work has attempted to deal with was the lack of detailed knowledge about potential inundation extents within rivers and estuaries which continues to be an area needing further research.

Limitations and qualifications

This study has involved the detailed numerical modelling of synthetic tsunami events propagating into complex nearshore and foreshore areas. The reliability and accuracy of the study outcomes are reliant on a range of underlying assumptions and data that have varying degrees of uncertainty. These relate to the numerical model setup and calibration which depends on the quality of data available. Boundary conditions have been derived from numerical modelling undertaken by the Bureau of Meteorology (Greenslade et al., 2011), which involves a number of assumptions based on the current understanding of subduction zone dimensions and seismic activity. It must be noted that the modelled scenarios will differ from real events and that no two events (even from the same source zone) will be the same.

Recurrence interval estimates identified within this study are based on the tsunami recurrence intervals presented in Tsu-dat (Geoscience Australia, 2010) through an aggregation process as described in Burbridge et al. (2008). Recurrence intervals are determined at the 100m depth contour. Tsunami run-up and inundation will be significantly influenced by the orientation of the coastline and the interaction of the incoming tsunami with the near shore region. As such, the resulting inundation from a (say) 500 year ARI tsunami in 100m water depth does not lead necessarily to the 500 year ARI inundation extent on land (could be higher or lower). Another consideration is the joint occurrence of the tsunami peak and tide level. In reality the peak of a tsunami could occur at any tide level, with those occurring at high tide presumably posing greater hazard. For most scenarios this study has adopted the highest astronomical tide (HAT) level at each site. It should be noted that while this seems conservative, non-astronomic contributors to coastal water levels (such as meteorological effects) result in this tide level being reached or exceeded several times a year. Furthermore, tsunami waves persist for some hours and would most likely encounter a high tide, even if not at a time of the highest tsunami wave amplitude.

No allowance has been made for geomorphic response (erosion/deposition) as a result of currents during a tsunami event.

Scenarios for other potential sources of tsunami, such as submarine slides, volcanos and shelf collapses, have not been considered within this assessment.

Readers should note that tsunami runup is dependent on local sea bed and coastal morphology. The runup heights reported here may be exceeded at other sites.

Conclusions and Recommendations

This paper summarises the results of inundation modelling for selected sites along the NSW coast undertaken as part of stage 2 of the NSW Tsunami Risk Assessment. This study has built upon earlier risk scoping work undertaken in stage 1 of this NSW assessment (Somerville et al. 2009.

This inundation modelling assessment has focused on subduction zone earthquake sources from around the Pacific basin, which account for most tsunami events that affect eastern Australia.

Numerical model simulations of selected tsunami scenarios have been undertaken using a calibrated Delft3D model system for five NSW coastal sites and the study has utilised data from the Tsu-dat and T2 databases developed by Geoscience Australia and Bureau of Meteorology, respectively. The model system has been demonstrated to reasonably simulate historical tsunami along the NSW coast and replicates the inundation from a benchmark event extremely well.

It is generally considered that the NSW coast has a moderate level of tsunami hazard, particularly when compared to other coastlines around Australia and the region. The results of this inundation modelling show the five sites are exposed to tsunami hazard with land inundation becoming significant particularly at the 1,000 to 2,000-year ARI level and above, although the results also indicate some potential inundation even at the lowest return intervals examined. In general overtopping of the open coast dunes is restricted to the rarest scenarios assessed with low lying estuary foreshores being more exposed at more frequent return periods.

The results of this inundation modelling show the NSW coast is exposed to tsunami hazard with. low lying estuary foreshores being more exposed at lower, more frequent return periods and overtopping of the open coast dunes possible at less frequent (very rare) return periods.

The results of this study confirm the need for and support the ongoing collaborative development of emergency management arrangements for tsunami.

The following recommendations are made:

- Further consideration of other potential sources of tsunami, such as shelf collapse, should be made in order to complete the understanding of tsunami risk along the NSW coast,
- Further investigation of tsunami behaviour within estuarine/coastal river systems is required to assess extent of penetration and rates of attenuation,
- Re-assess the Stage 1 coastal risk assessment based on the inundation modelling and new elevation data to revaluate exposure and its variability along the NSW coast.

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