Australian Disaster Resilience Handbook Collection

GUIDELINE

Tsunami hazard modelling guidelines

Australian Institute for
Disaster Resilience

AUSTRALIAN DISASTER RESILIENCE HANDBOOK COLLECTION

Tsunami hazard modelling guidelines

Supporting document for the implementation of *Australian Disaster Resilience Tsunami Emergency Planning in Australia* (AIDR 2010).

Australian Government
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Disclaimer

1. Acknowledgements

Development of these guidelines was overseen by the Australian Tsunami Advisory Group (ATAG), which is a reference group of the Australian-New Zealand Emergency Management Committee (ANZEMC). ATAG provides national leadership in the coordination of programs and projects relating to tsunami capability development, promoting research, information, knowledge management and education in Australia. Members represent emergency services agencies in each Australian state and territory, including all offshore territories, Surf Life Saving Australia, Emergency Management Australia, Geoscience Australia and the Bureau of Meteorology. Ministry of Civil Defence and Emergency Management in New Zealand and GNS Science are also members reflecting the arrangements of ANZEMC.

These guidelines were made possible by the financial contributions of Emergency Management Australia through the National Disaster Resilience Program during 2017-18. Geoscience Australia led this project with financial support provided to a broad section of the Australian tsunami modelling community to attend a workshop in Canberra in December 2017 to collaborate on the development of these guidelines. Contributors to these guidelines included:

- Government
  - Mineral Resources Tasmania
  - New South Wales Office of Environment and Heritage
  - Queensland Department of Environment and Science
  - Bureau of Meteorology
  - Geoscience Australia
- Industry
  - Arup
  - Baird
  - Cardno
  - MetOcean Solutions
  - AonBenfied
  - IAG
- Academia
  - Australian National University
  - University of Newcastle
  - University of Tasmania
- End-user
  - ATAG members
  - These guidelines, whilst aimed at ATAG, recognise that the responsibility for managing tsunami risks resides with a range of user-groups in the coastal zone; for example, local and state government, as well as port authorities and the oil and gas industry. They were developed through a collaborative process involving a broad cross-section of the Australian tsunami modelling community.

The Australian Institute for Disaster Resilience provided essential support for this project.

2. Introduction

A tsunami is a series of waves generated by the sudden displacement of a large volume of water, most often in the ocean. Small tsunamis are reasonably common, and damaging events occur somewhere globally every year or so. While not unusual at the global level, on any particular coastline damaging tsunamis are rare. Tsunami risks tend to be dominated by rare, high magnitude events, which can cause both major damage to coastal infrastructure and loss of life (Grezio et al., 2017). Our current knowledge of Australian tsunami hazard is broadly consistent with this picture (Sections 3 and 4). Dozens of events have been recorded historically in Australia, but damages have been limited, while hazard assessments suggest the potential for considerably larger events in the future (Section 3).

Because destructive tsunamis are rare on most coastlines they are often not represented in historical records, which tend to be short compared with the average return interval of large tsunamis (typically hundreds to thousands or more years). Recent history demonstrates that it is all too easy for societies to be unprepared for damaging tsunamis. For instance, events comparable to the 2004 Indian Ocean Tsunami and the 2011 Japan Tsunami were not widely anticipated or planned for in Indonesia or Japan prior to their occurrence (Satake and Atwater, 2007; Kagan and Jackson, 2013; Synolakis and Kanoglu, 2015).

The 2004 and 2011 tsunami disasters led to much progress in the scientific understanding of tsunami hazards, and recognition that tsunami hazards had been underestimated in many areas. Prior to the 2004 Indian Ocean Tsunami, many scientists thought that large earthquakes were restricted to particular subduction zones (with rapid convergence and a relatively young subducting plate; Ruff and Kanamori, 1980). Until this was clearly contradicted by both the 2004 and 2011 earthquakes (Stein and Okal, 2007; Okal, 2015), it was often used to disregard the possibility of large earthquake-tsunamis occurring on certain subduction zones, including some with high significance for Australian tsunami hazard (e.g. the eastern Sunda Arc in Indonesia, or the Kermadec-Tonga trench to the east of Australia). Additionally, the 2004 and 2011 earthquakes highlighted that tsunamis can be substantially affected by variations in earthquake properties beyond just the magnitude (e.g. variations in rupture size and slip distribution, which were commonly ignored in hazard assessments). The high impact of these events brought such issues into sharp focus, leading to increased efforts to quantify tsunami hazards and revisions to hazard assessments at many sites (e.g. Lovholt et al., 2014; Koshimura and Shuto, 2015; Hoechner et al., 2016; Li et al., 2016; Kalligeris et al., 2017; Power et al., 2017).

Despite recent scientific progress it remains true that the rarity of damaging tsunamis leads to large uncertainties in tsunami hazard assessments. For virtually all tsunami sources there are high uncertainties in the frequencies of large events. Because we have limited observations of large earthquakes (i.e. like 2004 and 2011), we cannot strongly constrain the variability of tsunamis they might generate, although this substantially affects tsunami hazard. Furthermore, most coastal locations do not have enough tsunami observations to rely on statistical techniques alone to estimate occurrence rates of damaging tsunami runup.

Guidelines such as this document have an important role to play in promoting adequate treatment of these uncertainties, and national consistency among studies conducted by different groups.

2.1 Purpose of these guidelines

The purpose of these guidelines is to provide further detail around the overarching tsunami hazard modelling methodology outlined in the Tsunami Emergency Planning in Australia Handbook (Australian Institute for Disaster Resilience 2010). They are designed to facilitate appropriate standards of rigour and improved national consistency in tsunami hazard modelling, without dictating software choices or otherwise suppressing innovative practices. We expect software and methodologies to continue to evolve in concert with improvements in tsunami science. Our target audience includes government and industry professionals who commission tsunami hazard studies for a particular purpose ('end-users'), as well as the tsunami modellers conducting such studies.

For the **end-users**, we aim to provide:

- Guidelines on tsunami hazard modelling methodologies and data that are appropriate for different applications. Methodologies will vary considerably depending on the ultimate purpose of the study; for example, model and data requirements for critical infrastructure hazard assessment will be more onerous than those for 'hazard screening and prioritisation' type studies. We suggest that final decisions on the hazard study methodology be made by agreement between the end-user and modeller, considering both the points raised herein, and other case-specific factors relevant to their study.

- Information on the uncertainties typically associated with current generation tsunami hazard models and their input data. It is important for end-users to qualitatively understand the typically large uncertainties that are associated with hazard models, and thereby avoid over-interpreting aspects of hazard studies which may not be robust.
- A 'shopping list' of model outputs that may be relevant to the study.
- A checklist of questions relating to procuring and publishing a hazard study. These aim to ensure all parties understand the study design and limitations; that appropriate quality control is undertaken; and that the contract facilitates the use and re-use of the study results as appropriate.

For tsunami **modellers**, we aim to provide:

- Principles-based guidelines on developing tsunami hazard models for different applications, which have been collaboratively developed by a broad cross-section of the Australian tsunami modelling community, and separately peer-reviewed.

The development of these guidelines was initiated by the Australian Tsunami Advisory Group (ATAG) with funding support from Emergency Management Australia. These guidelines, whilst aimed at ATAG, recognise that the responsibility for managing tsunami risks resides with a range of user-groups in the coastal zone; for example, local and state government, as well as port authorities and the oil and gas industry. They were developed through a collaborative process involving a broad cross-section of the Australian tsunami modelling community. These guidelines form a package of national guidance and community awareness and education material that is hosted by the Australian Institute of Disaster Resilience and supported by ATAG, i.e. Tsunami Emergency Management Planning Handbook, Tsunami Hazard Modelling Guidelines (companion document to the Handbook) and the online resource Tsunami: The Ultimate Guide.

Initially, ATAG members were surveyed regarding requirements and expectations of these guidelines. Key requirements from ATAG included; a better understanding of the modelling process including the data requirements for different modelling methods, a nationally consistent approach, use of common language, and inclusion of case studies. Subsequently a 'tsunami hazard modelling guideline development workshop' was held at Geoscience Australia on 5-6 December 2017 (see http://www.ga.gov.au/news-events/news/latest-news/a-wave-of-tsunami-modellers-descends-on-canberra), involving 18 tsunami modellers currently working in Australia, including representatives from Government, Academia and Industry. The end-user was represented by the Chair of ATAG.

Following the workshop, incomplete draft guidelines were posted to Google Docs and circulated among the workshop attendees and other members of the Australian tsunami modelling community, all of whom had the opportunity to contribute, edit, and review the content. The final document was peer reviewed by external international tsunami scientists and ATAG members.

These guidelines represent the current knowledge of tsunami science and hazard within the Australian context. As tsunami research advances, or new information and knowledge is gained from events, these guidelines will need to be reviewed.

2.2 Overview of these guidelines

These guidelines are structured as follows:

Section 3 reviews the current understanding of Australian tsunami hazard, and historical tsunami in Australia. Key points are:

- Dozens of tsunamis have been observed historically in Australia. They have generated marine hazards, and a few instances of locally significant inundation. However, hazard studies suggest the potential for larger events to occur.
- Australia's historical tsunami record is not a reliable guide to our tsunami hazard, because written history is short compared with the estimated frequency of damaging tsunamis. The geological record suggests that energetic marine inundations have occurred in some sites in the last few thousand years, but it is difficult to determine whether these deposits represent tsunamis or storm surges.
- The average return intervals of large tsunamis are very uncertain, due to limitations of observational data, and limitations in our understanding of key tsunami sources (e.g. earthquakes, landslides). Modelled average return intervals of large tsunamis should generally be interpreted as 'nominal' or 'indicative', rather than being accurate.

Section 4 reviews tsunami modelling methods for generation, propagation through the deep water to the nearshore environment and subsequent inundation. Key points are:

- Tsunamis are generated by the displacement of the water column over a large area, typically in the ocean. A range of geophysical mechanisms can achieve this, including earthquakes, landslides, volcanic activity, asteroids, and meteorological processes.
- Details of the generation process can have a significant impact on the tsunami magnitude and characteristics. Hazard studies can account for this with a multi-scenario or probabilistic approach.
- High quality onshore and nearshore elevation data is necessary to model tsunami inundation and nearshore behaviour with accuracy. Lower resolution

global datasets are generally only suitable for modelling oceanic scale tsunami propagation. If good quality elevation data is unavailable, then advanced tsunami models may be of little benefit compared with crude geometric models such as the bathtub, or attenuation laws.

- The nonlinear shallow water equations are well suited to modelling the propagation and inundation of earthquake tsunami for most hazard applications. For other tsunami generation mechanisms, more advanced hydrodynamic models are often employed.
- Tsunami modelling codes should be tested against a range of benchmark solutions to confirm their suitability for hazard studies.
- Tsunami models are often applied to hindcast well known historical tsunami events. In some benchmarks with a well understood tsunami source, many models can reproduce observed runup with errors of around 20 per cent on average. However, larger errors are often reported in some 'difficult to model' sites.
- It is difficult to quantify the accuracy of hazard models, in terms of how well they represent possible future events. However, individual hazard scenarios should be less accurate than hindcasts of historical events, because hindcast models can 'tune' their tsunami source using observational data.

Section 5 discusses options for the design of tsunami hazard studies. Key points are:

- Tsunami hazard assessments need to consider two independent issues: 1) the range of tsunami scenarios that are modelled, and; 2) the approach used for modelling tsunami propagation and inundation. Appropriate treatment of both issues is required to understand the hazard.
- The range of scenarios modelled varies from 'probabilistic approaches', which attempt to model all possible future tsunami events, through to 'scenario based approaches', which aim to model a few representative events. Hybrid approaches intermediate between these may also be used. All strategies have benefits and challenges, and the optimal approach will vary for each individual tsunami hazard assessment.
- Hydrodynamic modelling approaches vary in sophistication, from simple 'bathtub' type methods, through to 2D and 3D physics based models. Physics based models are usually preferred when good quality elevation data is available, but without good quality input data, all approaches may be subject to large errors.
- Inundation model results may be sensitive to the treatment of friction, buildings, and tides.
- Model outputs agreed to be relevant for a particular study should be provided to the end-user in portable electronic formats with appropriate metadata, as well as in the project report.

Section 6 outlines considerations for procuring a tsunami hazard study and publishing the results. Key points are:

- Copyright and licensing issues should be explicitly considered when drafting contracts for tsunami hazard studies.
- A checklist of questions is provided for end-users to ask before, during and at the end of a hazard study. These questions can help ensure appropriate care has been taken in model development and design, and that the procurer has considered copyright and licensing to ensure use and re-use of the data and information.
- National consistency can be achieved with the uptake of the checklist by end-users.

2.3 End uses considered in forming this guideline

Understanding tsunami behaviour is essential for making informed decisions on managing tsunami risk. This includes comprehending the range of different sources, and the interaction of a tsunami within the nearshore environment, which can result in varying degrees of hazard.

Effective tsunami risk management can enable a community to become as resilient as practicable to tsunami through informed preparation and prevention activities, and thereby knowing what to do in response to and recovery from tsunami. These guidelines can aid decision making in the following areas:

- Tsunami emergency response planning.
  These guidelines can inform the development of response plans by providing advice on variability of the hazard within the landscape and the dynamic nature of the event, both in the offshore and onshore environment.
- Tsunami risk management.
  These guidelines provide information on estimating the likelihood and scale of tsunami impact that may be considered to inform mitigation measures.
- Coastal risk management.
  These guidelines provide information on estimating the tsunami hazard within the all-hazards planning approaches in the coastal zone. This information could be used for example in assessing development, upgrade or maintenance of coastal infrastructure facilities.
- Insurance.
  These guidelines provide information on estimating the likelihood and scale of tsunami impact that may be considered to inform insurance premiums.
- Tsunami warning.
  While these guidelines do not specifically deal with tsunami warning systems, much of the scientific and technical content overlaps with requirements for tsunami warning, and may serve as useful background material.
- Tsunami research.
  These guidelines can be used as a relevant reference for tsunami hazard research in Australia.

- Data collection.
  These guidelines can be used to highlight the value in the collection of high resolution elevation data, especially in the nearshore environment and therefore assist end-users to influence targeted data collection if required.

While these guidelines can be used within a risk management context, they do not replace guidelines on assessing risk. Furthermore, while these guidelines can assist with the design of tsunami hazard assessments, they do not provide sufficient background for non-specialists to conduct such studies without the support of modelling experts.

3. Australian Tsunami Hazard

KEY POINTS:

- **Dozens of tsunamis have been observed historically in Australia. They have generated marine hazards, and a few instances of locally significant inundation. However, hazard studies suggest the potential for larger events to occur.**
- **Australia's historical tsunami record is not a reliable guide to our tsunami hazard, because written history is short compared with the estimated frequency of damaging tsunamis. The geological record suggests that energetic marine inundations have occurred at some sites in the last few thousand years, but it is difficult to determine whether these deposits represent tsunamis or storm surges.**
- **The average return intervals of large tsunamis are very uncertain, due to limitations of observational data, and limitations in our understanding of key tsunami sources (e.g. earthquakes, landslides). Modelled tsunami average return intervals in hazard studies should generally be interpreted as 'nominal' or 'indicative', rather than being accurate.**

3.1 Introduction

Dozens of tsunamis have been recorded in Australia, and at a number of sites older sedimentary deposits have been interpreted as reflecting tsunami inundation (Goff and Chague-Goff, 2014; Section 3.3). Known impacts of historical tsunami in Australia have mostly been marine hazards (i.e. unexpected water level changes and strong currents in beaches, ports and estuaries), sometimes accompanied by locally significant inundation (Section 3.3).

The fact that Australia is relatively far from most tectonic plate boundaries lessens the tsunami hazard, because tsunami sources are often located in these areas, and high tsunami runup most often occurs near the source (Section 3.2). However, hazard models suggest that a number of sources could generate large tsunami that are well suited to direct energy to parts of the Australian coastline, producing runup substantially larger than recorded historically (e.g. Burbidge and Cummins, 2007; Burbidge et al., 2008; Andrews et al., 2013; Davies et al., 2017). Globally there are many instances of tsunami generating high runup at sites far from where they were generated, because the initial tsunami location happened to be well suited to propagating tsunami energy to the affected area. For example, the 1960 Chile tsunami led to 12 m of runup at Pitcairn Island (~5000 km away), 11 m runup in Hilo, Hawaii (~10000 km away), and 7 m runup at sites on the Russian east coast (~16000 km away); while the 1946 Aleutian Islands tsunami led to runup exceeding 10 m at a number of sites in French Polynesia (~7500 km away). Other examples can be found in the NGDC historical tsunami database (NGDC, 2018). Below, further details are provided on the current knowledge of tsunami hazard in Australia, focussing on efforts to quantify the hazard. Subsequently we discuss the historical and paleo records of tsunami events.

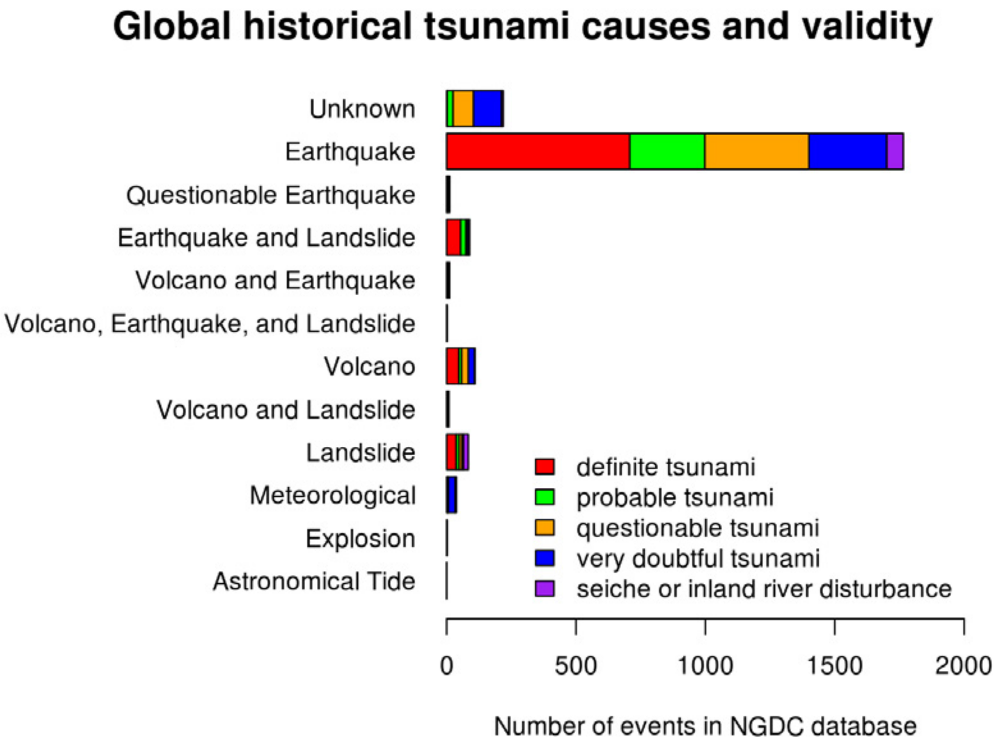


Figure 1 Figure 1: Causes of tsunami events, as categorised in the NGDC database (NGDC, 2018). Events classified as 'erroneous entry' have been removed.

3.2 Current knowledge of Australian tsunami hazard

Tsunami can be generated by a range of sources (Section 4), including submarine earthquakes, submarine landslides, subaerial landslides that subsequently flow into water bodies, volcanic processes, asteroid impacts, and travelling atmospheric pressure fronts (Grezio et al., 2017). Globally around 80 per cent of tsunami events have been generated by submarine earthquakes, with landslides and volcanoes being the next most common recorded sources (Figure 1). A significant percentage of historical events have no known source, or doubtful validity. Historically, known tsunami sources have been concentrated along subduction zones where tectonic plates are colliding (Figure 2), because these regions tend to host the majority of large oceanic earthquakes.

Given the dominance of subduction earthquakes in generating tsunamis, earthquake mechanisms have received much more scientific attention than other generation mechanisms (e.g. landslides, volcanic collapse), and there is more data to test models of the earthquake tsunami generation process and its variability. There is also more information available on modelling the frequency and magnitude of subduction earthquakes, compared with other tsunami sources, although uncertainties in the rates of large earthquake events remain high (e.g. Rong et al., 2014; Berryman et al., 2015).

Tsunami hazard assessments in Australia have thus tended to focus on subduction earthquake sources, as have global scale hazard studies. The first Australian Probabilistic Tsunami Hazard Assessment (PTHA) was released by Geoscience Australia in 2008 (Burbidge et al., 2008). While a new PTHA is currently in development, the 2008 PTHA modelled the oceanic tsunami propagation from thousands of hypothetical uniform-slip subduction earthquakes, storing the results at approximately 3500 points around Australia in 100 m water depth (Figure 3). The modelled time-series could be used as boundary conditions for detailed site-specific tsunami inundation models, which can be used for local-scale tsunami risk management. Burbidge et al., (2008) also estimated the rates of each earthquake event, allowing average return intervals to be assigned to scenarios. The results were widely used to support tsunami inundation hazard studies in Australia (e.g. Somerville et al., 2009; Van Putten et al., 2009; Andrews et al., 2013; Cardno, 2013; Dall'Osso et al., 2014; Power et al., 2015; Wilson and Power, 2016; Kain et al., 2017). Many of these studies also made use of the T2 tsunami database as a source of tsunami wave-forms (e.g. Andrews et al., 2013; Cardno 2013; Dall'Osso et al., 2014; Wilson and Power, Submitted). The T2 database contains hundreds of uniform-slip earthquake-tsunami scenarios that were developed to support Australia's tsunami early warning system by the Bureau of Meteorology (Greenslade et al., 2009, 2011).

More recently a number of coarse, global scale tsunami runup hazard assessments have been conducted

(Lovholt et al., 2014; Davies et al., 2017). Like the 2008 Australian PTHA, these are devised by modelling a large number of earthquake-tsunami and estimating their occurrence rates. However, rather than focusing on offshore wave heights, they estimate earthquake-tsunami runup hazards by combining coarse resolution tsunami propagation models with approximate runup predictions (the latter developed by combining offshore model predictions with historical tsunami observations). Because of their coarse global nature these studies are not suitable for use in local decision making. However, they serve as a useful cross-reference for detailed studies, and may assist with hazard prioritization and screening type analyses (preferably in conjunction with other information). A key result is the identification of high uncertainties in tsunami average return intervals, which mainly result from uncertainties in the occurrence rates of high magnitude earthquakes (Figure 4; Berryman et al., 2015). For instance, the Global Earthquake Model's Faulted Earth database suggests that the maximum earthquake magnitude on the Kermadec-Tonga trench is somewhere between moment magnitude (Mw) 8.1 and 9.6 (Berryman et al., 2015). The corresponding tsunami would range from a locally significant event with minimal impacts on Australia (for Mw 8.1), up to a Pacific-Ocean wide tsunami with major effects on Australia (for Mw 9.6).

Uncertainties in maximum magnitudes are thought to be one cause of the large differences in tsunami wave height exceedance rates presented in earlier studies in New South Wales (NSW). Cardno (2013) compared two estimates of tsunami wave heights at ~ 500, 1000, and 10000 year average return intervals at a number of sites in NSW. These two estimates were based on A) the results of Burbidge et al., (2008) combined with their own hydrodynamic model, and; B) the results of Thio and Somerville (2006). Cardno (2013) found that the wave heights for each average return interval differed by multiples between 1.6 and 5.7, with 'B' consistently producing smaller wave heights than 'A'. These large differences were attributed to different estimates of the maximum magnitude earthquake on the Kermadec-Tonga trench (see also Somerville et al., 2009), highlighting the significance of this poorly constrained parameter for tsunami hazard assessment. More recently, organisations such as the Global Earthquake Model foundation have produced 'expert-opinion' type advice on maximum magnitudes (with associated justifications and uncertainties) (Berryman et al., 2015). Such guidelines may allow for a more consistent treatment of the uncertainties in future studies, although large uncertainties are likely to persist for the foreseeable future.

There are other poorly constrained model parameters that may strongly impact modelled tsunami wave height exceedance rates. These include the seismic coupling coefficient (which determines the fraction of tectonic plate motion that occurs during earthquakes),

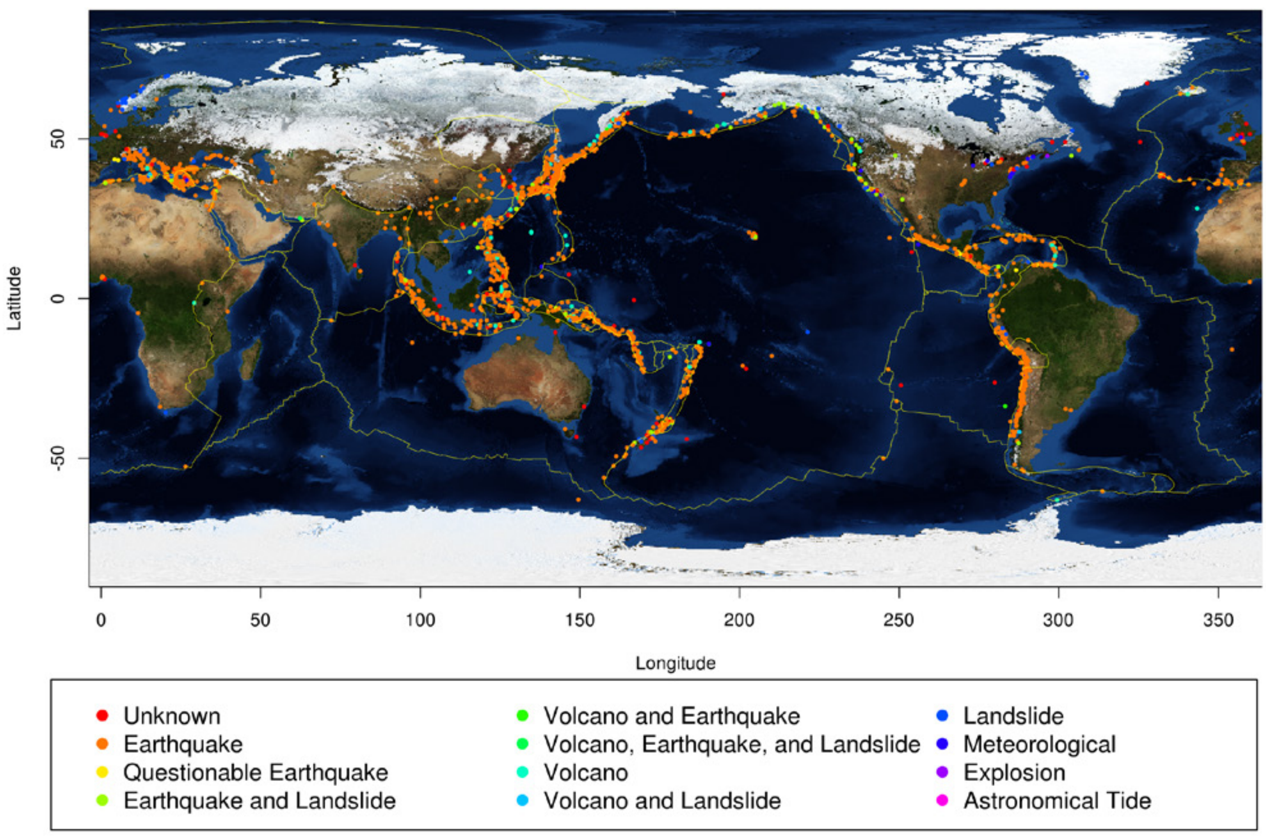


Figure 2 Historical tsunami source locations in the NGDC Database (NGDC, 2018). Thin lines show plate tectonic boundaries (Bird, 2003). Tsunami sources are concentrated along convergent plate boundaries, where one plate is being subducted underneath the other. Events classified as 'erroneous entry' have been removed.

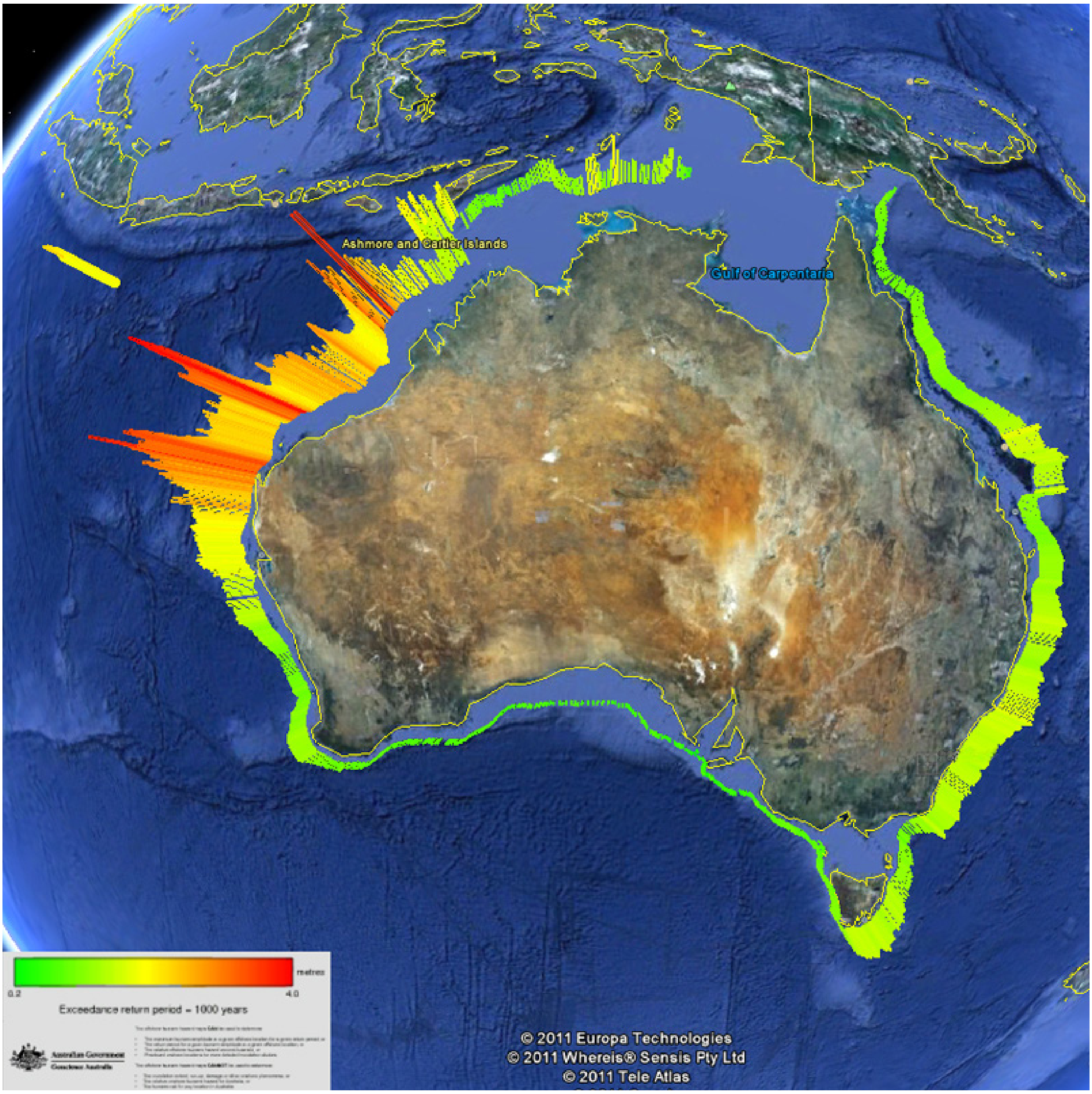


Figure 3 Offshore tsunami peak water level with an average return interval of 1000 years, from the 2008 Australian Probabilistic Tsunami Hazard Assessment (Burbidge et al., 2008). Offshore sites have a depth of about 100 m. Only major earthquake sources were considered. Note that onshore tsunami runup heights may be several times higher than these offshore wave heights. s classified as 'erroneous entry' have been removed.

and the type of probability distribution used to model earthquake rates. Probabilistic tsunami hazard assessments generally allow for variations in these parameters, accounting for uncertainties by weighting a range of separate hazard models to derive the overall hazard results (e.g. Horspool et al., 2014; Davies et al., 2017). This does not remove uncertainties in average return intervals, but at least provides a formal means of including them in the analysis.

Irrespective of uncertainties in average return intervals, existing offshore tsunami hazard studies suggest the key drivers of earthquake-tsunami hazard in Australia are (on the west coast) the eastern Sunda Arc, and (on the east coast) the Puysegur, Kermadec-Tonga, New Hebrides, Solomons/New-Britain and South-American trenches (Burbidge et al., 2008; Davies et al., 2017). Large tsunamis are estimated to be more likely on the central west and east coasts, with the south coast thought to have lower exposure to tsunami from major subduction zones, and the north coast having some exposure due to earthquake source-zones in the eastern Indonesian region (Figures 3 and 4). It is noteworthy that among the subduction zones most relevant to Australia, historically only the South-American trench and the western Sunda Arc are known to have produced large ocean-basin-scale tsunami (i.e. in 1960 and 2004). There is much uncertainty surrounding the potential of

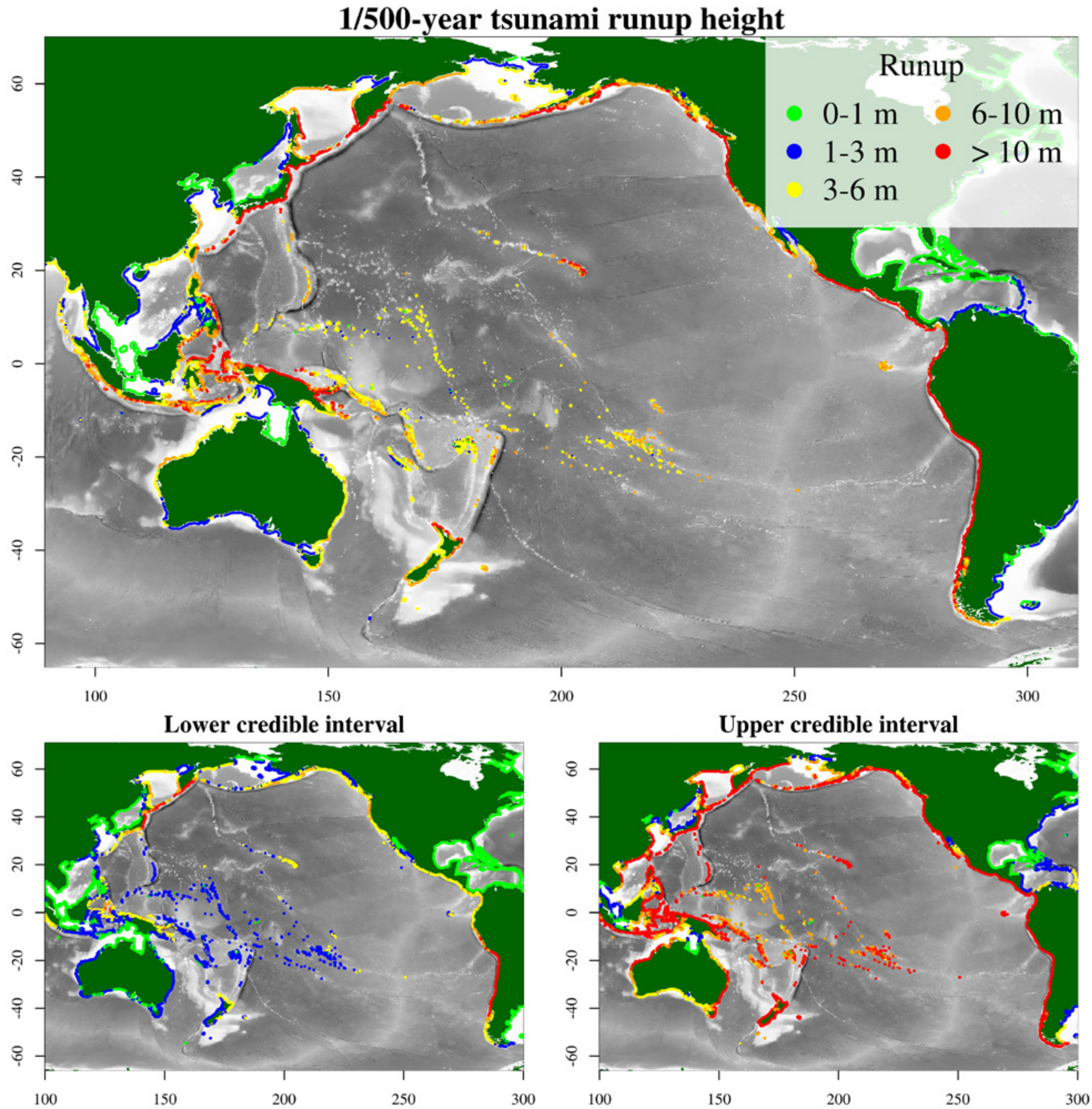
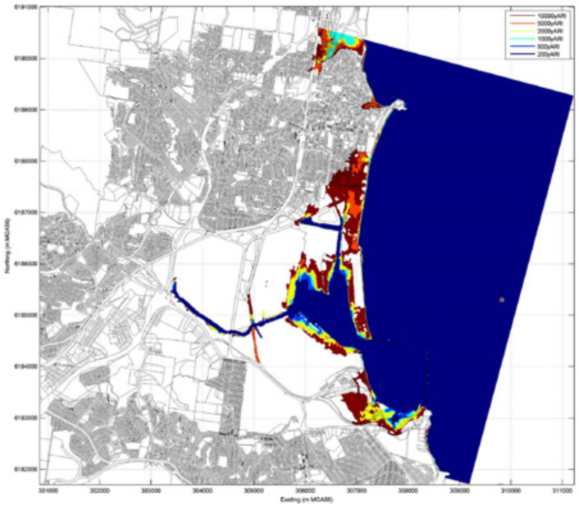


Figure 4 Estimated tsunami runup (m) with an average return interval of 500 years, with 95% credible intervals (Davies et al., 2017). This is a Pacific-scale zoom of the global results. Only major subduction earthquake sources are considered. Note the large uncertainties (lower and upper 95% credible intervals of runup height in the bottom panels), which are largely caused by uncertainties in the rates of large magnitude earthquakes.

other source-zones to generate large tsunami. While not observed historically, large earthquakes on all the aforementioned source-zones are widely considered to be plausible in recent literature, following the 'surprisingly high' magnitudes of the 2004 and 2011 tsunamigenic earthquakes (e.g. McCaffrey, 2008; Kagan and Jackson, 2013; Rong et al., 2014; Berryman et al., 2015; Davies et al., 2017; Kalligeris et al., 2017; Power et al., 2017).

Earthquake-tsunami inundation modelling studies have been undertaken in every state and territory in Australia and Macquarie Island (excluding Christmas and Cocos (Keeling) Island and Antarctica) (e.g. Stevens et al., 2008; Andrews et al., 2013; Boswood, 2013a,b).

One such study was undertaken by Cardno (Cardno 2013; Andrews et al., 2013) and involved numerical model simulations of selected tsunami scenarios using a calibrated Delft3D model system for five NSW coastal sites (Figure 5). This study utilised data from the 2008 Australian Probabilistic Tsunami Hazard Assessment and T2 databases developed by Geoscience Australia and the Bureau of Meteorology, respectively. The model system was demonstrated to reasonably simulate historical tsunami along the NSW coast and replicates the inundation from a benchmark event extremely well (Garber et al., 2011). Another study in NSW (Power et al., 2015) followed a similar approach, and continued inundation throughout estuarine systems. The results



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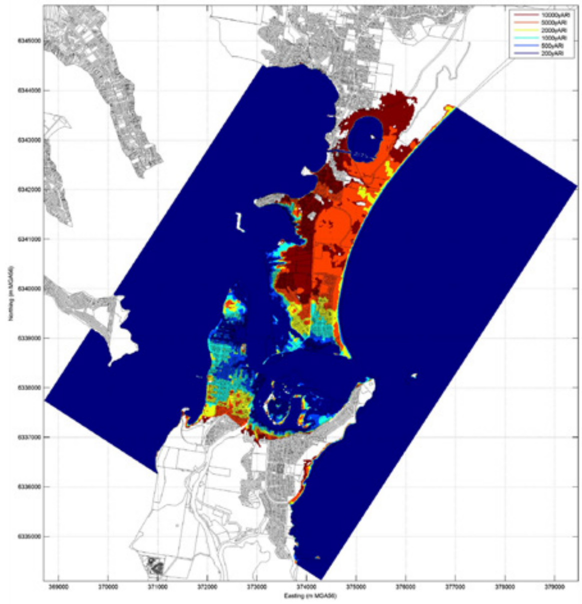
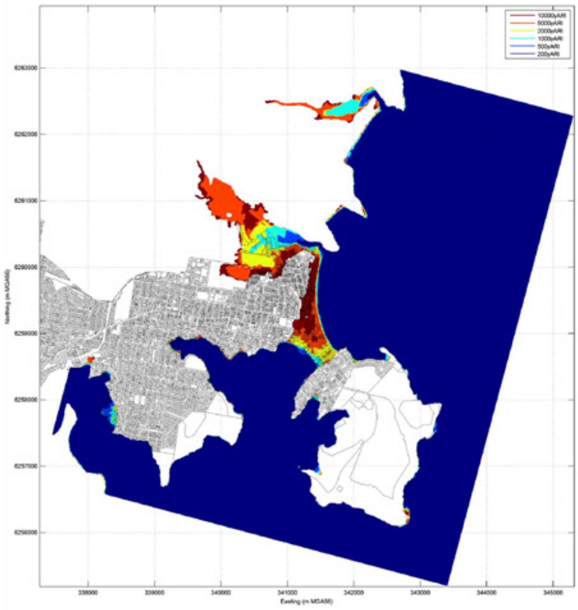
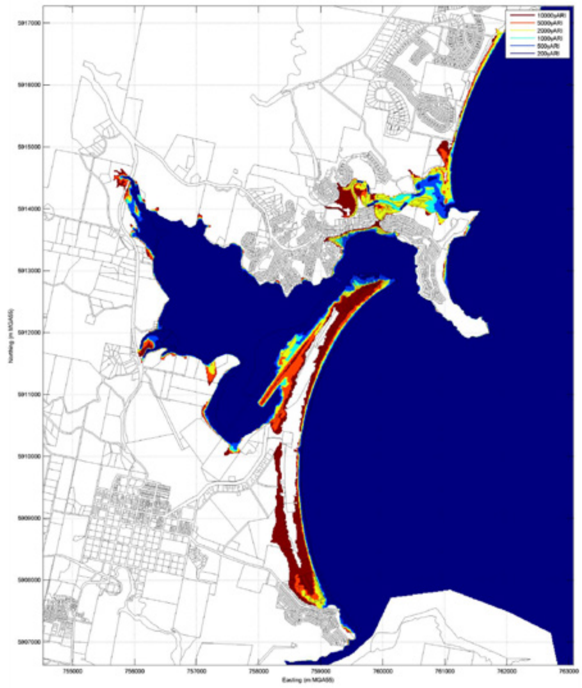


SWANSEA



MANLY



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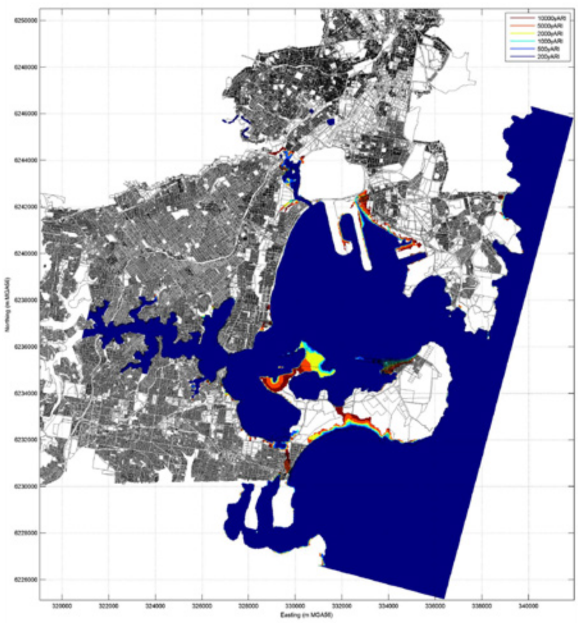


BOTANY BAY

10000yARI	1000yARI
5000yARI	500yARI
2000yARI	200yARI

Figure 5 Mapped inundation extents for various tsunami scenarios for Swansea, Manly, Botany Bay, Wollongong and Merimbula (Cardno, 2013).

of the Cardno (2013) inundation modelling suggest 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 (based on average return intervals estimated by Burbidge et al., 2008). The results also indicated 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 exposed at more frequent average return intervals.

In Queensland, Boswood (2013a) modelled tsunami propagation over the east Queensland Coast, including the Great Barrier Reef. It was found that the Great Barrier Reef and broad continental shelf north of Fraser Island tended to attenuate tsunami amplitudes, in agreement with Baba et al., (2008). Tsunami amplification tended to be greatest in south east Queensland where the continental shelf is narrow. A follow up study performed detailed tsunami inundation modelling in south east Queensland (Boswood, 2013b), identifying a number of towns at most risk from tsunami.

Less work has been undertaken to quantify non-earthquake tsunami hazards in Australia, and this is also true globally. However, a considerable body of work has identified submarine landslide scars on the east and west Australian continental slopes (Heap et al., 2008; Boyd et al., 2010; Clarke et al., 2012, 2014, 2016; Hengesh et al., 2013; Puga-Bernabeu et al., 2013, 2017; Talukder and Volker, 2014; Hubble et al., 2016; Webster et al., 2016), and similar events may be capable of generating significant tsunami. Radiocarbon dating suggests a number of these paleo submarine landslides occurred in the last 25,000 years (Clarke et al., 2012, 2016). While quantitative hazard estimation has not yet been undertaken, initial modelling suggests that if similar events occurred today, they may generate tsunami with onshore runup heights ranging from less than 1 m up to 10 m near the source, with predictions being quite sensitive to the unknown peak landslide velocity (Clarke et al., 2014). This sensitivity is a well-known challenge in modelling landslide tsunami more generally (e.g. Lovholt et al., 2017). More detailed hydrodynamic modelling of similar events in south-eastern Australia is currently being undertaken (Wilson et al., 2017). Further north, Webster et al., (2016) modelled a single landslide scenario based on the largest shelf edge slide they identified off the Great Barrier Reef. They found that if a similar event occurred today it would locally create a 2-3 m wave, but wave heights would rapidly attenuate to only 10s of cm at the coast, suggesting the consequences would be minimal.

There are a number of processes associated with volcanoes that can generate tsunamis including slope failures, underwater explosions, shock waves, pyroclastic flows and caldera collapse (Paris et al., 2015). There are many volcanoes associated with the subduction zones to Australia's north and east that have tsunamigenic potential, either having generated historically observed tsunami, or presenting evidence of past collapse, including in Indonesia and Papua New Guinea (Paris et al., 2014), Solomons and Vanuatu (Goff and Terry, 2016) and the Kermadec Arc (Watts et al., 2012). Volcanoes on the Kerguelen Plateau (Heard and McDonald Islands) are also capable of generating tsunami that could impact the Australian coast (Cox et al., 2016). Volcano-tsunami occur less frequently than earthquake generated tsunami, with only four events in the Australian tsunami database (Goff and Chagué-Goff 2014). Furthermore, they tend to have shorter wavelengths than earthquake generated tsunami and therefore typically reduced far field impacts (Paris et al., 2015). The most historically significant volcano tsunami for Australia was the 1883 Krakatau eruption and tsunami, which generated waves around 2.5 m at Geraldton and the loss of livestock in Onslow, Western Australia (Simpson et al., 2007; Goff and Chagué-Goff., 2014).

Meteotsunami refer to tsunami generated by atmospheric disturbances including storms, fronts and atmospheric gravity waves, Meteotsunami have not generated catastrophic events to the same extent as other tsunami sources, although damaging events have occurred globally, particularly in ports and harbours (Monserrat et al., 2006; Geist et al., 2014). Small events can occur quite frequently; however, the largest meteotsunami require very specific combinations of resonant effects, and are consequently quite rare (Pattiaratchi and Wijerante, 2015). Analysis of tide gauges records has shown that meteotsunami occur frequently along the Western Australian coast (Pattiaratchi and Wijerante, 2014), being generated by thunderstorms in summer and the passage of low pressure systems in winter. Meteotsunami wave heights at some gauges are comparable to or exceed wave heights from earthquake-generated tsunami (Pattiaratchi and Wijerante, 2014; Pattiaratchi and Wijerante, 2015). Observations of meteotsunami have also been reported at sites in Queensland (DSITIA, 2017) and New South Wales (Blumberg et al., 2016).

Tsunami hazard due to asteroids is not well understood globally. Morrison and Venkatapathy (2017) suggest that the asteroid tsunami hazard is small as compared with the hazard associated with an asteroid impacting on land. An early study by Ward and Asphaug (2000) attempted to quantify the asteroid tsunami hazard globally using an analytical model. They estimated that Sydney has an annual chance of approximately 1/5000 of experiencing asteroid tsunami waves exceeding 2 m in 2 m water depth (Ward and Asphaug, 2000, their Table 3). However, more recent work suggests these hazard values are probably too high, because they employed an analytical hydrodynamic approach which overestimates wave heights (by a factor between 2 to 10 times) compared with a range of more sophisticated numerical models (Wunneman and Weiss, 2015). Even ignoring the likely wave height overestimation, the 1/5000 event rate at Sydney is less frequent than the rate estimated for comparable earthquake tsunami (Andrews et al., 2013; Davies et al., 2017), assuming the asteroid tsunami runup is around one to three times the wave height in 2 m water depth. Overall, this suggests that the asteroid tsunami hazard is probably a fraction of the earthquake tsunami hazard, but substantial uncertainties remain.

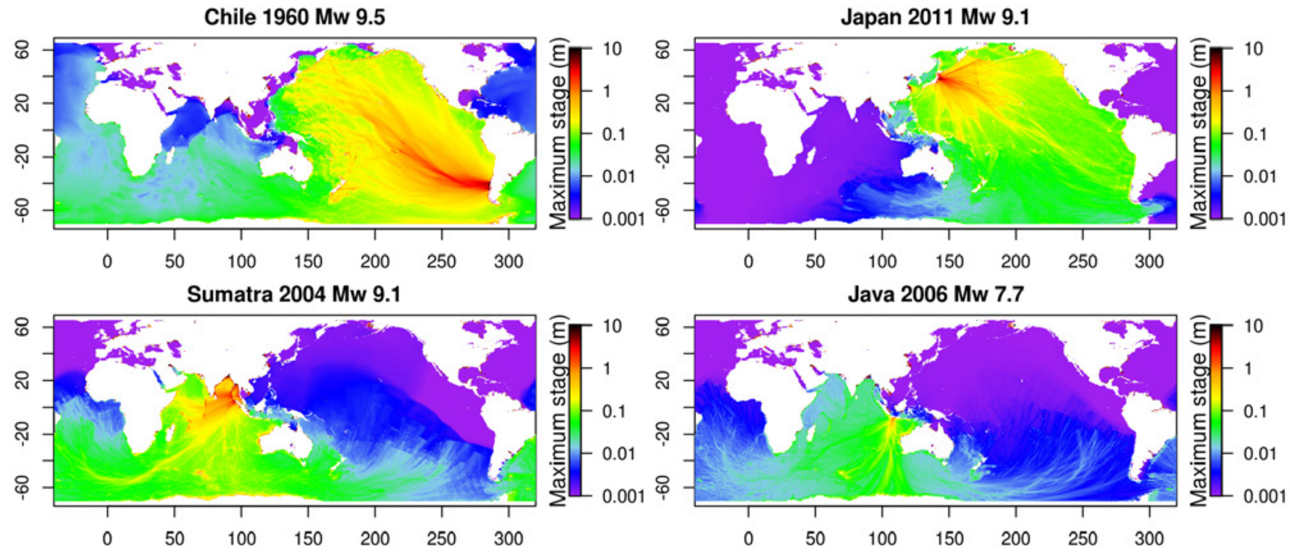


Figure 6 Maximum stage modelled from four recent tsunami events. The tsunami initial condition was computed using finite fault inversions of the corresponding earthquakes from Fuji and Satake, 2013 (Chile 1960), Satake et al., 2013 (Japan 2011), Piatanesi and Lorito, 2007 (Sumatra 2004), and Ammon et al., 2007 (Java 2006). The tsunami was modelled for 24 hours with the linear shallow water equations on a 4-arc minute grid. While these images show the general patterns of tsunami radiation in each of these events, they should not be interpreted as precise representations of the real events because of imperfections in the tsunami initial condition, and limitations in the coarse resolution bathymetry and numerical model.

3.3 Historical and Paleotsunami in Australia

The Australian tsunami database contains reports of historical and paleo tsunami in Australia (Goff and Chagué-Goff, 2014; Dominey-Howes., 2007). As of 2013 it contained 145 events, along with information on the source of each, and an estimate of its validity (i.e. the likelihood that the report truly indicates a tsunami). While most events in the last 70 years are assigned 'excellent validity', older historical records usually have lower validity ratings. This reflects the temporal evolution of measurement networks (e.g. for earthquakes and water levels) which are a key source of independent confirmation that a tsunami occurred, as well as the reduced volume of published material available from the earlier historical period, and the difficulty of unequivocally distinguishing paleo-tsunami deposits from those of paleo-storms or other marine inundation events.

Several recent well-known tsunamis led to regionally significant marine hazards and locally significant inundation in Australia. The largest recorded tsunami runup in Australia is currently 7.9 m, and was measured at a limestone cliff at Steep Point (Western Australia) following a Mw 7.7 earthquake offshore of Java (17/07/2006) (Prendergast and Brown, 2012). This runup was quite localised, but the same event led to runup of a few metres at a nearby beach which destroyed a number of campsites, with campers evacuating to nearby hills upon hearing the first wave (Fritz et al., 2007; Prendergast and Brown, 2012). An earlier earthquake of similar magnitude from Java (in 1994) is reported to have generated 3-to-4 m runup at Baudin, Western Australia (Lander et al., 2003; Goff and Chagué-Goff, 2014), while the 1977 Mw 8.3 Sumba earthquake is reported to have produced 6 m waves offshore of Cape Leveque, Western Australia, and runup of a few meters (Gregson et al., 1978). On the east Australian coast, the 1960 Chile tsunami led to runup of 1.7 m at Eden, NSW, with anecdotal reports of waves up to 5 m around NSW (Beccari, 2009). While this earthquake had a magnitude around 9.5 (inferred from seismic waves), its tsunami and geodetic displacement were actually 'small' for such a high magnitude earthquake, and are more consistent with an event of magnitude 9.2-9.3 (Fuji and Satake, 2013; Figure 7). More recently, the 2004 Indian Ocean tsunami and the 2011 Tohoku tsunami both generated unusual currents on the west and east Australian coasts respectively, and in both instances there were reports of swimmers and marine craft experiencing difficulties (BOM, 2018; Hinwood and McClean, 2013). However, there was only minor inundation during the latter events (Horspool et al., 2010; Hinwood and McClean, 2013).

Regarding non-earthquake sources, the 1883 volcanic eruption of Krakatoa generated a tsunami that was recorded in Western Australia, with waves around 2.5 m at Geraldton (Goff and Chagué-Goff, 2014). There are also many reports of unexpected large waves (but with no known tsunami source), at various sites in Australia (Goff and Chagué-Goff, 2014). An example is a 1953 event at Bridport in northern Tasmania, where an unexpected 2.4 m wave engulfed three children, one of whom drowned. Another example is the 1938 'Black Sunday' event at Bondi beach, where a sequence of unexpectedly large waves led to 5 drownings and the largest mass rescue in Australia's history (PMSEIC, 2005). While such events are not confirmed tsunami (because the source is unknown), it is plausible that some were of meteotsunami origin, or were generated by a local landslide source.

Considering the broader implications of recent well-known earthquake-tsunami events for Australian tsunami hazard, it is worth noting that none of the earthquake-tsunami noted above were simultaneously 'high magnitude' and 'well situated to affect Australia' (Figure 6). Tsunami waves have strong directionality, depending on the location and orientation of their source, and the effect of bathymetry on wave propagation. This has a major influence on their far-field impacts. Although the 2006 Mw 7.7 Java event caused the highest recorded tsunami runup in Australia (Prendergast and Brown, 2012), it resulted from a relatively low magnitude earthquake (albeit one which generated a large tsunami for its magnitude). Importantly, the Java earthquake event was well situated to send tsunami energy towards the central western Australian coast (Figure 6). On the other hand, the Chile 1960, Sumatra-Andaman 2004 and Japan 2011 events were all of much higher magnitude (> 9) and led to larger, ocean-basin scale tsunami events. However they were not particularly well situated to direct their energy towards Australia, and so the runup was not as large (Figure 6).

A number of possible paleo-tsunami deposits have also been identified in Australia, although it is unclear whether they were emplaced by tsunamis or coastal storm events (i.e. storm surge and/or high waves). Dodson et al., (2014) report on a number of wrack lines (i.e. high-water-level debris) which extend up to 10 m above sea level near Onslow and Karratha, WA, with ages ranging up to 2500 years before present. Clark et al., (2011) recorded five anomalous coarse sedimentary deposits in low-energy coastal environments in south-eastern Tasmania. A number of coarse deposits in low energy environments have also been identified on the NSW south coast (Switzer et al., 2005, 2006; Switzer and Jones 2008a, b). In all of the above studies, the authors note that it is possible the deposits were emplaced by either tsunamis or coastal storms. Distinguishing between these emplacement mechanisms is a key challenge in paleotsunami research.

From the mid-1990s several studies by Bryant and colleagues interpreted coastal geomorphic features in New South Wales as having been generated by extremely large tsunami, with several such tsunami interpreted to have occurred in the last few thousand years (e.g. Bryant et al., 1992, 1996; Bryant, 2001). This has been termed the 'Australian Megatsunami Hypothesis'. The 'Australian Megatsunami Hypothesis' has been critiqued in a number of studies, which suggest many of the interpretations are erroneous, and also suggest alternative non-tsunami interpretations (see Courtney et al., 2012 for further references and review). Critiques also emphasise that most of the criteria used by Bryant and colleagues to infer paleo-tsunami have not been observed to be produced by modern tsunami, and are different to features used to infer paleo-tsunami elsewhere. Courtney et al., (2012, p122) conclude that "… there is little reliable evidence to support the hypothesis that repeated large scale (mega) tsunamis have occurred. This does not mean there is no chance of future such events occurring".

4. Modelling Tsunami Dynamics

KEY POINTS:

- **Tsunamis are generated by the displacement of the water column over a large area, typically in the ocean. A range of geophysical mechanisms can achieve this, including earthquakes, landslides, volcanic activity, asteroids, and meteorological processes.**
- **Details of the generation process can have a significant impact on the tsunami magnitude and characteristics. Hazard studies can account for this with a multi-scenario or probabilistic approach.**
- **High quality onshore and nearshore elevation data is necessary to model tsunami inundation and nearshore behaviour with accuracy. Lower resolution global datasets are generally only suitable for modelling oceanic scale tsunami propagation. If good quality elevation data is unavailable, then advanced tsunami models may be of little benefit compared with crude geometric models such as the bathtub, or attenuation laws.**
- **The shallow water equations are well suited to modelling the propagation and inundation of most hazardous earthquake tsunami. For other tsunami generation mechanisms, more advanced hydrodynamic models are often employed.**
- **Tsunami modelling codes should be tested against a range of benchmark solutions to confirm their suitability for hazard studies.**
- **Tsunami models are often applied to hindcast well known historical tsunami events. In some benchmarks with a well constrained tsunami source, many models can reproduce observed runup with errors of around 20 per cent on average. However, larger errors are often reported in some 'difficult to model' sites.**
- **It is difficult to quantify the accuracy of hazard models, in terms of how well they represent possible future events. However, individual hazard scenarios should be less accurate than hindcasts of historical events, because hindcast models can 'tune' their tsunami source using observational data.**

4.1 Generation

Tsunamis are generated by the rapid non-uniform displacement of the entire water column over a significant area of seabed (in what follows, we assume the term 'seabed' applies to the earth beneath the ocean, or any other water body such as a lake). Processes that can generate tsunami include the deformation of the seabed due to an earthquake, or the rapid movement of a landslide along the seabed, both of which displace the entire water column above them. Models of tsunami generation thus vary greatly depending on the generation mechanism.

Irrespective of the generation mechanism, to effectively generate a tsunami the seabed motion needs to occur reasonably rapidly in time. If seabed motion is slow compared with the gravity wave speed in water, then the water column may essentially 'flow around' the disturbance without generating a tsunami, as occurs for slow moving landslides. Furthermore, tsunami generation is much more efficient if the area of the displacement is large compared with the water depth, because displacements with smaller horizontal scales tend to be 'smoothed out' by the three dimensional hydrodynamic response of the water column (e.g. Kajiura, 1963; Nosov and Kolesov, 2011).

Of the different methods of tsunami generation, generation by earthquakes is best understood (Figure 7). Earthquakes are usually represented as slip (relative displacement) on a fault plane buried in the Earth. The size of the slip and rupture area are both related to the earthquake magnitude, while the orientation and depth of the fault plane is related to the site specific conditions (e.g. the geometry of the subduction zone

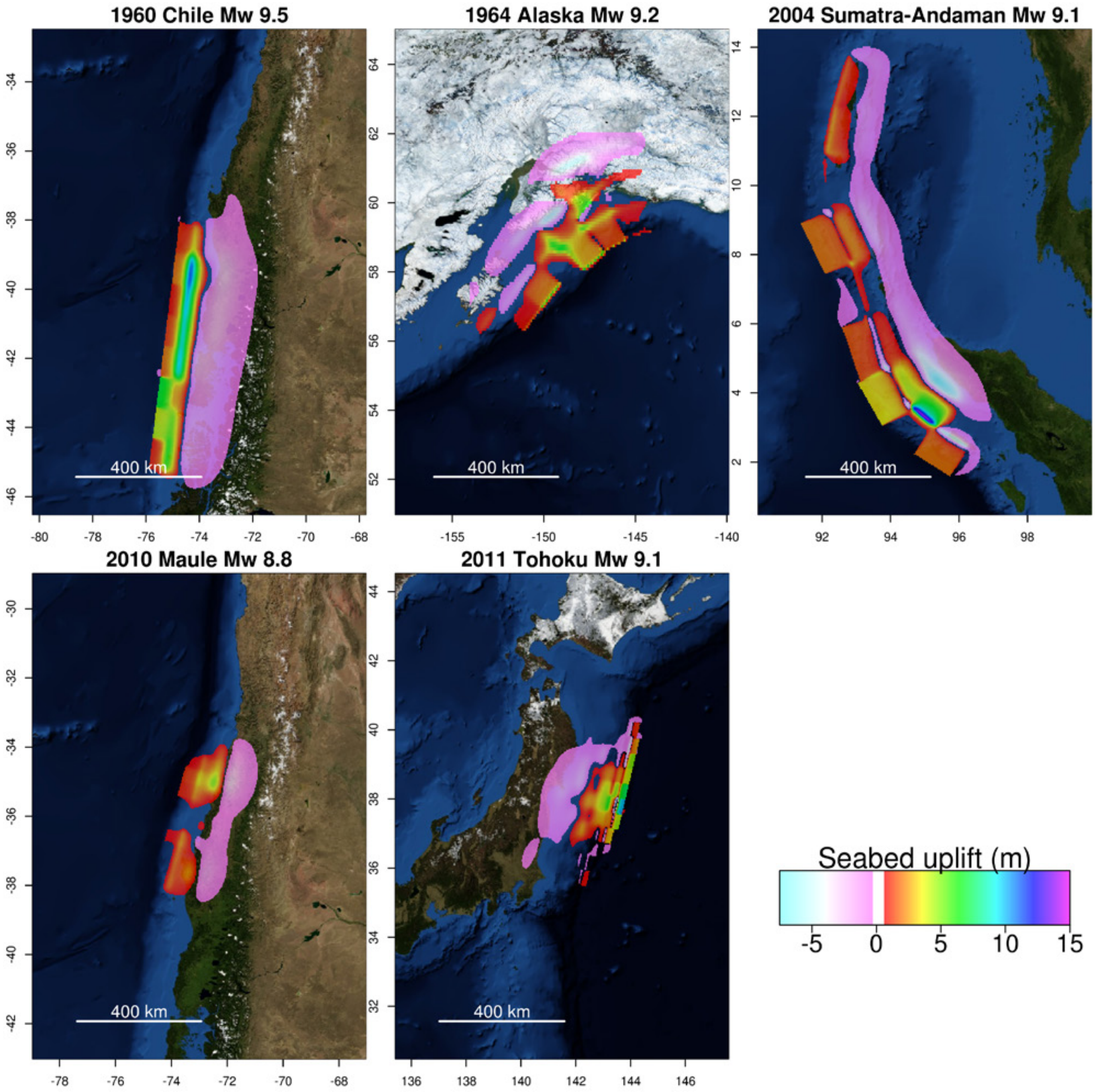


Figure 7 The uplift of the seabed estimated for a number of recent earthquakes. They were computed using Okada's (1985) model, using the 'best-fit' earthquake slip models provided in the following references, which estimate the earthquake slip using tsunami observations and geodetic measurements: 1960 Chile Mw 9.5 (Fuji and Satake, 2013); 1964 Alaska Mw 9.2 (Johnson et al., 1996); 2004 Sumatra-Andaman Mw 9.1 (Lorito et al., 2010); 2010 Maule Mw 8.8 (Fuji and Satake 2013); 2011 Tohoku Mw 9.1 (Satake et al., 2013).

where the earthquake occurs). Substantial variations in the earthquake slip and dimensions are likely even when the earthquake magnitude is fixed, because earthquakes show great natural variability (e.g. Allen and Hayes, 2017). For instance, the 2004 Sumatra-Andaman earthquake was much longer than the 2011 Tohoku earthquake, although both had a similar magnitude (Figure 7). This translates into considerable variation in the seabed displacements (Figure 7).

If the earthquake geometry and slip distribution are specified, then the seabed displacement can be computed in a number of ways. Most commonly, the model of Okada (1985) is used, which assumes the Earth is a homogeneous linear elastic body with flat topography (Figure 7). More complex approximations exist and can relax some of these assumptions (e.g. Wang et al., 2003), but for most hazard applications these are of second order importance compared with the uncertainties in the earthquake. The water column displacement may be computed from the seabed displacement, by smoothing out short wavelengths to reflect the 3D hydrodynamic response of the ocean (Kajiura, 1963; Nosov and Kolesov, 2011; Glimsdal et al., 2013; Saito, 2013). This step will have little impact (and may be skipped) if the seabed displacement is already almost uniform over spatial scales of a few times the water depth, which is true for most deeper earthquakes.

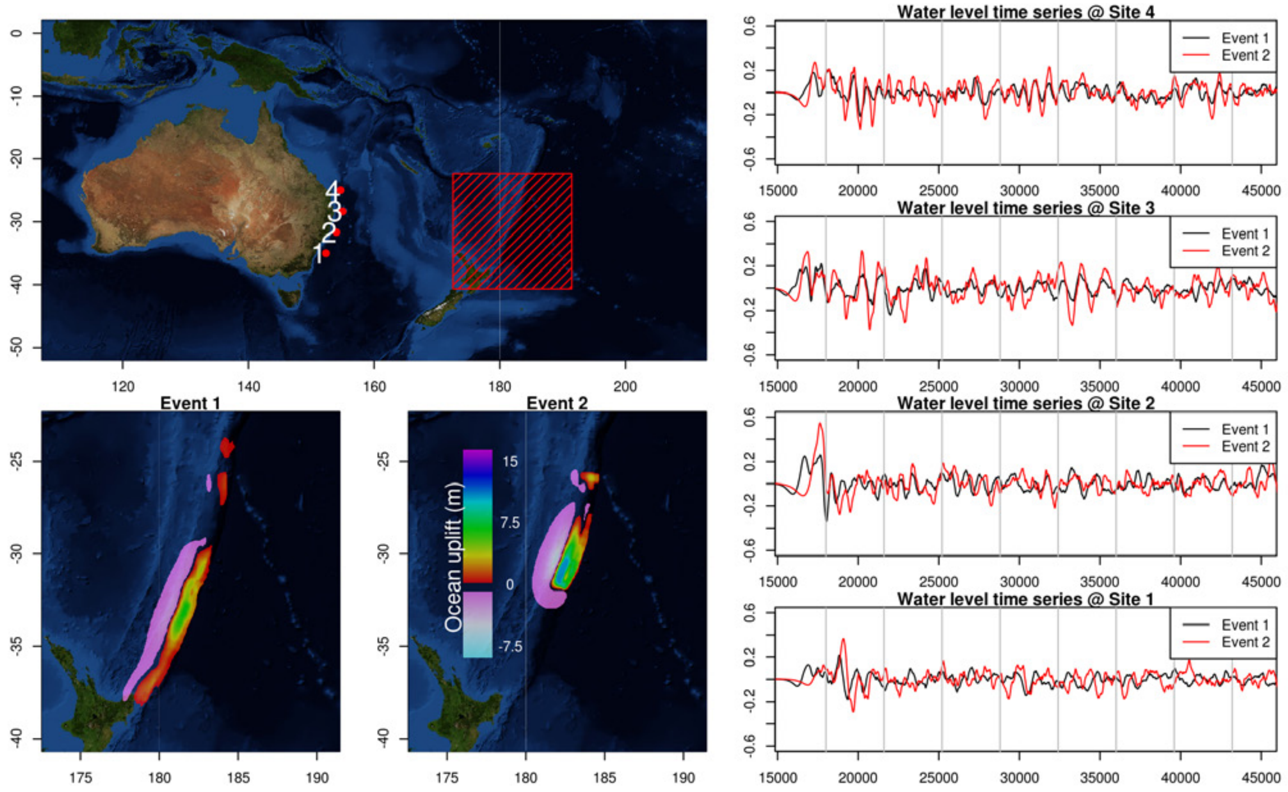


Figure 8 Hazard model scenarios illustrating the influence of earthquake rupture details on tsunami time-series. The top left hand panel shows the region, gauge locations, and site of the ruptures. The lower left panels show the modelled ocean uplift from two different Mw 9.1 rupture scenarios with spatially variable slip. The uplift from Event 1 is more spread-out than Event 2, with smaller extrema, and a maxima slightly to the south. The right hand panels show the predicted water level time-series for both events at the 4 sites offshore of Australia (all in water depths around 4-5 km).

For earthquake-tsunami hazard modelling it is necessary to construct reasonable hypothetical earthquake scenarios. Plausible earthquake magnitudes may be inferred based on statistical relationships between earthquake magnitude and rupture area (supposing the source fault area is known, e.g. McCaffrey et al., 2008; Kalligeris et al., 2017), or the advice of global expert panels (e.g. Berryman et al., 2015), or existing models of earthquake magnitude-frequency which integrate historical earthquake data with plate tectonic convergence rates (e.g. Bird and Kagan, 2004; Burbidge et al., 2008; Rong et al., 2014; Davies et al., 2017). On subduction zones, the fault geometry is usually estimated from existing models (such as SLAB 1.0, Hayes et al., 2011) or inferred from earthquake catalogues (such as the global centroid moment tensor catalogue; Ekstrom et al., 2012). Other site-specific geological or geophysical information may also be used to infer the fault geometry. Next, the fault plane length and width are usually estimated using published statistical 'scaling relations' between earthquake size and magnitude, most of which include predictive uncertainty terms which can be used to account for the additional variability in rupture size (e.g. Strasser et al., 2010; Blaser et al., 2010; Allen and Hayes, 2017). For large earthquakes, the length and width may be limited by the size of the source-zone's fault. Once the length and width are established, the depth may be chosen. Earthquakes generally occur at a range of depths, up to some site specific limit (on the order of 50 km) where the temperature becomes too great to host earthquakes. The average earthquake slip may be derived from the event magnitude and area given an estimate of the shear modulus. The latter is often poorly known but tends to vary around [2-7]x10^10 Pascals, although lower values may occur in shallow parts of subduction zones (Geist and Bilek, 2001; Lay et al., 2012). Once the average slip is determined, the spatial distribution of slip may be assumed to be constant, or random slip models may be employed to simulate the spatial variability of slip that is observed in real earthquakes (e.g. Geist et al., 2002; 2013; Davies et al., 2015; Figure 7). The slip direction (termed the 'rake') must also be chosen, although it is often set to 90 degrees because this value is typical for subduction-zone earthquakes, and often generates larger tsunamis than other rake values. The modelling choices discussed above (earthquake depth, length, width, shear modulus, slip distribution and rake) can have a substantial impact on the modelled seabed deformation and consequent tsunami, and the associated uncertainties can be dealt with by modelling multiple scenarios (Figure 8).

Models of tsunami generation from other sources are less well established than for earthquakes, and the physical mechanisms show greater diversity. Landslide-tsunami may be modelled by treating the landslide as a rigid translational block, or a rotational slide, or a retrogressive failure, or as a viscoelastic fluid (Lane et al., 2016; Smith et al., 2016). Although submarine landslides are most often considered, subaerial landslides can also generate tsunami if they fall into water (Xiao et al., 2015; Gylfadóttir et al., 2017). In any case the tsunami is caused by the water column being lifted up and/or down to accommodate the water displacement due to the landslide motion. The appropriateness of any particular landslide mechanism must be inferred based on site-specific information (e.g. Lovholt et al., 2017). In general the tsunami will be affected at first-order by the slide dimensions, speed and initial acceleration (Grezio et al., 2017). Uncertainties in these or other parameters may be assessed using multiple scenarios or probabilistic treatments (e.g. ten Brink et al., 2014; Pampell-Manis et al., 2016; Lovholt et al., 2017).

Modelling tsunami generation from volcanic sources is difficult due to the diversity of generation mechanisms, which may operate individually or concurrently. For example, Nomanbhoy and Satake (1995) argue that smaller tsunami waves generated by the 1883 Krakatau eruption were caused by pyroclastic flows, while the largest tsunami was generated by an underwater explosion. Mass failure of volcanic edifices can be modelled using the same approaches used for submarine/subaerial landslide generated tsunami, though again subject to the uncertainties discussed above. Historical analogues for events that are well characterised (e.g. the 1888 Ritter Island, PNG tsunami; Johnson, 1987; Ward and Day, 2003; Berndt et al., 2017) can be used to generate hazard models for volcanoes sharing similar characteristics (Silver et al., 2009). Eruptive processes, including explosions, pyroclastic flows and caldera collapse are complex physical processes that can be difficult to simulate (Paris et al., 2014), and are subject to large uncertainties in estimates of physical volume and period of time over which they occur. Although the relatively shorter wavelengths of volcanic tsunami relative to earthquake sources render them less threatening at regional (100-1000 km) and far-field (1000+km) distances, large events such as the 1883 Krakatau eruption and 1888 Ritter Island sector collapse caused impacts at regional distances (Paris et al., 2014).

Meteotsunami are generated when the speed of passage of an atmospheric disturbance is comparable to the phase speed of tsunami waves in the underlying ocean (Monserrat et al., 2006; Geist et al., 2014; Grezio et al., 2017). This leads to resonance (most commonly Proudman resonance, although 'Greenspan resonance' and 'shelf resonance' can also be important; Monserrat et al., 2006) between the atmospheric disturbance and the ocean, allowing energy from the atmosphere to continually be added to the ocean thereby generating and amplifying tsunami waves (Geist et al., 2014). Tsunami generation due to Proudman resonance can be modelled as a function of horizontal distance over which the pressure change occurs, the distance travelled (fetch) and the rate of change of atmospheric pressure (Monserrat et al., 2006; Geist et al., 2014). Geist et al., (2014) have presented a methodology for probabilistic hazard assessment for meteotsunamis. This method requires analysis of meteorological data to determine the frequency with which certain combinations of meteorological conditions occur, followed by numerical simulation of ocean waves generated by these conditions.

Modelling asteroid tsunami generation remains a research topic and area of controversy (see Wunneman and Weiss, 2015 for a review). The latter authors indicate '… no conclusive answer has been found to the question of whether (asteroid) impacts in the marine environment produce mega-tsunamis of greater dimensions than any other generation mechanism … due to deviating results from different methodological approaches'. Wunneman and Weiss (2015) review a number of models of the Eltanin impact (an asteroid of 0.75-1.5km diameter which impacted earth around 2.15 million years ago), finding that near and far field wave heights vary by around a factor of 10 in different published works. This largely stems from differences in the predicted wave heights immediately following impact, while all studies predict that the tsunami wave height will decrease approximately inversely with distance from impact. Morrison and Venkatapathy (2017) further discuss research needs for modelling asteroid tsunami.

4.2 Propagation

Tsunamis are usually initiated in water depths much greater than the initial sea surface displacement. Further, tsunami waves are typically 'long' compared to the water depth (i.e. wavelengths from several 10s to 100s of km, compared with typical oceanic water depths of 1 to 6 km), especially when generated by large earthquakes. For this reason, earthquake tsunami are not easily noticeable to people on ships in the deep ocean. However, nowadays deep ocean tsunami can be reliably detected with purpose built instruments for measuring long period waves (Deep Ocean Tsunami Detection buoys).

For such 'small amplitude, long wave' tsunamis, the main features of wave propagation away from nearshore areas are well modelled using the two dimensional linear shallow water equations (Figures 9 and 10). A common heuristic is that this works well in water depths greater than about 50-100 m (e.g. Shuto et al., 1991; Burbidge et al., 2008), although theoretically the latter threshold will increase with the tsunami amplitude (Ursell, 1953) and depend on other factors that affect the flow velocity (e.g. coastal morphology, wave period, etc). In shallower regions the nonlinear versions of the equations should be used (Section 3.3). If the propagation covers regions larger than around 500 km, the spherical version of the equations should be used to account for the curvature of the earth.

Typical oceanic tsunamis (i.e. having a small amplitude and long wavelength, compared to the water depth) propagate through the ocean at a celerity of (gravity x depth) ^ 0.5, which is about 100 m/s in 1 km water depth, and 200 m/s in 4 km water depth. This allows them to travel across the Pacific Ocean in less than a day. If the tsunami contains wavelengths of less than around 20 times the water depth, those waves will propagate more slowly than predicted by shallow water wave theory, and their amplitude will decay more rapidly in space (Lovholt et al., 2008; Wunneman and Weiss,

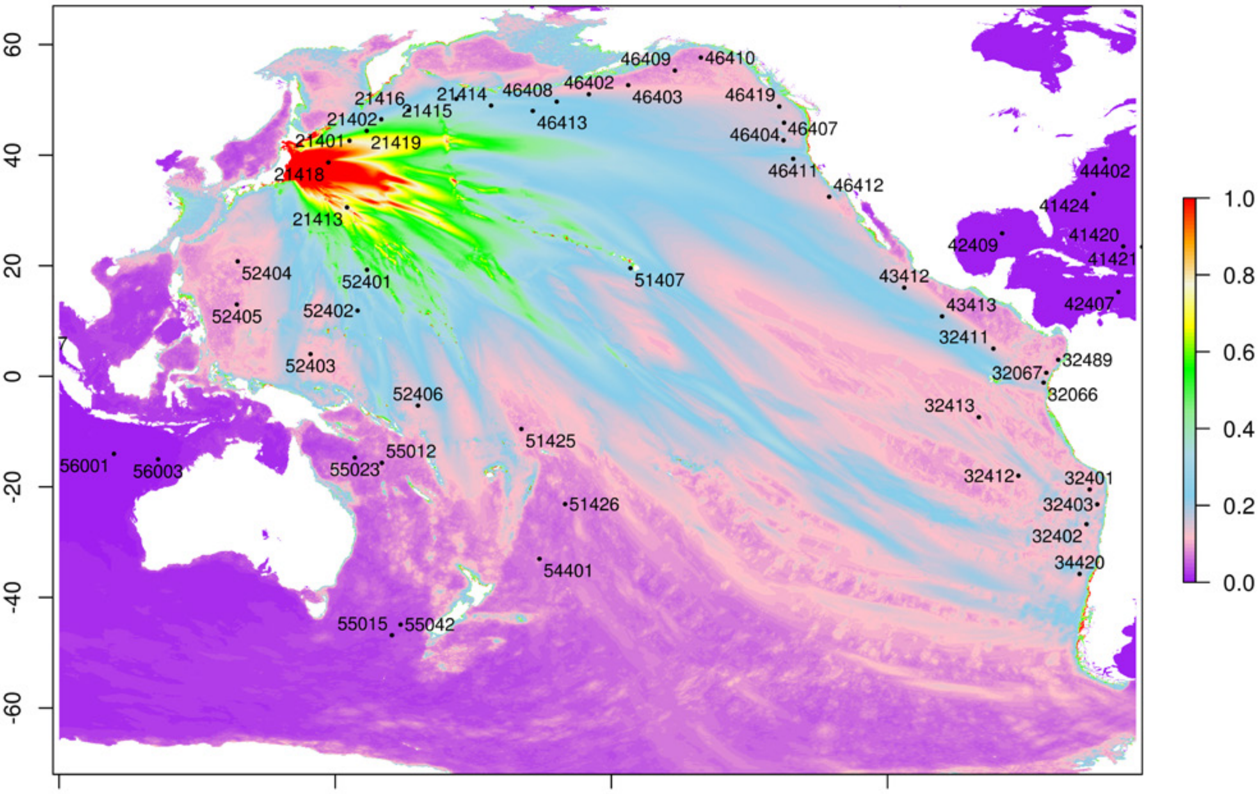


Figure 9 Peak water level from a hazard model scenario. The scenario was selected to be similar to the 2011 Tohoku tsunami at the Deep Ocean Tsunami Detection buoys (numbered locations). The latter wave time series are depicted in Figure 10 (Geoscience Australia 2018, revised Australian Probabilistic Tsunami Hazard Assessment, in prep).

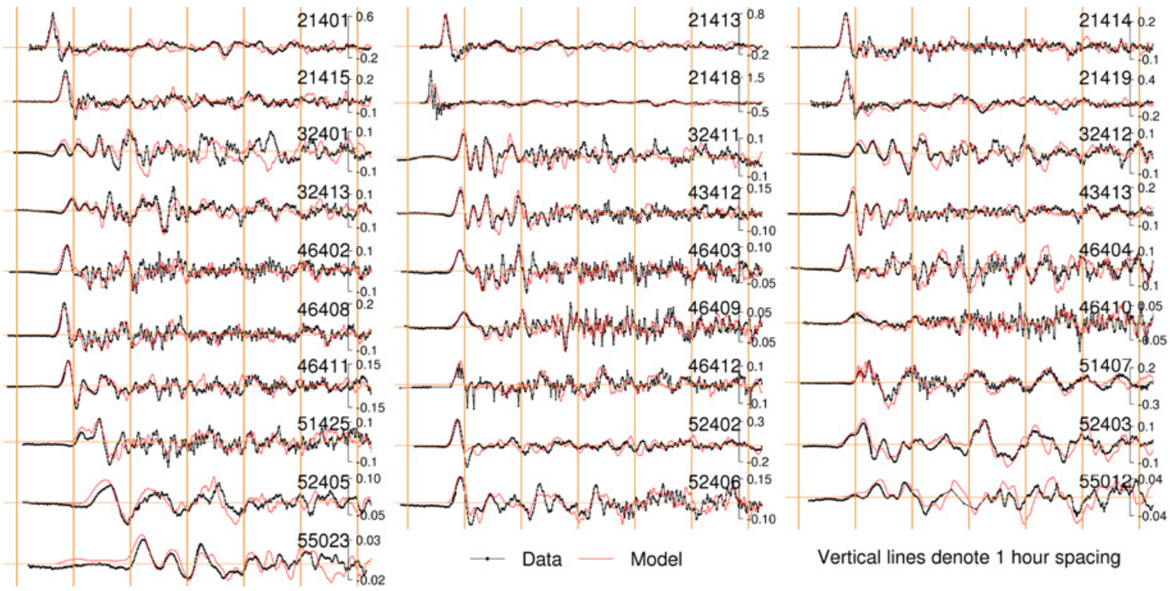


Figure 10 Comparison of observed Deep Ocean Tsunami Detection buoy water-level time-series during the 2011 Tohoku tsunami with the hazard model scenario depicted in Figure 9. Vertical lines denote one hour spacing. Both the start-times and vertical scale have been adjusted per-gauge for visual clarity. The linear shallow water equations were used to model the tsunami, using an earthquake source with spatially variable slip generated by a stochastic slip model. Model time-series were shifted by up to 2 minutes (near to the source) or 15 minutes (far from the source) to account for the finite duration of rupture, and time-delays not captured by the linear shallow water equations.

2015). Shorter wavelengths tend to be more significant for tsunami generated by non-earthquake sources or small earthquakes (Glimsdal et al., 2013). To model such waves additional dispersive terms may be appended to the shallow water equations (e.g. Baba et al., 2015), or the more fundamental Navier-Stokes equations may be used instead (Oishi et al., 2013). Other physical processes such as loading of the Earth, variations of seawater density, and self-gravitation also slightly affect oceanic tsunami propagation, reducing the wave celerity by around 1 per cent (Allgeyer and Cummins, 2014; Baba et al., 2017). This means that in comparison to observations, shallow water models predict slightly early tsunami arrival times (e.g. up to 15 minutes early at trans-Pacific distances). While this is a small effect it should be considered when comparing models and data (Figure 10).

The oceanic-scale distribution of tsunami wave heights (Figures 9 and 10) is controlled by a mixture of factors. Earthquake-tsunami sources tend to show strong directionality, with the dominant wave propagating perpendicular to the strike for subduction zone earthquakes (Figure 9). As tsunami propagate away from the source-zone, the wave field tends to decrease in height due to the geometric spreading of wave energy over a larger area (Figures 9 and 10). Conversely, the wave height tends to increase when propagating from deep to shallow waters, due to energy flux conservation, while bathymetric variation also tends to cause 'beaming' or 'focussing' of the tsunami wave in particular areas (Figure 9). In addition the wave front will reflect off land, and wave scattering tends to occur around small islands and bathymetric rises. Eventually the tsunami at any site represents the sum of the incident wave field and a large number of reflected waves that may have different periods, leading to a complex interference structure that determines tsunami wave heights and propagation directions.

When tsunamis propagate into shallow nearshore areas the height and flow velocities increase, leading to turbulent dissipation and some loss of tsunami energy. At the global level, this causes the tsunami energy to decay over several days (van Dorn, 1984; Rabinovich et al., 2011; 2013). Because 'ocean-basin scale' tsunami propagation models tend to be run on coarse grids, and often ignore friction, they are not well suited to modelling this dissipation. In such models the energy dissipation is often dominated by numerical dissipation, which will be a function of the model numerical method, grid size, and treatments of wetting and drying (Tang et al., 2012; Tolkova, 2014). This does not prevent models from simulating the first few hours of the tsunami well if the source is adequately represented (Figure 9), but makes it more difficult to simulate late arrivals accurately.

Given the above factors and the limited availability of high-resolution nearshore bathymetry, modelling late-time arrival tsunami waves is currently considered difficult (Kowalik et al., 2008; Geist, 2009; Nyland and Huang, 2013). Late arriving waves may originate from coastline irregularities far away from the site at which they are observed, and can rarely be well predicted (Kowalik et al., 2008; Geist, 2009; Hayashi et al., 2012). In the context of tsunami warning systems, Nyland and Huang (2013) indicate that while numerical models used in the West Coast and Alaska Tsunami Warning Centre are adequate for predicting the size of early arrival tsunami waves, they are not accurate enough for forecasting the duration of hazardous tsunami. Such estimates are desirable to help determine when tsunami warnings can be lifted, and statistical methods have been proposed for this purpose (Mofjeld et al., 2000; Nyland and Huang, 2013).

4.3 Nearshore behaviour and inundation

As tsunamis propagate from deep to shallow waters they begin to travel more slowly. This causes a reduction in the tsunami wavelength. Wave shoaling also increases the tsunami wave height, which in turn increases the flow velocities. These transformations eventually lead to a range of nonlinear processes significantly affecting the nearshore flow dynamics (see Lynett et al., 2016 for a more detailed discussion).

For tsunami hazard studies, physics based models are often used to simulate the tsunami. These are able to simulate the full time evolution of the tsunami (offshore, nearshore, and during inundation), and provide estimates of key time-varying quantities such as the flow velocity and depth, and the inundation extent. As of 2018, physics based models are most often based on the nonlinear shallow water equations (including a friction term). The shallow water equations are designed to model 'long waves' (wavelength greater than around 10 to 20 times the depth) when the flow field is not strongly three dimensional, and vertical velocities are small. This is a good description of many tsunami phenomena. If the dynamics of shorter waves are of particular interest (i.e. wavelength less than around ten to twenty times the depth) then dispersive terms may be appended to the shallow water equations (e.g. to model undular bores, Baba et al., 2015). More complex 3D models may also be applied if highly three-dimensional flows are of interest (e.g. runup at steep cliffs where vertical velocities are not negligible; Kim et al., 2015).

From a hazard modelling perspective it is often suggested that the inclusion of non-shallow-water terms is practically important for non-earthquake sources such as landslides, volcanoes or asteroids, while the nonlinear shallow water equations are usually considered adequate for modelling earthquake-generated tsunami hazards (Glimsdal et al., 2013; Behrens and Dias, 2015; Lynett et al., 2016; Grezio et al., 2017). For example, Baba et al. (2015) modelled inundation during the 2011 Japan earthquake-generated tsunami using a nonlinear shallow water model, comparing the solutions with and without inclusion of dispersive terms. Dispersive terms were required to model the visually striking undular bores that formed during this tsunami. However, this had a minor impact on the computed inundation, which was similar with and without dispersive terms (as suggested by Madsen, 2008). Synolakis and Kanoglu (2015) suggest the shallow water equations are preferable for hazard assessments because: 1) they are more robust and

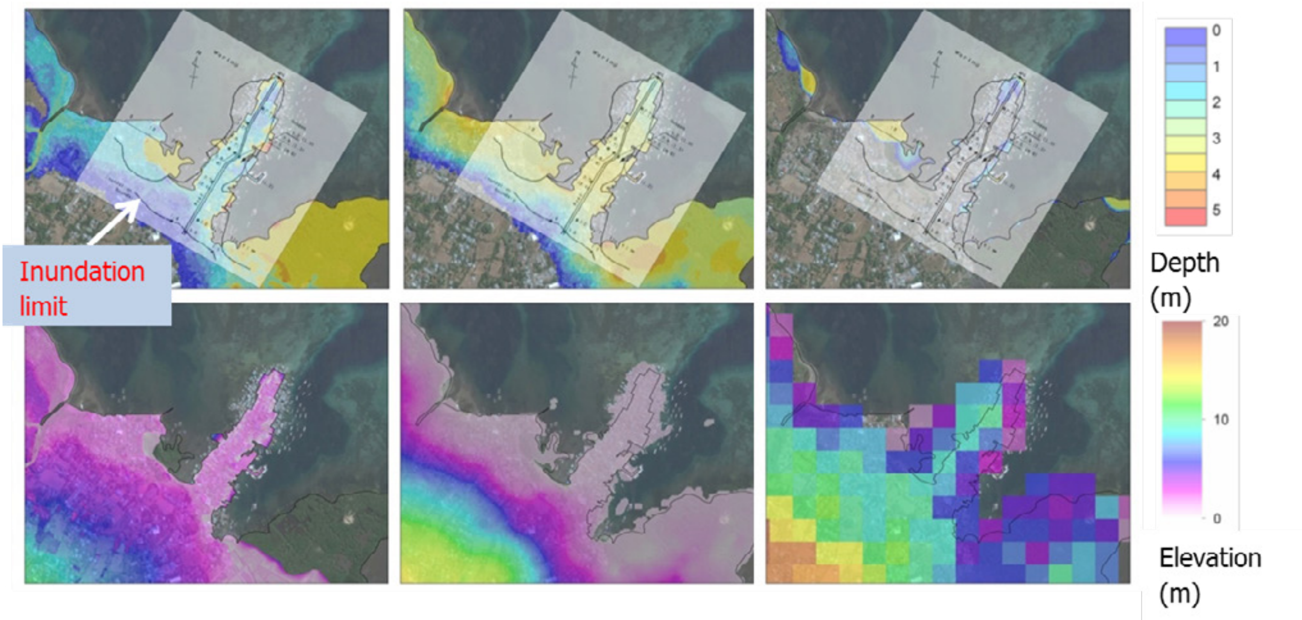


Figure 11 Modelled inundation for the 1992 tsunami in Flores, Indonesia (top) and underlying elevation data used in the model (bottom). Top images show inundation estimates from the 1992 tsunami in Flores, Indonesia, with arrow pointing to black line showing the observed inundation limit. The models use elevation data from LiDAR (left), airborne InSAR (middle), and SRTM (right). Bottom panels show the elevation data for each. Modified from Griffin et al., 2015.

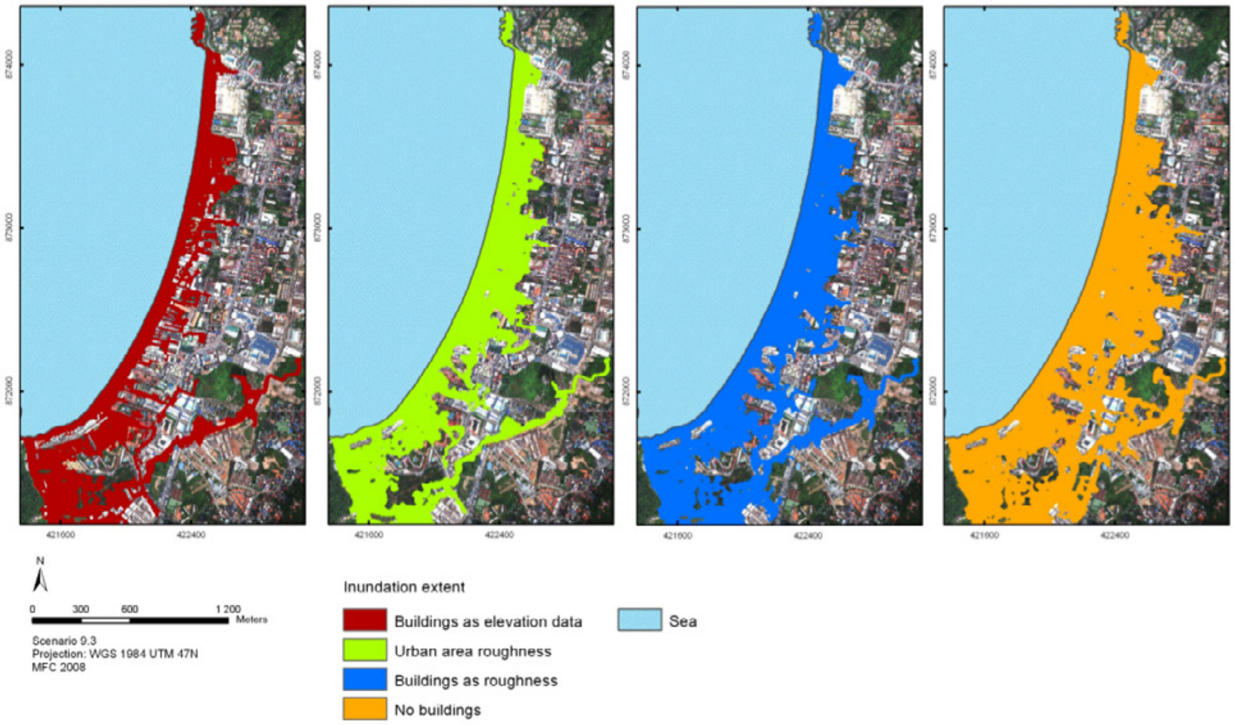


Figure 12 Impact of the schematization of roughness and buildings on the modelled inundation extent of the 2004 Indian Ocean tsunami. Source: Kaiser et al., 2011, The influence of land cover roughness on the results of high resolution tsunami inundation modeling. Natural Hazards and Earth System Sciences, 11, 2521-2540. Available at www.nat-hazards-earth-syst-sci.net/11/2521/2011/. Licenced under Creative Commons CC-BY 3.0: https://creativecommons.org/licenses/by/3.0/

less computationally costly to solve than higher order alternatives; 2) their predictions tend to be conservative compared to higher-order models, and 3) uncertainties in the source tend to be of greater significance than the aforementioned hydrodynamic factors.

Irrespective of the exact model used, results are very sensitive to the onshore topography and nearshore bathymetry (Figure 11). The availability of good quality topographic and bathymetric data (typically on the order of 1 m vertical accuracy or better, with horizontal resolutions <= 30 m e.g. Griffin et al., 2015; Lynett et al., 2016) is highly desirable to support tsunami inundation hazard assessment. Numerical models can be completely misleading if good quality elevation data is not available, particularly as their computational sophistication may imply a high level of certainty in the results to non-specialists (Griffin et al., 2015).

An additional consideration is that when developing tsunami inundation models, it is necessary to decide upon some schematization of roughness and the impact of buildings. A diverse range of schematizations have been used, which can have a first-order impact on the computed inundation extent (Jakeman et al., 2010; Kaiser et al., 2011; Yamashita et al., 2018). Typically modelled inundation extents are larger when roughness and buildings are ignored (i.e. using a 'bare earth' DEM, right hand panel in Figure 12), and smaller when buildings are included as topography (left hand panel in Figure 12). Other approaches include excluding buildings from the topography but accounting for them as areas of higher roughness, either at the scale of individual buildings, or by using high roughness in broad urban regions (Figure 12).

If good quality elevation data is unavailable, the application of physics based inundation models might not be worth the effort (or cost). In that case, it is common to estimate inundation footprints using geometric approaches such as the bathtub or attenuation rules, combined with conservative assumptions to set the tsunami wave height at the coast (Leonard et al., 2008; Jelinek et al., 2009; Fraser and Power, 2013; DSITIA, 2014). These geometric methods can produce crude tsunami inundation footprints, which may be refined later when improved elevation data is available. They should not be considered accurate depictions of the inundation extent, even if based on good quality elevation data, because there is considerable site-specific variation in tsunami attenuation onshore. However, if good quality elevation data is not available then physics based models suffer from similar uncertainties. In that situation geometric methods may help to distinguish regions with low and high tsunami exposure, with relatively low modelling effort.

In order to apply approaches such as the bathtub or attenuation rules, it is necessary to determine the tsunami wave height at the coast. In general this should be done conservatively, with consideration of the criticality of the intended application. Fraser and Power (2013) suggest using the 84th percentile peak coastal wave height at the average return interval of interest (information available from their PTHA), which is then doubled to account for possible effects of wave focussing by nearshore and onshore topographic features. If nearshore wave heights are not available, then they may be estimated from offshore wave heights using various coastal amplification rules, although care should be taken to account for the large uncertainties inherent in this approach (e.g. Lovholt et al., 2012; Hebert and Schindele, 2015; Davies et al., 2017). It should be emphasised that such results will be subject to large uncertainties (that are difficult to quantify), but may help to identify regions with high (or low) exposure to tsunamis.

4.4 Expected accuracy of tsunami models

There are a number of different aspects to the accuracy of tsunami models:

- Numerical Validation: How well can a given numerical model solve the equations of interest (e.g. the shallow water equations, or the 3D Reynolds Averaged Navier Stokes (RANS) equations).
  - This can be assessed using benchmark tests
- Hindcast modelling: How well can a given modelling methodology reproduce observations of past tsunami, given a good knowledge of the source and appropriate input data?
  - This can be assessed by modelling past tsunami events which have a reasonably well constrained source and observational data (i.e. for which a number of models are known to reproduce the observations well).
- Hazard modelling: How well can a given modelling methodology characterise the impacts of past and future tsunamis at a site?
  - This is more difficult to assess, because at most sites there are too few observations of past tsunamis to strongly constrain the hazard.

It is important that the above situations are not confused. Generally speaking, it is easier to achieve good performance in numerical validation problems than in hindcast modelling, and harder still to establish good performance of hazard modelling methodologies. End-users should be careful that they do not interpret the accuracy of numerical validation or hindcast results as a proxy for the accuracy of hazard scenarios (for which uncertainties are much larger).

Numerical validation is important to establish that a given computer program can solve the equations that it claims to solve. Its purpose is to reduce the chance that bugs or other poor algorithmic decisions will prevent a model from providing a good approximation to the intended equations. One widely used test suite has been developed for the National Tsunami Hazard Mapping Program in the USA, with problem definitions available on github (https://github.com/rjleveque/nthmp-benchmark-problems). NTHMP (2012) give a good discussion of these problems, and show the performance of numerous well known tsunami models against them. This serves as a useful reference point for determining the acceptability of new tsunami models. For instance, many models can

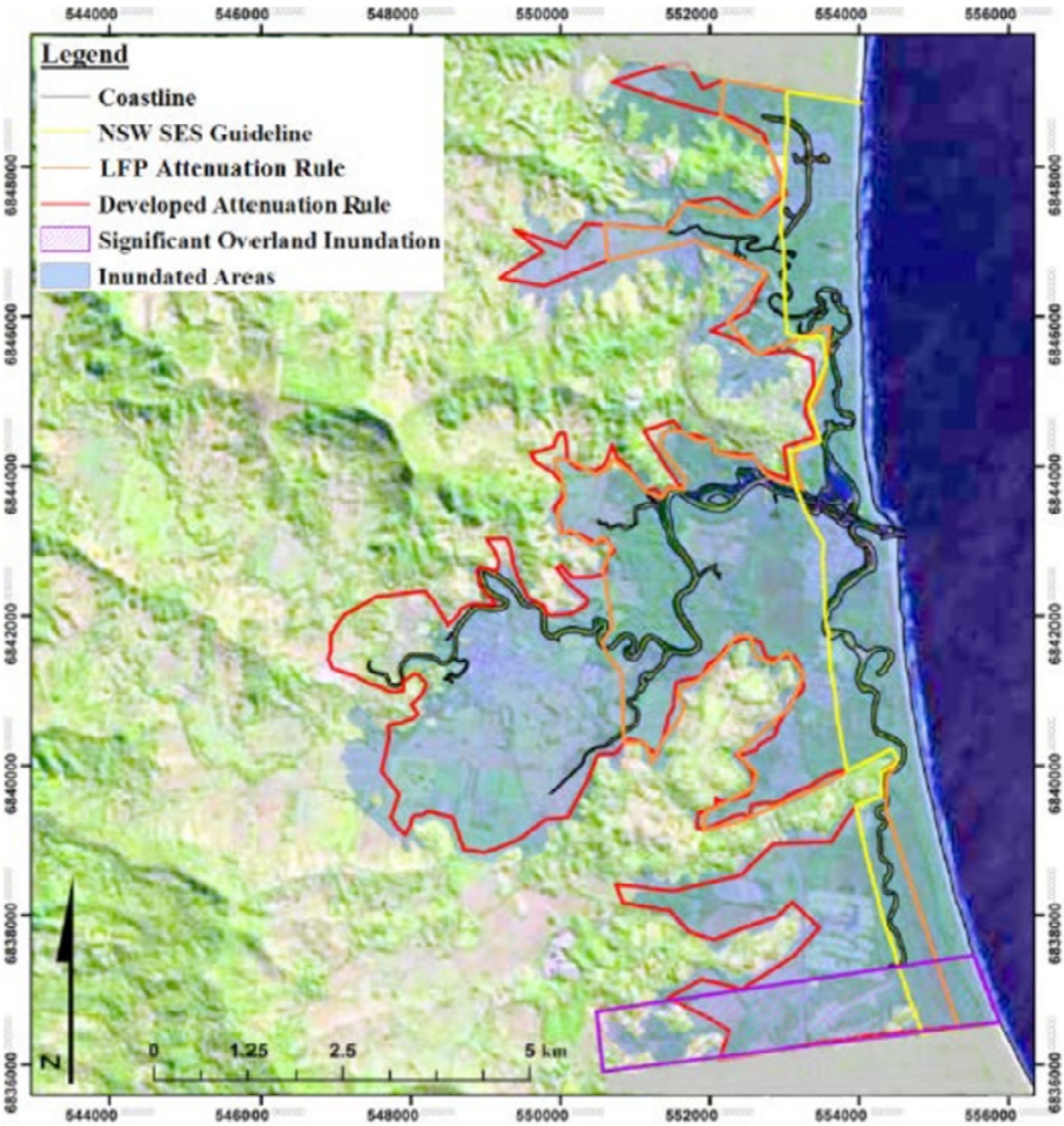


Figure 13 Inundation computed with a range of methods for a single tsunami scenario (Power et al., 2015). The methods include a physics-based nonlinear shallow water model (light blue), a range of locally calibrated attenuation rules (red and orange) and a bathtub approach based on a 10m peak water level that is limited to 1 km inland (yellow line). There are great differences among the methods, although all suggest substantial inundation.

accurately simulate (to within a few percent) various scenarios with known mathematically exact solutions (NTHMP, 2012). NTHMP (2012) also discuss some wave tank experiments which most models seem able to simulate to within around 10-20% accuracy. Additional benchmark problems relating to landslide tsunamis are available at http://www1.udel.edu/kirby/landslide/problems.html.

Many other suitable validation problems may be found in the literature and online. It is essential that models used in hazard applications should demonstrably perform well in a range of tsunami-like numerical validation tests, to reduce the chance that bugs or other poor algorithmic decisions are negatively affecting the results (Synolakis et al., 2008). However, because by definition these problems need to be well constrained, they usually focus more on analytical and wave-tank examples rather than real tsunamis.

Hindcast modelling involves simulating historical tsunami events. The key difference with hazard modelling (which models some aspect of future events) is that constraints can be placed on the tsunami source by inversion of observational data. Because of this, the performance of tsunami models on hindcast problems should be substantially better than their 'blind' performance on hazard problems (for which the source is less certain). Data from a number of historical tsunami events is included in the aforementioned NTHMP test suite, and some more recent problems are described in Lynett et al., (2017) with problem definition data downloadable at http://coastal.usc.edu/currents_workshop/index.html.

Hindcast scenarios are nonetheless subject to uncertainties associated with the source and input data, and so considerably greater variation can be seen in different model's predictions, as compared with 'numerical validation' problems. Typical hindcast model performance can be inferred from a number of relatively well understood historical tsunami events, which are known to be modelled well by many numerical codes. Examples include the 1993 Okushiri tsunami (NTHMP, 2012), and other recently reported model intercomparisons (Lynett et al., 2017). For example, models of the 1993 Okushiri tsunami can simulate peak wave runup at a range of sites with errors of around 20 per cent, averaged over all sites and all codes (NTHMP, 2012). However at some individual sites the errors are consistently worse (up to 74 per cent averaged over all codes, NTHMP, 2012). Qualitatively similar errors are commonly seen in tsunami hindcasts, where runup is simulated reasonably at many sites, but substantial errors remain at a few 'difficult-to-model' locations (e.g. Dilmen et al., 2015; Baba et al., 2015; Yamazaki et al., 2018). While not modelling inundation per-se, Allen and Greenslade (2016) evaluated tsunami model hindcasts of peak water level during 9 recent tsunamis at Port Kembla, NSW, using a calibrated tsunami source from the T2 database (rescaled to give optimal agreement with offshore DART buoy measurements). Among the 9 test events the model predicted the maximum tsunami stage at the main tide gauge with little bias, but substantial variance (mean of (|obs-model|/obs) = 36%). Performance at another nearby gauge was substantially worse, although at that site the data quality was questionable. Comparable results have been obtained more recently at Sydney (Wilson and Power, submitted). Overall, such results suggest that as of 2018, models have significant skill in hindcasting tsunami nearshore behaviour and runup. However, large site specific errors remain even when the tsunami source is well constrained.

Hazard modelling by definition applies to hypothetical tsunami sources. For instance we might simulate a Mw 9.2 earthquake-tsunami scenario on the Kermadec-Tonga trench which has no historical precedent, but could plausibly occur in future. Clearly in this situation, the model performance can only be evaluated after such an event has occurred. Furthermore, there may be significant uncertainty about whether the scenario could occur at all (see also Section 3.2). Because of these issues, it is generally difficult to quantify the accuracy of tsunami hazard scenarios, even for models which have performed well in benchmark tests and hindcasts. However, hazard scenario results will generally be 'less accurate' than hindcast tsunami models, because no opportunity exists to 'tune' the tsunami source to better match observations.

In the case of probabilistic hazard models, ideally the model would be tested by applying the modelling methodology in a 'blind' fashion (i.e. with no calibration or tuning of the source) at a site with abundant observational data, to enable statistical evaluation of the model performance. Although common in other fields (e.g. weather forecasting), this is uncommon in tsunami modelling because much less data is available. One exception is reported by Geist and Parsons (2006), who were able to compare their tsunami hazard model against empirical tsunami water level exceedance rates at a site in Mexico where many tsunamis have been observed. While comparisons against ten or more events are possible in some situations (e.g. sites with many historical tsunamis; global scale modelling of tsunamis), at most sites there are too few observations to permit the statistical testing of probabilistic hazard models.

5. Design of tsunami hazard assessments

KEY POINTS:

- **Tsunami hazard assessments need to consider two orthogonal issues: 1) the range of tsunami scenarios that are modelled, and; 2) the approach used for modelling tsunami propagation and inundation. Adequate treatment of both issues is required to understand the hazard.**
- **The range of scenarios modelled varies from 'probabilistic approaches', which attempt to model all possible future tsunami events, through to 'scenario based approaches', which aim to model a few representative events. Both strategies have benefits and challenges, and the optimal approach will vary for each individual tsunami hazard assessment.**
- **Hydrodynamic modelling approaches vary in sophistication, from simple 'bathtub' type methods, through to 2D and 3D physics based models. Physics based models are usually preferred if good quality elevation data is available, but without good quality input data, all approaches may be subject to large errors.**
- **Inundation model results may be sensitive to the treatment of friction, buildings, and tides.**
- **Model outputs deemed relevant for a particular study should be provided to the end-user in portable electronic formats with appropriate metadata, as well as in the project report.**

5.1 Introduction

There are a number of different approaches used for tsunami hazard assessment. The appropriate method for a particular study will depend on the purpose of the study, which will determine the required tsunami metrics and most appropriate treatment of uncertainty. In addition, the resources available for the study will place constraints on what can be achieved. At the end of this section a range of case studies that illustrate typical practices are presented.

In designing a hazard study, it is necessary to consider:

1. The range of scenario(s) to be modelled, including source type, location, magnitude and/or probability; and
2. The tsunami modelling approach, which can range from simple rules of thumb to sophisticated computational modelling of tsunami physics.

Together, these decisions will determine the fundamental data that is required to achieve the desired purpose, and how the results of the assessment should be used.

Below different approaches to treat 1) and 2) are reviewed. Whichever methods are applied, modellers and end-users should be aware that subjective modelling decisions can have a significant impact on the hazard model results. Subjective decisions include the choice of sub-models (e.g. how to treat roughness in the hydrodynamic model, or the parametric model used to simulate event frequencies), or the weights applied to multiple competing models (e.g. in the case of probabilistic methods). Where possible it is important to cross-check tsunami hazard model results against observations, so that unrealistic modelling assumptions can be identified and fixed. Unfortunately, for rare/large tsunamis there is generally insufficient data to test models. In sum, for rare events the modelled wave heights and average return intervals will be difficult to defend empirically but may be substantially affected by subjective modelling decisions.

The management of these subjectivities remains an important research topic in tsunami hazard assessment. At a minimum, modellers should use sensitivity testing to understand how their results are affected by key modelling decisions, and account for this in their discussion and interpretation of results. When sufficient resources are available, one may also consider formally eliciting the opinions of a community of experts to establish a 'community distribution' of modelling decisions to use in the study (SSHAC, 1997, 2012). The idea is that the 'community distribution' has intrinsic credibility by virtue of representing the opinions of the broader expert community rather than just a single expert. Multi-expert elicitation processes may also lead to more transparent justification of modelling decisions. However, a downside of these processes is that they tend to be resource intensive. Similar processes were originally developed for seismic hazard assessment of nuclear facilities, but are only just beginning to be adopted for tsunami studies (Selva et al., 2018).

5.2 Range of scenarios

5.2.1 PROBABILISTIC METHODS

Probabilistic methods attempt to simulate 'all' possible tsunami events, by modelling a large number of possible tsunami scenarios. Each event is assigned a rate of occurrence, and tsunami hazard is defined as the rate of exceedance of a given tsunami metric (e.g. 1 m wave height), determined from the sum of the rates of all events that exceed the metric (Grezio et al., 2017). These exceedance rates may be directly translated into a number of other hazard metrics, such the annual exceedance probability or the average return interval (Grezio et al., 2017).

A key advantage of probabilistic methods is that they enable exploration of a wide range of tsunami scenarios, and provide a framework for formally treating 'known uncertainties' in tsunami hazard assessments. For example, uncertainties in the maximum possible earthquake magnitude at a given source-zone can be accounted for using logic-trees and/or Bayesian statistics (Horspool et al., 2014; Davies et al., 2017; Grezio et al., 2017). However, this still requires that reasonable ranges are assigned to the uncertain variables, and if done poorly then the results of a probabilistic analysis may be misleading (e.g. if the maximum magnitude earthquake on an important source-zone is grossly underestimated). An analogous problem arises with scenario based methods (discussed below), so this issue is not specific to probabilistic methods.

Probabilistic methods have a number of limitations:

- Assigning occurrence rates to events is difficult. It is most difficult for the largest magnitude events, because they occur rarely and data is limited at the scale of individual source-zones. Therefore rates tend to be extrapolated from the frequency of smaller events, and/or based on theory linking earthquakes rates to tectonic plate motion (e.g. Kagan and Jackson, 2013; Rong et al., 2014; Davies et al., 2017). In any case the rates will be very uncertain, and may be sensitive to subjective modelling decisions (e.g. the choice of one or more magnitude-frequency model(s), and the weightings applied to competing models).
- Assigning rates to non-earthquake sources is significantly more difficult and subject to even larger uncertainties.
- Although probabilistic methods aim to represent 'all possible' events (in practice by using a large but finite set of possible events), it is difficult to ensure that the event distribution is not biased in some way. For example, we would not want the modelled scenarios for high magnitude earthquakes to produce overly large or small tsunami on average, compared with real earthquake-tsunami events. Although comparison of model scenarios with historical observations reduces the chance of significant bias, in practice there are too few observations of high magnitude earthquakes to strongly constrain the variability of their tsunami (e.g. only five Magnitude >= 9.0 earthquakes have generated tsunamis in the last century). Thus, for the foreseeable future, there will be substantial uncertainties in our ability to represent the 'extreme' tsunamis, which are likely to be the most important for hazard assessment. For non-earthquake sources even less observational data is available, implying even greater uncertainties exist.
- Probabilistic methods are computationally intensive, particularly if onshore inundation is considered. To reduce the computational burden a range of methods have been investigated to identify sets of events with 'similar' inundation extent, using computationally cheap methods (Gusman et al., 2014; Mueller et al., 2015; Lorito et al., 2015). This might allow using fewer high-resolution model scenarios, although this remains a research issue. More often for inundation studies a small subset of 'all possible' scenarios are taken (e.g. Gonzalez et al., 2009). Alternatively, global scale probabilistic tsunami hazard studies have used statistical methods to estimate inundation using offshore tsunami models, thereby greatly reducing the computational load (e.g. Horspool et al., 2014; Davies et al., 2017). However such coarse scale studies are not appropriate to support local scale decision making, for which inundation maps are generally required.

5.2.2 SCENARIO BASED METHODS

Scenario based methods model a limited number of tsunami scenarios. Scenarios may be chosen in a number of ways:

- Choosing one or more scenarios at selected average return intervals from an offshore PTHA. Scenarios can be selected by identifying the sources and event magnitudes that contribute most to the hazard at the average return interval(s) of interest (also called 'hazard deaggregation');
- As a credible worst case/maximum credible event;
- As an analogue to a previous event in the same location or another location (e.g what if the 2011 Tohoku earthquake happened on the subduction zone offshore of Java?).

Scenario-based methods have the advantage of being less computationally intensive than probabilistic methods. Furthermore, the results for a single scenario may be more easily communicated to non-technical audiences when compared with probabilistic assessments.

The main problem with scenario based methods is that, because only a few events are modelled, they may fail to adequately represent the hazard (e.g. by accidently selecting events that generate less hazardous tsunami, or by focussing only on extreme tsunami which might never occur). Therefore, scenario-based tsunami hazard studies should always carefully explain their choice of scenarios, and discuss the extent to which these are expected to be representative of the hazard (or to be conservative, etc).

Often a limited number of scenarios for different average return intervals are selected based on the results of an offshore PTHA. PTHA hazard curves at a point offshore of the location of interest can be deaggregated to identify the sources that contribute most to the hazard for a given average return interval (for further details see Horspool et al., 2014; Power et al., 2017). Then a number of events from these sources can be selected for modelling tsunami inundation, which are used to estimate the tsunami hazard for the average return interval of interest. This approach was taken for a number of tsunami inundation mapping studies in NSW (Garber et al., 2011; Andrews et al., 2013; Cardno, 2013; Power et al., 2015), which identified the Puysegur, Kermadec, Tonga, New Hebrides, and Chile source-zones as being the most significant sources, and modelled inundation for events from each source at a range of peak water level average return intervals. A limitation of this approach is that the PTHA average return interval is often computed based on the peak water level at an offshore point, and this may not correlate closely to the peak inundation (e.g. Mueller et al., 2015; Power et al., 2015). Because of this, we may expect a mismatch between the PTHA average return interval and the nominal inundation average return interval.

An alternative scenario design method is to create a 'credible worst case scenario' (sometimes also termed 'maximum credible event'). Although popular, this is inherently difficult to define rigorously. Even for earthquake sources, which are the best characterised, the maximum magnitude earthquake for a particular subduction zone is usually uncertain, with estimates provided by the global seismological community for subduction zones often varying by more than one magnitude unit (Berryman et al., 2015). For example, the proposed maximum magnitude for the Puysegur trench (south of New Zealand, which could generate a tsunami affecting south eastern Australia) ranges from Mw 7.8 to Mw 9.07, while for the New Hebrides trench (near Vanuatu, New Caledonia, and the Santa Cruz Islands), estimates range from 8.3 to 9.37 (Berryman et al., 2015). Credible worst-case scenarios may thus be very conservative if they focus on the upper bound magnitude (although that may be appropriate for some applications). An additional problem is that, even if the earthquake magnitude is known, the modeller must still decide on the earthquake dimensions, geometry and slip distribution, which may have a substantial impact on the result (Figure 8). Depending on how scenarios are constructed, the maximum magnitude scenario may not even correspond to the maximum impact scenario. It may be difficult to understand the impact of these factors without modelling a wide range of events, in which case the computational efficiency of the approach is reduced.

5.3 Hydrodynamic methodology and data requirements

The hydrodynamic methodology takes a tsunami source as input, and translates this into a model of tsunami hazard for the metric(s) of interest (e.g. onshore inundation extent). In most cases, this involves modelling the processes of tsunami propagation and inundation, although simpler methods can suffice for some purposes.

The main methods are:

1. Bathtub method (Table 1, Level 1). This involves taking a tsunami water level at the coast and identifying all areas that are below this height to determine an inundation footprint. Bathtub methods do not account for the complexities of real tsunami inundation, and may give unlikely results if naively applied (such as tsunami inundation 10s of km inland in low-lying areas, or beyond topographic barriers). Often other rules are added in attempt to deal with these issues, e.g. by limiting the maximum inundation distance, or by enforcing hydraulic connectivity. Bathtub methods require some other approach to infer the peak water level at the coast (Section 3.3; Table 1). For example, one might use an approach based on an offshore PTHA (e.g. Fraser and Power, 2013; Davies et al., 2017) or hazard model scenarios (Jelinek et al., 2009), see Section 4.3 for further discussion. Irrespective of the details, it should be assumed that large errors may exist in bathtub derived inundation extents. The chief advantage of the bathtub is that it has low input data requirements, and is simple to implement (e.g. it can be undertaken using standard GIS software if nearshore wave-heights are available). While considered low accuracy, it may allow the end user to make a preliminary estimate of inundation footprints, and determine whether more sophisticated hazard assessments are required..

2. Attenuation rules (e.g. Fraser and Power, 2013; Lovholt et al., 2015; Table 1, Level 2).

These are similar to bathtub methods, but include more complex rules whereby the peak water level at inland sites reduces with distance from the coast. The rules can also be modified to take account of the influence of rivers and other features (Fraser and Power, 2013; Power et al., 2015). As with the bathtub, attenuation rules are not considered highly accurate. Field data and complex numerical models suggest strong site-specific variation in rates of tsunami attenuation, such that large over-or-under prediction of inundation extents cannot be ruled out (Fraser and Power, 2013; Power et al., 2015). However, attenuation rules benefit from simplicity, and from having lower input data requirements than physics based methods. As with the bathtub, attenuation rules facilitate preliminary estimates of inundation footprints, which may help determine whether more sophisticated hazard assessments are required.

3. Physics based inundation models (Section 3.3; Table 1, Levels 3 and 4).

A wide range of physics based models exist which can potentially be used for modelling nearshore tsunami behaviour. These vary greatly, from 2D models based on the nonlinear shallow water equations, up to fully three dimensional models (e.g. Titov et al., 2011; Kim et al., 2015; Lynett et al., 2017). The physics that is represented in such models also varies independently of the dimensionality; for example, many different treatments of turbulence exist for both 2D and 3D models. In contrast to the bathtub and attenuation rules, which only provide inundation footprints and depths, physics based models can simulate a broader range of tsunami quantities (e.g. inundation footprints and depths, as well as flow velocities, tsunami arrival times, minimum water levels etc). However, to do this accurately they require high accuracy elevation and bathymetry data (Section 3.3; Table 1). Otherwise they may not be any better than bathtub or attenuation based approaches. They also require some treatment of friction due to surface features and consideration of the effect of buildings and other structures, and a wide range of approaches for doing this exist (e.g. Jakeman et al., 2010; Kaiser et al., 2011; Yamashita et al., 2018). As with other methods, the predictions of physics based inundation models may be sensitive to the nature of the proposed tsunami source. Their advantages and disadvantages are essentially opposite those of the previous methods: they tend to be computationally demanding, with high input data requirements, but are perceived as higher accuracy due to their strong physical basis, and demonstrated capacity to simulate a range of past tsunami events with well constrained sources.

Table 1 gives a four-level categorization of inundation methodologies. Levels 1 and 2 refer to bathtub methods and attenuation rules respectively, while levels 3 and 4 refer to physics based models with varying degrees of sophistication. In practice there is a continuum of approaches between these levels, which cannot be easily summarised in a single table. Modellers will have to use their expertise to make a case-by-case judgement as to the most appropriate model for each particular situation, and they should be able to justify this choice to end-users. In addition, the modeller will need to make a number of other 'first order important' decisions, including how to schematize tides, friction, buildings in urban areas, and flow structures (e.g. sea walls). These decisions will be affected by:

- the availability of input data (e.g. is the elevation data of sufficient quality to justify any physics based modelling approach?)
- the expected computational time (e.g. if the computational time is too high, it may be difficult to run a sufficiently wide range of tsunami scenarios to understand the hazard)
- the experience of the modeller (e.g. it may take too long to develop a model using software the modeller is unfamiliar with)
- the degree of accuracy or conservatism that is appropriate for the study (e.g. if a conservative treatment is desired, it may be preferable to ignore the impact of buildings on the flow, as this will usually act to decrease the inundation (Kaiser et al., 2011)
- the purpose of the study
- the resources available for the study
- the nature of the tsunami (e.g. are the tsunami wavelengths long enough for the shallow water equations to be a good approximation?).

Table 1 A four-level classification scheme for tsunami inundation methodologies. Higher levels attempt to provide a more sophisticated representation of the tsunami, but are not always appropriate to use. While higher levels have the potential to be more accurate than lower levels for some problems, they tend to require specific modelling expertise, better input data, and more computational effort.

Category	Level 1	Level 2	Level 3	Level 4
Inundation modelling methodology	Bathtub	Non-bathtub attenuation based methods.	2D inundation modelling (e.g. nonlinear shallow water equations).	More advanced hydrodynamic methods than Level 3 (e.g. 3D Reynolds Averaged Navier Stokes (3D RANS))
Elevation data requirements	Best available elevation data.	As for Level 1	High resolution Digital Elevation Model (DEM) in important nearshore areas and the inundation zone. If good quality data is not available, then these methods might not be more accurate than Level 2 or Level 1. Widely available global DEMS (e.g. GEBCO, ETOPO) are suitable for the offshore propagation modelling, but not for modelling nearshore flows.	As for Level 3

Category	Level 1	Level 2	Level 3	Level 4
Typical challenges and limitations	Need some method to conservatively determine water level at the coast for the scenario of choice. Results are physically questionable, because flow dynamics are ignored. Difficult to quantify the accuracy without further modelling. In general, not expected to be accurate.	Need some method to conservatively determine water level at the coast for the scenario of choice. Results are physically questionable, because flow dynamics are highly schematized. Difficult to quantify the accuracy without further modelling. In general, not expected to be accurate. Great variation in attenuation rules developed for different sites and by different groups.	Need to create or obtain tsunami initial conditions, or offshore boundary conditions, for the scenario of choice. In some locations, results may be sensitive to treatment of friction/ buildings/other structures. Proper treatment of these factors is likely to lead to additional data requirements (e.g. building footprints, land-use mapping, etc). Model should be run on a fine grid to achieve approximate convergence of the solution (for quantities of interest), but this may be computationally expensive or impossible. The computational expense may make it more difficult to run a sufficiently wide range of tsunami scenarios to understand the hazard. Numerical instabilities can potentially cause significant errors in the computed solution. Three dimensional flow features and short waves (wavelength < ~10-20 times depth) may not be well represented.	Need to create or obtain tsunami initial conditions, or offshore boundary conditions, for the scenario of choice. In some locations, results may be sensitive to treatment of friction/ buildings/other structures. Proper treatment of these factors is likely to lead to additional data requirements (e.g. building footprints, land-use mapping, etc). Model should be run on a fine grid to achieve approximate convergence of the solution (for quantities of interest), but this may be computationally expensive or impossible. The computational expense may make it more difficult to run a sufficiently wide range of tsunami scenarios to understand the hazard. Numerical instabilities can potentially cause significant errors in the computed solution. For more sophisticated models this might be more difficult to identify and resolve, as compared with 2D shallow water models.
Typical benefits	Computationally efficient, which may permit a more extensive treatment of uncertainties in the source. Lesser input data requirements. Easy to implement.	Computationally efficient, which may permit a more extensive treatment of uncertainties in the source. Lesser input data requirements. Potential for better representation of inundation extent than bathtub, IF the attenuation is well represented.	Physically defensible representation of long-wave tsunami dynamics (which covers most typical earthquake-generated tsunami, from offshore regions through to nearshore amplification and inundation). Often computationally cheaper than more advanced models (e.g. 3D RANS).	Potentially improved representation of the tsunami behaviour (compared with shallow water models) for non-shallow water waves, and strongly three-dimensional flows.
Typical hazard modelling applications	First pass identification of areas which may warrant further study ('hazard screening'). Treatment of regions without high quality elevation data.	First pass identification of areas which may warrant further study ('hazard screening'). Treatment of regions without high quality elevation data.	Adequate for most earthquake tsunami inundation hazard modelling problems. Adequate for modelling tsunami from other sources, so long as the dominant wavelengths are large compared with the water depth.	Modelling tsunami from landslides, volcanoes, asteroid impacts, etc, which may produce waves with wavelengths short enough to violate the shallow water approximations. Modelling situations where three dimensional flow processes are thought to be significant.

If physics based models are used, then the model mesh (or grid) size will also need to be chosen. It should be fine enough to ensure 'near convergence' for numerical model outputs of interest. In other words, further refinements of the grid should not change the computed solution in important ways. Modellers using physics based approaches should do convergence checks on their model setup, because first-order numerical errors may occur in non-convergent models. For instance, with an overly coarse grid some numerical schemes will dissipate the tsunami offshore and thus underestimate coastal impacts. Convergence can be checked by running a model scenario on meshes of different sizes (e.g. with one model having grid size and time step reduced by a factor of 2), and comparing the outputs, focussing on quantities that are important for the study at hand.

One exception to the above rule occurs for some oceanic tsunami models, which deliberately use coarse grids to match numerical dispersion with physical dispersion (e.g. Tanioka et al., 2018). If this is done there is no point checking convergence offshore, but checks should still be performed in the nearshore and inundation regions.

Elevation

Elevation data (both onshore topography and offshore bathymetry) are a fundamental requirement for any tsunami hazard assessment. Global datasets (such as GEBCO, ETOPO, SRTM, GA250m) have nearly complete coverage and are freely available. While their accuracy is suitable for tsunami propagation modelling in the deep ocean, they are subject to large errors in shallow waters (e.g. < 100 m deep), including errors on the order of 10 m in the vertical. In some cases these will be larger than the tsunami of interest, leading to very inaccurate estimates of inundation that are potentially dangerously misleading (Griffin et al., 2015). Therefore, for the majority of nearshore and inundation modelling applications, higher accuracy datasets are required. Typically LiDAR elevation data, with vertical accuracy on the order of 10 cm, allows good estimates of tsunami inundation extent, although there are other methods for collecting high resolution elevation data (e.g. high resolution stereoscopic cameras; airborne InSAR) that may provide vertical accuracies sufficient for inundation hazard assessment (Griffin et al., 2015). Increasingly, LiDAR data is available for many coastal areas in Australia. A 5 m horizontal resolution, open access, LiDAR derived elevation grid covering many key populated areas is available from Geoscience Australia's Elevation Information System (ELVIS) (http://www.ga.gov.au/elvis/). Bathymetry is often obtained from local chart data (e.g. port charts) or other remotely sensed methods such as coastal LiDAR, that are able to penetrate shallow water. Intertidal areas are often poorly characterised, often included in neither on- or offshore datasets, requiring interpolation and stitching between topographic and bathymetric datasets. Geoscience Australia's Intertidal Extents Model (Sagar et al 2017; http://www.ga.gov.au/interactive-maps/#/theme/earthobservation/map/intertidal) goes some way towards addressing this gap, allowing sub-metre elevation accuracies within the intertidal zone to be derived.

Tsunami inundation assessments using digital terrain models (DTM, where surface features such as trees and buildings are removed from the elevation model) may overestimate inundation extent while those using digital surface models (DSM, where such features are included in the elevation model) may underestimate inundation extent (Kaiser et al., 2011; Griffin et al., 2015). Various methods exist to include the effects of surface features. These include parameterisation as friction coefficients; equivalent occupancy methods; inclusion as solid and/or porous features within the elevation model; or the application of internal operators or boundary conditions (Schubert et al., 2008; Koshimura et al., 2009; Gayer et al., 2010; Jakeman et al., 2010; Kaiser et al., 2011; Suppasri et al., 2012; Wang et al., 2017). For a particular application, a mix of approaches may be appropriate for different surface features. For example, key structures and buildings may be included as solid features in the elevation model while the effect of other features (e.g. trees) may be parameterised using spatially varying friction coefficients. There is still debate within the scientific literature about the most appropriate methods. If a conservative inundation footprint is required, then the effects of friction can be ignored by applying a uniformly low (e.g. Mannings n=0.01 or 0) value of friction everywhere, noting that such approaches are likely non-conservative for estimating flow velocities (Wang et al., 2017). Where greater accuracy is required, it is recommended that sensitivity tests be undertaken to determine the impact on the final hazard results of the particular method applied (e.g. Kaiser et al., 2011).

Tides

Irrespective of the inundation methodology, it is necessary to consider how the results will be affected by tides. In particular, consideration should be given to the possibility that the tidal range varies strongly in space, as is common e.g. between sites in estuaries with constricted entrances and the coast. If this is ignored, then models may greatly over-predict inundation at sites where the tide is strongly attenuated, or under-predict inundation at sites where the tide is amplified.

The simplest tidal treatment is to use a 'static tide' where the sea level is fixed, often to mean sea level (MSL) or Highest Astronomical Tide (HAT). While running the model at HAT may be conservative for inundation extents, it may underestimate other quantities of relevance for marine hazard, such as velocities and minimum depths (Adams et al., 2015). Whatever tidal level is chosen, crude adjustments to water level predictions may be made by adding the tidal stage to the model as a post-processing step (e.g. Mofjeld et al., 2007; Gonzalez et al., 2009). Alternatively, the model can be run at a range of fixed tidal levels, and interpolation used to estimate the result for any tide (Adams et al., 2015). This has the advantage of incorporating some nonlinear effects associated with a change in sea level (e.g. the fact that wave shoaling may be greater at lower tides due to shallower water).

The 'static tide' approaches ignore dynamic tidal effects, which may be important in areas with significant tidal currents. Furthermore, 'static tide' methods may be difficult to apply to cases with significant spatial variations in tide range. As an alternative, fully dynamic tides can be treated by simultaneously forcing the model with tidal and tsunami boundary conditions. If this is done, it will be necessary to run the model for a 'burn in' phase initially to reasonably predict tidal currents, before the tsunami is applied. Testing and calibration should be conducted to ensure the model is able to reproduce the observed tides. The modelled tsunami behaviour may be quite dependent on the timing of the largest tsunami waves, which may arrive anywhere between high and low tide. To understand this, the model will probably need to be run at a range of tidal phases. As a result, the treatment of dynamic tides in tsunami models may be substantially more computationally demanding than the aforementioned approaches, and the benefit of this will have to be weighed against other alternatives (e.g. being able to run more scenarios using one of the simpler approaches).

5.4 Study outputs

It is not the purpose of these guidelines to prescribe the outputs that should be produced for a given study. However, a 'shopping list' of possible outputs is provided below. The outputs produced for a particular study should be determined through consultation between the end-user and the modeller according to the end-user's purpose. For example, for planning evacuation the most important outputs of interest may describe the potential inundation zone and tsunami arrival times. Conversely, for other purposes (e.g. engineering design) detailed model outputs of a range of tsunami metrics should be provided.

Irrespective of what outputs are of interest, a few key principles should be observed:

1. End-users should receive the underlying datasets in addition to figures in the written report.
2. Outputs should be provided in portable (i.e. widely supported) file formats, such as NetCDF, GeoTiff, Shapefile, ASCII grids, etc, rather than in formats that are only well supported by specific software (e.g. ESRI geodatabases, or bespoke binary formats used by many numerical models). Outputs should be translated into a portable format for provision to end-users.
3. All outputs should be accompanied by appropriate metadata (see below).

The provision of key datasets in a portable format greatly increases the end-user's capacity to understand and review the model results, re-use aspects of the modelling as appropriate, and compare the results with past and future studies. In general, this greatly increases the value of the study.

Typical outputs that can be generated by tsunami modelling studies include:

1. Rasters depicting quantities of interest (e.g. as a maximum or minimum, or at an instant in time):
    a. Inundation depth (onshore)
    b. Inundation extent
    c. Tsunami water level (on- or offshore)
    d. Water depth
    e. Flow speeds
    f. Flow vectors (as a snapshot in time to indicate eddies etc)
    g. Mass fluxes (velocity x depth)
    h. Momentum fluxes (velocity^2 x depth)
    i. Tsunami arrival time
    j. Duration of event (e.g. period of time before current speeds fall below a given threshold)
    k. Wave celerity (e.g. for the nonlinear shallow water equations, this is (speed + (gravity x depth)$^{0.5}$)
    l. Froude number (speed / (gravity x depth)$^{0.5}$)
2. Maps showing information from multiple events:
    a. Inundation extent from a limited number of events (e.g. showing the extents from different sources or for different average return intervals)
    b. Maps depicting key summary statistics from a range of events (e.g. showing the maximum inundation depth from all events used in the study).
    c. Probabilistic hazard maps giving either:
        i. Quantities listed in 1) for a given probability of exceedance; or
        ii. The probability of a certain tsunami metric (e.g. 1 m inundation depth) being exceeded.

    These products should typically indicate how uncertainty in the exceedance probabilities is treated (e.g. by using the mean of all modelled rates, or a particular percentile).
3. Summary statistics, usually taken at a representative point:
    a. Arrival time
    b. Maximum tsunami water level
    c. Wavelength or period of maximum tsunami wave
    d. Number of waves exceeding a given vertical reference
    e. Maximum tsunami speed
    f. Duration of event.
4. Time series of parameters at a given point:
    a. Water depth (often called the 'flow depth')
    b. Tsunami water level
    c. Current speed/velocity

5. Full model outputs (i.e. complete time series of all model parameters at all points within the model domain). Such files may be very large.

6. A final report that describes the purpose of the study, method adopted and the modelling results, including any limitations. Suggested metadata for the report itself includes:

   a. Title and date
   b. Geographic area
   c. Commissioning organisation
   d. Purpose of study
   e. Key assumptions
   f. Statement of limitations
   g. Specific issues
   h. Summary of findings
   i. Licence information
   j. Spatial metadata – this will follow recognised industry standards either ANZLIC or ISO 19115
   k. Description of the model code used, and references to supporting validation material (if not included in report).

5.5 Case studies

Below we provide examples of the tsunami modelling techniques used for different types of applications, which may help users with similar applications to select an appropriate methodology.

Screening and prioritization for detailed hazard assessment

In 2006 the NSW Government began a scoping study to investigate tsunami risk in NSW and prioritise areas for detailed inundation modelling (Risk Frontiers and URS, 2008). The study is summarised in Somerville et al., (2009). It included identification of tsunami sources and their relative tsunamigenicity, a review of available knowledge on previous tsunamis, estimation of travel times and maximum nearshore wave heights as well assessment of the influence of typical coastal configurations on tsunami runup. The study included a broad-based assessment of coastal vulnerability of the NSW coast, including ranking of sites based on elevation, population, buildings and relative exposure to tsunami impact.

The tsunami hazard prioritisation involved estimating runup heights by combining probabilistic estimates of the offshore tsunami wave amplitudes with coastal bay shape wave amplification factors (Baldock et al., 2007, 2008; Somerville et al., 2009). In combination with shoreline, elevation and exposure data, this was used to provide a broad indication of coastal vulnerability by postcode. It was acknowledged that the approach was subject to numerous limitations related to the coarseness of the elevation and exposure data available at the time, and the very approximate method of estimating tsunami runup using generic coastline shapes applied to a whole postcode. However, the information was useful for site prioritization purposes in support of a follow-up study which included detailed inundation modelling (see Section 3.2).

Evacuation routes and emergency management planning

Tsunami evacuation zones have been developed for much of New Zealand using modelling practices similar to those discussed in Section 5 (MCDEM, 2016). The evacuation zones are defined by a three level categorization which is used to educate the public on areas which should be evacuated during different tsunami events. A 3-tier modelling methodology has been developed to define the evacuation zones. This methodology takes into account the great variations in exposure and topographic data quality along the New Zealand coastline, as well as the practical difficulties in collecting high quality elevation data and setting up hydrodynamic models over a large coastline.

The most basic modelling approach recommended by MCDEM (2016) corresponds to 'Level 2' in Table 1. It uses an attenuation rule for inundation mapping (Fraser and Power, 2013), combined with water-level estimates from the New Zealand probabilistic tsunami hazard assessment (Power et al., 2017). More complex approaches are not recommended unless good quality elevation and bathymetry data is available. In any case, this approach may be used to provide 'interim' information prior to the development of physics based inundation models using high quality data.

The next most sophisticated approach recommended by MCDEM (2016) relies on physics based inundation models (corresponding to Level 3 or 4 in Table 1), which are used to simulate one or more tsunami scenarios (e.g. sourced from the New Zealand probabilistic tsunami hazard assessment). Because few scenarios are simulated this approach cannot account for the variability of tsunami sources, and to compensate for this it is suggested that the event magnitude be artificially increased. Power et al. (2017) specify one method of doing this, and we also note the results of Mueller et al. (2015) suggest an increase in earthquake magnitude of 0.3-0.4 may be appropriate for parts of north east New Zealand affected by earthquakes on the nearby Hikurangi subduction zone.

The most sophisticated approach recommended by MCDEM (2016) involves applying physics based inundation models to a large number of scenarios from the New Zealand Probabilistic Tsunami Hazard Assessment. This would correspond to a Level 3 or 4 hydrodynamic modelling approach (Table INUNDATION METH), combined with a probabilistic treatment of the inundation hazard.

Hazard assessment for critical infrastructure

Approaches to tsunami hazard assessment for nuclear power plants are discussed by Gonzalez et al., (2007) and Lynett et al., (2016). Many of the concepts therein may be applied to hazard assessments for other critical infrastructure. As an illustration of what can go wrong with hazard assessments, Synolakis and Kanoglu (2015) examine the failings in tsunami hazard assessments conducted for the Fukushima nuclear power plant, prior to its meltdown as a result of the 2011 Japan tsunami. A key problem with the latter tsunami hazard assessments was that they underestimated the maximum magnitude earthquake that could occur on the nearby Japan trench, as did many other hazard assessments in the region prior to 2011 (Kagan and Jackson, 2013; Synolakis and Kanoglu, 2015).

Either scenario based or probabilistic approaches may be used for assessing tsunami hazards to critical infrastructure. In the case of Nuclear Power Plants, Lynett et al., (2016) recommend that if scenario based approaches are used, they should be derived from 'the very worst credible source and most conservative set of model parameters'. They note that these scenarios can later be scaled down if sufficient scientific evidence is developed to justify the reduction. Alternatively, probabilistic approaches can be used to select scenarios with average return intervals appropriate considering the criticality and lifetime of the facility. In any case, care should be taken to account for uncertainties in the assumptions underlying the analysis.

For critical infrastructure hazard assessments, it is also important to understand the peculiarities of how tsunami might impact the facility in question. For example, nuclear power plants are affected not just by the maximum inundation and flow speeds, but also by minimum wave heights which can have a substantial impact on their cooling systems.

Port infrastructure needs, including ship evacuation

In 2017 a tsunami model was developed for southeast Tasmania (Kain et al., 2017) with two key aims:

1. Identify areas that could be inundated by tsunami; and
2. Provide detailed data for the Derwent Estuary sufficient to identify the risks to shipping, marine infrastructure and marinas in the Port of Hobart.

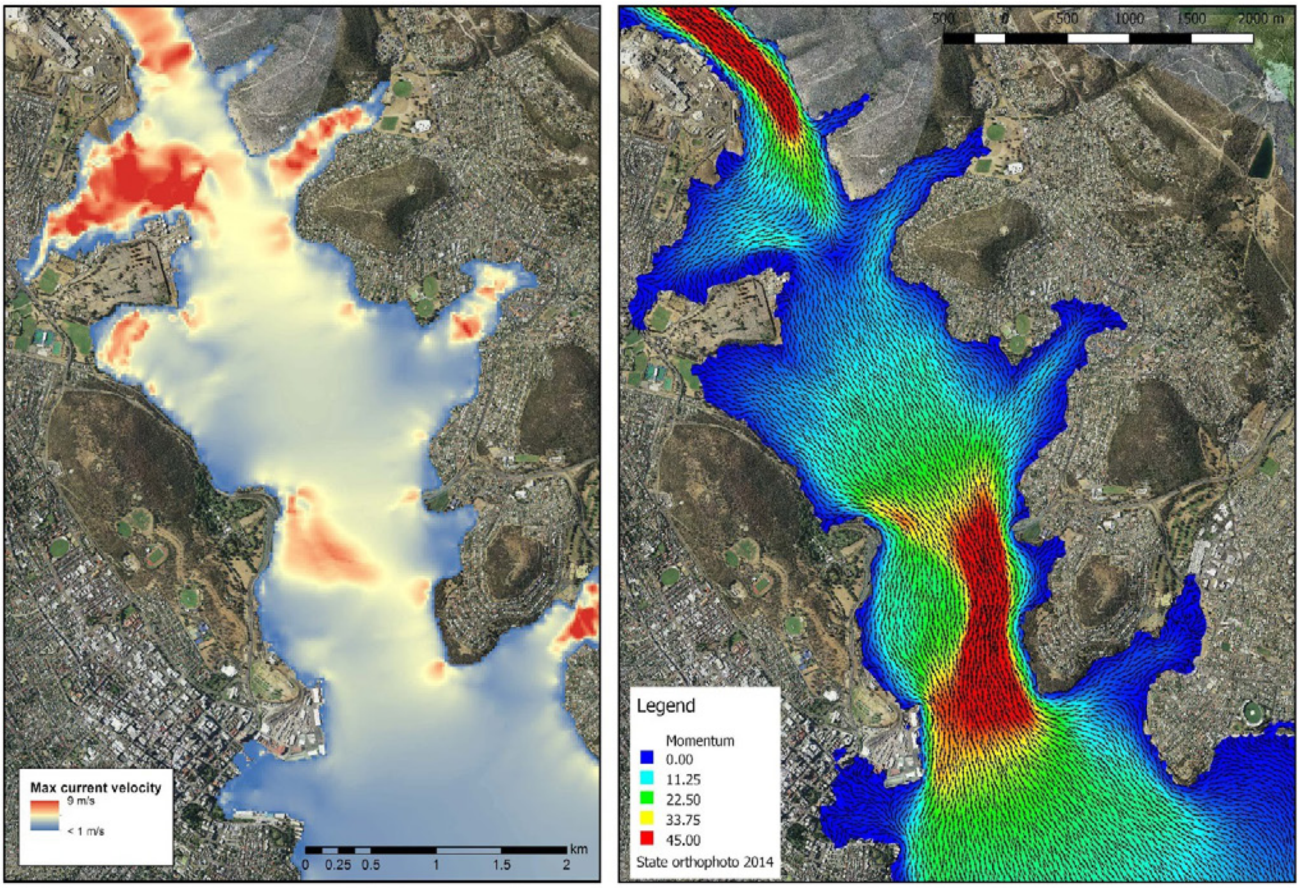
For this purpose a single 'maximum credible' tsunami scenario was modelled, corresponding to a Mw 8.7 earthquake on the Puysegur trench defined as a 1 in 13,000 year event by Burbidge et al., (2008). The tsunami was modelled using the ANUGA software, a widely used 2D nonlinear shallow water equations solver. The model was setup with an unstructured mesh, allowing variations in mesh resolution to balance computational efficiency and accuracy. Non-urban coastal areas were modelled at 50x50 m resolution; urban coastal area used a 20x20 m resolution; a 10x10 m resolution was used for two high priority locations (Blackmans Bay and Hobart Airport); while offshore regions used coarser resolutions. Spatially varying surface roughness was applied, with different land cover types mapped into eight different roughness classes. For simulating inundation a simulation time of 4 hours was sufficient, while for marine hazards a simulation time of 13 hours was used. Modelling was undertaken using a static tide, set at Highest Astronomical Tide (HAT).

As well as modelling the tsunami hydrodynamics, dune erosion was simulated to better understand potential impacts to Hobart Airport (Rigby et al., 2017). Finally, upon completion of the modelling, field validation visits to key sites were undertaken. These were able to identify additional features, such as subsurface drains, that were not specifically modelled but that could have an impact on the resulting tsunami inundation.

The key parameters of interest for the inundation study were inundation extent and depth. In contrast, a range of other parameters were of interest to the Port of Hobart due to their concern regarding impacts to ships, marine infrastructure and marinas in the Derwent Estuary. These included the arrival time of the first wave, the maximum wave height, the minimum water depth, the wavelength of the maximum wave, maximum current velocity (Figure 14), maximum celerity, turbulence and the period of time over which the estuary would be disturbed by the tsunami. Port managers were particularly interested in understanding the effects of resonance and turbulence within bays and its subsequent impact on marinas. For shipping berths, it was also required to report on the maximum/minimum water level above/below HAT and Lowest Astronomical Tide (LAT), and in turn the maximum deviations of the height of the berth relative to HAT/LAT. A series of animations showing water level and current velocity within the port were developed as part of this project and were considered to be an important product of the study by the end-users.

A key outcome of the study was identification of the time at which tsunami waves and accompanying strong currents could be expected to arrive at various points within the Derwent Estuary for tsunami generated on the Puysegur Trench. In general, arrival times of tsunami waves and strong currents are short relative to the time needed to issue warnings and then mobilise and evacuate large ships (including bulk carriers, oil tankers and cruise ships) to deeper water where current speeds are lower. This information allows port managers to make decisions concerning the most appropriate mitigation strategy for large ships in the event of a tsunami warning being issued, for example whether to moor ships in berths or attempt an evacuation to deeper water.

All data, scripts (including post-processing), maps and contributing reports were included electronically as attachments to the main report, fulfilling best-practice in data management, transparency and reproducibility.



a) Maximum simulated current velocity in the Derwent Estuary b) Snapshot of tsunami outflow momentum following the first wave

Figure 14 a) Map showing maximum current speeds in the Derwent Estuary, Hobart, for a tsunami generated by a Mw 8.7 earthquake on the Puysegur Trench. Note that values in the embayments have a high level of uncertainty, due to the unknown effects of turbulence and wave shoaling in these shallower zones. b) A snapshot of tsunami momentum at 1 hour 40 minutes post-earthquake.

Insurance

Insurance and reinsurance companies need quantitative estimates of the frequency that particular coastlines (or portfolios of risk) suffer financial losses due to tsunami. As for other natural perils, this kind of information is used for underwriting, premium setting, estimation of the pure risk premium, estimation of average annual losses, and/or assessing capital reserves.

Probabilistic approaches are thus fundamental for insurance applications. A fit for purpose tsunami hazard methodology would provide information on the frequency of occurrence, inundation depth, and onshore velocity for a range of events. Each event should be linked to the tsunami generation mechanism, because the latter may cause other losses (e.g. earthquakes cause building damages due to ground shaking). For financial risk management purposes, the fact that these losses do not occur independently needs to be taken into account.

The tsunami hazard information would then generally be linked with exposure and vulnerability models, and a financial engine. The exposure model details what is at risk and where it is located. The vulnerability model estimates the damages, based on the exposure and hazard models. The financial engine combines the latter information with knowledge of the insurance policies in force to model the financial implications of the event.

While insurance applications involve many challenging steps beyond tsunami modelling, the accuracy of the underlying tsunami hazard model is obviously crucial. On this point, an interesting comment was made by an insurance company employee who was consulted during the development of these guidelines:

"We have seen large departures from observations and discrepancies between models due to the bathymetry, topography, and simulation methods used. Key areas such as tides and land subsidence are very hard to model."

This emphasises a key theme of this guideline document: There are substantial uncertainties inherent in both tsunami scenario design and hydrodynamic modelling, which should be carefully considered and given fit-for-purpose treatment in the study methodology.

6. Procuring and publishing a hazard study

KEY POINTS:

- **Copyright and licensing issues should be explicitly considered when drafting contracts for tsunami hazard studies.**
- **A checklist of questions is provided for end-users to ask before, during and at the end of a hazard study. These questions can help ensure appropriate care has been taken in model development and design, and that the procurer has considered copyright and licensing to ensure use and re-use of the data and information.**
- **National consistency can be achieved by ensuring that the provided checklist is used by end-users**

6.1 Introduction

All levels of Australian government have Open Data policies. This is based on the recognition of the importance to optimise the use and reuse of public data for the benefit of the Australian people. Late in 2015, the Australian Prime Minister made the Public Data Policy Statement, stating that data is a "strategic national resource". Since the release of the Productivity Commissioner's report on Natural Disaster Funding Arrangements (Productivity Commission, 2014), which called for improvements in information consistency, sharing and communication, there have been increasing requests from industry and government to release data and information to manage the rising costs of natural disasters in Australia (Australian Business Roundtable, 2016).

However, experiences in making hazard information available to the public highlight the difficulties in achieving this aim when the data has not been procured and licenced appropriately. For example, the National Flood Risk Information Project (NFRIP) was initiated by the Australian Government in response to the National Disaster Insurance Review. That review, instigated in response to the widespread flooding over the summer of 2010/2011, highlighted the need for consumers to be more aware of the risks they may face from natural disasters.

The key component of NFRIP was to make flood mapping freely available through the Australian Flood Risk Information Portal (AFRIP). Geoscience Australia as custodians of AFRIP have identified:

1. Few studies have been procured which are consistent with open access principles.
2. Inconsistencies between the copyright permissions required under contract and the permissions expressed in the resulting study documents and data.
3. The contracts for procurement of these studies do not extend copyright permissions to electronic communication of the study, nor re-use by the public.

Two major impediments have been reported to the provision of flood information to AFRIP. The first was the perceived political and legal risks associated with making flood risk information (reports and maps) publicly available. For example, the potential negative impact on property prices and an increase in their tortious liability by releasing the information. The second issue relates to the Intellectual Property (IP) and Copyright assignments on the legacy flood study outputs; the reports, maps and spatial data.

In relation to the first impediment, Eburn and Handmer (2012) showed that, based on Australian law, "… there is no legal impediment to releasing reasonably accurate hazard information. Failure to do so will distort the property market and the potential liability to subsequent purchasers could be much greater than any risk of legal liability to current owners."

In relation to the second impediment, many contracts have not fully considered the copyright and licensing provisions to ensure appropriate sharing of the information or re-use by others (or indeed the procurer themselves). Additionally, based on the example with flood studies, there has been little or no compliance on these contracts.

The benefits in ensuring tsunami hazard information is open access include:

Benefits to the community:

1. Tsunami hazard information will be freely available for the community to use to better understand the risk tsunami poses at the household level.
2. The community will have access to the same information as the insurance companies are using to assess and price tsunami risk insurance premium, facilitating transparency for the consumer.
3. Re-use of this information will lower the cost to the taxpayer.

Benefits to the consultant:

1. Openly licensed tsunami studies showcase the tsunami modelling community's contribution to community tsunami resilience.
2. Simplifies the process of undertaking a tsunami study. It makes it easier (and cheaper) for the tsunami modelling community to legally re-use tsunami studies already produced.
3. Online publication will display a portfolio of work by tsunami modellers that will receive greater interest from the community, including from government and private clients alike.

Benefits to the commissioning organisation with Intellectual Property (IP) owned by the consultant:

1. Reduction in the costs to maintain and undertake compliance of IP custodianship, and costs associated with copyright management, protection and compliance
2. Openly licensed data allows the procurer to share or re-use data if they choose to do so.
3. Lowers transaction costs to other contractors/ developers who want to use the study outputs.

As stated by Eburn and Handmer (2012), "[r]eleasing hazard information is key to developing resilient communities and sharing responsibility for hazard management."

Whilst Australian Governments do have Open Data policies, there has been limited success in implementing these policies across Australia. A series of questions are posed below that the procurer may wish to ask the tsunami modellers in establishing the contract. Further information can be sourced from the Australian Governments' Open Access and Licensing Program (AusGOAL) or Geoscience Australia.

6.2 Other considerations

Australia experiences floods, cyclones (and storm surges) and bushfires on a regular basis and there is a corresponding level of hazard expertise available for those hazard studies. The tsunami modelling community has grown since the 2004 Indian Ocean Tsunami and the community draws on the knowledge and expertise from modellers who have had experience in coastal hazard assessments. Specific expertise in relation to tsunami sources resides in government and academia (e.g. Geoscience Australia and ANU for earthquake sources).

Some recent examples of tsunami hazard studies conducted in Australia have implemented a Steering Committee or Advisory Group which have consisted of the commissioning organisation (state government), the consultant, representatives from other departments in that jurisdiction, as well as technical representatives from Geoscience Australia and the Bureau of Meteorology. The group would review the proposed methodology during the early phases of the project, and also be involved in review of the final results. Anecdotal reports from both end-users and tsunami modellers suggest this approach is useful, as it gives all parties more assurance that the final results of a study will be fit for purpose and acceptable to end-users.

6.3 Checklist of questions

A checklist of questions are suggested below. End-users might ask these before, during and after a hazard assessment. The aim is to:

1) Help the end-user to gain a better understanding of the proposed modelling approach;

2) Check that the proposed methodology is appropriate for the study at hand;

3) Ensure the contract facilitates appropriate access by the end-user and the public to the results of the study.

The technical questions (on scenario design, and numerical model setup) would probably form part of a discussion with the modelling team and any associated technical panels. The questions on compliance and contracts will probably require discussion with contracts departments. The 'general project design' questions should be discussed with all parties.

Do not wait until the end of a project to discuss these topics! It is suggested these questions might help guide discussion at all stages of the modelling process (i.e. before modelling commences, during the project, and upon final delivery).

It is important to emphasise that the list is not exhaustive, and depending on the particulars of each application other issues may be significant. It is also important to recognise that this list includes suggestions and it is up to the end-user to decide what may be important. Final methodological decisions should be made by consensus between the modeller and end-user (and possibly the Advisory Group or Steering Committee, if one has been established, see Section 6.2), who are ultimately responsible for the study, and can give proper consideration to all the particulars of their application.

GENERAL PROJECT DESIGN

What is the purpose of the study?

This should strongly influence the scenario design, numerical modelling methods, and treatment of copyright.

Have you considered establishing an Advisory Group or Steering Committee that can assist with review of the methodology and results, QA/QC, etc, at multiple stages during the project?

Many contributors to the tsunami modelling guideline found the use of Advisory Groups made it more likely that study outputs are defensible and fit for purpose.

Who will provide third-party peer review for the study?

SCENARIO DESIGN

Which tsunami sources are included in the study (e.g. earthquake / landslide / …)? Where do they originate? Why were these decisions made?

Given the potential sensitivity of the model results to the tsunami source representation, it is important to have a good understanding of these issues at the beginning of the study.

Are the tsunamis to be modelled from source (as an initial condition), or using offshore wave time series (as a physical boundary condition)? Why?

Both methods are quite acceptable. Modelling from source is generally preferable because it allows the offshore tsunami to be directly affected by the modeller's own nearshore bathymetric data. However, it requires additional global-scale modelling of the tsunami.

How were the tsunami scenarios constructed, and what evidence is there that this might reasonably represent a future tsunami event (or otherwise appropriately characterise the hazard)?

Consider that for some studies, it may be more desirable to err on the side of conservatism (at the expense of realism) in designing the tsunami scenarios.

How are uncertainties in the source mechanism details being accounted for?

See above discussion on uncertainties associated with source mechanisms, which can have a significant impact on the modelled tsunami inundation.

If average return intervals or rates are assigned to events, how was this done, and what checks have been performed to confirm the reasonableness of the rates?

Rates might be assigned to events based on water level exceedances at a particular site (e.g. often an offshore gauge). For earthquake sources, rates may alternatively be assigned based on the generating earthquake magnitude using statistical and/or moment-conservation based methods.

Studies which assign rates to events should confirm that the rates are not grossly inconsistent with the historical earthquake record, or with observed event rates. Usually this will only provide a weak constraint.

In many situations, rates will have very high uncertainty.

NUMERICAL MODEL SETUP

What is the underlying hydrodynamic model (e.g. bathtub; attenuation law; 2D shallow water equations; Navier Stokes equations, etc)? Why is this an appropriate modelling approach, considering the type of scenarios to be modelled, the end user requirements, and available input data?

Generally the nonlinear shallow water equations with friction are considered appropriate for modelling earthquake tsunami hazards. Other tsunami sources more typically generate 'non-shallow-water' waves, for which it may be appropriate to use some higher order model (e.g. with dispersive terms).

For inundation computations, the modelling system must be able to handle wetting and drying (not all algorithms can do this), and output the required information (e.g. velocities, or forces on structures, etc).

What kinds of benchmark tests have been performed on the numerical model, to provide confidence that it can be suitable for modelling tsunamis?

The modeller may refer to published studies, or their own tests.

For physics based models, this would generally include solutions to a range of tsunami-like analytical, wave tank and historical field observations (see Section 4.4).

The National Tsunami Hazard Mapping Program in the US has a suite of benchmark problems that earthquake-tsunami codes should be able to solve reasonably well, and the performance of a number of different codes on these problems can be seen in the report NTHMP (2012).

What model calibration has been done for this study?

Commonly this is done by comparing models of historical events with observations, and 'tuning' model parameters to better agree with the data.

If data are unavailable, then this is impossible. However, if no tsunami data are available, the model may still be calibrated using tidal data.

Has any site-specific model validation been done on datasets that were not used for calibration?

In general, the performance of the model on datasets that were not directly used for calibration should better reflect its performance against future events.

However, if observational data is limited, it may be impractical to 'set aside' data for validation.

To what extent are the available nearshore and onshore elevation datasets 'accurate enough' to support the chosen inundation methodology? If the answer varies spatially, note this.

Refer to Section 3.3 which provides guidance on data requirements for different modelling methodologies.

Modellers should check that their elevation data does not generate unrealistic flooding under 'normal' sea levels, which may occur due to errors in elevation data.

What horizontal resolution (or grid size) is the model using? Why?

Typical horizontal model resolutions for tsunami modelling range from "100 metres to a few kilometres" in deep ocean regions, down to "one metre to a few tens of metres" in the inundation zone.

The best way to determine whether the horizontal resolution is fine enough is to do 'convergence testing', as mentioned in the next question.

Have any of the model scenarios been 'convergence tested' to check dependence of quantities of interest on the grid size and time-step? Which quantities are convergent (e.g. inundation footprint; peak water level; peak speed; ...) ? Are there regions or particular outputs of interest that do not seem convergent?

Convergence testing (or grid-size sensitivity testing) is done by running the same model twice (or more) with different grid sizes and time-steps. For example, 'model 1' might have a 20m grid size and 0.1s time-step, and 'model 2' a 10m grid size and 0.05s time-step. (The actual values will depend on details of the numerical model setup, and may vary spatially, but the key concept is that 'model 2' has twice the resolution of 'model 1'). If the results of 'model 1' and 'model 2' are indistinguishable, then we say the model has 'converged' on the 20m grid. This implies the selected grid size and time-step are not arbitrarily affecting the model results.

Some model results will converge more easily than others. For example, it may be impossible to get flow velocities to converge in eddy affected regions (Lynett et al. 2017), while for other models this may be achieved using grid-size-dependent eddy-viscosity parameterisations. But at a minimum any lack of convergence should be noted and considered in interpretations of the model results.

Some oceanic scale tsunami models deliberately use coarse grids in attempt to match numerical dispersion with physical dispersion (e.g. Tanioka et al., 2018). In that case it is not appropriate to do convergence testing for offshore model results. However, convergence tests should still be applied at nearshore and inundation scales.

How was the model's numerical stability checked? Are there any parts of the model which exhibit stability problems?

Numerical models can sometimes have stability problems, i.e. spurious oscillations in the flow.

Although dependent on the details of the numerical model used, experienced modellers can generally resolve such issues, e.g. by adjusting the model mesh, reducing the time-step, adjusting the boundary conditions, or altering some other parameters that affect the numerical algorithm.

Graphical checks, animations and convergence tests are helpful to check model stability.

Are there parts of the input data which you have lower confidence in? Why? How do you think this should affect interpretations of the output? Do you have suggestions for future data collection that might alleviate this?

The modeller may become aware of 'problem areas' or 'suspect areas' in the input data.

This kind of information might be helpful in interpreting the results, and in planning future studies.

Which structures are included in the hydrodynamic model (e.g. seawalls, flood-gates, wharves, bridges, etc)? How are they included? If they are not included/ schematized, why not?

Some numerical models include special treatments for a range of flow structures.

Alternatively, in some instances structures may be treated through variations in the model topography or roughness.

In some other cases the structure may not be thought important to the problem at hand.

For some structures, it may be desirable to consider scenarios where they fail (e.g. breach of sea-walls).

How have friction coefficients been chosen, and why do you think this is appropriate for the problem at hand?

Common approaches are: Assigning values based on a land-use classification at some resolution; Using a constant value; Using different values for 'sea' and 'land'; Using zero friction (a conservative approach, but may lead to stability problems for some numerical codes).

How are tides being schematized?

Does the model account for possible changes of topography during the event (e.g. scour of dunes)?

In some situations it may be desirable to run scenarios with topographic features removed (e.g. to represent dune scour).

In urban areas, how are buildings treated in the model (e.g. included in topography, or as roughness, etc)? Are buildings resolved? If modelled flow velocities are of interest, to what extent will the building treatment negatively impact on the model's capacity to simulate flow velocities during inundation?

Buildings may be included as topography, possibly with porosity, or as regions of enhanced friction. Any of these approaches may be suitable for modelling inundation extents and depths, but flow velocities might vary substantially depending on the approach taken.

The 'buildings as topography' approach requires that buildings are resolved in the model grid, which usually implies very high model resolution. On the other hand, 'buildings as roughness' may be applied at fine or coarse resolutions. A coarse resolution treatment is more likely to distort the model velocities but may be sufficient for estimating inundation extents.

A conservative treatment of the inundation extent may be obtained by ignoring the impact of buildings. However, buildings may locally cause higher flow depths due to flow convergence.

To what extent are the numerical model scenarios conserving mass? Can you explain why this amount of mass error is unlikely to be a problem?

Many models have some mass conservation error (i.e. they artificially create or remove water from the model domain). This most often occurs because of limitations in numerical treatments of wetting and drying. Small mass conservation errors may not be a problem, but if large enough they can significantly distort the computed solution.

Beware that not all numerical models report mass conservation statistics (including some that are widely used). In that case it may be impossible for the modeller to verify mass conservation.

CONTRACT AND COMPLIANCE

Based on the contract, who owns the Copyright and what are the licensing arrangements?

Many contracts would indicate that the copyright in the outputs are to be owned by the commissioning organisation, yet the copyright notice associated with the output has been known to be attributed to the consultant. Therefore contract compliance is strongly encouraged to ensure that the outputs carry the agreed necessary copyright and licensing details.

The Creative Commons Attribution 4.0 Licence (CC BY 4.0) has been adopted by most Australian Governments and should be used to licence the outputs for re-use by the community. An example copyright notice is outlined in Section 6.4 for use by the modeller.

Does the contract ensure that the procurer will receive all the required derived products as part of the contract? For example, the final report data (in portable format) of the tsunami model outputs, GIS files of all tsunami model outputs, maps, etc.

Many procurers wish to integrate the study outputs into their own analysis systems (e.g. response planning development), or publish the study and data online (to support community awareness). To enable this outcome, the procurer will require the derived products to provided in digital format.

Have you confirmed that the final report (and derived products) is licenced for your use and re-use by the public?

A compliance check on receipt of the contract deliverables will protect the procurer and the public from any potential breach of copyright.

Have you ensured that you have sufficient metadata that is consistent with international standards and best practice (see above for an example) for the contract products?

Ensuring metadata is reported can allow the procurer to integrate the study outputs into their own analysis systems or online data delivery systems.

Does the licensing of key input data (e.g. elevation and bathymetry) place significant restrictions on the use and distribution of the modelling results?

6.4 Example copyright notice

Below is a recommended copyright notice that can be incorporated into the services delivered by the consultant, thereby replacing the existing copyright notice.

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Glossary

Annual Exceedance Probability (AEP) - The chance of having an event above a given threshold occurring once or more in a year.

ATAG - Australian Tsunami Advisory Group

Average Return Interval (ARI) - The average time between events. This is the same as 'Average Return Period'. It is typically reported in units of years.

Average Return Period - The average time between events. This is the same as 'Average Return Interval'. It is typically reported in units of years.

Bathymetry - Undersea topography

Bias - The average difference between a model result (or some other prediction) and the observed result.

Celerity - The speed at which waves propagate. This is distinguished from the flow velocity (i.e. how quickly individual particles move) because the two quantities often differ greatly. For instance, a tsunami in 4 km depth will have a celerity of around 200 m/s, while the velocity of particles will be closer to 1 cm/s.

Coastal morphology - The shape of coastal landforms

Continental Slope - The undersea slope between the deep ocean floor and the continental shelf, both of which are much flatter than the continental slope.

Convergence test - In the context of hydrodynamic modelling, this involves testing whether model results change significantly when a finer grid size is used. Ideally, a fine enough grid size is used so that further refinements do not change the result.

Exceedance Rate - The mean number of events expected per unit time.

InSAR - Interferometric synthetic aperture radar, a radar based technique for remote sensing. Also sometimes called IfSAR.

Inundation - The wetting of land areas that would otherwise be dry (e.g. as a result of a tsunami, or a storm surge, or river flood).

ELVIS - ELVIS is the Elevation Information System.

Fault geometry - The shape of the fault plane on which earthquakes occur. This is generally a curved 2D surface inside the earth, although often earthquakes are modelled as having a planar fault (especially if they are small).

Far-field - Sites far from an earthquake. Precise definitions of this vary, but examples include "sites at which the tsunami arrival time is more than 2 hours after the generation event", or "sites that are more than 1000 km from the earthquake source".

Forecast - Prediction of an event that has not already happened.

Gravity waves - A generic term for waves which propagate due to gravity. This includes many waves of interest in the ocean or the atmosphere, including tsunamis. Note this term is unrelated to the 'gravitational waves' of recent interest to astronomy, which were experimentally discovered in 2015.

GIS - Geographic Information Systems. A general term for software designed to work with spatial or geographic information.

Global Earthquake Model - A foundation working on global earthquake hazard and risk. For more information see their website at https://www.globalquakemodel.org/

Hazard curves - Curves which relate the intensity of an event to its magnitude. This term is often used to describe curves relating tsunami wave height and average return interval.

Hindcast - Prediction of an event that has already happened.

Homogeneous linear elastic body - A material which moves in accordance with the linear elastic equations, and has the same properties everywhere. This is often used as a simple model of the earth, in order to predict its motion due to earthquakes.

LiDAR - Light Detection and Ranging, a remote sensing method that is used to measure the earth's elevation. As of 2018 it is the most common method of collecting large-scale high-quality elevation datasets.

Magnitude - A measure of earthquake size. Usually this is the same as the Moment Magnitude, although other magnitude scales can also be used. Less commonly the term is used in relation to tsunamis as 'tsunami magnitude' (i.e. a measure of tsunami size).

Marine hazards - Refers to tsunami hazards in beaches, estuaries, rivers and other coastal waterways. These hazards tend to be associated with unusual or unexpected water level oscillations or currents, rather than inundation. Many tsunami that do not inundate land will nonetheless generate significant marine hazard.

Magnitude-frequency - Relationship between the magnitude of an event (i.e. some measure of its size) and its frequency (i.e. how often the event occurs). Magnitude-frequency relations occur widely in the analysis of natural hazards, such as floods / earthquakes / tsunamis / storm surges. In all these applications there is a tendency for large events to be less frequent than small events.

Maximum magnitude - The largest magnitude earthquake that can occur.

Moment magnitude - A measure of earthquake size. This is the most common measure of 'earthquake magnitude', although other earthquake magnitude scales also exist.

Near-field - Sites near to the site of earthquake generation. Exact definitions vary, but examples include sites at distances within a few hundred km of an earthquake, or sites at which the ground deformation due to the earthquake is measurable, or sites at which the tsunami arrives less than 1 hour after the generation event.

Nearshore areas - Sites close to the coast.

NGDC - NGDC is the National Geophysical Data Centre https://www.ngdc.noaa.gov/ which has been recently incorporated into NOAA's National Centre for Environmental Information (where NOAA is the US National Oceanic and Atmospheric Administration).

Paleo - Pre-historical.

Paleotsunami - A tsunami that occurred in the pre-historical period. Usually the occurrence of this event will be inferred from sedimentary deposits.

Plate tectonics - A model of the structure of the outer part of the earth (i.e. surface, crust and upper mantle). According to the theory of plate tectonics, the outer part of the earth may be divided into a number of rigid plates which move relative to each other over time, with most earthquakes occurring at the boundaries between the plates. These rigid plates are termed tectonic plates. Many geological phenomena can be explained in this framework.

PTHA - Probabilistic Tsunami Hazard Assessment. A study that quantifies the frequency with which some measure of tsunami hazard is exceeded at a given site.

Radiocarbon Dating - A method for estimating the time of death of some plant or animal material. It is based on the fact that living things uptake carbon with a certain fraction of radioactive isotopes; and after death, these radioactive isotopes decay at a known rate.

Roughness - Many hydrodynamic models require parameters that describe how the flow energy is dissipated by interaction with topography. The characteristics of a landscape that control this are termed 'roughness'. The model parameters are often called 'roughness coefficients' or 'friction coefficients'.

Runup - The maximum vertical onshore elevation that a tsunami wave reaches at a particular site.

Rupture area - The area of a fault over which earthquake slip occurs.

Rupture length - The length of a fault over which earthquake slip occurs, in the horizontal direction.

Rupture width - The width of a fault over which earthquake slip occurs, in the down-fault direction.

Shear modulus - A material property of the earth (or another material). It is related to the propagation speed of shear waves in the material.

Slip - In relation to earthquakes, slip describes the relative motion of rocks on either side of the fault that occurs during an earthquake. Such slip causes the earth to move in the vicinity of the fault, which is one of the main causes of tsunami generation.

Stage - The height of the water surface above some vertical datum.

Statistical relationships - Patterns observed in data, which may or may not be understood theoretically.

Subduction zones - Regions at the boundary of 2 tectonic plates, where the plates are moving towards each other (converging) and one plate is sinking underneath the other. These areas tend to host the largest earthquakes on earth.

Tectonic plate - According to the theory of plate tectonics, the outer part of the earth may be divided into a number of rigid plates which move relative to each other over time, with most earthquakes occurring at the boundaries between the plates. These rigid plates are termed tectonic plates.

Uniform slip - A simple model of an earthquake, where the slip does not vary spatially. Real earthquakes often show significant spatial variations in slip, but for some purposes the uniform slip approximation is nonetheless useful.

Wave amplitude - Half of the peak-to-trough wave height. (Note that in much of the tsunami literature, this term is also used casually to mean 'the maximum water level', although that definition is uncommon in other fields).

Wave height - The vertical distance from the wave peak to the wave trough. (Note that in much of the tsunami literature, this term is also used casually to mean the 'maximum water level', although that definition is uncommon in other fields).

Wavelength - The distance between two successive wave crests at an instant in time.

Wave period - The time between the arrival of two successive wave crests at a given site.

Further tsunami terms are available through the IOC Tsunami Glossary (IOC 2016)

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