Tsunami emergency risk management in Australia: maintaining the momentum

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Scenario

Imagine that, early in the morning of 4 March 2044, the pressures from the plate boundaries along the Tonga-Kermadec trench reach their tipping point and release a powerful magnitude 9.4 earthquake. Advanced atmospheric analysis, courtesy of the global satellite system, captures the details of the rupture in near real-time. These details are transmitted to the 24/7 operations centre of the Joint Australian Warning Centre for automatic input into a fast tsunami propagation model implemented on a quantum computer. Within 15 minutes of the rupture, a first-pass inundation model is created of the Australian eastern seaboard and digitally disseminated to all registered users. Meanwhile, you wake to an alarm on your wearable device that alerts you of a tsunami warning for your location. You don't panic. You know what to do. Just a few months ago, during the 2043 World Tsunami Awareness Day, your local community exercised a tsunami evacuation. You know where to go, what to take and you also know who in your neighbourhood will need help. Gone are the days when you need to take insurance papers as they are saved to your wearable device. You don't even need a phone charger because wireless charging has become widely available. But you take your medication and a change of clothes and your beloved pets and exit. You knock on your neighbour's door and leave on foot to the agreed marshalling point beyond the tsunami evacuation zone. There you convene with your neighbours and check on who isn't there and let the emergency services personnel know.

This future is one the emergency management sector is working towards. We have the components in place, we know the gaps and we need to maintain momentum. At a high level, we are developing faster and more accurate warnings as well as evidence-based information to underpin effective community awareness and prepared communities.

It has been 20 years since the Indian Ocean Tsunami in 2004 and its devastating consequences. Since then, Australia has observed over 25 tsunamis. Of these events, 6 exceeded the warning level and the Joint Australian Tsunami Warning Centre issued appropriate warnings for 5 of these events excluding the 2006 Java event. There were 5 instances when the centre issued a tsunami warning but the tsunami either did not eventuate or was below the threat. For the remaining 14 events, the centre issued national No Threat bulletins, which were verified by observing only below marine warning level waves. Some key events are listed (a full event list is provided in the Appendix):

- 2006 Java event of 17 July from a M7.7 earthquake. It resulted in the largest run-up recorded in Australia at Steep Point in Western Australia (Prendergast and Brown 2011). There was no warning due to the Australian Tsunami Warning System not yet being operational.
- 2007 Solomon Islands event of 1 April from a M8.1 earthquake. It received a strong reaction among residents in Cairns with significant media interest and coverage (King 2008). Tsunami warnings were issued for Queensland but only below-warning tsunami waves up to 25cm were observed.
- 2010 Chile event of 27 February from a M8.8 earthquake. A marine warning was issued for the eastern states and offshore islands. Norfolk Island observed 61cm tsunami waves but other locations along the eastern seaboard only registered below-threat wave observations of up to 36cm.

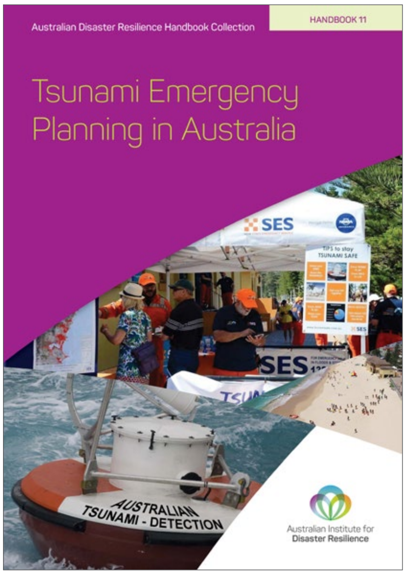
- 2022 Hunga Tonga-Hunga Ha'apai event of 15 January from a major volcanic eruption. This challenged the eastern seaboard's warning and response systems due to the complex nature in how the tsunami was generated. Marine warnings were issued for all eastern states and land warnings were issued for Norfolk Island and Lord Howe Island, all verified by observations.

This paper summarises the current state of tsunami risk management capability in Australia as well as current challenges and emerging opportunities.

Current capability

Following the Indian Ocean Tsunami, the Australian Government committed $68.9 million for the Australian Tsunami Warning System. This program commenced in 2005 and resulted in a major expansion of the seismic network and sea-level monitoring network, establishing the Joint Australian Tsunami Warning Centre and developing a national emergency management capability to manage tsunami risk. The latter is implemented through the Australian Tsunami Advisory Group whose members consist of all Australian jurisdictions, including offshore territories and New Zealand. Key achievements of the group include the roll-out of a tsunami education program for emergency managers (Introduction to Tsunami for Emergency Managers), the development of the Tsunami Emergency Planning Handbook and its companion Tsunami Hazard Modelling Guidelines and the award-winning online educational tool, Tsunami: The Ultimate Guide. The Australian Tsunami Advisory Group provides knowledge sharing with the aim to improve tsunami risk management in the Oceania region.

Australia is at the forefront of international efforts to develop a comprehensive Indian Ocean Tsunami Warning and Mitigation System (IOTWMS). It also supports the Pacific Tsunami Warning and Mitigation System (PTWS) under the auspices of the UNESCO Intergovernmental Oceanographic Commission (UNESCO-IOC). The Joint Australian Tsunami Warning Centre is one of 3 tsunami service providers for the IOTWMS and provides real-time threat advice to 27 tsunami warning centres across the Indian Ocean. Australia has funded and hosted the Secretariat Office to coordinate the IOTWMS development and sustainment. For the PTWS, the Australia Government provided ongoing support to the seismic and sea-level observation networks in the southwest Pacific region. Such a coordinated international development also helped improve the end-to-end Australian Tsunami Warning System from risk assessment, detection and warning, emergency response to community response. The system benefited from accessing the global monitoring networks and international best practice. It is regularly tested in the biennial tsunami exercises of IOWave and PacWave.



The Tsunami Emergency Planning in Australia handbook covers the scientific information and principles of risk assessment, warning systems, planning, education, response and recovery in the context of tsunami.

Since 2004, effort has been invested into tsunami modelling to improve warning systems and disaster management. The warning system is underpinned by a database of modelled tsunami scenarios (Greenslade et al. 2011). Once an earthquake has been assessed as having potential to generate a tsunami, relevant scenarios are selected to inform the warnings. As sea-level information comes to hand, the scenario selection is refined and warnings are updated. The warning centre is designed to provide emergency managers with a minimum of 90 minutes of warning time.

There have been great advances in hazard modelling for emergency management purposes—methodological and computational. The earlier hazard modelling projects were restricted to a limited number of scenarios and a limited extent of the coastline with coarser resolution elevation data than is available today. With the access to greater high-resolution nearshore elevation data, many modelling projects can capture broad extents of the coastline and apply sophisticated sampling of probabilistic scenarios to support local decision-making. This approach is being implemented in locations in Western Australia (Kendall et al. 2024) and in New South Wales and Queensland. Similar projects have been conducted in Tasmania involving Hobart port authorities and there have been numerous tsunami projects in Queensland.[1] These site-specific projects are possible through the offshore probabilistic tsunami hazard assessment (PTHA18) developed by Geoscience Australia. First developed in 2008 and

1. Tsunami Modelling along the East Queensland Coast and Meteotsunami in Queensland www.publications.qld.gov.au/dataset/tsunami-modelling-east-queensland-coast.

subsequently updated in 2018, PTHA18 is a step-change from the earlier version and benefits from new knowledge formed after the Tohuku event in 2011 (Davies and Griffin 2018). This knowledge challenged assumptions about the maximum magnitude possible on subduction zones around the world.

It is projects such as these that build understandings of risk at the local level and provide the evidence to develop evacuation plans, community communications and other risk-management activities. Where detailed inundation modelling is not available to inform evacuation plans, disaster managers can apply the general advice of 1km from the coast or 10m in elevation. Both Queensland and New South Wales have mapped this general advice and made it publicly available.[2]

Current challenges

The development of the Australian Warning System recognised that over 75% of tsunamis worldwide are generated by earthquake. Tsunamis are generated by mechanisms that result in a significant displacement of water and include submarine landslides, volcanic eruptions and meteorological driven events.

During the initial tsunami warning system program, bathymetric surveys were conducted along the New South Wales coast to develop an understanding of submarine landslides and their potential to generate a tsunami (Glenn et al. 2008). Tsunami generated by submarine landslides present a major challenge for Australia's coastline populations given the proximity to the coastline and the general lack of warning. This is a continuing area of research in Australia in collaboration with New Zealand counterparts.

The Hunga Tonga-Hunga Ha'apai event in 2023 reminded the world of volcanoes as sources of tsunami. This was not the first time that Australia had experienced tsunami from this source. Observations had been recorded at Onslow on the northwest of Western Australia following the 1883 Krakatau event (Simpson et al. 2007). There are a host of volcanic sources in the Oceania region, the obvious ones being along the Pacific Rim from Indonesia, Papua New Guinea into the Pacific but also in Australia's southwest and Heard Island.

The Hunga Tonga-Hunga Ha'apai event presented a major challenge to the Joint Australian Warning Centre and in the response by emergency managers. The event reinvigorated discussions about the need for an intermediary warning level between the 'Marine' and 'Land' threat levels. This is driven in part by the implications of evacuating large populations in the dense Gold Coast and northern New South Wales regions. Evacuation is informed by the general advice of 1 km inland or 10 m elevation in the absence of detailed modelling. Issuing emergency alerts also raises the considerations of prioritisation given the limitations of the system. Further complicating this situation is that the detailed modelling is generally based on earthquake-generated tsunami.

The rarity of the hazard means that communities may not be well prepared. In addition, the response system is rarely stress-tested. There remains high uncertainty about the tsunami hazard, especially over longer return periods. Pleasingly, some emergency management agencies test aspects of their tsunami management capability through scenarios (e.g. Indian Ocean-wide tsunami exercise (IOWave) and Pacific-wide tsunami exercise (PacWave)). This has yielded useful information about existing capability such as the importance of developing evidence-based tsunami evacuation maps. These findings are important to adapt practice and procedure as well as emergency management effectiveness. However, they are contingent on highly detailed, time consuming and expensive data acquisition, complex modelling and is reliant on significant state and federal investment and collaboration. Community awareness of tsunami risk in Australia is low as identified by Paton et al. (2017) who concluded that taking a multi-hazard view to community engagement would be most effective to include tsunami in the understanding of risk in the community. Focusing on tsunami alone in an environment with increasing frequency and intensity of storms, floods and fires might be politically unsound.

As community awareness of tsunami hazard is low, developing a good understanding of community and institutional exposure and vulnerability to this low-likelihood but potentially catastrophic event remains the cornerstone of effective emergency management. For example, in metropolitan Perth, following the Joint Australian Warning Centre issuing of a land warning, marine effects on coastlines can occur within 2.5 hours and land inundation in 3 hours. Tens of thousands of residents, workers and visitors as well as schools, hospitals, businesses and aged care facilities would need to be safely evacuated. This is an enormous, complex and challenging task and success would be reliant on people understanding the hazard, where the risks are, what areas are safe and what to do if a tsunami occurs.

The Western Australian Tsunami Inundation Modelling Project used extensive computer modelling of earthquake-generated tsunami to understand potential inundation and produce evidence-informed community evacuation maps covering Perth to Western Australia's southwest. Importantly, this has allowed emergency managers to understand the quantum of exposure and vulnerability and to discuss tsunami risk with local government. This understanding enables the emergency management sector to communicate risk to communities and address gaps

2. Tsunami evacuation areas of Queensland, at www.fire.qld.gov.au/prepare/tsunami/evacuation-areas.

in emergency management plans, communications plans and evacuation plans. With ambitions to continue this project along the Western Australian coastline, including the northwest (the most tsunami-prone area of Australia (Davies and Griffin 2018), knowledge and hazard awareness will improve.

With few events and no detailed modelling conducted in northern Queensland, there is an assumption that the Great Barrier Reef protects coastal communities. The Solomon Island's event in 2007 showed otherwise. This event was recorded on the tide gauges in northern Queensland in mainland communities 'behind' the Great Barrier Reef. Modelling of this event confirmed that tsunami can propagate through the reef (Baba et al. 2008). Expanding this evidence base will inform future community awareness activities in northern Queensland.

Low-frequency hazards like tsunami will inherently have a high level of uncertainty. Research through archives of newspapers, ship journals, port logs and entries in marine journals contribute to an event catalogue, as do palaeotsunami studies (including in Australia and the surrounding region). This provides evidence of events over the last tens to hundreds of thousand years. Clark et al. (2011) identified 5 deposits considered likely to have resulted from tsunamis in southeastern Tasmania. Given the urban development on the eastern seaboard of the Australian mainland, it is highly unlikely that studies similar to the Tasmanian study could be undertaken. Conducting palaeotsunami studies are important as they can constrain the likelihood of tsunami for sources that are important for Australia. One example is the research in Thailand (Jankaew et al. 2008) that identified a probable precedent for the 2004 Indian Ocean Tsunami.

Emerging opportunities

History of First Nations peoples offers intriguing insights about tsunamis in the Kimberley Region of Western Australia. Bryant et al. (2007) reported that, across parts of this region, place naming, art and oral history of a cosmogenic mega-tsunami were supported with geomorphic evidence of such an event at 2 locations. There is significant opportunity to learn from and understand this oral history, legends and experience with coastal hazards as a basis to better understand them.

Coastal systems such as mangroves have been shown to have a mitigating effect on coastal hazards, including tsunamis. These nature-based solutions are identified in the guidelines for the Australian Government's flagship initiative for disaster resilience and risk reduction. The Disaster Ready Fund is administered by the National Emergency Management Agency and funds eligible projects under either Stream One - Systemic risk reduction or Stream Two - Infrastructure. Stream Two includes investment in green-blue infrastructure, or nature-based solutions.[3] These solutions often involve local communities and help raise risk awareness as well as the value of these structures.

Advances in technology present exciting opportunities to progress risk management of tsunami in Australia. With quantum computing on the horizon, coupled with new sensors, we could have the ability to better characterise an earthquake rupture to input to fast tsunami models in near real-time that could result in targeted warnings. The rapid emergence of machine learning models presents vast opportunities for development in the modelling space (see an example by Mulia et al. 2022). There remains the question as to whether such investment is viable in the absence of not knowing the risk. Are efforts better spent elsewhere, at least in the short term, to improve inundation modelling for key parts of the Australian coastline so we can understand the risk, be better prepared and take mitigating steps?

Tsunami risk management will benefit from other advancements such as an improved emergency alert system. With spatial systems rapidly advancing, it is reasonable to envision a future where location-specific warnings can be received on a personal device for those who have them.

Conclusion

There has been significant investment in tsunami risk management over the last 20 years and there are challenges yet to overcome. The Australian Tsunami Advisory Group is implementing a faster and more accurate warning system to everyone as well as understanding and communicating risk so that people know what to do when they receive a warning. This progress will be achieved with collaboration with First Nations peoples and internationally to embrace ideas from other areas of knowledge and expertise. However, raising and sustaining risk awareness for a low-frequency hazard will always be challenge and will require ongoing effort.

3. Disaster Ready Fund, at https://nema.gov.au/disaster-ready-fund.

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Appendix

Tsunami events recorded in Australia since 2004

2006 Java event of 17 July from a M7.7 earthquake. It resulted in the largest run-up recorded in Australia at Steep Point in Western Australia (Prendergast and Brown 2011). There was no warning due to the Australian Tsunami Warning System still being established.

2007 Solomon Islands event of 1 April from a M8.1 earthquake. It received a strong reaction among residents in Cairns with significant media interest and coverage (King 2008). Tsunami warnings were issued for Queensland but only below-warning tsunami waves up to 25cm were observed.

2007 Sumatra event of 12 September from a M8.5 earthquake. Marine warning issued for Cocos Island and Christmas Island. No tsunami waves observed.

2009 New Zealand event of 15 July from a M7.8 earthquake. Land warning issued for Lord Howe Island, marine warning issued for Norfolk Island, New South Wales, Victoria and Tasmania. Below-threat waves were observed along the eastern seaboard and the named offshore islands.

2009 Samoa event of 28 September from a M8.1 earthquake. A national No Threat Bulletin issued and the below-threat level tsunami waves of up to 40cm were observed along the eastern seaboard.

2009 Sumatra event of 30 September from a M7.6 earthquake. Marine warning issued for Cocos Islands and cancelled 2 hours later. No noticeable tsunami waves were observed.

2009 Vanuatu event of 7 October from a M7.8 earthquake. National watch issued for potential tsunami threat to Queensland and cancelled 45 minutes later. Below-threat level tsunami waves of up to 10cm were observed along the Queensland coast.

2010 Chile event of 27 February from a M8.8 earthquake. Marine warning issued for eastern states and offshore islands. Norfolk Island observed 61cm tsunami waves and other locations along the eastern seaboard registered below-threat wave observations of up to 36cm.

2010 Sumatra event of 6 April from a M7.8 earthquake. A national No Threat Bulletin issued and below-threat tsunami waves were observed at some locations of the western seaboard.

2010 Vanuatu event of 10 August from a M7.3 earthquake. A national No Threat Bulletin issued and below-threat tsunami waves were observed at some locations of the eastern seaboard.

2010 Mentawai event of 25 October from a M7.7 earthquake. A national No Threat Bulletin issued and below-threat tsunami waves were observed along the western seaboard.

2010 Vanuatu event of 25 December from a M7.3 earthquake. A national No Threat Bulletin issued and below-threat tsunami waves were observed at some location of eastern seaboard.

2011 Tohuku event of 11 March from a M9.0 earthquake. A national No Threat Bulletin issued and below-threat waves were recorded along the eastern seaboard. Anecdotal report of several swimmers being washed into a lagoon at Merimbula in New South Wales.

2012 North Sumatra event of 11 April from a M8.6 earthquake. A national No Threat Bulletin issued and below-threat tsunami waves were observed along the western seaboard.

2013 Santa Cruz Islands event of 6 February from a M8.0 earthquake. A national No Threat Bulletin issued and below-threat waves were recorded along the eastern seaboard.

2016 Sumatra event of 2 March from a M7.8 earthquake. Marine warnings were issued for Cocos Island and Christmas Island and watch alert issued for most of the Western Australia coast. Below-threat waves of up to 10cm were observed on the mentioned islands and parts of the Western Australia coast.

2016 Solomon Islands event of 8 December from a M7.8 earthquake. A national No Threat Bulletin issued and below-threat waves were recorded at some locations of the eastern seaboard.

2017 Kermadec Islands event of 8 December from a M6.3 earthquake. There were no alerts issued due to the earthquake magnitude being below the criteria of M6.5. Below-threat tsunami waves of up to 14cm were observed at Norfolk Island.

2018 Loyalty Islands event of 5 December from a M7.6 earthquake. A national No Threat Bulletin issued and below-threat waves were recorded at some locations of the eastern seaboard.

2021 Loyalty Islands event of 11 February from a M7.6 earthquake. Marine warning issued and verified for Lord Howe Island and below-threat level waves observed along the eastern seaboard.

2021 Kermadec Islands event of 5 March from a M7.9 earthquake. Marine warning issued and verified for Norfolk Island and below-threat level waves observed along the eastern seaboard.

2021 South Sandwich Islands event of 12 August from a M8.1 earthquake. A national No Threat Bulletin issued and below-threat tsunami waves were observed along the western seaboard.

2022 Hunga Tonga-Hunga Ha'apai event of 15 January from a major volcanic eruption. It challenged the warning and response systems due to the complex nature of how the tsunami was generated. Marine warnings were issued for all eastern states and land warnings were issued for Norfolk Island and Lord Howe Island, all verified by observations.

2022 Loyalty Islands event of 30 March from a M7.0 earthquake. A national No Threat Bulletin issued and below-threat waves of up to 10cm were observed at Norfolk Island.

2023 Loyalty Islands event of 19 May from a M7.7 earthquake. Marine warning issued for Lord Howe Island, confirmed by waves observed on the island. Below-threat waves of up to 24cm were observed in some locations of the eastern seaboard.