



Tsunami Modelling along the East Queensland Coast

Report 4: Hervey Bay



Australian Government



Queensland
Government

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Front cover image – snapshot of modelled water levels for a 10,000 year average recurrence interval event originating in the Kermadec-Tonga subduction zone, seven hours and thirty-six minutes after the tsunami was generated.

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Executive summary

The 2004 Indian Ocean tsunami that devastated Indonesia, Thailand and Sri Lanka, brought about a heightened interest and focus into the science and disaster management for this hazard. In 2011, the Queensland Government commenced a project through the Natural Disaster Mitigation Programme (NDMP) to better understand the potential tsunami hazards along the east Queensland coastline. The first stage undertook nearshore tsunami modelling to identify regions of increased hazard to focus future detailed inundation modelling.

This current project has been undertaken through the Natural Disaster Resilience Program (NDRP), to continue the recommendations of Stage 1 by assessing the potential for tsunami inundation within and around Hervey Bay. This is achieved through demonstrated examples of hypothetical tsunami events for various average return intervals (ARI) from Geoscience Australia's revised draft probabilistic tsunami hazard assessment (PTHA) event database. Hydrodynamic modelling was undertaken using DHI's Mike21 flexible mesh software for events originating from the three primary subduction zones contributing to the hazard as identified in the revised draft PTHA. The ARIs chosen in Stage 2 as being representative of possible inundation and extreme (worst case) conditions were also selected for this study, being 750, 3,000, and 10,000 year. One event for each ARI was modelled at mean sea level (MSL) to examine the influence of the stage of tide. All other scenarios were modelled at Highest Astronomical Tide (HAT) to represent a worse case and to acknowledge that tsunami events occur over several hours and so could occur on high tide. Including sea level rise, a total of 23 scenarios were modelled, as well as an additional run to incorporate the Urangan and Burnett Heads marina breakwaters in finer detail.

Overall, approximately 365 km of coastline as well as waterways were modelled from Baffle Creek to Cooloola, incorporating the Gympie Regional, Fraser Coast Regional and Bundaberg Regional Local Government Areas. The model was calibrated against predicted tides and validated against the 2007 Solomon Island tsunami event captured by the Queensland Government's Storm Tide Monitoring network.

The modelling provides insight into tsunami propagation characteristics within the study area. Arrival times are dependent on the source location, with those from the New Hebrides having the shortest arrival time of just over 3 hours, while events from South America arriving much later at over 17 hours. Once the leading wave reaches Sandy Cape, the additional time it takes to reach mainland locations is consistently between 1 and 2.5 hours, and 2 hours to reach Bundaberg within the Burnett River.

Although not modelled, there is potential for shorter steep waves to travel on top of the underlying tsunami in areas where the tsunami wave steepens significantly (particularly close to the coast at Moore Park and approaching Hervey Bay just north of Fraser Island). Although these waves may have an impact on coastal structures, the run-up and inundation that occurs is a result of the underlying longer period tsunami.

In general, the hazard is significantly greater on the ocean side of Fraser Island that protects Hervey Bay and Bundaberg, producing a significant marine and land hazard with maximum currents up to 9 metres per second (m/s) and maximum water levels up to 7 metres (m). The exposed Great Sandy National Park showed the highest water levels of up to 10 m. Dangerous currents can also develop within the entrance passage to the Great Sandy Strait between Inskip Point and Fraser Island.

The hazard is significantly reduced on the bayside of Fraser Island, tsunami amplitudes increasing with ARI to a maximum of 4 m offshore of Miara and reducing southwards to generally below 2.5 m. Tsunami are dissipated through the Great Sandy Strait posing little hazard with water levels well below 0.5 m.

In general, the majority of the coastline will experience some inundation, especially at higher ARI and HAT levels. This may be restricted to the foreshore, with coastal properties in low lying areas being more susceptible at the higher tide levels. The communities identified as having a higher level of hazard (based on inundation extent) are in decreasing order:

- Camping and recreational areas at Rainbow Beach, Inskip Point and Fraser Island (ocean side);
- Moore Park and Miara;
- Dundowran Beach;
- Torquay;
- Toogoom;
- Burnett Heads; and
- Urangan.

Sea level rise associated with climate change may increase inundation extents at mainland locations, which warrants consideration in vulnerability studies from climate change. The areas at most risk include Poona, Boonooroo, Maaroom, Hervey Bay City to Burrum Heads, Woodgate, Elliott Heads to Burnett Heads, Moore Park, Miara, Inskip, and the southern end of Fraser Island. However the actual impact will depend on the geomorphological change of the coastline which was not considered in this study.

The developed overland DEM is a fixed bare earth model in that only ground points have been included, thereby removing all structures and vegetation. The influence of these features on inland inundation is introduced implicitly by the introduction of roughness factors. The DEM is also assumed to be static and non-erodible. Should a tsunami cause significant erosion of the dune system or nearshore bathymetry, then the extent of inundation may differ to these model results. The hazard considered relates to potential inundation and broad-scale currents. There may be secondary impacts associated with the tsunami such as coastal erosion, which have not been addressed in this study.

The events selected represent the mean of the maximum water levels for the chosen ARI based on the draft revised PTHA as of February 2018. Higher levels can occur within the 95 per cent confidence limits. Also, any changes to the PTHA since February 2018 may influence the outcomes of this report. Disaster managers may wish to consider appropriate factors of safety in any decisions based on the information provided through this study.

Overall, the study provides planners and disaster managers with a better understanding of the potential tsunami hazard within and around Hervey Bay.

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Glossary

AEST	Australian Eastern Standard Time
ARI	Average Recurrence Interval
ATWS	Australian Tsunami Warning System
BoM	Bureau of Meteorology
DEM	Digital Elevation Model
DES	Queensland Department of Environment and Science
DHI	Danish Hydraulic Institute
DSITI	Queensland Department of Science, Information Technology and Innovation
DSITIA	Queensland Department of Science, Information Technology, Innovation and the Arts
EHP	Queensland Department of Environment and Heritage Protection
EMA	Emergency Management Australia
EPA	Queensland Environmental Protection Agency
GA	Geoscience Australia
GBR	Great Barrier Reef
HAT	Highest Astronomical Tide
IOC	Intergovernmental Oceanographic Commission
IofA	Index of Agreement
JATWC	Joint Australian Tsunami Warning Centre
LGA	Local Government Authority (or Area)
MSL	Mean Sea Level
MSQ	Maritime Safety Queensland
NDMP	Natural Disaster Mitigation Program
NDRP	Natural Disaster Resilience Program
NOAA	National Oceanic and Atmospheric Administration
NSW	New South Wales
NTHA	Nearshore Tsunami Hazard Assessment of Australia
PTHA	Probabilistic Tsunami Hazard Assessment of Australia
R^2	Coefficient of Determination
RANSE	Reynolds averaged Navier-Stokes equations
RMSE	Root Mean Square Error
SEQ	South-east Queensland

SWL	Still Water Level
TsuDAT	Tsunami Data Access Tool
UNESCO	United Nations Economic and Social Council
UNISDR	United Nations Office for Disaster Risk Reduction
USGS	United States Geological Survey

1 Introduction

Following the 2004 Indian Ocean tsunami that devastated Indonesia, Thailand and Sri Lanka, the Australian Government through Geoscience Australia (GA), the Bureau of Meteorology (BoM) and Emergency Management Australia (EMA) developed the Australian Tsunami Warning System (ATWS) to provide independent advice of potential tsunami events through the Joint Australian Tsunami Warning Centre (JATWC).

To support the end-to-end warning system, GA undertook a probabilistic assessment of tsunami hazard (PTHA) along the Australian coastline in terms of tsunami amplitude (water level height above MSL) at the 100 m depth contour (Burbidge et al., 2008a and 2008b). The study was funded by EMA as part of the community awareness and capacity building component of the ATWS. The study was intended to assist the relevant state government departments to assess the tsunami risk along the coast and to prioritise regions that require further detailed assessment. However the study was limited in that for Queensland, the 100 m depth contour is offshore of the continental shelf and the Great Barrier Reef (GBR). Therefore, the influence of these significant features on tsunami propagation was uncertain.

To better understand the impact of the complex bathymetric features across the Australian continental shelf on tsunami propagation, GA undertook a national nearshore modelling study to examine the relative amplification of tsunami at 20 m depth compared to the 100 m depth contour for select locations (Fountain et al., 2009b). However that study did not include some locations such as the Sunshine Coast.

In 2012, the then Department of Science, Information Technology, Innovation and the Arts (DSITIA) was awarded a Natural Disaster Mitigation Program (NDMP) grant to further assess the tsunami hazard along the Queensland coast. The project was undertaken in two stages. Stage 1 undertook nearshore tsunami modelling to supplement the work undertaken by GA (Boswood, 2013a and 2013c). The study utilised hydrodynamic modelling software developed by the Danish Hydraulic Institute (DHI) together with the latest detailed digital elevation model (DEM) to examine the nearshore amplification to 10 m depth along the east Queensland coast from Cooktown to the New South Wales (NSW) border. Stage 1 identified that South-east Queensland (SEQ) from Fraser Island to the NSW border, was at higher risk to tsunami amplification than the rest of the east Queensland coast. The report identified the following regions of higher nearshore tsunami hazard in decreasing order of magnitude:

- Gold Coast (completed by GA (Fountain et al., 2009a));
- Ocean side of Bribie, Moreton, and Stradbroke Islands (completed by DES (Boswood et al., 2018));
- Sunshine Coast (completed by DSITIA (Boswood, 2013b));
- Fraser Island (this study);
- Bundaberg (this study);
- Flying Fish Point;
- Capricorn Coast;
- Agnes Waters; and
- Hervey Bay.

The report also concluded that detailed inundation modelling would be required to assess the full risk to coastal communities.

Tsunami inundation modelling for the Gold Coast had previously been undertaken by GA (Fountain et al., 2009a), by examining three scenarios: an event representing the JATWC land inundation warning wave amplitude of 0.3 m (1 in 200 year event); an event representing overtopping of the coastal dunes; and the largest credible event (1 in 10,000). These scenarios were modelled at both Mean Sea Level (MSL) and Highest Astronomical Tide (HAT). In 2013, DSITIA (Boswood, 2013b) undertook Stage 2 of the NDMP grant study that involved tsunami inundation modelling for the Sunshine Coast. A similar methodology to GA was used whereby three scenarios representing average recurrence intervals (ARI) of 750, 3,000 and 10,000 years were modelled at both MSL and HAT. The lowest ARI chosen to represent an event that produces inundation beyond the beach.

In 2016, the then Department of Science, Information Technology and Innovation (DSITI) and now Department of Environment and Science (DES), was awarded a Natural Disaster Resilience Program (NDRP) grant to continue the previous work by examining the potential for tsunami inundation for two more regions identified in the list above. The final two regions within SEQ were selected and are identified as Stages 3 and 4. The model domains cover the following Local Government Areas (LGA):

- Stage 3: Moreton Bay Regional, Brisbane City and Redland City; and
- Stage 4: Gympie Regional, Fraser Coast Regional and Bundaberg Regional.

These model domains represent four of the locations identified in the list above.

This report describes the processes that influence tsunami propagation and documents the tsunami inundation modelling undertaken for Stage 4.

2 Tsunami Dynamics

To better understand tsunami hazard, this section will briefly describe the processes that influence tsunamis. In basic terms, a tsunami is a series of long period waves generated by a disturbance in the ocean water column arising from abrupt geophysical events. These disturbances are more likely from movement of tectonic plates along faults in the form of submarine earthquakes, but could also be from submarine landslides, volcanic eruptions or a possible meteorite strike (in the extreme). More than 80 per cent of the world's tsunamis were caused by earthquakes (IOC, 2016). The earthquake scenario is the focus of this report.

A simple analogy would be dropping a pebble in a pond. The pebble generates a deformation of the water surface. This in turn creates a wave or series of waves that radiate or spread away from the source in concentric circles of increasing circumference as they propagate away. As the circumference increases, the amplitude decreases or attenuates due to energy being transferred along the wave crest. In reality, tsunami generation is not a point source but a complex pattern of bed movements. The three main stages are: tsunami generation; propagation; and run-up/inundation.

The main source of tsunamigenic earthquakes (that is, capable of generating tsunami) that could produce tsunami hazard along the east Queensland coast come from the subduction zones along the Pacific Rim. Friction between the continental and oceanic plates opposes movement until energy build-up causes the plates to suddenly slip past one another, generating an earthquake. The resulting uplift of the seabed generates a vertical rise in the full water column, which splits to propagate as a tsunami in all directions. The resulting tsunami propagates as a set of waves whose energy is concentrated at wavelengths corresponding to the earth movements (~100 km), at wave heights determined by vertical displacement (typically <1 m), and at wave directions determined initially by fault shape and orientation, and later by the adjacent coastline geometry. Because each earthquake is unique, every tsunami has unique wavelengths, wave heights, and directionality (NOAA, 2018).

As the displacement occurs through the entire water column, and wave lengths are much greater than depth, the tsunami behaves as a shallow water wave even in deep water. The wave period is generally in the range of 5 to 40 minutes. In general, the tsunami may experience the same processes that influence short period wind waves, not limited to attenuation, shoaling, scattering, focusing, diffraction, reflection, trapping and resonance, but at a larger scale and at greater depths. These processes produce an extended wave train of many waves even though the original source was a single impulse. The latter waves in a tsunami form very complicated patterns in which it is difficult to determine the relationship of a latter wave to the initial source. Hence, only the observations of the first few waves at a site are used for comparison with model simulations and estimation of the earthquake source parameters (Mofjeld et al., 2004). A tsunami event can therefore last for several hours, and the first wave may not necessarily be the largest. However, IOC (2016) suggest that the largest wave is usually one of the first five waves.

As the tsunami approaches the coastline, it is influenced by coastal features (such as bays and headlands) and nearshore bathymetry such that the amplitude can amplify and vary along the coastline. Unlike wind waves, which steepen, break and dissipate on beaches; the length to wave height ratio of tsunamis rarely steepens to breaking point. As tsunamis reach the coast, the approaching tsunami can appear as a fast moving tide or surge. The leading edge of some may decay and can appear like a fast moving tidal bore. The flow is horizontal in pattern (more like river flow) and can be very strong and turbulent. The momentum of these waves can push water much further inland than wind waves, and the currents can be too strong for a person to remain upright.

Of course the ability to inundate depends on a number of factors including tsunami height and period, stage of tide, height of any barriers (such as seawalls and beach dunes), obstacles (such as buildings), and land coverage (for example a dense forest will impede tsunami movement more than cleared pastoral land). For small amplitude tsunamis, the stage of tide may be a critical factor. As well as inundating low lying coastal regions, tsunamis will also propagate up rivers and waterways much faster than they inundate some coastal zones.

For coastal structures such as ports and marinas, strong currents can develop at the entrances. Within the port, circulation systems can develop as well as potential resonance that will amplify the tsunami amplitude.

Further detail about tsunami dynamics is provided in Appendix A.

3 Scope

The overall aim of this work is to provide local government authorities and disaster managers a better understanding of the potential tsunami hazards (focused on inundation) along the east Queensland coastline, through demonstrated examples of hypothetical tsunami events for various average return intervals (ARI).

This study is one in a series of reports to access the tsunami hazard through numerical modelling. The project, Tsunami Modelling along the East Queensland Coast, originated in 2011. Two reports were completed in 2013:

- **Report 1:** Regional Modelling (nearshore modelling to 10 m depth along the east Queensland coast to assess amplification factors relative to the 100 m depth contour, and to assess regions requiring more detailed studies (Boswood, 2013a)); and
- **Report 2:** Sunshine Coast (detailed tsunami inundation modelling for select synthetic scenarios of various ARI (Boswood, 2013b).

This study is a continuation of the initial project by examining tsunami inundation for two more regions as identified in Report 1:

- **Stage 3:** Moreton Bay Region, Brisbane City and Redland City local government areas; and
- **Stage 4:** Gympie Region, Fraser Coast Region and Bundaberg Region local government areas.

This is Report 4, which describes Stage 4 model development and hazard assessment.

The reports focuses on earthquake generated tsunamis from GA's draft revised PTHA (as of February 2018), and the broad scale inundation along the open coast and the major river systems where bathymetric data is available. It does not include small waterways and has limited resolution within small scale features such as ports, marinas and canal estates. The study is limited to the data that was available at the time of the project as detailed in the following sections.

- **Stage 3:** Develop a hydrodynamic model to assess tsunami inundation hazard covering Moreton Bay Regional Council, Brisbane City Council and Redland City Council
- **Stage 4:** Develop a hydrodynamic model to assess tsunami inundation hazard covering Gympie Regional Council, Fraser Coast Regional Council and Bundaberg Regional Council.

All reports can be accessed through the Queensland Government website (<https://www.qld.gov.au/environment/coasts-waterways/beach/studies>), and the Queensland Government Open Data Portal (<https://data.qld.gov.au/>).

4 Locality

The Stage 4 region comprises the Gympie Regional, Fraser Coast Regional and Bundaberg Regional LGAs (refer to Figure 1), a cumulative coastline of approximately 365 km in length from Cooloola in the south to Baffle Creek in the north. There are numerous coastal towns within these regions holding significant populations, as well as popular recreational camping sites on Fraser Island and along the Cooloola coast. The combined population is over 247,000 with about 42 per cent located within the Fraser Coast Regional LGA (ABS, 2016).

The term Hervey Bay refers to both the bay and the city, which is located along the southern mainland coastline of the bay. In this report, reference to Hervey Bay relates to the bay. Hervey Bay is formed by the Queensland coastline to the west and Fraser Island to the east. The dominant entrance faces a northerly direction, protected from south-easterly wind waves by Fraser Island. The southern entrance connects to the Great Sandy Strait, which exists between the southern tip of Fraser Island and Inskip Point.

All LGAs share a boundary with either Hervey Bay or the adjoining Great Sandy Strait. The coastline consists of sandy beaches and rocky headlands, with a number of shore stabilisation structures including rock groynes and revetments. Coastal communities are interspersed between rural or remnant vegetation, the largest being the city of Hervey Bay. The local economy relies on tourism, being a popular destination for camping, fishing and whale watching.

The study area focuses primarily on the coastline from Rainbow Beach in the south to Moore Park Beach in the north, including Fraser Island.



Figure 1 - Stage 4 study region.

5 Model Development

5.1 Modelling Approach

The tsunami inundation modelling was undertaken using DHI's MIKE21 flexible mesh hydrodynamic modelling software (MIKE21FM), which was successfully applied to Stages 1 to 3. The hydrodynamic model is based on the numerical solution of the two-dimensional (depth averaged) incompressible Reynolds averaged Navier-Stokes equations (RANSE) invoking the assumptions of Boussinesq and of hydrostatic pressure (DHI, 2017a). The model consists of the continuity, momentum, temperature, salinity and density equations and it is closed by a turbulent closure scheme. The spatial discretisation of the primitive equations is performed using a cell-centred finite volume method. Unstructured meshes can be generated comprising both triangular and quadrilateral elements in either Cartesian or spherical coordinate systems. An explicit scheme is adopted for time integration.

Modelling software that solves the shallow water equations have been successfully applied to tsunami propagation and inundation. Horrillo et al. (2014) undertook benchmarking of a number of models ranging from full 3D Navier-Stokes implementations to 2D long wave models with frequency dispersion (Boussinesq) or without dispersion (nonlinear shallow water equations – similar to the selected modelling software). The results indicating that all models tested were suitable for inundation modelling for the benchmark problems investigated. Further details on the suitability of this software can be found in Boswood (2013a).

The modelling approach involves developing a mesh of the study area that represents the topographic and bathymetric characteristics that will influence tsunami propagation, including bed roughness characteristics, and applying forcing conditions that represent the range of conditions expected within the study area. The following sections will go through the data and model development in more detail.

5.2 Supporting Data

5.2.1 Bathymetric and Topographic Data

A number of bathymetric and topographic datasets were sourced during the project to develop the digital elevation model (DEM) employed for mesh interpolation (refer to Section 5.3 for more detail). Table 1 details the datasets and sources.

Table 1 - Bathymetric and topographic data sources.

Source	Description	Resolution	Usage
International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO	The GEBCO_08 Grid, version 20100927, http://www.gebco.net	unknown	Solomon Validation Model (areas outside the GA250 extent)
Geoscience Australia (GA)	Australian Bathymetry and Topography, June 2009 (GA250) (Webster, 2005), https://data.gov.au/dataset/australian-bathymetry-and-topography-grid-june-2009	250 m	Solomon Validation Model (areas outside the gbr100 extent)
James Cook University (JCU)	High-resolution depth model for the Great Barrier Reef and Coral Sea 2017 (gbr100) (Beaman, 2010), https://www.deepreef.org/bathymetry/65-3dgbr-bathy.html	100 m	Solomon Validation Model
GA / Dr R Beaman	High-resolution depth model for the Great Barrier Reef – 30 m (gbr30) (GA, 2017), http://pid.geoscience.gov.au/dataset/ga/115066	30 m	Hervey Bay tsunami model
GA	Digital Elevation Model (DEM) of Australia derived from LiDAR 5 Metre Grid – State Mosaic QLD, http://www.ga.gov.au/metadata-gateway/metadata/record/89644/	5 m	Hervey Bay tsunami model
Bundaberg Regional Council	Hydrographic survey of Elliott River (2012), Burrum River (2013), Kolan River (2012, 2013), Burrum River, Isis River, Gregory River, Cherwell River, Stockyard Creek (2015)	5 m	Hervey Bay tsunami model
GA	Intertidal Extents Model Confidence Layer (ITEM CL) http://pid.geoscience.gov.au/dataset/ga/100464	25 m	Hervey Bay tsunami model

Source	Description	Resolution	Usage
Queensland Government	Queensland Land Use Mapping Program (QLUMP). https://www.qld.gov.au/environment/land/vegetation/mapping/qlump	N/A	Roughness Map
Queensland Government	Queensland Digital Cadastral Database (DCDB) https://www.business.qld.gov.au/running-business/support-assistance/mapping-data-imagery/data/digital-cadastral	N/A	Roughness Map
Queensland Government	Queensland Wetland habitat mapping https://wetlandinfo.ehp.qld.gov.au/wetlands/facts-maps/wetland-background/	N/A	Roughness Map

5.2.2 Tide Data

The tidal harmonics used to develop the large scale tidal model boundary conditions were supplied by the National Tidal Centre (NTC), Commonwealth Bureau of Meteorology. For locations further east than longitude 156° east, tidal constituents from NASA's GOT00.2 global tidal model were provided by NTC. The eight primary tidal constituents were provided for 63 locations along the perimeter of the tidal model domain, the constituents being K1, O1, M2, P1, S2, N2, K2 and Q1.

For calibration purposes, tidal constituents at a number of monitoring sites were provided by Maritime Safety Queensland (MSQ).

Highest Astronomical Tide (HAT) levels for the tsunami modelling scenarios were obtained from MSQ (2018), and provided below in Table 2 and Table 3 for ocean side and within the bay respectively.

Table 2 - Highest Astronomical Tide (HAT) levels outside of Hervey Bay (ocean side) (MSQ, 2018).

Site	AHD (m LAT)	HAT (m LAT)	HAT (m AHD or m MSL)
Double Is Point	1.12	2.28	1.16
Rainbow Beach	1.12	2.28	1.16
Waddy Point (Fraser Is)	1.007	2.37	1.36
Burnett Heads	1.693	3.67	1.98
Seventeen Seventy	1.61	3.58	1.97
AVERAGE:	1.31	2.84	1.53

Table 3 - Highest Astronomical Tide (HAT) levels within Hervey Bay (MSQ, 2018).

Site	AHD (m LAT)	HAT (m LAT)	HAT (m AHD)
Bargara	1.69	3.67	1.98
Elliott River entrance	1.7	3.78	2.08
Woodgate (Theodolite Ck)	1.77	3.89	2.12
Burrum Heads	1.82	3.9	2.08
Point Vernon	1.89	4.11	2.22
Urangan	2.04	4.28	2.24
River Heads (Mary R)	2.17	4.6	2.43
Boonooroo	1.19	2.75	1.56
Tin Can Bay	1.36	2.94	1.58
AVERAGE:	1.87	4.03	2.16

5.2.3 Probabilistic Tsunami Hazard Assessment Database

A Probabilistic Tsunami Hazard Assessment (PTHA) was undertaken by GA to provide a means of assessing the hazard along the Australian coastline to assist state government agencies in identifying potential areas at risk and so requiring more detailed studies (Burbidge et al., 2008a). The assessment provided deep water return period curves for maximum tsunami amplitude along the 100 m depth contour and relative tsunami hazard rankings for locations around Australia. Tsunami propagation modelling was undertaken using a finite difference model based on the linear shallow water equations. Over 70,000 tsunamis were modelled and the time series were recorded at points along the 100 m depth contour. GA developed the Tsunami Data Access Tool (TsuDAT) so that state governments could access this database to assess the potential hazard along their coastline and to undertake inundation modelling (GA, 2010).

Tsunami scenarios for Stages 1 and 2 were obtained from TsuDAT at defined hazard points along the 100 m depth contour based on user define criteria of area of interest, ARI and subduction zone. As the probabilistic assessment varies for each hazard point, one hazard point within the area of interest is selected to define the return period statistics for event selection. TsuDAT provided a time series of water level and momentum (velocity x depth) along the two major axes (u_h (positive east) and v_h (positive north)) at defined points along the 100 m contour.

In 2017, GA advised DES that a major revision of the PTHA was in progress, with a planned release in 2018. The scenarios used to define the hazard for the Stage 3 and Stage 4 assessments are events from the draft revised PTHA provided directly to DES by GA prior to the official release of the update.

The revised PTHA incorporates the latest best-practice methods for modelling earthquake for tsunami generation, with updated global elevation data, and validation against observational data not previously available during the development of the original PTHA. Specifically, the update utilises:

- Subduction zone geometries from Slab1.0 (Hayes, 2012);
- Subduction zones discretised at a resolution of 50 x 50 km² (previously 100 x 50 km²);
- Stochastic slip earthquake models (previously uniform-slip); and
- Different method to set earthquake rates based on Davies et al. (2017) leading to higher tsunami event exceedance rates (events per year) than the original PTHA.

The revision also provides some flexibility with output locations, with outputs available along the RL -20 m, RL -100 m and RL -1000 m contour lines, as well as offshore model grid points. The format of the return period curves have also been updated to account for uncertainty by including the mean and 95 percentile (refer Figure 4). For this study, events were selected based on the mean exceedance curve.

It is noted that any changes to the final PTHA release from that provided by GA in February 2018 may influence the results provided in this report.

5.3 Digital Elevation Model (DEM)

A tsunami is a long wave that is felt through the whole water column, even in relatively deep water. As such, the propagation of the tsunami will be sensitive to the underlying bathymetric data used in the model. Considerable effort was therefore directed towards producing a Digital Elevation Model (DEM) that best represented the overland, nearshore and deep water bathymetry within the model domain based on the most complete set of available data.

The Stage 4 model DEM was developed from a range of sources including (see Table 1):

- Bathymetry and topography from the gbr30;
- Topography from the 5 m State Mosaic QLD DEM; and
- Hydrographic survey data provided by Bundaberg Regional Council.

The gbr30 is a comprehensive compilation of available bathymetric and topographic data collected from 1967 to 2017 covering the GBR and Coral Sea extending along the entire Queensland east coast. The dataset is provided in raster format with a spatial resolution of 0.0003 decimal degrees (approximately 30 metres). It is noted that although the gbr30 is of relatively high resolution, the underlying bathymetry data within the nearshore can be sparse. The intertidal zone can be dynamic, particularly on the beaches exposed to the open ocean.

The State Mosaic QLD DEM contains topographic data from various airborne Light Detection and Ranging (LiDAR) surveys conducted along the Queensland coastline between 2009 and 2015. Data for the study area was extracted from this dataset. The DEM includes some areas of erroneous reflections from water surfaces within the intertidal zone giving incorrect elevations. This required processing before integrating with the other datasets. Satellite overlays along with the Intertidal Extents Model (ITEM) Confidence Layer (GA, 2016) were used to identify these error areas within the data, which were then removed. The ITEM Confidence Layer's use as a mask for the topographic data has previously been verified by a field survey conducted along the Sandgate-Brighton foreshore in November 2017 for Stage 3 (Boswood et al., 2018).

Bundaberg Regional Council provided hydrographic survey data of surveys conducted at various rivers and tributaries (see Table 1) between 2012 and 2015. These surveys were received as 3-dimensional point data and processed in to 5 m raster formats for inclusion in the final DEM.

Considerable effort was invested in creating a seamless transition at the coastline interface between the topographic and bathymetric datasets, where artificial steps could develop at the interface of the higher resolution (and higher accuracy) 5 m topographic DEM and the lower

resolution gbr30 DEM. A 1 km wide transition zone was created based on nearest neighbour interpolation performed on each of the datasets where they met to create a smooth transition.

The developed overland DEM is a bare earth model in that only ground points have been included, thereby removing all structures and vegetation. The influence of these features on inland inundation is introduced implicitly by the introduction of roughness factors. The DEM is also assumed to be static and non-erodible. Should a tsunami cause significant damage to soft/natural defences (such as dune systems), then this could impact the inundation extent provided in this report.

The final DEM was developed over the duration of the project, as more data became available. The gbr30 DEM did not become available until January 2018. The initial model domain and mesh size testing (refer to Section 6) was undertaken with the gbr100, with further mesh size testing conducted after receiving the gbr30. All model validation and scenario modelling was undertaken with the final DEM, which was a layered compilation of all quality assured DEMs to maintain available resolution, as well as the transition zone mentioned above.

5.4 Model Domain and Mesh Development

The entire model domain for Stage 4 is shown in Figure 2. A number of test runs using 10,000 year ARI events were undertaken to optimise the inland extent of the model and mesh resolution in the offshore (i.e. depths >10 m) to maintain feasible computation times whilst reducing numerical dispersion and adequately representing key geomorphological features within the bathymetry.

The offshore boundary was set to correspond with GA's PTHA tsunami event database output locations. The original PTHA database (TsuDAT – GA, 2010) provided event time series at the 100 m depth contour. The draft revised PTHA (refer to Section 5.2.3) can provide output at the 100 m and 1,000 m depth contour. As the 100 m depth contour comes in relatively close to Fraser Island (about 19 km offshore), an offshore boundary at the 1,000 m depth contour was selected for this study to maximise the distance of the offshore boundary from the study area. This is a variation to the Stage 2 study (Boswood, 2013b) where the offshore boundary was set along the 100 m depth contour, being the only available output location for the original PTHA database. The land boundary provides for flooding and drying associated with inundation. The model domain extends to the north and south of the study region to mitigate any numerical boundary effects.

MLITT (2012) suggest that grid sizes should be selected such that 20 grid points represent a wavelength. For wave periods in the range of 5 to 10 minutes, this would suggest grid sizes of 1.5 to 3.0 km at 1000 m depth, and 150 to 300 m at 10 m depth. Generally, finite volume models refer to mesh area rather than mesh dimension. The Sunshine Coast tsunami inundation study (Boswood, 2013b) examined the impact of mesh resolution on tsunami inundation extents by comparing the results for two mesh resolutions (200,000 m² offshore to 75,000 m² at 10m depth against 35,000 m² offshore to 10,000 m² at 10 m depth). The comparison showed a reduction in spatial resolution by about half, resulting in over a two fold increase in computation time for an average 3 per cent increase in maximum amplitude, with little difference in inundation extent. The area modelled for the Sunshine Coast was significantly smaller than the area being modelled in this study. A balance is required to assure the processes that influence tsunami inundation are replicated, whilst maintaining reasonable computation times based on the number of elements and the time step for model stability governed by the Courant-Friedrich-Lévy (CFL) number (DHI, 2017b).

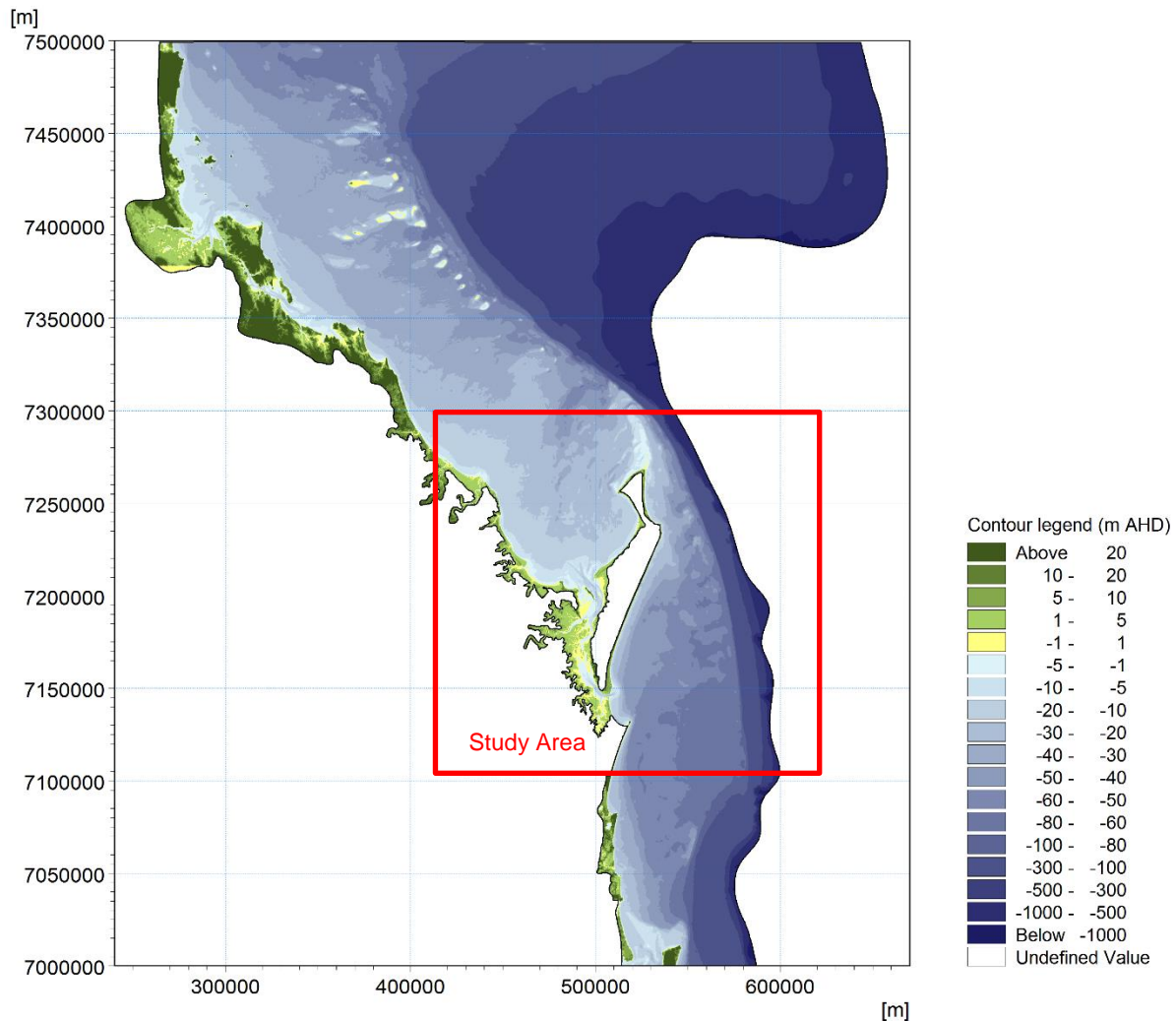


Figure 2 - Stage 4 model domain

The final mesh comprises 3,011,009 triangular mesh elements. The maximum offshore resolution is 240,000 m² (an equivalent spatial resolution (dx) of about 690 m). A number of transition zones results in a higher detailed mesh within the study area, with maximum resolution of 7,500 m² ($dx \approx 120$ m) within Hervey Bay and the nearshore zone on the ocean side. This is sufficient to capture tsunami shoaling and refraction processes. Major rivers were modelled up to the limit of reliable bathymetric data, which is typically not to the tidal limit. The replication of smaller waterways is reliant on the hydrographic datasets obtained. Although, the gbr30 DEM (refer to Section 5.2.1) is of high resolution, the nearshore data used to generate it can be sparse.

Developed inland areas, rivers, marinas and canal estates are typically 800 m², ($dx \approx 40$ m). This inland mesh size was considered adequate for emergency management purposes as it approximately represents a block of land but is not too fine to cause unreasonable simulation times. This will provide general inundation extents, but will not provide detailed flow characteristics around buildings or along residential streets, as demonstrated in Figure 3. In undeveloped inland areas, a coarser resolution was adopted ranging from 2,400 m² ($dx \approx 70$ m) to 10,000 m² ($dx \approx 140$ m) on the steep dunes of Fraser Island. Sensitivity testing on mesh size indicated that the coarser mesh would generally be more conservative. Care was taken to capture potential barriers to tsunami inundation such as coastal ridges, dunes and the crest of revetments.

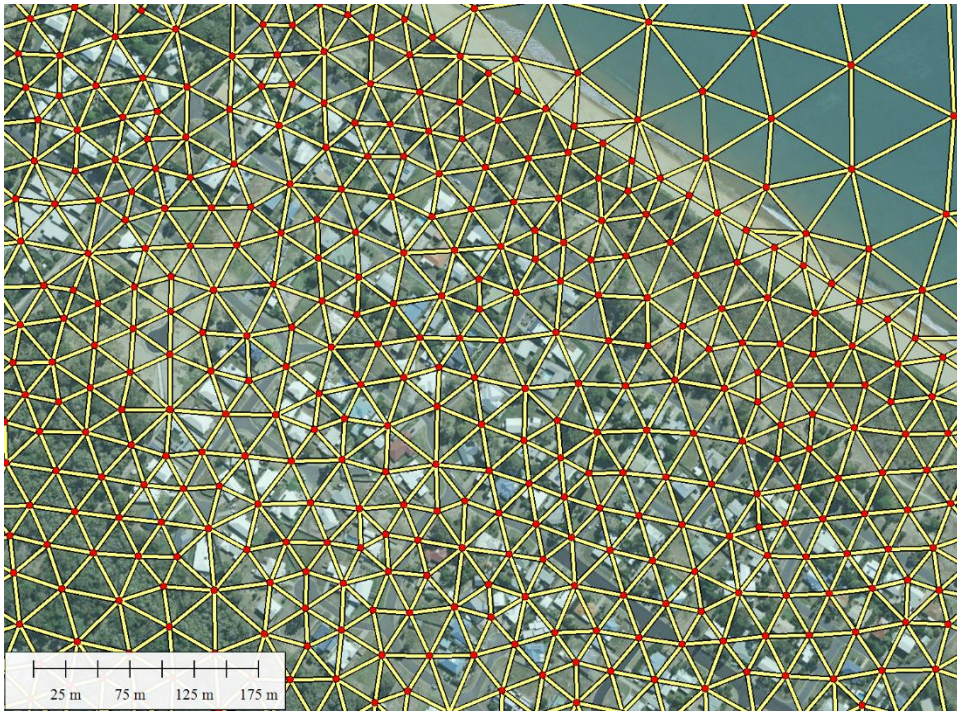


Figure 3 – An example of the overland mesh resolution at Moore Park Beach.

6 Model Calibration, Validation and Sensitivity

6.1 Approach

The standard approach to calibrating 2D hydrodynamic models involves adjusting model parameters such as bed roughness, horizontal eddy viscosity, and bathymetry to match measured water level and/or velocity data collected within the study area. This may involve a range of conditions that are expected to influence the local hydrodynamics. Once calibrated, the model is then validated against measured events.

As explained in Boswood (2013a), the availability of measured tsunami events along the Queensland coast is scarce, and inundation mapping from historic events is non-existent. As water level data associated with tides are more readily available, the 2013 study (Stage 1) calibrated the regional models against tidal predictions for 83 sites over a spring tide period in January to February 2011. The calibrated models were then validated for a specific tsunami event originating from the Solomon Islands in 2007 that was measured by the DES storm tide network (EPA, 2007). Boundary conditions consisting of water level time series was provided by GA.

To have further confidence in the detailed mesh developed for the current project, this process of calibration and validation was again undertaken, the detail of which is provided in Appendix B and Appendix C for calibration and validation respectively.

Calibration was undertaken against astronomical tides for thirteen prediction sites within the model domain, with eight sites within the detailed mesh study area (Bundaberg, Burnett Heads, Elliot Heads, Urangan, Ungowa, Boonlye Point, Elbow Point, and Waddy Point). For the validation event, four measurement sites within the model domain were available, including two within the study area being Burnett Heads and Urangan. Due to the size and computational effort required to run the Hervey Bay model, particularly tides, the process involved testing the model against the roughness and horizontal eddy viscosity parameters adopted in Stage 3. This seemed a reasonable approach given that both studies considered large shallow bays with main entrances facing north, with similar mesh resolutions.

Overall, the model performed well in reproducing both the tides and 2007 Solomon Island tsunami event, suggesting no further refinement of the initially adopted parameters is required. Details of Stage 3 model sensitivity testing are provided in Appendix C.5. Hervey Bay is deeper than Moreton Bay. Therefore the influence of bed roughness is expected to be less sensitive, apart from the shallow regions of the Great Sandy Strait. Some sensitivity testing was undertaken by varying the roughness and horizontal eddy viscosity parameters during validation. However, there were only marginal changes to the modelled water levels, most likely contributable to the very small amplitudes being modelled.

6.1.1 Adopted Parameters

Given the performance of the model against tides and the 2007 Solomon Island tsunami based on the Stage 3 parameters, the parameters adopted for Stage 3 were also applied to this study. The final parameter settings were chosen on the more conservative side to produce slightly higher amplitudes but within commonly accepted values for coastal applications. Horizontal eddy viscosity is defined by the Smagorinsky formulation (Smagorinsky, 1963), adopting a constant coefficient of 0.28 (default value).

6.1.2 Seabed Roughness

The seabed roughness is defined by the Manning's coefficient (n), a commonly adopted parameter for both riverine and coastal applications. A constant value of 0.02 was adopted, as applied by Cardno (2013) and Stage 3 (Boswood et al., 2018).

6.1.3 Overland Roughness

As a tsunami travels overland, it will experience obstacles and land cover that will obstruct or impede its motion. The adoption of a "bare earth" topography requires the application of overland roughness values that represent the expected effect of the removed obstacles on inundation extent for each overland cell. Roughness coefficients are typically adjusted to match measured inundation levels. However, such data for a tsunami event is lacking for the study region.

Bricker et al. (2015) concluded that tsunami models would benefit from leveraging roughness values from open channel flow literature, and cites the work of Bunya et al. (2010), which provides an extensive list of Manning's values based on land use mapping for a storm surge modelling study. The approach applied to the current study was the development of a detailed roughness map based on land use. Further detail is provided in Appendix D.

Manning's values for overland areas were chosen following a literature review of values as discussed in Appendix D. The final list of values is reproduced in Table 4, based on the work of Bricker et al. (2015), Bunya et al. (2010), and Cardno (2013). This list has been purposely kept to a minimum, to prevent undue complexity that at present cannot be verified. It is expected that this will produce a more conservative result.

Table 4 - Table of Overland Manning's values used within the model domain.

Land Use Category	Manning's n	Manning's $M (1/n)$
Coastal Waters	0.025	40.00
Roads	0.020	50.00
Wetland Barren	0.030	33.33
Wetland Shrub	0.045	22.22
Grassland	0.030	33.33
Farmland	0.040	25.00
Coastal Woody Wetland	0.070	14.28
Forest	0.070	14.28
Low Density Urban	0.050	20.00
Medium Density Urban	0.100	10.00

7 Scenarios

As previously mentioned in Section 5.2.3, model boundary time series were provided by GA based on a defined hazard point, area of interest, ARI and subduction zone. The hazard was defined at a point offshore from Fraser Island (longitude 153.33° east, latitude 24.41° south) from which the exceedance rate based on maximum tsunami amplitude (peak stage) is derived (Figure 4). The PTHA considers only earthquakes as source to the tsunami hazard, which contribute to approximately 80 per cent of all tsunami events (Davies et al., 2017 and Appendix A).

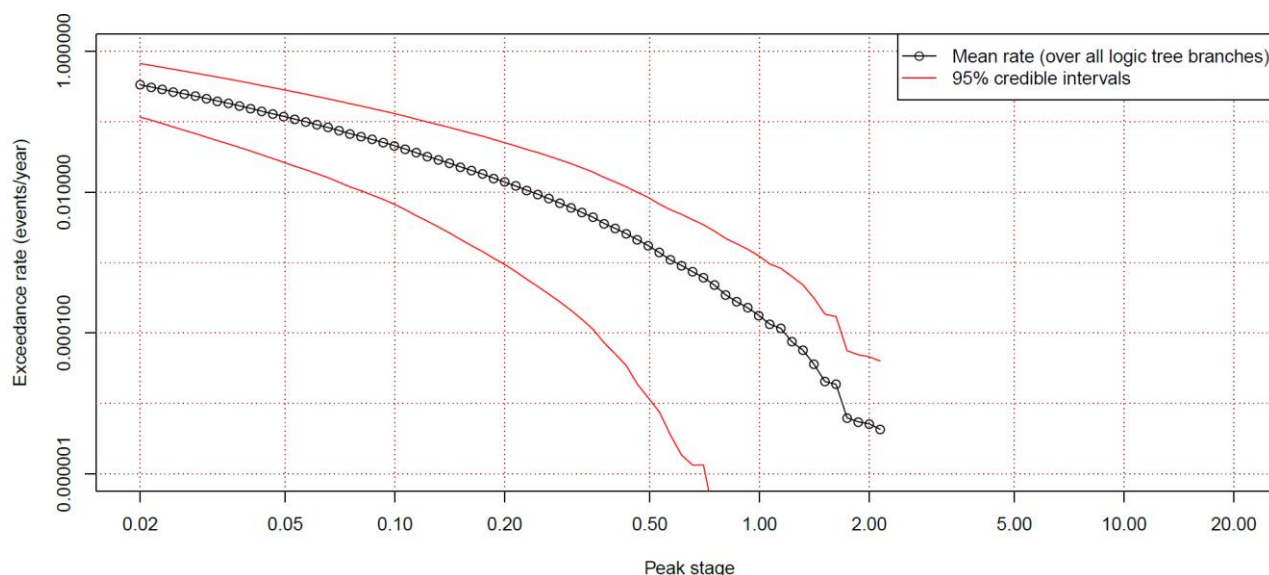


Figure 4 - Exceedance Rate for Stage 4 defined at longitude 153.33° E, latitude 24.41° S.

Events are then extracted from the draft revised PTHA database for ARI (inverse of the exceedance rate) of 750, 3,000 and 10,000 years consistent with the Stage 2 Sunshine Coast study (Boswood, 2013b). The higher ARI being the largest credible event and the other two arbitrarily chosen to demonstrate inundation that would overtop the coastal dunes. Figure 5 shows the contribution to the hazard at the defined offshore point by earthquake subduction zone with Figure 6 showing subduction zones within proximity to the east Queensland coast. It can be seen that the Kermadec-Tonga trench has the highest contribution across all ARI, followed by New Hebrides and South America. This is consistent with Stage 3 but a change to the Sunshine Coast study, which showed the New Hebrides Trench as having the highest contribution to the hazard (based on the original PTHA). The three highest contributing subduction zones were considered for this study.

It is noted that although the study has adopted the mean exceedance rate, there can be considerable spread in maximum stage within the 95 per cent creditable intervals. For example, the mean 750 year ARI maximum stage of about 0.5 m is also within the 95 percentile for just over a 100 year ARI. So although the events modelled may seem extreme, they can also occur at lower recurrence intervals. It is also noted that the events provided by GA are from the draft revised PTHA as of February 2018. Any changes in the final release may influence the results and conclusions provided in this report.

The model run schedule is shown in Table 5, listing all Stage 4 runs varying over ARI, subduction zone and still water level. Models were run with still water levels at MSL, HAT, and HAT with sea level rise (SLR). The MSL condition is provided for one event each ARI, being the level applied to the PTHA and to demonstrate variations due to stage of tide. Given that a tsunami event can

persist over several hours, it is likely that waves will occur on high tide. Therefore, the remainder of the runs are undertaken at HAT. Adopting HAT will provide a conservative result and is consistent with the NSW study (Cardno, 2013). HAT values within and outside the bay are provided in Table 3 and Table 2 respectively. The average difference between both is 0.63 m, so it was decided to apply two HAT levels: Waddy Point HAT for the ocean side, and Urangan HAT for the bay. These sites are close to the average value and Urangan is also a long standing monitoring site.

Sea level rise is considered as a constant 0.8 m increase for the year 2100 from the Coastal Hazard Technical Guide (EHP, 2013). The ARI provided by the PTHA is for MSL, consequently model runs at HAT and SLR water levels may have an ARI greater than the reported values.

Each ARI is modelled for three events generated from different subduction zones at HAT. Only the Kermadec-Tonga event is considered for MSL. Along with one event from the New Hebrides, two events from Kermadec-Tonga were selected for the 10,000 year ARI, reflecting the dominance in hazard contribution and to examine the variability between different tsunami events from the same source. SLR was only considered for the worst case event (10,000 year Kermadec-Tonga; event id 35360) representing the upper-limit of the hazard for all scenarios considered in this study. Statistical properties of each event time series at the defined hazard point is summarised in Table 6.

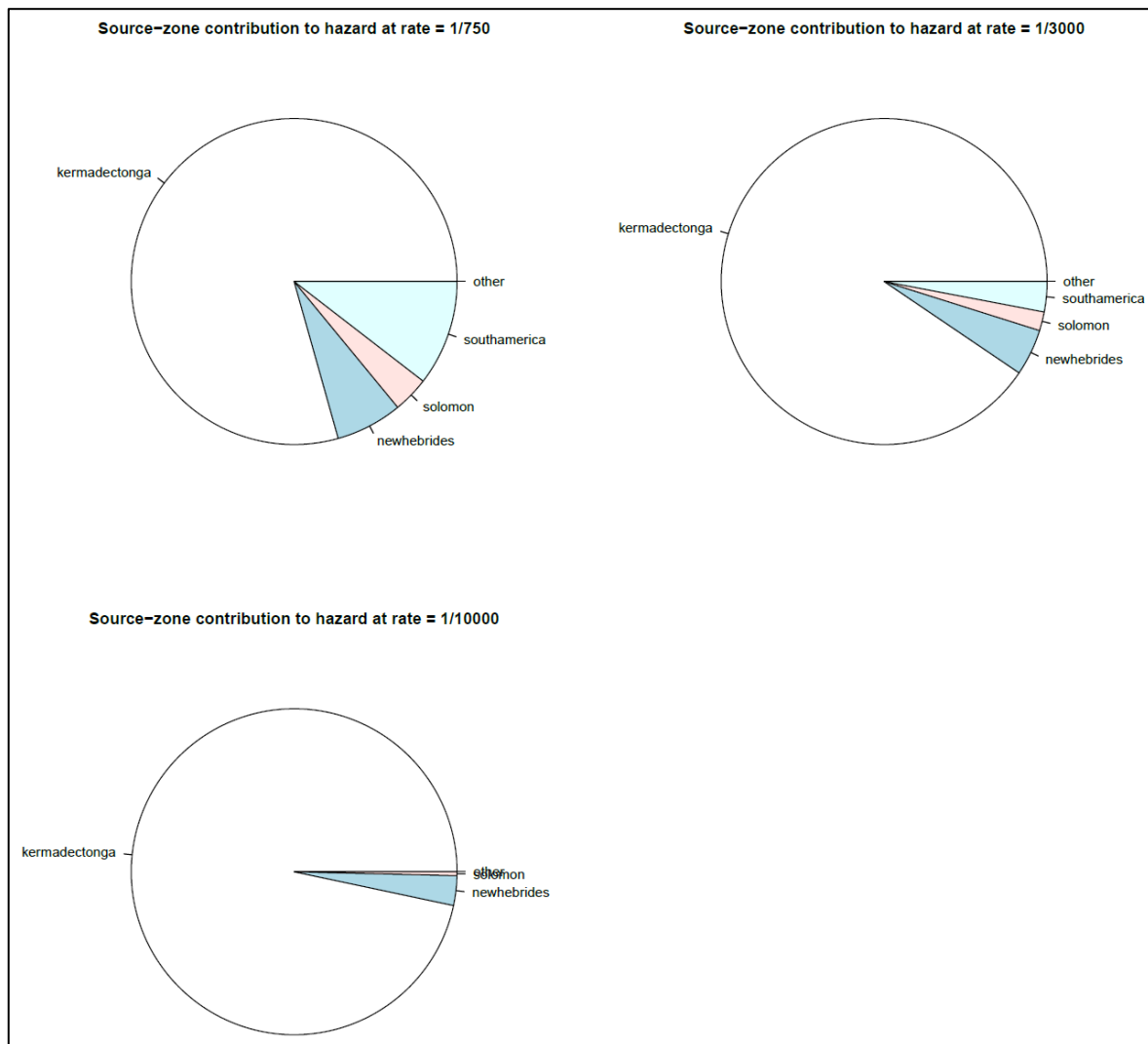


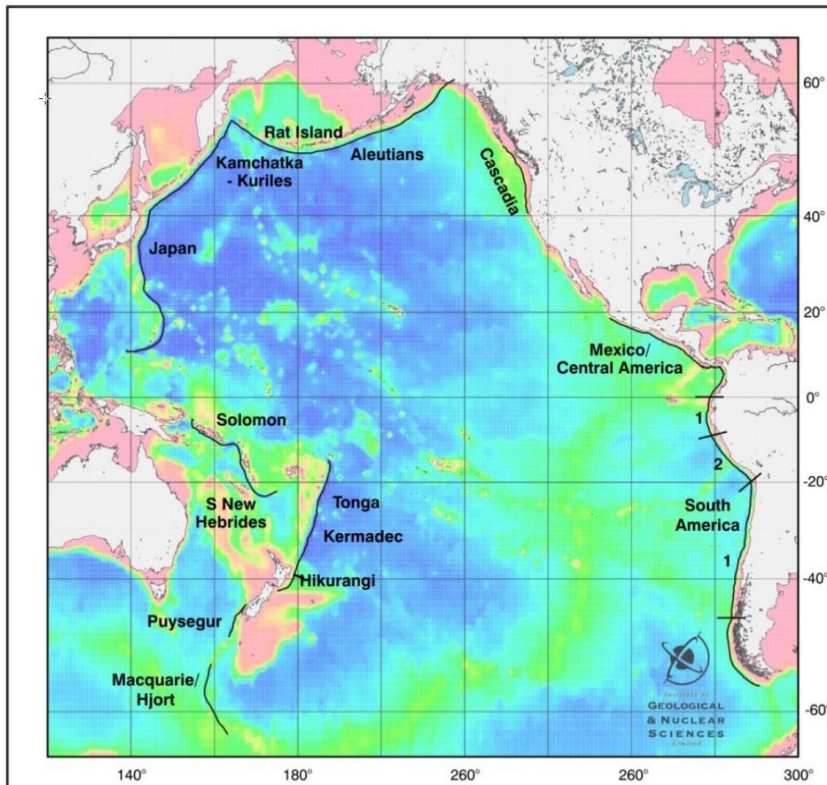
Figure 5 - Source-zone contribution by ARI at the defined hazard point (provided by GA).

Table 5 - Model run schedule

Run No.	ARI	Source	PTHA Event ID	Max Amplitude (m)	Earthquake Magnitude (Mw)	Nominal Water Level	Water Level (m AHD)
1	750	Kermadec-Tonga	34711	0.549	9.2	MSL	0.00
2	750	Kermadec-Tonga	34711	0.549	9.2	HAT BAY	2.20
3	750	Kermadec-Tonga	34711	0.549	9.2	HAT OCEAN	1.36
4	750	New Hebrides	9994	0.548	9.1	HAT BAY	2.20
5	750	New Hebrides	9994	0.548	9.1	HAT OCEAN	1.36
6	750	South America	148140	0.515	9.6	HAT BAY	2.20
7	750	South America	148140	0.515	9.6	HAT OCEAN	1.36
8	3,000	Kermadec-Tonga	35115	0.846	9.3	MSL	0.00
9	3,000	Kermadec-Tonga	35115	0.846	9.3	HAT BAY	2.20
10	3,000	Kermadec-Tonga	35115	0.846	9.3	HAT OCEAN	1.36
11	3,000	New Hebrides	9859	0.804	9.0	HAT BAY	2.20
12	3,000	New Hebrides	9859	0.804	9.0	HAT OCEAN	1.36
13	3,000	South America	145640	0.795	9.5	HAT BAY	2.20
14	3,000	South America	145640	0.795	9.5	HAT OCEAN	1.36
15	10,000	Kermadec-Tonga	35360	1.178	9.4	MSL	0.00
16	10,000	Kermadec-Tonga	35360	1.178	9.4	HAT BAY	2.20
17	10,000	Kermadec-Tonga	35360	1.178	9.4	HAT OCEAN	1.36
18	10,000	Kermadec-Tonga	35360	1.178	9.4	HAT BAY + SLR	3.00
19	10,000	Kermadec-Tonga	35360	1.178	9.4	HAT OCEAN + SLR	2.16
20	10,000	New Hebrides	10112	1.154	9.1	HAT BAY	2.20
21	10,000	New Hebrides	10112	1.154	9.1	HAT OCEAN	1.36
22	10,000	Kermadec-Tonga	35415	1.185	9.4	HAT BAY	2.20
23	10,000	Kermadec-Tonga	35415	1.185	9.4	HAT OCEAN	1.36

Table 6 - Statistical Summary of event time series at the defined hazard point.

PTHA Event ID	Source	ARI	Max Amplitude (m)	Earthquake Magnitude (Mw)	Hm0 (m)	Tp (hh:mm:ss)	Tz (hh:mm:ss)
34711	Kermadec-Tonga	750	0.549	9.2	0.45	0:16:31	0:08:28
9994	New Hebrides	750	0.548	9.1	0.44	0:26:45	0:10:42
148140	South America	750	0.515	9.6	0.68	1:08:12	0:30:03
35115	Kermadec-Tonga	3,000	0.846	9.3	0.68	0:19:20	0:10:51
9859	New Hebrides	3,000	0.804	9.0	0.55	0:17:22	0:09:52
145640	South America	3,000	0.795	9.5	0.78	1:34:23	0:35:28
35360	Kermadec-Tonga	10,000	1.178	9.4	1.04	0:15:36	0:11:34
10112	New Hebrides	10,000	1.154	9.1	0.57	0:28:22	0:08:29
35415	Kermadec-Tonga	10,000	1.185	9.4	0.70	0:20:10	0:09:56

**Figure 6 - Subduction zones around the Pacific Rim (Power, 2013).**

8 Results

A summary of provided Stage 4 result formats is displayed in Table 7. Although a number of scenarios were modelled for each ARI at HAT, the results are provided for the worst case for each ARI. Refer to these for further context to the following sections.

Table 7 - Stage 4 results summary

Name	Description	Format
Appendix F	Spatial maximum water level (amplitude or stage) and current speed of worst case scenario for each ARI at HAT (Kermadec-Tonga).	Separate PDF Map Booklets
Appendix G	Select study location maps of modelled inundation extent for each ARI at MSL (Kermadec-Tonga).	Separate PDF Map Booklet
Appendix H	Select study location maps of modelled inundation extent of worst case scenario for each ARI at HAT (Kermadec-Tonga).	Separate PDF Map Booklet
Appendix I	Select study location maps of modelled inundation extent of SLR scenario (Kermadec-Tonga).	Separate PDF Map Booklet
GIS Database	Entire study domain GIS files of modelled worst case scenario for each ARI (Kermadec-Tonga).	Separate ESRI Database

The separate documents and datasets listed in Table 7 can be accessed through the Queensland Government website (<https://www.qld.gov.au/environment/coasts-waterways/beach/studies>), and the Queensland Government Open Data Portal (<https://data.qld.gov.au/>).

8.1 General Overview

Across all ARI, tsunami events generated from the Kermadec-Tonga subduction zone resulted in the most extreme wave amplitudes, current speeds and inundation levels for the modelled scenarios. The spatial distribution of maximum current speeds and maximum water levels is consistent between ARI, increasing in magnitude as ARI increases (Appendix F). Further detail is provided below.

8.1.1 Wave Propagation

This section provides a general description of tsunami propagation into Hervey Bay based on observation of the model results. Each tsunami will be different, but there will be characteristics that will be more generic based on coastline shape and bathymetric features. These characteristics will assist in understanding the potential hazard for Hervey Bay and are summarised below. To illustrate some of these characteristics, the model results from runs 13 and 16 in Table 5 will be presented.

The study area is a complex section of the Queensland coastline, being the transition from a narrow continental shelf in the south, to the wide and complex bathymetry of the Great Barrier Reef lagoon in the north (refer Figure 2). As such, there are two distinct zones in regards to tsunami hazard, bound by the northern tip of Fraser Island. To the south, the narrow continental shelf and steeper inner shelf is conducive to substantial tsunami shoaling. The hazard is greatest in this zone. To the north, a wide, gently sloping and complex continental shelf reduces the hazard within and to the north of Hervey Bay (refer Figure 7).

In general, tsunami propagation into the study region can be characterised by:

- The first or leading wave, in the absence of any ambient conditions, is well formed and continuous across the study region as it approaches the continental shelf (refer Figure 8).
- The first wave is not always preceded by a recession or drop in water level (also referred to as leading depression N-wave or LDN). Of the model scenarios considered, those from the Kermadec-Tonga subduction zone were LDN; whereas, those generated from the New Hebrides and South America had no initial recession (leading elevation N-waves or LEN). This fits with subduction zone slip mechanics and tsunami generation discussed in Appendix A, where the coast on the overriding plate (as opposed to the subducting plate) will generally experience a LDN.
- The first wave is not necessarily the largest wave. The largest wave may occur several hours after the first wave as demonstrated in Figure 9. Of the scenarios modelled, the offshore leading wave is typically the largest wave. However, as the tsunami reaches the coast, interactions with the coastline and the shelf produce complicated patterns between the incident and reflected waves in both space and time, such that the resulting time series can look much different to the offshore wave train. The timing of the largest wave will depend on these interactions. The timing of the maximum water level will also depend on the stage of tide.
- The tsunami will impact the ocean side of Fraser Island first, followed by the Great Sandy National Park and Rainbow Beach/Inskip. These are the locations where the largest tsunami heights will occur. However, Fraser Island and the Great Sandy National Park are also the locations of the highest dune elevations.
- The oblique angle of both Fraser Island and the Great Sandy National Park relative to the general continental shelf alignment can generate reflected waves that propagate southwards (Figure 11). These transient waves can become shelf trapped to impact distant locations such as Moreton Bay (Boswood et al., 2018).
- Tsunamis generated from the Kermadec-Tonga and New Hebrides subduction zones have similar behaviour within Hervey Bay as shown in Figure 10. There are two regions of focused tsunami energy: the south west coast of Hervey Bay (Hervey Bay City), and north of Burnett Heads (red arrows in Figure 10). Tsunami propagation into Hervey Bay is guided by Breaksea Spit and the bay bathymetry. Although there is diffraction into the bay, the bay side of Fraser Island is not sheltered due to the presence of coastal trapped waves.
- Tsunamis generated from South America can have much longer wave periods, such that they are less sensitive to bathymetric features that influence those from the Kermadec-Tonga and New Hebrides subduction zones, so not demonstrating the same energy focusing (Figure 12).
- Tsunami energy entering the Great Sandy Strait from both the bay and ocean entrances are significantly attenuated, although less so for the very long period waves from South America.
- Considerable wave scattering occurs at headlands, generating reflected and coastal trapped waves along the coastline (black arrows in Figure 10 and Figure 11).
- The presence of shelf trapped waves and coastal trapped edge waves can influence the timing and spatial distribution of the largest tsunami amplitude, as well as the duration that

the tsunami event will persist.

- Tsunamis will propagate up waterways, but are attenuated at the entrances.
- Although not modelled, there is potential for shorter steep waves to travel on top of the underlying tsunami in areas where the tsunami wave steepens.

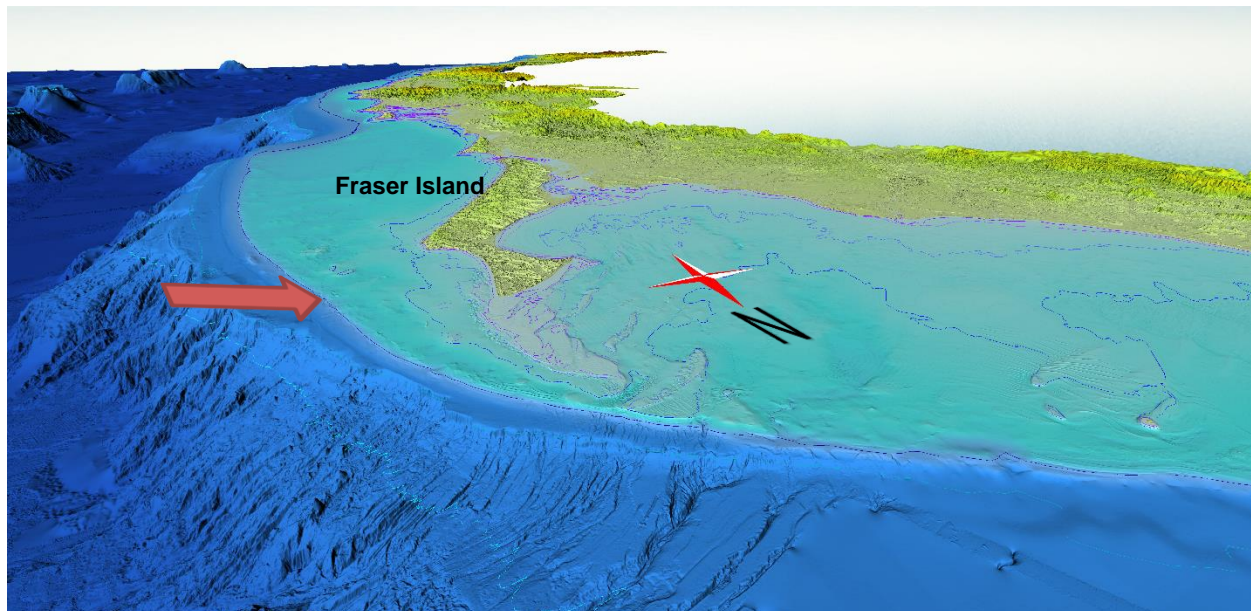


Figure 7 - The complex bathymetry of Hervey Bay (looking south, red arrow indicates tsunami direction).

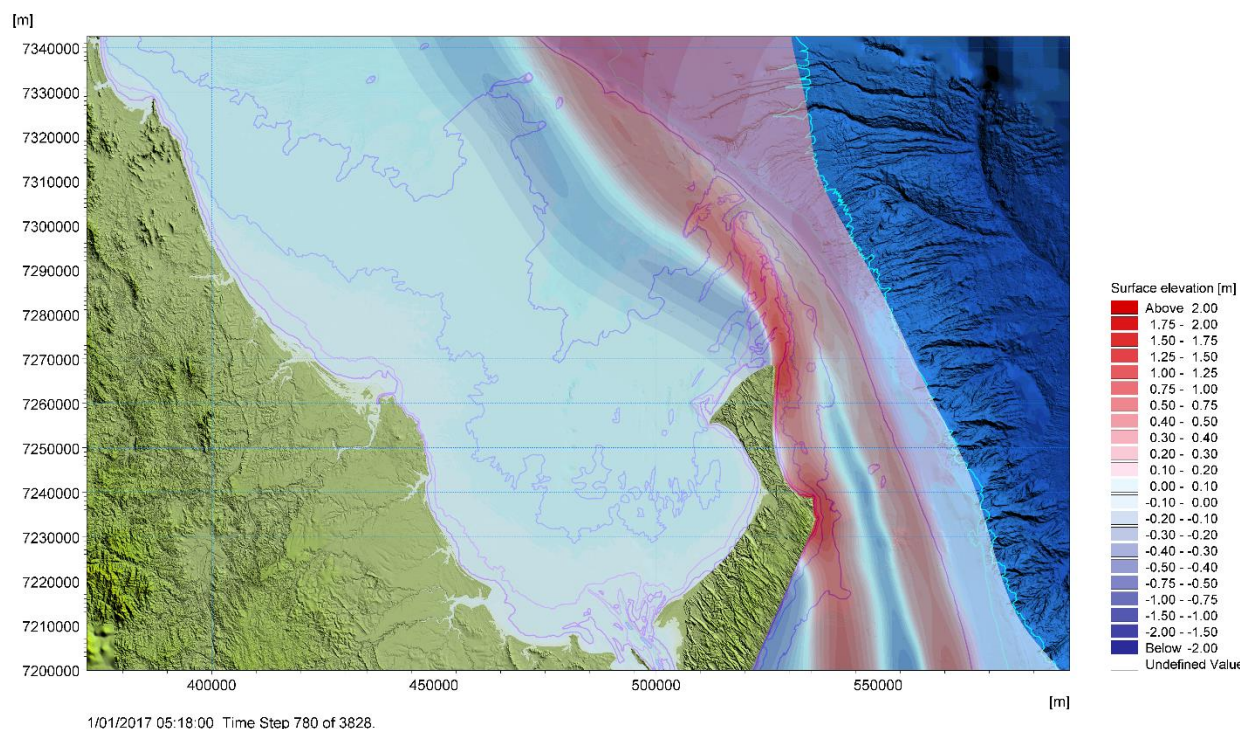
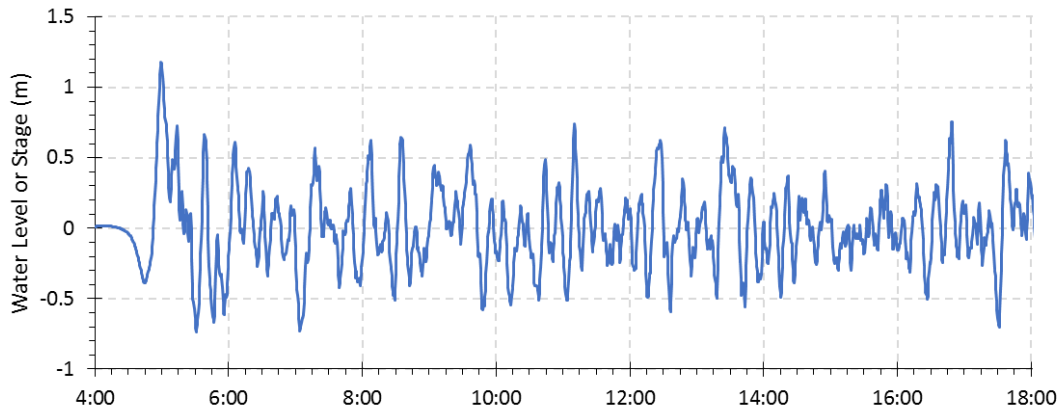
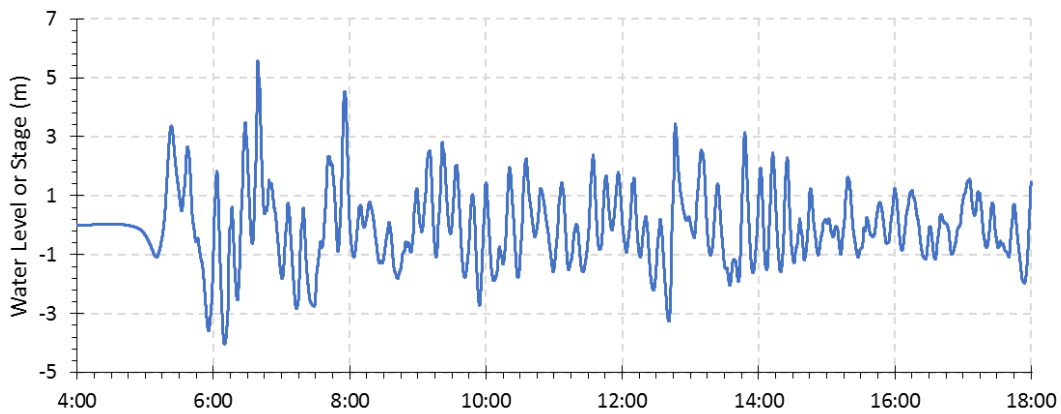
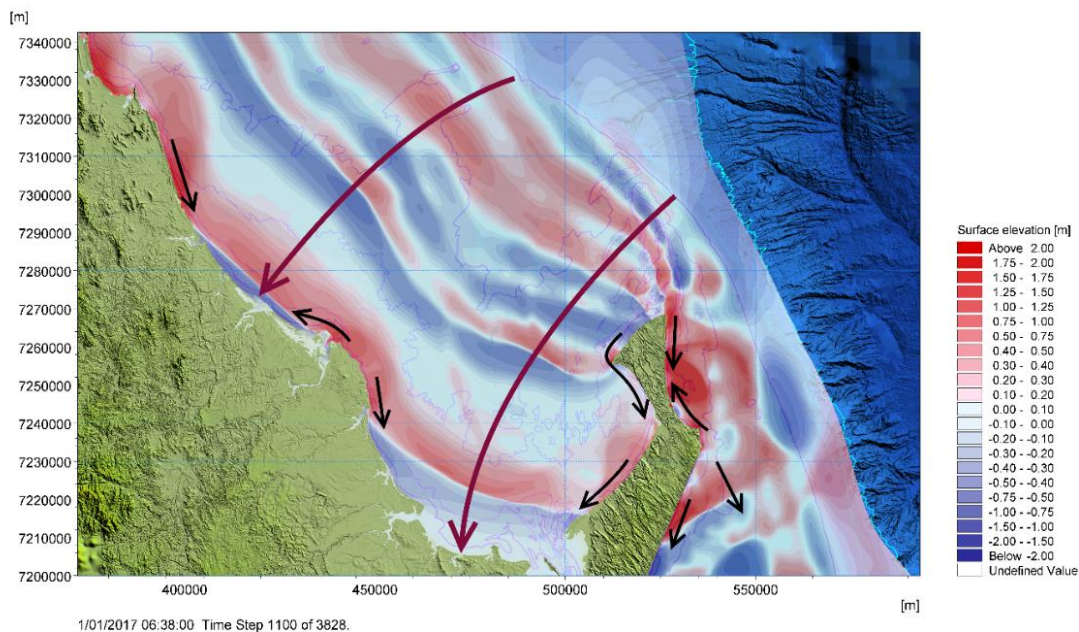


Figure 8 - Leading wave approaching for run 16 (Kermadec-Tonga, 10,000 yr ARI).

(a) Boundary condition at defined hazard point (10,000 year ARI event, depth = 1000m)



(b) North Fraser Island (10,000 year ARI event, depth ≈ 5m)

**Figure 9 - Example of tsunami time series for the 10,000 year ARI event at HAT, originating from Kermadec-Tonga.****Figure 10 - Tsunami propagation into Hervey Bay (run 16). Red arrows indicate direction of progressive waves, black indicates reflected or trapped waves.**

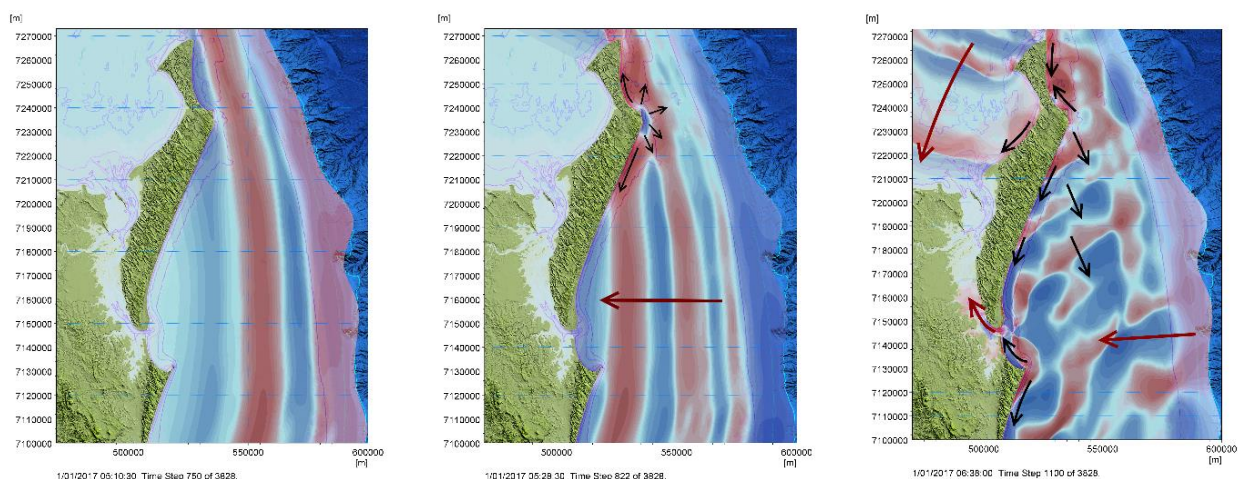


Figure 11 - Tsunami propagation onto Fraser Island (run 16). Red arrows indicate direction of progressive waves, black indicates reflected or trapped waves.

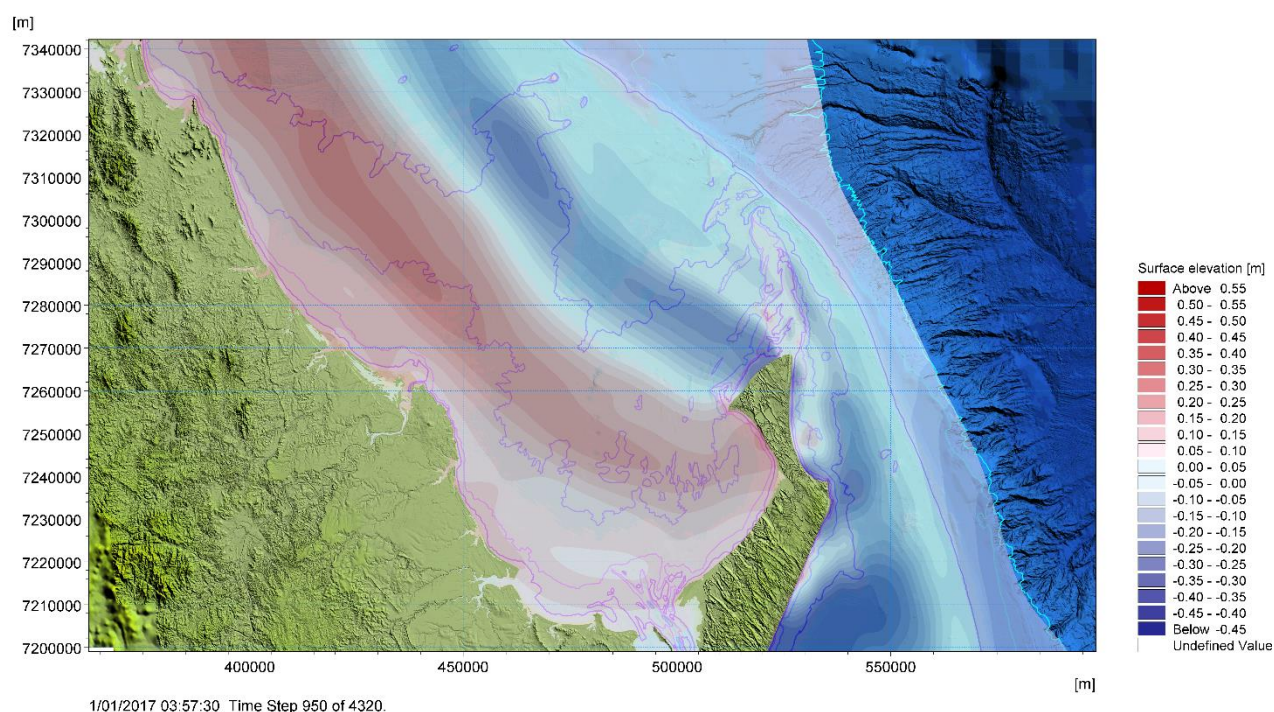


Figure 12 - Tsunami approaching Hervey Bay from South America (run 13). The leading wave having a period of over two hours.

8.1.2 Maximum Amplitudes

Appendix F (refer Table 7) provides maximum water level maps for the worst case scenario for each ARI at HAT, being events from the Kermadec-Tonga subduction zone. The maximum water level is relative to the still water level and so is a measure of the maximum amplitude or maximum stage. The location of the largest wave amplitudes occur on the exposed beaches of the Great Sandy National Park (south of Double Island Point), followed by the ocean side of Fraser Island. Maximum amplitudes through the Great Sandy Strait between Turkey Island and Poona are small and relatively constant below 0.5 m for all ARI, showing small increases with increasing ARI. This suggests wave energy is being attenuated, likely due to the shallow and complex channel configurations around the numerous low lying islands (Figure 1).

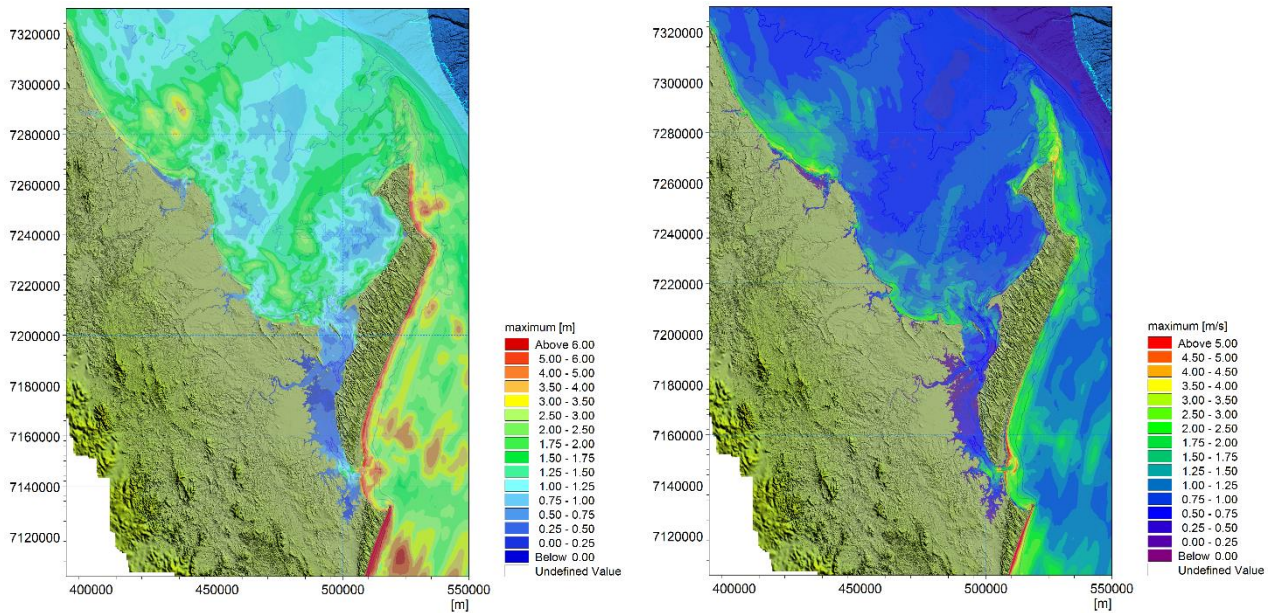


Figure 13 - Maximum water level (left) and current speed (right) for run 16 (Kermadec-Tonga, 10,000 yr ARI).

Maximum water levels range from 5 m for 750 year ARI, 6 m for 3,000 year ARI and 10 m for 10,000 year ARI (amplification factors up to 9) at the exposed Great Sandy National Park Beach (southern limit of study area), and 2 m for 750 year ARI, 4 m for 3,000 year ARI and 7 m for 10,000 year ARI (amplification factors up to 6) on the ocean side of Fraser Island. The wide, gentle and complex bathymetry of the continental shelf north of Fraser Island results in some wave attenuation, reducing maximum amplitudes north of Bundaberg at Miara and Moore Park Beach, with maximum water levels up to 3 m (amplification factors up to 3). Within Hervey Bay (south of Burnett heads) maximum water levels do not exceed 2.5 m (amplification factors up to 2.3). An example for run 16 is provided in Figure 13.

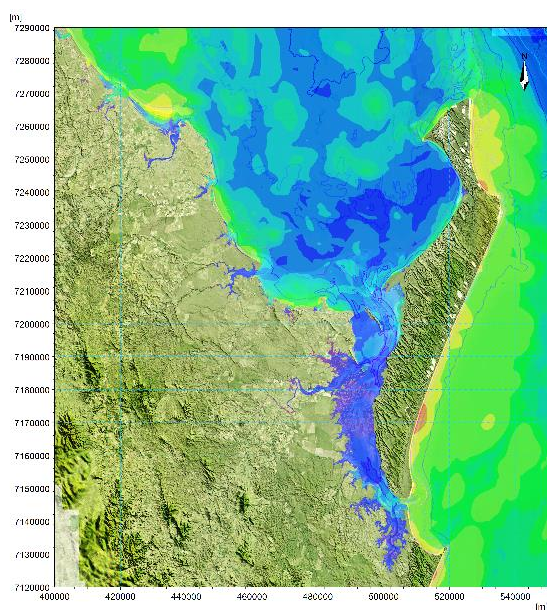
Table 8 shows for select points near the coast, the variation in maximum water level above SWL (a proxy for maximum amplitudes) for all runs. As can be seen, the variation is larger for exposed sites on the ocean side of Fraser Island and outside of the bay. Within the bay and within the rivers (Bundaberg and Mary River) the variation is very low.

Breaksea Spit off Sandy Cape creates a control for tsunami propagation into Hervey Bay. Figure 14 shows the typical tsunami amplification relative to the offshore hazard point maximum water level (Table 5) for events from the three subduction zones. There is significant shoaling on Breaksea Spit for all events, followed by wave attenuation and diffraction. For events originating from both the New Hebrides and Kermadec-Tonga subduction zones, the combination of the bay bathymetry and Breaksea Spit focuses energy into the Hervey Bay City region. There is also focused energy to the north of Burnett Heads. This is less obvious for the South America event, most likely due to the much longer wave periods.

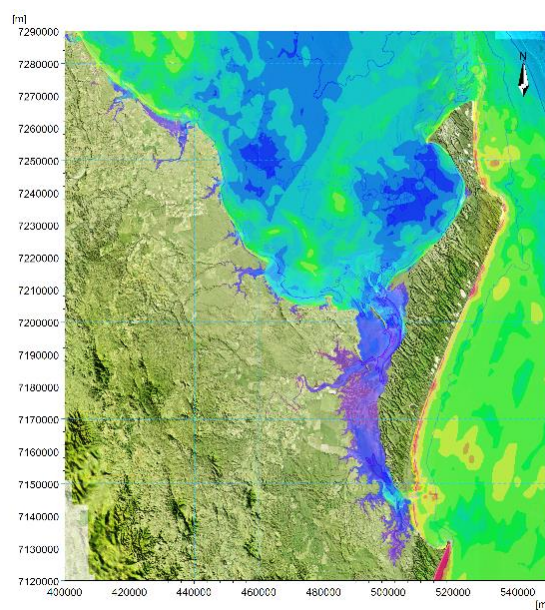
There is some wave attenuation in the lee of Fraser Island. However, the formation of coastal trapped waves as well as subsequent reflections off Burnett Heads and Burrum Heads, increases the modelled maximum water level close to the coast as demonstrated in Figure 16 for a section across the width of the bay (yellow line in Figure 14). Within the Great Sandy Strait, tsunami amplitudes are relatively consistent across all ARI (right side of Figure 15). The spatial amplification patterns are similar across ARI for each subduction zone as illustrated in Figure 17 for events originating from Kermadec-Tonga.

Areas identified as having a higher nearshore hazard (in terms of tsunami wave height) are in decreasing order of magnitude:

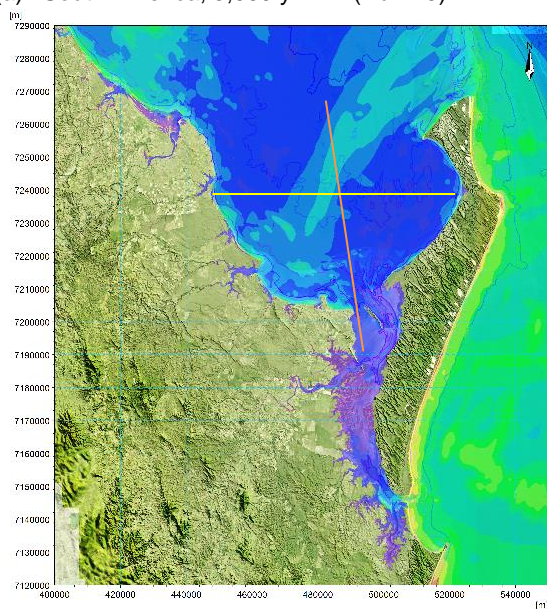
- Great Sandy National Park;
- Fraser Island (ocean side);
- Inskip Point;
- Rainbow Beach;
- Moore Park and Miara;
- Woodgate Beach;
- Hervey Bay City; and
- Wide Bay Training Area.



(a) South America, 3,000 yr ARI (Run 13).



(b) Kermadec-Tonga, 10,000 yr ARI (Run 16).



(c) New Hebrides, 10,000 yr ARI (Run 20).

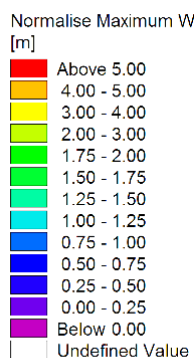


Figure 14 – Maximum water level amplification factors (relative to offshore maximum water levels at Hazard Point).

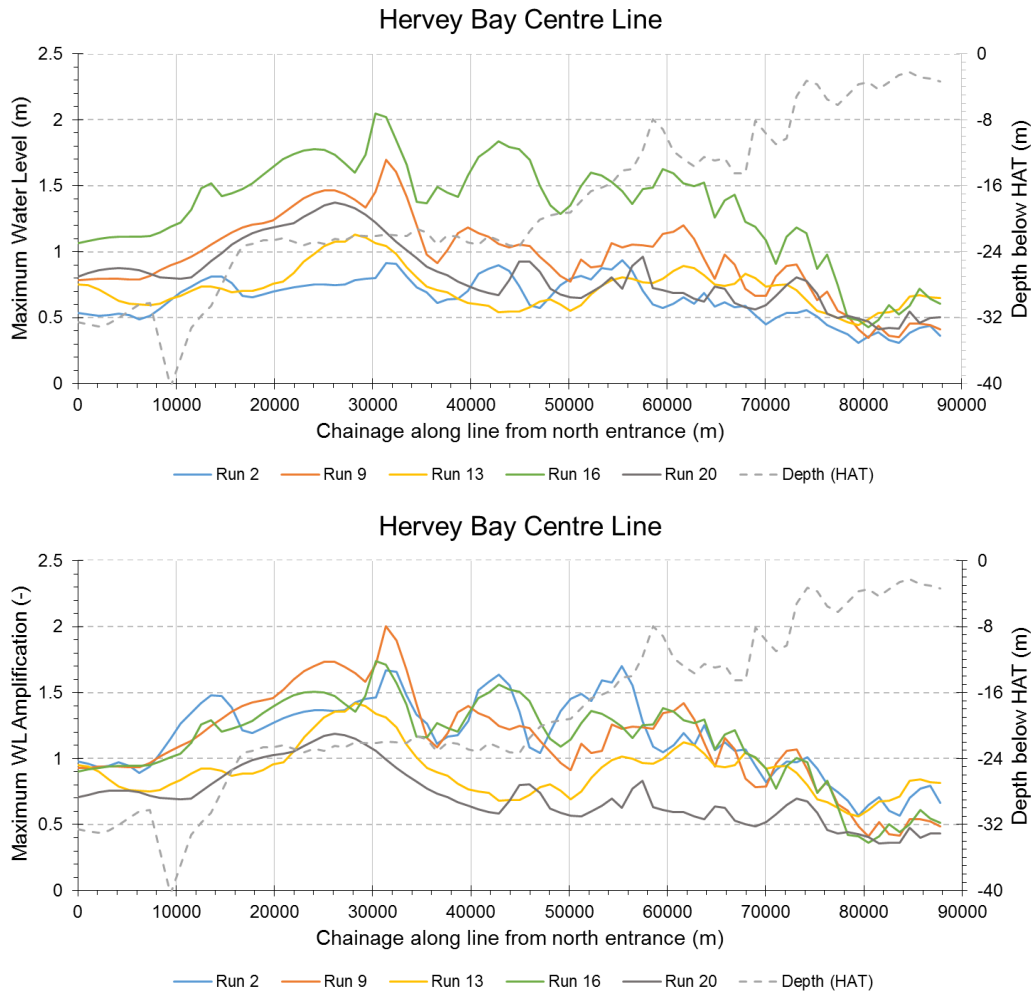


Figure 15 - Maximum water level (top) and amplification factor for centre line through Hervey Bay (orange line in Figure 14).

Table 8 - Variation in maximum water level (in metres above SWL) at select sites for all runs

	Moore Park	Bargara	Bundaberg	Woodgate	Hervey Bay City	Mary River	Inskip Ppoint	Rainbow Beach	Eurong	Fraser Island
Easting	426649	446147	433647	455869	485415	481410	507767	509614	513300	531850
Northing	7266818	7254728	7249910	7224056	7203756	7180575	7143950	7135395	7178018	7239757
Depth (m MSL)	1.7	1.1	0.4	5.0	0.8	8.8	3.3	8.0	6.6	3.1
Average	2.2	1.5	0.5	1.6	0.8	0.4	3.2	3.0	3.3	3.1
Standard Deviation	0.6	0.5	0.1	0.4	0.2	0.2	1.1	0.8	1.0	1.2
Max	3.0	2.4	0.7	2.3	1.2	0.9	6.0	4.2	4.8	5.0
Min	1.2	0.7	0.3	0.9	0.5	0.3	1.6	1.6	1.7	1.6
Max Range	1.9	1.7	0.4	1.4	0.8	0.7	4.4	2.6	3.1	3.4

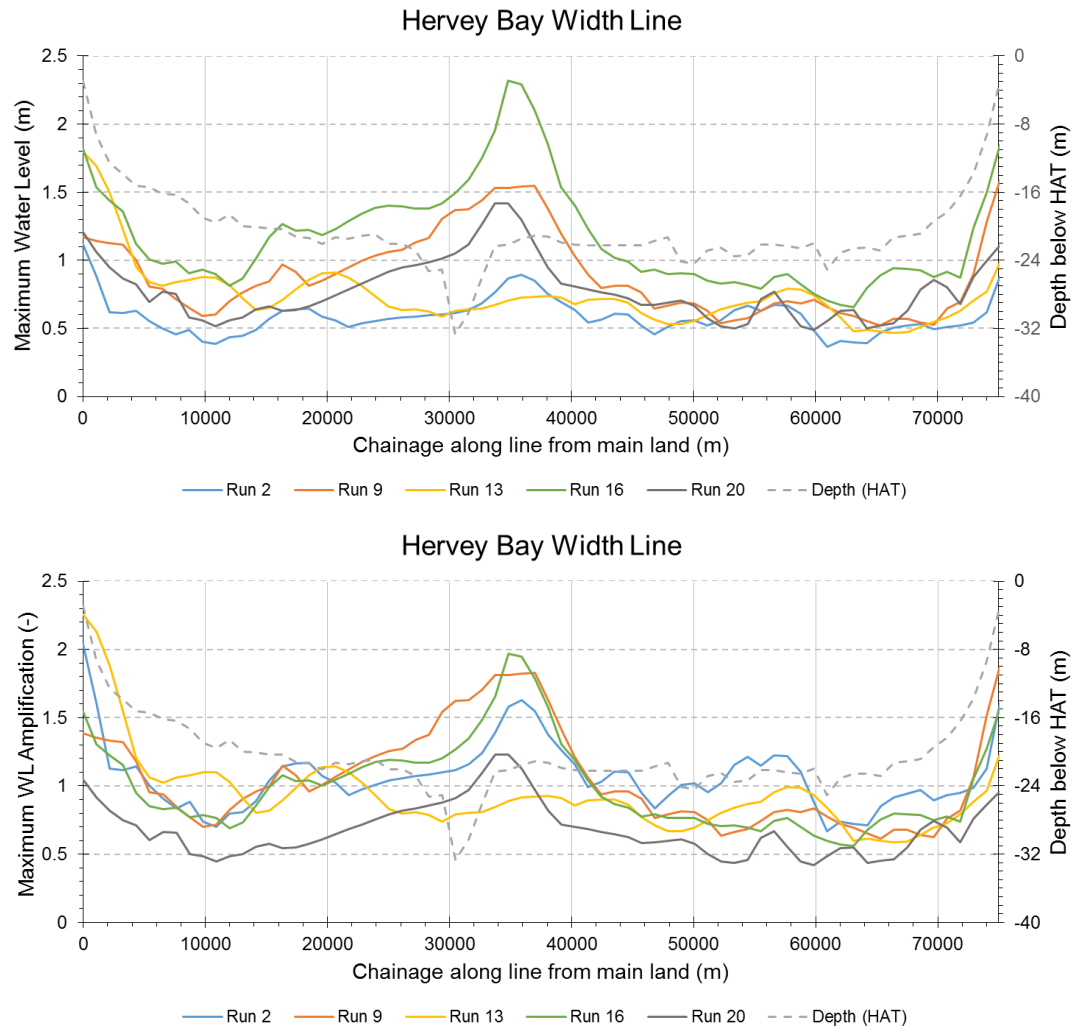


Figure 16 - Maximum water level (top) and amplification factor across the width of Hervey Bay (yellow line in Figure 14).

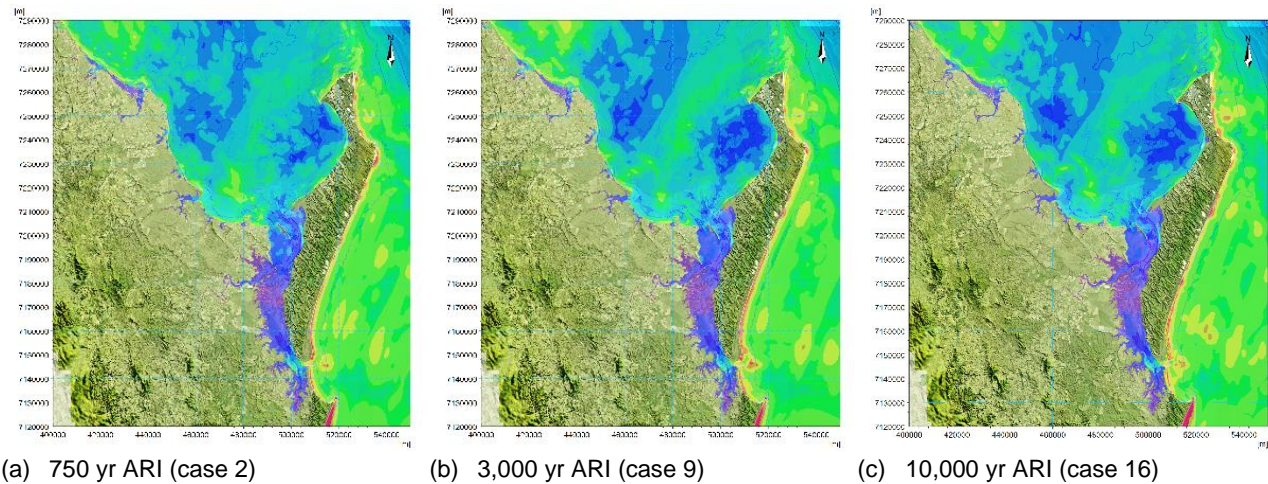


Figure 17 - Variation in amplification factor across ARI for events from Kermadec-Tonga.

8.1.3 Maximum Currents

Appendix F (refer Table 7) provides maps of the cell centred maximum depth-averaged current speeds for the worst case scenario of each ARI at HAT, being events from the Kermadec-Tonga subduction zone. Depth-averaged currents are greatest along the southern and northern extents of Fraser Island, the entrance to the Great Sandy Strait between Inskip Point and Fraser Island, and the exposed beaches of the Great Sandy National Park. At these locations currents speeds range from 2 metres per second (m/s) at 750 year ARI to 9 m/s at 10,000 year ARI. In the nearshore around populations from Urangan to Burrum Heads, current speeds increase from 2 m/s (750 year ARI) to 3 m/s (for 10,000 year ARI). Current speeds at Miara and Moore Park Beach reach speeds up to 4 m/s. Through the Great Sandy Strait between River Heads and Tinnanba, current speeds are low remaining below 0.5 m/s.

Areas identified as having a higher nearshore hazard (in terms of depth average current speeds) are in decreasing order of magnitude:

- Great Sandy National Park
- Inskip;
- Fraser Island (ocean side, south);
- Fraser Island (north side);
- Moore Park and Miara;
- Urangan to Burrum Heads;
- Woodgate; and
- Elliott Heads; and
- Wide Bay Training Area.

8.1.4 Arrival Times

Arrival times depend on a number of factors including the distance the tsunami needs to travel from its generation source, the depth of water it travels across, and interference from transoceanic propagation including trenches, seamounts and land masses. As tsunamis travel as shallow water waves across the open ocean, it is expected that arrival times will be similar at a given location for events from the same subduction zone, with some variations to account for differences in the particular fault zone location. Tsunamis will reach the ocean side of Fraser Island first where the continental shelf is the narrowest at Sandy Cape and Breaksea Spit.

Appendix E provides the arrival times of the positive leading wave for a number of locations and subduction zones. It is noted that the leading wave from the Kermadec-Tonga subduction zone will be preceded by a leading trough (negative wave). The tables have been categorised into broad regions: ocean side (Fraser Island and south); Hervey Bay and north; and rivers. In general, events from the New Hebrides have the shortest arrival time of just over 3 hours after the earthquake, while the events from South America have the longest travel times of 17 to 19 hours (depending on the fault location along the 5,900 km long Peru-Chile trench).

Another way to examine this data is to consider the time differences relative to first arrival within the study region, thereby removing variations associated with trans-Pacific travel times.

By calculating the travel time relative to arrival times to Sandy Cape, there is much less variation for a particular site for all events (refer tables 9-11), giving an indication of expected arrival times once the tsunami first reaches the coast. In general, once the tsunami reaches Sandy Cape, it will take between 1:05 and 2:30 hours for the tsunami to reach the mainland within the bay, and about 2:00 hours to reach Bundaberg within the Burnett River (Table 9). The variability indicated by the

standard deviation can be contributed to variations in wave forms (rapid versus slow rising) and signal strength (such as the weaker tsunami amplitudes within waterways).

The first arriving tsunami waves generated from Kermadec-Tonga for water level HAT Bay over all ARI for a point located offshore Fraser Island (longitude 153.19° E, latitude 25.61° S) at a depth of 41.7 m is shown in Figure 18. It is seen that the leading wave is not necessarily the wave with the highest amplitude, and that larger waves can potentially arrive hours after the initial wave.

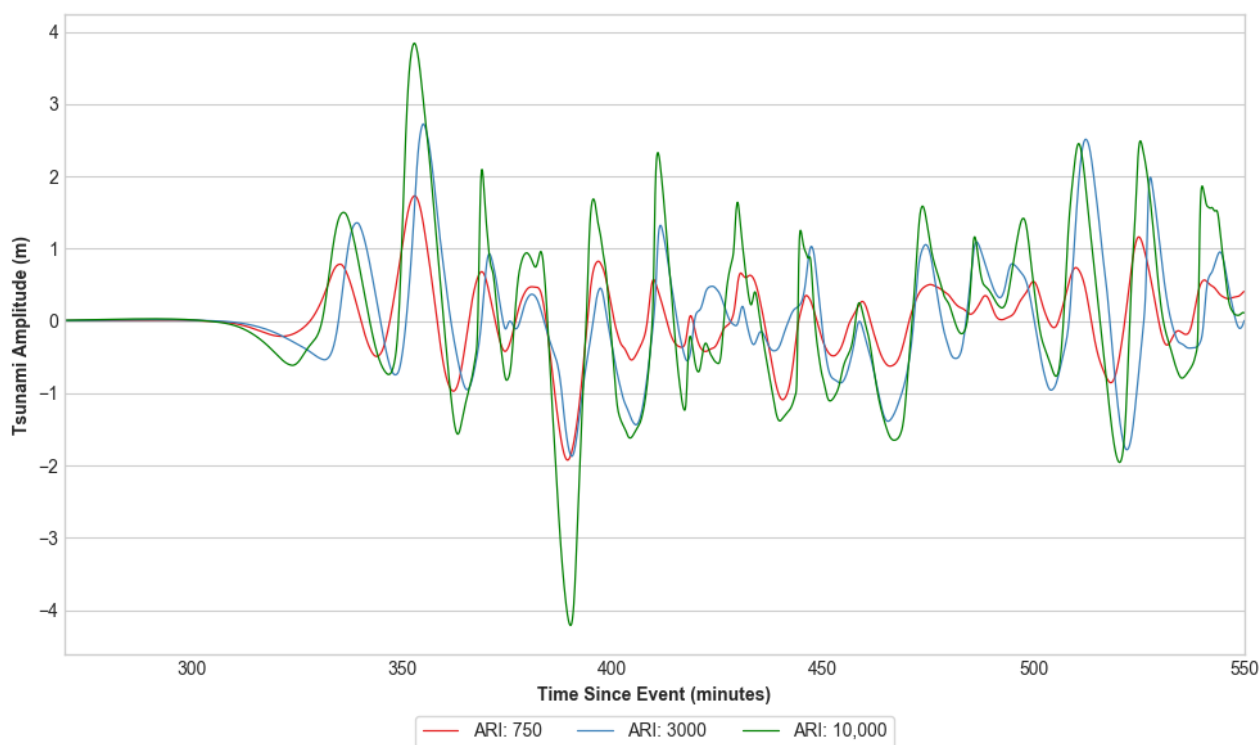


Figure 18 - Kermadec-Tonga wave heights by ARI offshore Fraser Island for water level at HAT Bay.

Table 9 - Variation in arrival time after arriving at Sandy Cape.

Region	Location	Arrival time (hrs:min)	
		Average	Std Deviation
Ocean Side	Beer Beer Creek	0:09	0:02
	Eurong	0:23	0:05
	Fraser Island	0:02	0:01
	Inskip	0:30	0:07
	Rainbow Beach	0:28	0:07
	Sandy Cape North	0:17	0:03
	Sandy Cape Outside	0:00	0:00
	South Fraser Entrance	0:34	0:06
Hervey Bay	Bargara	1:12	0:02
	Boonooroo	1:16	0:06
	Booral	2:05	0:03
	Burnett Heads	1:13	0:01
	Coral Cove	1:15	0:02
	Dundowran Beach	1:47	0:01
	Kingfisher Bay Resort	2:07	0:05
	Hervey Bay	1:51	0:01
	Iris River	1:48	0:02
	Moore Park	1:25	0:02
	Point Vernon	1:44	0:02
	Poona	1:06	0:05
	River Heads	2:27	0:02
	Tin Can Bay	1:13	0:06
	Toogoom	1:48	0:01
	Urangan	1:50	0:03
	Woodgate	1:35	0:01
Burnett River	Burnett River Entrance	1:20	0:02
	Bundabarg West	2:02	0:04
	Bundaberg Central	2:01	0:03
	Bundaberg East	1:56	0:03
Mary River	Mary river	3:07	0:05
	Maryborough	4:26	0:12

8.2 Location Specific

Below are specific comments that relate to particular areas within the study domain. Note that inundation maps provided in Appendix G (refer Table 7) are for the extreme upper-limit of the modelled scenarios for each ARI.

8.2.1 Rainbow Beach and Inskip Point

Although model results showed the largest waves across the study region occur along the beach to the southern side of Double Island Point, the presence of large coastal dunes mitigates inundation beyond the beach. The orientation of Rainbow Beach provides some sheltering from wave energy and combined with the coastal dunes, results show low levels of inundation along the beach and no inundation to the main Rainbow Beach town, which is located above RL 15 m AHD. To the north of the main town, there is increased inundation to a number of resorts on the ocean side with increased ARI. The modelled bathymetry shows the southern end of Rainbow Beach to be relatively deep close to the beach, reducing shoaling. Should the modelled bathymetry be incorrect, wave amplitudes may change.

The lower topographic elevation of Inskip Point and greater exposure to wave energy (see Section 8.1.1) results in significant levels of inundation which increase in extent with ARI, potentially impacting properties on Rainbow Shores Drive. Camp sites and recreational areas north of Rainbow Shores Drive, particularly along Inskip Point Road, are inundated for all ARI, including access to the barge to Fraser Island. The high wave heights and current speeds create a land and marine hazard.

8.2.2 Great Sandy Strait

The townships of Tin Can Bay, Tinnanbar, Poona, Tuan, Boonooroo and Maaroom located within the Great Sandy Strait show very little to no inundation occurring at MSL even during higher ARI scenarios. The inundation extents increase for HAT scenarios effecting coastal properties in these towns. The low variability in maximum water levels across all ARI through the Great Sandy Strait (ranging 0.25 to 0.5 m) suggests that increased inundation extents are mainly a result of increased water levels and not increased wave heights (this is discussed further in Section 9.1). The Strait south of Tinnanbar is still subject to maximum water levels of up to 2 m along the shoreline of the Wide Bay Training Area, as well as a considerable marine hazard.

8.2.3 Maryborough

Along the Mary River in Maryborough, model results show no inundation for MSL scenarios and small amounts of inundation for HAT scenarios with no variability between ARI. Inundation is contained to low-lying areas and to some river-front locations around the Mary River Marina. Current speeds in the Mary River are low remaining below 0.5 m/s. It is noted that the quality of the tsunami modelling up the waterways is highly dependent on the quality of the modelled bathymetry.

8.2.4 River Heads and Booral

Model results show no inundation for MSL scenarios at River Heads and Booral. Inundation extents increase for HAT scenarios, with no variability between ARI, but do not reach levels to impact any properties. It is noted that the marine hazard increases northwards of River Heads in terms of both maximum water levels and currents.

8.2.5 Urangan

Around Urangan, model results show small amounts of inundation for MSL scenarios at the Hervey Bay Boat Club. For HAT scenarios inundation occurs to coastal properties surrounding Urangan Pier. Inundation extents increase for higher ARI, and have a maximum extent of three street blocks, reaching inland to King Street south of Urangan Pier for ARI 10,000 year scenarios at HAT.

Although the marina is not modelled to a high resolution, model results suggest some amplification of water level and increase in current speed at the marina entrance creating a marine hazard. Maximum water level within the marina increases with ARI and is higher for MSL scenarios reaching 0.8 m for ARI 10,000 year. Current speeds across all stages of tide are comparable reaching 2 m/s at the entrance and 1.5 m/s throughout the marina for 10,000 year ARI scenarios.

8.2.6 Hervey Bay City

No inundation is seen along the coastline within Hervey Bay for MSL scenarios for all ARI. Inundation occurs for HAT scenarios, with extents increasing for higher ARI. Most significant inundation is in unpopulated regions between Point Vernon and Dundowran Beach, though some coastal bordering properties at Dundowran Beach and Torquay show some inundation for ARI 3,000 and 10,000 year scenarios.

8.2.7 Burrum Heads and Toogoom

Model results show no inundation for Burrum Heads and Toogoom for MSL scenarios for all ARI. Inundation occurs for HAT scenarios, with extents increasing for higher ARI. At Toogoom, properties on Moreton Street along Beelbi Creek are most at risk, with model results for 10,000 year ARI at HAT showing significant inundation. Similarly, properties at Burrum Heads along the Isis River show inundation, with greater inundation to properties along the beach due to greater exposure to wave energy.

8.2.8 Woodgate

No inundation occurs at Woodgate for MSL scenarios for all ARI. Inundation is minimal for HAT scenarios, effecting coastal bordering properties for ARI 3,000 and 10,000 year scenarios.

8.2.9 Bundaberg

Model results show no inundation occurring at Bundaberg for MSL and HAT scenarios across all ARI. There is some inundation of farmland off the Burnett River between Bundaberg and Burnett Heads, with the extent increasing for HAT scenarios and for higher ARI. Current speeds through Bundaberg in the Burnett River are low across all stages of tide and ARI remaining below 1 m/s. The quality of the results is only as good as the modelled bathymetry, which is limited within the river.

8.2.10 Elliott Heads to Nielsen Park

The population at Elliott Heads does not experience any inundation for MSL or HAT scenarios across all ARI.

The populations from Innes Park to Bargara do not experience any inundation for MSL scenarios across all ARI. Inundation is minimal for HAT scenarios, effecting coastal bordering properties for

ARI 3,000 and 10,000 year scenarios. There is also inundation of McCavanagh Street and Fred Courtice Drive.

There is some minor inundation at Neilson Park for higher ARI scenarios at MSL, which increases for HAT scenarios.

8.2.11 The Oaks to Burnett Heads

The Oaks experiences some minor inundation of coastal properties at MSL for the 10,000 year ARI events. Coastal properties along Shelley Street are inundated for all ARI at HAT.

At Burnett Heads inundation is limited to coastal bordering properties at Port Bundaberg and Bundaberg Port Marina along the Burnett River for MSL scenarios across all ARI. Current speeds at the Burnett River entrance create a marine hazard for all stages of tide ranging from 0.8 m/s at 750 year ARI to 3.2 m/s at 10,000 year ARI. Higher current speeds occur at narrow tributary and marina entrances, such as the Jan McDonald Bicentennial Park marina entrance. Inundation extents increase for HAT scenarios and are larger for higher ARI having greatest impact in low elevation areas which are mostly unpopulated, though there are properties around Zunker Street on the ocean side and Power Street at Port Bundaberg which are at risk in these scenarios.

8.2.12 Moore Park and Miara

Model results show inundation to coastal bordering properties at Moore Park in the north at Royal Palms Estate Park and in the south situated near Wetlands Reserve for the MSL scenario at 10,000 years ARI. For HAT scenarios the inundation extent greatly increases impacting a larger number of properties at 750 year ARI and inundating the entire town for 10,000 year ARI scenarios. The higher wave energy offshore of Moore Park (see Section 8.1.1) in combination with the low-lying lands increase the risk of inundation at Moore Park. Across Yandaran Creek, Miara Caravan Park is susceptible to inundation for all scenarios (MSL and HAT).

8.2.13 Fraser Island

The ocean side of Fraser Island has greater exposure to tsunami waves, and being popular recreational areas they create land and marine hazard due to high wave heights and high current speeds (see Section 8.1). Coastal dunes provide protection, thus limiting the inundation extent beyond the beach, though there remains a risk for beach camping grounds with lower dune elevations, or gaps between dunes, and to the frequented ocean side 4WD tracks.

The Fraser Island community located on the north-east of the island is adequately protected showing no inundation for all model scenarios, though the nearby Waddy Point Beachfront Campground shows risk of inundation for both MSL and HAT scenarios. For MSL scenarios, model results show run-up levels at 750 year ARI of up to 3 m AHD increasing to 30 m AHD for 10,000 year ARI. For HAT scenarios, run-up levels show little variability between ARI reaching up to 35 m AHD.

Kingfisher Bay resort is protected for all MSL scenarios, but has some inundation of some complexes closer to the coast for HAT events above 750 year ARI as shown in Figure 19.

The access track at the southern end of Fraser Island is also at risk of inundation for both 3,000 and 10,000 year ARI at HAT.

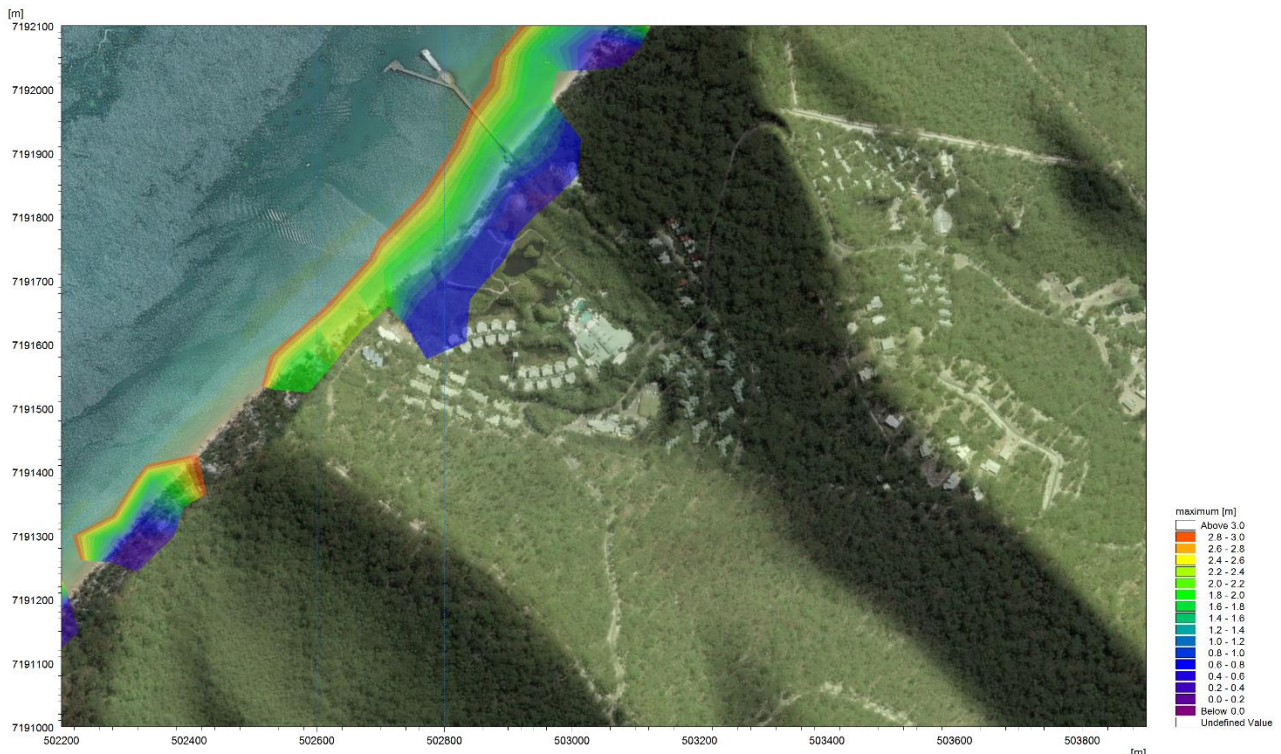


Figure 19 - Inundation extent at Kingfisher Bay Resort for 3,000 year ARI at HAT Bay (run 9).

8.3 Climate Change (Sea Level Rise)

Although expected climate change outcomes relate to meteorological changes, the increased water level due to sea level rise (SLR) may increase tsunami amplitudes (see Section 9.1), and will make low-lying areas more susceptible to inundation.

Models were conducted with SLR included for the 10,000 year ARI Kermadec-Tonga HAT scenarios (Table 5). The inclusion of SLR has minimal change to the spatial distribution and values of maximum amplitudes when compared to lower tide level model runs. SLR does significantly increase the inundation occurring throughout some of the study region. Notably this is mostly limited to uninhabited low-lying areas off tributaries or within wetlands, though there are locations which experience greater levels of inundation than the extents identified in Section 8.2. These include Poona, Boonooroo, Maaroom, Hervey Bay City to Burrum Heads, Woodgate, Elliott Heads to Burnett Heads, Moore Park, Miara, Inskip, and the southern end of Fraser Island.

Note that the inclusion of SLR does not account for the geomorphological change which the coastlines would endure during this process.

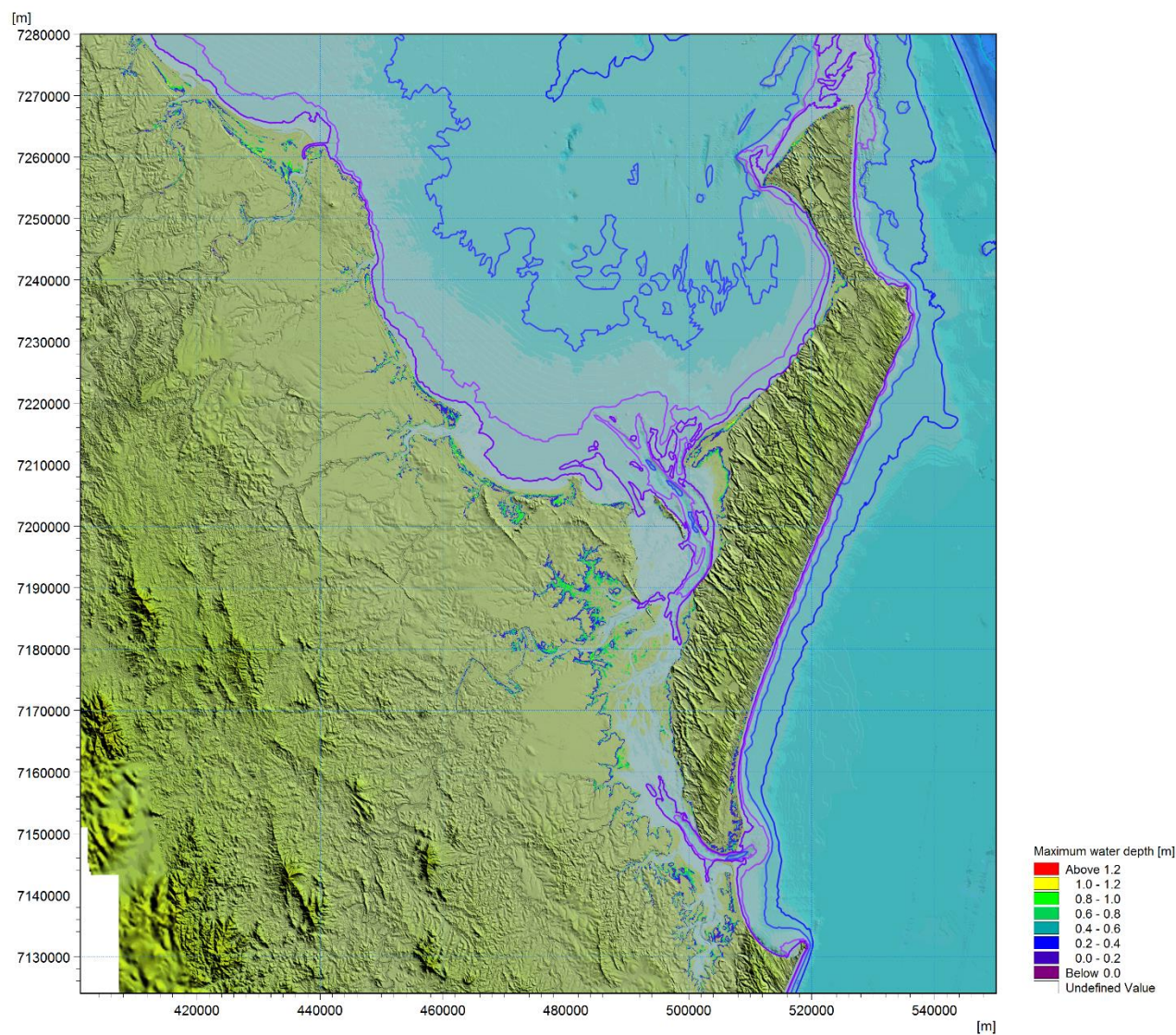


Figure 20 - Increase of inundation extent for SLR condition (run 18 relative to run 16).

9 Discussion

9.1 Stage of Tide

Modelling undertaken of three still water levels (SWL) allows us to consider the influence of the stage of tide on tsunami inundation for the study area. The distribution of maximum water levels of the same 10,000 year Kermadec-Tonga scenario over the different SWL is shown in Figure 21. The histograms show a count of the maximum water level that occurs during the modelled scenario for each respective mesh element in the model (Section 5.4). Mesh elements which did not experience any deviation in water level (threshold level below 0.01 m) are not included in each respective plot, resulting in a difference in the total amount of elements included in each histogram. Overland elements that are not above this threshold can be considered to have not been flooded indicating no inundation.

The histograms show two distinct peaks: one below 0.5 m and another around or slightly above 1 m. This pattern is consistent across all SWL, with noticeable increases in the lower peak counts for increasing SWL. For maximum water levels above 2 m, the distribution across all the tide levels are similar with increases in maximum water level counts between 2 and 4 m for increasing SWL. As SWL increases, the right side of the diagram resembles a Gaussian distribution with a positive skewness and kurtosis.

This is consistent with the spatial distribution of maximum water level for these scenarios (see GIS Database as referred to in Table 7), where the first peak is most likely contributable to the consistency in water levels with increasing SWL and ARI within the Great Sandy Strait, and the second peak associated with slight increases with the bay. The tail is therefore associated with increases occurring outside and to the north and south of Hervey Bay.

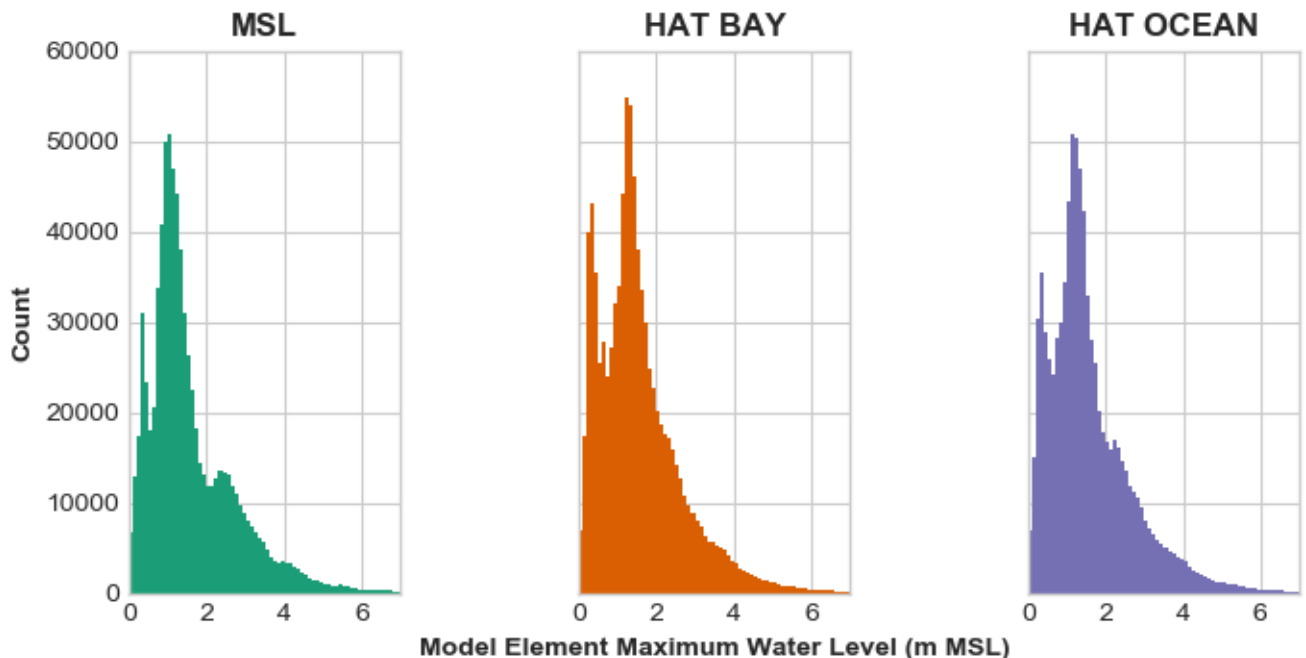


Figure 21 - Kermadec-Tonga 10,000 year (Event ID 35360) modelled maximum water levels across study region by stage of tide.

Figure 22 shows a comparison of amplitudes for the different SWL at locations outside (same as Figure 18) and inside Hervey Bay (longitude 153.00° E, latitude 25.30° S, depth of 21.7 m). The effect of the stage of tide on wave height is less noticeable outside of Hervey Bay compared to inside. Within the bay there is increased attenuation and lag with decreasing SWL, owing to the shallower depths within Hervey Bay leading to increased sensitivity to friction.

Therefore, it can be concluded that the main factor contributing to increases in inundation is the stage of tide (2.2 m difference between MSL and HAT within the bay), allowing for increased tsunami inundation in low-lying areas. Although tsunami amplitude is relatively lower within Hervey Bay, the higher water level increases tsunami amplitudes within the bay, which will also contribute to the increased inundation.

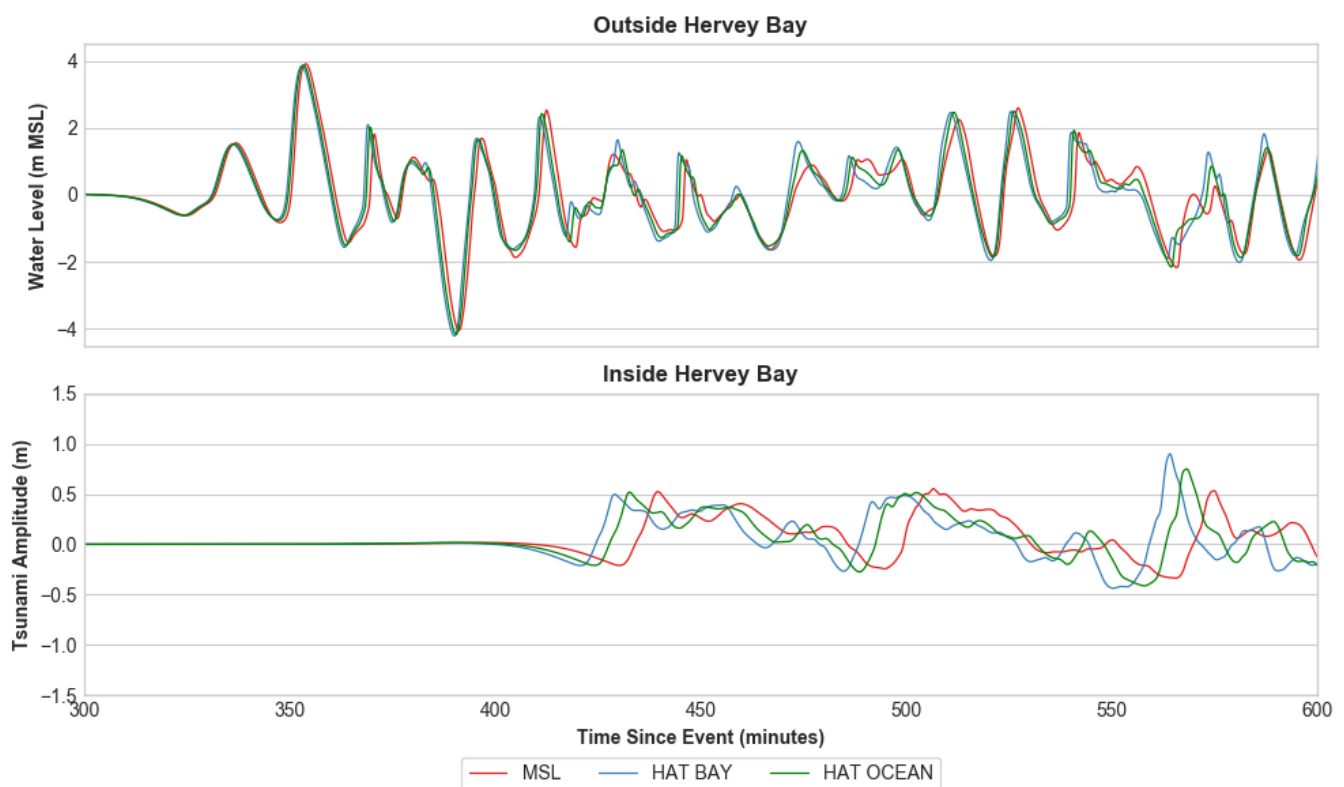


Figure 22 - Kermadec-Tonga 10,000 year (Event ID 35360) wave height by stage of tide at a location outside and inside of Hervey Bay.

Mofjeld (2007) examined the influence of tides on the maximum water level by superimposing theoretical tsunami wave time series based on an exponential decay coefficient of 2 days over a duration of five days (based on measurements within the Pacific Ocean), on tides typical for Oregon, USA. The results showed that for small tsunami amplitudes, the maximum water levels tend to occur near mean higher high water with little spread. As the tsunami increases, the maximum water level tends towards a limit of MSL plus the tsunami amplitude (for tsunami amplitude > tide range). Although the principle of an exponentially decaying tsunami time series may be applicable in the open Pacific Ocean, the nearshore tsunami time series in this study is complicated by interaction of reflections, shelf trapped waves and coastal trapped waves. The approach undertaken in this study is considered to provide a conservative result.

9.2 Offshore Boundary

The location of the offshore boundary has been based on the output locations from the draft revised PTHA. Stages 1 (Boswood, 2013a) and 2 (Boswood, 2013b) relied on the original TsuDAT product provided by GA (refer Section 5.2.3), which provided stage and momentum time series at the 100 m depth contour at MSL. The revised draft PTHA provides more flexibility of event output locations. For the current study, the 1000 m depth contour was considered given the close proximity of the continental shelf to Fraser Island, particularly at Seabreak Spit.

Examination of model results has shown the presence of shelf trapped waves, an example of which is provided in Figure A. 9. Although the 1000 m depth contour allowed for the development of this phenomena, issues arose with downscaling as the finer model mesh created high irregularities along the boundary that were a source of instability and iterative adjustment. These irregularities are due to the numerous canyons that incise the continental slope, as illustrated in Figure 23.

To assure that these processes can develop within the model domain and to limit numerical instabilities, it is suggested that the offshore boundary for tsunami modelling within Queensland is situated offshore of the continental shelf. Similarly, the lateral boundaries should be of sufficient distance away from the model domain to allow the development of shelf and coastal trapped transient waves.

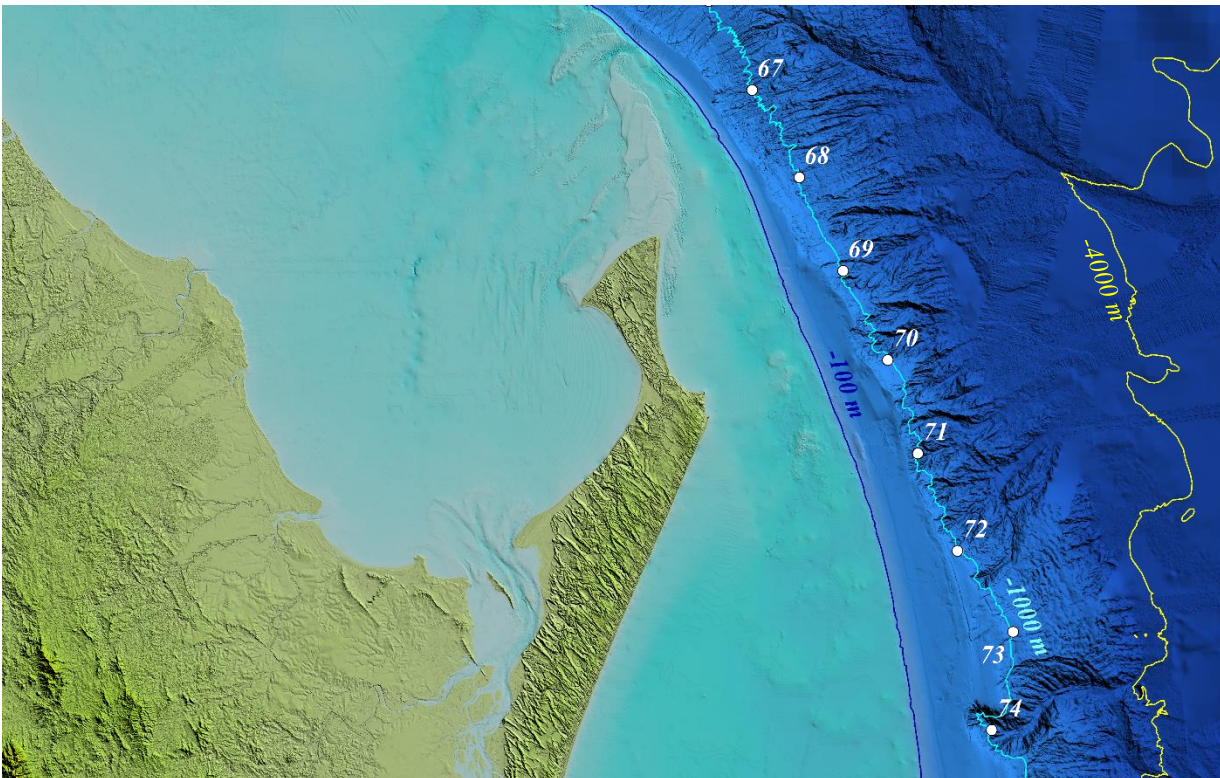


Figure 23 - Continental shelf off Fraser Island (dots represent PTHA points).

9.3 Undular Bores (Short Waves)

During the 2004 Indian Ocean tsunami, media reports showed what appeared to be a series of waves approaching the coast of Thailand (refer to Figure A. 16). Research has shown that these shorter period waves are in fact riding on top of the underlying tsunami, and are produced when the front face of the tsunami wave becomes steep enough to disintegrate into an undular bore with

short and steep transient waves of periods in the order of 10 to 15 seconds. Madsen et al. (2008) were able to reproduce this phenomena with the aid of a high order Boussinesq numerical model with a grid spacing of 10 metres. They also concluded that although these transient waves will have an impact on coastal structures, the run-up and inundation that occurs is a result of the underlying longer period tsunami.

The computational demand of such models precludes their use on a large scale. However, closer inspection of the time and line series from the modelled water levels can give an indication based on the steepness of the front face of the wave.

Figure 24 provides snapshots (in elapsed time) of tsunami wave profiles along a line through Hervey Bay and offshore of Moore Park beach. The profiles are complicated by the interaction of incident and reflected waves but as can be seen, the waves are asymmetric with steep front faces. It is possible that these conditions are conducive to the formation of undular bores.

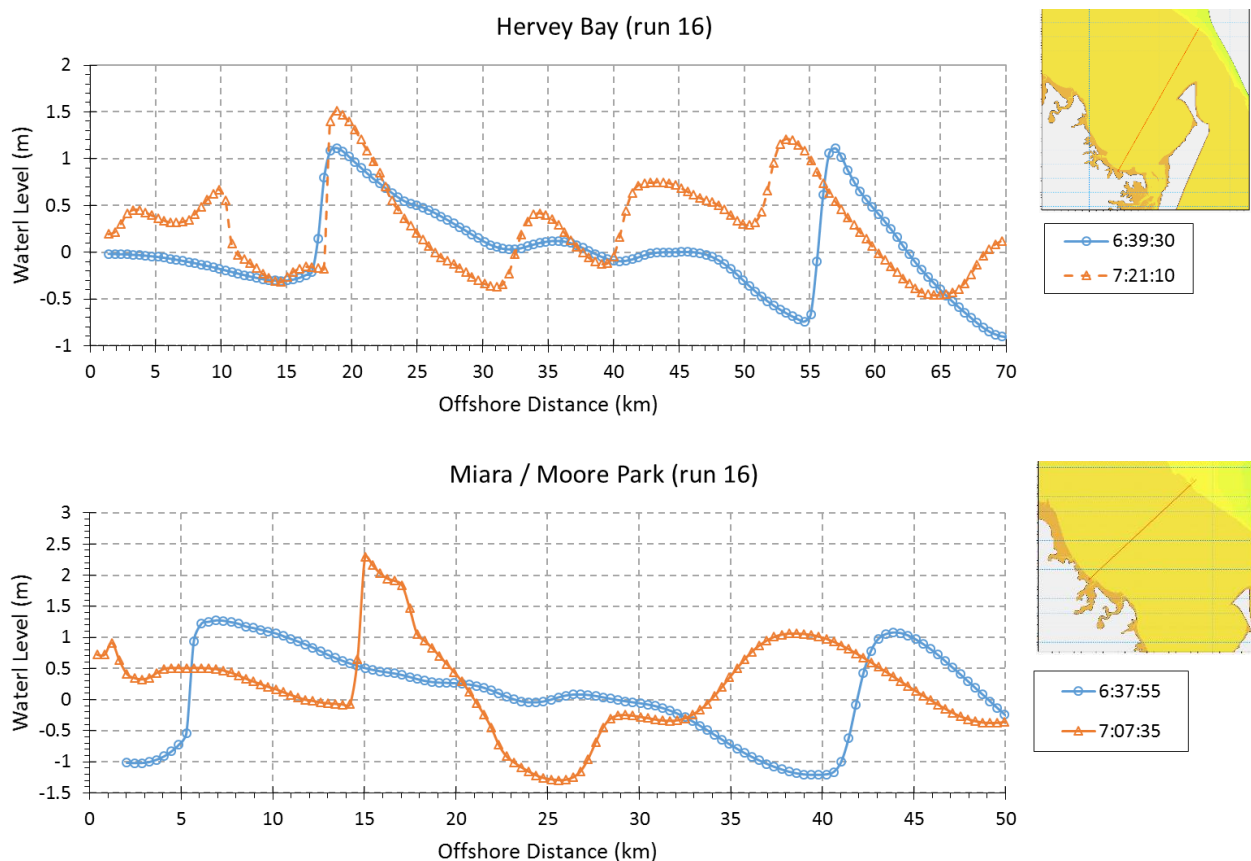


Figure 24 - Tsunami wave profile snapshots during run 16 through Hervey Bay (top) and off Moore Park (bottom).

9.4 Sub-grid Structures (Urangan and Burnett Heads Example)

Modelling is a balance between mesh resolution and computation times. Reducing the spatial distance between nodes by half will introduce four times more mesh elements and can significantly increase computational times. Coastal management structures such as breakwaters are designed to provide shelter from short period waves in their lee, thereby providing protection to vessels or the coastline. Murata et al. (2010) advise that small scale features such as detached breakwaters do not provide protection from tsunamis given their size is small relative to the tsunami wavelength,

and their crests are typically too low to block tsunamis. Therefore their impact on inundation extents is limited. Mesh resolution within the study area was selected to replicate tsunami propagation characteristics to the coast, and inundation at a typical property block scale.

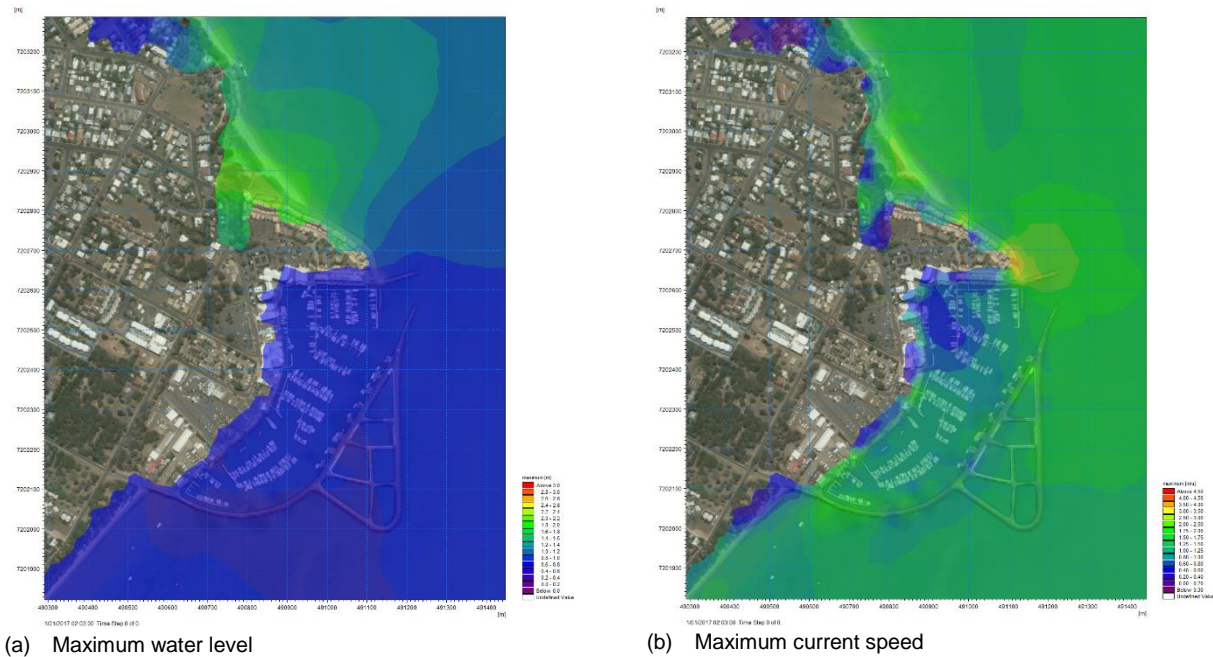


Figure 25 - Maximum water levels and currents in the vicinity of the Urangan marina for run 16 (Kermadec-Tonga, 10,000 year ARI)

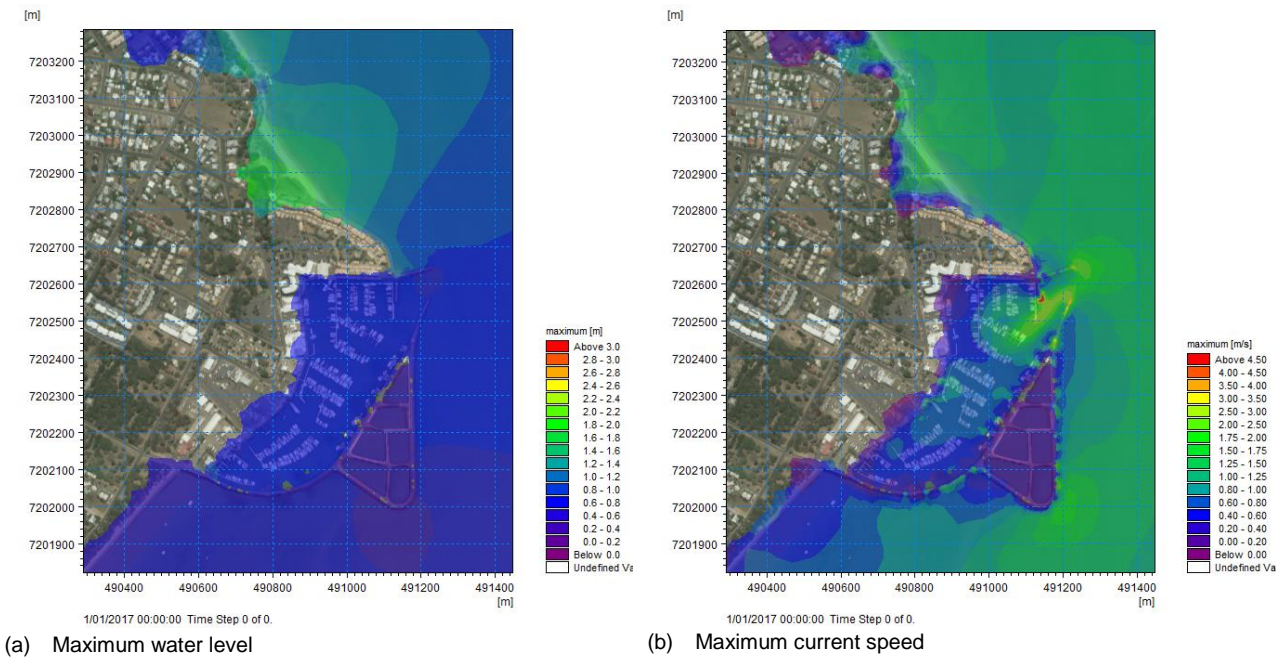


Figure 26 - Maximum water levels and currents in the vicinity of the Urangan marina for run 16 after mesh refinement (Kermadec-Tonga, 10,000 year ARI)

Mesh resolution at the Urangan marina and Burnett Heads marina are typically about 100 m, reducing to 30 m on the coastline. Therefore subscale size features such as the breakwaters at both marinas are not fully resolved. To test that the adopted mesh resolution is sufficient for the current study, an additional model run was undertaken for run 16 with a further refinement of the mesh in the vicinity of the Urangan and Burnett Heads marinas down to 20 to 30 m. As can be seen from Figure 25 to Figure 28, the refinement of the breakwaters has little impact on the

tsunami amplitudes though do impact currents. Urangan shows a decrease in currents within the marina but an increase in the vicinity of the entrance. This suggests that current speeds may be higher than modelled through entrances to marinas and harbours, but lower within these features. Similar results are seen at Burnett Heads though less pronounced, which is likely due to the marina entrance being parallel with the dominant current flow direction.

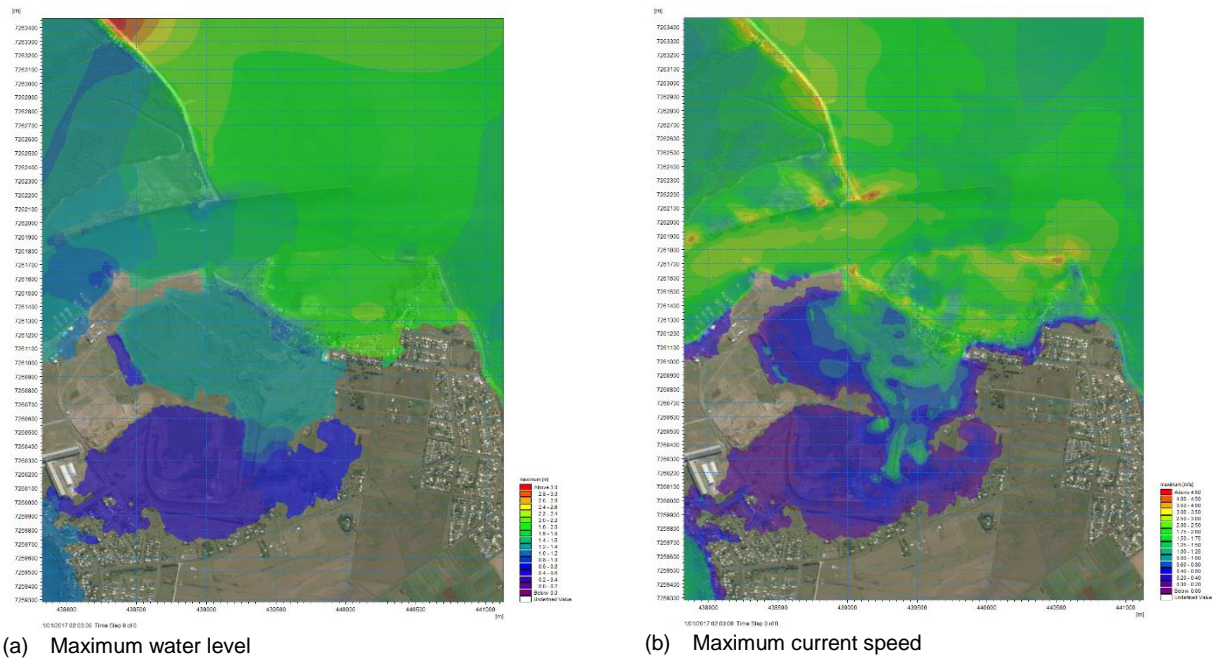


Figure 27 - Maximum water levels and currents in the vicinity of the Burnett Heads breakwater for run 16 (Kermadec-Tonga, 10,000 year ARI)

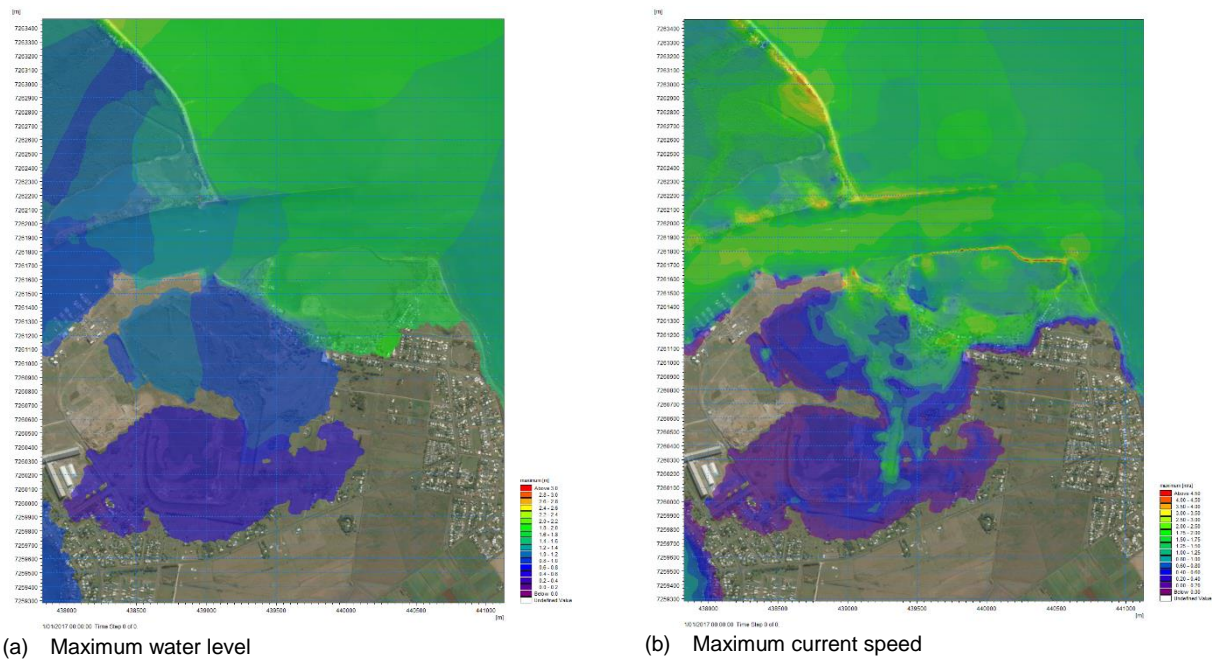


Figure 28 - Maximum water levels and currents in the vicinity of the Burnett Heads breakwater for run 16 after mesh refinement (Kermadec-Tonga, 10,000 year ARI)

9.5 Community Vulnerability

Although a complete exposure, vulnerability and risk assessment is beyond the scope of this study, it is useful to examine metrics that would assist disaster managers in assessing their risk. The vulnerability of a community to tsunami hazard can be categorized into physical, social, economic, and environmental (UNESCO, 2015 and UNISDR, 2017). The physical aspects relate to factors such as human casualties, building damage and loss of infrastructure. The concept and quantification of vulnerability is well understood for other water hazards that occur more frequently such as riverine flooding and storm surge (refer Section A.5).

Research into vulnerability measures for tsunami hazard has mostly developed post 2004, but particularly following the 2011 Great East Japan tsunami. As such, the tsunami community is still in the early stages of understanding how to quantify the physical and social vulnerability. Building vulnerability research has focused on developing empirical damage or fragility functions (probability of exceeding a given damage state based on a measure of tsunami intensity) for a range of structure types and predefined damage states based on post event assessments and laboratory experiments. However, there is still a degree of uncertainty associated with the fragility estimations as well as variability for different locations, limiting their generic use (Charvet et al., 2015). This is affected by a number of factors including the current state of understanding of the primary tsunami intensity measures, variability in the classification and assessment of building type and damage state, variability in building quality, locality specific influences (bathymetry, topography, typology), incomplete field survey databases, and the statistical approaches adopted (Charvet et al., 2017). They also do not capture all failure mechanisms such as debris impact, foundation scour and liquefaction. Further information is provided in Section A.5.2.

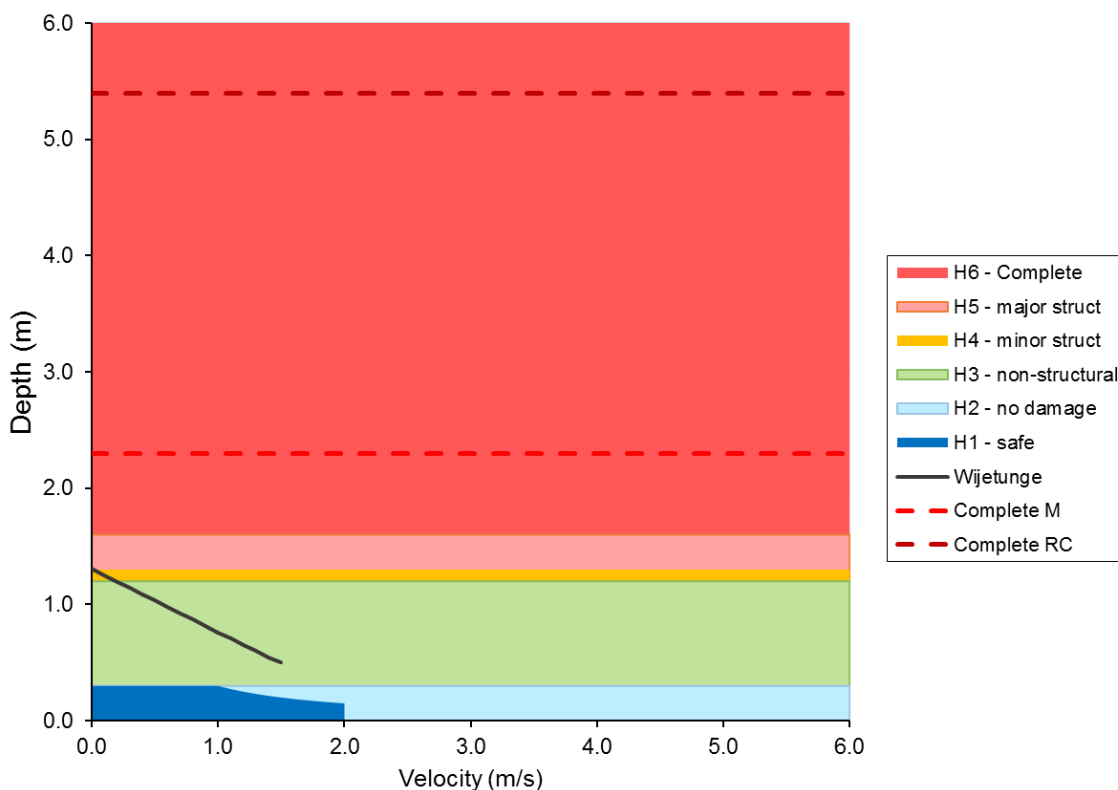


Figure 29- Combination of general vulnerability curves for tsunami inundation.

UNESCO (2015) provides some generic median damage states from Nanayakkara and Dias (2013) for single-storey buildings constructed from commonly used materials based on inundation

depth. Figure 29 summarises these based on the lower limits for timber structures. Complete damage for masonry (M) and reinforced concrete (RC) are also shown as lines. The figure also includes the human stability criteria from Wijetunge (2009), based on the experimental results of Takahashi (2005). Further detail is provided in Section A.5.2.

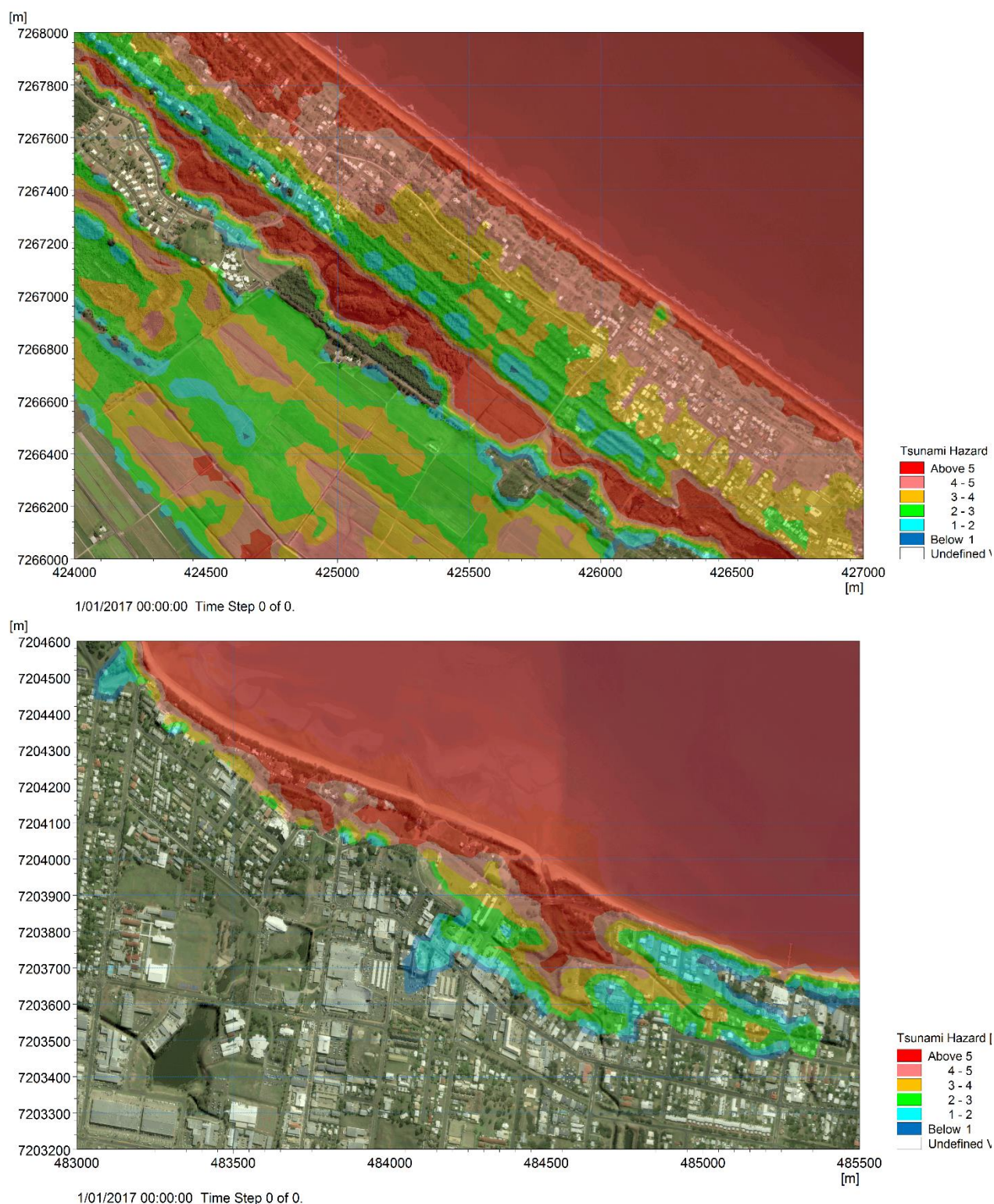


Figure 30 - Example of application of hazard levels for run 16 at Moore Park (top) and Torquay.

Figure 29 represents the median state based on data from Sri Lanka and Thailand during the 2004 Indian Ocean tsunami, as well as Samoa during the 2009 South Pacific tsunami. Therefore it may

not be suitable for locations with different building standards and typology (refer Section A.5.2). However, it provides a general indication of potential vulnerability. Figure 30 demonstrates the vulnerability based on this criteria for run 16 at two of the higher hazard locations: Moore Park and Torquay.

Further research is required into developing tsunami vulnerability curves specific for the Australian built environment. Should overland flow velocity become an important variable, then a finer model mesh may be required to resolve velocity patterns around buildings.

9.6 Marine Hazard and Vulnerability

Although tsunami inundation is perhaps the most considerable and obvious risk to the public, there can still be significant damage to maritime facilities from events that do not pose an inundation threat. Within ports and marinas, maritime assets are vulnerable to significant damage from strong currents and associated drag forces (Lynett et al., 2014).

Lynett et al. (2014) undertook a review of recorded vessel damage against measured and modelled tsunami current speeds within ports and harbours predominantly in California following the 2010 Chile and 2011 Great East Japan tsunamis, to note distinct damage thresholds as summarised in Table 10. Further detail is provided in Section A.5.1.1.

Table 10 - Marine facility damage classification from Lynett et al. (2014).

Damage Index	Damage Type	Threshold Velocity (m/s)
0	no damage/impacts	<1.5
1	small buoys moved	<1.5
2	1–2 docks/small boats damaged and/or large buoys moved	1.5
3	Moderate dock/boat damage (<25% of docks/vessels damaged) and/or midsized vessels off moorings	1.5
4	Major dock/boat damage (<50% of docks/vessels damaged) and/or large vessels off moorings	3
5	Extreme/complete damage (>50% of docks/vessels damaged)	4.6

The above criteria was applied to the maximum current speeds for run 16 (refer Figure 31), showing the potential for extreme marine damage along the open coastline of Fraser Island and some areas north of Burnett Heads.



Figure 31 - Example of marine vulnerability for run 16, based on the criteria of Lynett et al. (2014).

10 Conclusion and Recommendations

The tsunami modelling undertaken has given a better understanding into tsunami propagation and potential inundation for Hervey Bay and the Fraser Coast region, including identification of regions of higher hazard exposure. Although the mean recurrence intervals (ARI) selected are quite high, it is important to consider the confidence limits associated with these estimates. For example, the mean 100 year ARI event is about 0.2 m, but could be between 0.07 and 0.5 m. The upper limit being only 5 centimetres below the mean 750 year ARI. Below are some key learnings from the study:

- Across all ARI, tsunami events generated from the Kermadec-Tonga subduction zone resulted in the most extreme wave amplitudes, current speeds and inundation levels for the modelled scenarios.
- The hazard is significantly greater on the ocean side of the Fraser Island that protects Hervey Bay and Bundaberg, producing a significant marine and land hazard with maximum currents up to 9 m/s and maximum water levels up to 7 m. The exposed Great Sandy National Park showed the highest water levels of up to 10 m.
- Tsunamis propagate into the Great Sandy Strait through the passage between Inskip Point and Fraser Island to the South, and through refraction occurring on the northern extents of Fraser Island. Dangerous currents can develop through the southern passageway.
- The hazard is reduced on the bayside of Fraser Island, with little hazard at Bundaberg and through the Great Sandy Strait, and some increased land and marine hazard around Hervey Bay City and Moore Park where maximum water levels can reach 3 m and currents up to 4 m/s.
- Arrival times are governed by the subduction zone from which they were generated. Those from New Hebrides have the shortest arrival time of just over 3 hours, while events from South America arrive much later at over 17 hours.
- Once the leading wave reaches Sandy Cape and Breaksea Spit, the additional time it takes to reach mainland locations is consistently between 1 and 2.5 hours, and 2 hours to reach Bundaberg within the Burnett River.
- The first wave is not necessarily the largest. The largest wave may occur several hours after the leading wave reaches the coast.
- The stage of tide will significantly influence inundation along the mainland and especially within the Great Sandy Strait, with minimal inundation for tide levels below mean sea level.
- Strong currents can develop around coastal protection structures, canals and marinas.
- Maximum water levels within the Burnett River and Mary River range between 0.3 to 0.7 m and 0.3 to 0.9 m respectively across all model runs with low standard deviations of 0.1 and 0.2 m.
- Although not modelled, there is the potential for shorter steep waves to travel on top of the underlying tsunami in areas where the tsunami wave steepens significantly (particularly close to the coast at Moore Park and approaching Hervey Bay just north of Fraser Island).

- Sea level rise associated with climate change may increase inundation extents at mainland locations, which warrants consideration in vulnerability studies from climate change. The areas at most risk include Poona, Boonooroo, Maaroom, Hervey Bay City to Burrum Heads, Woodgate, Elliott Heads to Burnett Heads, Moore Park, Miara, Inskip, and the southern end of Fraser Island. However the actual impact will depend on the geomorphological change of the coastline which was not considered in this study.

Based on the modelling undertaken, the areas identified as having a greater marine hazard (based on maximum water level and currents) are grouped below in decreasing order:

- Great Sandy National Park;
- Fraser Island (ocean side);
- Inskip Point;
- Rainbow Beach;
- Moore Park and Miara;
- Woodgate Beach; and
- Hervey Bay City; and
- Wide Bay Training Area.

In general, the majority of the coastline will experience some inundation, especially at higher ARI and HAT levels. This may be restricted to coastal properties in low lying areas being more susceptible at the higher tide levels. The communities identified as having a greater land hazard (based on inundation extent) are:

- Camping and recreational areas at Rainbow Beach, Inskip Point and Fraser Island (ocean side);
- Moore Park and Miara;
- Dundowran Beach;
- Torquay;
- Toogoom;
- Burnett Heads; and
- Urangan.

The locations identified at Rainbow Beach, Inskip Point and the ocean side Fraser Island experience some inundation for the MSL cases, whereas the other locations are more exposed at higher tide levels.

The developed overland DEM is a bare earth model in that only ground points have been included, thereby removing all structures and vegetation. The influence of these features on inland inundation is introduced implicitly by the introduction of roughness factors. The DEM is also assumed to be static and non-erodible. Should a tsunami cause erosion of the dune system, then the extent of inundation may differ to these model results. The hazard considered relates to potential inundation and broad-scale depth-averaged currents. There may be additional impacts associated with the tsunami such as coastal erosion, which have not been addressed with this study.

The events selected represent the mean of the maximum water levels for the chosen ARI based on the draft revised PTHA as of February 2018. Higher levels can occur within the 95 per cent confidence limits. Also, any changes to the PTHA since February 2018 may influence the outcomes of this report. Disaster managers may wish to consider appropriate factors of safety in making any decision based on the information provided through this study.

Overall, the study provides planners and disaster managers a better understanding of the potential tsunami hazard to coastal communities within and around Hervey Bay.

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Appendix A – Tsunami Dynamics

A.1 Introduction

To better understand tsunami hazard, this section will briefly describe the processes that influence tsunamis. In basic terms, a tsunami is a series of long period waves generated by a disturbance in the ocean water column arising from abrupt geophysical events. These disturbances are more likely from movement of tectonic plates along faults in the form of submarine earthquakes, but could also be from submarine landslides, volcanic eruptions or a possible meteorite strike (in the extreme). More than 80 per cent of the world's tsunamis were caused by earthquakes (IOC, 2016). The earthquake scenario is the focus of this report.

A simple analogy would be dropping a pebble in a pond. The pebble generates a deformation of the water surface. This in turn creates a wave or series of waves that radiate or spread away from the source in concentric circles of increasing circumference as they propagate away. As the circumference increases, the amplitude decreases or attenuates due to energy being transferred along the wave crest. In reality, tsunami generation is not a point source but a complex pattern of bed movements. The three main phases are tsunami generation, propagation, and run-up/inundation. These phases will be briefly described below.

The following discussion has attempted to keep the subject matter as basic as possible. However, the topic itself can be complex, and so there is a need to provide some technical content for completeness.

A.2 Tsunami Generation

A.2.1 Earthquake

The main source of tsunamigenic earthquakes (that is, capable of generating tsunami) that have notable effects on Queensland come from the so called “Ring of Fire”, also referred to as the circum-Pacific seismic belt. It is a collection of oceanic trenches, volcanoes and plate movements along the rim of the Pacific Ocean, and is responsible for about 70 per cent of the world's tsunamis (IOC, 2016). There are three types of plate boundaries: convergent boundaries (where two plates are colliding); divergent boundaries (moving apart); and transform boundaries (plates sliding horizontally passed each other) (refer Figure A. 1). The oceanic crust of a convergent boundary is denser than the continental crust and will be thrust beneath the continental shelf to form subduction zones. Friction between the plates opposes movement until energy build up causes the plates to suddenly slip past one another, generating an earthquake. The surface where the slip occurs is referred to as the fault and energy radiates outward from the fault in all directions in the form of seismic waves that can last for minutes. The magnitude of the earthquake is related to the length of the fault and the amount of slip. The location or epicentre and time of initiation of the earthquake can be determined from triangulation of available seismogram recordings based on the primary (P-wave) and secondary (S-wave) waves (Kayal, 2006 and USGS, 2018a).

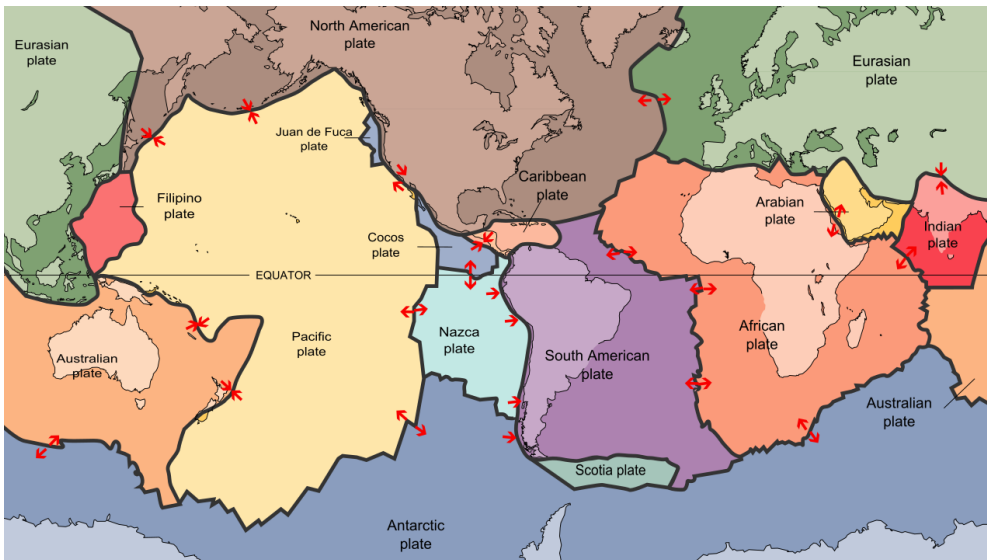
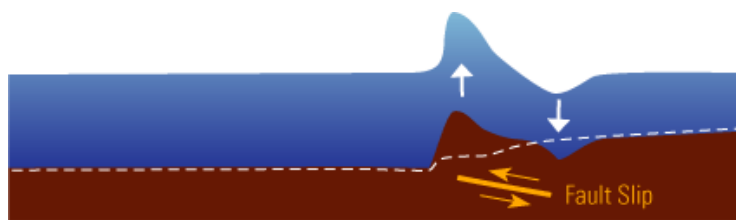


Figure A. 1 - Tectonic plates (source: <http://pubs.usgs.gov/publications/text/slabs.html>).

In general, a subduction zone slip results in the leading edge of the overriding plate (typically the continental plate) breaking free from its grip with the inducing plate, and to spring seaward. This generates a vertical rise in the full water column, which splits to propagate as a tsunami in all directions (refer Figure A. 2). Although the tsunami will propagate out in all directions from the generating area, the main energy propagation is generally orthogonal to the direction of the earthquake fracture zone (IOC, 2016).



(a) Initiation of tsunami from seabed deformation.



(b) Tsunami wave splits and radiates out from subduction zone.



(c) Deep water wave travels faster, whilst shallow wave shoals.

Figure A. 2 - Tsunami generation (distorted scale) (source: <https://walrus.wr.usgs.gov/tsunami/basics.html>)

As well as the uplift of the seabed, there can also be some subsidence of the overriding plate as shown in Figure A. 2. Communities that experience the tsunami on the continental shelf side (right in Figure A. 2) will experience a drawdown of the ocean prior to the tsunami reaching the coast. Communities to the left will not experience a drawdown prior to the tsunami. However, this is a simplified explanation, and a number of factors will influence tsunami generation.

A commonly adopted model for tsunami generation is to discretise the fault area into rectangular sub-faults. The deformation of the seafloor is then defined for each sub-fault by the use of a planar fault model (Okada 1985 and 1992), which considers parameters such as the depth below the seabed, orientation, and slip (Yamazaki, 2010). For specific events, tsunami waveform inversion analysis such as that proposed by Satake (1987) are used to estimate fault slip distribution (Adriano et al., 2018), as illustrated in Figure A. 3 for the 2016 Fukushima earthquake. The fault model as well as the initiation and rise time for each sub-fault are then used to determine the temporal and spatial seabed deformation, which is translated to sea surface displacement.

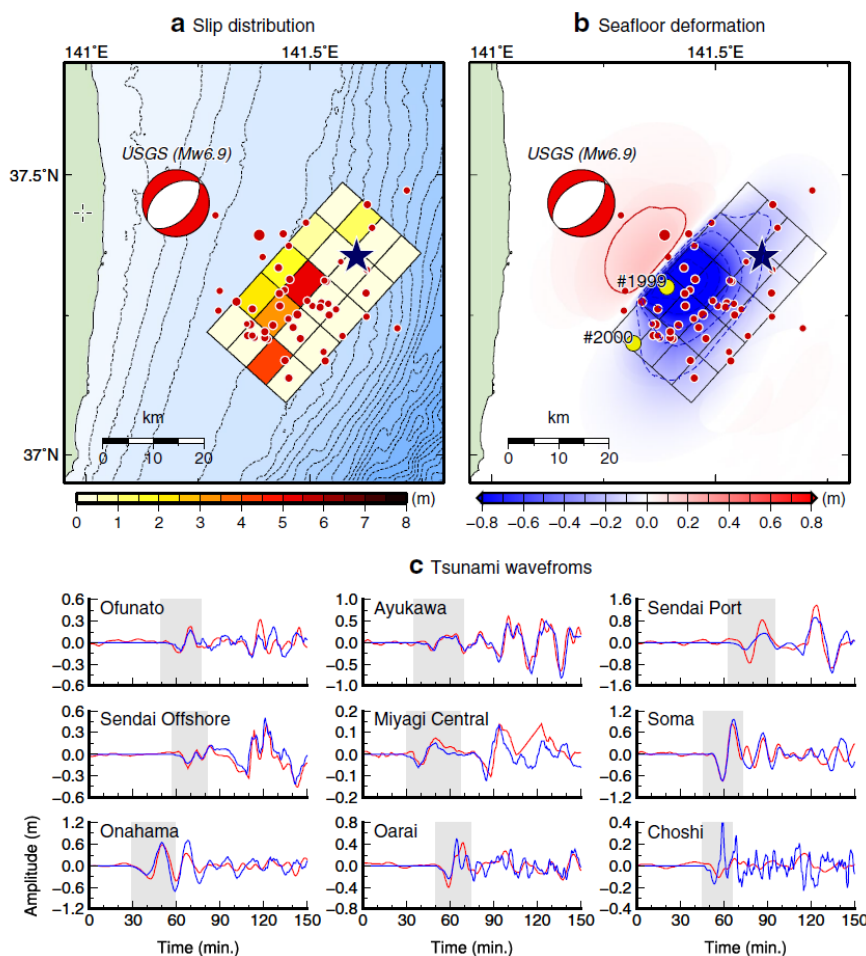


Figure A. 3 - Slip distribution, seafloor deformation and resulting tsunami fit to measurements from an inversion analysis for the 2016 Fukushima Earthquake (Adriano et al., 2018).

Tsunamis amplitudes are governed by the seabed deformation, whereas wave periods are determined by the fault area. Tsunamis have very long wavelengths of tens to hundreds of kilometres as the abrupt bottom movements that generated them have large horizontal scales (hundreds of kilometres). Multiple reflections and partial wave trapping, especially near the source, produce an extended wave train of many waves even though the original source was a single impulse. The latter waves in a tsunami wave train form very complicated patterns in which it is difficult to determine the relationship of a latter wave to the initial source. Hence, only the

observations of the first few waves at a site are used for comparison with model simulations and estimation of the earthquake source parameters, (Mofjeld et al., 2004).

A.2.2 Landslide

Although not considered in this study, an introduction into tsunami generation would not be complete without mentioning tsunami generated from landslides. Submarine landslides can occur on continental slopes and are similar to those that occur on land. They can be triggered by earthquakes. The tsunami that devastated Papua New Guinea in 1998 was much greater than expected for the magnitude 7 earthquake that preceded it. A subsequent seafloor survey indicated that a submarine landslide may have been triggered by the earthquake (González (1999), Synolakis et al. (2002), Bernard et al. (2006), and Tappin et al. (2008)), resulting in the unusually high tsunami waves.

The earthquake triggers a mass of seabed to break away and travel down the continental slope by gravity. As with earthquake generated tsunami, this in turn generates a movement in the column of water above the slide. The tsunami that is generated is related to a number of factors such as the dimensions of the failed mass and the speed and distance this mass travels down the slope. The closer the landslide speed is to the wave speed, the larger the tsunami (Geist et al., 2009). The impact zone of a tsunami generated by submarine landslide is typically more localised than that generated by earthquakes. As the continental shelf can be narrow, the land adjacent to the landslide may be impacted by powerful tsunamis with little warning. The Papua New Guinea event produced runup heights of over 10 m for a 25 km stretch of coastline, killing over 2,100 people (Synolakis et al., 2002). The tsunami will also travel offshore. Refraction processes as well as coastal and shelf trapped waves may result in tsunamis being felt at further distances for an extended duration. However, the largest waves will occur along the coastline within the immediate vicinity of the landslide.

Geist et al. (2009) found that for continental slope landslides, frequency dispersion and nonlinearity are important in modelling tsunami evolution. They modelled the Currituck landslide in North America with a 1D high resolution model based on the fully nonlinear Boussinesq equations, to show the formation of short period fission waves riding on the tsunami (discussed further in Section A.4) before it breaks into a tsunami bore.

A.3 Tsunami Propagation

A.3.1 Transoceanic Propagation

The resulting earthquake-generated tsunami propagates as a set of waves whose energy is concentrated at wavelengths corresponding to the earth movements (~100 km), at wave heights determined by vertical displacement (typically <1 m), and at wave directions determined initially by fault shape and orientation, and later by the adjacent coastline geometry. Because each earthquake is unique, every tsunami has unique wavelengths, wave heights, and directionality (NOAA, 2018a).

As the displacement occurs through the entire water column, and wave lengths are much greater than depth, the tsunami behaves as a shallow water wave even in deep water. From shallow water wave theory, the speed of the tsunami can be calculated from:

$$c = \sqrt{gD}$$

Equation A.1

Where c is the wave celerity (m/s), g is the acceleration by gravity (about 9.81 m/s^2) and D is depth (m). This means that the tsunami in deep water can travel very fast (in the order of 600–800 km/hr in 3,000–5,000 m depth).

The wave period is generally in the range of 5 to 40 minutes. If the wave has to travel considerable distances, the shorter period wave energy will dissipate more. Therefore, the period of the tsunami increases with distance travelled. Periods of up to one hour were observed at Japan following the Great Chilean Earthquake of 1960 (Murata et al., 2010).

As the waves propagate away from the source in deep water, they also spread (as in the pebble analogy), causing some attenuation. As tsunamis are sensitive to water depth variations at all ocean depths, submarine features will influence the wave train. Wave refraction (described below) will occur at all depths. Linear features such as such as escarpments and ridges can act as wave guides, redirecting and concentrating wave energy. Other features such as seamounts can scatter wave energy. Basically, submarine features that extend to within 500 m depth can cause significant wave scatter (Mofjeld et al., 2004). Mofjeld et al. (2000 and 2001) mapped the distribution of a scattering index within the Pacific Ocean. They found that the southwestern Pacific exhibits the highest density of significant scatter features, which includes Australia, such that any tsunami within this region will experience strong scattering with a tendency to become trapped.

In addition to the above processes, oceanic islands will reflect and scatter wave energy. These processes tend to complicate and extend the tsunami wave train as it approaches the Australian continental slope. At this stage, amplitudes are relatively small and so may go unnoticed by a ship.

A.3.2 Continental Shelf Propagation

As the tsunami reaches the continental slope, the depth can change drastically and abruptly compared to the long wavelength. In general, the tsunami may experience the same processes to that of short period waves, not limited to attenuation, shoaling, scattering, focusing, diffraction, reflection, and resonance, but at a larger scale. The more significant processes will be briefly described below.

A.3.2.1 Refraction, Shoaling and Reflection

As the tsunami approaches shallower water it will slow down, thereby adjusting direction such that the crest will tend to become more parallel with the contours (known as refraction). As the wave slows down, the amplitude will increase (shoaling). For steep coastlines (narrow continental shelf), such as South-east Queensland, the tsunami amplitude can increase considerably as there is less dissipation as the wave approaches. In areas where there is a wide and shallow continental shelf, or fringing reefs, the wave may dissipate. However, the wave may again increase as it reaches the shoreline due to shoaling. A first approximation of the shoaling wave height from linear wave theory, is Green's Law (Synolakis and Skjelbreia (1993), Geist (1998), Truong (2012), and Bryant (2014)):

$$\frac{H_1}{H_o} = \left[\frac{d_o}{d_1} \right]^{1/4}$$

Equation A.2

Where H_1 is the wave height at the intermediate depth, d_1 and H_o is the deep water wave height at depth d_o .

As the tsunami approaches the coastline, it is influenced by coastal features and nearshore bathymetry. Refraction can focus energy on particular features such as prominent headlands or diverge energy such as the back beach of an embayment. Complex bathymetry may also cause crossing (superposition) of waves, generating localised amplification. Another feature of tsunami is they can reflect off the coastline. Unlike short waves, which steepen, break and dissipate on beaches; the length to wave height ratio of tsunamis rarely steepens to breaking point.

The tsunami approaches the coast without breaking. Energy is transferred to run-up (refer next section) and reflections. If the coastline is of steep rocky headlands, the reflection will be more pronounced. The reflected wave can then be redirected by refraction and again returns to the coast (Murata et al., 2010). This can occur in V-shaped bays, resulting in higher than expected tsunami heights at the back beach as demonstrated in Figure A. 4. There is also potential for amplification within bays should the period of the tsunami be close to a harmonic of the natural period of the bay. If the tsunami travels along a solid surface such as a rocky headlands, Mach-stem waves may occur, greatly amplifying the tsunami against the steep surface (Bryant, 2014).

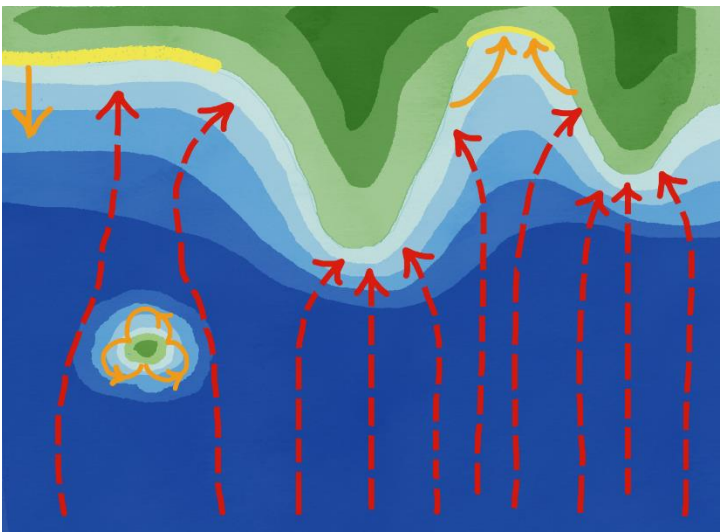


Figure A. 4 - Schematic representation of refraction (red) and reflection (orange) of a tsunami. The curving near the islands is an indication of diffraction.

A.3.2.2 Trapped Waves

A trapped wave is a wave that becomes bound by a particular feature, whether it be the coastline (coastal trapped waves), or the abrupt change in bathymetry (shelf trapped waves). For steep continental shelves where there is an abrupt change in depth over a length scale that is shorter than the tsunami wavelength, there can be partial reflection of the tsunami as it approaches the shelf, and then a further reflection from the coast. This bouncing back and forth is called shelf trapping (refer Figure A. 5). This process can also occur due to refraction when the tsunami is reflected at an angle to the coast. As the oblique reflected wave reaches the shelf, the rapid depth changes on the continental slope can cause the wave to refract back further along the coast in a leapfrogging pattern (a pattern analogous to skipping a pebble across the water surface).

Coastal trapped or edge waves are surface gravity waves that are trapped against a rigid body (the coastline) by refraction. In the offshore direction, the wave height diminishes rapidly, depending on the wave length and mode. The fundamental mode ($n = 0$) producing an exponential decay offshore. Figure A. 6 provides an example of the theoretical profile of the first four modes based on the theory provided in Mei et al. (2005) and González et al. (1995), and in three dimensions in Figure A. 8, while Figure A. 7 shows modelled wave profiles off the coast of North Stradbroke Island for a hypothetical event originating from the Kermadec-Tonga subduction zone.

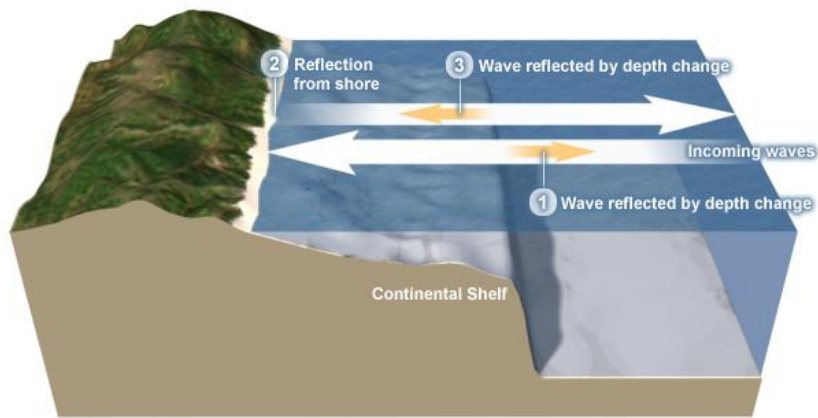


Figure A. 5 - Shelf trapping mechanism (source: COMET® Website at <http://meted.ucar.edu/> of the University Corporation for Atmospheric Research (UCAR)).

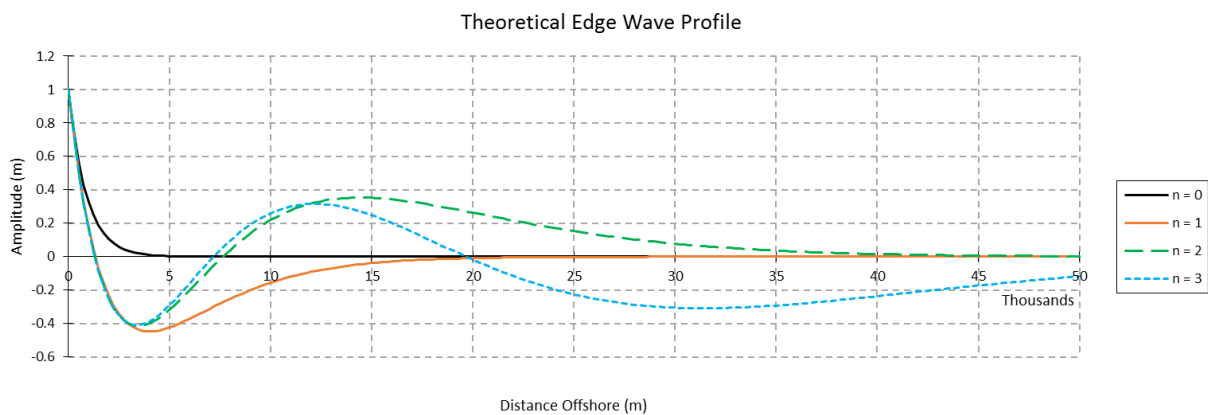


Figure A. 6 - Theoretical edge wave offshore profile for the first four modes ($n = 0$ to 3) of a long wave (Amplitude = 1m, Period = 10 min).

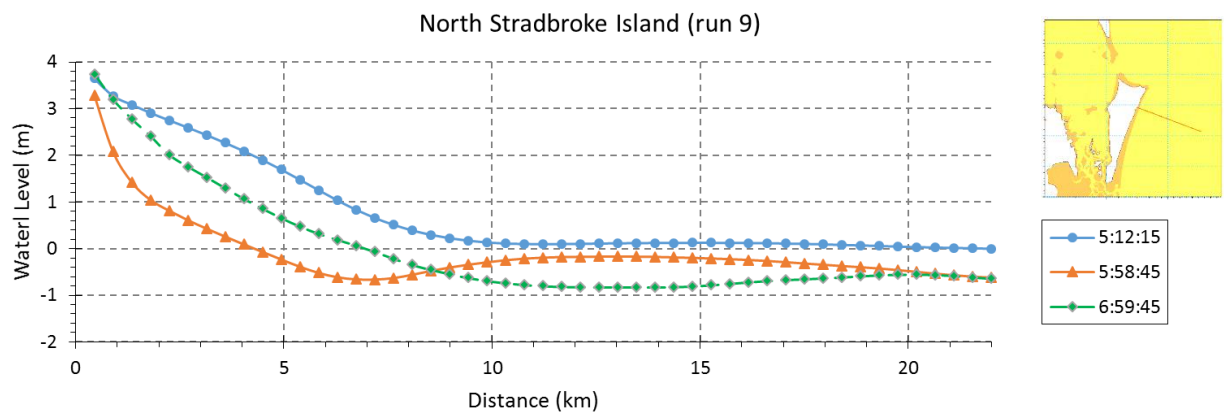


Figure A. 7 - Modelled coastal trapped wave profiles generated off North Stradbroke Island by a hypothetical 3,000 year ARI event from the Kermadec-Tonga subduction zone (times given in hr:min:sec after initial generation).

Coastal trapped waves can be described as either standing (stationary in space, but oscillating in time) or progressive (moving along the coastline). However, the progression of these waves is greatly affected by the complexity of the coastline. Progressive edge waves can be steered or guided by sudden drop-off in bathymetry such as the continental shelf.

Coastal and shelf trapped waves have been found to be important phenomena in understanding tsunami hazard along the coastline. The trapped and incident wave can interact, such that the wave train will be complex, of longer duration, and vary along the coast. More importantly, the constructive interaction between edge waves and the non-trapped modes of the tsunami can produce higher than expected secondary waves and associated run-up (Geist, 1998). The literature refers to two broad conditions of exciting trapped waves: those excited by tsunamigenic earthquakes on the continental shelf close to the coastline; and those excited from scattering of the incident tsunami from offshore sources by irregular coastlines.

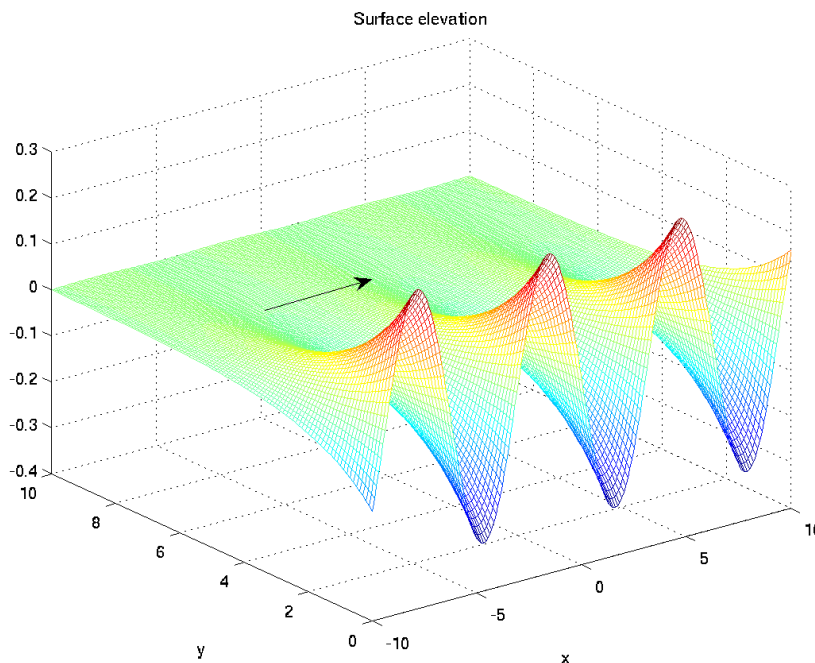


Figure A. 8 - Three dimensional profile of edge waves propagating in the x direction, being the coastline(Source: https://en.wikipedia.org/wiki/Edge_wave).

Trapped edge waves excited from tsunamigenic earthquakes generated on shelves have been documented by González et al. (1995) when they analysed data captured during the April 1992 Cape Mendocino tsunami, which generated both incident and trapped edge waves along the Californian and Oregon Coast from a nearfield earthquake. They found these waves were of the fundamental mode (that is, exponential decay offshore); propagate much slower than the incident tsunami waves, and can travel long distances along the coast. Rabinovich et al. (2006) found the presence of trapped edge waves during the June 2005 tsunami generated by an earthquake offshore of California. The excitation of trapped edge waves from shelf generated tsunamis was also found by Neetu et al. (2011) following a reanalysis of the 1945 tsunami that impacted the Makran coast. They also found that these modes can be trapped in the alongshore direction due to longshore variations in shelf width. Yamazaki and Cheung (2011) modelled the 2010 Chile earthquake that occurred offshore of the central Chile coast to find that the continental shelf slope refracts and traps the radiated energy initially as progressive edge waves on the shelf. Reflections between headlands and the shelf generated a number of standing waves along the coast.

Fuller and Mysak (1977) demonstrated theoretically that trapped edge waves can be generated on a shelf with a straight coastline with small irregularities, due to energy transfer from scattering effects. They also indicated that the amplitude of trapped edge waves excited by a tsunami is about 70 per cent of the incident amplitude and that they slowly attenuate from scattering along

irregular coastlines. The presence of edge waves from tsunami generated offshore can be found in references that also discuss resonance as discussed in the following section.

Figure A. 9 demonstrates a shelf trapped transient wave generated during a modelled 3,000 year average recurrence interval (ARI) tsunami event on the south east Queensland coast. The wave is initially reflected off the Great Sandy National Park coast. As it nears the continental shelf, it is refracted back towards the coast to impact Bribie Island, some 120 km south of the initial reflection. As the wave reaches the Bribie coast, it splits to propagate along the coast in both directions as a coastal trapped wave (Figure A. 10). The combination of the trapped and incident waves resulted in the highest water level at Bribie for this event, about 207 minutes after the leading wave (Figure A. 11). Abraimi (2014) observed a similar phenomenon when analysing the results of modelling the 2010 Chilean Tsunami on the central Chilean coast.

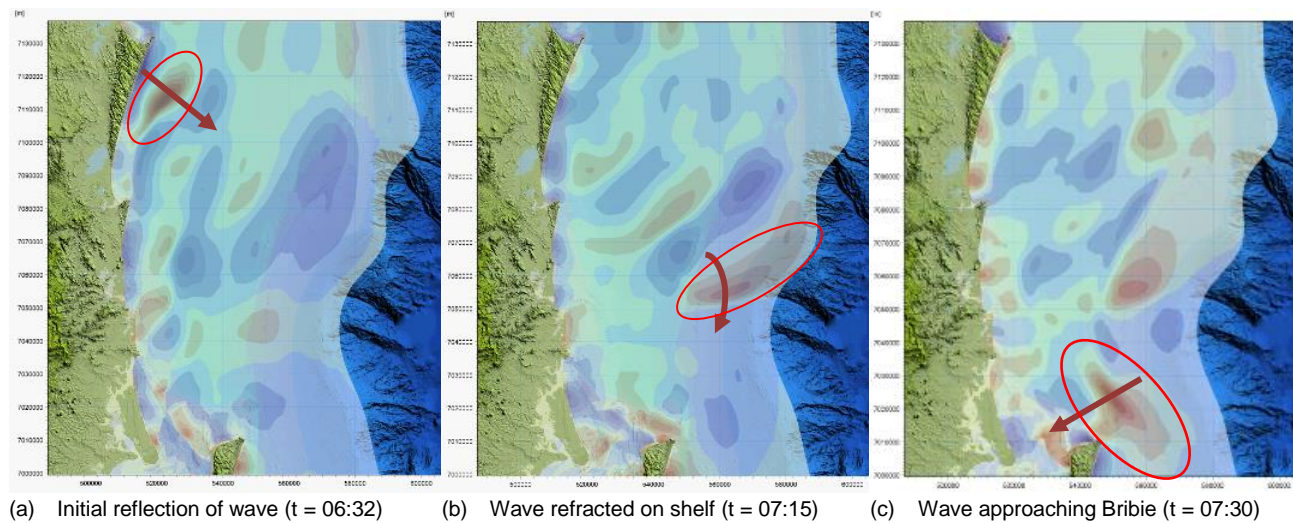


Figure A. 9 - Shelf trapped wave along south east Queensland coast (3,000 year ARI event). Arrows indicate direction. Dark red shading represents 4 m. Time is elapsed time in hours:minutes.

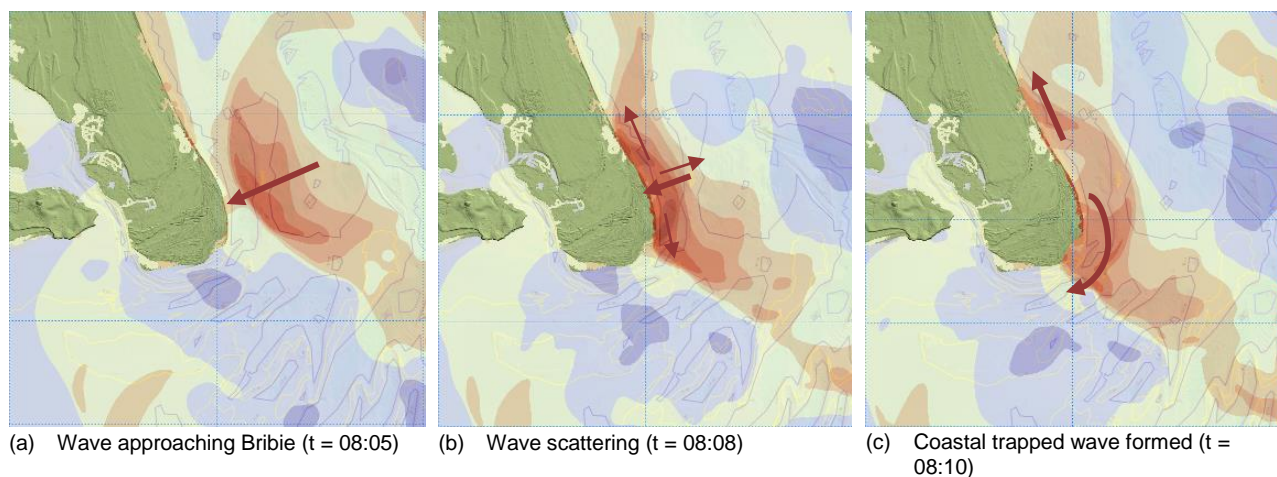
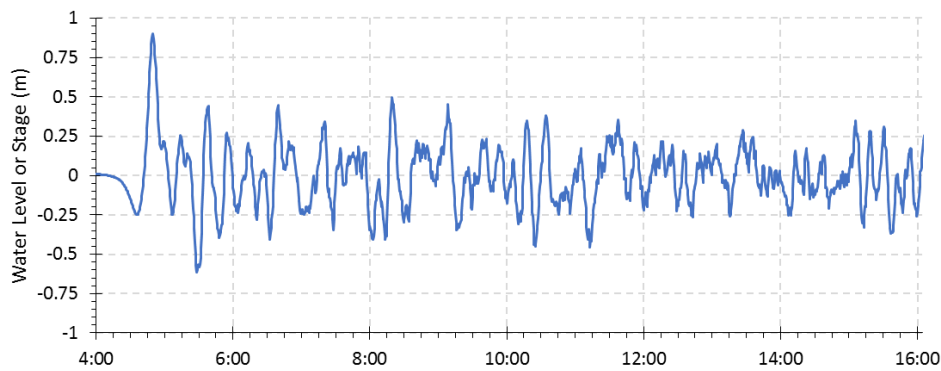
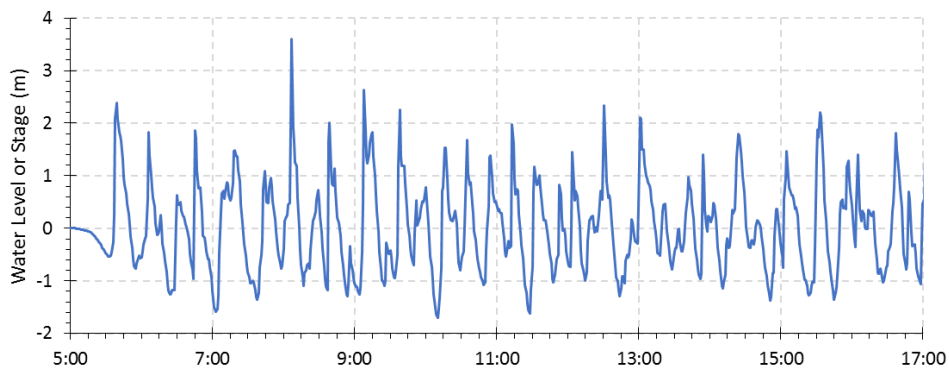


Figure A. 10 - Coastal trapped wave example for Bribie Island, Queensland. (3,000 year ARI event). Arrows indicate direction. Dark red shading represents 4 m. Time is elapsed time in hours:minutes.

(a) Boundary condition at defined hazard point (3000 year ARI event, depth = 1000m)

(b) Southern Bribie Island (3000 year ARI event, depth \approx 5m)**Figure A. 11 - Time series of tsunami near the coast of Southern Bribie Island (3,000 year ARI event).****A.3.2.3 Standing Waves and Resonance**

Standing waves is the name given to the combination of two waves travelling in opposite directions at particular periods and timing that their interference creates the appearance of a wave where the crest appears to be stationary. For tsunami, the two waves will be the incoming wave and the reflected wave. Standing waves occur when the wave period (or frequency being the inverse of period) matches a natural period of the water body. In simple terms, when the wave period (or wave length) of the arriving tsunami matches a harmonic (an integer fraction) of the natural (or eigen) period (or length) of a water body (such as the length of a bay), a standing wave is generated that can amplify the tsunami height. A standing wave is the combination (or superposition) of the incident wave and a reflected wave (refer Figure A. 12). If the wave length is an integer factor of the overall length, the reflected and incident wave will combine to form nodes and antinodes in the spatial domain. The nodes are where the two waves are out of phase and so cancel each other out. The water level at nodes will be minimal due to destructive interference. The antinodes are where the two waves are in phase and the amplitude will be at a maximum due to constructive interference.

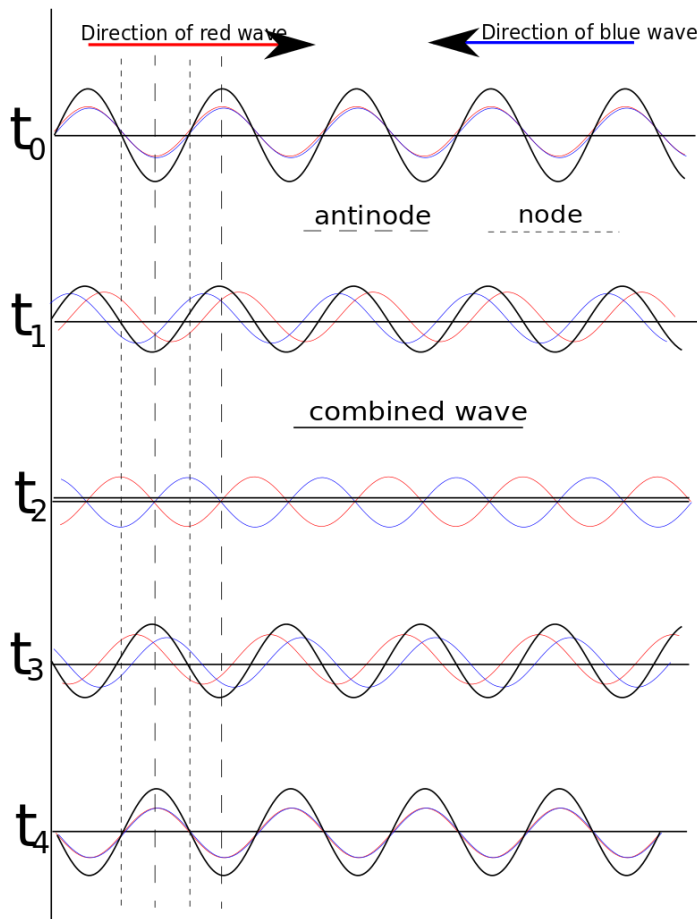


Figure A. 12 - Standing wave example caused by an incident (red) and reflected (blue) wave (Source: https://en.wikipedia.org/wiki/Standing_wave).

The fundamental mode (also referred to as the zero mode or first harmonic) is the simplest mode and is the most commonly seen as it is subject to the least energy dissipation because they involve smaller velocities for a given amplitude (Nielsen, 2012). The wave length required to generate the fundamental node depends on the end conditions. For a simple condition of a semi-enclosed basin, the node will appear near the entrance. Therefore the fundamental mode will occur when the basin is a quarter of the wave length. The wave period can then be calculated with consideration of wave celerity (Equation A.1) giving (Bryant, 2014):

$$T_s = \frac{4L_b}{\sqrt{gD}}$$

Equation A.3

Where L_b is the length of the basin and T_s is the wave period required to initiate seiche. For an edge wave, the wave length is along the coast with nodes at either end. The fundamental mode will occur when the length between nodes is half the wavelength. In reality, the wave lengths required to generate the modes will be more complicated due to factors such as irregular coastlines, partial reflections, oblique waves, and irregular wave conditions to name a few. As the tsunami wave train consists of many waves over a wide range of wave periods, it is possible that this phenomena can occur and be excited at a number of modes.

Resonance is always associated with standing waves. To understand resonance, let us consider a wave entering a harbour. Reflections will cause the water level to oscillate after the passage of the wave, which will decay rapidly. However, if the wave frequency matches the natural frequency of

the harbour, then the waves will continue to oscillate for some considerable time (or resonate). The natural frequency being the frequency at which the harbour tends to oscillate in the absence of any driving or damping force.

If the external wave is a series of waves at the natural period, then each successive wave will add energy to the harbour oscillation which may grow larger than any individual wave in the original wave series. Resonance can appear in everyday life. The coffee in your cup that spills when you increase your walking pace is resonance caused by your motion matching the natural period of the cup. Resonance is a known issue for ports and harbours (referred to as a seiche), and can cause significant damage to moored vessels. Given the wavelength of tsunamis can still be tens of kilometres in the nearshore, the phenomena can also occur at larger scales such as bays and even the continental shelf.

The presence of shelf resonance has contributed to unusually high tsunami wave heights at: Hawaii (Munger and Cheung, 2008) and Crescent City (Horrillo et al., 2008) from the 2006 Kuril Islands tsunami; the American Samoa from the 2009 Samoa tsunami (Roeber et al., 2010); and the Chilean coast following the 2010 Chilean earthquake (Yamazaki and Cheung, 2011). In these examples, standing edge waves resulted in a spatially and temporally complex tsunami patterns that would not be explained by solely examining the leading tsunami wave.

A.3.2.4 Obstructions and Islands

Obstructions such as islands, peninsulas or capes, may cause the tsunami to circle around to the back of the obstruction with reduced amplitude (referred to as diffraction). The obstruction must be significant enough in size to be felt by the long period tsunami. Murata et al. (2010) suggests the obstruction needs to exceed 500 m to have a notable influence.

For short period wind waves, the process of diffraction around islands has been known to produce a region of calmer water (known as the shadow zone) in the lee of the obstruction (such as islands) which may offer protection to the mainland coastline directly behind the obstruction. This concept has been utilised by coastal engineers through the design of detached offshore breakwaters as a coastal defence approach.

The behaviour of tsunamis around features such as islands can be quite different. The combination of refraction and edge waves can cause the wave to wrap around the island to reunite on the leeward side, such that the run-up levels can be as high as on the exposed side (Murata et al., 2010 and Wong et al., 2008). Yamazaki (2010) examined this phenomena by numerical modelling of a solitary wave approaching a conical island and compared the results against physical model results (Figure A. 13). Stefanakis et al. (2014) undertook 200 simulations of an idealised conical island in front of a coastline. They found that unlike short period waves, tsunamis tend to wrap around the island and form a focusing lens of energy on its lee side, amplifying wave heights on the mainland behind the island. Rasyif et al. (2016) examined the influence of small islands on tsunami propagation on the Sumatran coast by numerical modelling of three actual events and three hypothetical cases. The report found that under certain conditions (that is, the tsunami propagates from both sides of the island), the tsunami will focus on the lee of the island and amplify the tsunami on mainland communities behind the island.

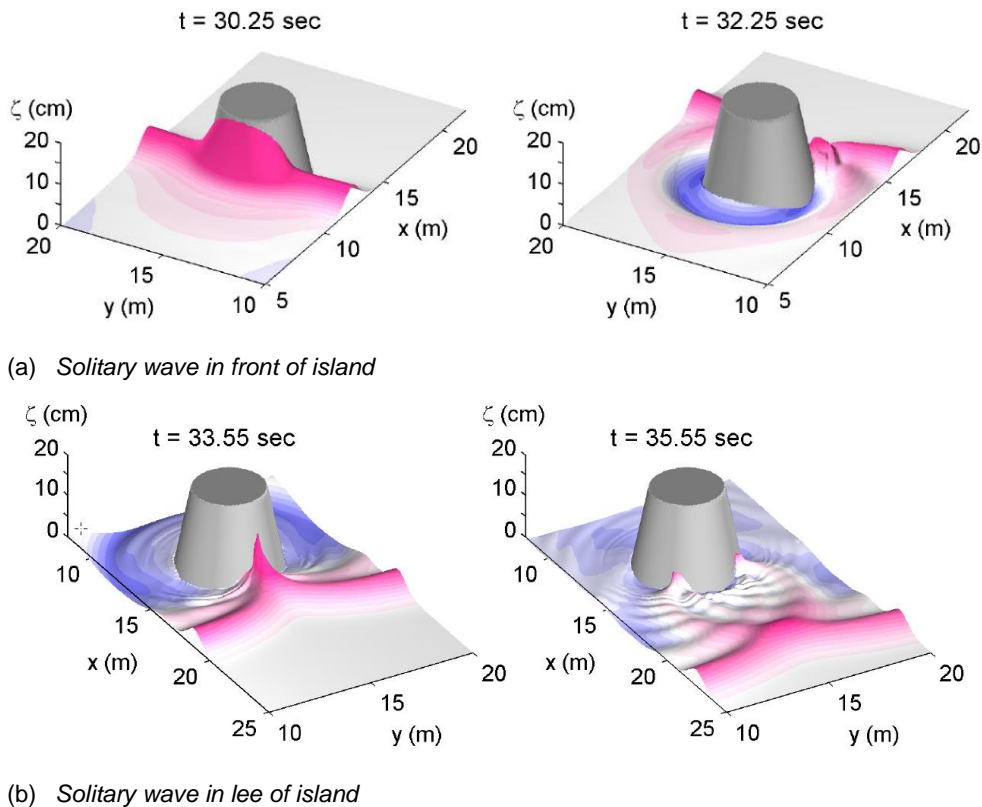


Figure A. 13 - Solitary wave wrapping around idealised conical island (Yamazaki, 2010).

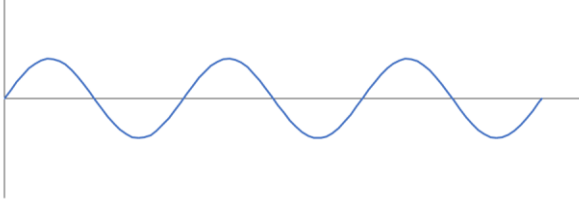
A.3.2.5 Ports and Marinas

Because of the long length scale of tsunamis even on the coast, small structures such as marinas and detached breakwaters for coastal erosion works have little influence on wave attenuation, unless their crest is above the tsunami run-up height. Under these conditions, there will be very strong currents at the openings. For ports and marinas, strong currents can develop as well as circulation systems. As flows accelerate around port structures, boundary shear leads to flow separation that can create transitional turbulent structures. These structures are referred to as coherent eddies or turbulent coherent structures (Borrero et al., 2015) and at first glance can be misconstrued as whirlpools.

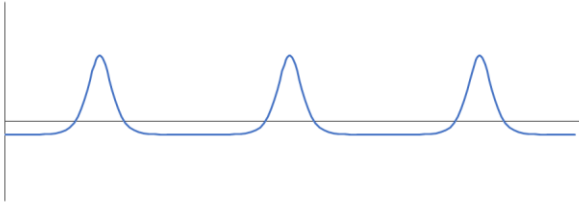
A.3.2.6 Wave Characteristics

The theory of waves is a complex subject and will not be discussed in any detail. Some of the more common terminology will be provided. The description of the tsunami wave form relates specifically to the leading wave, being the initial impulse of the tsunamigenic earthquake. Subsequent waves are a result of the processes mentioned earlier. In the deep ocean, the wave train follows an exponentially decaying envelope with the leading wave much larger than subsequent waves (Geist, 2009). As the tsunami approaches the coast, the wave form becomes more complex with no discernible characteristic envelope. However, there has been analytical work undertaken in describing the run-up (described below) in relation to the shape of the leading wave. Early work considered the leading wave as a solitary wave (being the infinite wavelength limit of cnoidal waves). Madsen et al. (2008) examined the solitary wave and concluded that it is not applicable for long waves on a sloping bottom. Tadepalli and Synolakis (1994) introduced the concept of the N-wave (in analogy to dipole waves in gas dynamics – Synolakis and Bernard, 2006) to describe analytical wave run-up from tsunami. They consider two forms: leading depression N-waves (LDN), being a drawdown of the ocean before the tsunami hits the coast, and leading elevation N-waves (LEN). These different wave profiles depicted by these theories are depicted in Figure A. 14.

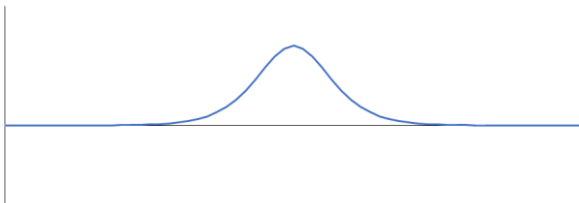
(a) Linear sinusoidal waves



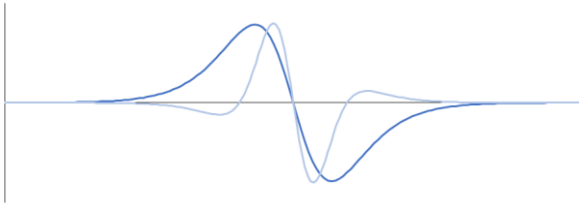
(b) Cnoidal waves



(c) Solitary wave



(d) Leading elevation N- wave (LEN)



(e) Leading depression N- wave (LDN)

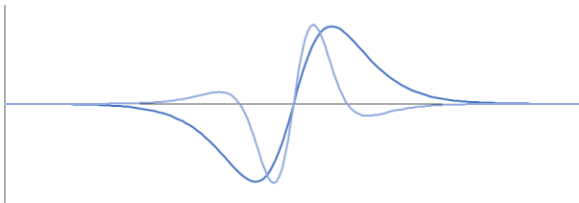


Figure A. 14 – Different nonlinear wave theories adopted in literature to describe the leading tsunami wave. The first plot is based on linear wave theory provided as a reference. The lighter of the lines in the last two plots are double N-waves.

In deep water, tsunami can be described by linear wave theory (assuming small amplitude, homogenous and incompressible fluid). For depths of less than about 50 m, it is suggested that nonlinear wave theory applies (Geist, 1998), as the waveform will change with time. Cnoidal waves are considered nonlinear waves. Therefore, numerical modelling within the coastal region should be undertaken with models based on the nonlinear shallow water equations (NLSWE) or Boussinesq equations.

Tsunami are generally described by the amplitude (height of the crest above the mean water level) and period (time between successive crests). However, the wave train will consist of numerous waves of varying amplitude and period. Short wave statistics can be used to describe the wave

train in terms of wave height (crest to trough height, approximately twice the amplitude) and period. Some common parameters include significant wave height (H_s being the average of the highest one-third of wave heights), root-mean-square wave height, peak period (T_p being the period corresponding to the peak spectral energy) and the zero up-crossing period (T_z being the average period based on the time each wave rises above the mean water level).

The water level at a particular moment in time is sometimes referred to as the stage.

All of the processes previously mentioned add to the complexity and length of the tsunami wave train. A tsunami event can therefore last for several hours, and the first wave may not necessarily be the largest. However, IOC (2016) suggest that the largest wave is usually one of the first five waves. As mentioned earlier, all these processes and their complex interactions will decrease the reliability of modelling the longer wave train.

A.3.2.7 Tsunami and Tides

The tide range in the open ocean is small relative to the depths (typically less than one metre). As the tides travel across the Australian continental shelf, amplification occurs. The largest tide ranges within Queensland occur around Central Queensland, with the highest documented tide range 9.1 m at McEwen Islet (MSQ, 2017).

Traditionally to minimise computation times, tsunami forecast and hazard modelling have decoupled the tides, adopting a constant level of Mean Sea Level (MSL). Mofjeld et al. (2007) examined the influence of tides on the maximum water level by superimposing theoretical tsunami wave time series based on an exponential decay coefficient of two days over a duration of five days (based on measurements within the Pacific Ocean), on tides typical for Oregon, USA. Maximum envelopes of tide plus tsunami were calculated by stepping the tsunami time series through a full year of tides representing an average year during the 18.6 year tidal cycle. The results showed that for small tsunami amplitudes, the maximum water levels tend to occur near mean higher high water (MHHW) with little spread. As the tsunami increases, the maximum water level tends towards a limit of MSL plus the tsunami amplitude (for tsunami amplitude > tide range), and the probability density function approaches that of the tides.

Although the principle of an exponentially decaying tsunami time series may be applicable in the open Pacific Ocean, the tsunami time series on the Australian continental shelf will be further complicated by the processes discussed above such that the largest wave may occur several hours after the onset of the leading wave. This is not discussed in the paper but it is possible that a tsunami time series with large amplitudes persisting for some time may increase the limit from MSL to a tidal plane above MSL.

A.4 Tsunami Run-up/Inundation

The behaviour of tsunamis as they reach the coast is different to the behaviour of wind waves (refer Figure A. 15). Short period wind waves will continue shoaling until their steepness causes the wave to break. The broken bore will then continue to wash up the beach until its energy has been dissipated (referred to as the swash zone). The vertical height that is reached above the still water level is referred to as the run-up. The run-up depends on wave characteristics and beach slope. The particle motion within wind waves is orbital, becoming more elliptical in shallow water. Depending on wind wave and bathymetry characteristics within the surf zone, current patterns can develop including undertow, rip currents, and longshore currents.

With tsunamis, the wave length even in very shallow water can still be in the order of kilometres. Bryant (2014) describes that the wave form close to shore appears similar to either Stokes or N -

waves. These waves typically do not break, unless they are very large. Instead, they can appear as a fast moving tide or surge. The leading edge of some may decay into one or more bores or solitons (Bryant, 2014), and can appear like a fast moving tidal bore. The flow is horizontal in pattern (more like a river flow) and can be very strong and turbulent. The momentum of these waves can push water much further inland than wind waves at rates of 5 to 8 m/s (Bryant, 2014), and the currents can be too strong for a person to remain upright.

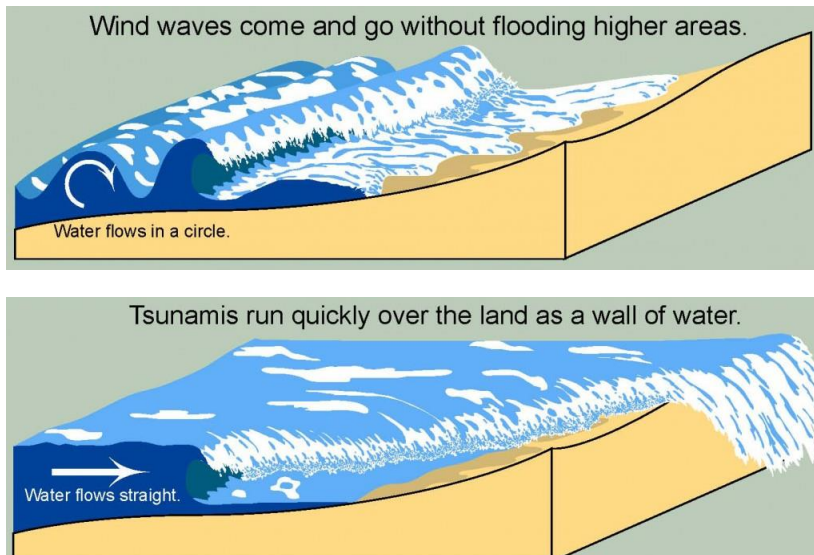


Figure A. 15 - Differences between wind waves and tsunami at the coast. (source: <http://earthweb.ess.washington.edu/tsunami/>).

Madsen et al. (2008) investigated the use of solitary waves to model tsunamis, and in doing so, examined some characteristics of long waves as they approach the coastline. With the aid of a high order Boussinesq numerical model based on Madsen et al. (2006), they concluded the following:

1. In general, there is insufficient distance for tsunamis to generate solitons in the ocean or continental shelf.
2. During shoaling from deep to shallow water, wave asymmetry will increase (seen as steepening of the leading face of the wave), whereas skewness remains low.
3. With decreasing water depth, nonlinearity grows rapidly while the effects of dispersion reduces. Nonlinear shallow water equations (NLSWE) provide a good approximation of this process.
4. As the wave propagates close to the beach, the front face of the wave may become steep enough to disintegrate into an undular bore with short and steep transient waves of periods in the order of 10 to 15 seconds riding on top of the tsunami. This process explains the observed short period waves during the 2004 Indian Ocean tsunami (Figure A. 16). Dispersion now becomes important and nonlinear dispersive models such as Boussinesq models are required to model this phenomenon. Although the NSWE may indicate this process due to numerical dispersion.
5. Even on a flat, shallow, and wide shelf, the asymmetry of the waves will continue to grow until the front face steepens to the point that undular bores develop.
6. Typically the bores develop close to the coast and hence do not have sufficient time or travel distance to develop leading solitons.
7. Wave breaking that is observed during events is typically related to the short period bores, and not the underlying tsunami.

8. Although these transient waves will have an impact on coastal structures, the run-up and inundation that occurs is a result of the underlying longer period tsunami.
9. Constant depth theory for cnoidal or solitary waves cannot be applied to approximating long waves on sloping bottoms.



(a) Undular bores riding on the underlying tsunami which is not apparent in the photo due to its gentle slope.



(b) Close up of approaching bores.

Figure A. 16 - The 26 December 2004 Indian Ocean tsunami approaching the North Beach of the island Koh Jum, off the coast of Thailand. Photo taken from the top of Mt Pu (Copyright Anders Grawin. Reproduced from <http://www.kohjumonline.com/anders.html> with permission).

For sloping topography, the inundation extent will be defined by the run-up limit. Murata et al. (2010) suggests that run-up will be greater on a gentle slope. For regions where there is a beach of uniform slope followed by a flat coastal plain, the momentum of the tsunami will travel further inland until friction overcomes it. For regions where the inland region slopes downward (such as behind dunes) the tsunami may accelerate with increased velocity. For both of these cases, tsunami velocities are slow to dissipate.

Extreme events have been known to destroy buildings, infrastructure and stripping vegetation, moving several kilometres inland (inundation extent). With such devastating events, like the 2004 Indian Ocean tsunami, a booming roar can be heard as the tsunami approaches (UNESCO/IOC,

2010). Circulation patterns can develop along the coast such as large eddies. As the trough of the wave approaches, the water level can recede rapidly generating strong offshore currents that wash obstacles out to sea.

Of course the ability to inundate depends on a number of factors including tsunami height and period, stage of tide, height of any barriers (such as seawalls and beach dunes), obstacles (such as buildings), and land coverage (for example a dense forest will impede tsunami movement more than pastoral land). For small amplitude tsunamis, the stage of tide may be a critical factor.

As well as inundating low lying coastal regions, tsunamis will also propagate up rivers and waterways much faster than they inundate some coastal zones.

A.5 Tsunami hazard and Community Vulnerability

The preceding sections describe the processes that can influence the tsunami hazard at a specific geographic location. Once the hazard is quantified, vulnerability and risk assessments can be undertaken. Charvet et al. (2017) define tsunami risk as:

$$\text{Tsunami Risk} = \text{Tsunami Hazard} \times \text{Vulnerability} \times \text{Exposure}$$

Where exposure is the number of people, buildings and infrastructure at risk; and vulnerability is the likelihood of losses, defined as:

$$\text{Vulnerability} = \text{Fragility} \times \text{Loss Model}$$

Where fragility is the probability of damage given a particular tsunami intensity; and the loss model defines the probable losses (financial and casualty) for a given level of damage. The above definition being consistent with the risk assessment process defined in QFES (2018).

The vulnerability of a community to tsunami hazard can be categorized as physical (human casualties and structural damage), social, economic, and environmental (UNESCO, 2015 and UNISDR, 2017). The following relates to the physical aspects.

The science behind vulnerability and risk assessments is well developed for other coastal hazards that occur more frequently. There is extensive literature and guidelines regarding vulnerability metrics for riverine flood events, based on field and laboratory investigations. The Flood Hazard Guideline published by the Australian Institute for Disaster Resilience (AIDR, 2017) quantifies flood hazard as the product of flood depth and velocity. Figure A. 17 illustrates the combined general flood hazard vulnerability curves provided in the guideline, which set hazard thresholds that relate to the vulnerability of the community when interacting with floodwaters.

Further guidance in regards to human stability in riverine flood events can be found in Engineers Australia (2010), which is based on a review of previous laboratory experiments. The results are summarised in Table A. 1 as a function of the product of individual height and mass (H.M) and the product of depth and velocity (D.V).

However, there are fundamental differences in the physics of these two hazards. Riverine flooding of floodplains is generally characterised by the gradual and steady rise in water level over an extended period, with currents being typically low within the floodplain: the main cause of damage being from water damage. Their occurrence is much more frequent, and as such there has been significant field assessments and physical modelling investigations to develop vulnerability relationships.

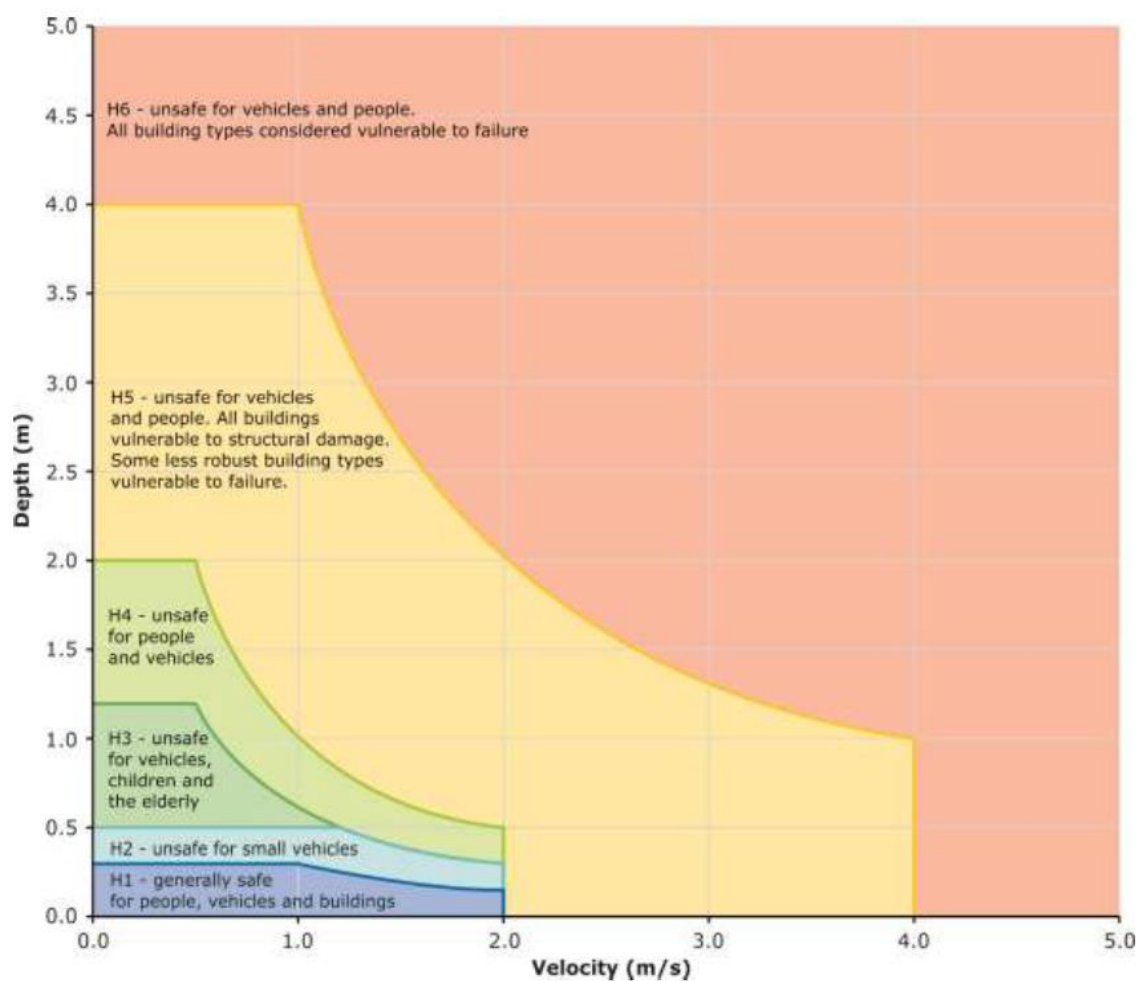


Figure A. 17 - General flood hazard vulnerability curves (AIDR, 2017).

Table A. 1 - Human Stability during flood event (reproduced from Engineers Australia, 2010).

D.V (m/s)	Infants, small children (H.M ≤ 25) and frail/older persons	Children (H.M = 25 to 50)	Adults (H.M > 50)
0	Safe	Safe	Safe
0–0.4	Extreme Hazard; Dangerous to all	Low Hazard	Low Hazard
0.4–0.6		Significant Hazard; Dangerous to most	
0.6–0.8		Extreme Hazard; Dangerous to all	Moderate Hazard; Dangerous to some
0.8–1.2			Significant Hazard; Dangerous to most
>1.2			Extreme Hazard; Dangerous to all

Although the overland flow associated with tsunami is predominantly horizontal (Bryant, 2014), the inundation is more rapid with stronger currents and turbulence. The sequence of a number of waves will see reversing currents. The formation of undular bores (refer Section A.4) can introduce additional forces on structures. Scour can be significant, compromising foundation stability. In addition, the occurrence of tsunami events with recorded damage assessments are much scarcer, relying on documented events post 2004.

The Joint Australian Tsunami Warning Centre (JATWC) provides warnings within Australia based on a no threat, marine warning or land warning. The following sections consider hazard and vulnerability metrics based on the latter two threats.

A.5.1 Marine Hazard

Although tsunami inundation is perhaps the most considerable and obvious risk to the public, there can still be significant damage to maritime facilities from events that do not pose an inundation threat. Within ports and marinas, maritime assets are vulnerable to significant damage from strong currents and associated drag forces (Lynett et al., 2014). The following provides some guidance in relation to vessels and maritime structures.

A.5.1.1 Maritime Users

Hazards to maritime users from tsunami are most acute in nearshore areas as the tsunami wave enters shallower waters close to the shore.

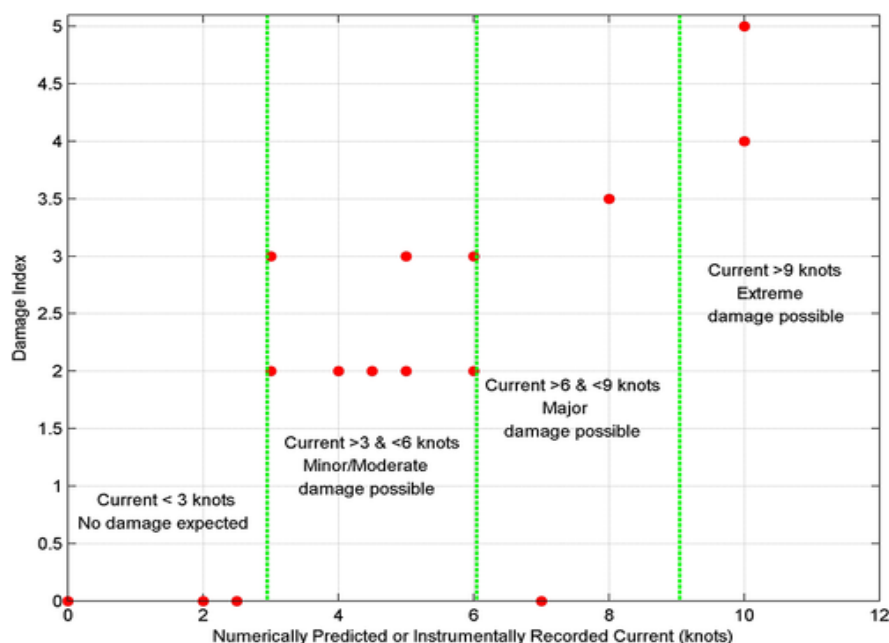
Tsunamis can pose a significant risk to vessels of all sizes in nearshore areas and ports, due to wave steepness, high current velocities and debris. Tsunami forces on vessels at anchor are likely to impose significant loads on moorings. Due to the impact of tsunamis on the maritime industry from the 2004 and 2011 events, a considerable research effort has seen a variety of guides being produced for the marine industry on tsunami, including estimates of impact based on tsunami amplitude and current velocity (Muhari et al. 2015).

Lynett et al. (2014) undertook a review of recorded damage against measured and modelled tsunami current speeds within ports and harbours predominantly in California following the 2010 Chile and 2011 Great East Japan tsunamis. The results demonstrated distinct thresholds for different levels of damage (defined in Table A. 2) as shown in Figure A. 18, with initiation of damage occurring for speeds above 1.5 m/s. Muhari et al. (2015) developed loss functions for marine vessels based on a multivariate analysis of data collected from the 2011 Great East Japan tsunami together with numerical hydrodynamic modelling of flow velocities. Loss estimation surfaces were developed based on tsunami height, velocity, impact (from floating or static obstructions), and boat material. They found that their results were consistent with that of Lynett et al. (2014), with the model being more sensitive to velocity. They also concluded that collision is a major factor in the determination of vessel loss, significantly reducing the velocity and depth thresholds.

For recreational maritime users, Queensland Government guidance is to where possible moor your vessel and move to high ground. Otherwise, if at sea move offshore into deep water and stay there until further advised (Queensland Government, 2018). Lynett (2014) undertook hydrodynamic modelling for the Californian coast to examine a “safe” depth for evacuation of vessels should there be sufficient lead time prior to tsunami arrival. The modelling showed that navigable currents was the controlling factor, requiring depths greater than 50 m to reduce currents below 1 m/s, and depths greater than 180 m for currents below 0.5 m/s.

Table A. 2 – Marine facility damage classification from Lynett et al. (2014).

Damage Index	Damage Type
0	no damage/impacts
1	small buoys moved
2	1–2 docks/small boats damaged and/or large buoys moved
3	Moderate dock/boat damage (<25% of docks/vessels damaged) and/or midsize vessels off moorings
4	Major dock/boat damage (<50% of docks/vessels damaged) and/or large vessels off moorings
5	Extreme/complete damage (>50% of docks/vessels damaged)

**Figure A. 18 - Damage against tsunami current speed from Lynett et al. (2014).**

A.5.1.2 Maritime Structures

Tsunamis have the potential to cause significant damage to coastal and estuarine structures due to the significant forces that can be applied to structures as they may be subject to hydraulic forces beyond tolerable design levels.

Tsunami waves apply exceptional hydraulic forces as they propagate over and around structures, dissimilar to surges and wind derived waves, potentially resulting in significant additional loading on a structure from wave impact forces and debris. Structures can also be impacted by scour due to increased current velocities and water depths. Although these forces are relatively well understood in terms of structure design, they are not well understood in the context of tsunami and are the subject of research.

Although the Australian design standards for maritime structures (Council of Standard Australia, 2002 and 2005) are rigorous in their requirements to assess the resilience of structures from a

variety of hydraulic impacts, the risk from tsunami is neither specifically identified nor particularly well understood.

For port facilities, some guidance is provided in Lynett et al. (2014) as described in the preceding section.

A.5.2 Land Hazard

The obvious hazards associated with overland progression of tsunamis are inundation or flow depth and extent, high velocities, and debris. A number of factors influence building damage including hydrostatic forces, buoyant forces, hydrodynamic forces, surge forces, impact of floating objects, breaking wave forces, inundation duration and footing scour (Tinti, 2011).

Research into vulnerability measures has mostly developed post 2004, but particularly following the 2011 Great East Japan tsunami. As such, the tsunami community is still in the early stages of understanding how to quantify the physical and social vulnerability. Nevertheless, there is literature available that provides rough guidance. Wijetunge (2009) provides human stability criteria based on the experimental results of Takahashi (2005) as reproduced in Table A. 3.

Table A. 3 - Human stability in tsunami based on laboratory experiments (Wijetunge, 2009).

Depth, D (m)	Stability
D < 0.5	Stable, if V < 1.5 m/s
0.5 < D < 1.3	Unstable if V > -1.84D + 2.4
D > 1.3	Unstable for all V

This criteria is similar to classification H3 from the general flood hazard vulnerability curves (Figure A. 17). The above being based on the stability of people caught in currents and so should be considered only as a first approximation. Other factors will influence human stability such as floating debris.

Building vulnerability research has focused on developing empirical damage or fragility functions (probability of exceeding a given damage state based on a measure of tsunami intensity) for a range of structure types and predefined damage states based on post event assessments and laboratory experiments. Most of the recent work in this field has come from the 2011 Great East Japan tsunami. Figure A. 19 provides an example of the typical 2-D fragility functions as developed by Charvet et al. (2015) based on flow depth, where the damage state (DS) relates to the criteria defined by the Japanese Ministry of Land Infrastructure Tourism and Transport as summarized in Table A. 4, noting that they combined DS5 and DS6 as these damage states were seen to not be mutually exclusive.

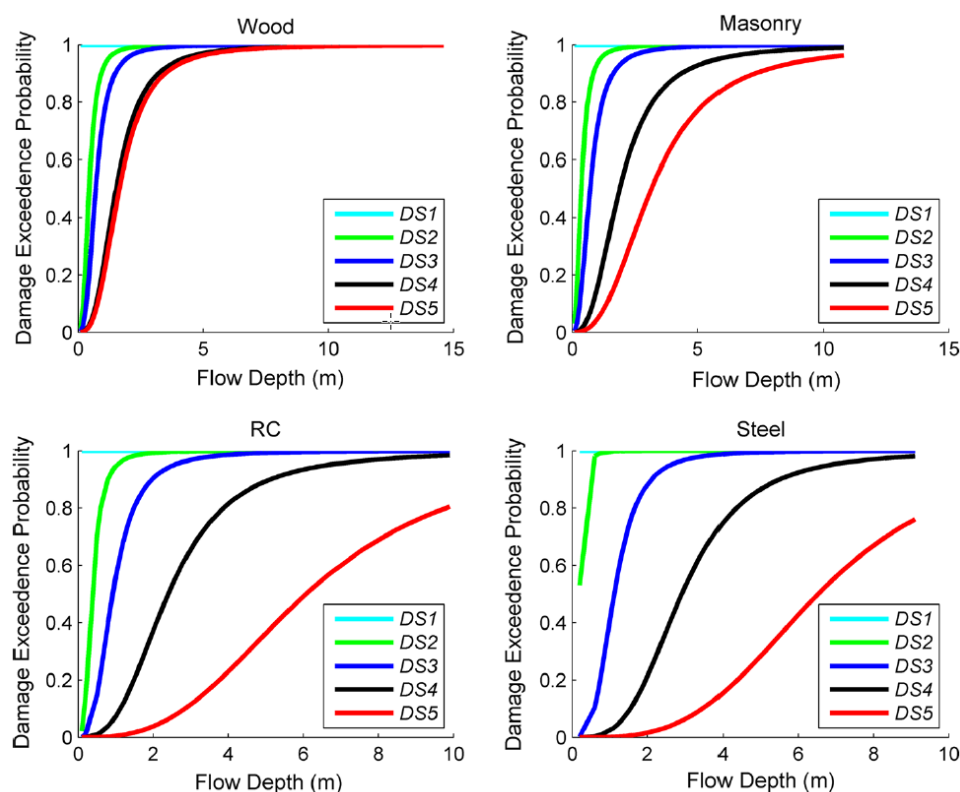


Figure A. 19 - Two-dimensional fragility functions for Kesennuma City following the 2011 Great East Japan tsunami (Charvet et al., 2015).

Charvet et al. (2015) also undertook a multivariate analysis using improved statistical methods to develop 3-D fragility surfaces based on flow depth, velocity, structure material, damage state, and debris impact; an example of which is provided in Figure A. 20. They found that flow depth alone is a poor predictor of damage for the stronger construction types (such as reinforced concrete (RC) and steel) at higher damage states, and suggested that both flow velocity and debris impact were important parameters (refer Figure A. 21). The work concluded that the approach provided better fits to the available damage data, but still showed a high level of uncertainty such that further research is required particularly into debris impact, numerical modelling methods for estimating velocities, scour effects, and the influence of additional parameters such as combined depth and velocity.

Charvet et al. (2017) undertook a review of the current state of knowledge in relation to estimating tsunami-induced building damage through fragility functions. The review found that flow depth is the main measure (referred to as Tsunami Intensity Measure or TIM in the paper) adopted in literature, as it can be readily determined from field assessments. Other information such as velocity is important at higher damage states, but difficult to measure in the field without pre-deployed instrumentation. Therefore, estimates of velocities rely on hydrodynamic models that are typically only validated for inundation depth or run-up extent. Park et al. (2013 and 2014) examined the sensitivity of modelled tsunami inundation water level, velocity and momentum flux to overland friction to show that although a tenfold reduction in friction had minor impacts on surface elevation (15% increase), velocity and momentum flux were more sensitive with increases of 95% and 208% respectively. When considering hydrodynamic forces (which are typically proportional to the velocity squared) then the sensitivity can become substantial.

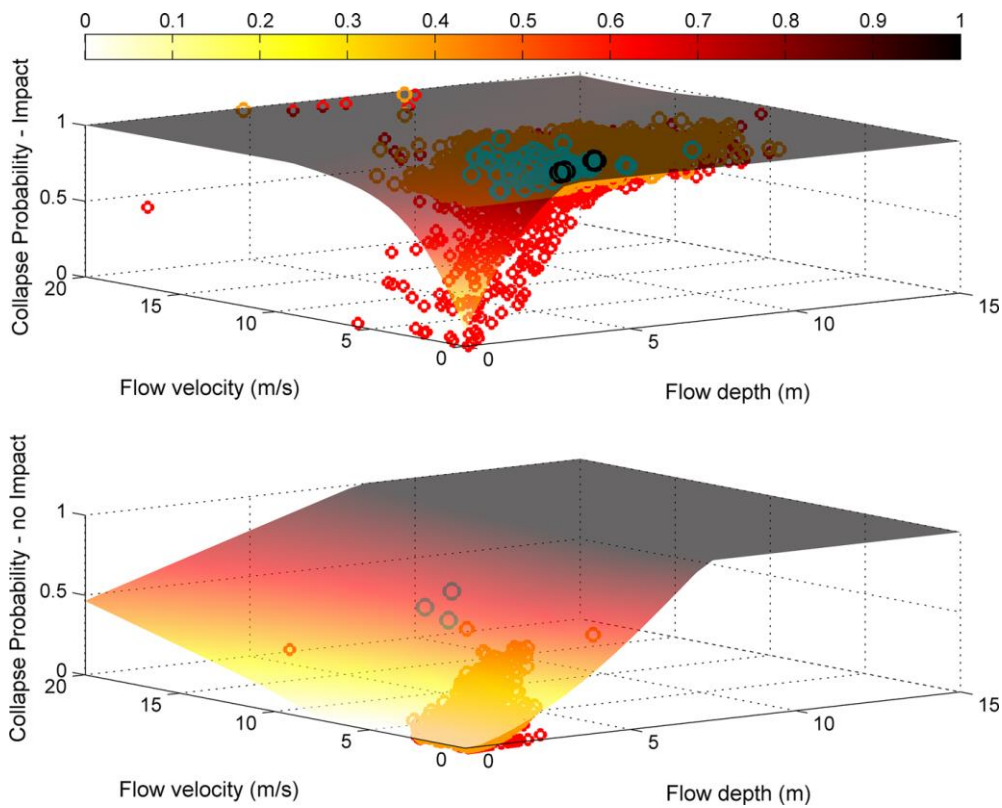


Figure A. 20 - Example fragility surfaces showing the probability of collapse (DS5) for wood buildings, with and without debris impact (radius: 130 m) based on field survey data following the 2011 Great East Japan tsunami (Charvet et al., 2015).

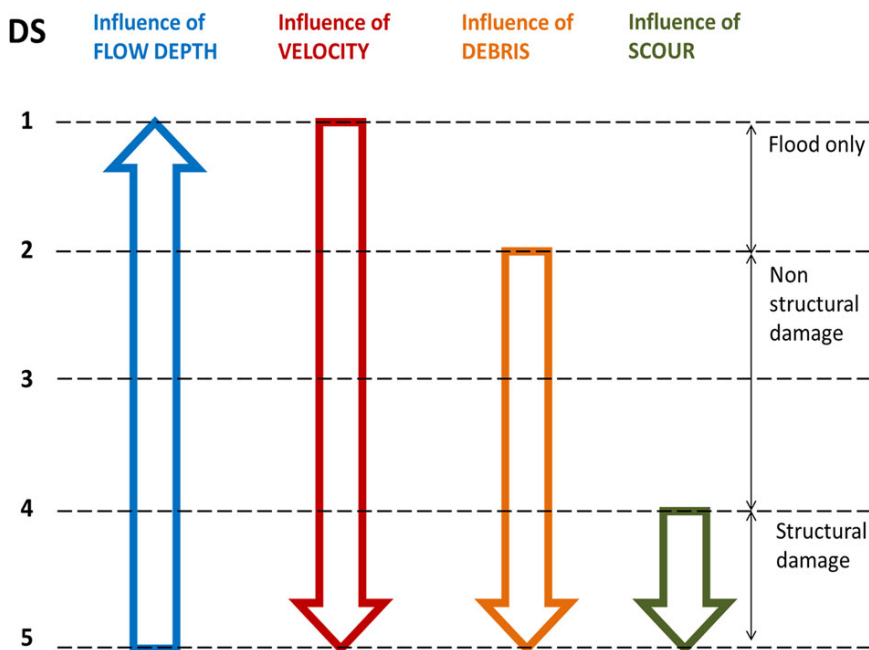








Figure A. 21 - Schematic representation of the contributions of different tsunami intensity measures to the severity of observed damage (Charvet et al., 2015).

Table A. 4 - Damage state definitions used by the Japanese Ministry of Land Infrastructure Tourism and Transport following the 2011 Great East Japan Earthquake (source: Charvet et al., 2017).

Damage	State	Description	Use	Image
DS1	Minor damage	Inundation below ground floor. The building can be reused by removing mud below the floor boards.	Possible to use immediately after minor floor and wall cleanup.	
DS2	Moderate damage	The building is inundated less than 1 m above the floor.	Possible to use after moderate repairs.	
DS3	Major damage	The building is inundated more than 1 m above the floor (below the ceiling)	Possible to use after major repairs	
DS4	Complete damage	The building is inundated above the ground floor level	Major work is required for re-use of the building	
DS5	Collapsed	The key structure is damaged, and difficult to repair to be used as it was before	Not repairable	
DS6	Washed away	The building is completely washed away except for the foundation	Not repairable	

Charvet et al. (2017) also concluded that fragility relationships that have been developed are not necessarily comparable or translatable to other locations due to a number of factors including choice of tsunami intensity measures, building codes (for example engineered structures in Japan versus non-engineered structures in Indonesia), differences in damage state criteria and mutual exclusiveness of each defined damage state, building classifications, field assessment approach (field survey by qualified personnel or remote sensing), completeness of database records, and variations in statistical approaches. Research into fragility functions following the 2011 Great East Japan tsunami also showed they can be location specific, sensitive to local bathymetry, topographic features, building distribution, and the presence of coastal defences. For locations that were also subject to the earthquake, it is difficult to separate earthquake related damage or contributions such as liquefaction. It was therefore concluded by Charvet et al. (2017) that for the

development of fragility functions for locations where damage data is not available, analytical methods for fragility function derivation based on structural analysis are required, incorporating multiple TIMs.

The above discussion outlines the complexity and issues of developing generic vulnerability curves for Tsunami. UNESCO (2015) provides some generic median damage states from Nanayakkara and Dias (2013) for single-storey buildings constructed from commonly used materials based on inundation depth (Table A. 5). The table is based on the median of data from Sri Lanka and Thailand during the 2004 Indian Ocean tsunami, as well as Samoa during the 2009 South Pacific tsunami. Data from the 2011 Great East Japan tsunami were intentionally omitted as these structures performed better given they were newly constructed with proper quality controls. It is likely that Australian building codes would also have higher quality controls.

Table A. 5 - Median inundation depth ranges by construction and damage state (reproduced from UNESCO, 2015).

Damage State	Timber (T)	Masonry (M)	Reinforced Concrete (RC)
Complete (H6)	~1.6 m	2.3–2.5 m	5.4–7.3 m
Major structural (H5)	~1.3 m	~1.9 m	~3.5 m
Minor structural (H4)	~1.2 m	1.3 m	1.4–1.9 m
Non-structural (H3)	0.3–0.5 m	0.3–0.5 m	0.3–0.5 m

Figure A. 22 summarises Table A. 1 and Table A. 5 based on the lower limits for timber structures. Complete damage for masonry and reinforced concrete are also shown as lines. In Figure A. 22, H1 relates to “generally safe for people and buildings” adopted from the general riverine flood vulnerability curves (Figure A. 17), and H2 represents no structural damage. The figure only provides a general indication of potential vulnerability, and should only be used with due consideration of the limitations mentioned above.

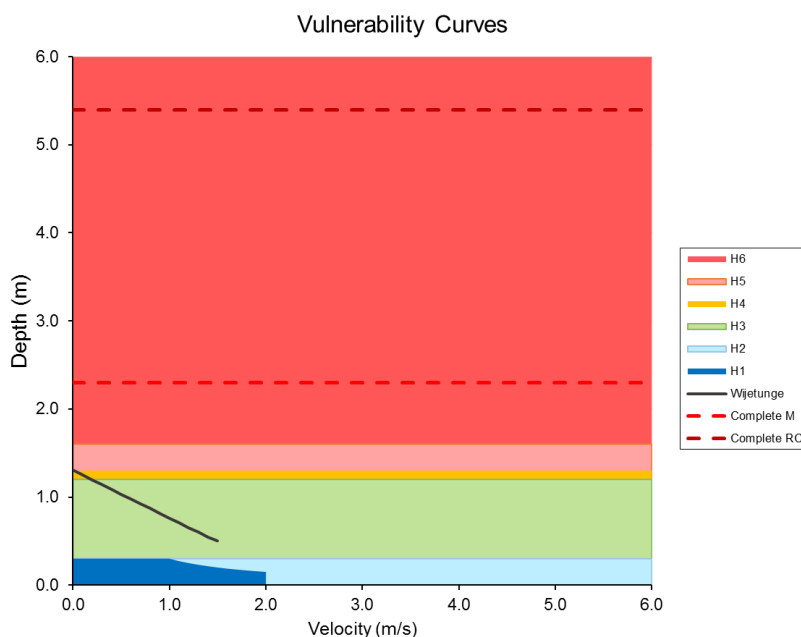


Figure A. 22 - Combination of general vulnerability curves for tsunami inundation.

A.6 Further Information

As discussed above, tsunami generation, propagation and inundation can be complex. Further information can be found in UNESCO/IOC (2010), IOC (2012), IOC (2016), Murata et al. (2010), Bryant (2014), Mofjeld et al. (2004), Geist (1998 and 2009), Synolakis and Bernard (2006), and Borrero et al. (2015). Useful websites include those of National Oceanic and Atmospheric Administration (NOAA, 2018a), the International Tsunami Information Center (ITIC, 2018), and a website produced by the COMET program (UCAR, 2010).

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Appendix B – Model Calibration

B.1 Introduction

The standard approach to calibrating 2D hydrodynamic models involves adjusting model parameters such as bed roughness, horizontal eddy viscosity, and bathymetry to match measured water level and/or velocity data collected within the study area. This may involve a range of conditions that are expected to influence the local hydrodynamics. Once calibrated, the model is then validated against measured events.

As explained in Boswood (2013), the availability of measured tsunami events along the Queensland coast is scarce, and inundation mapping from historic events is non-existent. As tidal water level data are more readily available, the 2013 study (Stage 1) calibrated the regional models against tide water level predictions for 83 sites over a spring tide period in January to February 2011.

For consistency, the current study undertook to calibrate against predicted tides for the same period considered in the Stage 1 study (Boswood, 2013). However, due to the computation time required to model tides over the 39-day period for the fine resolution Stage 4 mesh, a subset of two weeks from 15–28 January 2011 was considered. This represented a spring to neap cycle.

B.2 Tide Data and Boundary Conditions

Calibration is based on astronomical tides only (no meteorological component). Model results are compared against predicted tides for sites where tidal constituents are available. This provides a good measure of model skill with minimal complication from uncertainty in model boundary condition data that can occur by introducing meteorological components from forecast or hindcast models.

Boundary conditions were provided by a larger scale tide model of the Coral Sea, originally developed in 2006 (Callaghan et al., 2007), and later refined for Stage 1 (Boswood, 2013) (refer Figure B. 1). The open boundaries of the regional tide model are forced by water levels defined by eight harmonic constituents previously provided by the National Tidal Centre. Inland areas were omitted from the modelling to reduce computation times.

For this study, thirteen prediction sites within the model domain were considered, with eight sites within the detailed mesh study area (Bundaberg, Burnett Heads, Elliot Heads, Urangan, Ungowa, Boonlye Point, Elbow Point, and Waddy Point).

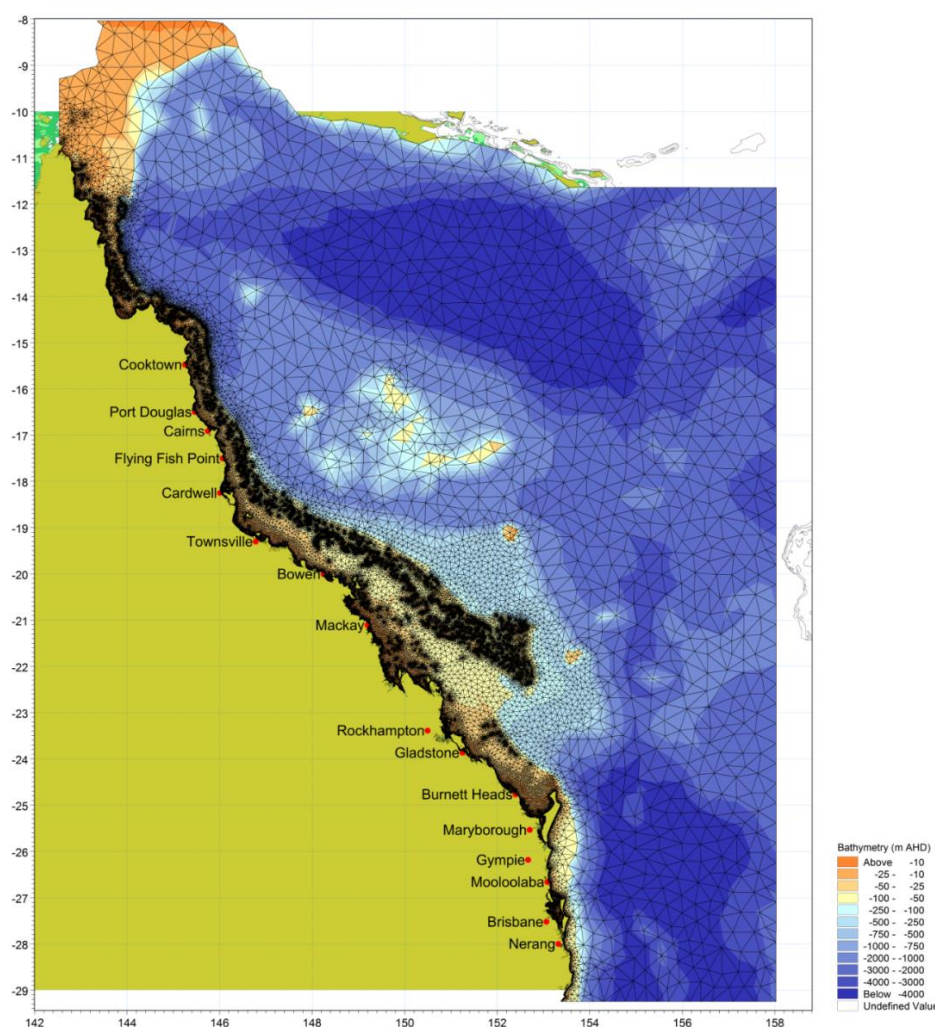
B.3 Assessment Approach

The calibration undertaken in Stage 1 involved assessing the skill of the model. The assessment was based on the Index of Agreement (IofA) (Wilmott, 1981), the Coefficient of Determination (R^2) (Kreyszig, 1999), along with the Root Mean Square Error (RMSE) normalised to the amplitude of the Highest Astronomical Tide (HAT) (that is, the height of HAT above Mean Sea Level (MSL)). The criteria adopted are detailed in Table B. 1. The skill scores provide a statistical measure of agreement between the observed (predicted tides) and modelled data.

Table B. 1- Skill score classification (Boswood, 2013).

Criteria	lofA	R ²	RMSE (percentage)
excellent	>0.95	>0.925	<10
satisfactory	0.85–0.95	0.85–0.925	10–20
poor	0.5–0.85	0.5–0.85	20–30
reject	<0.5	<0.5	>30

The resulting calibration for Stage 1 indicated that over 90 per cent of the 83 sites to be of excellent agreement and 99 per cent to be above satisfactory based on this criteria. Only one site was deemed to be poor, but the tide site is located within Runaway Bay on the Gold Coast which is not adequately resolved within the Stage 1 mesh (Boswood, 2013).

**Figure B. 1 - Regional tide model domain (Boswood, 2013).**

B.4 Calibration Results

The Stage 3 study for Moreton Bay (Boswood et al., 2018) assessed a range of uniform Manning's roughness values between $n=0.02$ to 0.03 (Manning's $M = 50$ to 33.3), as well as variations in the horizontal eddy viscosity based on the Smagorinsky formulation (Smagorinsky, 1963). Each scenario was scored in a similar way to the Stage 1 assessment and the best performing scenario overall was chosen for final modelling.

The Stage 3 study found that increases in roughness had little influence on the open coast sites due to the narrow continental shelf, and some reduction in ranges and increased lag in tidal phase within Moreton Bay. Changes in eddy viscosity had little impact on the tides. The Stage 4 mesh is much larger than the Moreton Bay model, precluding any sensitivity testing for tides owing to the considerably computation times. The final calibration parameters for Stage 3 (constant Manning's M of 40 and constant Smagorinsky value of 0.28) were therefore applied to the current study calibration phase.

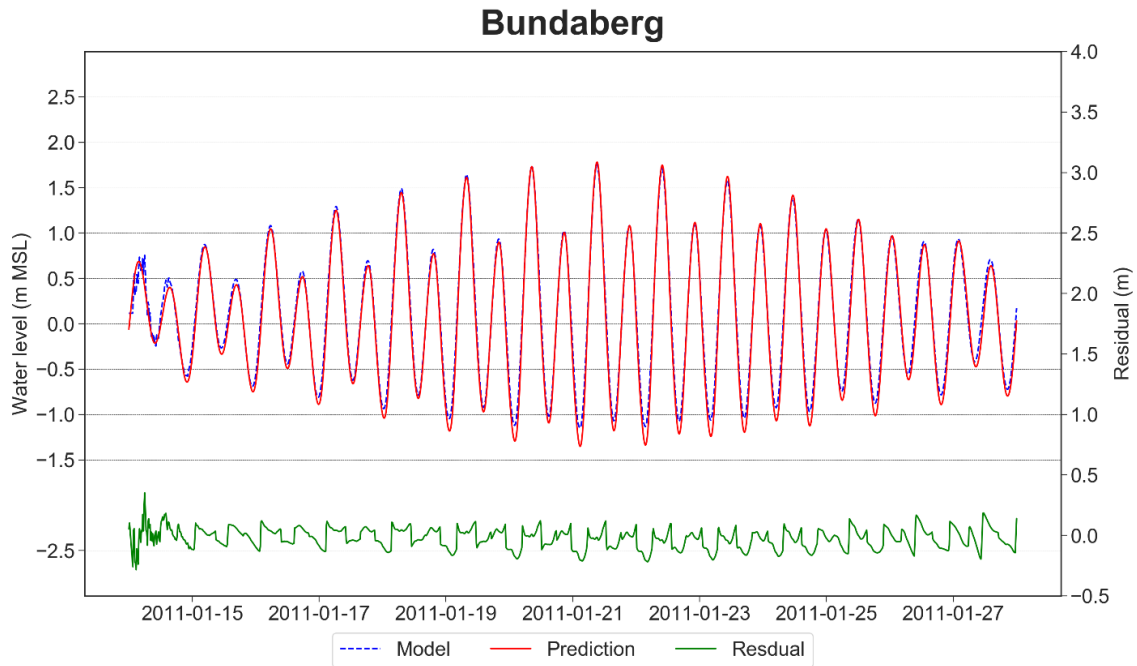


Figure B. 2 - A comparison of model results against predicted tides at Bundaberg.

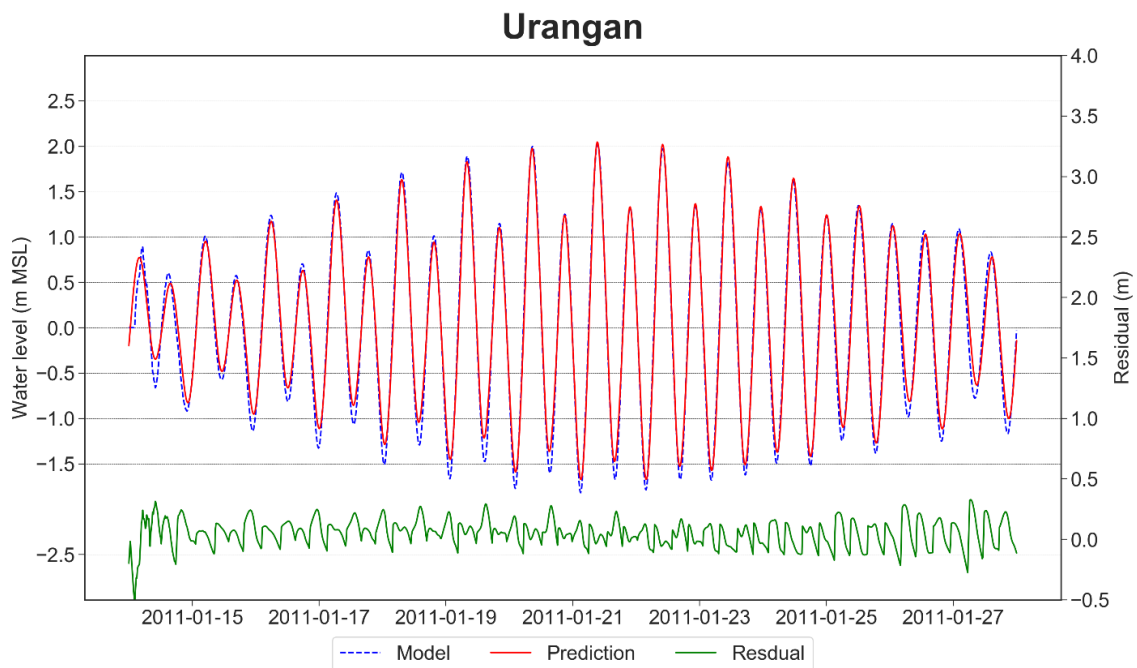


Figure B. 3 - A comparison of model results against predicted tides at Urangan.

Figure B. 2 and Figure B. 3 demonstrate the performance of the model for the chosen calibration parameters at Bundaberg and Urangan respectively. Overall, the results show excellent agreement for all but two sites, being Ungowa and Boonlye. Both of these sites are located within very shallow reaches of the Great Sandy Strait. The model results have excellent fit with predictions for tide stage above MSL. The poorer fit at low tide can be contributed to differences in specific bathymetry and site location compared to the actual tide prediction site where the original measurements were collected. Without this detail, it is difficult to improve the comparison for these sites. However, the fit is excellent for the tide levels to be considered for the tsunami scenarios – MSL and HAT. This is an improvement to the previous calibration during Stage 1, an expected outcome given the finer resolution and improved bathymetry data sets applied to Stage 4. The results indicate that the model captures the hydrodynamics associated with long period tides.

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Appendix C – Validation and Sensitivity Testing

C.1 Introduction

The original Stage 1 model (Boswood, 2013) was validated against the 2007 Solomon Islands tsunami event that was captured by the then Queensland Environmental Protection Agency's (EPA) storm tide monitoring network. Given the purpose of Stage 1 was to assess nearshore amplification up to the 10 m depth contour, this model was coarser than the current mesh and did not include overland flooding (i.e. a fixed land boundary at RL -0.5 m AHD). The previous validation was therefore revisited for the current mesh.

C.2 2007 Solomon Islands Tsunami Event

On 01 April 2007, at about 20:39:58 UTC, an 8.1 magnitude earthquake occurred at latitude 8.481° south and longitude 156.978° east as a result of shallow thrust faulting along the boundary of the Pacific plate with the Australia, Woodlark, and Solomon Sea microplates (Hayes et al., 2017). The epicentre of the quake was about 43 km south southeast of Gizo in the Solomon Islands, and approximately 540 km west northwest of the capital Honiara (EPA, 2007). The earthquake (which lasted for more than one minute) generated a tsunami that devastated the local islands with run-up heights up to 12.1 m, resulting in 52 deaths and destroying 2,500 buildings (McAdoo et al., 2008 and NOAA, 2018b). Over three hours later, the tsunami started to reach the Queensland coastline. The waves that were measured by a number of Queensland tide gauges were of much smaller magnitude. Amplitudes along the east coast of Queensland were typically less than 0.1 m with the exception of Clump Point and Rosslyn Bay, which recorded in the order of 0.25 metres (EPA, 2007).

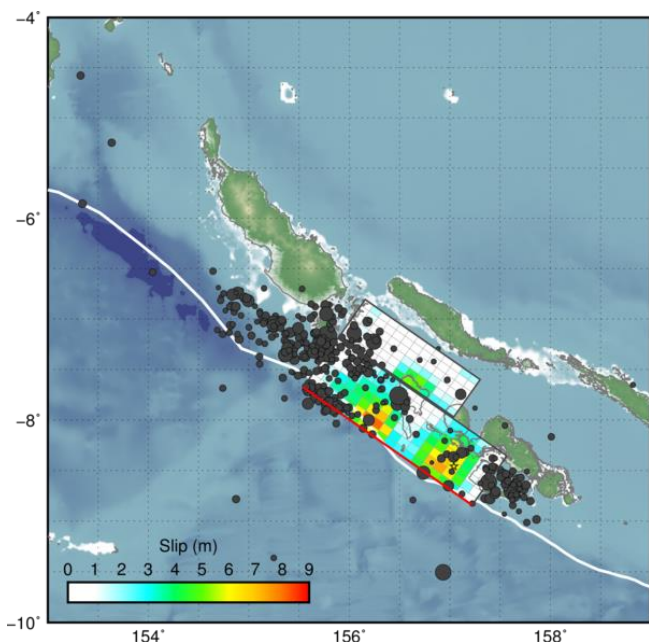


Figure C. 1 - Surface projection of the slip distribution for the 2007 Solomon Island earthquake superimposed on GEBCO bathymetry (USGS:

<https://earthquake.usgs.gov/earthquakes/eventpage/usp000f83m#finite-fault>).

A number of sources describe the sea bed deformations with some variations. NOAA (2018b) refers to an uplift of up to 3.6 m and subsidence down to 1.5 m, resulting in reports of tsunami

waves between 2 to 10 m. USGS (2018b) have the origin at latitude 8.466° south and longitude 157.043° east with a depth of 24 km (last updated 7 February 2017). Their preliminary finite faults analysis is shown in Figure C. 1 based on two segments with a strike of 305 degrees and dip of 14 and 30 degrees respectively. Their modelling of the earthquakes implies a fault area of 200 x 80 kilometres.

Based on a fault area of 180 x 60 km, a 300 degree strike and 14 degree slip, Koshimura (2018) developed the deformation map shown in Figure C. 2. Further information about the earthquake can be found in Fisher et al. (2007) and Chen et al. (2009).

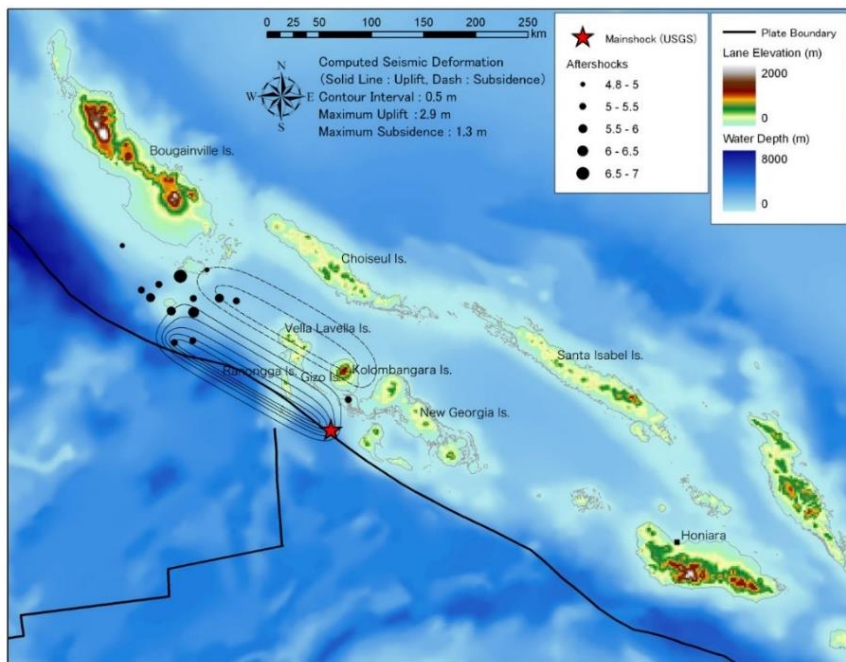


Figure C. 2 - Seabed deformation during 2007 Solomon Island earthquake (Dr S Koshimura:
http://www.tsunami.civil.tohoku.ac.jp/hokusai2/disaster/07_Solomon/event.html)

C.3 Tsunami Event Data and Boundary Conditions

The 2007 Solomon Island tsunami event was captured by the then Queensland Environmental Protection Agency's (EPA) storm tide monitoring network at a 1 min sampling rate. There are four measurement sites within the model domain, with two of those situated within the study area being Burnett Heads and Urangan.

Boundary conditions for the Stage 4 model, in the form of water level and depth averaged velocity time series, were obtained from the Stage 1 validation model (as shown in Figure C. 3).

The offshore boundary of the Stage 1 validation model is located at 158° longitude. The north-east corner has been clipped to be more parallel with the wave crest, connecting to the south-east extent of Papua New Guinea (refer Figure C. 3). As the tsunami was generated from an earthquake some 500 km north of the north-east corner of the mesh, boundary conditions in the form of a varying water level time series along the open offshore boundaries were provided courtesy of Geoscience Australia (GA) and consists of a maximum leading wave ranging between 0.7 m in the north and 0.05 m in the south. Although the land boundary was based on a GIS shapefile polyline representing 0 m AHD, the depths along the boundary interpreted from the gbr100 DEM varied between -1.5 m and -15 m AHD. The mesh consists of 1,179,240 triangular elements with areas generally ranging from 17 km² offshore to 31,000 m² near the coast. This

equates approximately to an equivalent spatial resolution of 6 km offshore to 250 m along the coast. Finer meshes with equivalent spatial resolutions down to 50 m were incorporated in the vicinity of storm tide gauge locations. Tides were excluded, with the tsunami time series applied to a constant water level set to Mean Sea Level (MSL). The mesh extent and modelled maximum water levels are shown in Figure C. 3.

The Stage 1 model was re-run to provide time series output of water level and depth averaged velocities at the 1,000 m depth contour. This was then used as boundary conditions for the Stage 4 model.

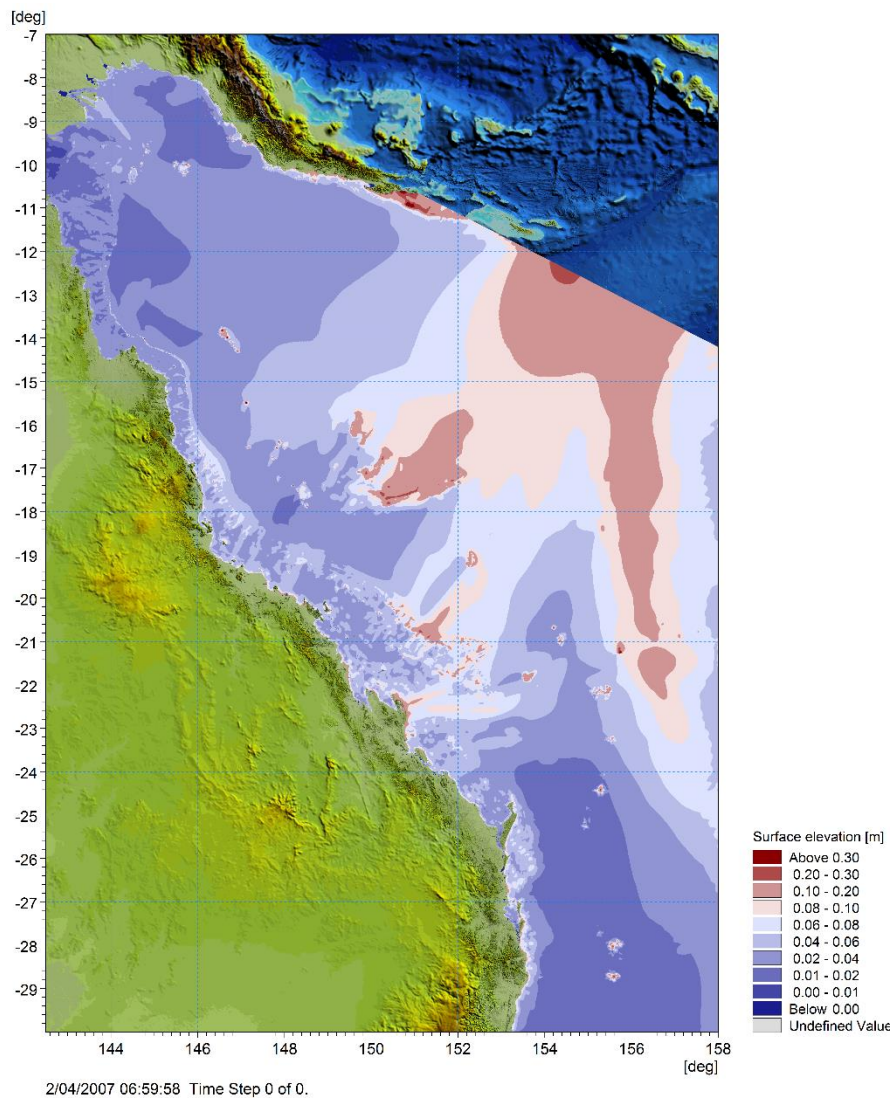


Figure C. 3 - Stage 1 mesh domain and maximum water level for 2007 Solomon Islands tsunami model validation.

C.4 Validation Results

The results of the validation for the Stage 4 mesh within the study area are provided in Figure C. 4 and Figure C. 5 for the two locations within the study area (Burnett Heads and Urangan respectively), and are summarised in Table C. 1 in terms of the maximum amplitude and Table C. 2 for arrival times. The two locations within the study area are located within boat harbours. The resolution is a maximum of 800 m² within the harbours, representing an equivalent length size of 30 to 40 metres. At this resolution, the detail of the breakwaters and shoreline revetments are not

fully captured. Therefore, the model will not capture secondary waves associated with reflections. The sites at Mooloolaba and South Trees are towards the limits of the model domain where the mesh is much coarser. The Mooloolah River is not resolved within the Stage 4 mesh as it is outside the study region. The model also does not replicate any tide effects.

There is also some uncertainty associated with the boundary water level time series as there were no offshore measurement sites in the Coral Sea to validate the Stage 1 model against, and as described in Pedersen et al. (2005) and Luger and Harris (2010), it is possible that there may be some numerical dispersion with a 6 km offshore mesh resolution. Sensitivity testing demonstrated that the model became too dispersive when the offshore mesh resolution was increased. The boundary conditions for the Stage 1 model are also the result of a model run from Geoscience Australia.

Despite these limitations, the modelled results perform well against the measured data in terms of arrival times and the maximum amplitude. Table C. 2 provides the measured and modelled arrival times relative to the time of the earthquake. The arrival time is defined as the time when the leading edge of the tsunami deviates by more than 1 cm from MSL. Determination of the recorded arrival times for the monitoring sites can be complicated by the tsunami amplitude being comparable in magnitude to the background meteorological fluctuations preceding the event. All sites are within 11 minutes of the recorded arrival times, the greatest difference being for Urangan for both arrival time and maximum amplitude. This could be a result of the model resolution not fully capturing the harbour detail and also the quality of the bathymetric data in this region. The measured amplitudes for Urangan are very low and are comparable with the residual that existed prior to the event, making it difficult to capture the pure tsunami signal from background noise. The growth in amplitude and the higher frequency oscillations not captured by the model suggests that there are other factors influencing tsunami amplitude within the harbour such as reflections and possible resonance.

Some sensitivity testing was undertaken by varying the roughness and horizontal eddy viscosity parameters similar to undertaken in Stage 3 (Boswood et al., 2018). However, there were only marginal changes to the modelled water levels, most likely contributable to the very small amplitudes being modelled.

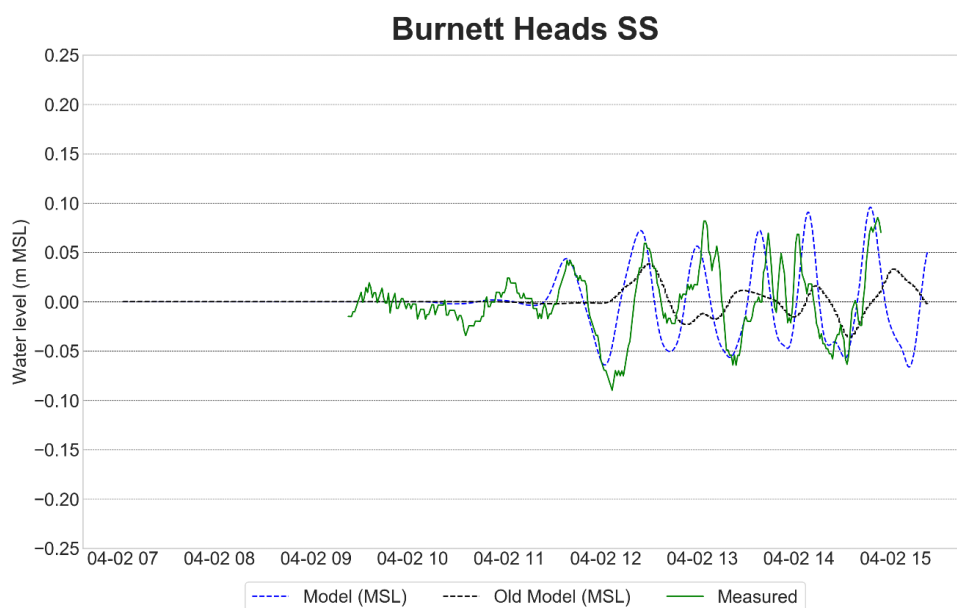
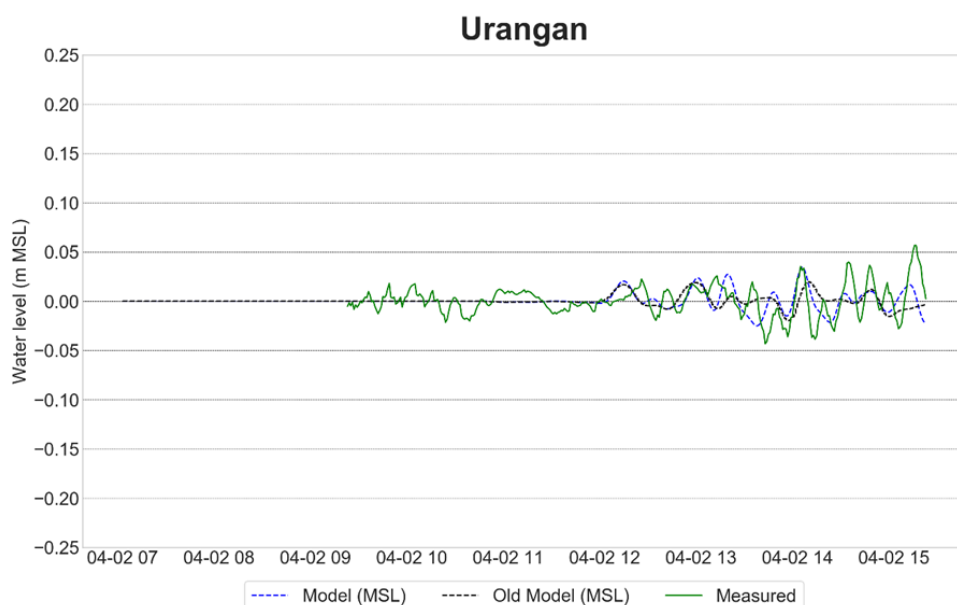
In general, the validation exercise for the 2007 Solomon Island tsunami event supports the use of MIKE21FM and the developed mesh for tsunami propagation studies. It is noted though that this validation has relied solely on one event.

Table C. 1 - Measured and modelled maximum tsunami amplitude for the 2007 Solomon Islands tsunami.

Site	Location	Measured Maximum Amplitude (m)	Stage 1 Max Amplitude (m)	Stage 4 Max Amplitude (m)
South Trees	Within Port Curtis protected by facing islands	0.03	0.11	0.03
Burnett Heads	Within Burnett Heads boat harbour	0.09	0.12	0.09
Urangan	Within Urangan boat harbour Great Sandy Strait	0.06	0.06	0.03
Mooloolaba	Pilot jetty within Mooloolah River	0.12	0.10	0.13

Table C. 2 - Tsunami arrival times following the 2007 Solomon Islands earthquake for select tide sites.

Site	Measured Arrival Time (h:min)	Stage 1 Model (MSL) Arrival Time (h:min)	Stage 4 Model (MSL) Arrival Time (h:min)
South Trees	5:36	5:30	5:33
Burnett Heads	4:51	5:29	4:46
Urangan	5:37	5:26	5:26
Mooloolaba	4:11	4:09	4:07

**Figure C. 4 - Comparison of modelled and measured water levels near Burnett Heads for the 2007 Solomon Island tsunami.****Figure C. 5 - Comparison of modelled and measured water levels at Urangan for the 2007 Solomon Island tsunami.**

C.5 Sensitivity Testing

The model's response to roughness and eddy viscosity parameters thus far has been consistent with Stage 3 (Boswood et al., 2018). Similar to Stage 3, the sensitivity testing undertaken during validation showed little sensitivity to these parameters. No sensitivity testing was undertaken during calibration due to lengthy computation times required to run tides on a large fine mesh. However, the calibration parameters adopted for Stage 3 also demonstrated excellent skill scores for the Hervey Bay model (refer Appendix B.4). Sensitivity testing during the Stage 3 calibration phase demonstrated that for tides, the model behaviour in terms of amplitude and phase were slightly sensitive to roughness, and to a lesser degree, horizontal eddy viscosity. This was more noticeable within the shallow bay.

Cardno (2013) undertook an assessment of tsunami inundation risk for the New South Wales government. Sensitivity testing undertaken in that study indicated that for seabed roughness, the model was not particularly sensitive, and a Manning's roughness, $n = 0.02$ was adopted. The report also discussed sensitivity to tides, structures, and overland roughness. It did not discuss viscosity as a sensitivity parameter.

To further test model sensitivity, Stage 3 undertook a number of runs for a 10,000 year ARI event at HAT for a range of Manning roughness values ($n = 0.02$ to 0.03), as well as a constant horizontal eddy viscosity, eddy viscosity as a function of depth, and viscosity defined by the Smagorinsky formulation (Smagorinsky, 1963). Stage 3 sensitivity testing found that the results for the open ocean showed similar results to Cardno (2013). That is, the tsunami is not particularly sensitive to open ocean seabed roughness and eddy viscosity. However, within Moreton Bay the model is sensitive to both parameters, more so for bed roughness with reductions in maximum water level with increasing roughness. As there were no measured tsunami events within Moreton Bay to assess the skill of the model for tsunami, a conservative approach was adopted by applying a constant seabed roughness of Manning's $n = 0.02$, with a constant Smagorinsky coefficient of 0.28 (default value).

Hervey Bay exhibits some similar characteristics to Moreton Bay in that it is a shallow bay with the main entrance facing northwards, and smaller entrances to the south. However Hervey Bay is generally deeper, particularly at the northern entrance being in the order of 20 m deep, whereas the numerous shoals across Moreton Bay's entrances are as shallow as 5 m. Such shallow depths only occur along the coastline and Great Sandy Strait within Hervey Bay. Therefore, the Stage 4 model is expected to be less sensitive to these parameters.

Given the performance of the model during calibration and validation, the same final parameters have been employed for this study: a constant seabed roughness of Manning's $n = 0.02$, with a constant Smagorinsky coefficient of 0.28 (default value). Overland roughness was defined by interpolation of the roughness mapping described in Appendix D.

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Appendix D – Overland Roughness Mapping

D.1 Background

The Mike21 software seeks to balance the external forces acting on a mesh cell with the local resistant forces. As a tsunami travels overland, it will experience obstacles and land cover that will obstruct or impede its motion. Including such structures within the model requires very fine mesh of 1 to 2 metres. Even smaller scale is required to capture features such as trees. However, the computation time of such a fine resolution over large extents becomes prohibitive, being considerably slower than prototype time and requiring large storage capacity for result files. At very fine resolution, the flow interaction with buildings can further complicate the problem. For problems focused on inundation extent and depths, a simplified approach has been broadly and successfully applied (for example Gayer et al., 2010). The approach replaces the obstacles with a representative roughness that replicates the behaviour of the obstacle in resisting the inland flow.

Typically, overland grid sizes are limited by computation (and storage) requirements. For inundation extent, grid sizes in the order of 5 to 50 m are typical for built-up areas, with larger sizes in areas of mostly uniform vegetation. These models are based on a “bare earth” DEM, that is the structures have been removed leaving only the ground surface. To facilitate the effect of obstacles, an apparent roughness is adopted, the value of which depends on the type and coverage of the obstacle relative to the area of consideration. Syme (2008) considered the apparent roughness to be a valid option for freshwater flood modelling, as this tries to replicate the effect of water being restricted as it flows through the building, whilst preserving the full storage covered by the building.

Roughness coefficients are typically adjusted to match measured inundation levels. However, such data for a tsunami event is lacking for the study region. Other approaches include determining roughness coefficients from physical models (for example Aida (1977), or Kotani et al. (1998)), or by adjusting numerical model inundation extents to match smaller scale numerical models that include buildings as solid structures (for example Gayer et al. (2010) or Cardno (2013)). MLITT (2012) provides guidance for tsunami inundation modelling and gives the roughness coefficients from Kotani et al. (1998) as an example. Stage 2 (Boswood, 2013b) adopted three values representing: ocean and waterways; beach and dune system; and built-up areas based on a range of values from Aida (1977), Kotani et al. (1998), Cardno (2013), and Garber et al. (2011).

Bricker et al. (2015) undertook a review of roughness values used in tsunami modelling. The paper concluded that the values provided by Kotani et al. (1998) were smaller than those based on field measurements and large-scale experiments for open channel flow (for example Chow (1959), Arcement and Schneider (1984), and Gibson (2005)). They attributed this to the physical model scales not being large enough to avoid the effects of surface tension and viscosity. Housing-density-dependent and flow-depth dependent urban Manning’s n relations (Koshimura et al., 2009) produce values similar to those found in open channel flow literature. Bricker et al. (2015) conclude that tsunami models would benefit from leveraging roughness values from open channel flow literature, and cites the work of Bunya et al. (2010), which provides an extensive list of Manning’s values based on land use mapping for a storm surge modelling study.

The approach applied to this study was the development of a detailed roughness map based on land use. Further detail is provided in the subsequent section.

D.2 Roughness Map Generation

Manning's values for onshore areas were chosen following a literature review of values as discussed above. The final list of values is provided in Table D. 1, based on the work of Bricker et al. (2015), Bunya et al. (2010), and Cardno (2013). This list has been purposely kept to a minimum, to reduce complicated areas that are at present, impossible to verify given the lack of tsunami inundation levels for actual events. It is expected that this will produce a more conservative result.

A number of different datasets were used to generate a land use map, listed below (refer to Table D. 1 for details), for which roughness values were then applied:

- Queensland Land Use Mapping – QLUMP;
- Queensland Digital Cadastral Database – QDCDB;
- Queensland Wetland Habitat Mapping.

The Queensland Land Use Mapping Program (QLUMP) was the principle dataset used. This is an aggregated product derived from a number of sources, including remote sensing and field survey developed and maintained by DES in collaboration with other government departments and councils. The dataset provides a series of land use categories and types which are sorted by a code. These were then mapped against the land use types identified in the literature review (refer Table D. 1). This provided the base layer for roughness mapping as it has no gaps. However for the purposes of detailed roughness mapping it missed a number of key elements including roads and detail in urban and coastal areas.

Table D. 1 - Table of Manning's values used with the model domain.

Land Use Category	Manning's n	Manning's M
Coastal Waters	0.025	40
Roads	0.02	50
Wetland Barren	0.030	33.33
Wetland Shrub	0.045	22.22
Grassland	0.030	33.33
Farmland	0.040	25
Coastal Woody Wetland	0.070	14.28
Forest	0.070	14.28
Low Density Urban	0.050	20
Medium Density Urban	0.100	10

To improve the QLUMP base dataset a number of subsequent layers were used, the QDCDB provided detailed cadastral information for roads and urban areas. Manning's numbers were assigned based on attribute information which contained details on land use. The Wetland Habitat Mapping layer was also used to better define vegetation areas in the coastal floodplains; this allowed better inclusion of Mangroves and Wetlands which have different roughness characteristic but were not separated within the QLUMP data. These supplementary layers were then stamped into the QLUMP data to produce a complete roughness map. Results were then reviewed against aerial mapping to produce the final roughness map. Figure D. 1 shows an example of the roughness map for Bribie Island.

The final land use map has the associated Manning's n and Manning's M (adopted by the MIKE21 software and is the reciprocal of Manning's n) within the attribute table, to convert the product into a roughness map. These are then tied to the model domain mesh node points using a spatial join and those values are ingested into MIKE21.

It is important to note that the final roughness values applied within the model are interpolations at the mesh nodes and therefore the resolution of the roughness map used within the model domain was dependant on the resolution on the model mesh. Figure D. 1 shows good agreement with the original roughness map.

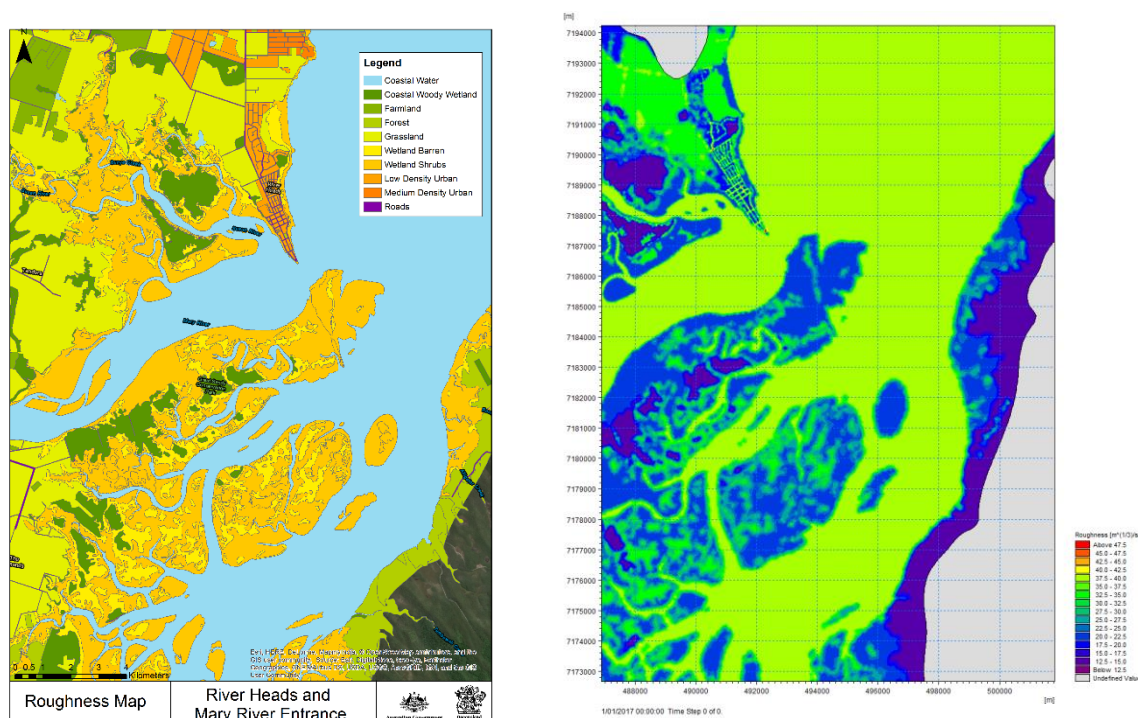


Figure D. 1 - Land use map example in the Great Sand Strait near River Heads, compared with the roughness map interpolated for the MIKE21 model.

D.3 References

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Appendix E – Tsunami Arrival Times

The following tables provide the arrival times for various Average Recurrence Intervals (ARIs) and subduction zones. The locations are shown in the following figures.

The boundary conditions showed two characteristics of the leading wave. The leading wave generated from the Kermadec-Tonga (KT) subduction zone exhibited a drawdown prior to the leading wave, symptomatic of a leading depression N-wave (LDN). Whilst the South America (SA) and New Hebrides (NH) wave forms were similar to a leading elevation N-wave (LEN) in form. Due to the differing leading wave forms, different criteria were developed for calculating arrival times for each subduction zone scenario as outlined below:

- Kermadec-Tonga and New Hebrides < 10,000 yr ARI – defined as a deviation of 2.5 cm away from the still water level.
- Kermadec-Tonga and New Hebrides 10,000 yr ARI – defined as an up-crossing deviation of 5cm from the still water level.
- South America – defined as an up-crossing or down-crossing of 5 cm from the still water level.

Table E. 1 - Arrival time statistics (hours: minutes after earthquake) for locations within Hervey Bay by ARI and subduction zones of Kermadec-Tonga (KT), New Hebrides (NH), and South America (SA).

Arrival Time (hours: minutes after earthquake) in Hervey Bay									
ARI (year)	750			3,000 (MSL)	3,000			10,000	
Source	KT	NH	SA	KT	KT	NH	SA	NH	KT
1. Bargara	6:25	4:29	20:15	6:35	6:31	4:44	18:15	4:43	6:28
2. Boonooroo	6:26	4:49	20:17	6:39	6:32	4:46	18:19	4:45	6:28
3. Booral	7:18	5:24	21:09	7:39	7:23	5:35	19:10	5:34	7:19
4. Burnett Heads	6:26	4:30	20:15	6:36	6:33	4:45	18:13	4:44	6:29
5. Coral Cove	6:28	4:32	20:18	6:38	6:34	4:47	18:19	4:46	6:31
6. Dundowran Beach	7:01	5:07	20:51	7:14	7:06	5:20	18:46	5:19	7:02
7. Kingfisher Bay Resort	7:20	5:28	21:12	7:36	7:25	5:35	19:14	5:34	7:21
8. Hervey Bay	7:05	5:10	20:54	7:21	7:11	5:25	18:47	5:23	7:06
9. Iris River	7:02	5:07	20:52	7:16	7:06	5:20	18:49	5:19	7:02
10. Moore Park	6:39	4:43	20:27	6:51	6:46	4:58	18:18	4:57	6:41
11. Point Vernon	6:56	5:01	20:47	7:10	7:02	5:16	18:46	5:15	6:58
12. Poona	6:16	4:40	20:06	6:32	6:22	4:38	18:07	4:37	6:18
13. River Heads	7:41	5:47	21:31	8:11	7:47	5:58	19:25	5:55	7:43
14. Tin Can Bay	6:23	4:46	20:14	6:39	6:28	4:43	18:15	4:42	6:23
15. Toogoom	7:02	5:08	20:52	7:15	7:07	5:21	18:47	5:20	7:02
16. Urangan	7:02	5:09	20:53	7:17	7:08	5:20	18:56	5:19	7:04
17. Woodgate	6:49	4:54	20:38	7:00	6:55	5:08	18:33	5:07	6:51

Table E. 2 - Arrival time statistics (hours: minutes after earthquake) for locations inside rivers by ARI and subduction zones of Kermadec-Tonga (KT), New Hebrides (NH), and South America (SA).

Arrival Time (hours: minutes after earthquake) in rivers									
ARI (year)	750			3,000 (MSL)	3,000			10,000	
Source	KT	NH	SA	KT	KT	NH	SA	NH	KT
18.Burnett River Entrance	6:33	4:38	20:23	6:44	6:39	4:51	18:22	4:49	6:35
19.Bundabarg West	7:17	5:24	21:07	7:31	7:22	5:31	19:04	5:29	7:18
20.Bundaberg Central	7:15	5:22	21:05	7:28	7:20	5:30	19:02	5:28	7:16
21.Bundaberg East	7:11	5:17	21:00	7:24	7:16	5:25	18:58	5:23	7:12
22.Mary river	8:24	6:29	22:12	8:49	8:30	6:34	20:04	6:31	8:26
23.Maryborough	9:49	7:48	23:35	NAN	9:54	7:34	21:24	7:51	9:47

Table E. 3 - Arrival time statistics (hours: minutes after earthquake) for locations outside Hervey Bay by ARI and subduction zones of Kermadec-Tonga (KT), New Hebrides (NH), and South America (SA).

Arrival Time (hours: minutes after earthquake) outside Hervey Bay									
ARI (year)	750			3,000 (MSL)	3,000			10,000	
Source	KT	NH	SA	KT	KT	NH	SA	NH	KT
24.Beer Beer Creek	5:20	3:32	19:09	5:28	5:27	3:44	17:04	3:44	5:22
25.Eurong	5:34	3:54	19:22	5:42	5:41	3:59	17:15	3:58	5:36
26.Fraser Island	5:13	3:23	19:03	5:21	5:20	3:37	16:58	3:36	5:16
27.Inskip	5:40	4:05	19:28	5:49	5:47	4:05	17:19	4:04	5:43
28.Rainbow Beach	5:38	4:04	19:25	5:46	5:44	4:03	17:18	4:03	5:40
29.Sandy Cape North	5:29	3:37	19:19	5:41	5:35	3:49	17:23	3:48	5:31
30.Sandy Cape Outside	5:11	3:19	19:01	5:20	5:19	3:34	16:58	3:33	5:14
31.South Fraser Entrance	5:43	4:09	19:32	5:52	5:50	4:09	17:26	4:08	5:46

Based on the above criteria, events from the New Hebrides have the shortest arrival time of just over 3 hours after the earthquake, with events from South America arriving much later at over 17 hours.

