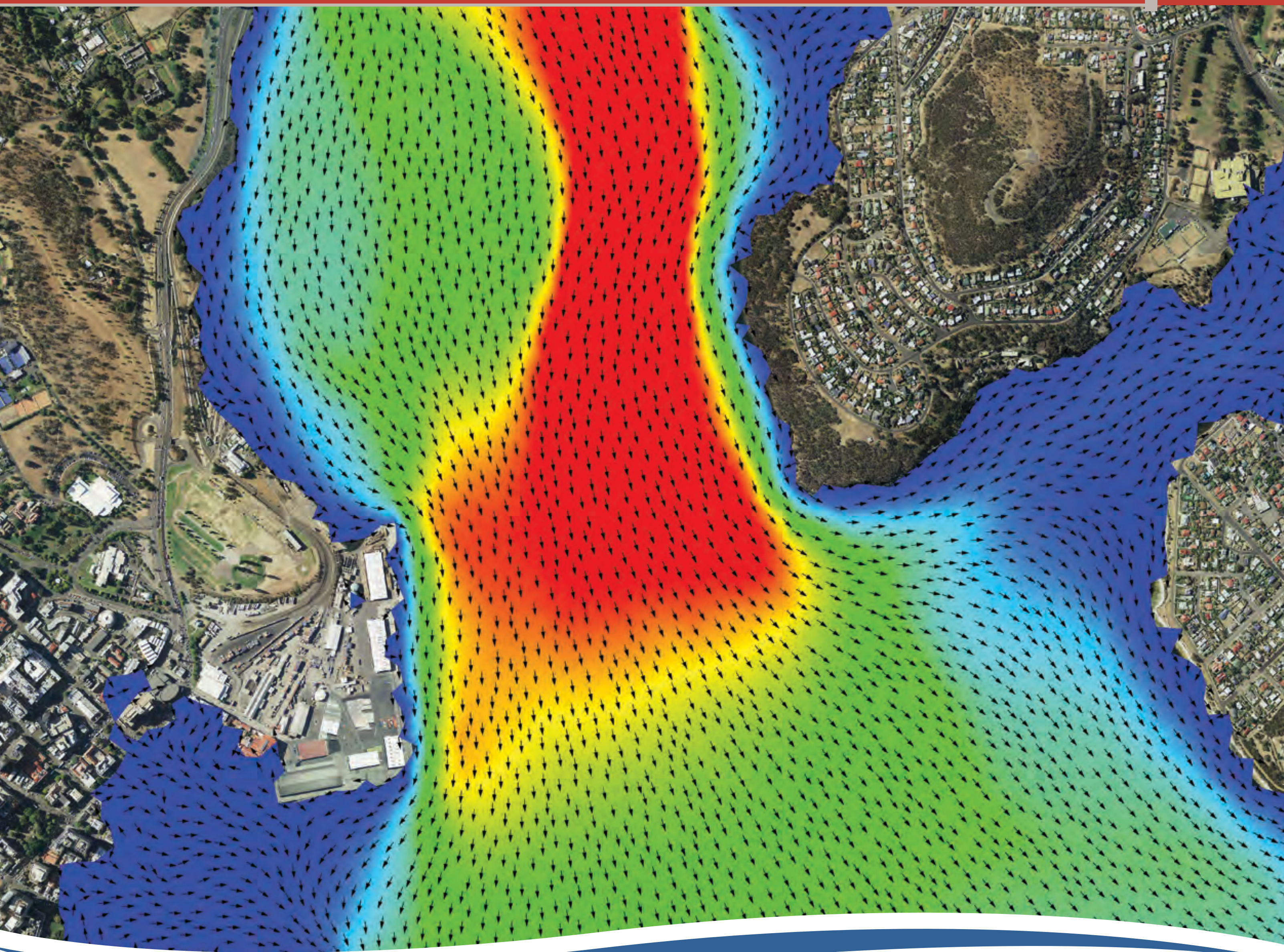
Technical report on

TSUNAMI INUNDATION MODELLING IN SOUTH EAST TASMANIA



Mineral Resources Tasmania
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TSUNAMI INUNDATION MODELLING IN SOUTH EAST TASMANIA

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Cover image: *Snapshot of the simulated tsunami momentum as the receding wave travels down the Derwent Estuary.*

Tasmanian Geological Survey Record UR2018_02

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EXECUTIVE SUMMARY

Tsunami modelling undertaken by Geoscience Australia (GA) in 2009 indicated that Southeast Tasmania could be significantly impacted by a maximum credible tsunami generated from a rupture of the Puysegur subduction zone, which is located off New Zealand's southwest coast. Since the release of the GA report, emergency managers in Tasmania have sought greater detail on areas of potential inundation and have raised further questions regarding maritime hazards that were not in the original GA project brief. Mineral Resources Tasmania (MRT) received funding from the Natural Disaster Resilience Grant Programme in order to re-model the impacts of a maximum credible earthquake/tsunami/high tide scenario in southeast Tasmania (a Mw 8.7 earthquake that represents a 1 in 13000 year tsunami hazard) using newly available high-resolution data and to explore the maritime hazard posed by such an event. The study area extends from South West Cape to Bicheno and covers an area of 17 000 km^2.

The main body of this report documents the methods, results and implications of this project. All data, scripts, map outputs and contributing reports have been reproduced in the Appendices (supplied digitally on the attached DVD).

Modelling was performed using the ANUGA hydrodynamic modelling library, which is free and open source code that was developed by GA and the Australian National University (ANU). The modelling strategy comprised five scenarios, of which the first two were designed to reproduce the 2009 modelling and validate our new input data. The Maritime Hazard scenario (Scenario 3) was run as a 13 hour simulation of tsunami activity, with the Coastal Inundation modelling (Scenario 4) and Airport Hazard plus Dune Erosion modelling (Scenario 5) run as 4 hour simulations.

Modelling results predict severe inundation (> 4 m) in exposed eastern coastal areas (Tasman Peninsula, Eaglehawk Neck, Bruny Island). Significant but less severe inundation (≤ 3 m) is predicted at Hobart city waterfront and many of the embayments on both shores of the Derwent estuary. The maritime hazard assessment suggests that the expected water disturbance would pose a significant threat to marine craft. The feasibility of shipping evacuation is questionable given the timeframes involved, and suggested management options for various shipping types are detailed in Appendix 3. Inundation and dune erosion modelling of the Hobart Airport vicinity shows that a tsunami of maximum credible magnitude would not breach the current dune line at Seven Mile Beach and so the airport would not be inundated. However, breaching could occur if the dune ridge was to be lowered or partially removed. Other areas where tsunami-induced dune erosion could cause greater tsunami inundation were also identified.

It is important to note that these results represent the risk from a maximum credible tsunami event and do not cover the variety of scenarios with different return periods and magnitudes that would be required for a comprehensive tsunami hazard assessment. From the map series produced in this study, an analysis of vulnerable places, properties and infrastructure should be undertaken alongside a review of Southeast Tasmania's tsunami emergency response plan(s). Particular attention should be focused on the maritime response procedures, given that the impacts of a large tsunami in the port of Hobart had not been investigated in detail prior to this project. Further detailed modelling of some of the heavily impacted eastern areas is also recommended (e.g. Eaglehawk Neck), as well as an investigation of the effect of the Hobart Rivulet on possible inundation at Royal Hobart Hospital. In addition, palaeotsunami studies would be useful to explore modelled inundation distances.

The key outputs from this project (in addition to the main body of this document) that may be most useful for tsunami planning and emergency management are as follows:

— A report detailing the maritime hazard assessment compiled by the Australian Maritime College (AMC; Appendix 3).

— A coastal inundation map series, which covers 71 coastal communities. These maps detail the maximum inundation extent, flooding depths and nearshore velocity at each location and provide a graph of tsunami water level fluctuations over time for each community (Appendix 4).

— Further comments on the results of the Hobart Airport inundation assessment and tsunami dune erosion modelling, performed by E Rigby (Appendix 5).

1. INTRODUCTION

The east coast of Australia, including Tasmania, is exposed to tsunamis originating from many source regions around the Pacific Ocean. Several small tsunamis have been recorded in Tasmania since 1858 (Morris and Mazengarb, 2009), but no large events have occurred in recorded history. However, geological evidence suggests the occurrence of three significant tsunami events, all of which occurred in the last 4 000 years (Clark et al., 2011).

In the absence of eyewitness records of damaging tsunami events, numerical modelling of tsunamis can provide a method of predicting potential impacts and investigating the risk to coastal communities. Modelling is a best approximation of reality, based on a number of assumptions and underlying data types. Assumptions can change with advances in knowledge and input data will improve over time, both of which may influence modelling outputs if run again.

In 2009 Geoscience Australia (GA) produced a tsunami inundation model for Southeast Tasmania (Van Putten, et al., 2009). Results indicated that parts of the coastline could be significantly affected by a tsunami generated from a Mw 8.7 rupture of the Puysegur subduction zone, off New Zealand's southwest coast (Van Putten et al., 2009). In the six years since the release of these results, emergency managers in Tasmania have sought greater detail regarding areas of potential inundation and have raised further questions concerning maritime hazard that were outside the scope of the original GA project.

Mineral Resources Tasmania (MRT) received funding from the Natural Disaster Resilience Grant Programme to re-model the impacts of a maximum credible earthquake/tsunami scenario in southeast Tasmania using newly available high-resolution bathymetric and topographic data and to explore the maritime hazard posed by such an event. The study area extends from South West Cape to Bicheno (Figure 1) and covers an area of approximately 17 000 km^2. The scope of the project includes a detailed investigation of maritime hazard for port areas, shipping and major coastal infrastructure, as well as a focused assessment of the risk to the Hobart airport runway and terminal from potential tsunami inundation.

The ANUGA modelling library (developed by the Australian National University and GA) was used to build a tsunami inundation model for Southeast Tasmania and to simulate shallow water wave propagation and coastal inundation from the maximum credible tsunami event. Since 2009, Light Detection and Ranging (LiDAR) data has become available for much of Southeast Tasmania, which allowed the construction of a high-resolution elevation (topographic) model that significantly improved the onshore model. Additionally, the inclusion of variable surface roughness and the development of a dune erosion operator have brought the modelling to a closer approximation of reality.

The modelling strategy comprised five scenarios, of which the first two were undertaken to test the modelling software and validate the methodology and input data. The remaining three scenarios (*) provide new results that will be of assistance to stakeholders to inform hazard and emergency management policies and plans. The five scenarios were as follows:

1) Repeat of the 2009 modelling, using GA's inputs
2) Coarse-resolution modelling using MRT's new inputs (model validation)
3) *Maritime hazard (13 hour simulation)
4) *Coastal inundation and hazard (4 hour simulation)
5) *Hobart airport hazard and dune erosion modelling (4 hour simulation)

1.1. Report structure

This report documents the methods, results and implications of the project. The main body of the report is intended to provide a cohesive overview of the project as a whole. Several contributing reports were prepared as part of this project and these are appended to this document (Appendices 2, 3, 5 and 11). In addition, detailed technical details of methods and challenges related to the input data construction are given in Appendix 1 for the benefit of researchers who may seek to reproduce the methods applied here. The primary outputs from this project include a series of inundation maps that show the maximum inundation depths, run-up limits and nearshore velocities for 71 coastal communities across the study area (Appendix 4). In addition, the raw data and time series graphs that informed the marine hazard assessment are provided in Appendices 6 and 7, alongside video animations of the simulated tsunami at various locations (Appendix 8) and site photographs showing areas of inundation (Appendix 9). An archive of the scripts developed and used for the modelling and post-processing of the data is also supplied (Appendix 10).

2. METHODOLOGY

Modelling was performed using the free and open source ANUGA hydrodynamic modelling library. An earlier version of this package was used by GA to generate the initial tsunami model for Southeast Tasmania in 2009. To run a simulation, a model specific set of Python scripts must be created by the user to reference the ANUGA library. The inclusion of new high resolution elevation information in the input data, along with the addition of variable surface roughness and dune erosion, has improved the approximation of reality compared with the 2009 base model.

ANUGA uses a finite volume modelling method for solving shallow water wave equations and the DE0 flow algorithm was used in this study. The modelled event constitutes a maximum credible (Mw 8.7) earthquake at the Puysegur subduction zone, as per the published Probabilistic Tsunami Hazard Assessment (PHTA) for Australia (Burbidge et al., 2008). This event corresponds with 'Event 1' in GA's 2009 modelling and represents a 1 in 13 000 year tsunami return period (Van Putten et al., 2009). The initial water level was set at Highest Astronomical Tide (HAT, equal to approximately 0.8 m above AHD), to represent a worst case scenario of tsunami and tidal interaction. However, the model was not run with a dynamic tide, as this would add considerably to the already heavy computational time. Furthermore, it would then be necessary to perform extra model runs to examine the sensitivity of the model to tidal phase.

The input data and modelling strategy are described below.

2.1. Input data types and preparation

Five main categories of input data were required to accurately model nearshore tsunami propagation and inundation:

1) Boundary condition hydrographs
2) Mesh resolution boundaries
3) Elevation model
4) Surface roughness model (Manning's Roughness Coefficient – *n*)
5) Gauge locations (points for time series data of simulated water level and current speed)

In addition, a polygon file was also required for Scenario 5, in order to specify areas where potential dune erosion may occur. The model for this scenario is discussed further in Section 2.2.1.

2.1.1. Boundary Conditions

The boundary condition hydrographs represent the incoming tsunami water level and momentum in deep water (100 m depth contour). These data are freely available from GA for a range of tsunami rupture and deep water modelling scenarios (Burbidge et al., 2008) and we have taken the levels for the above mentioned event as the inputs to our nearshore modelling.

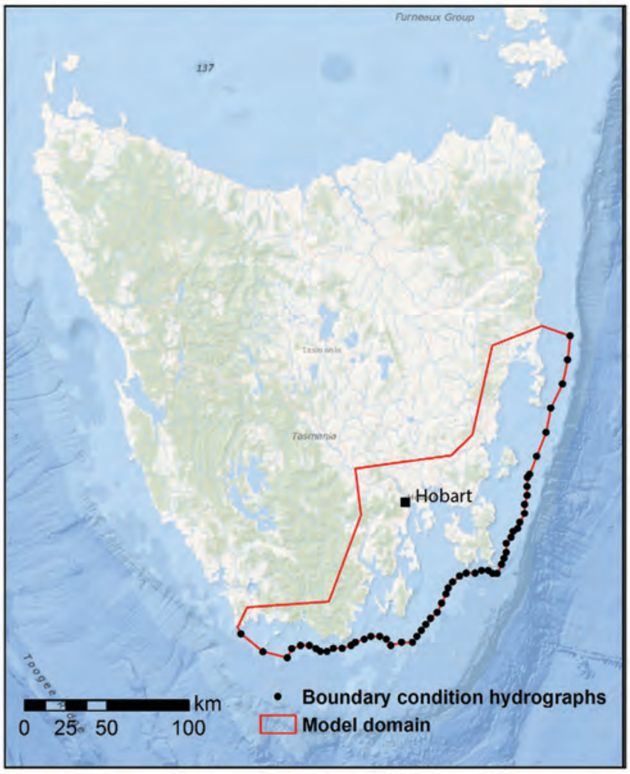


FIGURE 1: Location of the study area and boundary condition hydrographs. Base imagery from ESRI online.

2.1.2. Mesh Resolution

The resolution of the modelling mesh controls the level of detail of the modelling process and outputs; however, processing time increases substantially when a finer mesh is used. An unstructured triangular mesh was used, to allow variation in mesh resolution across the study area and to reduce computational overheads (Figure 2). A coarse mesh (400 x 400 m triangles) was used in open ocean areas and land areas above 15 m AHD, and a medium mesh (200 x 200 m) was applied to offshore areas between 10 m and 30 m depth. Non-urban coastal areas between – 10 m and + 10 m AHD were modelled at fine resolution (50 x 50 m) and urban areas of interest were modelled at very fine resolution (20 m x 20 m). An extra fine mesh (10 x 10 m) was used in two locations: Blackmans Bay and Hobart Airport.

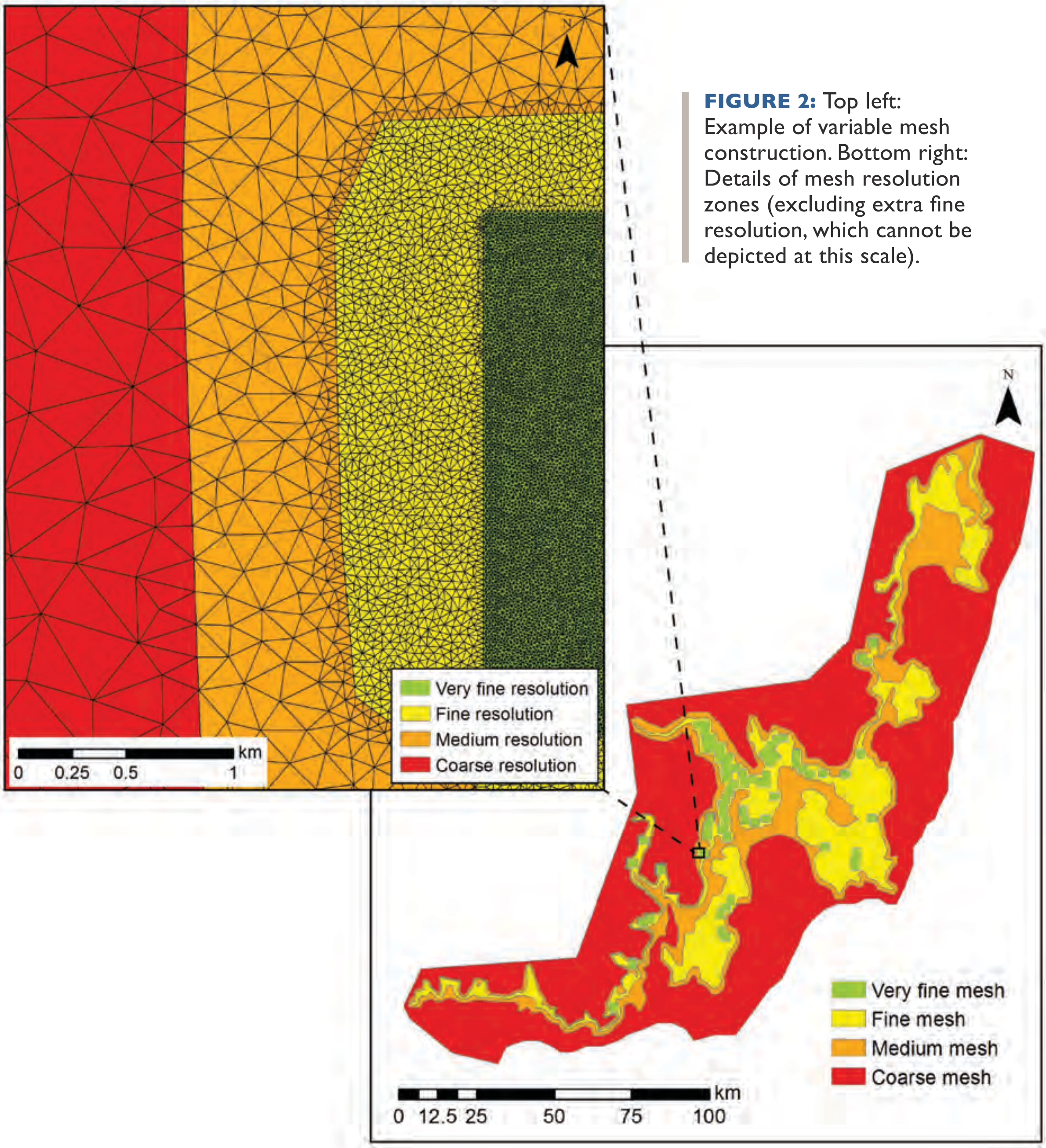


FIGURE 2: Top left: Example of variable mesh construction. Bottom right: Details of mesh resolution zones (excluding extra fine resolution, which cannot be depicted at this scale).

2.1.3. Elevation Model and Surface Roughness

The elevation model developed for the 2016 modelling was significantly enhanced from that used in 2009. A number of LiDAR datasets have since become available, which has improved the elevation control and resolution of topographic data in the current model. The model was constructed by combining bathymetric and topographic data from a variety of sources (described in detail in Appendix 1), using a digital terrain model built in ArcGIS.

Surface roughness is an important control on wave attenuation and run-up distances. Factors such as vegetation cover, rivers and the presence or density of buildings can result in considerable variation in flooding patterns. Variations in surface cover were mapped in ArcGIS and accounted for in the model, using the Manning's ***n*** parameter (e.g. Bricker et al., 2015; Chow, 1959). The Manning's *n* coefficient for each surface type is listed in Table 1 and a spatial representation is given in Figure 3. Note that the piers of Tasman Bridge were not included in the elevation model.

TABLE 1: Manning's *n* coefficients of roughness applied in the model, as assigned by surface type.

Manning's *n*	Surface Type
0.5	Solid buildings
0.071	Built-up areas
0.055	Vegetated areas
0.035	Land (default)
0.03	Bare ground
0.025	Water courses
0.018	Roads
0.01	Oceans and estuaries

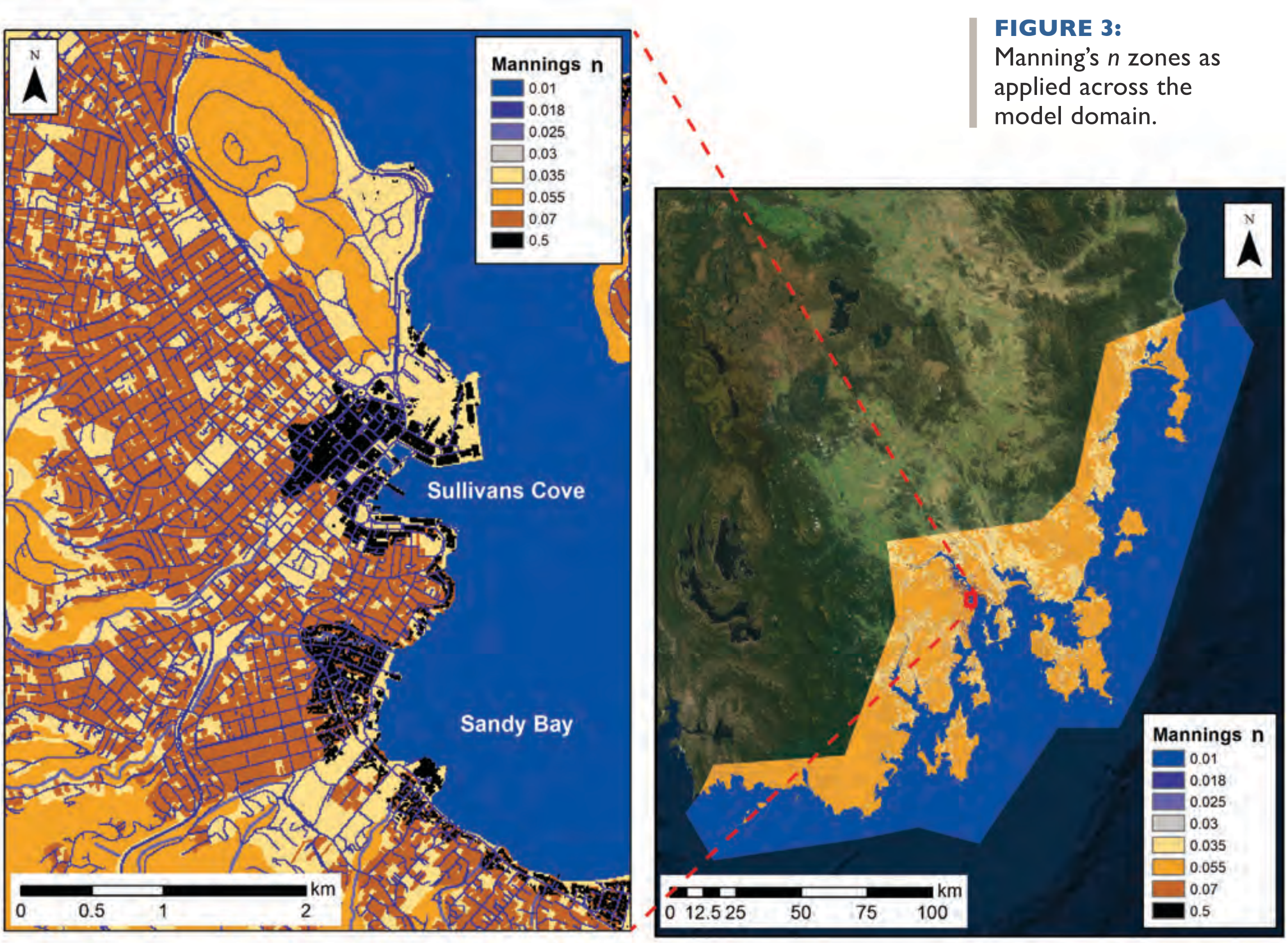


FIGURE 3: Manning's *n* zones as applied across the model domain.

2.1.4. Gauge Locations

Gauge locations refer to points of interest that were chosen to display time series data of water level and current speed. The GA 2009 gauges were retained to allow comparison of the models and a number of new gauges were added in areas where maritime hazard may be significant (e.g. shipping lanes, marinas, embayments). The locations of gauges used to inform maritime hazard are displayed in Figure 4.

Further detail of technical procedures and challenges related to input data construction is provided in Appendix 1.

FIGURE 4: Gauge locations for the maritime hazard scenario (Scenario 3)

2.2. ANUGA simulation

The tsunami modelling scripts were built in Python 2.7 and modelling was performed using high-performance computer hardware. In the case of Scenarios 3 and 4, processing was performed through cloud hosted computing on Amazon Web Service. The processing time for the longest model run (Scenario 3; a 13 hour simulation) was approximately 80 hours. However, a large number of technical difficulties were encountered in the modelling process, which slowed progress and required the assistance of the ANUGA developers at ANU to rectify. Details of the computing resources and processes are provided in Appendix 2.

The output files obtained from ANUGA are in .sww format. These are netcdf files, which are hierarchical files that can store multiple parameters for time-varying data in a compact manner. In the case of this modelling, the result files contain the values for water depth and momentum (x and y) at each mesh node for each time-step of the simulation.

2.2.1. Development of the dune erosion operator (Scenario 5)

In undertaking the simulations for Scenarios 3 and 4, it became clear that there were several locations where sand dunes were providing some level of protection for property or assets behind the dune line. Hobart Airport is one such location. To better understand and quantify the protection provided by these dunes, a new model was needed that could include consideration of erosion of the dunes during the simulation process. At the time the study commenced, ANUGA had no such functionality but it did include tools, in the form of 'Operators', which could be developed for this purpose.

A Python operator script was developed by Ted Rigby and incorporated into the model scripts for Scenario 5. The primary objective was to explore the level of protection afforded by the present (2015) Seven Mile Beach dune line, which separates Hobart Airport from the waters of Frederick Henry Bay. However, the opportunity was also taken to investigate the possible loss of protection at other potentially erosion prone sites in South Eastern Tasmania (Figure 5). Erosion was modelled at a lower resolution at these other sites, but results identify areas that warrant more detailed investigation in the future.

The development of the dune erosion operator is detailed in Rigby et al., 2017 (Appendix 11).

FIGURE 5: Location of the areas modelled with the active dune erosion operator in Scenario 5.

2.3. Post-processing and outputs

Raster and time series outputs were extracted from the .sww files and analysed in ArcGIS. The ANUGA source code contains functions to generate rasters from quantities stored within the .sww file, and Python scripts were developed to export rasters of maximum/minimum depth and calculate maximum velocity (from momentum). These rasters were analysed in ArcGIS to generate contours for offshore velocities and turbulent areas (maritime hazard) and inundation depths and distances (coastal inundation hazard). Raster, water level time series and contour data are all depicted in the final maps (e.g. Figure 6).

CSV files of time series data for water level and velocity were extracted at each gauge location using a Python script to call inbuilt time series functions in ANUGA. The CSV files were then analysed in R, to calculate the following parameters (definitions provided in the Glossary on page 27) for maritime hazard assessment: tsunami arrival time, maximum wave height, time of maximum wave height, period, wavelength, maximum current speed, maximum celerity (wave speed), maximum possible instantaneous speed (current speed + celerity), maximum water level, minimum water level and turbulence ratio (wave height: water depth). A summary table for all gauges was delivered to AMC to inform their marine hazard assessment (Appendix 6).

The final outputs include video animations of the modelled tsunami (Appendix 8) and a series of maps depicting maximum possible impacts, which show coastal inundation, offshore current velocity and potentially turbulent areas (Figure 6; Appendix 4). Video animations were generated in QGIS using an open source plugin called Crayfish (Lutra Consulting, 2016), which allows the visualisation of .sww/netcdf files in a GIS environment. The map series was generated in ArcGIS.

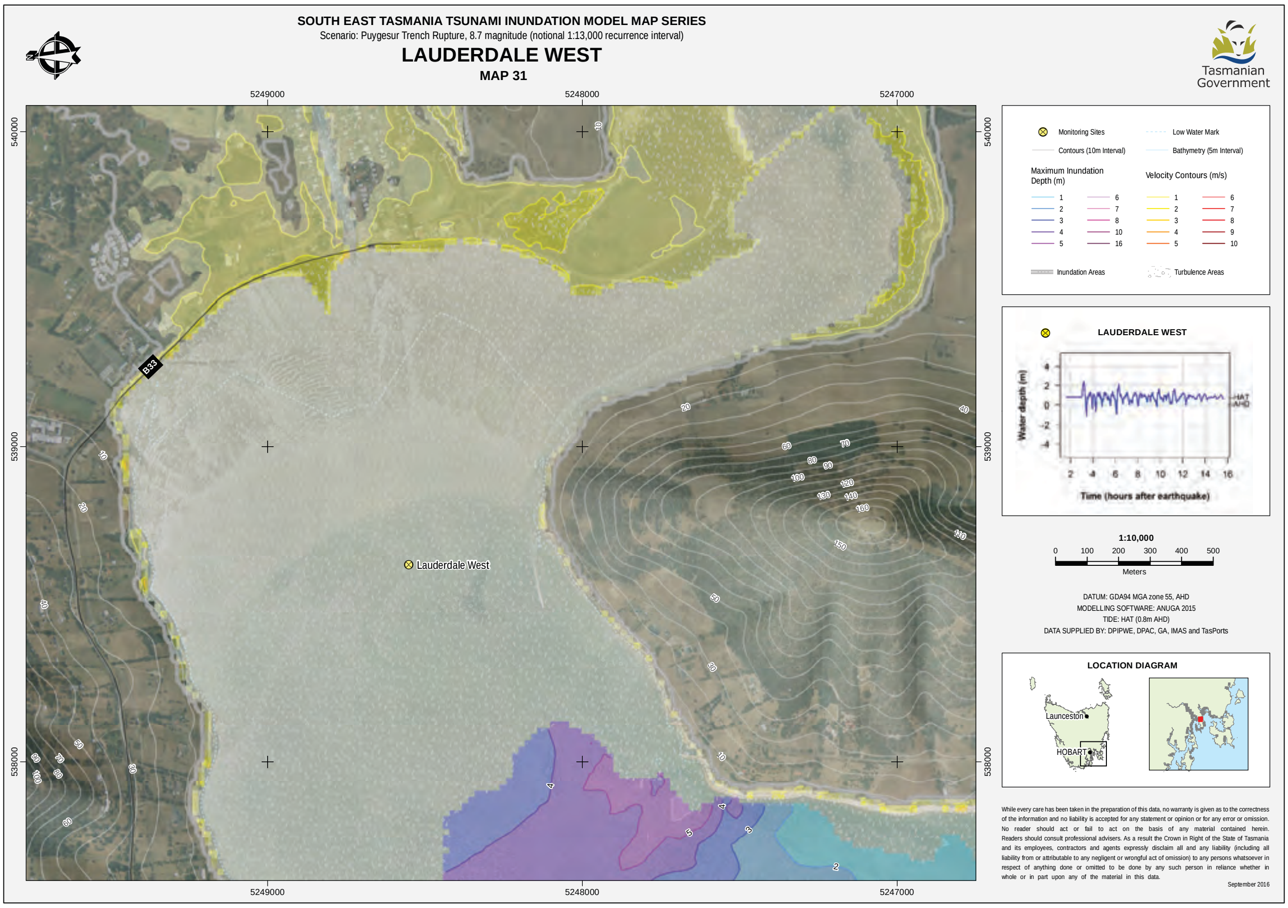


FIGURE 6: Example of a final inundation map. These were produced for 71 inhabited locations across the study area. Note that inundation depths and velocity/turbulence data are presented in raster form, while a time series graph of water level fluctuations is displayed to the right of the map image.

2.4. Field validation

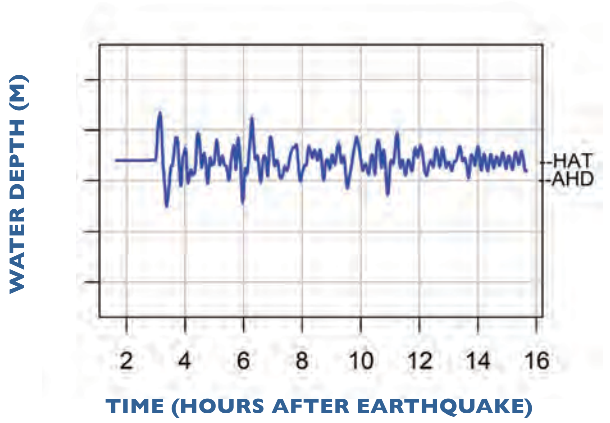
Site visits were undertaken in late February – early March 2017, in order to visually assess the inundation extents at important sites or areas where modelled impacts were significant. Sites were photographed and key infrastructure at risk of flooding was identified. In some cases, features were identified that may increase or mitigate the mapped risk; for example, subsurface drains could allow greater tsunami penetration, whereas dense vegetation may limit it.

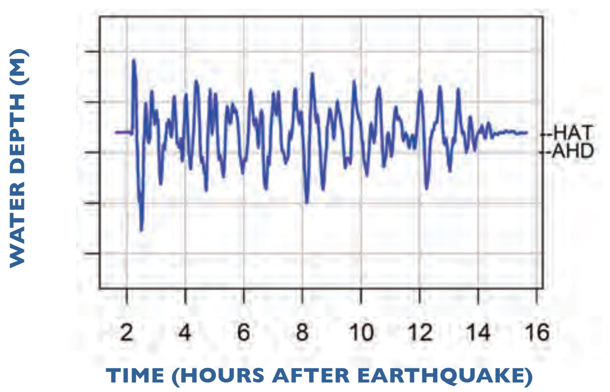
This validation exercise is not exhaustive. An additional study is needed to perform a risk assessment based on the findings presented here, and to develop appropriate emergency plans and responses.

3. MODELLING RESULTS

3.1. Scenarios 1 and 2 – Model testing and validation

These scenarios were undertaken to test our input data and modelling approach and results suggested our data and processes are robust. Scenario 1 involved replication of the 2009 GA model, using the original input data, in order to ensure there were no inconsistencies in results arising from use of the updated ANUGA version (2016) and new modelling scripts. The 2009 version of ANUGA is no longer available, so a total replication of the 2009 model was not possible. However, the results obtained by Van Putten et al. (2009) were duplicated using the latest release of ANUGA and new modelling scripts. Scenario 2 was used to develop the code with respect to the inclusion of the new elevation data, Manning's ***n*** layer and mesh resolution variations. The successful completion of this validation process provided the baseline for the following scenarios, which are discussed in detail below. Maritime Hazard will be discussed first (Scenario 3), followed by Coastal Inundation (Scenario 4) and a specific focus on Hobart Airport and Seven Mile Beach (Scenario 5).





3.2. Scenario 3 – Maritime hazard

The purpose of this scenario is to provide information on the potential hazards to shipping and maritime activity arising from a maximum credible tsunami in Southeast Tasmania. Results show the first tsunami wave would reach the exposed east coast approximately 2 hours and 10 minutes post-earthquake, and predicted tsunami arrival times for the principal shipping channel range from 2.5 hours post-earthquake (off Iron Pot) to 3 hours in the Hobart port areas. Water disturbance persists in the model for 13-15 hours at most locations. The Australian Maritime College (AMC) performed a maritime hazard assessment based on time series data of the modelled tsunami in the port of Hobart (e.g. Figure 7) and the full report is reproduced in Appendix 3. A record of the extracted data for each gauge (as per parameters described in Section 2.3) and time series graphs of water level and velocity are provided in Appendices 6 and 7.

The modelling results show the tsunami waves adhere to the general rules of wave behaviour in shallow water. As the wave approaches shore, the wave height increases and wavelength decreases. Simulated wave heights are generally lower in the shipping channel, becoming higher in the port and dock areas. The geometry of the subduction zone and rupture scenario is such that the wave would arrive as a leading peak, rather than a trough, which means the tsunami would arrive as a rise in water level rather than a recession. The modelled tsunami wavelengths are within the expected range (in the order of 500 m nearshore, to > 5 km offshore) and, consequently, the tsunami manifests as a gradual rise and fall in water level that occurs over a period of 10-20 minutes. Significant seiching and wave reflections are predicted in the channel and embayments, and these would generate considerable water disturbance and localised amplification. In particular, a funnelling of the tsunami energy is observed in the simulation as it passes through the narrow channel northwest of the Tasman Bridge, which may also be exacerbated by wave reflection from the steep bathymetry on the eastern shore.

FIGURE 7: Example tsunami gauge plots for Port Arthur (bottom left) and the primary shipping channel near Tasman Bridge (top left).

Within the principal shipping channel, modelled wave heights vary from 2.4 m at PSC6 (off Blinking Billy Point), to 5.1 m at PSC21 (off New Town Bay). Many values fall between 3.5 and 4.5 m. Maximum modelled wave speed falls between 15.5 knots (mid channel at the entrance to Prince of Wales Bay) and 32.7 knots (at PSC3, off Blinking Billy Point). Maximum induced current speeds are in the order of 2 to 7 knots and turbulence would not be expected in the shipping channel, as the water there is deep relative to the wave height.

The tsunami impacts would be variable in the port and dock areas. Maximum predicted wave heights range from 2.7 m at POW4 (INCAT jetty) to 5.0 m at Pauline Point marina and Prince of Wales Marine dock facilities (POW6). Maximum simulated wave speeds vary between 4.8 knots at POW4 (INCAT slipway) and 31 knots off Macquarie Point (HP19). In general, predicted wave speeds are < 10 knots within the dock areas and along the shore, but higher values occur further out in the channel. Turbulence would be expected in most port and dock areas, with Prince of Wales Bay, Macquarie Wharf and Princes Wharf particularly affected. A backup of water is observed in places, most notably at Constitution Dock. Following inundation by the first wave in the model, the water does not fully drain from the area before the arrival of the second wave and the water level remains at least 1.5 m higher than the starting level for the duration of the model run. However, at no point does the water height exceed that of the first wave peak level.

Based on the modelled results and a review of existing literature, a document advising of shipping hazards and outlining potential emergency response options has been developed by AMC (full report reproduced in Appendix 3). Potential consequences of tsunami include damage to boats and infrastructure from collisions, breakage of moorings due to water level or currents, spills and pollution, and foundering or sinking of smaller craft. Because most of the commercial shipping around the port of Hobart have drafts greater than the inundation levels, there is little likelihood of these ships being lifted onto the berth. However, there is a significant risk of vessels breaking adrift if moorings are not tended to deal with the rising and falling levels. This could cause major damage to the drifting ship, other vessels and infrastructure.

Given an evacuation warning time window of 1 hour and sufficient crew, pilot boat availability and standby engine power, it may be possible for some large ships to evacuate from Hobart port and Nyrstar/Risdon wharves. The decision to evacuate to deeper water depends on the available warning time and distance to deeper water, and in many cases it may be safer to remain in port and evacuate crew to higher ground. AMC have calculated specific mobilisation and evacuation times for vessels that frequent the Hobart port areas (summarised in Table 2), and this information is detailed in tables 15-18 of their report (Appendix 3). For smaller craft, the primary advice is to secure the craft and evacuate the crew to higher ground. Significant water disturbance and turbulence is expected at all marinas and anchorages around Hobart, making small craft manoeuvrability difficult and/or unsafe.

TABLE 2: Estimated time required to mobilise and evacuate to deeper water for ships that commonly frequent Hobart port.

		Estimated time to reach	
Location	Vessel type	Open ocean*	Deep water in shipping channel**
Nyrstar Wharf	Bulk carrier	2 hours 35 minutes	1 hour 20 minutes
Selfs Point Wharf	Oil tanker	2 hours 25 minutes	1 hour 25 minutes
Princes Wharf	*Aurora Australis*	1 hour 50 minutes	55 minutes
Macquarie Wharf	Cruise ship	1 hour 35 minutes	50 minutes

* 45 metres depth in Storm Bay

*** 33 metres depth off White Rock Point*

3.3. Scenario 4 – Coastal hazard and inundation

The focus of Scenario 4 was the onshore impacts of a maximum credible tsunami event. The results cover the entire model domain in Southeast Tasmania and a sequence of maps was generated at 71 key locations (Appendix 4). As previously explained, in Section 3.2, the tsunami wave would arrive as a rise in water level and predicted arrival times range from 2 hours and 10 minutes to over 3 hours and 30 minutes (Table 3). Simulated coastal inundation is generally greatest in areas that are directly exposed to the open ocean, or where rivers act as a conduit for inland penetration. The modelled impacts are summarised by region.

TABLE 3: Summary of tsunami arrival times (time from earthquake to first wave arrival) at key locations across the study area.

Location	Arrival time	Map number	Wider area for this arrival time
Off Iron Pot	2:30	19-22, 37-39	Harbour entrance and South Arm tip
Tasman Bridge	3:00	12-13, 27	Central city, Sullivans Cove, Bellerive
POW Bay	3:10	9-10	Selfs Point, Nyrstar
Maria Island Jetty	2:15	–	–
Triabunna	2:30	59	Spring Bay Wharf, Louisville Jetty
Kingston Beach	2:40	18-19	Blackmans Bay
Seven Mile Beach	2:40	40-41	Hobart Airport (not inundated)
Lauderdale East/West	2:50/3:00	31-33	–
Nubeena	2:10	56	–
Port Arthur	2:10	53-55	Oakwood, Carnarvon Bay
Orford	2:30	57-58	Shelly Beach
Eaglehawk Neck	2:10	52	Pirates Bay

3.3.1. Hobart City and Derwent Estuary

The upper part of the Derwent Estuary (Bridgewater to the Bowen Bridge) is largely unaffected by the simulated tsunami (Maps 1-8). However, flooding of coastal infrastructure and low-lying areas is predicted at the heads of more southern embayments on both shores, and these impacts are summarised below.

Most of the area surrounding Lutana and Prince of Wales Bay (Map 9) is above the maximum simulated inundation line, but overtopping could occur into the storm water pond at Nyrstar Wharf zinc works. Some flooding of low-lying areas is modelled for Prince of Wales Bay, as well as Cornelian Bay and New Town Rivulet (Map 10). Flooding could be exacerbated by the canal at New Town Rivulet, where the simulation suggests the tsunami would travel upstream along the watercourse and inundate residential areas adjacent to the canal, and may cover the Brooker Highway at the bridge.

Modelled flooding around the central Hobart waterfront (Figure 8; Map 13) extends up to 100 m inland in places, but depths are no more than 1 m. The results indicate that the wharf areas and surrounding carparks would be inundated, and that the water could penetrate through a low point at the head of Campbell St. The buildings along the waterfront would most likely be affected, as well as potential impacts for underground infrastructure (e.g. the carpark at the Hotel Grand Chancellor). At the southern end of Sullivan Cove, the predicted flooding extent reaches the Parliament Square gardens and covers the carpark between Brooke St Pier and Princes Wharf. However, most of Salamanca is beyond the predicted area of impact. The area around Tasman Bridge is also largely unaffected in the simulation, due to the steep topography at the coast (Map 12). Simulated inundation is also extensive in the low-lying parts of Sandy Bay (Map 14), extending over 200 m inland via the stream at Quayle St and flooding a significant number of residential properties between Quayle St and York St. Much of the Wrest Point complex would also be affected.

Further work is needed to determine whether or not the Royal Hobart Hospital is at risk of flooding via Hobart Rivulet. The above-ground inundation modelling suggests it is outside the flooding zone, but the elevation model did not include below-ground channels and there is potential for the tsunami to penetrate via the underground stream conduit and/or stormwater system and emerge adjacent to the hospital on Collins Street. A basic elevation check suggests that the hospital is above

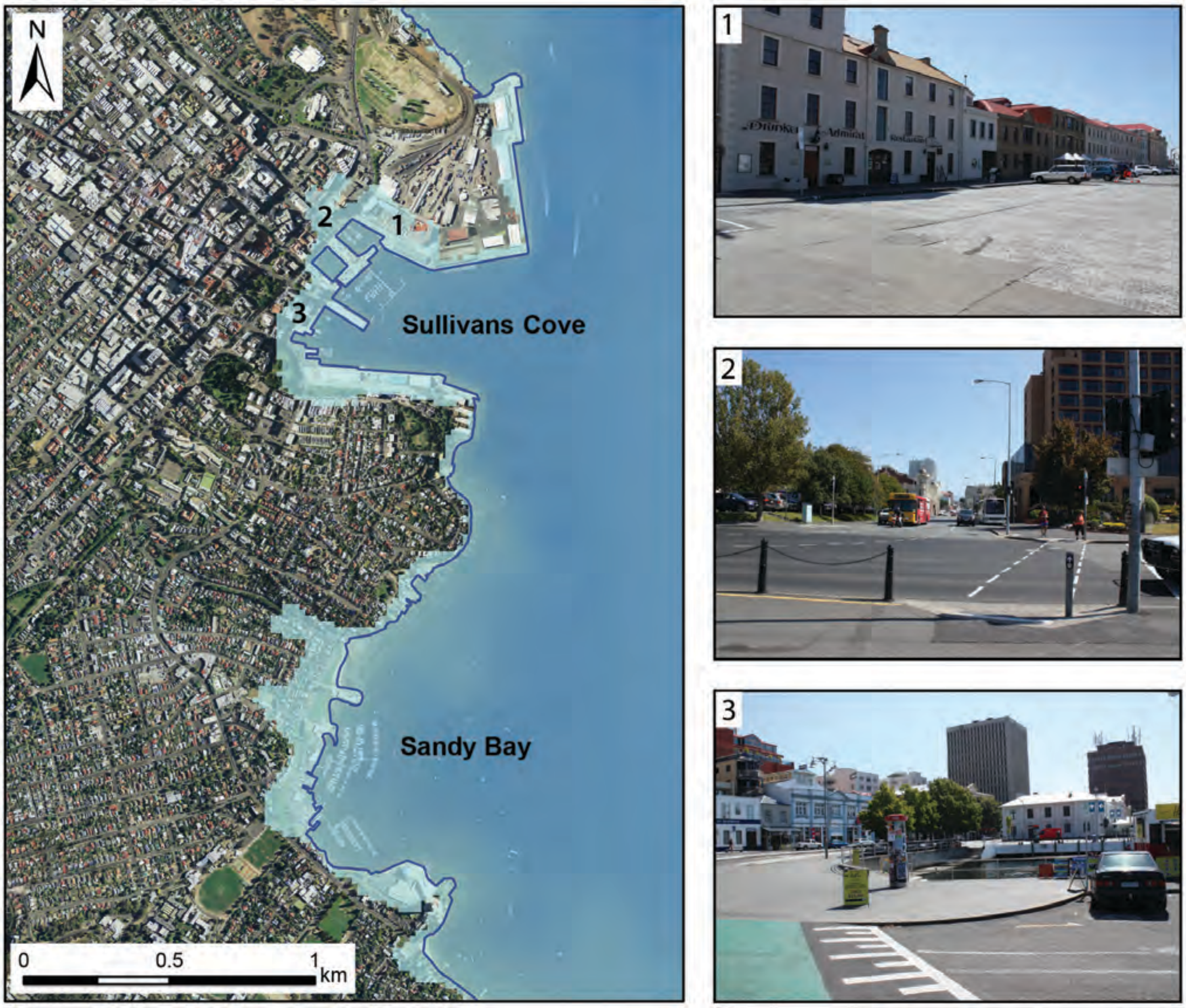


FIGURE 8: Modelled inundation in Hobart CBD and Sandy Bay, accompanied by field validation photos of areas that would be inundated around the city waterfront.

the maximum run-up elevation at the CBD (approximately 2.5 m AHD) and the bottom of the Hobart Rivulet channel on Collins Street is also above this value, at 2.75 m AHD. However, tsunami infiltration of underground systems is a complex process and some flooding of the hospital basement and ground levels could occur due to a backing up of water.

On the eastern shore, the modelling suggests that the tsunami would be funnelled into the narrow embayments between Geilston Bay (Map 11) and Bellerive (Map 27), causing flooding at the head of these areas and potentially impacting the nearshore marinas (Figure 9). Recreational areas at Geilston Bay, Lindisfarne and Bellerive would be flooded, and the modelled inundation extends beyond Rosny Hill Road at Bellerive/Kangaroo Bay. The impacts would be largely constrained to parks and recreational areas along the more open and undeveloped coastline between Bellerive Beach and Rokeby (Maps 28-30), but some flooding of residential properties could occur at Bellerive if the dunes were to be breached.

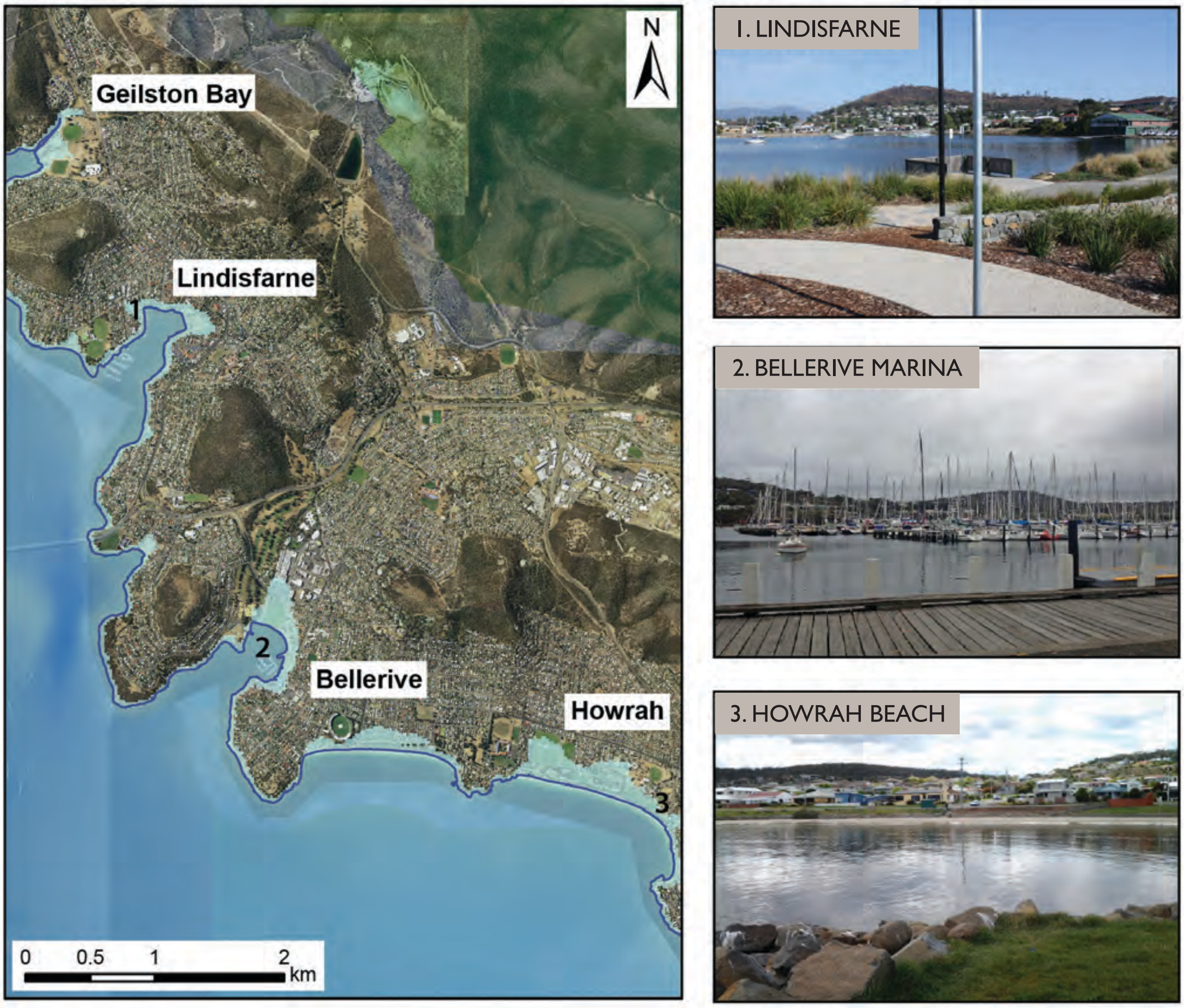


FIGURE 9: Maximum inundation extent in selected embayments along Hobart's eastern shore.

3.3.2. Airport-Carlton (Northern Frederick Henry Bay)

Simulated impacts are relatively minor in the areas to the north of Frederick Henry Bay (Maps 42-50). The modelled wave attenuates rapidly as it passes through the protected and shallow embayment, and so maximum water levels would generally be low in the surrounding settlements (Midway Point, Sorell, Lewisham, Dodges Ferry, Primrose Sands and Carlton). The airport and Seven Mile Beach (Maps 40-41) will be discussed in depth in Section 3.4 (Scenario 5).

3.3.3. Taroona-Tinderbox Point

Results suggest that flooding would be minimal or non-existent at Taroona, Bonnet Hill (Maps 16-17), Tinderbox Hill and Tinderbox Point (Maps 20-21), due to steep topography at the coast. Significant inundation is predicted at Kingston Beach (Figure 10; Map 18), with up to 2 m of inundation simulated in the residential streets at the coast, and 1 m further inland. The tsunami would also travel up the river, flooding part of the low-lying golf course and riverside flats. A limited number of properties would also be affected at Blackmans Bay (Figure 10; Map 19), but predicted impacts are generally restricted to within 100 m of the beach and flooding depths of < 1 m.

FIGURE 10: Maximum modelled inundation extent at Kingston and Blackmans Bay. A stormwater drainage conduit is present at Blackmans Bay and could result in inundation distances that are greater than predicted.

3.3.4. Ralphs Bay and South Arm

Results suggest that tsunami impacts around Ralphs Bay and South Arm would be highly variable, with some localities heavily impacted while others would remain largely unaffected. Inundation maps show Lauderdale could be extensively flooded from both the ocean and the canal (Figure 6; Maps 31-33), affecting a large number of houses, and South Arm Neck (Map 37) would be overtopped at several locations. In contrast, Clifton Beach and Calvert Beach (Maps 35-36) would not be particularly affected. A small number of properties are situated in the predicted inundation zone at Opossum Bay and Cremorne (Maps 39 and 34 respectively), but otherwise impacts would be generally restricted to the beachfront at these two locations.

3.3.5. East Coast and Tasman Peninsula

This area would likely be the most heavily impacted in the modelled region. In particular, simulated water levels at Eaglehawk Neck (Map 52) reach 14 m AHD and severe flooding could occur through dune breaching and overtopping (Figure 11). This extreme water level arises from the interaction of the tsunami wave with the shape of Pirates Bay in the simulation. We suggest this water level not be taken at face value, as the reality could vary with a small change in wave characteristics, timing or approach direction at this location. In this simulation, a combination of wave refraction from the neighbouring bay and wave reflection from the semi-circular embayment results in the formation of large vortices at each end of the embayment, along with constructive wave interference and focusing that together cause the simulated wave amplitude of 14 m. Notably, the actual incoming wave crest elevation (prior to the amplification) is approximately 7 m, which is in line with other exposed coastal locations such as Bruny Island and Tasman Peninsula. Regardless of the occurrence of the amplification, the impact would remain severe and a significant pre-existing low point in the dunes would still be exploited as a conduit by an incoming tsunami of 7 m. This level of inundation would result in the highway becoming compromised, which would have far-reaching implications for the greater Tasman Peninsula area.

Significant inundation is also predicted at Port Arthur (Figure 11) and Nubeena (Maps 53-56), with simulated flooding reaching several hundred metres inland and a maximum water depth of 5 m near the coast. In contrast, model results suggest that impacts at Dunalley (Map 51) would be minor, as the neck is protected here by Marion Bay Spit (Map 46).

Further north, Orford and Triabunna (Maps 57-59) also show simulated water depths of up to 3 m and extensive areas of flooding (Figure 12). At Orford, the modelled tsunami overtops the low-lying spit and the resulting inundation area covers approximately 70 houses. The waves would also travel up the river, and could inundate road infrastructure, shops and potentially the bridge across the A3 highway. Raspins Beach would also likely be overtopped, and the simulated flooding extends beyond the A3 highway at this location. The wharf area would be the most heavily impacted part of Triabunna, where modelled flooding reaches 2 m depth and extends 200 m inland.

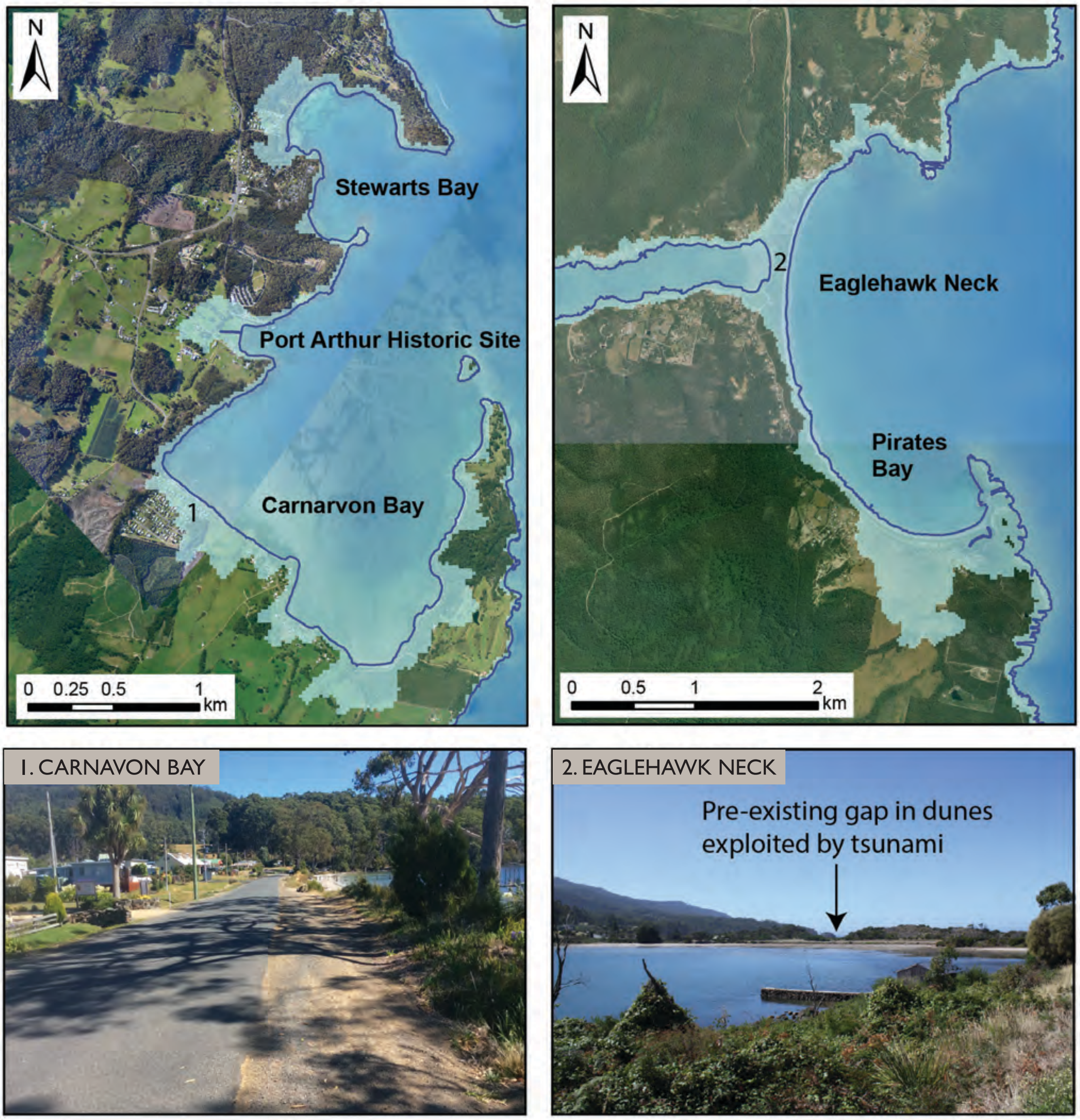


FIGURE 11: Maximum modelled inundation extent at selected locations on Tasman Peninsula. Eaglehawk Neck is the most heavily affected location across the whole study area, which has implications for transport routes to and from Tasman Peninsula.

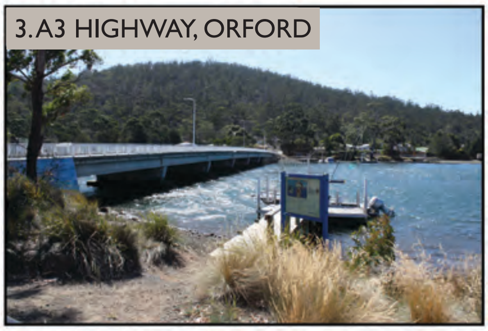


FIGURE 12: Maximum inundation extent in the eastern coastal communities of Orford and Triabunna. Image 3 shows a bridge that is part of the A3 highway, which would be inundated in the case of a large tsunami, possibly isolating communities further north.

3.3.6. Bruny Island

Results suggest that the eastern coast of Bruny Island (Maps 60-64) would be significantly impacted by a tsunami of this magnitude. In particular, extensive flooding and erosion is predicted at the southern end of Bruny Neck (Map 62) and around Adventure Bay (Figure 13; Map 64). A significant stream system at Adventure Bay could act as a tsunami conduit and simulated water depths reach 4 m in parts of the surrounding lowlands, although these depths have a high level of uncertainty.

3.3.7. Margate-Recherche Bay

The simulated inundation is relatively minor between Margate and Kettering (Maps 23-26), where the embayments are sheltered by Bruny Island. Similarly, the modelled water level fluctuations in the Huon River (Maps 65-66) are subdued. However, some flooding of coastal infrastructure could be expected, particularly as the water may become backed up with repeated wave incursions across the duration of the event. Cygnet and Dover

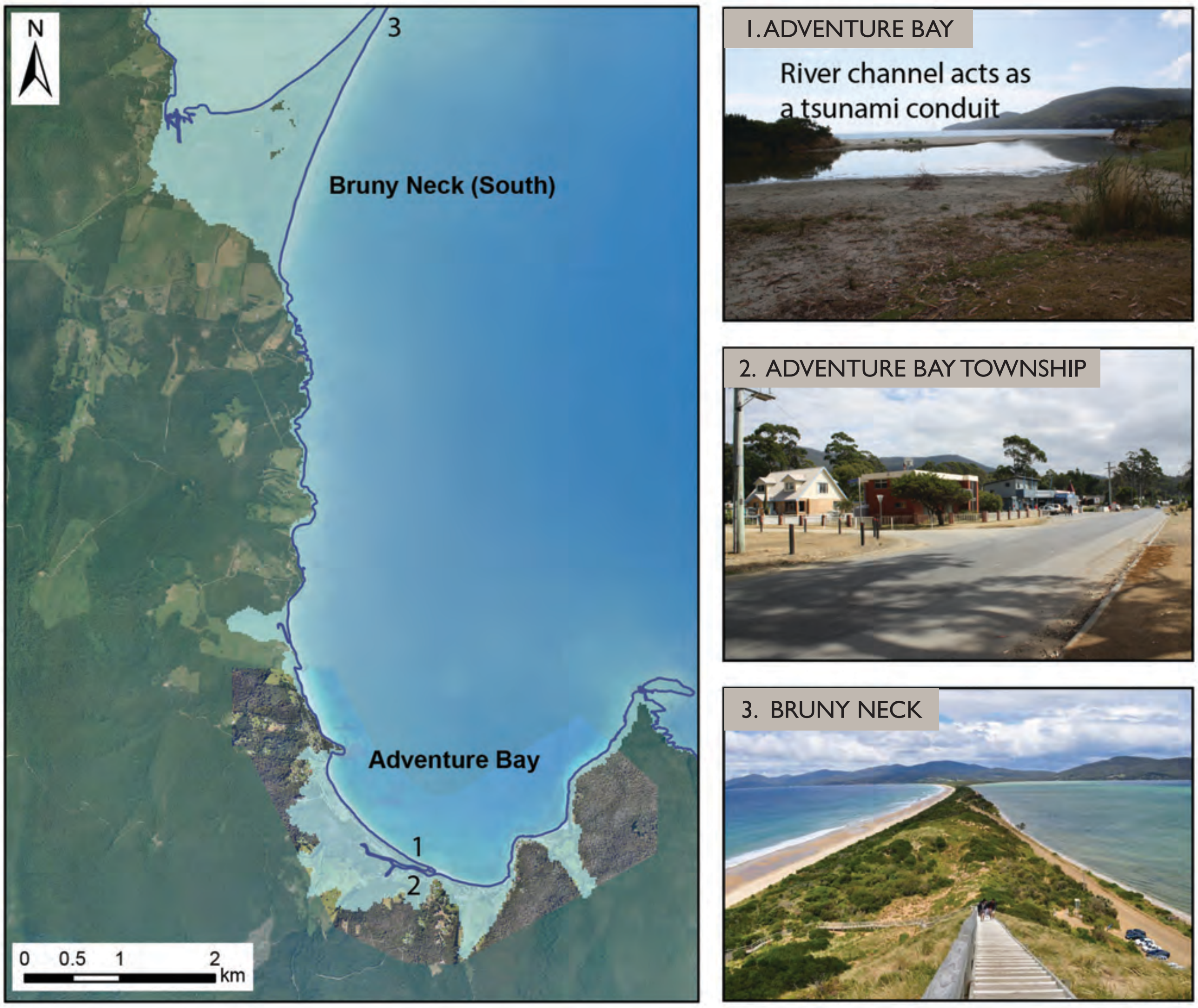


FIGURE 13: Maximum inundation extent at the south end of Bruny Neck and Adventure Bay (on Bruny Island.

(Maps 67-69) could experience some flooding of coastal lowlands (1-2 m depth), which may affect those lowland properties closest to the coast and/or river.

In contrast to those areas protected by Bruny Island, both Southport and Cockle Creek (Maps 70-71) are affected by significant water depths and inundation extents in the modelling. Simulated inundation depths reach 5 m in parts of Southport, with a significant number of properties predicted to be affected by 2-4 m of inundation. The anthropogenic impacts of tsunami flooding at Cockle Creek would be largely constrained to the spit at the mouth of the river, where dwellings and infrastructure are concentrated.

3.4. Scenario 5 – Risk of inundation and dune erosion at Hobart Airport

Scenario 5 was developed to explore the potential impact of a tsunami on Hobart Airport, given the current level of protection afforded by the dune line at Seven Mile Beach. Modelling results show that the wave height would be significantly reduced as the tsunami travels through Frederick Henry Bay (Figure 14). As such, the dune line (as present in 2016) is sufficient to protect the airport runway and infrastructure from inundation for the modelled event. Little dune erosion was apparent in the simulation at Seven Mile Beach, although this could change if the dune structure altered (for example, through a blowout or removal of part of the dune). It is also important to note that part of the dune line is only marginally higher than the approaching wave height, so a relatively minor reduction in dune height could create significant local breaches. The dune line in front of the runway is well developed, but if it were to be removed, an incoming tsunami wave would likely breach the barrier at this location (Figure 15).

FIGURE 14: Snapshot of the modelled wave as it reaches Seven Mile Beach. The dune line is sufficiently high that the wave is largely reflected back from the beach (red pattern, nearshore) and does not penetrate the dunes in front of the runway.

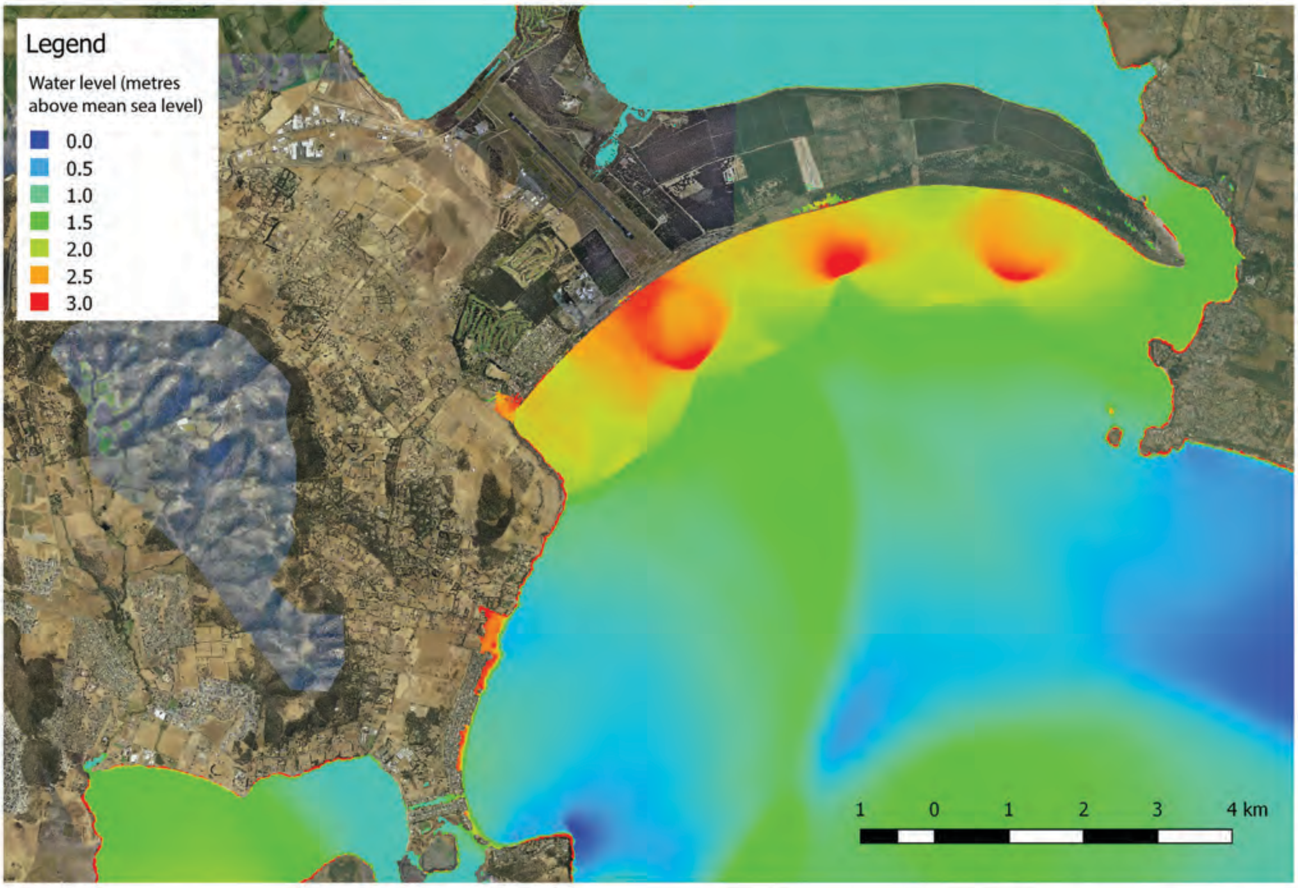


FIGURE 15: Cross section of the dunes in front of the airport runway, showing the height of the incoming tsunami wave in relation to the dune crest.

In addition to the detailed modelling of the airport site, the opportunity was taken to investigate the possible loss of dune protection at other erosion prone sites in Southeast Tasmania. These sites were modelled at a lower resolution, but the results highlight several areas where further work would be beneficial to gain a comprehensive understanding of the potential tsunami impacts. Significant erosion and inundation could potentially affect infrastructure and/or settlements at the following sites: Eaglehawk Neck, Bruny Island Neck, Adventure Bay Beach, South Arm Neck and Pirates Bay Beach. See Appendix 5 for the stand-alone Scenario 5 report produced by E. Rigby (Rienco Consulting).

4. LIMITATIONS AND CHALLENGES

Modelling is an excellent tool for estimating the impacts of a tsunami event, but some inherent limitations in the data must be recognised. Firstly, ANUGA is a 2D model library, which means that vertical motion cannot be resolved in any simulation built with its functions. As such, factors such as wave breaking and turbulence are not directly simulated. Areas that would likely be affected by turbulence were roughly estimated through calculation of the ratio of wave height (distance from peak to trough) to water depth, where a ratio ≥ 0.72 could be expected to result in wave breaking and water disturbance. The interaction of the tsunami with tidal fluctuations was not simulated, in order to minimise computational overhead as explained in Section 2. The tidal level was set to HAT at the beginning of the simulation and the subsequent water level and current fluctuations do not account for ongoing tidal variation and currents.

Onshore, tsunami flooding is controlled by coastal geometry, erosion and land use/cover. The event was modelled based on elevation data from a snapshot in time, so changes in dune form (e.g. dune height reduction or gaps, or tsunami-induced changes as modelled in Scenario 5) or land cover would influence actual tsunami behaviour. Every effort was made to accurately model the effects of vegetation and building cover through the Manning's roughness model input, but this is again a best approximation of reality.

The resolution of the mesh with respect to topographic changes has caused anomalous run-up values in areas of steep relief. Because the mesh represents a modelled surface generated from an elevation model, it does not properly represent vertical or near-vertical surfaces such as coastal cliffs and artificial structures like wharf edges. It is possible to use breaklines in ANUGA to account for buildings and vertical features, but due to the large spatial extent and complexity of our model this was not attempted. As a consequence, the maps may occasionally show inundation depths that appear extreme (e.g. 10 m along the cliffs at Lindisfarne). The higher the mesh resolution, the less this problem occurs, as the closer the modelled surface reflects reality (i.e. the sudden vertical change is distributed over a smaller horizontal distance in the triangle, giving a closer approximation of a vertical surface). These anomalies are relatively easy to identify in the maps – they appear as small contained areas of high inundation in conjunction with a sudden rise in contour value or the presence of a wharf, and have little effect on the interpretation of the flooding extent.

5. FUTURE WORK

It is important to note that these results represent the inundation from a maximum credible tsunami event and are not intended to provide the basis for a comprehensive tsunami risk assessment. Such a task would require consideration of a variety of tsunami sources with a range of magnitudes and return periods. However, given that the tsunami magnitude from a Puysegur rupture will be unknown until it is very close to landfall in Tasmania, it is prudent to maintain a response plan based on the "worst case" scenario. The results of this project have also raised some questions and avenues for additional scientific work. Some recommendations for auxiliary analysis of these results and for further scientific studies are as follows:

- From the accompanying map series, an analysis of vulnerable places, properties and infrastructure should be undertaken alongside a review
  of Southeast Tasmania's tsunami emergency response plan(s). Particular attention should be focused on the maritime response procedures, given that the impacts of a large tsunami in the port of Hobart had not been investigated in detail prior to this project.
- Further detailed modelling of some of the exposed eastern areas is needed to more accurately understand the risks at these locations. Eaglehawk Neck is of particular concern, as the simulation predicted extremely high wave heights and significant dune erosion at the neck. The erosion-enabled model resolution along the east coast was only 50 m x 50 m, so detailed maps of erosion could not be provided at this stage. Other areas that could benefit from higher resolution dune erosion-enabled modelling include Adventure Bay, Pirates Bay and South Arm Neck.
- Additional detailed modelling is recommended for the Hobart CBD, where the Hobart Rivulet travels underground. This could be important, as the Royal Hobart Hospital is located adjacent to the first above-ground exposure of the rivulet, yet the model results do not show whether or not flooding could occur via this conduit. The piers of the Tasman Bridge were also excluded from the elevation model and would need to be included in a detailed study of this conduit.

- To complement this modelling work and understand past tsunamis that have affected Tasmania, it would be useful to search for geological palaeotsunami evidence in some of the most affected areas. Previous work has recognised the scope for palaeotsunami studies in Tasmania (e.g. Morris and Mazengarb, 2009; Sharples, 2006) and a previous palaeotsunami site has been studied at Bruny Island (Clark et al., 2011), but further work is needed to connect this evidence with a wider event and compare modelled inundation distances and flooding locations with sedimentary tsunami evidence.
- The tsunami risk to other areas of Tasmania has not been modelled to date. Further work could address the impact of the maximum credible Puysegur tsunami on the northeast coast of Tasmania, and also explore the potential for other tsunami sources to affect the island, such as a South Sandwich Trench tsunami for Tasmania's west coast.

6. CONCLUSIONS

Modelling results suggest that Southeast Tasmania could be significantly affected by a maximum credible tsunami event, resulting from a Mw 8.7 rupture of the Puysegur subduction zone. The work presented here builds upon initial inundation modelling performed by Geoscience Australia in 2009, by incorporating new high-resolution elevation data and addressing specific questions related to maritime hazard and risk to Hobart Airport.

Tsunami arrival times range from approximately 2 hours at the eastern coast, to 3 hours at Hobart wharves. Significant water disturbance in the form of currents, extreme water level changes and turbulence is predicted in all coastal and nearshore environments, but does not generally extend to the main shipping channel in the Derwent estuary. Such disturbance would cause considerable risk to marine craft and could result in ships breaking adrift, damage to boats and infrastructure, and pollution. The maritime hazard assessment suggests that the feasibility of evacuation to deeper water is questionable, given the short timeframes involved, and securing/tending of vessels and evacuation of crew to land is generally recommended.

The simulations predict severe inundation levels (> 4 m depth) in exposed coastal communities on the east coast (e.g. Bruny Island, Eaglehawk Neck and Tasman Peninsula). Significant inundation (≤ 3 m depth) is predicted in the embayments along both shores of the Derwent estuary, including the Hobart city waterfront and wharves. The potential for dune erosion was included in the modelling for Hobart Airport, and results suggest that the current dune line would not be breached or overtopped by a tsunami of this magnitude at this location. However, inundation could occur if the dune was to be substantially lowered or partially removed in the future. Several other areas were found to be at an increased risk from tsunami when erosion of protective dunes was factored into the modelling. These areas include Marion Bay Spit, Eaglehawk Neck, Pirates Bay Beach, South Arm Neck and Bruny Island Neck.

No risk assessment has been undertaken from this work, as such a task would require consideration of many more tsunami scenarios of differing magnitudes and frequencies. However, these results could be useful for an analysis of vulnerable communities and infrastructure for the case of a maximum credible tsunami. Further research is needed to more accurately understand the risks at some severely affected locations, particularly Eaglehawk Neck. In addition, palaeotsunami studies could help validate the modelling results and provide useful information regarding inundation extents and recurrence intervals of tsunamis that have previously affected Tasmania.

7. ACKNOWLEDGEMENTS

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9. GLOSSARY

Adapted from Van Putten et al. (2009).

AHD	Australian Height Datum – approximate mean sea level (MSL)
ANUGA	A free and open source hydrodynamic modelling library developed by the Australian National University (ANU) and Geoscience Australia (GA)
Bathymetry	The depth of the ocean floor from the water surface (mean sea level)
HAT	Highest Astronomical Tide – the highest water level that can be predicted to occur under any combination of astronomical conditions
LAT	Lowest Astronomical Tide – the lowest water level that can be predicted to occur under any combination of astronomical conditions
LiDAR	Light Detection and Ranging – a laser remote sensing system used to collect topographic data
Manning's *n*	A model input parameter representing surface roughness, i.e. a measure of the amount of frictional resistance water experiences when passing over land and channel features
Maximum current speed	The maximum induced current speed at a given location across the duration of the tsunami simulation
Maximum wave height	The distance from peak to trough (at a given location) of the wave that generated the highest water level across the duration of the tsunami simulation
MSL	Mean Sea Level. The arithmetic mean of hourly heights of the sea at the tidal station observed over a period of time
Mw	Moment magnitude of an earthquake
Palaeotsunami	A tsunami that occurred prior to historical records. Usually identified by signatures left in the geological record
Run-up height	The maximum elevation (above AHD) reached by the uprush of the tsunami onto land
Stage or stage height	The level of the water surface above mean sea level
Subduction zone	A region of the Earth where two tectonic plates are converging and one plate is sliding beneath the other e.g. the Puysegur Trench
Topographic height	The elevation of the land surface above the Australian Height Datum stated in metres above AHD
Wave amplitude	The vertical distance between the crest of the tsunami and the still water level
Wave height	The vertical distance between the tsunami crest and trough. Approximately twice the wave amplitude.
Wave length	The distance between successive crests in a wave. In this case, it was approximated from the simulated velocity and 2 x the time period between the maximum peak and its associated trough
Turbulence	Represents areas in which the shoaling and breaking of the wave(s) would likely create significantly turbulent conditions. ANUGA cannot simulate vertical motion, so areas of high turbulence were approximated using a simple breaking wave relationship. Areas in which a ratio of maximum wave height to water depth exceeded 0.72 were considered areas of high turbulence.

10. LIST OF APPENDICES

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Appendix 2	Bill Cohen (ENTURA)	ENTURA Modelling Summary [computing information]
Appendix 3	Barrie Lewarn (AMC)	Tsunami hazards in the port of Hobart: Maritime advice
Appendix 4	Genevieve Simard (MRT)	Coastal inundation map series
Appendix 5	Ted Rigby (Rienco Consulting)	Scenario 5 – Airport hazard and dune erosion impacts; Report summary
Appendix 6	Claire Kain (MRT)	Table of data for gauge locations
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TECHNICAL REPORT ON TSUNAMI INUNDATION MODELLING IN SOUTH EAST TASMANIA

Input Data Preparation: Methodology and Challenges

Colin Mazengarb,
Mineral Resources Tasmania

APPENDIX ONE

Mineral Resources Tasmania
Department of State Growth

Tasmanian Government

INTRODUCTION

This report documents the input sources and the methods used for construction of the spatial inputs consumed by the ANUGA modelling process. While it was initially presumed that data compilation would be a relatively straightforward GIS exercise, it has proven to be far more complicated process requiring a detailed summary. Issues encountered include the considerable size of the datasets that challenged both the hardware and software, errors discovered in supplied data that required a considerable level of manual intervention, and constraints of the ANUGA software itself.

ANUGA INPUT CONSTRUCTION

ANUGA uses a finite volume modelling method for solving shallow water wave equations and requires four main inputs, described below:

1. boundary condition hydrographs representing tsunami scenarios
2. mesh resolution boundaries
3. elevation model
4. surface roughness model
5. gauge locations

Boundary condition hydrographs

Boundary condition hydrographs have been previously generated for a range of tsunami scenarios by Geoscience Australia (Burbidge *et al.* 2008) and are located along the continental shelf at the 100m mark (Figure 1). The project team have chosen to accept these inputs without further question but realise that they are based on assumptions and computer models that may change with further research. To this end, MRT is actively collaborating with a PhD candidate at the Karlsruhe Institute of Technology in Germany to better understand the tsunami generation potential of the Puysegur Trench and the uncertainties in magnitude and likelihood of the tsunamis that could be produced. Preliminary results involving modelling a range of variations of rupture geometries indicate that expected wave height has a significant standard deviation about the mean (Schäfer, *et al.*, 2016).

FIGURE 1: Model area with location of boundary condition hydrographs

Mesh Boundaries

ANUGA performs its calculations within a triangular mesh environment, either structured (equally spaced triangles similar to a raster) or unstructured mesh, where triangles are created using the Delaunay method. In this study an unstructured mesh is used as it allows us to vary the triangle dimensions across the study area. The construction of the mesh is performed within ANUGA based on a series of input GIS polygons (shapefiles) which define the triangle sizes. High mesh densities (small triangles) are assigned in priority areas where detail is required to delineate hazard boundaries, such as within low lying coastal settlements. Lower mesh density triangles (larger triangles) can be assigned to areas where detail is not required.

In constructing a mesh in a large area, such as that in this study, the limitations of the computing hardware must be considered in order to reduce the processing overhead and achieve acceptable run times (days rather than weeks). The two main constraints are the total number of triangles in the mesh (a question of size) and the size of the smallest triangle considered (the smallest triangle determines the size of the time step).

While the initial polygon shapefile contained a number of topologically correct features (no overlaps or underlaps) at least two issues arose. Some of the polygon shapes were too complex, having incorporated natural features such as shorelines into their boundaries. The triangle dimensions created by the ANUGA meshing process are controlled by the node spacing and therefore "sliver" triangles (at times <1 m^2) were formed in the vicinity of mesh zone boundaries where polygons were too complex. As previously explained, incorporating these into the model would significantly reduce the time step and consequently greatly increase the processing time. As such, the polygons were simplified in order to ensure a suitable node spacing. Some difficulties were also encountered regarding the relative proximity of different polygon resolutions. After some trial and error, finer resolutions were always nested within coarser, and intermediate resolution polygons were not omitted. In addition, the spacing between each intermediate polygon (i.e. the distance between the inner and outer boundary) was set at a minimum dimension of the desired triangle size in order to prevent undesirable slivers forming. The downside of this approach is that the interior of larger islands contained unnecessary detail, adding to processing overhead.

While most of the GIS preparation was undertaken using *ArcGIS desktop basic* software, some functions in other software (*Global Mapper*) were employed in order to achieve the desired outputs.

In this study a series of mesh boundaries have been created (Figure 2):

- Coarse resolution: 80 000 m2 (maximum 400 m x 400 m triangles)
  - Ocean areas > 30 m depth.
  - Land areas above 15 m AHD (this is expected to be well above maximum run-up distance for expected tsunamis).
- Medium resolution: 20 000 m2 (maximum 200 m x 200 m triangles)
  - Ocean areas between 10 m and 30 m depth.
- Fine resolution: 1 250 m2 (maximum 50 m x 50 m triangles)
  - Non-urban areas of coastline from +10 m to -10 m AHD
- Very-fine resolution: 200 m2 (maximum 20 m x 20 m triangles).
  - Urban areas of interest to be modelled and plotted in detail. The resolution is required to reflect flow paths on roads between buildings in built up areas and to yield clearer inundation plots than previously produced.
- Extra-fine resolution: 100 m2 (maximum 10 m x 10 m triangles)
  - An urban area, at Blackmans Bay, was chosen specially to test inundation on an elevation model that includes buildings in 3D as extracted from LiDAR data (Figure 3).

Construction of the Elevation Model

A variety of data sources were integrated in order to build a complete model of elevations within the modelled area. The initial intention was to use the elevation data created by Geoscience Australia (Van Putten et al. 2009) wherever possible, and replace those parts where subsequent more detailed information had become available. However, an inspection of the dataset revealed a number of significant problems and the 2009 dataset was discarded.

The metadata statement for the 2009 elevation dataset is comprehensive in describing the data sources but not the methods employed to merge them. The data was loaded into an ESRI *Terrain* model (a triangulated irregular network) in order to visualise the data. The analysis shows that the 2009 elevation model is composed of regularly spaced arrays of xyz points of varying density that have been combined into a single file. In offshore areas, the regular spacing of points indicates that it was created by an undocumented interpolation process(es), it is therefore derived data and not the original input points. This method is of concern as potential mistakes in the interpolation process cannot be reversed if source data is not supplied.

The most significant issues are:

a. Obvious elevation errors in proximity to the coastline where some points offshore have positive values and conversely some points onshore have negative values, and whose values are well outside the tidal range. In one instance the coastline is effectively about 1 km from its correct position.

b. Some of the offshore areas have unrealistic morphology and do not conform to reliable bathymetric information contained on navigational charts.

c. There is a serious mismatch of elevations about an arbitrary offshore boundary that probably relates the join between two (interpolated?) datasets.

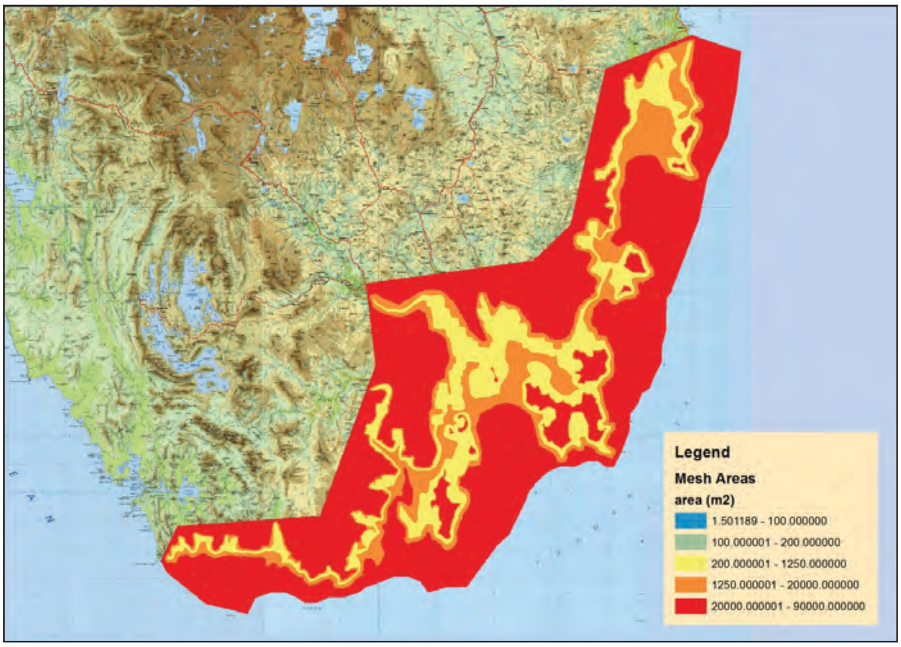


FIGURE 2 Variation in mesh resolution across the study area

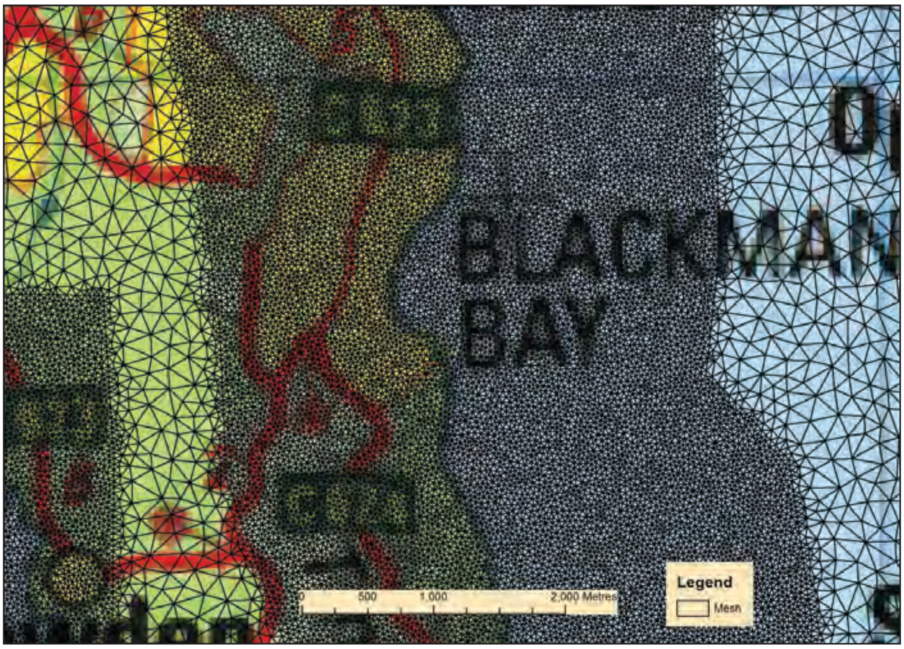


FIGURE 3 Detail of mesh resolution boundaries around Blackmans Bay where extra fine mesh sizes have been used

MRT has therefore completely rebuilt the elevation dataset using mostly publicly available data that largely supersedes the 2009 GA dataset. One of the key offshore datasets used by GA was provided under license from the Australian Hydrographic Office (AHO), which prohibited GA from passing on to MRT. Fortunately, MRT was able to purchase this data under a license agreement from AHO.

The underlying philosophy of the data compilation methodology was to populate areas with the most reliable and accurate information available. This task was performed in a GIS environment, using ESRI ArcGIS Desktop 10.1, Basic license level, with the 3D Analyst extension enabled. Despite having a reasonably powerful computer for its time (HP Z600 Workstation, Intel 2.13GHz processor, 8 core, 16 Gb RAM with a SSD drive), the huge data volumes involved restricted the performance of the hardware and limited the geoprocessing tools that could be used. ESRI *terrain* geoprocessing tools were found to be the most practical, time efficient and robust methods to perform edits such as masking (deleting unwanted areas or erroneous points) on very large datasets.

Data were acquired by MRT in various digital formats, and using a range of datums and coordinate systems, all of which required conversion to a common datum and projection (GDA94 MGA zone 55, AHD (Tasmania)). All of the data sources were imported into feature classes within separate *file geodatabases* in order to do this task and temporary *terrain* models were built for each data source as a quality assurance exercise and to rapidly visualise problem areas. Masking was necessary to ensure spatially overlapping datasets were not mixed.

The creation of merged point cloud type elevation datasets is not without its problems. For instance, in areas of complex terrain, shallow water and sparse data will all affect the reliability of the modelling. To partly address this issue, additional artificial elevation points were added at regular intervals along the mapped shoreline to ensure that the land – water interface was sufficiently defined. However, unrealistic interpolation may have occurred, for example, in small embayments where bathymetric data is sparse and the artificial shoreline points interpolated horizontally across the bay. In situations where data is more plentiful, the use of breaklines along the shoreline (something that ANUGA supports) could be used to control the interpolation. However, in data poor areas such as these they will not make much difference and it would take somewhat intensive desktop work to better control the interpolation. The use of breaklines was not adopted in this study for reasons of expediency as it is considered that, in any case, they may make little difference to the run up of the tsunami wave.

In reviewing other examples of tsunami modelling, it is noted that the *Service hydrographique et océanographique de la marine* agency (SHOM) in Brest, France is systematically undertaking investigations for coastal nuclear power stations (Maspataud, *et al.*, 2015). Their method involves creating DEMs (rasters) from a rich variety of overlapping data sources of varying accuracy and utilising the *Multi Level B-Spline* (MSB) method available in the SAGA GIS software (www.saga-gis.org). The MSB is an inexact interpolation algorithm that fits a smooth surface through scattered data while minimising local approximation error for each control point. Their study areas are relatively small compared with that in this project, and while the MSB method is probably very good, it would require a significant amount of tiling (and effort) in order to work within the constraints of the computer resources available. For this reason alone, the method was not adopted.

Each of the data sources employed will be described below, but first one important data source that was not used will be discussed.

The CSIRO swath data available from its data portal, is derived from multiple cruises over many years and consists of densely spaced (<1 m and irregular) xyz points of considerable data size. At the time of compilation, for some of the cruises, the data have not been tidally corrected and cannot be used in their present form. In addition these datasets appear to be internally noisy and inconsistent with other overlapping swaths. To contemplate using these data would require significant processing and smoothing to achieve an acceptable form using specialised software and expertise not available to MRT. We note that these data have been used in national bathymetric models and even on Google Earth imagery despite containing obvious elevation mismatches across the continental shelf (Figure 4). For these reasons the CSIRO data was not used to build the elevation model.

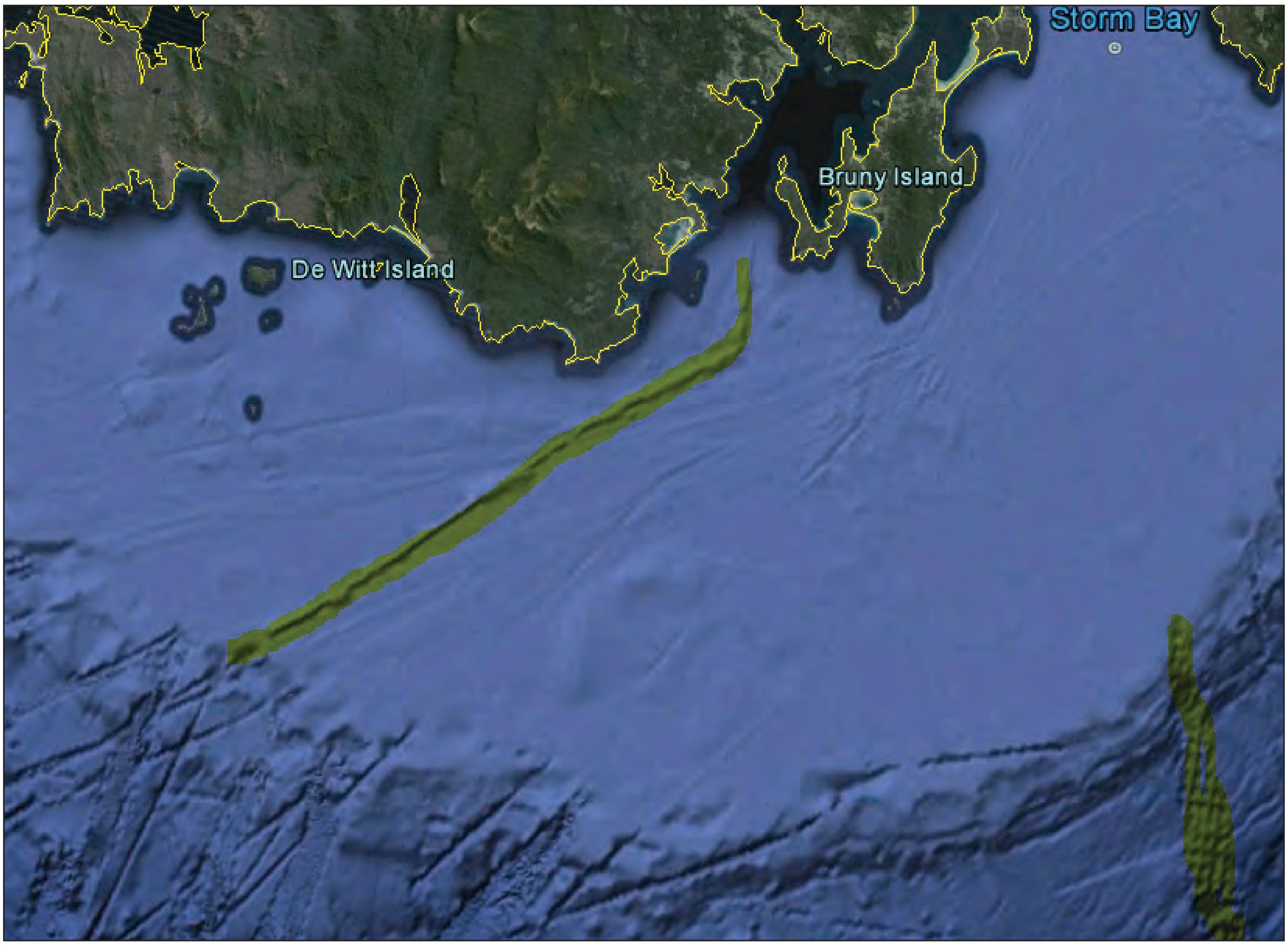


FIGURE 4 Examples of probable bathymetric artefacts on the continental shelf and slope (two of many are highlighted in yellow) used on publicly available imagery (e.g. Google Earth).

Bathymetric Data

Several data sources were available to construct the bathymetric model.

1. TasPorts swath data (acquisition date: 2010 – 2013)

A local and detailed swath dataset was obtained from TasPorts but did not come with a metadata statement. This dataset extends over four small areas; Sullivans Cove, Tasman Bridge Risdon Wharf and Selfs Point (Figure 5). Depth information required conversion from LAT (Lowest Astronomical Tide and depths in positive values) to AHD (bathymetry elevations in negative values). The data appears to be a good representation of reality at the time of acquisition but it is important to note that subsequent dredging has occurred at the overseas wharf (Sullivans Cove) that cannot be accounted for by this data.

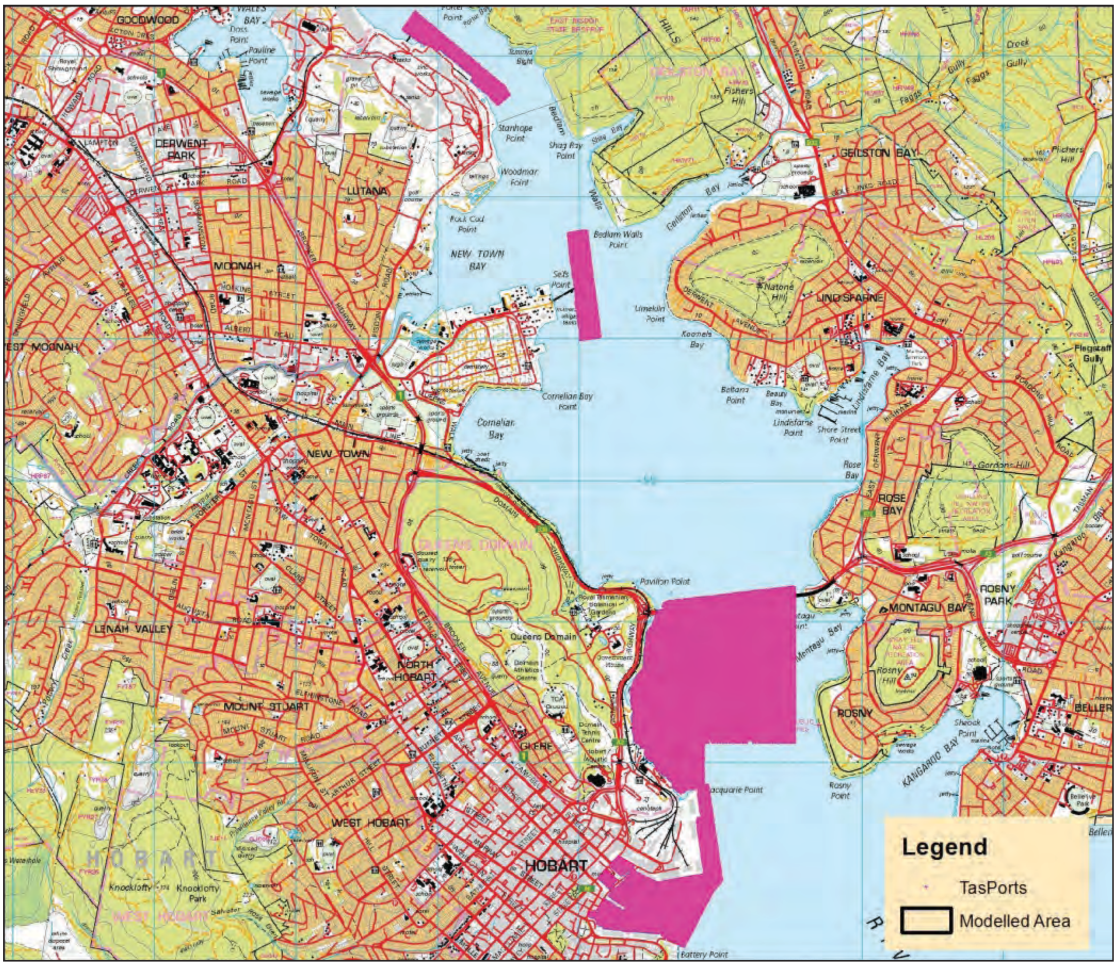


FIGURE 5 TasPorts swath data

2. SeaMap sonar data (formerly TAFI (Tasmanian Aquiculture and Fisheries Institute) now IMAS (Institute of Marine and Antarctic Science, University of Tasmania)

Several point datasets were obtained including a dataset used in the 2009 modelling by Geoscience Australia (the Bruny Bioregion described below) (Figure 6). The data have been collected by a small vessel traversing the coastal and estuarine waterways using a sonar device.

a. Bruny Bioregion dataset (acquisition date: 2001)

This coastal dataset extends from South East Cape through to Marion Bay but excludes the inner estuaries, such as the Derwent and Huon. A report by Barrett et al. (2001) describes the purpose and main findings of the study. A point file of elevations was kindly supplied to MRT on request, delivered as a single shapefile but without a projection file, inadequate metadata and with many spatial problems. A published contour dataset available on the LIST web viewer (Southeastern Tasmania marine contour map 1:25 000) is presumably derived from a clean version of the point file and provided a means of identifying and fixing the data problems.

On assigning an AGD66 datum most of the data lined up with coastal features. However, one day of data collection transgressed onto land in parts. It was determined that the data on this day was in GDA94 MGA projection and once reprojected, the data fitted the coastal constraints well. All of the data were subsequently reprojected to the common datum.

There were also obvious problems close to sea cliffs, particularly on the Tasman Peninsula, where data transgresses onto land, probably due to poor GPS signals, and this data was selectively removed.

There were multiple instances where streams of data had fixed elevations or clearly were not realistic for their setting. A considerable amount of manual editing was undertaken to remove anomalous points. Problematic points were identified through the construction of contours using Delaney triangulation in an ESRI Terrain Dataset. Problem areas where the depth value was zero or showed a fixed value over large distances and showed as linear ridge lines. Another common problem was unrealistic depth values in intertidal zones or spurious isolated values (too deep or too shallow) that showed a bullseye pattern on the plotted contours. Once the problematic points were removed the contours closely matched those published by TAFI.

The data are transect-based with highly variable distances between each transect; exceeding 1 km in places and with individual data points tens of metres apart.

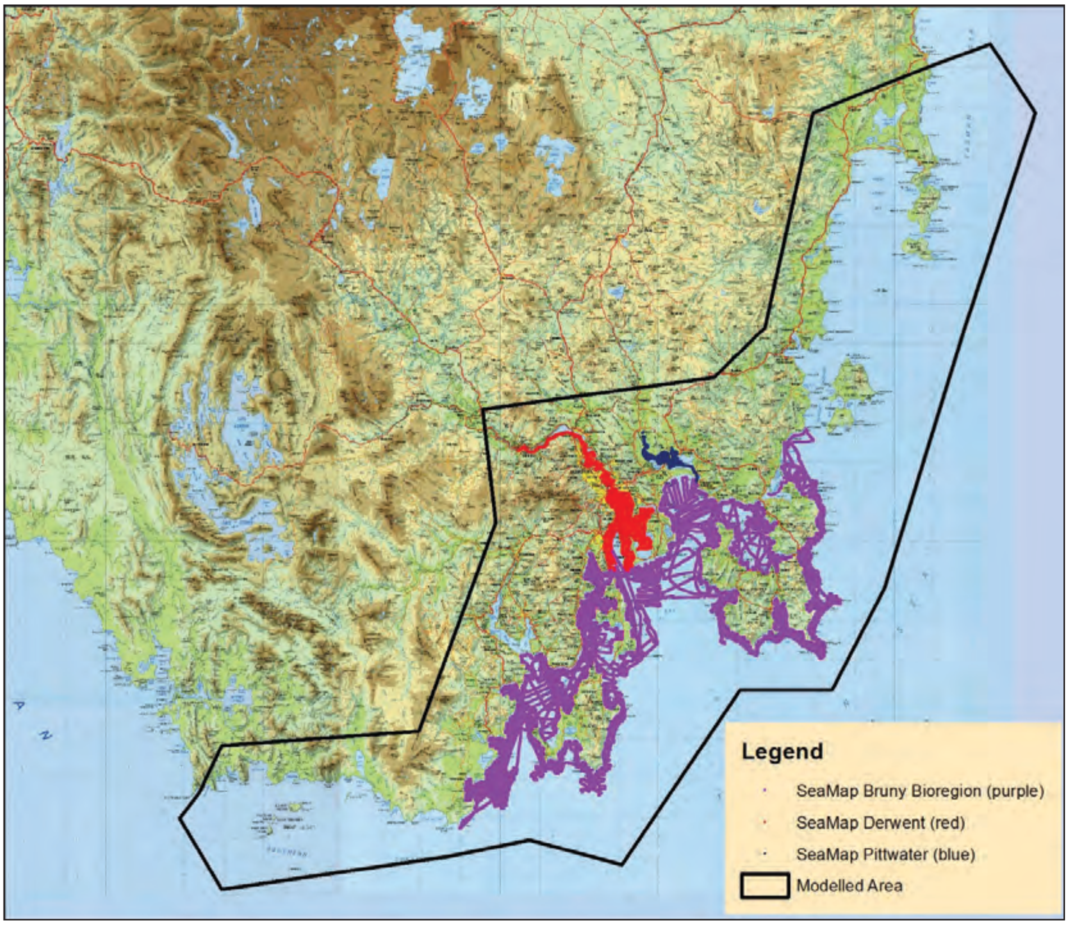
b. Derwent Estuary Program (acquisition date: 2007)

This dataset is a transect based acquisition along the Derwent Estuary, extending upstream of New Norfolk down to the Iron Pot near Kingston and including Ralphs Bay (Lucieer, et al., 2007). Transects are spaced approximately 200 m apart and individual points are at approximately 2 m separation. The data were in good condition and no anomalies were detected. However, the data were trimmed to remove points that intersected the TasPorts dataset in order to avoid introduction of artefacts.

c. Pittwater Estuary (acquisition date: 2002)

Data were obtained for the Pittwater Estuary in shapefile format based on a study by Davies *et al*. (2002). Unfortunately the data had issues in common with the Bruny Bioregion dataset, containing mixed projections and anomalous elevations requiring significant manual editing to produce a realistic model. The data were trimmed so as not to overlap with the TasPorts swath data.

FIGURE 6 Distribution of SeaMap datasets



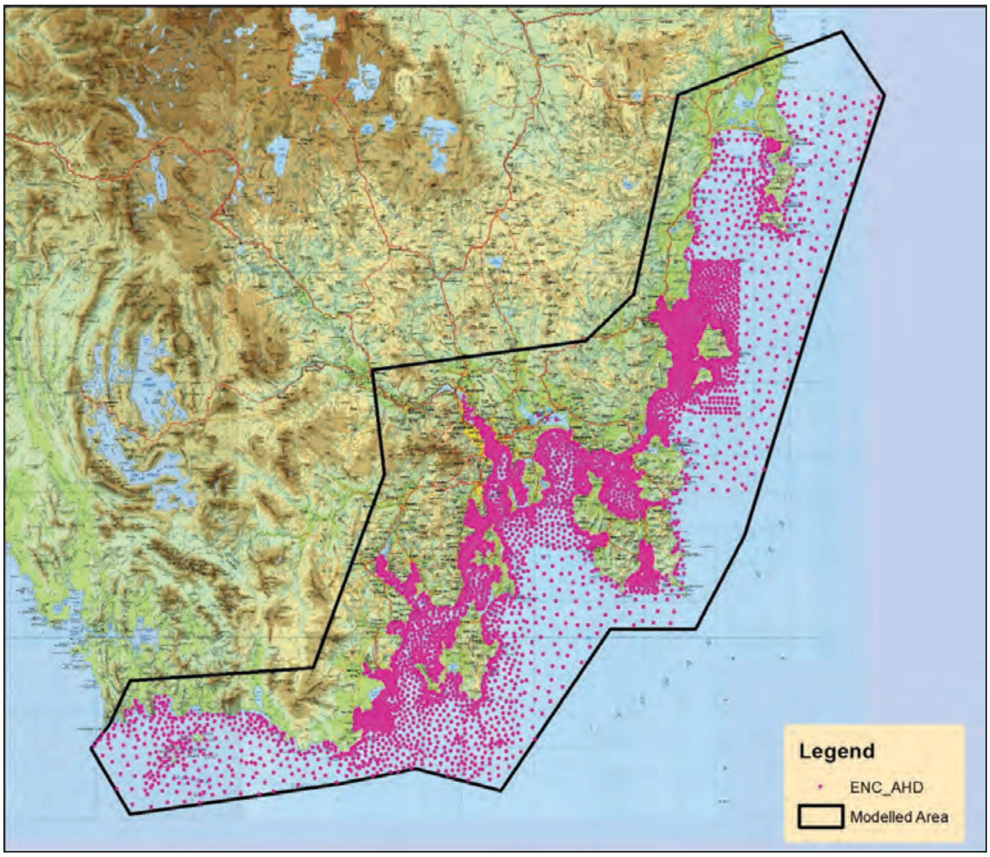


FIGURE 7 Electronic Nautical Chart data from the Australian Hydrographic Office used in the study

3. Australian Hydrographic Office Electronic Nautical Charts

Areas covered by the ENC (Electronic Nautical Charts) series were purchased under a licence agreement with the Australian Hydrographic Office (Figure 7). The data were in an uncommon vector format but which can be viewed and exported to other GIS formats utilising a free S57 viewer extension in the ArcGIS environment. The ENC data were derived from a variety of sources with varying accuracies. It is supplied in files corresponding to each nautical chart and where overlaps occur, data are duplicated. However, in viewing duplicate data from adjacent charts, it is observed that some of the data points are in slightly different locations. I suspect that this shifting of points resulted from a cartographic exercise to prevent overlaps with other features on the chart. While not an ideal situation, all duplicates were left in the elevation dataset and the process of creating the mesh should not have been seriously compromised.

4. CSIRO Bathymetry

A small dataset derived from the CSIRO was incorporated in to the model in the Huon area (Figure 8). These data have been smoothed by unknown parties into a regular grid of 50 m cell size.

5. Private kayak soundings on the Huon

A kayak based dataset of soundings in the Huon area was provided to Entura from a private individual (Figure 8). Not much is known about this information other than that the XY locations were probably collected using a hand held GPS device (~5 m accuracy) but no information is available regarding the vertical accuracy and whether it is tidally corrected. Given that other data sources were absent upstream of Port Huon, the inclusion of the poorly constrained information significantly improves the model in this area.

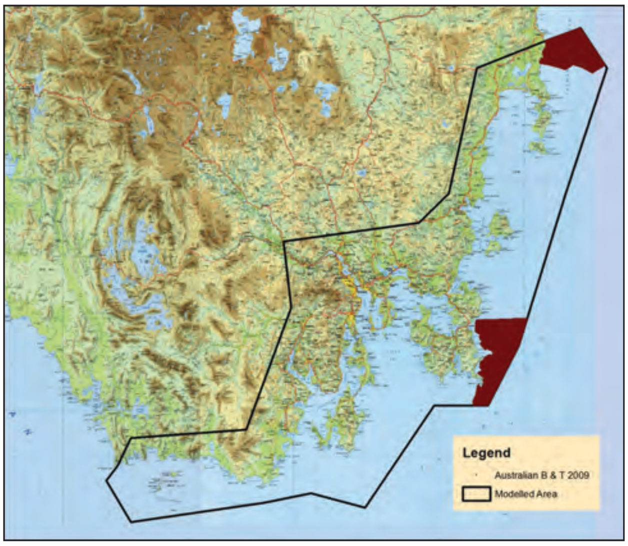


FIGURE 8 Data sources in the Huon area

FIGURE 9 Selected data from the Geoscience Australia national bathymetry and topography dataset

6. Australian Bathymetry and Topography Grid 2009 (Whiteway, 2009)

This is a national bathymetric gridded dataset (raster) with approximately 200 m cell spacing. The grid was converted to point elevations and is used in a limited manner (Figure 9). On comparison with other datasets, it appears that there are many interpolation errors in this dataset, especially in shallow water where it conflicts with nautical charts. For this reason it has been used as a last resort to complete the elevation model.

Terrestrial Data

Public LiDAR datasets

A number of publicly available terrestrial LiDAR datasets were used in this study, all of which have been acquired since 2009. The Climate Futures of Tasmania LiDAR dataset used by Geoscience Australia in 2009 was not used as it is known to have sub-standard elevation control and sit has been superseded by subsequent surveys. All of the datasets listed below have index files available on the LIST website so only the names and acquisition dates are provided in this report.

1. Mt Wellington 2011
2. Geoscience Australia Greater Hobart 2013
3. Geoscience Australia Huon 2013
4. DPAC Coastal 2014
5. Coal Mines (Tasman Peninsula) 2015

For the first three datasets listed, the data were trimmed to extract the points below 15 m AHD to minimise the file size. 15 m AHD was considered to be comfortably above the highest run-up value. The remaining datasets were relatively small and were included without modification.

In working with this data it was discovered that the Geoscience Australia datasets listed above contained many discernible classification errors, where points clearly overlying water have been classified as ground returns (Figure 10). In this case, the points were manually deleted.

A similar, albeit more subtle, problem occurred with the Mt Wellington LiDAR dataset. In the area adjacent to the TasPorts bathymetry datasets (Figure 5), there were areas of LiDAR ground returns in water that conflicted with the bathymetric data. In these areas LiDAR points were carefully deleted. This was considered most important wherever there were wharves in the vicinity to ensure that an accurate model was created. The extent of the combined LiDAR datasets is shown on Figure 11.

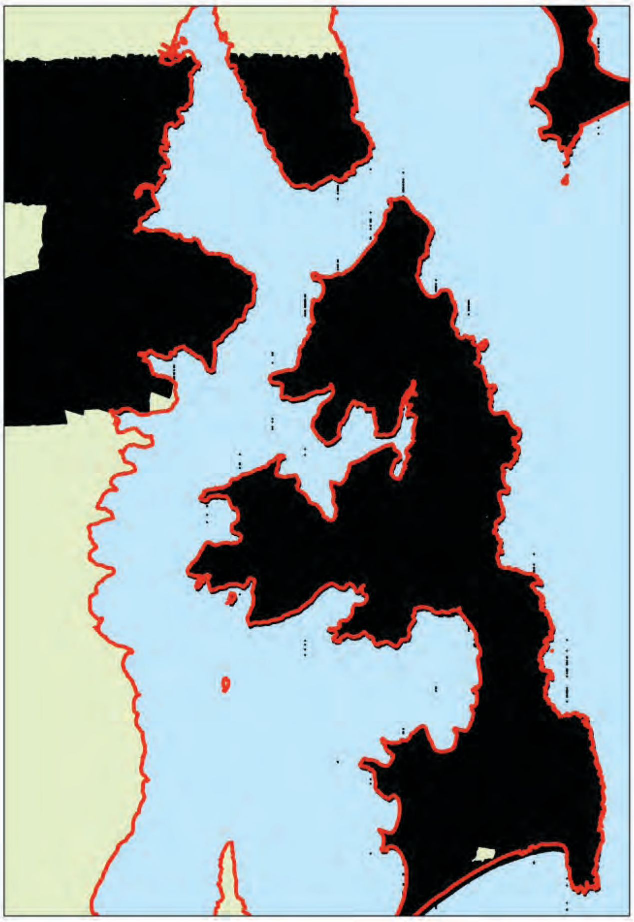


FIGURE 10: Example of LiDAR classification errors adjacent to North Bruny Island. These are all classified as ground returns.

A second dataset of points classified as buildings was extracted from the datasets listed above. This dataset was added to the elevation model as a trial of detailed inundation modelling in selected areas and as an alternative to the Mannings-N approach at a detailed level.

Photogrammetric derived topographic DEM

XYZ points were extracted from the Statewide 25m DEM to populate the remaining terrestrial areas. This dataset originates from Land Tasmania, DPIPWE and has been created from photogrammetric contours at 10 m spacing.

A seamless elevation model for South East Tasmania

The *ESRI Terrain* model provides a powerful data type with associated tools to manage large volumes of diverse elevation data effectively. A particular strength of the terrain model is its ability to rapidly visualise the elevation model and identify potential errors before the data is used by the ANUGA software. A considerable amount of time was spent in the QA process ensuring that there were no serious errors or join artefacts visible. Two visualisations are provided (figures 12 and 13) that compare results between the GA 2009 and the MRT elevation models.

The final stage in the compilation process involved exporting the completed terrain model (Figure 14) as a single point file for importing into ANUGA.

Surface Roughness Model

A surface roughness model of the entire area was compiled from publically available datasets into the form of a raster grid with assigned Mannings-N values (Figure 15). This information is an important control on wave and run-up attenuation over the modelled area. For instance, some objects, such as buildings have high attenuation effects on run-up whereas smooth surfaces such as road pavement have low values. This project has used the Mannings-N coefficients listed below based on commonly used values and experience within the team. It is important to note that the modelling undertaken by Geoscience Australia in 2009 used a single Mannings-N value over the entire area and therefore did not account for variation in roughness.

Mannings Value	Surface Type
0.5	Solid buildings
0.071	Built up areas
0.055	Vegetated areas
0.035	Land (default)
0.03	Bare ground
0.025	Water courses
0.018	Roads
0.01	Oceans and estuaries

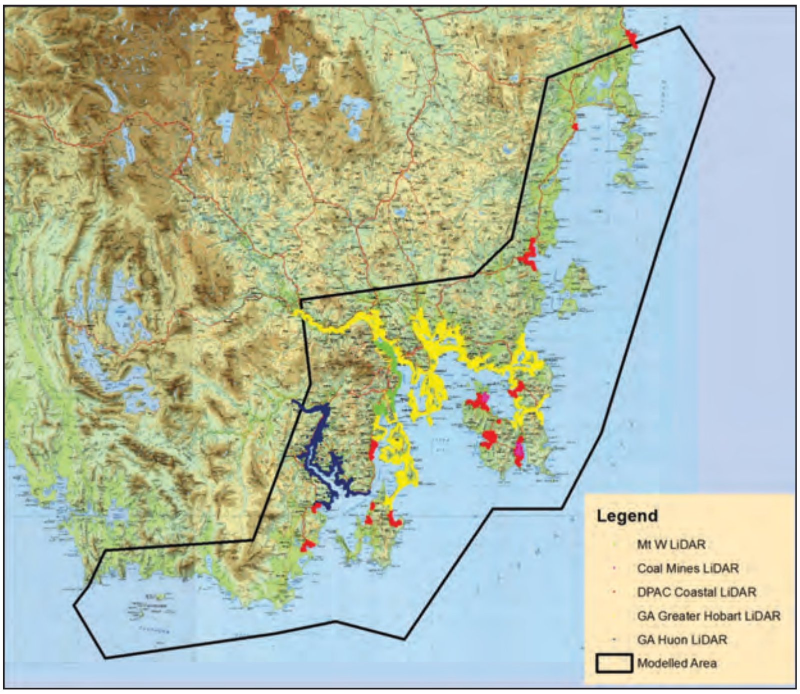


FIGURE 11 Ground classified LiDAR used in elevation model. Most of the datasets were trimmed to a maximum of 15m elevation.

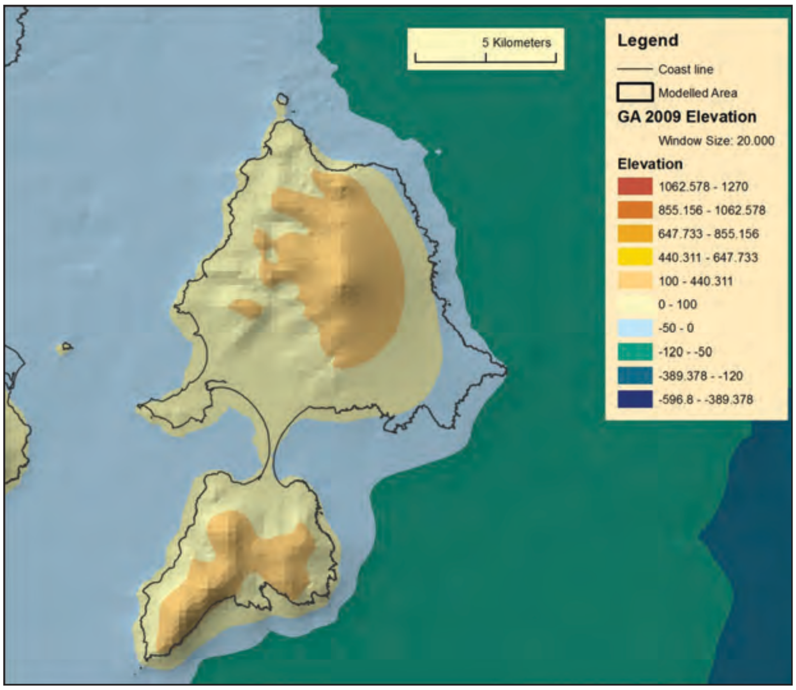


FIGURE 12 GA 2009 elevation model in detail at Maria Island. Note the mismatch of the model with the official coastline

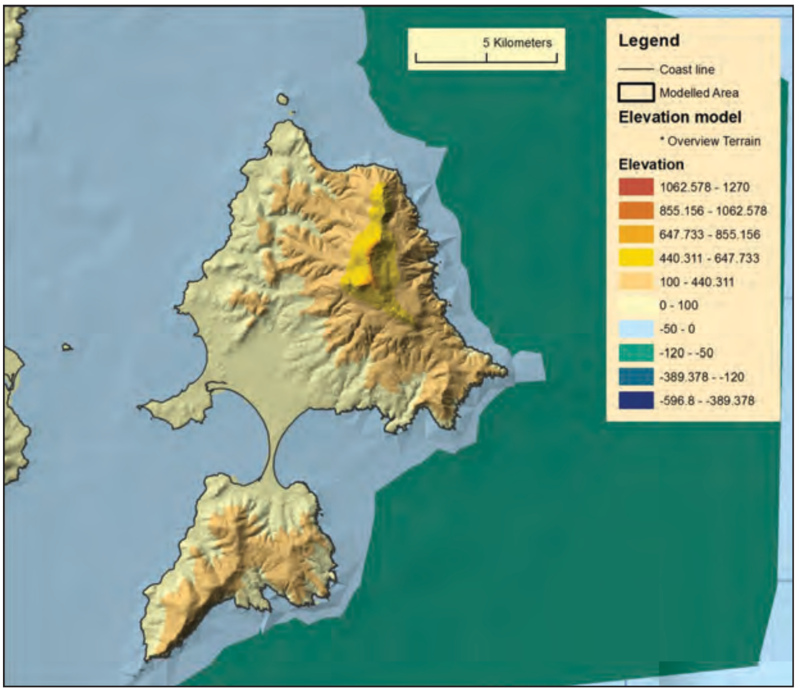


FIGURE 13 Detail at Maria Island for the 2016 elevation model to compare with the 2009 model (Figure 12)

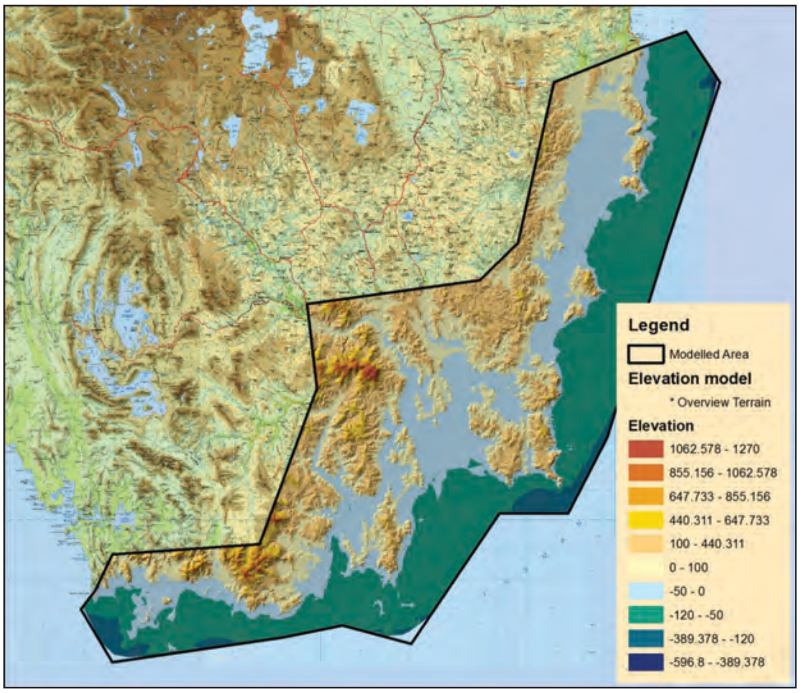


FIGURE 14 Elevation model adopted for the 2016 modelling (this study).

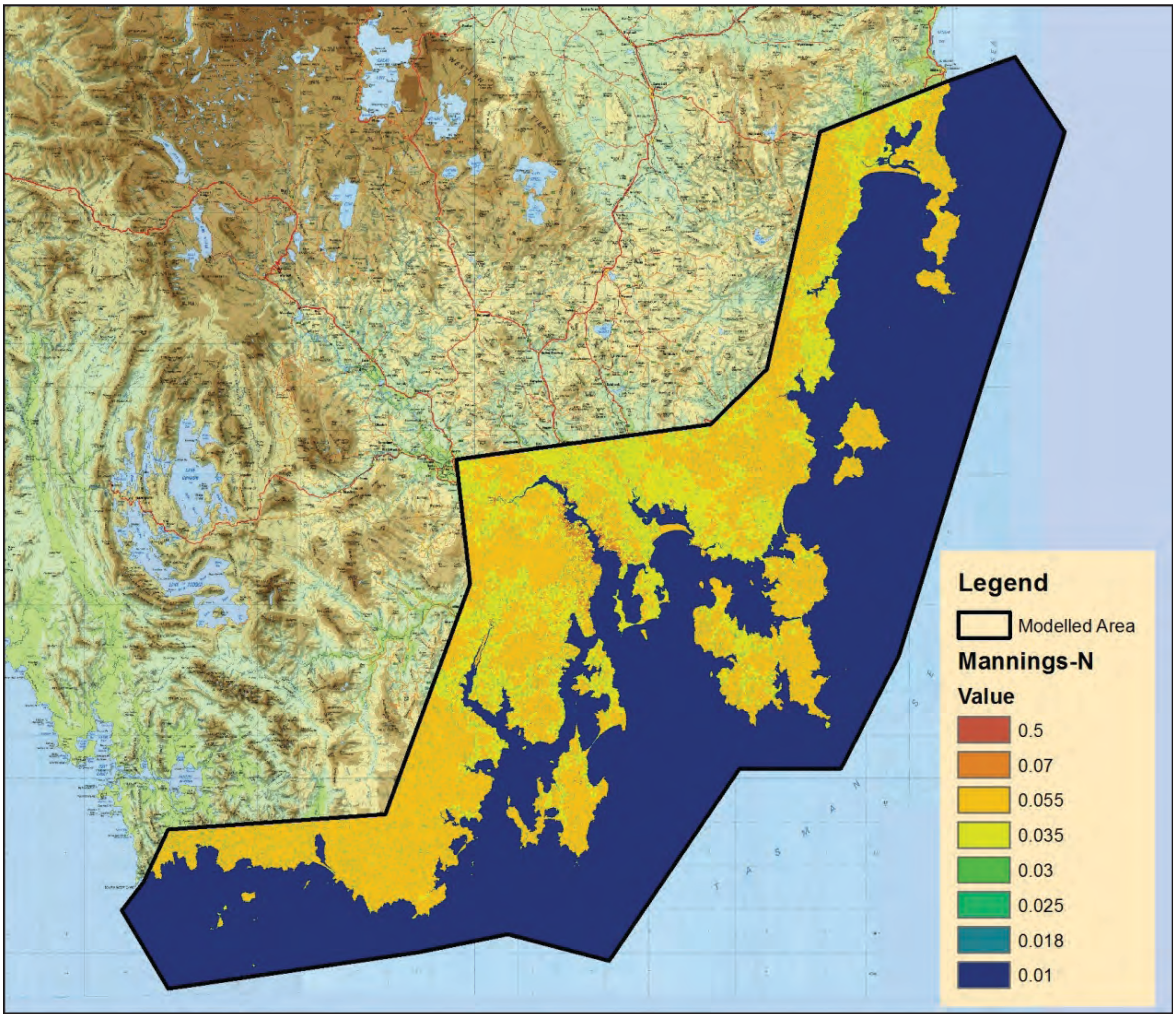


FIGURE 15 Mannings roughness map at a regional scale

The process of compiling this layer was based on a method originally developed by M. Hannon (Department of State Growth). The method he used was entirely a polygon vector-based geoprocessing operation using a third party extension to avoid using functionality only available at the "Advanced" licensing level of ArcGIS.

The method used here requires only the "basic" licensing level of ArcGIS but with *Spatial Analyst* enabled. It differs in that all vector layers are converted to raster and a very efficient raster algebra operation is performed assigning values based on a priority system at a resolution of 10 m.

The vector layers used are listed below in decreasing order of priority:

1. Roads derived from the LIST transport layer (polyline) with bridges removed
2. Buildings extracted from all LiDAR layers discussed above
3. Water courses from the LIST water course polyline layer
4. Vegetation derived from the TASVEG polygon layer
5. Land use derived from the LIST cadastre polygon layer
6. Oceans and estuaries based on the LIST coastal polygon

The geoprocessing operation was constructed using *Model Builder*, a graphical user interface for coding within ArcGIS. Through experimentation a set of queries and geoprocessing operations were developed to prepare the data for assembly.

For the buildings layer, the LiDAR points classified as buildings and under 15 m elevation were converted to raster format (cell size 5 m) using the *point to raster* geoprocessing tool and excluding a count < 3 (less than 3 points in the cell). These cells were assigned a Mannings-N value of 0.5. A buildings polygon layer is also available from the LIST, which is used in the Tasmanian Street Atlas product. Unfortunately, the completeness of this layer is highly variable within local government areas and individual buildings are not sufficiently accurate for this purpose.

For the roads layer, the query consisted of selecting the following from the TRAN_CLASS field in the LIST transport layer and assigning a Mannings-N value of 0.071 (Built Areas): 'Arterial Road', 'Access Road', 'Local Road' ,'National/State Highway', 'Sub Arterial Road', 'Collector Road'.

For the landuse layer, entries in the CAD_TYPE2 field were assigned the following values:

'Private Parcel' = 0.071 #Built Areas

'Aurora Energy Pty Ltd' = 0.030 #Open ground

'Department of Health and Human Servic' = 0.071 #Built Areas

'Housing Tasmania' = 0.071 #Built Areas

For the vegetation layer, records with the following entries in the VEGCODE field were excluded: 'FUR', 'FPE', 'OAQ', 'FAG', 'OSM', 'FUM', 'FMG', 'FRG', 'ASS', 'AHS', 'AHF', 'ASF', 'AUS', 'GHC'. The remaining records were assigned a Mannings-N value of 0.055.

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TECHNICAL REPORT ON TSUNAMI INUNDATION MODELLING IN SOUTH EAST TASMANIA

Entura Modelling Summary: Computing Information

Bill Cohen,
Entura

APPENDIX TWO

Mineral Resources Tasmania
Department of State Growth

Tasmanian Government

Project note

19 September 2016

To	Colin Mazengarb/Ted Rigby Mineral Resources Tasmania/Rienco
From	Bill Cohen **p** +61 3 6245 4513 **e** Bill.Cohen@entura.com.au
Project	South East Tasmania Tsunami Modelling
Project reference	E304976/P510568
Document number	ENTURA-C28B3
Subject	Modelling Summary

Introduction

The objective of the 2015-2016 South East Tasmania Tsunami project has been to take a Tsunami event from a Geoscience Australia database, with a collection of elevation data (bathymetry and land elevation) and roughness surfaces, and update the original Geoscience Australia tsunami modelling of the region. A critical component of this study is the ANUGA hydrodynamic modelling software, developed by Geoscience Australia and the Australian National University.

ANUGA is a very complex software application, is not widely adopted, and has little support and development budget. As such, many of the issues encountered with this project were related to ANUGA, generally for the following reasons:

- Lack of operator experience using the ANUGA software
- ANUGA documentation was not always up to date
- Bugs in the software that were detected during the project

These issues were mitigated as:

- Ted Rigby (Rienco) was made available to the project as a specialist consultant; his understanding of numerical computation and hydraulic modelling in general and ANUGA in particular have been of tremendous support in getting around issues as they were encountered
- Stephen Roberts (ANUGA development team) was very quick to respond to any bugs encountered with the software

The project team wishes to thank and acknowledge the roles that Ted and Stephen played in this project; without their timely support, modelling would not have been possible.

The general modelling issues are described below, as are any issues specific to certain scenarios.

Computing hardware

Entura used one physical workstation and rented several cloud hosted virtual instances (EC2: elastic cloud compute) from Amazon Web Services (AWS).

	Physical workstation	'Compute optimised' AWS	'General purpose' AWS
Label	HP Z400 Workstation	c4.8xlarge	m4.10xlarge
Processor	Intel Xeon 5645 Processor at 2.4 GHz	vCPU (High frequency Intel Xeon E5-2666 v3 (Haswell) processors optimized specifically for EC2)	vCPU (2.4 GHz Intel Xeon® E5-2676 v3 (Haswell) processors)
Memory	16 GB	60 GB	160 GB
Swap space	60 GB	0 GB	0 GB
Cost	Embedded	$2.195 per Hour (USD)	$3.363 per Hour (USD)

The 'general purpose' AWS machine was found to give the most reliable performance. No time was invested into working out how the AWS machines could enable swap space. This is possible, but was not trivial at the time of the project. One concern was that EBS (elastic block storage, the standard disk used by AWS EC2 instances) would charge for large amounts of read/write actions. Swap space has a large amount of read/write actions.

General modelling issues

Swap space

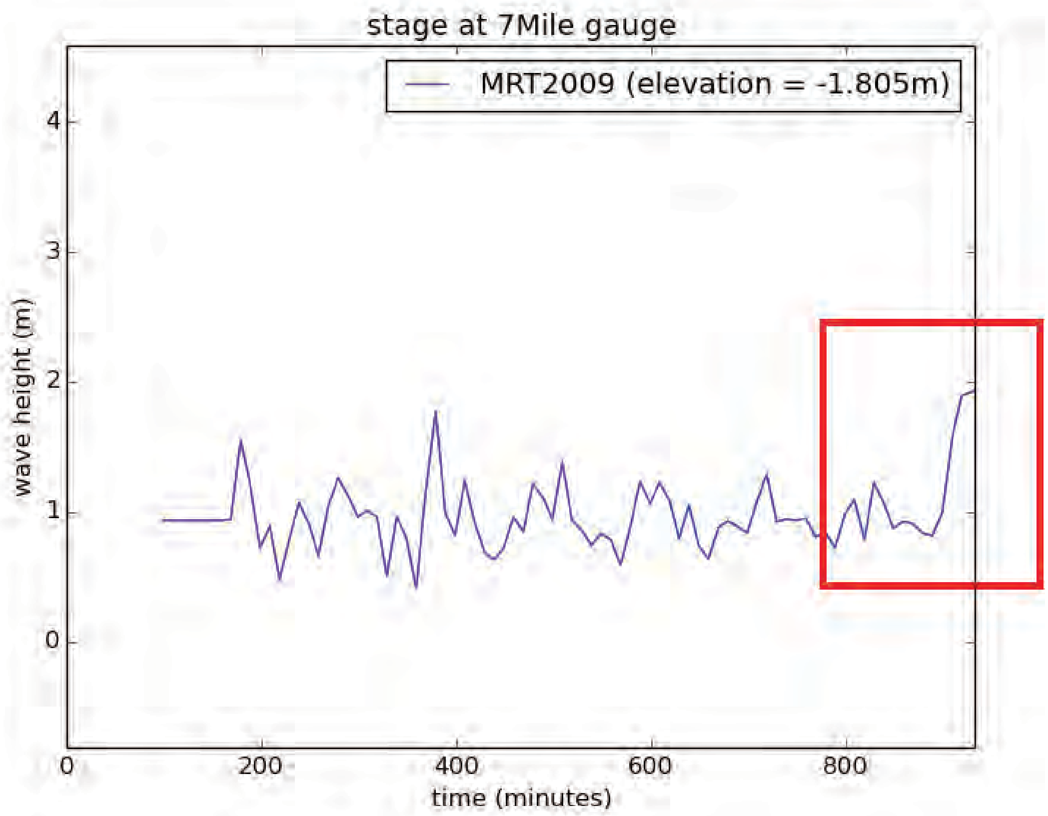
As stated in the install guide, ANUGA is memory-intensive. The desktop workstation used by Entura used the Ubuntu/Linux operating system with 16 GB memory. The initial disk configuration had very little swap space, however. Swap space is hard disk space set aside to be used as memory should the actual physical memory be insufficient. As such, ANUGA would fail before completing model runs. The error messages provided, however, did not point directly to this as an issue. It is possible that the cause of this was due to MPI (Message Passing Interface, the software that ANUGA uses for multi-processing), and not ANUGA itself. A typical message would be:

"mpirun noticed that process rank 0 with PID 3549 on node anuga-workstation exited on signal 9 (Killed)"

The SSD (solid state drive) used by the workstation was repartitioned with 60GB set aside for swap space. This addressed the issue and model runs could then be completed.

Rising hydrograph tail

Some early model runs had a rising hydrograph tail, which was out of character for a tsunami event. It was found that the ANUGA model was double-counting the default stage beyond the timeseries of tsunami boundary. This issue was corrected by setting the initial stage of the tsunami Dirichlet boundary to 0 m instead of the HAT value of 0.8 m.



Resolution polygons

ANUGA is quite sensitive to the structure of shapefiles it will accept. Polygon shapefiles cannot have holes in the polygons, these must be infilled. This can be accomplished using GIS software such as ArcGIS or QGIS. Likewise, ANUGA has had difficulties loading polygons with coincident boundaries. Some editing of polygon extents has been required to allow ANUGA to use the polygon extent data.

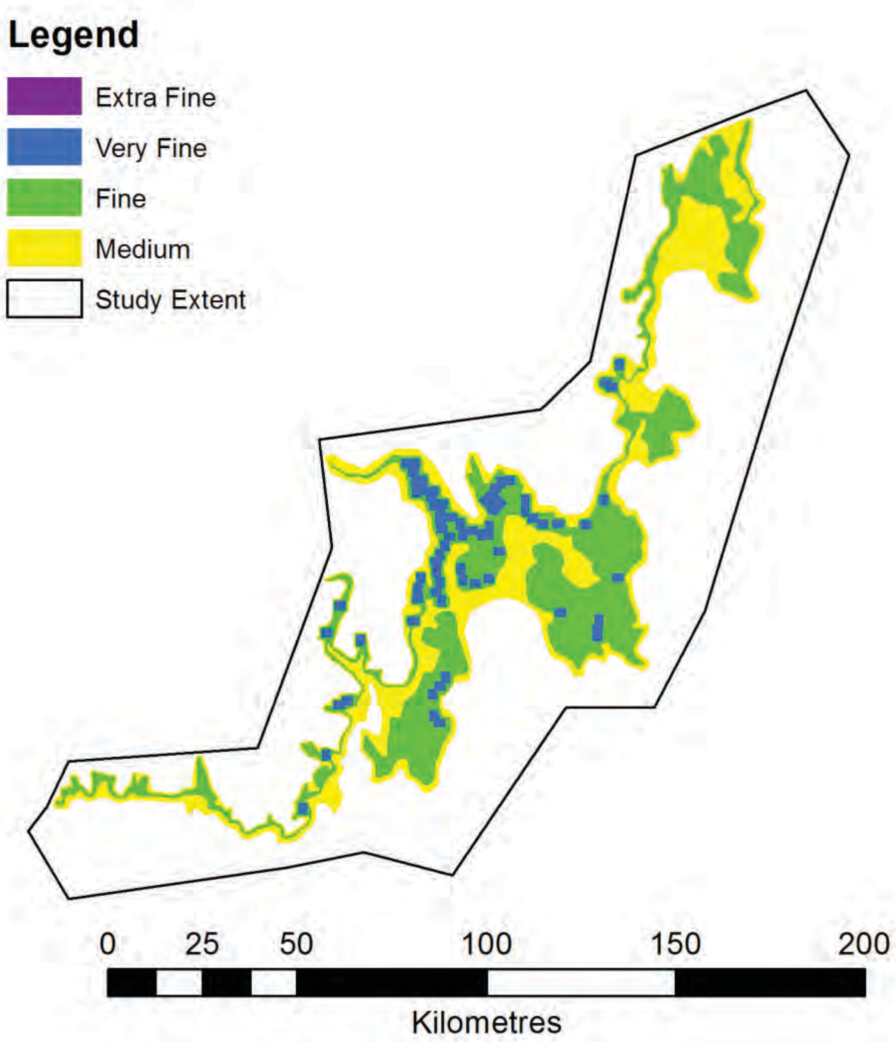
Run-up issue

Some difficulties were encountered with the calculation of inundation depth in shallow water areas, as described by Ted Rigby (pers. Comms 20 July 2016). Please see Ted's report for more detail on this issue.

General modelling details

Variable mesh resolution was used throughout the model domain. The following resolutions were applied to regions. The extents of these resolution areas are given in the map below. Areas not shaded (ie white) are at the coarse resolution.

Label	Region applied	Mesh resolution	Triangle size
Extra fine	Blackmans Bay	50	10 m x 10 m
Very fine	Study areas	200	20 m x 40 m
Fine	Coastal zone, mean sea level +/- 10 m	1250	50 m x 50 m
Medium	Ocean approaches mean sea level +/- 30 m	20000	200 m x 200 m
Coarse	All other areas	80000	400 m x 400 m



Scenario 1: reinstatement

The objective of scenario 1 has been to reinstate the original model done by Geoscience Australia in 2009 with new data. Potential changes that could have an impact on these results include changes to the ANUGA engine, changes to the elevation data, and the new model resolution extents.

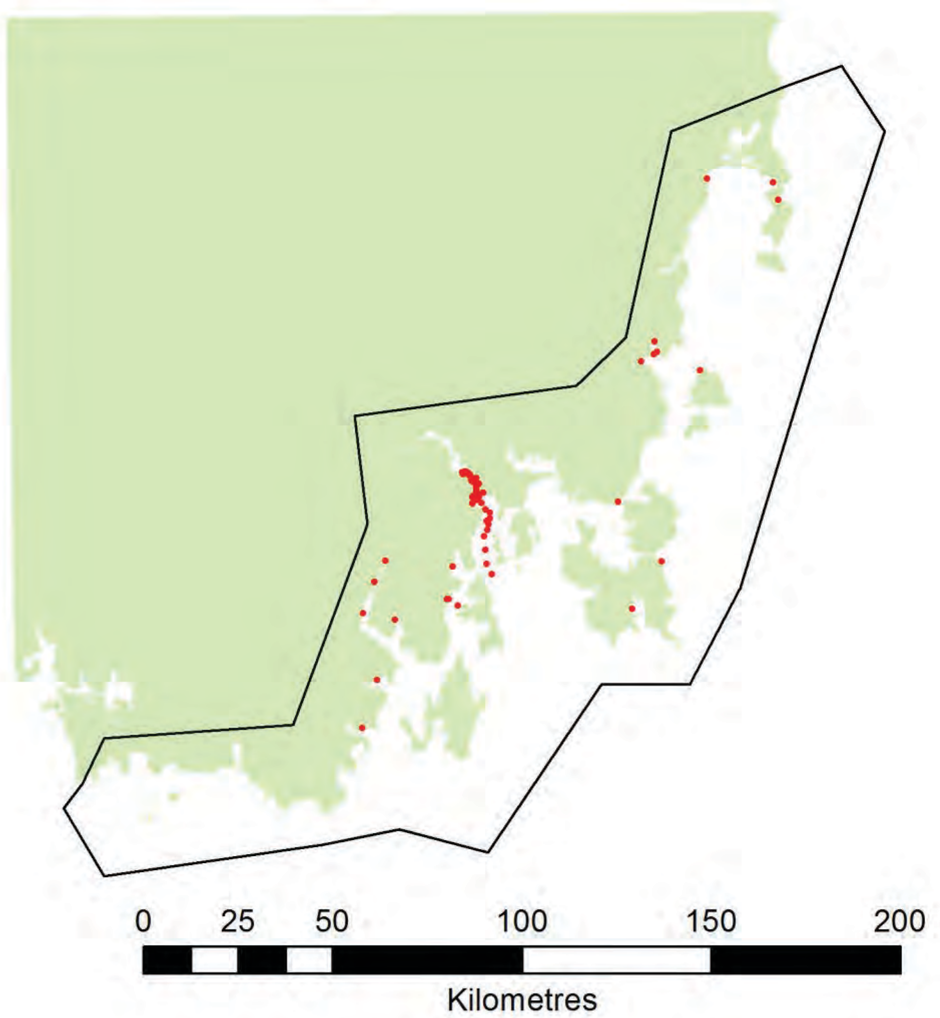
Scenario 2: Core model

The core model has been run for a simulation period of 4 hours. This model ran successfully on an Entura desktop computer. This study used all resolution polygon extents except for the extra fine.

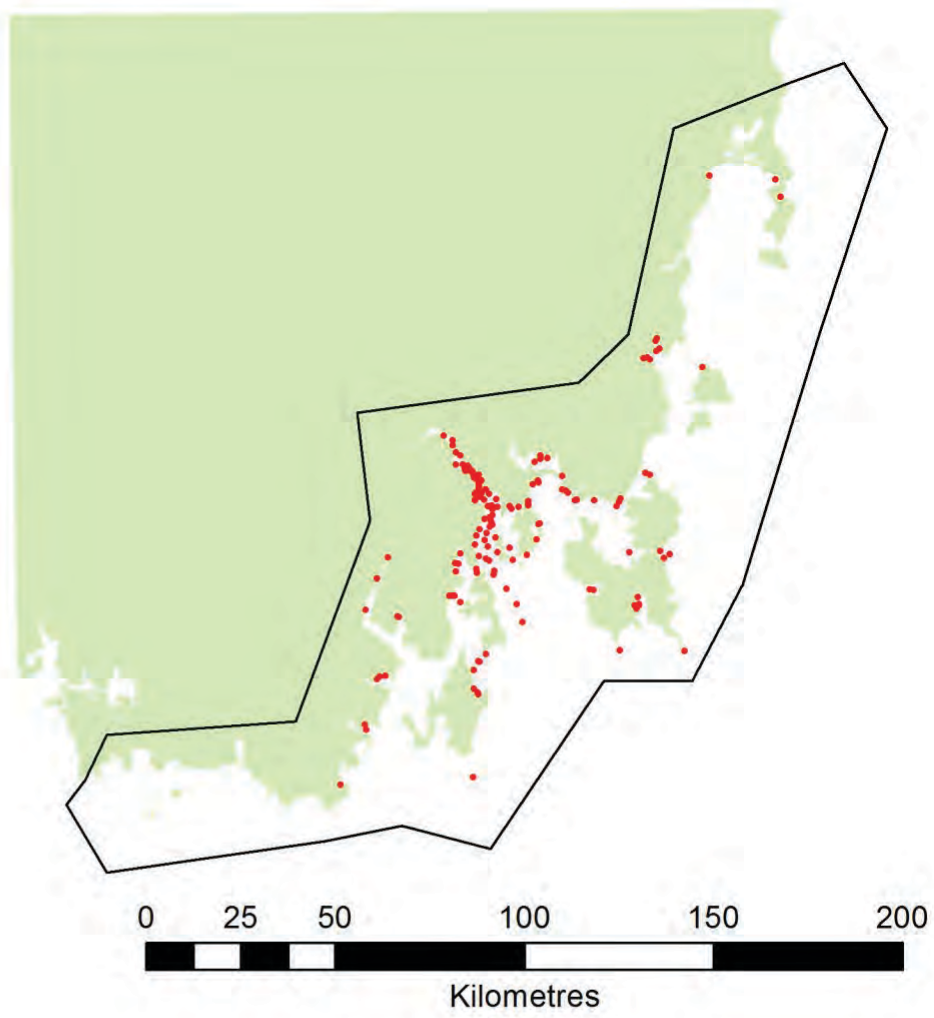
Scenario 3: Navigation Hazard

The Navigation Hazard model took a long time to process on the AWS machine (~80 hours). In addition, a considerable amount of memory was required for the SWW merge process to work. A 'compute optimized' CPU intensive machine with 60 GB of memory failed the final SWW merge step, but a general purpose machine with 160 GB memory was successful. Allocating swap space on the AWS instances was not investigated, but it could prove useful. This study used all resolution polygon extents except for the extra fine.

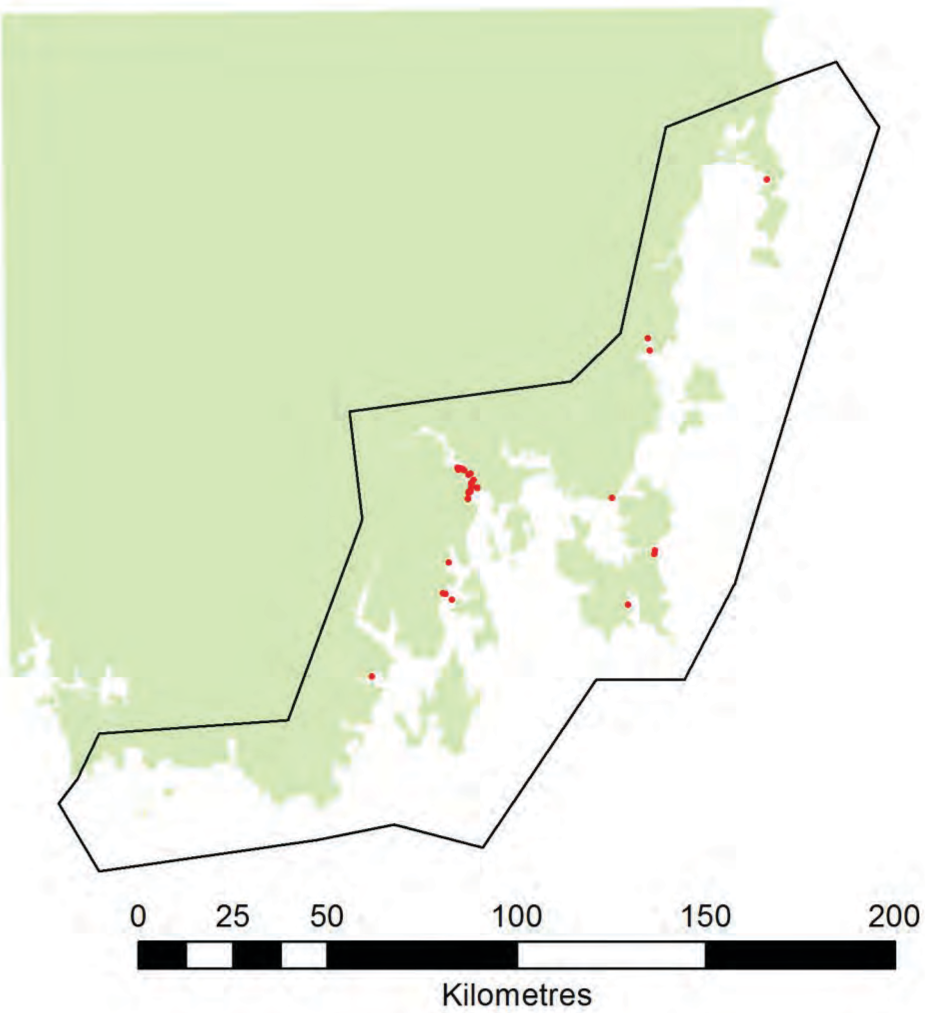
Timeseries and summary data have been extracted for several series of gauges for the Australian Maritime College. These are given below.



Locations for AMC Gauges 1



Locations for AMC Gauges 2



Locations for AMC Gauges 3; these locations are from AMC Gauges 2 that have been moved further offshore due to the ANUGA run-up issue

Scenario 4: Coastal Hazard

The coastal hazard model had a much finer spatial resolution in key analysis locations throughout the model, and extra fine spatial resolution in the Blackman's Bay area. This model was run for a simulation period of 4 hours, which took approximately 50 hours of runtime on an AWS instance, and was expected to take approximately 2 weeks on a desktop computer. This study used all resolution polygon extents.

General recommendations

Generally, it is recommended to keep track of all model configuration files in a version control system, such as git, and use this to track any and all changes to model runs. This allows the tracking of changes to the model and to revert back to previous configurations if required.

The use of cloud services (Amazon Web Services, AWS) has been very beneficial in this study; without it, some model runs would have taken weeks to complete.

Another major challenge of this project has been to handle the volume of data. Not just the size of the datasets, but the number of model configuration options and the number of outputs for each model run. A flexible framework/document for recording all of these details that can work well with the git version control system is recommended. In addition, some restructuring of the Python files could enable greater flexibility and tracking of changes.

References

Entura 2016, ANUGA: Guide to ANUGA on AWS, ENTURA-B9D6D, 25 May 2016

TECHNICAL REPORT ON TSUNAMI INUNDATION MODELLING IN SOUTH EAST TASMANIA

Tsunami Hazards in the Port of Hobart: Maritime Advice

Barrie Lewarn,
Australian Maritime College

APPENDIX THREE

Mineral Resources Tasmania
Department of State Growth

Tasmanian Government

AMCS
AMC SEARCH
Commercial arm of the Australian Maritime College

Tsunami Hazards in the Port of Hobart: Maritime Advice

Prepared by: Barrie Lewarn

11 October 2017

Department of State Growth, Tasmania

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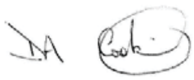
B	11 October 2017	Final document	Dean Cook / Chief Executive Officer	

- This report is prepared solely for the use of the Department of State Growth, Tasmania; Department of Police, Fire & Emergency Management, Tasmania; and Department of Premier and Cabinet, Tasmania (Division of Local Government, Security and Emergency Management). No responsibility to any third party shall be accepted, as the report will not be prepared, and shall not be intended for any other purpose.
- The Department of State Growth, Tasmania; Department of Police, Fire & Emergency Management, Tasmania; and Department of Premier and Cabinet, Tasmania (Division of Local Government, Security and Emergency Management) acknowledges that they are, and will continue to be, solely responsible for making management decisions and functions when implementing any advice or recommendations in this report.

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Executive Summary

1. The primary objective of the project is to provide advice on possible hazards to shipping (commercial, scientific research, and other agreed significant vessels) from modelled tsunami scenarios in the Derwent Estuary, Tasmania, for the principal Hobart port area (including Constitution Dock and Macquarie Point); Selfs Point Wharf; Risdon Wharf; Prince of Wales Bay wharf and dock facilities; the principal navigational channels and established anchorage areas from Iron Pot to Risdon Wharf; and the navigational channel specifically in the vicinity of the Tasman Bridge. The project was conducted as a desktop study and, whilst comprehensive in approach, the findings should be viewed as preliminary in nature. Further research is needed to test the reliability and validity of the findings to improve/ensure their accuracy.

2. A literature review was undertaken to assess and summarise the types of advice being provided to similar organisations, particularly port authorities, in other jurisdictions in Australia and internationally. The literature has three common themes, namely the provision of timely warning systems and procedures; evacuation of personnel; and advice to shipping and small craft. Although advice to shipping exists, it does not figure prominently in the emergency management/response literature. However, conventional wisdom (good seamanship practice), supported by general and academic literature is that the safest place to be for shipping is at sea in deep water. Information on what actions should be taken by a ship in port which is unable to get to deep water appears relatively limited, but that which does exist is based primarily on the Japanese experience. The literature also provides general advice to small craft, such as, if weather and time-permit move the vessel to deep water (over 45 metres) if it is able to handle the conditions. If it cannot handle the conditions, then it may be safer to leave the boat tied up and physically move personnel to higher ground.

3. The South East Tasmania Tsunami Inundation Model, developed for this project, indicates:

- Tsunami waves adhere to the general rules of wave behaviour in shallow water i.e. As the wave approaches shore (with water becoming shallower), the wave height increases, wavelength decreases and velocity decreases
- Wave heights are generally lower in the outer shipping channel, becoming higher in the port and dock areas
- A funnelling of the wave is observed as the channel narrows to the north of the Tasman Bridge and the maximum wave height is higher. This may also be exacerbated by reflection of waves from the steep bathymetry on the eastern shore
- Because of the long wavelengths, the tsunami waves arrive as a rise in water level that occurs over a period of 10-20 minutes (from starting level to peak wave height). The water level then decreases to a minimum value across the following 10-20 minutes
- In addition to the tsunami waves themselves, significant seiching and wave reflections are evident and may also generate significant water disturbance

4. The *2016 Tasmanian State Natural Disaster Risk Assessment: All Hazard Summary* indicates the likelihood of a disastrous tsunami is assessed as EXTREMELY RARE, with its overall consequence being MAJOR, and its overall risk rating being MEDIUM.

5. Based on the modelled tsunami scenarios, possible hazards to shipping and related maritime infrastructure were developed by considering the possible worst case consequences for Property (Vessel, Small craft, and Infrastructure); Life (Vessel, Small craft, and Vicinity); and Environment (Land, and Water). The potential consequences are detailed in the table

series 6-7, 9-12. From this a number of potential mitigating scenarios and actions were developed.

6. For shipping, appropriate mitigating actions are:
- If there is enough time before the arrival of the tsunami ships should evacuate outside the port
- If there is not enough time before the tsunami arrives ships should aim to remain in the deepest water in the port area. (This is considered feasible when the expected wave height is not excessive as is the case in the Principal Shipping Channel off White Rock Point)
- If evacuation is not possible the mooring system should be reinforced by increasing the number of mooring ropes, and regulating the mooring ropes so the ship cannot 'hang' on the ropes. It is noted that the mooring forces are usually smaller when the tsunami current is parallel to the ship. (This is the case for ships moored at Selfs Point Wharf and Nyrstar Wharf)

7. Based on the speculative evacuation times in Tables 15-18 and provided that a 1 hour warning is received it is probable that:
- A Handymax bulk carrier originally berthed at Risdon (Nyrstar) Wharf would meet the incoming tsunami wave to the south of the Tasman Bridge in the Principal Shipping Channel but still to the north of the deeper water off White Rock Point
- A Handymax oil tanker originally berthed at Selfs Point Wharf would meet the incoming tsunami wave a little to the south of the Tasman Bridge in the Principal Shipping Channel.
- The *Aurora Australis* originally berthed at Princes Wharf would meet the incoming tsunami wave in the vicinity of the deepest water off White Rock Point in the Principal Shipping Channel.
- A cruise ship similar to the *Sapphire Princess* and originally berthed at Macquarie Wharf would meet the incoming tsunami wave in the vicinity of the deepest water off White Rock Point in the Principal Shipping Channel.

8. Because most of the commercial shipping using the berths in the Port of Hobart have drafts greater than the inundation water levels above the berth deck, there is limited likelihood of these vessels being bodily lifted by the tsunami wave on to the berth. However, smaller vessels/craft with shallower drafts, e.g. less than 1.2 metres at the CSIRO Wharf, are at risk of being lifted on to the berth deck.

For shipping alongside that cannot, or decides not to, evacuate to deeper water the main risk is breaking adrift. Consequences of breaking adrift include major damage to the drifting ship, and other vessels and infrastructure struck by the drifting ship.

As the tsunami wave approaches, a ship alongside is lifted and may heel against the berth or break adrift if mooring lines are not tended to deal with the rising water. Mooring lines will slack off as the water recedes which may cause the ship to range away from the berth or break adrift if mooring lines are not tended to deal with the receding water. Extra mooring lines should be utilised if possible and crew should be stationed to slack off/tighten mooring lines as necessary.

For smaller vessels with shallower drafts it may be more prudent to put out extra moorings and then evacuate the crew to a safe, higher location ashore.

9. For small craft, appropriate mitigating actions are:

- Small craft underway
  Small craft constructed for use in offshore waters which have sufficient warning may be safer in deeper water. If it is not feasible to reach deeper water then the small craft should attempt to land, be secured, and the crew evacuated to a safe location.

  Small craft constructed for use in sheltered waters are less likely to be able to ride out a tsunami wave or be able to evacuate to deeper water. For small craft of sufficient engine power, it may be feasible to reach deep water, but only if it is considered safe to do so. Consequently, the most appropriate course of action may be to land, secure the craft, and evacuate the crew to a safe location.

- Small craft at designated anchorages, marinas and alongside a berth
  There is evidence of turbulence (e.g. breaking waves) at all Marinas and all Designated Small Craft Anchorages. Consequently, the most appropriate course of action may be to secure the craft, and evacuate the crew to a safe location. If sufficient time is available, small craft of sufficient engine power may be able to reach deep water, but only if it is considered safe to do so. Some of the larger craft alongside at a berth (e.g. fishing boats, ocean cruising yachts, ferries) may be able to let go and reach deep water, if sufficient time is available. If this is not feasible then the craft should be secured, and the crew evacuated to a safe location.

10. In summary, this preliminary report indicates the possible hazards to shipping from a worst case scenario tsunami in the Port of Hobart. The report is a high level review and potentially forms the basis for further more detailed consideration and research. In order to improve the accuracy and validity of the hazards and effects of a tsunami on vessels using the Port of Hobart more detailed research is needed. This could include:

- Improved data on vessels using the Port of Hobart e.g. types, size, speed
- Improved data on the alongside status of vessels using the Port of Hobart e.g. time taken for a vessel to let go and clear a berth including availability of crew and engines, mooring lines and gangways, manoeuvring issues, meteorological conditions
- Simulating ship evacuation scenarios on the Australian Maritime College simulators
- Reviewing potential hazards, damage criteria, mitigating actions including evacuation scenarios
- Consideration of the effects of 'smaller' tsunamis and different states of the tide
- Possibly testing the effects of a tsunami on vessels alongside a berth in the Australian Maritime College Model Test Basin

Outcomes from this research could be used to develop/refine/improve the advice to vessels and small craft in the Port of Hobart in the event of a tsunami warning being received.

1. Introduction

1.1. Background

The Department of State Growth commissioned AMC Search Ltd to provide advice on possible hazards to shipping based on modelled tsunami scenarios in the Derwent Estuary, Tasmania. Details of the full scope of the project are at Appendix 1.

AMC Search Ltd (AMCS) is the commercial arm of the Australian Maritime College and is a wholly owned subsidiary of the University of Tasmania. It is a company that provides solutions to maritime and maritime related organisations through its well-regarded consultancy services. With the backing of its parent institution, the Australian Maritime College, AMCS has provided training and consultancy services since 1985, using the internationally-renowned resources of the College.

1.2. Project Objective

The primary objective of the project is to provide advice on possible hazards to shipping (commercial, scientific research, and other agreed significant vessels) from modelled tsunami scenarios in the Derwent Estuary, Tasmania, for the following specific areas:

a) The principal Hobart port area (including Constitution Dock and Macquarie Point);
b) Selfs Point Wharf;
c) Risdon Wharf;
d) Prince of Wales Bay wharf and dock facilities;
e) The principal navigational channels and established anchorage areas from Iron Pot to Risdon Wharf; and
f) The navigational channel specifically in the vicinity of the Tasman Bridge.

1.3. Project Methodology

To achieve the objectives of the project a five stage approach was adopted, namely:

- Advice on the design of the tsunami computer model was provided to ensure that the model outputs provided the necessary information for shipping hazards to be adequately assessed
- A literature review was undertaken to assess and summarise the types of advice being provided to similar organisations, particularly port authorities, in other jurisdictions in Australia and internationally
- The tsunami computer model (South East Tasmania Tsunami Inundation Model) outputs were analysed to assess the implications for shipping at specified locations
- Some mitigating action scenarios were developed to further illustrate the implications for shipping
- A draft report summarising the findings, identifying any potential constraints and recommendations for further work and actions was prepared and presented at a workshop for stakeholders
- A final report incorporating comments from stakeholders and feedback from the workshop was prepared and delivered to the Department of State Growth

1.4. Tasmanian Emergency Plans - Tsunamis

Tasmanian emergency plans are well developed and the plans of direct relevance to this project are:

- Tasmanian Emergency Management Plan (TEMP)
- TasPorts Emergency Management Plan

The Tasmanian Emergency Management Plan (TEMP), Issue 8 [1] is the overarching plan for the management of emergencies in Tasmania. TEMP Table 4 lists the State Emergency Management Committee's Advisory Agencies and Management Authorities for Hazards**;** for tsunamis the State Emergency Service is responsible for *"Prevention and Mitigation"* whilst the Department of Police and Emergency Management is responsible for *"Preparedness"* and *"Response".* TEMP Section 3.1.17 lists tsunamis as a research and risk assessment theme currently being considered.

The Tasmanian Ports Corporation (TasPorts) Emergency Management Plan, Version 1.5 [2] includes tsunamis under its Severe Weather Warning Procedure; it states:
"In preparation for a storm, Port Control is to initiate safety precautions and actively monitor weather conditions. Severe Weather/Thunderstorm Warnings are issued by the Bureau of Meteorology for any of the following conditions:

- *wind gusts 90kph/49kts or more*
- *average wind speeds across land of 63kph/34kts or more*
- *heavy rainfall that is conducive to flash flooding or a reported flash flood*
- *abnormal high tides caused by winds (expected to exceed highest astronomical tide), and*
- *Tsunami warning"*

Details of the procedure to be followed are at Appendix 2.

The Tasmania State Emergency Services website [3] contains resources aimed at improving knowledge and awareness of tsunamis; it indicates that tsunamis have been experienced in Tasmania:
"There are two types of tsunami threat – land inundation threat and marine environment threat. A marine threat is the most likely type to occur but is more difficult to identify than the land threat. As opposed to wind driven waves, a tsunami is more like a wall of water. It usually appears as a series of waves, with the time between each wave ranging from ten minutes to two hours. At the beach, a tsunami wave does not break like normal beach waves, but continues to push ashore and may be seen as a rapidly rising tide. While Tasmania has not been significantly impacted by a tsunami in recent history, its proximity to the subduction zones that stretch from Papua New Guinea to New Zealand give rise to the potential for tsunami activity, particularly along the east coast. Geoscience Australia has identified the greatest tsunami risk to Tasmania is likely to be from the Puysegur Trench area off the south coast of New Zealand, an active region for earthquakes. If a tsunami is generated from this location it will approach Tasmania across the Tasman Sea. Research into tsunami activity in Tasmania indicates that unusual wave activity has been detected around the coastline on at least 16 occasions since 1852, and that this activity was likely to have been associated with a tsunami event."

2. South East Tasmania Tsunami Inundation Computer Model

To ensure that outputs from the tsunami computer model provided the necessary information for hazards to shipping to be adequately assessed, advice on the design of the model was provided by AMC Search Ltd to the Department of State Growth on 15 August 2015. The full scope of the advice requested is contained at Appendix 3.

The following indicative wave data was requested for 69 specific locations:

- Wave height (Amplitude peak to trough, in metres)
- Wave length (Peak to peak or trough to trough, in metres and duration e.g. minutes/seconds)
- Wave velocity (Preferably in knots; or metres per second)
- Wave form (Profile and descriptor e.g. slow water level rise, rapid water level rise; a 'wall of water', breaking wave)
- Time of arrival at each location relative to location 1 i.e. location 1 is time zero
- Time taken for the Tsunami wave to arrive at locations

Meetings were held in Hobart on 10 May 2016 to review the progress of the development of the tsunami model and in Launceston on 28 July 2016 to review the outputs from the model to ensure they provided the necessary information for shipping hazards to be adequately assessed.

The South East Tasmania Tsunami Inundation Model results provided data for the 69 requested locations in the form of:

- A spreadsheet containing the requested wave data (see Appendix 4)
- Six data maps namely:
  - Marine Hazard Map1 (PSC 8-30)
  - Marine Hazard Map2 (PSC 5-8, ANC 1-4)
  - Marine Hazard Map3 (PSC 1-3, ANC 4)
  - Constitution Dock (HP 2-19) (see Appendix 5)
  - Risdon Wharf (RW 1-4) (see Appendix 6)
  - Prince of Wales Bay (POW 1-8) (see Appendix 7)
- Four videos showing the depth of the tsunami, and four videos showing the momentum of the tsunami as it progresses up the Derwent, namely:
  - Channel and Docks
  - Hobart
  - Selfs Point
  - Prince of Wales Bay

These data were used to identify the possible hazards to shipping in the Port of Hobart.

3. Literature Review - Tsunami Advice in Other Jurisdictions

3.1. Introduction

A literature review was undertaken to assess and summarise the types of advice being provided to similar organisations, particularly port authorities, in other jurisdictions in Australia and internationally. The review focused on literature associated with Tsunami high risk zones as illustrated in Diagram 1 [4]. The diagram denotes every location where a tsunami run-up has been recorded in historical time and this includes the south of Tasmania.

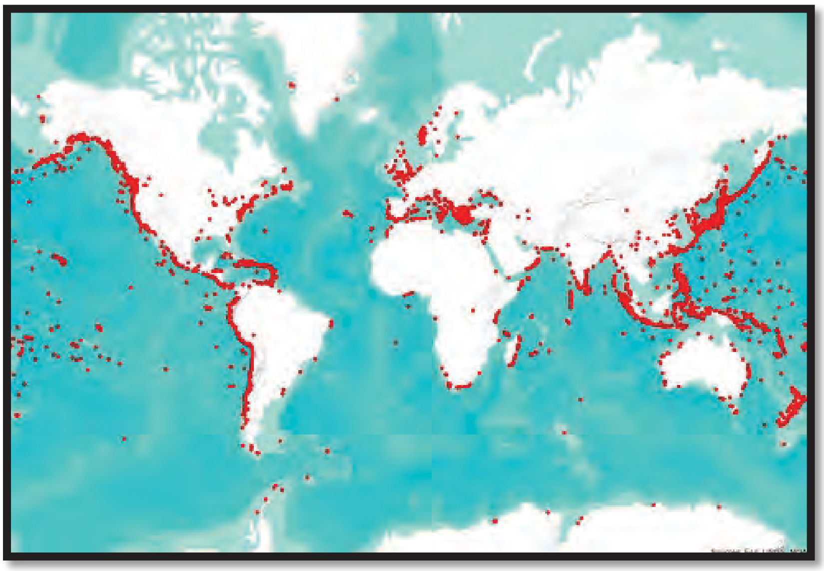

Diagram 1: World Tsunami Zones
(Source: Generated from the data in the NGDC global tsunami database [4])

It is noted that there are many descriptions of tsunamis in the literature and Anderson [5] provides a generic description of tsunamis:
"In deep, open-ocean water, these waves are often less than a metre high and can travel at speeds up to 1,000 kilometres per hour. However, as they reach shallow water and approach shorelines the leading edge of the waves begin to slow down, and the wave begins to "pile up" behind causing the wave to grow in height. The crests of these waves can be many metres high by the time they reach the shoreline. Sometimes, however, the crest of the wave isn't the first to arrive, the trough is. In this case, instead of very high water levels, the first sign of a tsunami is what appears to be a very, very low tide exposing unusually wide or unprecedented stretches of the seabed. It is important to note that the largest of the tsunami waves is often the third or fourth wave and there can be anywhere from a few tens of minutes, to more than an hour between wave crests."
However, in the case of the Port of Hobart it is the wave crest which arrives first.

The tsunami related documents which were reviewed are contained in the lists of References and Additional Tsunami Related Documents Reviewed. In addition to the literature search a number of videos of tsunami effects were sourced from YouTube and are listed following the list of references.

3.2. Summary of Advice

The literature has three common themes, namely:

- Provision of timely warning systems and procedures
- Evacuation of personnel
- Advice to shipping and small craft

Warning systems and procedures are almost exclusively aimed at notifying emergency response organisations and those likely to be directly affected by the tsunami. There is limited evidence of shipping being mentioned in response plans. Persons liable to be affected by a tsunami, including port workers, are generally advised to move to higher ground away from the coast or congregate on top of structures that will remain above the water.

Although general advice to shipping exists, it does not figure prominently in the emergency management/response literature. However, conventional wisdom (good seamanship practice), supported by general and academic literature is that the safest place to be for shipping is at sea in deep water. Information on what actions should be taken by a ship in port which is unable to get to deep water appears relatively limited, but that which does exist is based primarily on the Japanese experience. Port specific information on the detailed actions to be taken by a ship in port is also relatively limited. The literature also provides general advice to small craft, such as, if weather and time-permit move the vessel to deep water if it is able to handle the conditions. If it cannot handle the conditions, then it may be safer to leave the boat tied up and physically move to higher ground.

3.3. Literature Extracts

The following extracts from the literature indicate the relevant scope of advice for shipping and small craft:

With respect to warnings the *Tasmanian State Tsunami Emergency Response Plan* [6] indicates the following:

"3.2.3 Warnings and Public Information - National
The official tsunami warning centre for Australia is the Joint Australian Tsunami Warning Centre (JATWC) that is operated by the BoM and GA. Based in Melbourne and Canberra, the JATWC has been established so that Australia has an independent capability to detect, monitor, verify and warn the community of the existence of tsunami in the region and possible threats to Australian coastal locations and offshore islands.
The BoM Tasmanian Regional Forecasting Centre maintains distribution lists for Tsunami Bulletins, Watches and Warnings. The distribution lists contain contacts for TasPol, SES, TasALERT, Marine and Safety Tasmania (MAST), Tasmanian Ports Corporation and the media. The bulletin and warning messages are also automatically uploaded to the BoM website and are available on local radio and TV announcements or via a phone information line (1300 tsunami or 1300 878 626)."

"3.3.6 Warnings and Public Information - Tasmania
Tsunami warnings may not always be possible for all tsunamis e.g. those caused by sources other than earthquakes. For tsunamis originating from the Puysegur Trench (south of NZ) there may be as little as 60 minutes until the tsunami arrives at the Tasmanian coastline. It is therefore critical that warnings reach affected communities quickly and efficiently and by all appropriate means.
As detailed in Section 3.2.3 and Appendix 3 of this plan, Tsunami Warnings are initially issued by the BoM and are distributed to media outlets and emergency management agencies.
TasPol RDS will coordinate the dissemination of Tsunami Watches, Warnings and Bulletins issued by the JATWC through the BoM, to commercial and recreational vessels, ports and marinas via marine radio distress and calling frequencies."

"5.3 Appendix 3 - Tsunami Warnings and the Australian Tsunami Warning System (ATWS)
Effective warning time, and therefore warning arrangements, will vary depending on the proximity of tsunami generation, for example:
• A distant tsunami (e.g. Chile, California or Alaska) may arrive over 12 hours after it has been generated

• An earthquake along the Puysegur Trench in New Zealand may arrive approximately 2 hours after impact
• A local tsunami possibly caused by a submarine landslide may arrive at the initial point of impact along the Tasmanian coast within minutes. Under these circumstances, limited warning time may be available to adjacent coastal communities outside the initial impact area. (BoM may not be able to provide a Tsunami Warning under this circumstance)
• Meteorological tsunami – caused by high winds."

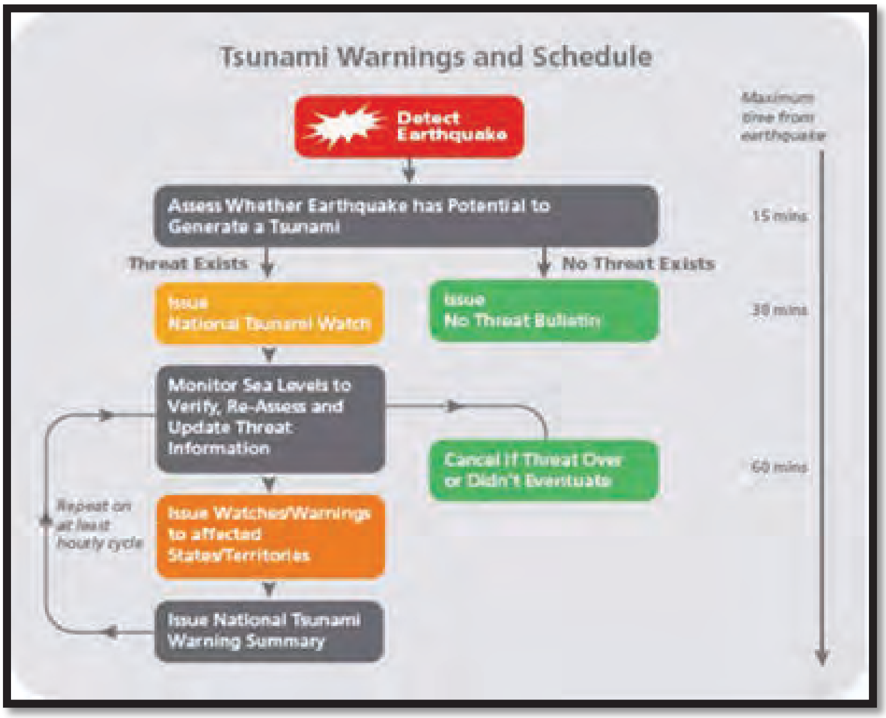

Diagram 2: Tsunami Warnings and Schedule (Source: Figure 2 *Tasmanian State Tsunami Emergency Response Plan* [6])

With respect to advice to shipping and small craft the *Tasmanian State Tsunami Emergency Response Plan* [6] indicates the following:
"3.3.7.2 Management of Waterways
People on boats or ships will be encouraged to:

- *If in shallow water, get out of the water and move away from the immediate water's edge of harbours, coastal estuaries, rock platforms and beaches*
- *When sufficient warning time is available, return any boats in harbours, estuaries and in shallow coastal water to shore, then secure the boat and move away from the waterfront*
- *Move vessels already at sea to deep water well offshore and remain there until further advised.*
- *When sufficient warning time is available, ocean capable ships currently in port or at anchorage may be instructed to move to deep water offshore to a depth greater than 30 metres. Vessels instructed to move from ports or harbours to deep water offshore will be prioritised in terms of risk posed to the nearby port facilities and population and their potential to provide assistance during rescue and recovery phases. It may be difficult for smaller vessels to move to deep water if there is a concurrent severe weather event occurring or predicted. Tasmanian Ports Corporation (Tasports) will coordinate the movement of ships within the port limits."*

Mikami et al in their *Field Survey of the 2011 Tohoku Earthquake and Tsunami in Miyagi and Fukushima Prefectures* state the following:
"Essentially when there is a tsunami alert all ships are ordered to go to the sea, as otherwise they risk floating over defences and exacerbate the damage (many examples of ships were left stranded inland during the Tohoku and Chile tsunamis). I am not sure whether any document actually indicates this, but it is "common knowledge" in areas frequently hit by tsunamis, such as Japan." [7]

The Hong Kong Weather Service advice is:
"... the impact of tsunamis to vessels at deep sea would be minimal. Hence, the general guidelines for countermeasures to be taken for vessels in case of tsunamis are:

- *those at port, harbour or in shallow water should evacuate to an area with deep water (sea depth of 50 m or more for tsunamis at coast smaller than 3 m, but deeper for more significant tsunamis, according to the Ministry of Agriculture, Forestry and Fisheries of Japan) if there is enough time to do so before tsunami arrival, or*
- *secure the vessels and evacuate the crew away from the waterfront if the time is not enough for the ships to evacuate to the deep sea or if evacuation is difficult. Furthermore, vessels which are already in or have evacuated to deep sea areas should take control to avoid being upset by or caught in the flow of the current."* [8]

The United States Department of Commerce, National Oceanic and Atmospheric Administration's / National Weather Service, National Tsunami Warning Center suggests: *"If you are on a boat or ship, weather and time-permitting, move your vessel to deeper water (at least 150 feet). If it is the case that there is concurrent severe weather, it may safer to leave the boat at the pier and physically move to higher ground. Damaging wave activity and unpredictable currents can affect harbor conditions for a period of time after the tsunami's initial impact. Be sure conditions are safe before you return your boat or ship to the harbor."* [9]

Queensland Government advice is:
"On a boat or ship

- *if in a harbour, estuary or shallow water close to shore, and there is enough time, return to land, secure your vessel and move to higher ground*
- *if at sea, move to deep water (open ocean) well off-shore and stay there until further advised."* [10]

The International Tsunami Information Center *What to do? Tsunami safety for boaters* brochure indicates:
"1 ... do not return to port if you are at sea and a tsunami warning has been issued. Port facilities may become damaged and hazardous with debris. Listen to mariner radio reports when it is safe to return to port.
2 ... rapid changes in water level and unpredictable dangerous currents are magnified in ports and harbors. Damaging wave activity can continue for many hours following initial tsunami impact. Contact the harbor authority or listen to mariner radio reports. Make sure that conditions in the harbor are safe for navigation and berthing.

3 Boats are safer from tsunami damage while in the deep ocean (> 100 m) rather than moored in a harbor. But, do not risk your life and attempt to motor your boat into deep water if it is too close to wave arrival time.
4 For a locally-generated tsunami, there will be no time to motor a boat into deep water because waves can come ashore within minutes. Leave your boat at the pier and physically move to higher ground.
5 For a tele-tsunami generated far away, there will be more time (one or more hours) to deploy a boat. Listen for official tsunami wave arrival time estimates and plan accordingly.
6 Most large harbors and ports are under the control of a harbor authority and/or a vessel traffic system. These authorities direct operations during periods of increased readiness, including the forced movement of vessels if deemed necessary. Keep in contact with authorities when tsunami warnings are issued." [11]

The Bureau of Meteorology (2016), *Tsunami Frequently Asked Questions* states:
"If your boat is in deep water and offshore, maintain your position. If your boat is berthed or in shallow water, secure your vessel and move inland or to higher ground." [12]

Wiśniewski and Wolski [13] in their journal article, *The safety of the shipping and ports in the aspect of the tsunami events,* develop actions for shipping in port in the event of a tsunami warning. Table 1 illustrates:

Table 1: Standard recommendations for the operations of the ship before the tsunami

Tsunami magnitude forecast		**Time until tsunami arrival**	**Moored ship in port**	**Anchored and buoy moored ships**	**Ships underway in the port and roads**
Tsunami Warning	Strong tsunami (3-10m+)	Short (under 0.5h)	Halt cargo handling. The recommended evacuation of the crew to land	Use engine	The recommended offshore evacuation
		Medium (0.5-1.5h)	Halt cargo handling. The recommended offshore evacuation of the ship. Possible evacuation of the crew to land	Use engine or possible offshore evacuation	
		Long (over 1.5h)	Halt cargo handling. Offshore evacuation	Offshore evacuation	
	Average tsunami (1-3m)	Short (under 0.5h)	Halt cargo handling. Strengthen mooring. Possible evacuation of the crew to land	Use engine	Offshore evacuation
		Medium (0.5-1.5h)	Halt cargo handling. Strengthen mooring. Offshore evacuation or evacuation of the crew to land	Use engine or possible offshore evacuation	
		Long (over 1.5h)	Halt cargo handling. Strengthen mooring Offshore evacuation or evacuation at designated places of refuge in the port	Offshore evacuation	
Tsunami Advisory	Small tsunami (under 1m)		Halt cargo handling. Strengthen mooring. Possible offshore evacuation	Note the conditions (if not worse in the next message). In these cases, use engine or offshore evacuation	Offshore evacuation

Note: Based on Wiśniewski and Wolski, *The safety of the shipping and ports in the aspect of the tsunami events* [13]

The 9th Regional Japan Coast Guard Headquarters brochure, *To secure Life and Ship from Tsunami* [14], states the following:
"When warning and/or advisory are issued, all ships are supposed to suspend loading and work regardless of situations such as alongside, anchorage and the like, and then respond by reference to the table below." Table 2 illustrates:

Table 2: Shipping in Port - Response to Tsunami Warning

Tsunami Warning Category	Estimated Maximum Tsunami Height		Adequate time before arrival of tsunami	Ships at Berth in Port		Ships Anchored and on a mooring buoy	Navigating Ships
	Quantitative expression	For earthquakes		General Ships	Ships with dangerous cargo		
Major Tsunami Warning	Above 7.5m	Huge	NO	Evacuate mooring or evacuate on shore		Evacuate in port	
	Below 7.5m		YES	Evacuate out of port		Evacuate out of port	
Tsunami Warning	3m	High	NO	Evacuate mooring		Evacuate in port	
			YES	Evacuate out of port or evacuate mooring	Evacuate out of port	Evacuate out of port	
Tsunami Advisory	1m	N/A	N/A	Evacuate out of port or evacuate mooring		Evacuate in port or evacuate out of port	Evacuate out of port

Note 1: Terminology explanation
ADEQUATE TIME BEFORE ARRIVAL OF TSUNAMI:

- *YES: After TSUNAMI WARNING issued, there are adequate time to evacuate ships and secure their safety.*
- *NO: After TSUNAMI WARNING issued, there are little time to evacuate ships and secure their safety.*

MOORING EVACUATION: To keep moored against TSUNAI by reinforcement of mooring along with engine. (Consider evacuating land workers and the like aboard the ship for emergency shelter.)
EVACUATION IN PORT: To remain at waters for emergency evacuation in a port, by using anchor, engine, thruster and the like.
EVACUATION OUT OF PORT: To evacuate offshore from a port to the open sea where the water is deep. (Consider EVACUATION IN PORT when it becomes difficult to sail during EVACUATION OUT OF PORT)
EVACUATION ON SHORE: To evacuate ship crew ashore and then to high ground, after taking all possible measures to secure the safety of dangerous cargo and to prevent a ship from being drift."
Note 2: Based on 9th Regional Japan Coast Guard Headquarters, *To secure Life and Ship from Tsunami* [14]

There is considerable similarity in the advice to shipping in port when a tsunami warning is received and Table 3 is a compilation of the advice to shipping and small craft based on the literature in general and specifically:

- Hong Kong Weather Service, *List of Countermeasures against Tsunami,*[15]
- 9th Regional Japan Coast Guard Headquarters brochure, *To secure Life and Ship from Tsunami* [14]
- Wiśniewski B and Wolski T (2012) article, *The safety of the shipping and ports in the aspect of the tsunami events* [13]

Table 3: Tsunami Warning-Summary of Advice to Vessels in Port

Predicted Tsunami height	Able to get to deep water	Vessels alongside in port			Anchored/ moored v/ls	Vessels underway in port area	
		Large & mid size v/ls		Small craft		Large & mid size v/ls	Small craft
		V/ls with DG	Other v/ls				
Over 3 metres	No	Evacuate to deep water	Evacuate to land	Evacuate to land	Use engine	Evacuate to deep water	Land and evacuate
	Maybe		Evacuate to land, or to deep water	Evacuate to land, or (to deep water if safe to do so)	Use engine, or evacuate to deep water		Evacuate to deep water, or (land and evacuate if safe to do so)
	Yes		Evacuate to deep water		Evacuate to deep water		Evacuate to deep water, or land and evacuate
1 - 3 metres	No		Evacuate to land, or strengthen moorings	Evacuate to land	Use engine		Land and evacuate
	Maybe		Evacuate to deep water, or to land, or strengthen moorings	Evacuate to land, or (to deep water if safe to do so)	Use engine, or evacuate to deep water		Evacuate to deep water, or (land and evacuate if safe to do so)
	Yes		Evacuate to deep water, or strengthen moorings		Evacuate to deep water		Evacuate to deep water, or land and evacuate
0.5 - 1 metre		Evacuate to deep water, or strengthen moorings		Secure craft, or evacuate to deep water	Use engine, or evacuate to deep water		Secure craft, or evacuate to deep water

Note: Based on Hong Kong Weather Service, *List of Countermeasures against Tsunami* [15];
9th Regional Japan Coast Guard Headquarters, *To secure Life and Ship from Tsunami*, 9th Regional Japan Coast Guard
Headquarters [14]; and
Wiśniewski and Wolski, *The safety of the shipping and ports in the aspect of the tsunami events* [13]

It is noteworthy that there is no consistency on precisely what depth constitutes deep water, as the literature variously describes deep water as:

- Offshore 30+ metres {*Tasmanian State Tsunami Emergency Response Plan* [6]}
- Deeper water 150+ feet (45+ metres) {National Oceanic and Atmospheric Administration [9]}
- Sea depth of 50+ metres (Tsunamis under 3 metres; deeper for higher tsunamis) {Hong Kong Weather Service [8]}
- Deep ocean 100+ metres {International Tsunami Information Center [11]}
- Open ocean {Queensland Government [10]}

4. Analysis of Computer Model Outputs

South East Tasmania Tsunami Inundation Model Results

4.1. Model Outputs

- *A table of results for gauges across the entire modelling area, including 65 within the Derwent estuary, shipping channel and marina or dock areas. These are identified in the description field of Appendix 4*
- *A sequence of maps showing the location of the 69 gauges of interest, summarising the key results at each location and showing areas of turbulence (i.e. where the maximum wave is breaking). Appendices 5, 6, and 7 contain the gauge data for Constitution Dock, Risdon Wharf, and Prince of Wales Bay*
- *Movie animations showing the model results over time. Two copies of each file were produced – one showing the changes in depth over time and the other showing the momentum. Although not strictly showing velocity, the vectors (arrows) on the momentum plots are a useful tool for visualising the direction of the tsunami propagation*

4.2. Summary of computer model findings and interpretations

General observations:

- Tsunami waves adhere to the general rules of wave behaviour in shallow water. As the wave approaches shore (with water becoming shallower), the wave height increases, wavelength decreases and velocity decreases. This pattern can be seen in both the gauge data and the animations of the model run. Wave heights are generally lower in the outer shipping channel, becoming higher in the port and dock areas
- A funnelling of the wave is observed as the channel narrows beyond (upstream) the Tasman Bridge. Maximum wave height is higher here, which may also be exacerbated by reflection of waves from the steep bathymetry on the eastern shore
- With such long wavelengths, the tsunami waves arrive as a rise in water level that occurs over a period of 10-20 minutes (from starting level to peak wave height). The water level then decreases to a minimum value across the following 10-20 minutes
- In addition to the tsunami waves themselves, significant seiching and wave reflections are evident in the time series data. In some cases, this results in maximum water levels that are out of sync with the tsunami wave timing, and may also generate significant water disturbance

Shipping channel:

- Tsunami arrival times vary between 2.5 and 3.25 hours after the earthquake, with a difference of 36 minutes between PSC1 (off Iron Pot) and PSC30 (entering Prince of Wales Bay)
- End times show disturbance that persists for 13-15 hours at most locations
- Maximum wave heights vary from a minimum of 2.4 m at PSC6 (off Blinking Billy Point), to a maximum of 5.1 m at PSC21 (off New Town Bay). Many values fall between 3.5 and 4.5 m
- Wavelengths for the largest wave in each sequence are generally between 3 and 5 km. This is within the expected range for tsunami waves as they enter shallow water

- Most of the tsunami-induced velocity fluctuations relate to wave speed, with maximum values falling between 15.5 knots (mid channel at the entrance to Prince of Wales Bay) and 32.7 knots (at PSC3, off Blinking Billy Point). Maximum induced current speeds are in the order of 2 to 7 knots
- No evidence of turbulence was observed in the shipping channel, as the water depth is large relative to the wave height
- Data reliability for these gauges is satisfactory, as they are all located offshore and in suitably deep water

Port area and wharves:

- Arrival times of the first wave range from 3 hours at HP2 (east of Battery Point) to 3 hours 12 minutes at POW8 (Pauline Point)
- Maximum wave heights range from 2.7 m at POW4 (INCAT jetty) to over 5 m at Selfs Point, PSC21 and Geilston Bay Marina
- Wavelengths for the first wave vary significantly, depending on the water depth and thus the degree of shoaling the wave has experienced. In shallower areas next to the shore, wavelengths are in the order of 100 to 500 m, while in deeper locations wavelengths remain at several kilometres
- Maximum wave speeds vary between 4.8 knots at POW2 (INCAT slipway) and 30.9 knots off Macquarie Point (HP19). In general, wave speeds are less than 10 knots within the dock areas and next to the shore. Higher velocities occur further out in the channel
- Turbulence is observed at 13 of the 35 gauges in the port and dock areas. Prince of Wales Bay is particularly affected, as is Macquarie Wharf and Princes Wharf 1
- A backup of water level is observed in some locations, most notably in the centre of Constitution Dock. Following inundation by the first wave, the water does not fully drain before the arrival of the second wave and the water level remains at least 1.5 m higher than the starting level for the duration of the model run. However, at no point does the water height exceed that of the first wave peak level
- The reliability of gauges in the port and dock areas is variable. There were some concerns regarding the reliability of gauges located close to the shoreline, particularly in areas with steep relief such as around the docks and cliffs. A reliability index was constructed to indicate the level of confidence in the data at each gauge location. Gauges located offshore are rated as satisfactory, but those situated at or near the shoreline boundary are generally rated marginal. Only four are deemed unreliable. These gauges were not removed from the final output, but new gauges were added a short distance away to provide extra information that is more reliable.

4.3. Definitions

- **Max wave height** – The distance from peak to trough of the wave that generated the highest water level in the time series
- **Max stage** - The maximum water level above Highest Astronomical Tide (HAT) reached during the tsunami event.
- **Wave length** – An approximate value calculated from the velocity and 2 x the time period between the maximum peak and its associated trough

- **Max current** – The maximum current velocity, provided in both ms-1 and knots. This value represents the absolute particle movement throughout time (i.e. a persistent induced current)
- **Turbulence** –An approximation of the areas likely to be affected by turbulence associated with shoaling and tsunami wave breaking (e.g. generating a bore) was calculated using the ratio of wave height (h) to water depth (d). Areas were designated 'turbulent' where $h/d \geq 0.72$. (Note: Modelling is based on 2D shallow water wave equations and as such, cannot resolve vertical movement. Consequently, the model cannot simulate 3D turbulence or breaking waves).
- **Wave speed** – The maximum celerity (wave speed), provided in both ms-1 and knots, derived from the water depth by the formula $c = \sqrt{gd}$. This is the instantaneous speed encountered as the wave passes a point. The effect of tsunami wave speed on marine craft is difficult to quantify and will depend on the length and draw of the boat (as with normal wind-waves).

5. Possible Hazards to Shipping Based on Modelled Tsunami Scenarios In The Derwent Estuary

Implications for Shipping

5.1. Tsunami Waves: General Effects

Research into tsunami activity in Tasmania indicates that unusual wave activity has been detected around the coastline on at least sixteen occasions since 1852, and that this activity is likely to have been associated with a tsunami event. Geoscience Australia has identified the greatest tsunami risk to Tasmania is likely to be from the Puysegur Trench area off the south coast of New Zealand, an active region for earthquakes. The likelihood of a disastrous tsunami is assessed as EXTREMELY RARE, with its overall consequence being MAJOR, and its overall risk rating being MEDIUM [16].

Of specific note is that a Tsunami initiated by an earthquake in the Puysegur Trench could reach Tasmania in 2 hours, the JATWC aims to issue a National Tsunami Watch within 30min of the earthquake and issue specific Watches and Warnings within 60mins of the earthquake. These would then be followed by additional warnings issued by Tasmania Police. This in effect means that the public in Hobart could realistically expect 1hrs warning. [6]

"The risk of tsunami to people was increased from 'Medium' in 2012 to 'High' in 2016 due to an increase in consequence from 'Major' to 'Catastrophic', despite a decrease in likelihood to 'Extremely Rare'. Experts believed that the rapid onset of this event (less than 3 hours warning in best-case conditions) limited the capacity of the emergency services to inform all vulnerable areas or people and as such it seemed realistic to expect more than 50 deaths or serious injuries. As the region of greatest vulnerability includes the Hobart waterfront, a busy place at regular times throughout the week and year, the evacuation during a large event was also considered." [16] The assessed levels of risk posed by a tsunami are contained in Table 4.

Table 4: Levels of Risk posed by a Tsunami			
Risks to:	**Likelihood**	**Consequence**	**Risk level**
People – Deaths	Extremely rare	Catastrophic	High
People – Injury	Extremely rare	Catastrophic	High
Economic – General	Extremely rare	Catastrophic	High
Economic – Industry	Extremely rare	Major	Medium
Environment – Species	Extremely rare	Major	Medium
Environment – Value	Extremely rare	Moderate	Medium
Public Administration	Extremely rare	Major	Medium
Social Setting – Community Wellbeing	Extremely rare	Moderate	Low
Social Setting – Cultural Significance	Extremely rare	Major	Medium
Note: Extracted from 2016 Tasmanian State Natural Disaster Risk Assessment: *All Hazard Summary* [16]			

The South East Tasmania Tsunami Inundation Model shows that the tsunami waves follow the basic rules of wave behaviour in shallow water i.e. as the wave approaches the shore, where the water becomes shallower, the wave height increases, the wavelength decreases and wave velocity also decreases. In broad terms wave heights are generally lower in the outer reaches of the shipping channel and tend to increase in the port/dock areas.
Because the tsunami waves have very long wavelengths the effect is a rise in water level, from starting level to peak wave height, over a period of 10 – 20 minutes. The water level then decreases to a lower level over the following 10 – 20 minutes.

Wave heights reduce to 1 metre after about 10 -12 hours and disturbance of the water due to the tsunami persists for 13 – 15 hours at most locations.

"A tsunami poses a significant risk only to those ships in shallow waters and in port areas. Ships in port are not required to maintain watch on the GMDSS communications equipment; consequently, a separate system for promulgating warning messages needs to be established within each port. Tsunami warnings need to be rapidly sent to those ships most at risk." [17]

" One of the major hazards due to tsunamis, even of small amplitudes, are the very strong currents that can be generated, that can rip the tie lines and moorings of vessels and cause serious damage to piers and docks" [18]

Wiśniewski and Wolski [13] conducted an analysis of the effects of the Japanese tsunami of 11 March 2011 on shipping in port. Whilst recognising Japanese tsunami waves were of greater magnitude than the modelled waves for the Derwent and the Port of Hobart, their findings are illustrative of the consequences for shipping caught in port and are contained in Table 5a. From their analysis they produced a more generalised description of the effects of a tsunami on ships in port which are contained in Table 5b.

Table 5a: Effects of the Japanese Tsunami of 11 March 2011 on Shipping in Port					
Ran aground or ashore			**Broke moorings and drifted in harbour**		
Number	**Ship type**	**DWT**	**Number**	**Ship type**	**DWT**
4	Bulk	175000-3200	2	Tanker	75000-9500
4	Freighter	6900-530	1	Bulk	51000
3	Fishing	380-220	1	Container	44500
			1	Research	27000
			2	General cargo	24000

Table 5b: Effects of Tsunamis on Ships in Port		
Tsunami Magnitude	**Ship Size**	**Damage Pattern**
Small (Tsunami height: more than 2 or 3 m)	Small Ship	– Drifting – Collision with quay wall – Overturning / Sinking – Being cast ashore
Large (Tsunami height: more than 5 or 6 m)	Small Ship	– Being cast ashore – Collision with buildings
	Large Ship	– Drifting – Collision with quay wall – Being cast ashore – Collision with buildings
Source: Wiśniewski B and Wolski T, *The safety of the shipping and ports in the aspect of the tsunami events* [13]		

5.2. Tsunami Effects and Potential Consequences

The following explains the various heights referred to in the rest of the report; Diagram 3 illustrates, using the data for the CSIRO Wharf as an example.

- **Inundation height**
  Height of wave crest above berth deck
- **Stage height**
  The level of the water surface above the highest astronomical tide (MS on maps)
- **Maximum Wave height**
  Height of the wave from crest to trough
- **Berth height**
  Height of the berth deck above Chart Datum
- **Mean Higher High Water (MHHW)**
  The mean of the higher of the two daily high waters over a long period of time. When only one high water occurs on a day, this is taken as the higher high water
- **Highest Astronomical Tide (HAT)**
  This is the highest level which can be predicted to occur under average meteorological conditions and any combination of astronomical conditions. This level will not be reached every year. HAT is not the extreme level which can be reached, as storm surges may cause considerably higher levels to occur
- **Lowest Astronomical Tide (LAT)**
  This is the lowest level which can be predicted to occur under average meteorological conditions and any combination of astronomical conditions. This level will not be reached every year. LAT is not the extreme level which can be reached, as storm surges may cause considerably lower levels to occur
- **Chart Datum**
  LAT has been used as port and chart datum since 1994
- **Charted depth**
  Depth of water below Chart Datum (LAT)

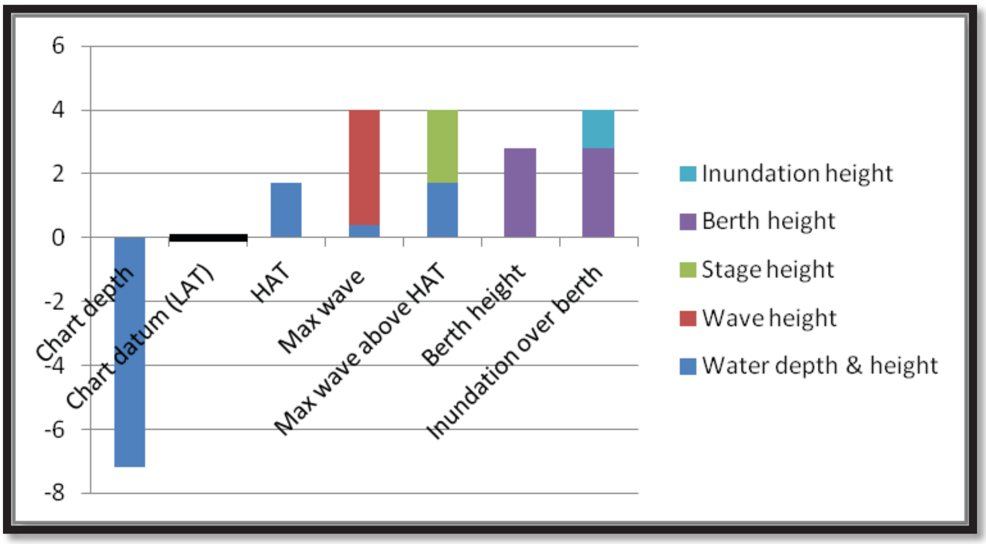

Diagram 3: Tsunami Wave - Depths and Heights (Example CSIRO Wharf)

The following terminology applies for the sections and tables listing the effects and potential consequences of a worst case tsunami:

- Vessel (commercial vessels including bulk carriers, oil tankers and cruise ships; scientific research vessels including *Aurora Australis, L'Astrolabe* and *Investigator*)
- Small craft (fishing vessels; river ferries and tourist craft; tug boats; leisure craft including cabin cruisers, power boats and yachts)
- Infrastructure (wharves and docks; navigation and mooring buoys; marina pontoons and associated infrastructure)
- Property damage-vessel
  - Minor (loose objects move; minor dents and scrapes)
  - Moderate (secured objects break loose; dents requiring repair; equipment damage)
  - Major (loss of watertight integrity of hull, sinking; collisions; grounding)
- Property damage-small craft
  - Moderate (damage to fittings, superstructure, masts, equipment)
  - Major (capsize; loss of watertight integrity of hull, sinking; foundering; collisions; grounding)
- Property damage-infrastructure
  - Damage caused by wave, uncontrollable vessels and small craft, and floating wreckage; loss of navaids; damage to bridge piers;
- Life-vessel (Note: These descriptors are consistent with the *National Emergency Risk Assessment Guidelines* [19])
  - Minor - Injuries requiring basic medical aid that could be administered by paraprofessionals, which would require bandages or observation. Examples include a sprain, a severe cut requiring stitches, a minor burn (partial thickness on a small part of the body) or a bump on the head without loss of consciousness
  - Serious - Injuries requiring a greater degree of medical care and use of medical technology such as X-rays or surgery, but not expected to progress to life-threatening status. Examples include full thickness burns across a large part of the body or partial thickness burns to most of the body, loss of consciousness, fractured bones, dehydration or exposure

    - Fatal/Critical - Mortally injured, is certain to lead to death regardless of available treatments. Injuries that pose an immediate life-threatening condition if not treated adequately and expeditiously. Examples include uncontrolled bleeding, a punctured organ, other internal injuries, spinal column injuries or crush syndrome
- Life-small craft
    - Minor/Serious
    - Fatal/Critical
- Life-vicinity
    - Fatal/Critical

5.3. Tsunami Effects and Potential Consequences: Principal Shipping Channel Iron Pot to Prince of Wales Bay (and specifically in the vicinity of the Tasman Bridge)

Bulk Carrier *Mount Baker* transiting Tasman Bridge
L 177 B 29.4 DWT 32040
http://www.mast.tas.gov.au/

The tsunami waves create a rise in water level, from starting level to peak wave height, over a period of 10 – 20 minutes and because of this there is no evidence of turbulence (e.g. breaking waves) in the principal shipping channel. Wave heights are generally lower in the outer reaches of the shipping channel and tend to increase in the port/dock areas. As the waves pass to the north of the Tasman Bridge, where the channel narrows, a funnelling effect occurs. This causes the wave height and current to increase in this region. Within the principal shipping channel wave heights are reduced to approximately 1 metre after 10 – 12 hours.

The minimum depth at the entrance to the River Derwent is 14.1m at the Iron Pot Bar. The maximum size vessel allowed to transit the Tasman Bridge is 185 metres in length. The Centre Line of the Main Navigation Span of the Tasman Bridge is 44 metres above Mean High High Water (MHHW is 1.5 metres above chart datum) [20] and the Main Navigational Channel is approximately 100 metres wide [21].

The following Table 6 illustrates the potential consequences of a worst case scenario tsunami wave in the Principal Shipping Channel at the highest astronomical tide (HAT). For ease of analysis the potential consequences were considered for the five sections of the channel from Iron Pot to the entrance to Prince of Wales Bay. Potential consequences were considered for maritime property (commercial shipping, small craft and related maritime infrastructure) and the potential consequences damage to maritime property may have for life and the environment.

Table 6: Principal Shipping Channel - Summary of Tsunami Wave (worst case scenario) Model Data (see note below) and Summary of Tsunami Potential Consequences					
Location	**Maximum wave heights (m)**	**Wave lengths (m)**	**Currents (knots)**	**Turbulence (breaking waves)**	**Wave speed (knots)**
PSC1 - 4	3.6 - 4.7	1871 - 2412	2.2 - 3.5	No	25 - 35
Site ID PSC1 mid channel off Iron Pot: to Site ID PSC4 slightly East of mid channel off White Rock Point					
Consequences					
Property					
Vessel	Minor damage				
Small craft	Moderate/major damage				
Infrastructure	Loss of navaids caused by wave				
Life					
Vessel	Minor injury				
Small craft	Minor/serious injury				
Vicinity	Serious/critical injury				
Environment					
Land	Coast/beach wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				
Location	**Maximum wave heights (m)**	**Wave lengths (m)**	**Currents (knots)**	**Turbulence (breaking waves)**	**Wave speed (knots)**
PSC 4 -8	2.4 - 3.8	1940 - 6715	2.1 - 2.7	No	29 - 35
Site ID PSC4 slightly East of mid channel off White Rock Point: to Site ID PSC 8 mid channel off Sullivans Cove, due South of Rosny Point					
Consequences					
Property					
Vessel	Minor damage				
Small craft	Moderate/major damage				
Infrastructure	Loss of navaids caused by wave				
Life					
Vessel	Minor injury				
Small craft	Minor/serious injury				
Vicinity	Serious/critical injury				
Environment					
Land	Coast/beach wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				

Location	**Maximum wave heights (m)**	**Wave lengths (m)**	**Currents (knots)**	**Turbulence (breaking waves)**	**Wave speed (knots)**
PSC 8 - 15	3.1 - 4.5	1080 - 3060	2.2 - 4.8	No	21 - 37
Site ID PSC 8 mid channel off Sullivans Cove, due South of Rosny Point: to Site ID PSC 15 in Tasman Bridge approach channel on 353° leads off Lindisfarne Bay					
Note:	Site ID PSC 11 is the south end of the Tasman Bridge Main Navigational Channel Site ID PSC 12 is mid channel immediately under the Tasman Bridge Site ID PSC 13 is the north end of the Tasman Bridge Main Navigational Channel (see Chart Aus172 Port of Hobart for details)				
Consequences					
Property					
Vessel	Major damage (Steering difficulty-hits Tasman Bridge)				
Small craft	Major damage (Steering difficulty-hits Tasman Bridge)				
Infrastructure	Loss of navaids caused by wave; Damage to Tasman Bridge caused by vessel striking piers				
Life					
Vessel	Serious/critical injury (if vessel strikes Tasman Bridge)				
Small craft	Minor/serious injury				
Vicinity	Serious/critical injury				
Environment					
Land	Coast/beach wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				

Location	**Maximum wave heights (m)**	**Wave lengths (m)**	**Currents (knots)**	**Turbulence (breaking waves)**	**Wave speed (knots)**
PSC 15 - 21	4.5 - 5.1	1980 - 3468	2.9 - 4.7	No	13 - 29
Site ID PSC 15 in Tasman Bridge Channel on 353° leads off Lindisfarne Bay: to Site ID PSC 21 mid channel off New Town Bay					
Consequences					
Property					
Vessel	Moderate damage				
Small craft	Major damage				
Infrastructure	Loss of navaids caused by wave				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Coast/beach wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				

Location	Maximum wave heights (m)	Wave lengths (m)	Currents (knots)	Turbulence (breaking waves)	Wave speed (knots)
PSC 21 - 27	3.7 - 5.1	2448 - 4200	3.5 - 6.3	No	25 - 29
Site ID PSC 21 mid channel off New Town Bay: to Site ID PSC 27 mid channel between Dowsings Point and Store Point on 308° leads					
Consequences					
Property					
Vessel	Major damage (Steering difficulty- vessel grounds)				
Small craft	Major damage				
Infrastructure	Loss of navaids caused by wave				
Life					
Vessel	Serious/critical injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Coast/beach wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				
Note: The figures in this table are derived from the SE Tasmania Tsunami Modelling results and are indicative. For precise data see the results from the SE Tasmania Tsunami Model.					

5.4. Tsunami Effects and Potential Consequences: Designated Shipping Anchorages

Anchorage
http://timspages.blogspot.com.au/2012/04/sapphire-princess-2008-post-1.html

The tsunami waves create a rise in water level, from starting level to peak wave height, over a period of 10 – 20 minutes and because of this there is no evidence of turbulence (e.g. breaking waves) at the designated shipping anchorages. Wave heights are generally lower in the outer reaches of the shipping channel and tend to increase in the port/dock areas.
The following Table 7 illustrates the potential consequences of a worst case scenario tsunami wave at the Designated Shipping Anchorages at the highest astronomical tide (HAT).

Table 7: Designated Shipping Anchorages - Summary of Tsunami Wave (worst case scenario) Model Data (see note below) and Summary of Tsunami Potential Consequences					
Location	**Maximum wave heights (m)**	**Wave lengths (m)**	**Currents (knots)**	**Turbulence (breaking waves)**	**Wave speed (knots)**
ANC1 - 4	2.8 - 3.1	1080 - 1512	2.2 - 2.6	No	31 - 33
Site ID ANC 1-4 Vessel anchorages 1-4 (East of Principal Shipping Channel site ID PSC 4-6)					
Consequences					
Property					
Vessel	Major damage (Drags anchor-vessel grounds)				
Small craft	Moderate/major damage				
Infrastructure	Loss of navaids caused by wave				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Coast/beach wreckage, oil pollution				
Water	Drifting wreckage; oil pollution				
Note: The figures in this table are derived from the SE Tasmania Tsunami Modelling results and are indicative. For precise data see the results from the SE Tasmania Tsunami Model.					

5.5. Tsunami Effects and Potential Consequences: Principal Hobart Port Area Constitution Dock and Macquarie Wharf

Sullivans Cove (Macquarie Wharf, Victoria Dock, Constitution Dock, Kings Pier Marina, Elizabeth Street Pier, Princes Wharf, CSIRO Wharf)
http://www.tasmania.australiaforeveryone.com.au/sullivans-cove.htm

Tides at Hobart are irregular, the maximum rise and fall being 1.37 metres. [20]

Chart Aus172 Port of Hobart notes the Highest Astronomical Tide (HAT) is 1.7 metres above chart datum. Chart datum is the level of water that charted depths displayed on a nautical chart are measured from. The Australian Hydrographic Service use the Lowest Astronomical Tide (LAT) to define chart datums. LAT is the height of the water, under average meteorological conditions, at the lowest possible theoretical tide. [22]

This means that at the Highest Astronomical Tide (HAT) the height of a berth above the HAT can be as much as 1.7 metres less than the height above chart datum listed in Table 8.

Table 8: Hobart Port Information

Berth	Declared depth (metres)	Height of berth above chart datum (metres)	Number of bollards	Usage
Princes 1	7.3	3.31	13	Antarctic Supply, Small
Princes Inter	7.6	3.34	6	
Princes 2	8.0	3.34	4	Cruise, Naval
Princes 3	9.0	3.25	8	Cruise, Naval
Princes 4	7.2	2.79		CSIRO
Elizabeth South	8.1	3.11	9	
Elizabeth North			9	
Macquarie 1	4.1	3.1 to 4.01		Small Fishing, Fish Unloading Facility
Macquarie 2	9.1	4.01	10	Larger Fishing, Caustic Acid
Macquarie 3	9.9	4.01	12	Car Carriers, Bulk Products, Cruise, Antarctic
Macquarie 4	13.0	4.01 to 2.79	15	Container Traffic, Break Bulk, Cruise, Antarctic
Macquarie 5	13.0	2.79	10	Container Traffic, Break Bulk, Cruise, Antarctic
Macquarie 6	11.4	2.79 to 3.2	13	Lay-up berth
Self's Point	14.4	3.71	10 on wharf; 4 on dolphins	Fuel Terminal, Bunkering Facility
Risdon (Nyrstar)	10.2	3.33	19	Concentrates, Acid, Fertiliser

Source: Tasports, *Port Information Port of Hobart Berth Data* [20]

The CSIRO wharf is used by the research vessel *Investigator*. It is 94 metres in length, with a beam of 18 metres, a draft of 8.5 metres and a DWT of 4,000.

National Research Facility vessel *Investigator* off CSIRO Wharf
http://www.marinetraffic.com/se/ais/details/ships/shipid:697740/imo:9616888/mmsi:503791000/vessel:INVESTIGATOR

Princes Wharf is used by the Antarctic Resupply vessel *Aurora Australis*. It is 95 metres in length, with a beam of 20.35 metres, a draft of 7.85 metres and a deadweight tonnage (DWT) of 3910.

***Aurora Australis* at Princes Wharf 2 and *L'Astrolabe* at Princes Wharf 1**
https://en.wikipedia.org/wiki/Aurora_Australis_(icebreaker)

Macquarie Wharf 3 is used by Car Carriers, Bulk Products, Cruise and Antarctic vessels. The cruise ship *Sapphire Princess* which has used the wharf is 290 metres in length, with a beam of 37.75 metres, a draft of 8.2 metres and a DWT of 14,600.

***Sapphire Princess* at Macquarie Wharf 2**
http://timspages.blogspot.com.au/2012/04/sapphire-princess-2008-post-1.html

Wave heights are generally lower in the outer reaches of the shipping channel and tend to increase in the port/dock areas. There is evidence of turbulence (e.g. breaking waves) at Constitution Dock, Victoria Dock and Macquarie Wharf 1-3.

The following Table 9 illustrates the potential consequences of a worst case scenario tsunami wave in the Principal Hobart Area at Constitution Dock and Macquarie Wharf at the highest astronomical tide (HAT).

Table 9: Principal Hobart Port Area Constitution Dock and Macquarie Wharf - Summary of Tsunami Wave (worst case scenario) Model Data (see note below) and Summary of Tsunami Potential Consequences

Location	**Maximum wave heights (m)**	**Wave lengths (m)**	**Currents (knots)**	**Turbulence (breaking waves)**	**Wave speed (knots)**
HP1 - 3	3.9 - 4.1	500 - 800	1.1 - 1.8	No	26 - 29
Site ID HP1-3 Approaches to Sullivans Cove					
Consequences					
Property					
Vessel	Moderate damage				
Small craft	Major damage				
Infrastructure	Loss of navaids caused by wave				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Coast/beach wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				

Location	Maximum wave heights (m)	Wave lengths (m)	Currents (knots)	Turbulence (breaking waves)	Wave speed (knots)
HP4	3.6	600	1.2	No	16
HP5	3.1	300	1.0	No	14
HP6	3.4	300	0.6	No	13
Site ID HP4 CSIRO Wharf (Research v/l) 1.1m above HAT Site ID HP5 Princes Wharf 2&3 (Cruise & Naval v/ls) 1.6m above HAT Site ID HP6 Princes Wharf 1 (Antarctic Supply & Small v/ls) 1.6m above HAT					
Consequences					
Property					
Vessel	Major damage (Vessel lifted & heeled; breaks adrift)				
Small craft	Major damage (Craft lifted on to wharf; breaks adrift)				
Infrastructure	Major damage to wharves caused by wave and floating wreckage				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Inundation; Wharf area wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				

Location	Maximum wave heights (m)	Wave lengths (m)	Currents (knots)	Turbulence (breaking waves)	Wave speed (knots)
HP7	4.4	200	0.5	No	15
HP8	4.0	150	0.4	No	15
Site ID HP7 Between Brooke Street Pier and Ferry Pier Site ID HP8 Elizabeth Street Pier, south side					
Consequences					
Property					
Vessel	N/A				
Small craft	Major damage (Craft lifted on to pier; breaks adrift)				
Infrastructure	Major damage to piers caused by wave and floating wreckage				
Life					
Vessel	N/A				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Inundation; Wharf area wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				

Location	Maximum wave heights (m)	Wave lengths (m)	Currents (knots)	Turbulence (breaking waves)	Wave speed (knots)
HP9	4.4	200	0.6	No	21
HP10	4.0	950	0.8	Yes	6
HP11	3.3	900	1.3	Yes	8
Site ID HP9 Kings Pier Marina entrance Site ID HP10 Constitution Dock (Small craft) Site ID HP11 Victoria Dock (Small craft)					
Consequences					
Property					
Vessel	N/A				
Small craft	Major damage (Craft lifted on to dock; breaks adrift)				
Infrastructure	Major damage (Inundation; Destruction of marina; Loss of navaids)				
Life					
Vessel	N/A				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Inundation; Waterfront wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				

Location	Maximum wave heights (m)	Wave lengths (m)	Currents (knots)	Turbulence (breaking waves)	Wave speed (knots)
HP12	3.1	300	0.8	Yes	10
HP13	3.8	480	1.1	Yes	14
HP14	3.5	600	1.4	Yes	13
Site ID HP12 Macquarie Wharf 1 (Small Fishing v/l) 1.4m above HAT Site ID HP13 Macquarie Wharf 2 (Large fishing and Caustic Acid v/ls) 2.3m above HAT Site ID HP14 Macquarie Wharf 3 (Car Carriers, Bulk Products, Cruise & Antarctic v/ls) 2.3m above HAT					
Consequences					
Property					
Vessel	Major damage (Vessel lifted & heeled; breaks adrift)				
Small craft	Major damage (Craft lifted on to wharf; breaks adrift)				
Infrastructure	Major damage caused by wave and floating wreckage				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Inundation; Wharf area wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				

Location	Maximum wave heights (m)	Wave lengths (m)	Currents (knots)	Turbulence (breaking waves)	Wave speed (knots)
HP15	3.8	660	2.3	No	30
HP19	3.3	2500	3.8	No	30
Site ID HP15 200m east of end of Macquarie Wharf 3/4 Site ID HP19 200m east of Macquarie Point					
Property					
Vessel	Moderate damage				
Small craft	Major damage				
Infrastructure	Loss of navaids caused by wave				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Coast/beach wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				

Location	Maximum wave heights (m)	Wave lengths (m)	Currents (knots)	Turbulence (breaking waves)	Wave speed (knots)
HP16	3.2	730	1.6	No	17
HP17	3.1	660	1.4	No	17
HP18	3.3	1200	2.0	No	18
Site ID HP16 Macquarie Wharf 4 (Container, Break Bulk, Cruise & Antarctic v/ls) 1.1m above HAT Site ID HP17 Macquarie Wharf 5 (Container, Break Bulk, Cruise & Antarctic v/ls) 1.1m above HAT Site ID HP18 Macquarie Wharf 6 (Lay-up berth) 1.1m above HAT					
Consequences					
Property					
Vessel	Major damage (Vessel lifted & heeled; breaks adrift)				
Small craft	Major damage (Craft lifted on to wharf; breaks adrift)				
Infrastructure	Major damage caused by wave and floating wreckage				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Inundation; Wharf area wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				
Note: The figures in this table are derived from the SE Tasmania Tsunami Modelling results and are indicative. For precise data see the results from the SE Tasmania Tsunami Model.					

5.6. Tsunami Effects and Potential Consequences: Selfs Point Wharf

***British Fidelity* at Selfs Point Wharf**

https://www.marinetraffic.com/en/photos/by/%20-%20forward/page:3/photo_keywords:hobart

Selfs Point Wharf is an oil terminal and is used by Handymax oil tankers which are typically 150-200 metres in length, with a beam of 28 metres, a draft of 12 metres and 35,000 - 45,000 DWT.The tanker *British Fidelity* which has used the wharf is 183 metres in length, with a beam of 32 metres and a DWT of 46,800.

The tsunami waves create a rise in water level, from starting level to peak wave height, over a period of 10 – 20 minutes and because of this there is no evidence of turbulence (e.g. breaking waves) at Selfs Point Wharf. Wave heights are generally lower in the outer reaches of the shipping channel and tend to increase in the port/dock areas.

The following Table 10 illustrates the potential consequences of a worst case scenario tsunami wave at Selfs Point Wharf at the highest astronomical tide (HAT).

Table 10: Selfs Point Wharf - Summary of Tsunami Wave (worst case scenario) Model Data (see note below) and Summary of Tsunami Potential Consequences					
Location	**Maximum wave heights (m)**	**Wave lengths (m)**	**Currents (knots)**	**Turbulence (breaking waves)**	**Wave speed (knots)**
SPW1	4.9	2528	4.0	No	26
SPW3	5.1	2332	3.5	No	24
Site ID SPW1 100 m to the South of Selfs Point Wharf Site ID SPW3 100m to the North of Selfs Point Wharf					
Consequences					
Property					
Vessel	Moderate damage				
Small craft	Major damage				
Infrastructure	Loss of navaids caused by wave				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Coast/beach wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				
Location	**Maximum wave heights (m)**	**Wave lengths (m)**	**Currents (knots)**	**Turbulence (breaking waves)**	**Wave speed (knots)**
SPW2	5.0	2246	4.7	No	25
Site ID SPW2 Selfs Point Wharf (Oil Tanker) 2.0m above HAT					
Consequences					
Property					
Vessel	Major damage (Vessel lifted & heeled; breaks adrift)				
Small craft	Major damage (Craft lifted on to wharf; breaks adrift)				
Infrastructure	Major damage caused by wave and floating wreckage				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Inundation; Wharf area wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				

Location	Maximum wave heights (m)	Wave lengths (m)	Currents (knots)	Turbulence (breaking waves)	Wave speed (knots)
SPW4	4.9	2281	4.3	No	16
Site ID SPW4 Selfs Point Jetty					
Consequences					
Property					
Vessel	N/A				
Small craft	N/A				
Infrastructure	Major damage caused by wave and floating wreckage				
Life					
Vessel	N/A				
Small craft	N/A				
Vicinity	Serious/critical injury				
Environment					
Land	Inundation; Wharf area wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				
Note: The figures in this table are derived from the SE Tasmania Tsunami Modelling results and are indicative. For precise data see the results from the SE Tasmania Tsunami Model.					

5.7. Tsunami Effects and Potential Consequences: Risdon (Nyrstar) Wharf

***IVS Raffles* at Risdon (Nystar) Wharf**
https://www.marinetraffic.com/en/photos/by/%20-%20forward/page:3/photo_keywords:hobart

Risdon (Nystar) Wharf is used by Handymax bulk carriers which are typically 150-200 metres in length, with a beam of 25 metres, a draft of 12 metres and 52,000-58,000 DWT with five cargo holds and four cranes. The bulk carrier *IVS Raffles* which has used the wharf is 180 metres in length, a draft of 10.6 metres, with a beam of 28.4 metres and a DWT of 32,050.

The tsunami waves create a rise in water level, from starting level to peak wave height, over a period of 10 – 20 minutes and because of this there is no evidence of turbulence (e.g. breaking waves) at Risdon (Nyrstar) Wharf. Wave heights are generally lower in the outer reaches of the shipping channel and tend to increase in the port/dock areas.

The following Table 11 illustrates the potential consequences of a worst case scenario tsunami wave at Risdon (Nyrstar Wharf) at the highest astronomical tide (HAT).

Table 11: Risdon (Nystar) Wharf - Summary of Tsunami Wave (worst case scenario) Model Data (see note below) and Summary of Tsunami Potential Consequences

Location	Maximum wave heights (m)	Wave lengths (m)	Currents (knots)	Turbulence (breaking waves)	Wave speed (knots)
RW1	4.5	3400	5.1	No	21
RW4	3.8	3000	5.2	No	17
Site ID RW1 100m to the South East of Nyrstar Wharf 2 Site ID RW4 100m to the North West of Nyrstar Wharf facilities					
Consequences					
Property					
Vessel	Moderate damage				
Small craft	Major damage				
Infrastructure	Loss of navaids caused by wave				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Coast/beach wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				
Location	**Maximum wave heights (m)**	**Wave lengths (m)**	**Currents (knots)**	**Turbulence (breaking waves)**	**Wave speed (knots)**
RW2	3.3	3000	5.2	No	17
Site ID RW2 Nyrstar Wharf 2 (Bulk Carrier- Concentrates, Acid, Fertiliser) 1.6m above HAT					
Consequences					
Property					
Vessel	Major damage (Vessel lifted & heeled; breaks adrift)				
Small craft	Major damage (Craft lifted on to wharf; breaks adrift)				
Infrastructure	Major damage caused by wave and floating wreckage				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Inundation; Wharf area wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				
Location	**Maximum wave heights (m)**	**Wave lengths (m)**	**Currents (knots)**	**Turbulence (breaking waves)**	**Wave speed (knots)**
RW3	2.7	4000	5.4	No	14
Site ID RW3 Nyrstar Wharf 1 (Bulk Carrier- Concentrates, Acid, Fertiliser) 1.6m above HAT					
Consequences					
Property					
Vessel	Major damage (Vessel lifted & heeled; breaks adrift)				
Small craft	Major damage (Craft lifted on to wharf; breaks adrift)				
Infrastructure	Major damage caused by wave and floating wreckage				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Inundation; Wharf area wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				
Note: The figures in this table are derived from the SE Tasmania Tsunami Modelling results and are indicative. For precise data see the results from the SE Tasmania Tsunami Model.					

5.8. Tsunami Effects and Potential Consequences: Prince of Wales Bay Wharf and Dock facilities

Kilimanjaro VI **at Richardson Devine yards, Prince of Wales Bay**
Incat fitting out wharves, Prince of Wales Bay
https://www.marinetraffic.com/en/photos/by/%20-%20forward/photo_keywords:prince%20of%20wales%20bay
https://www.marinetraffic.com/en/photos/by/%20-%20forward/photo_keywords:incat

Wave heights are generally lower in the outer reaches of the shipping channel and tend to increase in the port/dock areas. There is evidence of turbulence (e.g. breaking waves) at INCAT Jetty and Slip, Prince of Wales Bay Marine P/L Dock facilities and Derwent Marine Dock facilities.

The following Table 12 illustrates the potential consequences of a worst case scenario tsunami wave in Prince of Wales Bay at the highest astronomical tide (HAT).

Table 12: Prince of Wales Bay Wharf and Dock facilities - Summary of Tsunami Wave (worst case scenario) Model Data (see note below) and Summary of Tsunami Potential Consequences

Location	**Maximum wave heights (m)**	**Wave lengths (m)**	**Currents (knots)**	**Turbulence (breaking waves)**	**Wave speed (knots)**
PSC28	3.7	2686	6.9	No	17
PSC29	3.8	1800	4.9	No	17
PSC30	4.0	2100	4.0	No	16
Site ID PSC28 Off Dowsings Point Site ID PSC29/30 Entering Prince of Wales Bay					
Consequences					
Property					
Small vessel	Moderate damage				
Small craft	Major damage				
Infrastructure	Loss of navaids caused by wave				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Coast/beach wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				

Location	Maximum wave heights (m)	Wave lengths (m)	Currents (knots)	Turbulence (breaking waves)	Wave speed (knots)
POW1	3.8	2232	3.5	No	17
POW3	3.7	2080	4.0	Yes	13
Site ID POW1 100m East of north end of INCAT Slip Site ID POW3 100m East of INCAT Jetty					
Consequences					
Property					
Small vessel	Moderate damage				
Small craft	Major damage				
Infrastructure	Loss of navaids caused by wave				
Life					
Vessel	Serious/critical injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Coast/beach wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				

Location	Maximum wave heights (m)	Wave lengths (m)	Currents (knots)	Turbulence (breaking waves)	Wave speed (knots)
POW2	2.7	2200	1.7	Yes	5
Site ID POW 2 INCAT Slip					
Consequences					
Property					
Vessel [High speed catamaran]	Major damage (Lifted on to shore; breaks adrift)				
Small craft	Major damage (Lifted on to shore; breaks adrift)				
Infrastructure	Major damage caused by wave and floating wreckage				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Inundation; Slip area wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				

Location	Maximum wave heights (m)	Wave lengths (m)	Currents (knots)	Turbulence (breaking waves)	Wave speed (knots)
POW4	2.8	1250	2.7	Yes	8
Site ID POW4 INCAT Jetty					
Consequences					
Property					
Vessel [High speed catamaran]	Major damage (Lifted on to jetty/shore; breaks adrift)				
Small craft	Major damage (Lifted on to jetty/shore; breaks adrift)				
Infrastructure	Major damage caused by wave and floating wreckage				
Life					
Vessel	Serious injury				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Inundation; Jetty area wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				

Location	Maximum wave heights (m)	Wave lengths (m)	Currents (knots)	Turbulence (breaking waves)	Wave speed (knots)
POW6	2.8	Turbulence	5.0	Yes	7
Site ID POW6 Prince of Wales Bay Marine P/L Dock facilities					
Consequences					
Property					
Vessel	N/A				
Small craft	Major damage (Lifted on to dock/shore; breaks adrift)				
Infrastructure	Major damage caused by wave and floating wreckage				
Life					
Vessel	N/A				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Inundation; Dock area wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				
Location	**Maximum wave heights (m)**	**Wave lengths (m)**	**Currents (knots)**	**Turbulence (breaking waves)**	**Wave speed (knots)**
POW7	3.1	Turbulence	3.1	Yes	6
Site ID POW7 Derwent Marine Dock facilities					
Consequences					
Property					
Vessel	N/A				
Small craft	Major damage (Lifted on to dock/shore; breaks adrift)				
Infrastructure	Major damage				
Life					
Vessel	N/A				
Small craft	Serious/critical injury				
Vicinity	Serious/critical injury				
Environment					
Land	Inundation; Dock area wreckage, oil pollution				
Water	Drifting wreckage, oil pollution				
Note: The figures in this table are derived from the SE Tasmania Tsunami Modelling results and are indicative. For precise data see the results from the SE Tasmania Tsunami Model.					

6. Discussion-Shipping

Some Specific Implications for Shipping in the Port of Hobart

6.1. Introduction

UNESCO [23] makes the following recommendations:

"When a tsunami warning is issued, the harbour authority will issue warnings, orders and restrictions for offshore evacuation. Port authorities, ship and boat owners and fishing cooperatives should meet and agree on pre-planned safety measures. The following points should be organized based on the tsunami's estimated time of arrival:

- *Medium and large vessels will be evacuated outside the port*
- *Vessels that cannot be evacuated will be safely moored*
- *Medium and large vessels will be withheld from entering the port*

Fishing boats:

- *Three main objectives relating to boat safety measures are the protection of life, the protection of property (the boat itself) and the prevention of secondary damage caused by a drifting vessel.*
- *During a tsunami, the evacuation of fishing boats endangers those involved and this fact makes it impossible to draw up general guidelines for their evacuation.*

- *Pay close attention to the advisory issued by the National Tsunami Warning Centre regarding the tsunami's estimated time of arrival.*
- *If there is enough time, fishing boats preferably should evacuate to deeper waters (around 100 metres depth); if not, it will be extremely dangerous to evacuate to offshore waters.*
- *Instead, a combination of loose mooring and loose anchorage can reduce the risk of boats drifting onto land. Keeping the mooring and anchor cables loose is widely believed effective in preventing them from being severed by the collision of the first wave or strain from buoyancy."*

A further important consideration is:
"*Tsunami harbor effects include geometric amplification, resonance, and large eddy creation. Even when tsunami is 'small' (~1 m), generated currents can be strong enough to breaking lines.*" [18]

Wiśniewski and Wolski [13] summarise the ways to prevent damage to shipping in port from a tsunami as follows:

- If there is enough time before the arrival of the tsunami the best way to prevent damage to the ship by a tsunami is evacuation outside the port.
- If there is not enough time before the tsunami arrives ships should aim to remain in the deepest water in the port area. This is considered feasible when the expected wave height is not excessive.
- If evacuation is not possible the mooring system should be reinforced. Countermeasures for mooring during the tsunami should be increasing the number of mooring ropes and automatic regulation of mooring ropes so the ship cannot 'hang' on the ropes. It is noted that the mooring forces are usually small when the tsunami current is parallel to the ship.

6.2. Deeper Water

For shipping in the Principal Shipping Channel, at the Designated Shipping Anchorages, and alongside in the Port of Hobart, and it may be necessary/safer to evacuate to deep water. There is no agreement on what constitutes deep water as deep water depths noted from the literature review vary between at least 30 metres, at least 45 metres, 50 metres or more, and over 100 metres. Water depths in the principal shipping channel range between 15 metres off Iron Pot, 21 metres off Sullivans Cove and a maximum of 33 metres off White Rock Point. Depths of 45 metres are not reached until Storm Bay, about 10 nautical miles (18.5km) to the south east of Iron Pot.

The approximate distances from the three main berthing locations and the shipping anchorages to deeper water are shown in Table 13.

Table 13: Distances from Berths to Deeper Water (Nautical miles - approximate)

Distance from: -	**Distance to: -**			
Risdon (Nyrstar) Wharf	Tasman Bridge	Off White Rock Point-PSC Deepest (33m depth)	Off Iron Pot	Storm Bay (45m depth)
0	2.5	9.5	15	24.5
Selfs Point Wharf				
0	1.5	8.5	14	23.5
Princes/Macquarie Wharf				
0	n/a	6.5	12	21.5
Anchorages 1 - 4				
0	n/a	4 - 1.5	9.5 - 7	19 - 16.5

Note: Distances are approximate as there will be variations depending on the actual courses followed
Source: Australian Hydrographic Office, *Port of Hobart, Chart Aus172* corrected to 2015 # 782 [21]

6.3. Warning Times

Experts believed that the rapid onset of this event (less than 3 hours warning in best-case conditions) limited the capacity of the emergency services to inform all vulnerable areas or people and as such it seemed realistic to expect more than 50 deaths or serious injuries [16]

A Tsunami initiated by an earthquake in the Puysegur Trench could reach Tasmania in 2 hours, the JATWC aims to issue a National Tsunami Watch within 30 minutes of the earthquake and issue specific Watches and Warnings within 60 minutes of the earthquake. These would then be followed by additional warnings issued by Tasmania Police. This in effect means that the public in Hobart could realistically expect 1 hour warning. [6]

Based on the results of the South East Tasmania Tsunami Inundation Model, tsunami arrival times vary between 2.5 and 3.25 hours after the earthquake, with a difference of 36 minutes between PSC1 (off Iron Pot) and PSC30 (entering Prince of Wales Bay). Warnings and the arrival of the tsunami wave are summarised in Table 14.

Table 14: Warnings and Wave Arrival Summary (approximations)

Event	Elapsed time
Earthquake occurrence	0
National Tsunami watch alert	30 min
Specific watches and warnings issued	1 hr
Tasmania Police issue additional warnings	
Realistic notification of Hobart public	2 hr
Wave reaches Tasmania	2 hr
Wave reaches Iron Pot	2 hr 35 min
Wave reaches Sullivans Cove	3 hr
Wave reaches Selfs Point	3 hr 05 min
Wave reaches Risdon (Nyrstar)	3 hr 08 min
Wave reaches Prince of Wales Bay	3 hr 10 min

Source: *Tasmanian State Tsunami Emergency Response Plan*, extracts [6]
South East Tasmania Tsunami Inundation Model Results

6.4. Shipping in the Principal Shipping Channel

Any shipping underway in the Principal Shipping Channel, which is in communications with Hobart Port control when a tsunami warning of at least 1 hour is received, should be able to reach deeper water at either White Rock Point or Storm Bay before the tsunami wave arrives. The rationale for this is:

- Shipping underway should be able to make sufficient speed to reach deeper water

For shipping in the Principal Shipping Channel south of the Tasman Bridge when the tsunami wave arrives it is postulated that they may well be able to successfully ride waves of this nature. The rationale for this is:

- Modelled maximum wave height in the Principal Shipping Channel south of the Tasman Bridge is 4.7 metres off Iron Pot. North of Iron Pot to off Sullivans Cove the wave height varies between 2.4-3.8 metres
- Because the tsunami waves have very long wavelengths the effect is a rise in water level, from starting level to peak wave height, over a period of 10 – 20 minutes which most shipping should be able to successfully navigate

For shipping in the Principal Shipping Channel north of the Tasman Bridge when the tsunami wave arrives it is postulated that they may well have difficulty in manoeuvring in these conditions and attempting to pass under the Tasman Bridge should be avoided. The rationale for this is:

- Modelled maximum wave height in the principal shipping channel, north of the Tasman Bridge, varies between 3.7-5.1 metres
- The channel is narrower north of the Tasman Bridge with stronger currents of up to 6.3 knots predicted by the model
- Because of the strong current and the higher wave heights most shipping is likely to experience some difficulty in manoeuvring in these conditions in this more confined area

6.5. Shipping at the Designated Shipping Anchorages

Shipping anchored at the Designated Shipping Anchorages, which is in communications with Hobart Port control when a tsunami warning of at least 1 hour is received, should be able to evacuate and reach deeper water off White Rock Point before the tsunami wave arrives. The rationale for this is:

- Shipping at anchor will have engines ready.
- Weighing anchor should take no more than 15 minutes.

6.6. Shipping Alongside-Letting Go and Clearing the Berth

Mercado-Irizarry and Liu [24] suggest that within an hour most modern vessels can easily move out of port (clear the berth?). The one hour can be reduced depending on the state of readiness of the engines and crew, and the ease by which a vessel can manoeuvre clear of its berth.

For shipping alongside at Constitution Dock and Macquarie Wharf in the Principal Hobart Port Area, Selfs Wharf, and Risdon (Nyrstar) Wharf it may be feasible to reach a relatively safe location south of the Tasman Bridge within the principal shipping channel or in deeper water off White Rock Point. However, the feasibility of achieving this depends on a number of factors which include the amount of notice given of an impending tsunami, the time taken for a vessel to let go and clear a berth, the distance from a berth to a safer location, and the speed of the ship in question.

The time taken for a vessel to let go and clear a berth depends on a number of factors including:

Cargo Issues

- Ceasing cargo operations
- Clearing away cargo handling equipment (e.g. oil lines, shore based loading/discharging equipment)

Availability of Crew

- Capability and capacity of crew actually aboard as some may be ashore or the vessel may be ‘laid up’ with only a skeleton care crew

Availability of Engines

- Availability depends on whether the vessel is ‘laid up’, alongside with engines shut down or with engines on ‘stand by’

Mooring Issues

- Letting go mooring lines depends on the availability of linesmen at the berth, capability to let go from on board, and the type of mooring line arrangements (e.g. automatic berthing/mooring system, self-tensioning winches, ropes/wire and bollards)
- Gangways are commonly a part of the ship's equipment but may be provided from ashore for vessels such as cruise ships and tankers. Consequently, the safe removal of a gangway depends on the availability of crew or shore based personnel.

Manoeuvring Issues

- Need for and availability of a pilot
- Need for and availability of tugs
- Capability of Master/officers to manoeuvre the vessel
- Difficulty of manoeuvres to clear the berth

Meteorological conditions

- Wind direction and speed
- Current direction and speed

6.7. Shipping Alongside-Tentative Evacuation Scenarios

Different ship types have different characteristics which affect their manoeuvrability and, hence, the time taken to clear a berth and reach full speed. The following speculative scenarios are 'best case' scenarios and were calculated using tentative estimates. The scenarios illustrate the potential time differences for ships alongside in evacuating to deep water. Further, more detailed research is needed to determine more reliable outcomes.

-Risdon (Nystar) Wharf is used by Handymax bulk carriers which are typically 52,000-58,000 DWT, 150-200 metres in length, with a beam of 25 metres, a draft of 12 metres and a service speed of 13-15 knots.

Assumptions:

- Vessels tend to berth starboard side to with the bow facing down river
- Single propeller
- Crew and engines available
- Crew able to remove gangway and let go mooring lines
- Pilot and tugs unavailable
- After clearing the berth, the vessel can head direct to the Principal Shipping Channel
- The vessel can pass safely under the Tasman Bridge

Table 15: Evacuation Estimates - Risdon (Nyrstar) Wharf - Handymax Bulk Carrier

From	To	Estimated Time	Running Time
Risdon (Nyrstar) Wharf	Letting go/clearing berth	30 min	30 min
Clearing berth	Tasman Bridge	15 min	45 min
Tasman Bridge	Increasing to Full speed by PSC deepest	35 min	1 hr 20 min
PSC deepest	Iron Pot	25 min	1 hr 45 min
Iron Pot	Storm Bay 45metres depth	50 min	2 hr 35 min
Total		**2 hr 35 min**	**2 hr 35 min**

-Selfs Point Wharf is an oil terminal and is used by Handymax oil tankers which are typically 35,000 - 45,000 DWT, 150-200 metres in length, with a beam of 28 metres, a draft of 12 metres and a service speed of around 15 knots.

Assumptions:

- Vessels tend to berth port side to with the bow facing up river

- Single propeller
- Crew and engines available
- Crew able to remove gangway and let go mooring lines
- Pilot and tugs unavailable
- After clearing the berth, the vessel needs to turn short round (180°) to head to the Principal Shipping Channel
- The vessel can pass safely under the Tasman Bridge

Table 16: Evacuation Estimates - Selfs Point Wharf - Handymax Oil Tanker			
From	**To**	**Estimated Time**	**Running Time**
Selfs Point Wharf	Letting go/clearing berth	45 min	45 min
Clearing berth	Tasman Bridge	10 min	55 min
Tasman Bridge	Increasing to Full speed by PSC deepest	30 min	1 hr 25 min
PSC deepest	Iron Pot	20 min	1 hr 45 min
Iron Pot	Storm Bay 45metres depth	40 min	2 hr 25 min
Total		**2 hr 25 min**	**2 hr 25 min**

-Princes Wharf is used by the Antarctic Resupply vessel *Aurora Australis* which has a DWT of 3910, is 95 metres in length, with a beam of 20.35 metres, a draft of 7.85 metres and a service speed of 16.5 knots. The *Aurora Australis* is fitted with 3 thrusters.

Assumptions:

- *Aurora Australis* tends to berth port side to
- Single propeller, one thruster forward and two thrusters aft
- Crew and engines available
- Crew able to remove gangway and let go mooring lines
- Pilot unavailable and tugs not required because of thrusters
- After clearing the berth, the vessel needs to turn to starboard to head to the Principal Shipping Channel

Table 17: Evacuation Estimates - Princes Wharf - Antarctic Supply Vessel *Aurora Australis*			
From	**To**	**Estimated Time**	**Running Time**
Princes Wharf	Letting go/clearing berth	30 min	30 min
Clearing berth	Increasing to Full speed by PSC deepest	25 min	55 min
PSC deepest	Iron Pot	20 min	1 hr 15 min
Iron Pot	Storm Bay 45metres depth	35 min	1 hr 50 min
Total		**1 hr 50 min**	**1 hr 50 min**

-Macquarie Wharf 3 has been used by the cruise ship *Sapphire Princess* which has a DWT of 14,600, is 290 metres in length, with a beam of 37.75 metres, a draft of 8.2 metres and a service speed of 20-24 knots. The *Sapphire Princess* is fitted with 6 thrusters.

Assumptions:

- Cruise ships tend to berth starboard side to
- Two propellers, three thrusters forward and three thrusters aft
- Crew and engines available
- Crew able to remove gangway and let go mooring lines
- Pilot unavailable and tugs not required because of thrusters
- After clearing Macquarie 2 the vessel needs to turn to starboard, and from Macquarie 3 needs to turn short round to head to the Principal Shipping Channel

Table 18: Evacuation Estimates - Macquarie Wharf - Cruise Ship *Sapphire Princess*			
From	**To**	**Estimated Time**	**Running Time**
Macquarie Wharf	Letting go/clearing berth	30 min	30 min
Clearing berth	Increasing to Full speed by PSC deepest	20 min	50 min
PSC deepest	Iron Pot	15 min	1 hr 5 min
Iron Pot	Storm Bay 45metres depth	30 min	1 hr 35 min
Total		**1 hour 35 min**	**1 hr 35 min**

As previously stated, the Tasmanian State Emergency Service expects to provide an approximate warning time for an impending tsunami for the Principal Hobart Port Area of approximately 1 hour. This means that the tsunami wave would reach Iron Pot approximately 35 minutes after the warning was received. Table 19 illustrates.

Table 19: Tsunami Wave • Travel Time from Site ID PSC1, Mid channel off Iron Pot & • Modelled Arrival Time after Earthquake		
Location	**Wave Travel time from PSC1**	**Wave Arrival time after earthquake**
From: PSC1 Mid channel off Iron Pot	0 minutes	2 hr 35 min
To:		
ANC1 Vessel anchorage 1	19 minutes	2 hr 54 min
HP3 Approaches to Sullivans Cove (200m to the East of Battery Point)	25 minutes	3 hr 00 min
SPW2 Selfs Point Wharf	30 minutes	3 hr 05 min
RW2/3 Risdon (Nyrstar Wharf)	33 minutes	3 hr 08 min
POW1 Prince of Wales Bay (100m East of north end of INCAT Slip)	35 minutes	3 hr 10 min
Source: South East Tasmania Tsunami Inundation Model Results		

Based on the speculative evacuation times in Tables 15-18 above and provided that a 1 hour warning is received it is probable that:

- A Handymax bulk carrier originally berthed at Risdon (Nyrstar) Wharf would meet the incoming tsunami wave to the south of the Tasman Bridge in the Principal Shipping Channel but still to the north of the deeper water off White Rock Point
- A Handymax oil tanker originally berthed at Selfs Point Wharf would meet the incoming tsunami wave a little to the south of the Tasman Bridge in the Principal Shipping Channel.
- The *Aurora Australis* originally berthed at Princes Wharf would meet the incoming tsunami wave in the vicinity of the deepest water off White Rock Point in the Principal Shipping Channel.
- A cruise ship similar to the *Sapphire Princess* and originally berthed at Macquarie Wharf would meet the incoming tsunami wave in the vicinity of the deepest water off White Rock Point in the Principal Shipping Channel.

Recognising that the evacuation time estimates are speculative and the conditions described by the assumptions will not occur in all circumstances, it is recommended that further research is undertaken to develop more reliable outcomes and for a wider range of conditions. This would enable better decisions to be made on whether a ship should evacuate or stay.

6.8. Shipping Alongside- Berth Inundation

The following Table 20 illustrates approximate inundation water levels above the wharf deck height at maximum wave height and highest astronomical tide (HAT).

Table 20: Inundation Levels above Wharf Deck Height (metres; approx)					
Location	**Berth Height above Chart Datum**	**Height of HAT above Chart Datum**	**Berth Height above HAT**	**Stage Height above HAT**	**Inundation Height above Berth Deck**
CSIRO Wharf	2.8	1.7	1.1	2.3	1.2
Princes Wharf 2-3	3.3	1.7	1.6	2.3	0.7
Macquarie Wharf 1-4	4.0	1.7	2.3	2.3	0
Macquarie Wharf 5-6	2.8	1.7	1.1	2.1	1.0
Selfs Point Wharf	3.7	1.7	2.0	2.5	0.5
Risdon (Nyrstar) Wharf	3.3	1.7	1.6	1.7	0.1
Source: Tasports, *Port Information Port of Hobart Berth Data* [20] Australian Hydrographic Office (2005), *Port of Hobart*, Chart Aus172 corrected to 2015 # 782 [21] South East Tasmania Tsunami Inundation Model results					

Because most of the commercial shipping using the berths in the Port of Hobart have drafts considerably greater than the inundation water levels above the berth deck, there is almost no likelihood of these vessels being bodily lifted by the tsunami wave on to the berth. However, smaller vessels/craft with shallower drafts, e.g. less than 1.2 metres at the CSIRO Wharf, are at risk of being lifted on to the berth deck.

For shipping alongside that cannot, or decides not to, evacuate to deeper water the main risk is breaking adrift. Consequences of breaking adrift include major damage to the drifting ship and other vessels, and infrastructure struck by the drifting ship.

As the tsunami wave approaches, a ship alongside is lifted and may heel against the berth or break adrift if mooring lines are not tended to deal with the rising water. Mooring lines will slack off as the water recedes which may cause the ship to range away from the berth or break adrift if mooring lines are not tended to deal with the receding water. Extra mooring lines should be utilised if possible and crew should be stationed to slack off/tighten mooring lines as necessary.

For smaller vessels with shallower drafts it may be more prudent to put out extra moorings then evacuate the crew to a safe, higher location ashore.

7. Possible Hazards to Small Craft Based On Modelled Tsunami Scenarios In The Derwent Estuary

Implications for Small Craft

7.1. Tsunami Waves: General Effects

Wave heights are generally lower in the outer reaches of the shipping channel and tend to increase in the port/dock areas. There is evidence of turbulence (e.g. breaking waves) at all Marinas and all Designated Small Craft Anchorages. Because of their construction, inundation of marina infrastructure is almost inevitable.

Most small craft marinas are built in sheltered, shallow waters and, as such, are likely to be subject to seiches. Seiches are oscillations of enclosed and semi-enclosed bodies of water, such as bays, lakes or reservoirs, due to strong ground motion from seismic events, wind stress, volcanic eruptions, large landslides and local basin reflection of tsunamis. [25]

Wiśniewski and Wolski [13] report on the numbers of small craft in Brookings Harbor, Oregon and Crescent City Harbor, California which were damaged or sunk as a result of the Japanese 2011 tsunami. These small craft harbours are approximately 4320 nautical miles (8000 km) from the Japanese port of Sendai, which was devastated during the tsunami, and arrived about 10 hours after the earthquake. In Brookings Harbor 6 small craft between 34 - 92 feet (10 - 28m) in length were sunk (3) or damaged (3), and in Crescent City Harbor 16 small craft between 29 - 68 feet (9 - 21m) in length were sunk (12) or damaged (4).

Precisely what constitutes a small craft is ill defined. However, in Brookings Harbor and Crescent City Harbor of the vessels sunk, one was 92 feet (28m) and another was 68 feet (21m) in length; whilst one of the damaged vessels was 68 feet (21m) in length and weighed 220 tons. The 220 ton vessel is a common size for an American offshore fishing vessel.

7.2. Tsunami Effects and Potential Consequences: Designated Small Craft Anchorages and Marinas


Geilston Bay Boat Club anchorage
Motor Yacht Club Tasmania Marina, Lindisfarne Bay
https://www.flickr.com/photos/witnesskingtides/8276720056
https://au.pinterest.com/pin/36802921928885333/


Bellerive Yacht Club Marina, Kangaroo Bay
Royal Yacht Club of Tasmania Marina, Sandy Bay
http://burburyconsulting.com.au/portfolio_category/maritime/
http://www.fsc.com.au/about/reciprocal-yacht-clubs/

The following Table 21 illustrates the potential consequences of a worst case scenario tsunami wave at Designated Small Craft Anchorages and Marinas at the highest astronomical tide (HAT).

Table 21: Designated Small Craft Anchorages and Marinas - Summary of Tsunami Wave (worst case scenario) Model Data (see note below) and Summary of Tsunami Potential Consequences

Location	Maximum wave heights (m)	Wave lengths (m)	Currents (knots)	Turbulence (breaking waves)	Wave speed (knots)
G1	5.2	624	2.3	Yes	11
G2	4.3	Turbulence	3.8	Yes	10
G3	4.1	Turbulence	3.2	Yes	6
G5	4.0	Turbulence	1.9	Yes	5
G6	3.5	Turbulence	2.0	Yes	5
POW5	3.2	Turbulence	7.2	Yes	9
POW8	3.9	Turbulence	5.0	Yes	10

Site ID G1 Geilston Bay: Geilston Bay Boat Club marina and anchorage
Site ID G2 Lindisfarne Bay: Motor Yacht Club Tasmania marina and anchorage
Site ID G3 Kangaroo Bay: Bellerive Yacht Club marina and anchorage
Site ID G5 Sandy Bay: Royal Yacht Club of Tasmania marina and anchorage
Site ID G6 Sandy Bay: Derwent Sailing Squadron marina and anchorage
Site ID POW5 Prince of Wales Bay: Prince of Wales Bay Marina Wharf
Site ID POW8 Prince of Wales Bay: Pauline Point Marina
Domain Slipyard small craft anchorage
Cornelian Bay small craft anchorage
New Town Bay small craft anchorage
Koomela Bay small craft anchorage
Montagu Bay small craft anchorage

Consequences	
Property	
Small craft	Major damage caused by wave; Capsize/sinking caused by wave; breaking adrift from anchorage
Infrastructure	Inundation; Destruction of marina; Loss of navaids caused by wave
Life	
Small craft	Serious/critical
Vicinity	Serious/critical
Environment	
Land	Inundation; Coast/beach wreckage, oil pollution
Water	Drifting wreckage, oil pollution

Note: The figures in this table are derived from the SE Tasmania Tsunami Modelling results and are indicative. For precise data see the results from the SE Tasmania Tsunami Model.

Marina, Prince of Wales Bay
https://www.youtube.com/watch?v=Zov-d8PwJUU

8. Discussion-Small Craft

Some Specific Implications for Small Craft in the Port of Hobart

8.1. Introduction

There is no clear definition of a small craft. However, in the context of tsunamis it is useful to consider small craft in two categories, namely small craft constructed for use in:

- Offshore waters (e.g. fishing boats, ocean cruising yachts)

- Sheltered waters (e.g. ferries, leisure craft including cabin cruisers, yachts, dinghies)

A further consideration is whether the small craft is powered by an engine and, if it is, is the engine sufficiently powerful to deal with a tsunami wave and associated currents.

Table 22 is a summary of the advice to small craft based on the literature in general and specifically:

- List of Countermeasures against Tsunami, Hong Kong Weather Service, March 2012 [15]
- 9th Regional Japan Coast Guard Headquarters, *To secure Life and Ship from Tsunami* [14]
- Wiśniewski B and Wolski T (2012), " *The safety of the shipping and ports in the aspect of the tsunami events* ", Scientific Journals, Maritime University of Szczecin 2012, Vol.30 (102) pp 150–157 [13]

Table 22: Tsunami Warning-Summary of Advice to Small Craft in Port

Predicted Tsunami height	Able to get to deep water	Small craft alongside in port	Small craft underway in port area
Over 3 metres	No	Evacuate to land	Land and evacuate
	Maybe	Evacuate to land, or (to deep water if safe to do so)	Evacuate to deep water, or (land and evacuate if safe to do so)
	Yes		Evacuate to deep water, or land and evacuate
1 - 3 metres	No	Evacuate to land	Land and evacuate
	Maybe	Evacuate to land, or (to deep water if safe to do so)	Evacuate to deep water, or (land and evacuate if safe to do so)
	Yes		Evacuate to deep water, or land and evacuate
0.5 - 1 metre		Secure craft, or evacuate to deep water	Secure craft, or evacuate to deep water

Note: Based on Hong Kong Weather Service, *List of Countermeasures against Tsunami* [15];
9th Regional Japan Coast Guard Headquarters, *To secure Life and Ship from Tsunami* [14]; and
Wiśniewski and Wolski, *The safety of the shipping and ports in the aspect of the tsunami events* [13]

8.2. Small craft underway

Small craft constructed for use in offshore waters which have sufficient warning may be safer in deeper water. If it is not feasible to reach deeper water then the small craft should attempt to land, be secured, and the crew evacuated to a safe location.

Small craft constructed for use in sheltered waters are less likely to be able to ride out a tsunami wave or be able to evacuate to deeper water. For small craft of sufficient engine power, it may be feasible to reach deep water, but only if it is considered safe to do so. Consequently, the best course of action may be to land, secure the craft, and evacuate the crew to a safe location.

8.3. Small craft at designated anchorages, marinas and alongside a berth

There is evidence of turbulence (e.g. breaking waves) at all Marinas and all Designated Small Craft Anchorages. Consequently, the best course of action may be to secure the craft, and evacuate the crew to a safe location. If sufficient time is available, small craft of sufficient engine power may be able to reach deep water, but only if it is considered safe to do so.

Some of the larger craft alongside at a berth (e.g. fishing boats, ocean cruising vessels, and ferries) may be able to let go and reach deep water, if sufficient time is available. If this is not feasible then the craft should be secured, and the crew evacuated to a safe location.

9. Further Research

The project was conducted as a desktop study and, whilst comprehensive in approach, the findings should be viewed as preliminary in nature. Further research is needed to test the reliability and validity of the findings to improve/ensure their accuracy.

In summary, this preliminary report indicates the possible hazards to shipping from a worst case scenario tsunami in the Port of Hobart. The report is a high level review and forms the basis for further more detailed consideration and research. In order to improve the accuracy and validity of the hazards and effects of a tsunami on vessels using the Port of Hobart more detailed research is needed. This could include:

- Improved data on vessels using the Port of Hobart e.g. types, size, speed
- Improved data on the alongside status of vessels using the Port of Hobart e.g. time taken for a vessel to let go and clear a berth including availability of crew and engines, mooring lines and gangways, manoeuvring issues, meteorological conditions
- Possibly simulating ship evacuation scenarios on the Australian Maritime College simulators
- Reviewing potential hazards, damage criteria, mitigating actions including evacuation scenarios
- Consideration of the effects of 'smaller' tsunamis and different states of the tide
- Possibly testing the effects of a tsunami on vessels in port in the Australian Maritime College Model Test Basin

Outcomes from this research could be used to develop/refine/improve the advice to vessels and small craft in the Port of Hobart in the event of a tsunami warning being received.

Additionally, recognising that the evacuation time estimates are speculative and the conditions described by the assumptions will not occur in all circumstances, it is recommended that further research is undertaken to develop more reliable outcomes and for a wider range of conditions and scenarios. This would enable better decisions to be made on whether a ship should evacuate or stay.

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[21] Australian Hydrographic Office, (2005), *Port of Hobart*, Chart Aus172 corrected to 2015 # 782

[22] Wikipedia, (2016), *Chart Datum*
https://en.wikipedia.org/wiki/Chart_datum

[23] Intergovernmental Oceanographic Commission, (2008), *Tsunami Preparedness–Information Guide for Disaster Planners, IOC Manuals and Guides No. 49,* UNESCO

http://www.proteccioncivil.org/documents/11803/65816/Tsunami%2Bpreparendness.pdf

[24] Mercado-Irizarry, A. and Liu, P., (2004), *Caribbean Tsunami Hazard,* World Scientific Publishing
https://books.google.com.au/books?id=OVz0DNfCdYMC&pg=PA261&lpg=PA261&dq=ship+safety+tsunamis&source=bl&ots=sSWU4sH5kf&sig=HnZppo-cPUPEP5CiQTzt8qCspNQ&hl=en&sa=X&ved=0ahUKEwjo8u2a3tHOAhWFk5QKHdvTCs84ChDoAQgsMAM#v=onepage&q=ship%20safety%20tsunamis&f=false

[25] City & County of San Francisco, (2011), Emergency *Response Plan Tsunami Response Annex*
http://sfdem.org/sites/default/files/FileCenter/Documents/1115-Tsunami%20Annex%20-%202011.pdf

10.1. Videos

Japanese Coastguard ship in deep water in 2011 tsunami waves
https://www.youtube.com/watch?v=nWPR1HavsCE

Japanese fishing vessels in port waters in 2011 tsunami waves
https://www.youtube.com/watch?v=cC8wuj31MWs

Tsunami 2011 effect on ship Asia Symphony-lifted on to deck of berth
https://www.youtube.com/watch?v=2yjnEJ2nbD0

Inundation of small Japanese port by 2011 tsunami waves
https://www.youtube.com/watch?v=181EBnSsliY

Small craft off Crescent City, USA in 2011 tsunami waves
https://www.youtube.com/watch?v=c2IuqXyx2NU

Effect of tsunami on fishing vessels in Coquimbo Port, Chile
https://www.youtube.com/watch?v=t9M4MOUjNGs

Small craft harbour damage from 2011 tsunami waves in Santa Cruz, California, USA
https://www.youtube.com/watch?v=jltIeWB1XH8

Tsunami 2011 effect on small craft in Crescent City Harbor, California, USA
https://www.youtube.com/watch?v=8ltLkvZYnxQ

Tsunami Surge Depoe Bay, Oregon, Aboard C/V Morning Star
https://www.youtube.com/watch?v=bXeZqMAe3-Y

Tsunami 2011 effect on small craft in Brookings Harbor, Oregon, USA
https://www.youtube.com/watch?v=VG08lsGzoP4

10.2. Additional Tsunami Related Documents Reviewed

The following additional tsunami related documents were reviewed:

- International (High Risk Zones), *PIANC (2010), PIANC Report No. 212 Mitigation of Tsunami Disasters in Ports,* PIANC, Brussels, Belgium
  https://books.google.com.au/books?id=4O6XkBaF_ZEC&pg=PA84&lpg=PA84&dq=tsunami+effect+on+ships&source=bl&ots=Om9UggTp4G&sig=xAZZHvU8oXA9DWgjros66irdC0o&hl=en&sa=X&ved=0ahUKEwiDlt3qrNPLAhXB2SYKHa6MBGE4ChDoAQhEMAc%20-%20v=onepage&q=tsunami%20effect%20on%20ships&f=false#v=snippet&q=tsunami%20effect%20on%20ships&f=false

- North America:
  - Canada
    - British Columbia Tsunami Notification Plan http://www2.gov.bc.ca/assets/gov/public-safety-and-emergency-services/emergency-preparedness-response-recovery/provincial-emergency-planning/tsunami-notification-process-plan.pdf
    - Port McNeill, B.C. Emergency Plan http://static1.squarespace.com/static/55ca2350e4b08d9e4143db86/t/571aa9f9555986bfe84e495e/1461365251817/1+-+PM+EMERGENCY+PLAN+-+Updated+April+2016.pdf
    - Port Hardy, B.C. Earthquake and Tsunami Poster http://www.porthardy.ca/sites/default/files/port_hardy_tsunami_preparedness_poster.pdf
  - USA
    - Hawaii Tsunami Emergency Plan http://files.hawaii.gov/dlnr/dobor/contacts/Plan-TSUNAMI.pdf
    - The Seattle Globalist describes some evacuation procedures for Tacoma http://www.seattleglobalist.com/2015/03/18/northwest-detention-center-tsunami-disaster-evacuation-tacoma/34981

- Central and South America
  - Caribbean
    - Communication Plan for the Interim Tsunami Advisory Information Service to the Caribbean Sea and Adjacent Regions http://www.ioc-unesco.org/index.php?option=com_oe&task=viewDocumentRecord&docID=6354
- East Asia: Japan/Korea
  - Japan
    - Assessment of tsunami hazards in ports and their impact on marine vessels derived from tsunami models and the observed damage data (Academic Paper) http://link.springer.com/article/10.1007/s11069-015-1772-0
    - Safety of vessels against tsunamis (Academic Paper) http://www.hko.gov.hk/wservice/tsheet/pms/images/tsunami_marine_safety_2.pdf

        - Yokohama and Kawasaki (Action Plan for Ships against Tsunamis) http://www6.kaiho.mlit.go.jp/03kanku/yokohama/info/information/tunamien.pdf
        - Analysis of Ship Refuge Action in Tsunami Using AIS Data: Case of the 2011 East Japan Earthquake and Tsunami (Academic Paper) http://www.davidpublishing.com/davidpublishing/Upfile/3/4/2014/2014030481780921.pdf
        - Some recommendations to the ship master in order to evacuate a cruise ship due to tsunami arrival by Trika Pitana, Eiichi Kobayashi Коbе University Коbе, Japan (Academic Paper) http://iamu-edu.org/wp-content/uploads/2014/07/Some-recommendations-to-the-ship-master-in-order-to-evacuate-%D0%B0-cruise-ship-due-to-tsunami-arrival.pdf
    - Korea
        - Tsunami response system for ports in Korea (Academic paper) http://www.nat-hazards-earth-syst-sci.net/15/1999/2015/nhess-15-1999-2015.pdf

Australia and New Zealand (Moderate Risk Zones)

- Australia
    - Australia
        - Tsunami Emergency Planning in Australia https://www.aidr.org.au/media/1461/manual-46-tsunami-emergency-planning-in-australia.pdf
        - Earthquake and Tsunami Awareness for Australians http://www.tsunamisafe.com.au/uploads/36/brochure-tsunami-awareness-brochure-pdf-spread-final.pdf
    - Western Australia
        - State Emergency Management Plan for Tsunami https://extranet.fesa.wa.gov.au/sites/emwa/Lists/StateEmergencyManagementDocumentLibrary/State%20EM%20Plans/Hazard%20Plans/Westplan%20Tsunami.pdf
    - Victoria
        - State Tsunami Emergency Plan http://www.ses.vic.gov.au/em-sector/em-planning/em-partners-resources/state-tsunami-emergency-plan
    - NSW
        - State Tsunami Plan https://www.emergency.nsw.gov.au/media/admin/765/_/l99n5kyvkblzc4kcgs/SubPlan_Tsunami_20150301.pdf
        - Lord Howe Island Tsunami Emergency Sub Plan http://www.tsunamisafe.com.au/uploads/43/plan-lhi-plan.pdf
    - Queensland
        - Brisbane City Council Disaster Management Plan 2015 Tsunami Management Sub-Plan https://www.brisbane.qld.gov.au/community/community-safety/disasters-emergencies/disaster-management-plans

        - Bundaberg (Regional Council Tsunami Response Plan) http://www.bundaberg.qld.gov.au/files/bundaberg-tsunami-response-plan.pdf
        - Mourilyan (MSQ Port Procedures and Information for Shipping) http://www.msq.qld.gov.au/search-results.aspx?query=tsunami
        - Brisbane (MSQ Port Procedures and Information for Shipping) http://www.msq.qld.gov.au/search-results.aspx?query=tsunami
- New Zealand
    - New Zealand
        - GeoNet New Zealand, Tsunami http://info.geonet.org.nz/display/tsunami/Tsunami
        - Tsunami Research Co. NZ, Hazards from far-field tsunamis in New Zealand ports and harbours http://tsunamiresearch.co.nz/projects/tsunamis-in-new-zealand-ports/introduction/
        - Government Tsunami advice http://www.getthru.govt.nz/disasters/tsunami/
        - Lyttelton, South American Tsunamis in Lyttelton Harbour (Academic paper) http://link.springer.com/article/10.1007%2Fs00024-014-1026-1#/page-1
        - Marsden Point, Tauranga, Taranaki and Lyttelton, Far-Field Tsunami Hazard in New Zealand Ports (Academic Paper) http://link.springer.com/article/10.1007%2Fs00024-014-0987-4#/page-1
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Appendices

Appendix 1: Project Scope

1. Provide advice on possible hazards to shipping (commercial, scientific research, and other agreed significant vessels) from modelled tsunami scenarios in the Derwent Estuary, Tasmania;
2. Provide advice on the design of the computer model being developed by MRT to ensure that outputs provide the necessary information for shipping hazards to be adequately assessed;
3. Undertake a literature assessment and summarise the types of advice being provided to similar organisations, particularly port authorities, in other jurisdictions in Australia and internationally;
4. Analyse the tsunami computer model outputs and assess the implications for shipping at the locations specified below;
5. The following specific areas at a minimum are to be considered for hazards to shipping:
    a. the principal Hobart port area (including Constitution Dock and Macquarie Point);
    b. Selfs Point Wharf;
    c. Risdon Wharf;
    d. Prince of Wales Bay wharf and dock facilities;
    e. the principal navigational channels and established anchorage areas from Iron Pot to Risdon Wharf; and
    f. the navigational channel specifically in the vicinity of the Tasman Bridge.
6. Prepare and submit to the Department's Representative a draft report addressing the above tasks, summarising the Consultant's findings, identifying any potential constraints and any recommendations for further work and actions;
7. Present the draft Report to stakeholders at a workshop in Hobart;
8. Provide to the Department's Representative a final Report incorporating any comments from stakeholders or feedback from the workshop attendees;
9. Comply with any reasonable requests of the Department's Representative in relation to the provision of any aspect of the Service (including any Departmental policies or requirements that need to be adhered to); and
10. Provide such ad hoc or further information as the Department's Representative may reasonably require.

Appendix 2: Tasports Tsunami Warning Procedure

RESPONSIBILITIES

Daily Procedure

- Port Control to monitor TasPorts wind instruments approximately hourly
- Bureau of Meteorology emails checked promptly

Immediate Actions

- Port Control to notify the Duty Pilot/s
- Port Control to notify the Marine Manager
- Security Centre to notify Port Operations Supervisor/s, Operations Manager and the Site Coordinator/s to secure loose items, floating plant and cease cargo operations as required
- Port Control (Radio Room) to notify the Manager of Devonport Airport (if the warning includes Devonport)
- Security Centre to notify the Event Manager of any specific public 'event' occurring in the Port
- Port Control to monitor wind speeds and sea states every 30 minutes
- Port Operations to dispatch Patrolman/Wharf Officers to check moorings of all vessels (small boats and ships)
- Port Control to notify Kings Pier small vessels owners via landline and/or text message to mobile phones in the event of strong easterlies 'Severe storm imminent, please attend to your vessel'
- Port Control to notify vessels in port as directed by Duty Pilot
- Port Control to advise port users via a VHF Channel 16 broadcast
- Port Control and Security Centre to monitor small boats via CCTV and patrols in case they come adrift Port Control to liaise with the Marine Manager on whether the Port is to be closed or vessel movements restricted

Post-Incident

- Stand down when Severe Weather Warning is cancelled by the Bureau of Meteorology
- Contribute to debrief by compiling a detailed incident report

(Source:
http://www.tasports.com.au/pdf/Safety/201504_Emergency_Management_Plan.pdf)

Appendix 3: Wave Data for shipping hazards to be adequately assessed

Wave data incorporated into the design of the computer model to ensure that outputs provide the necessary information for shipping hazards to be adequately assessed

This is the request made to the Department of State Growth for the following to be incorporated into the tsunami computer model.

1. WAVE DATA

The following indicative wave data is required for the listed locations:

- Wave height (Amplitude peak to trough, in metres)
- Wave length (Peak to peak or trough to trough, in metres and duration e.g. minutes/seconds)
- Wave velocity (Preferably in knots; or metres per second)
- Wave form (Profile and descriptor e.g. slow water level rise, rapid water level rise; a ‘wall of water’, breaking wave)
- Time of arrival at each location relative to location 1 i.e. location 1 is time zero
- Time taken for the Tsunami wave to arrive at location 1

2. LOCATION DATA

Wave data locations were chosen to ensure the ‘form’ of the wave is understood at the following locations:

- Principal shipping channel from Iron Pot to Prince of Wales Bay (including in the vicinity of the Tasman Bridge)
- The four designated anchorages
- Principal Hobart port area (including Constitution Dock and Macquarie Point)
- Selfs Point Wharf
- Risdon (Nyrstar) Wharf
- Prince of Wales Bay wharf and dock facilities

Location co-ordinates used for the generation of wave data were derived from Google Maps. Each location is described in terms of its latitude and longitude. For ease of analysis the wave data for each location is numbered with a location number.

Each location also has a descriptor e.g. Off Iron Pot-mid channel; 200m to the East of Battery Point etc. However, these are not accurate positions and were not used as locations to generate wave data.

3. LOCATION CO-ORDINATES

PRINCIPAL SHIPPING CHANNEL; IRON POT TO PRINCE OF WALES BAY (INCLUDING IN THE VICINITY OF THE TASMAN BRIDGE) (Latitude and longitude data from Google Maps)	
1. Off Iron Pot; mid channel **43°04'02.1"S 147°23'42.4"E** **-43.067257, 147.395121**	2. Off John's Point; slightly East of mid channel **43°02'32.0"S 147°22'45.4"E** **-43.042224, 147.379269**
3. Off Flowerpot Point; slightly East of mid channel **43°00'34.3"S 147°22'28.1"E** **-43.009533, 147.374462**	4. Off White Rock Point; slightly East of mid channel **42°58'36.6"S 147°22'14.5"E** **-42.976825, 147.370685**
5. Off Trywork Point; slightly West of mid channel **42°56'24.7"S 147°22'40.4"E** **-42.940204, 147.377895**	6. Off Blinking Billy Point; West of Mid channel **42°54'50.3"S 147°22'27.8"E** **-42.913981, 147.374376**
7. Off RYCT; South of Kangaroo Bluff **42°53'54.8"S 147°21'39.9"E** **-42.898543, 147.361083**	8. Off Sullivans Cove; due South of Rosny Point **42°53'03.0"S 147°21'09.6"E** **-42.884164, 147.352672**
9. Off Macquarie Point; on 353° leads (Tasman Bridge Channel) **42°52'35.0"S 147°20'50.9"E** **-42.876385, 147.347458**	10. Off Ross Bay; on 353° leads (Tasman Bridge Channel) **42°52'14.8"S 147°20'43.5"E** **-42.870791, 147.345430**
11. Off Montagu Bay; on 353° leads (Tasman Bridge Channel) **42°52'03.6"S 147°20'43.2"E** **-42.867673, 147.345333**	12. Under Tasman Bridge: on 353° leads (Tasman Bridge Channel) **42°51'54.1"S 147°20'43.0"E** **-42.865027, 147.345269**
13. Off Pavilion Point; on 353° leads (Tasman Bridge Channel) **42°51'41.9"S 147°20'42.1"E** **-42.861642, 147.345038**	14. Off Rose Bay; on 353° leads (Tasman Bridge Channel) **42°51'25.4"S 147°20'42.1"E** **-42.857057, 147.345017**
15. Off Lindisfarne Bay; on 353° leads (Tasman Bridge Channel) **42°51'11.9"S 147°20'41.0"E** **-42.853301, 147.344727**	16. Off Beltana Point; on 135° leads **42°51'04.1"S 147°20'29.7"E** **-42.851142, 147.341594**
17. Off Koomela Bay; on 135° leads **42°50'56.9"S 147°20'19.4"E** **-42.849140, 147.338729**	18. Off Limekiln Point: on 135° leads **42°50'50.9"S 147°20'10.0"E** **-42.847461, 147.336122**
19. Off Selfs Point Wharf South end; slightly East of mid channel **42°50'42.4"S 147°20'03.3"E** **-42.845113, 147.334255**	20. Off Selfs Point Wharf North end; mid channel **42°50'32.8"S 147°19'56.6"E** **-42.842435, 147.332388**
21. Off New Town Bay; mid channel **42°50'22.5"S 147°19'50.0"E** **-42.839583, 147.330564**	22. Off Shag Bay; mid channel **42°50'12.3"S 147°19'44.3"E** **-42.836751, 147.328966**
23. Off Stanhope Point; mid channel **42°50'00.4"S 147°19'35.4"E** **-42.833435, 147.326488**	24. Off Nyrstar Wharf South end; mid channel **42°49'49.9"S 147°19'24.9"E** **-42.830528, 147.323580**
25. Off Nystar Wharf North end; mid channel **42°49'41.1"S 147°19'11.9"E** **-42.828093, 147.319964**	26. Off Store Point; mid channel **42°49'32.5"S 147°18'56.9"E** **-42.825705, 147.315807**
27. Off INCAT slip; on 308° leads **42°49'25.3"S 147°18'44.0"E** **-42.823683, 147.312234**	28. Off Dowsings Point; midway between Dowsings Point and INCAT jetty **42°49'27.4"S 147°18'25.6"E** **-42.824279, 147.307116**
29. Entering Prince of Wales Bay; mid channel **42°49'29.4"S 147°18'16.7"E** **-42.824834, 147.304627**	30. Entering Prince of Wales Bay; mid channel **42°49'32.8"S 147°18'09.5"E** **-42.825782, 147.302631**

DESIGNATED ANCHORAGES (Latitude and longitude data from Google Maps)	
40. Anchorage 1 **42°55'17.7"S 147°23'17.6"E** **-42.921576, 147.388207**	41. Anchorage 2 **42°56'06.0"S 147°23'18.0"E** **-42.935000, 147.388333**
42. Anchorage 3 **42°56'54.0"S 147°23'06.0"E** **-42.948333, 147.385000**	43. Anchorage 4 **42°57'42.0"S 147°22'54.0"E** **-42.961667, 147.381667**

PRINCIPAL HOBART PORT AREA; INCLUDING CONSTITUTION DOCK AND MACQUARIE POINT **(Latitude and longitude data from Google Maps)**	
50. Off Secheron Point; 500m to the East **42°53'27.0"S 147°20'45.8"E** **-42.890836, 147.346042**	51. 200m to the East of Battery Point **42°53'12.1"S 147°20'34.9"E** **-42.886689, 147.343038**
52. 250 m to the North of Battery Point **42°53'04.1"S 147°20'21.5"E** **-42.884484, 147.339304**	53. CSIRO Wharf; mid length **42°53'10.8"S 147°20'19.1"E** **-42.886327, 147.338650**
54. Princes Wharf 2 & 3; mid length **42°53'09.1"S 147°20'09.8"E** **-42.885873, 147.336070**	55. Princes Wharf 1; mid length **42°53'08.6"S 147°20'00.7"E** **-42.885722, 147.333533**
56. Between Brooke Street Pier and Ferry Pier **42°53'04.8"S 147°19'58.1"E** **-42.884663, 147.332809**	57. Elizabeth Street Pier; South side, mid length **42°53'03.5"S 147°20'00.9"E** **-42.884303, 147.333581**
58. King Pier Marina entrance **42°53'02.5"S 147°20'06.6"E** **-42.884022, 147.335158**	59. Centre of Constitution Dock **42°52'57.4"S 147°19'59.2"E** **-42.882621, 147.333120**
60. Centre of Victoria Dock **42°52'54.6"S 147°20'03.9"E** **-42.881837, 147.334402**	61. Macquarie Wharf 1; mid length **42°52'56.6"S 147°20'09.9"E** **-42.882387, 147.336076**
62. Macquarie Wharf 2; mid length **42°52'57.7"S 147°20'19.8"E** **-42.882696, 147.338844**	63. Macquarie Wharf 3; mid length **42°52'56.9"S 147°20'25.5"E** **-42.882462, 147.340416**
64. 200 m to the East of end of Macquarie Wharf 3 & 4 **42°52'55.8"S 147°20'41.3"E** **-42.882177, 147.344799**	65. Macquarie Wharf 4; mid length **42°52'50.4"S 147°20'28.7"E** **-42.880655, 147.341296**
66. Macquarie Wharf 5; mid length **42°52'46.3"S 147°20'27.9"E** **-42.879519, 147.341084**	67. Macquarie Wharf 6; mid length **42°52'40.1"S 147°20'28.2"E** **-42.877799, 147.341181**
68. 200m to the East of Macquarie Point **42°52'35.8"S 147°20'38.6"E** **-42.876610, 147.344067**	

SELFS POINT WHARF **(Latitude and longitude data from Google Maps)**	
80. 100 m to the South of Selfs Point Wharf **42°50'47.8"S 147°19'51.5"E** **-42.846596, 147.330985**	81. Selfs Point Wharf; mid length **42°50'41.0"S 147°19'50.2"E** **-42.844720, 147.330599**
82. 100m to the North of Selfs point Wharf **42°50'34.3"S 147°19'48.4"E** **-42.842860, 147.330105**	83. Selfs Point Jetty; mid length **42°50'43.0"S 147°19'44.7"E** **-42.845271, 147.329086**

RISDON (NYRSTAR) WHARF **(Latitude and longitude data from Google Maps)**	
90. 100m South East of Nyrstar Wharf 2; South end **42°49'55.0"S 147°19'21.1"E** **-42.831943, 147.322530**	91. Nyrstar Wharf 2; mid length **42°49'51.4"S 147°19'14.0"E** **-42.830956, 147.320545**
92. Nyrstar Wharf 1; mid length **42°49'48.4"S 147°19'08.8"E** **-42.830110, 147.319107**	93. 100m North West of Nyrstar Wharf facilities; North end **42°49'43.5"S 147°19'00.1"E** **-42.828761, 147.316704**

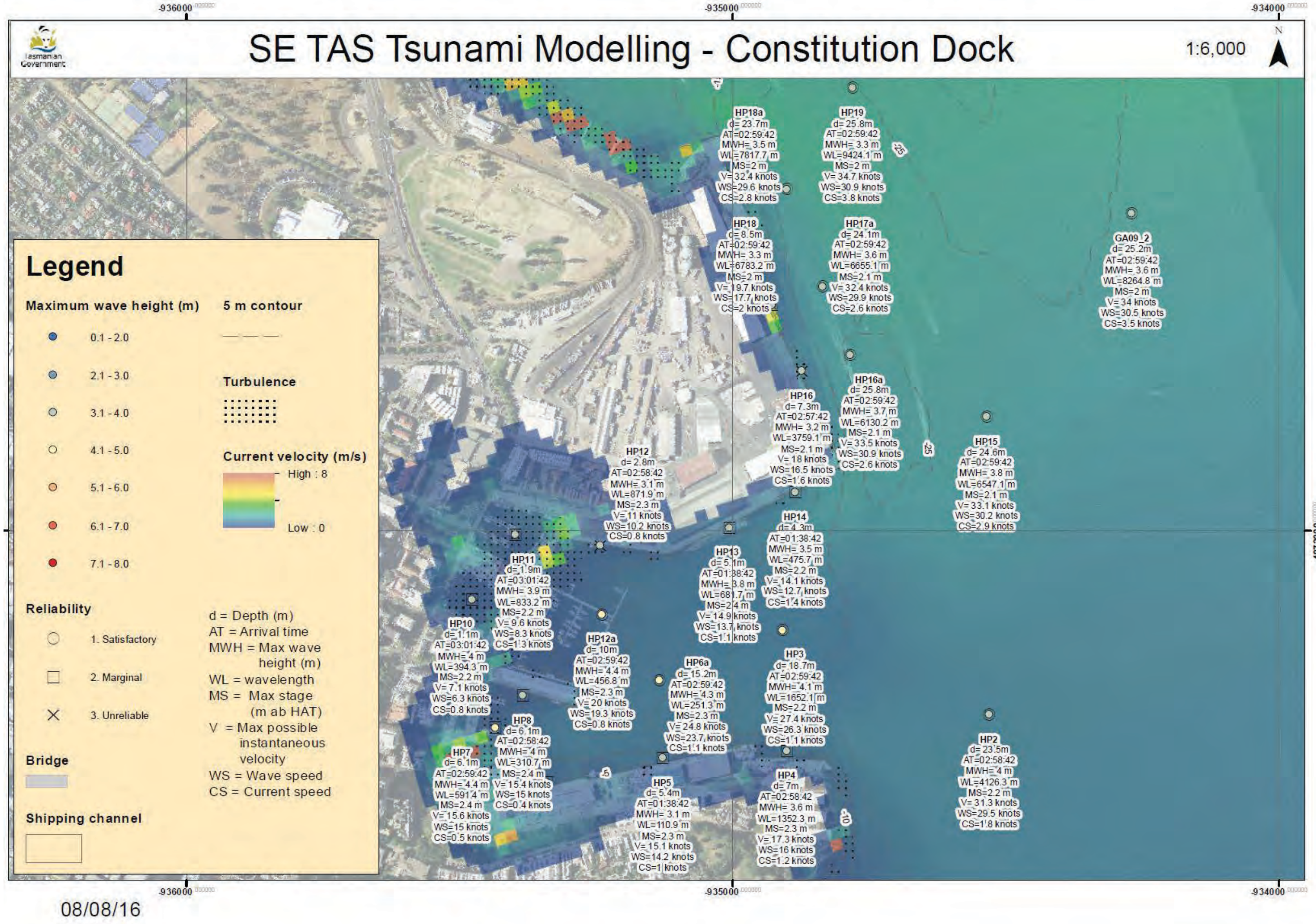
PRINCE OF WALES BAY WHARF AND DOCK FACILITIES (Latitude and longitude data from Google Maps)	
100. 100m East of North end of INCAT slip **42°49'35.9"S 147°18'43.3"E** **-42.826640, 147.312026**	101. INCAT slip **42°49'35.7"S 147°18'34.3"E** **-42.826581, 147.309537**
102. 100m East of INCAT jetty; North end **42°49'32.1"S 147°18'29.1"E** **-42.825593, 147.308089**	103. INCAT Jetty; mid length **42°49'33.7"S 147°18'23.1"E** **-42.826022, 147.306426**
104. Prince of Wales Bay Marina wharf; mid length **42°49'41.0"S 147°18'10.4"E** **-42.828048, 147.302896**	105. Prince of Wales Marine P/L dock facilities **42°49'38.8"S 147°18'03.7"E** **-42.827430, 147.301040**
106. Derwent Marine dock facilities **42°49'30.9"S 147°17'58.1"E** **-42.825262, 147.299474**	107. Pauline Point marina facilities **42°49'49.0"S 147°18'05.8"E** **-42.830286, 147.301609**

Appendix 4: SE Tasmania Tsunami Model Results

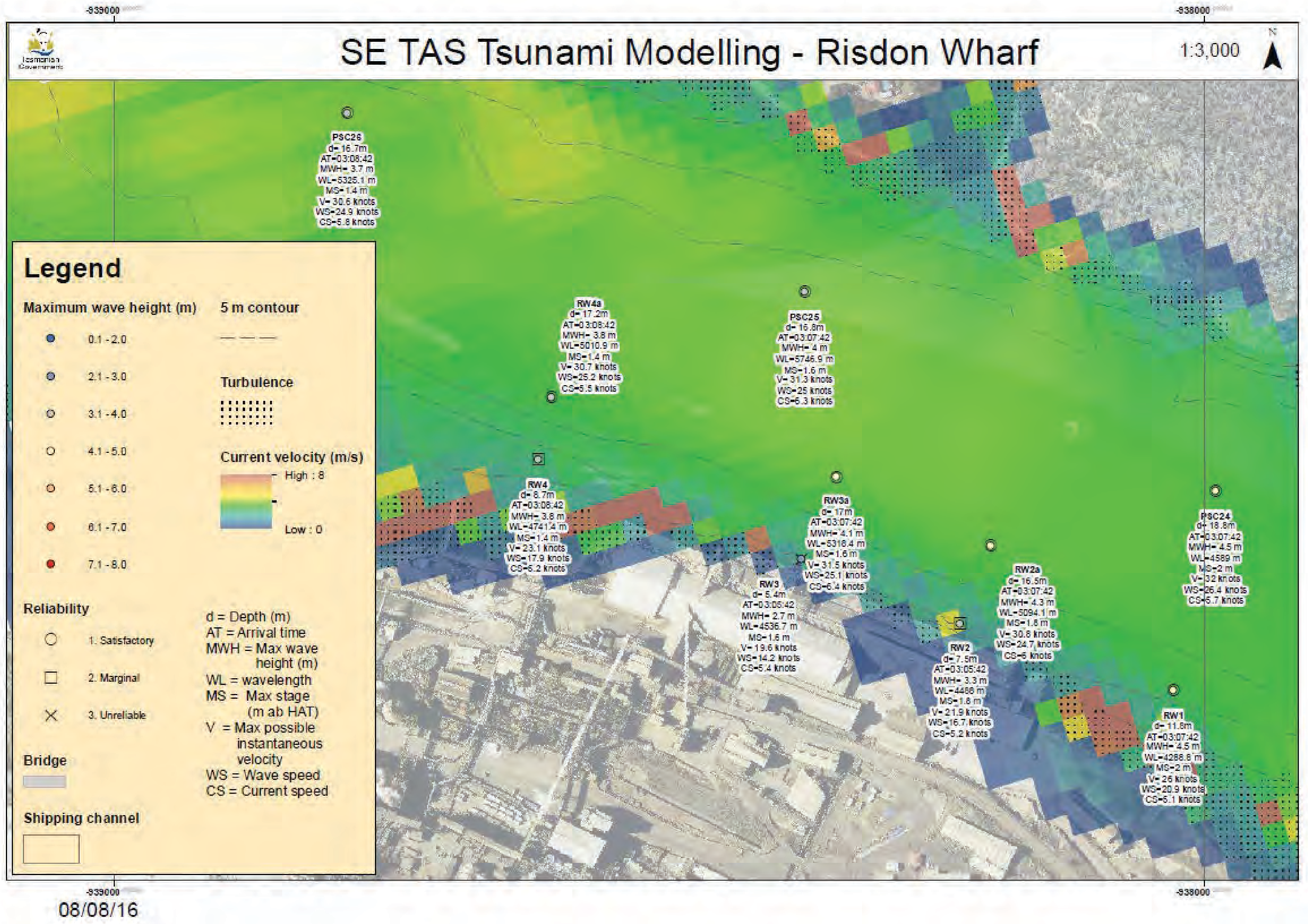
ID	SiteID	SiteName	Description	Type	Easting	Northing	DistAlongChannel (km)	Depth (m, hat)	Arrival time	End time	Max h (m)	MWH time	Max stage (ab HAT)	Wavelength first wave (m)	Time max current	Max current (m/s)	Max current (knots)	Wave speed (m/s)	Wave speed (knots)	Upper velocity (m/s)	Upper velocity (knots)	Turbulence	Reliability
31	ANC1	Anchorage 1		DESIGNATED ANCHORAGES	531682.3433	5247820.903	NA	25.7	2:53:42 AM	11:01:42 AM	2.8	2:56:42 AM	1.6	1080.0	2:56:42 AM	1.1	2.2	15.9	30.8	17.0	33.0	N	1
32	ANC2	Anchorage 2		DESIGNATED ANCHORAGES	531685.745	5246330.159	NA	25.8	2:51:42 AM	1:08:42 PM	2.9	2:55:42 AM	1.7	1254.0	3:08:42 AM	1.2	2.4	15.9	30.9	17.1	33.3	N	1
33	ANC3	Anchorage 3		DESIGNATED ANCHORAGES	531407.0132	5244850.815	NA	27.5	2:49:42 AM	1:08:42 PM	2.8	2:53:42 AM	1.7	1440.0	3:07:42 AM	1.3	2.6	16.4	31.9	17.7	34.5	N	1
34	ANC4	Anchorage 4		DESIGNATED ANCHORAGES	531128.3966	5243371.346	NA	28.7	2:47:42 AM	1:31:42 PM	3.1	2:52:42 AM	1.6	1512.0	2:52:42 AM	1.3	2.4	16.8	32.6	18.0	35.1	N	1
70	G1	Geilston Bay Boat Club		Marina	528116.4703	5257121.736	NA	3.0	3:06:42 AM	3:35:42 PM	5.2	3:10:42 AM	2.9	624.0	6:06:42 AM	1.2	2.3	5.4	10.5	6.6	12.8	Y	2
79	G10	Bruny Island Jetty		Jetty or wharf	523322.3045	5223273.594	NA	7.9	1:38:42 AM	3:38:42 PM	4.9	2:52:42 AM	1.9	NC	3:21:42 AM	0.3	0.5	8.8	17.1	9.0	17.6	N	4
79	G10a				523073	5223630	gauge_G10a	23.4	2:51:42 AM	3:43:42 AM	1.8	2:52:42 AM	0.5	NC	3:21:42 AM	0.4	0.8	15.2	29.5	15.6	30.3	N	1
80	G11	Lymington Yacht Club		Marina	506721.7838	5219678.958	NA	1.1	3:02:42 AM	2:01:42 PM	2.6	3:11:42 AM	1.4	NC	3:19:42 AM	1.9	3.7	3.3	6.5	5.3	10.2	Y	3
81	G12	Franklin Wharf		Jetty or wharf	501213.5888	5219647.111	NA	1.2	3:42:00 AM	NA	1.8	3:43:42 AM	0.3	NC	3:38:42 AM	0.4	0.8	3.4	6.7	3.8	7.5	Y	3
82	G13	Huonville Boat Ramp		Miscellaneous	504126.3595	5235243.357	NA	0.7	4:15:00 AM	NA	0.1	2:45:42 PM	0.2	NC	6:29:42 AM	0.0	0.0	2.7	5.2	2.7	5.2	N?	3
83	G14	Port Huon		Jetty or wharf	498116.4693	5221372.151	NA	8.9	3:07:42 AM	12:11:42 PM	2.0	3:12:42 AM	1.1	NC	4:22:42 AM	0.4	0.8	9.3	18.1	9.8	19.0	N	1
84	G15	Dover Wharf		Jetty or wharf	501854.7079	5203743.126	NA	6.9	2:41:42 AM	12:58:42 PM	2.7	2:44:42 AM	1.5	NC	2:44:42 AM	0.7	1.4	8.2	16.0	8.9	17.4	N	2
84	G15a				501973	5203433	gauge_G15a	19.7	2:41:42 AM	11:42:42 AM	2.6	2:44:42 AM	1.5	NC	2:52:42 AM	0.5	1.1	13.9	27.0	14.4	28.1	N	1
85	G16	Southport Wharf		Jetty or wharf	497981.1014	5191075.585	NA	2.4	2:32:42 AM	2:55:42 PM	7.2	3:40:42 AM	4.8	NC	3:38:42 AM	3.3	6.3	4.9	9.5	8.1	15.8	Y	1
86	G17	Port Arthur		Jetty or wharf	569349.0245	5222459.614	NA	4.2	2:13:42 AM	2:22:42 PM	7.7	2:19:42 AM	3.7	NC	2:26:42 AM	1.9	3.8	6.4	12.5	8.4	16.3	Y	2
86	G17a				569698	5222367	gauge_G17a	16.2	2:12:42 AM	2:22:42 PM	7.8	2:19:42 AM	3.3	NC	2:35:42 AM	4.4	8.5	12.6	24.5	17.0	33.0	N	1
87	G18	Pirates Bay Jetty		Jetty or wharf	577039.4522	5234953.727	NA	2.0	2:08:42 AM	2:46:42 PM	12.9	3:22:42 AM	11.4	NC	2:24:42 AM	5.1	9.9	4.4	8.6	9.5	18.5	Y	2
87	G18a				576624	5235734	gauge_G18a	15.2	2:07:42 AM	2:45:42 PM	19.7	2:10:42 AM	8.7	NC	2:20:42 AM	9.4	18.3	12.2	23.7	21.6	42.0	Y	1
88	G19	Dunalley Wharf		Jetty or wharf	565533.1971	5250757.225	NA	0.5	3:08:42 AM	3:18:42 PM	4.3	7:03:42 AM	2.9	NC	7:12:42 AM	1.5	2.9	2.2	4.3	3.7	7.3	Y	3
88	G19a				565353	5250555	gauge_G19a	1.7	3:09:42 AM	3:17:42 PM	4.3	7:03:42 AM	2.8	NC	6:55:42 AM	2.8	5.5	4.1	8.0	6.9	13.5	Y	1
70	G1a				527994	5257073	gauge_G1a	3.6	3:06:42 AM	3:34:42 PM	5.8	3:10:42 AM	2.8	1500.0	6:06:42 AM	3.7	7.3	5.9	11.5	9.7	18.8	Y	1
70	G1b				527481	5256641	gauge_G1b	7.8	3:05:42 AM	3:24:42 PM	5.1	3:10:42 AM	2.7	NC	6:06:42 AM	1.6	3.1	8.8	17.0	10.4	20.1	N	1
71	G2	Motor Yacht Club Tasmania		Marina	528824.4968	5255554.87	NA	2.5	3:03:42 AM	3:31:42 PM	4.3	3:08:42 AM	2.5	NC	5:48:42 AM	1.9	3.8	4.9	9.6	6.9	13.3	Y	2
89	G20	Maria Island Jetty		Jetty or wharf	587222.2112	5285481.716	NA	1.8	2:14:42 AM	2:19:42 PM	5.6	2:31:42 AM	3.9	NC	2:29:42 AM	4.5	8.7	4.2	8.2	8.7	16.9	Y	2
90	G21	Spring Bay Wharf		Jetty or wharf	575892.9947	5290436.048	NA	2.9	2:26:42 AM	2:23:42 PM	2.9	3:44:42 AM	1.6	NC	2:41:42 AM	2.9	5.6	5.3	10.4	8.2	16.0	Y	1
91	G22	Triabunna Wharf		Jetty or wharf	575179.6634	5293171.153	NA	0.9	2:34:42 AM	3:38:42 PM	3.9	2:40:42 AM	2.4	NC	2:37:42 AM	2.9	5.7	3.0	5.9	5.9	11.5	Y	3
1	G22a				574952	5292740	gauge_G22a	1.3	2:32:42 AM	3:38:42 PM	3.7	3:40:42 AM	2.6	3018.1	4:20:42 AM	3.2	6.3	3.5	6.9	6.8	13.1	Y	1
92	G23	Louisville Jetty		Jetty or wharf	575093.4973	5289642.045	NA	1.4	2:24:42 AM	3:22:42 PM	2.9	3:32:42 AM	2.0	NC	3:29:42 AM	1.0	1.9	3.7	7.2	4.7	9.2	Y	3
92	G23a				575461	5289603	gauge_G23a	15.5	2:25:42 AM	2:24:42 PM	3.5	3:32:42 AM	1.7	NC	2:41:42 AM	2.2	4.2	12.3	24.0	14.5	28.2	N	1
93	G24	Prosser River Jetties		Jetty or wharf	571680.3125	5287860.417	NA	1.8	2:32:42 AM	3:36:42 PM	4.7	2:36:42 AM	3.0	NC	2:33:42 AM	2.0	3.9	4.2	8.1	6.2	12.0	Y	3
94	G25	Swansea Jetty		Jetty or wharf	589080.5707	5336035.935	NA	1.2	2:45:42 AM	3:28:42 PM	2.6	4:35:42 AM	1.4	NC	11:58:42 AM	3.1	6.0	3.4	6.7	6.5	12.7	Y	1
95	G26	Coles Bay Jetty		Jetty or wharf	606555.8056	5335139.191	NA	2.4	2:41:42 AM	3:00:42 PM	4.3	3:40:42 AM	2.3	NC	4:07:42 AM	2.8	5.4	4.8	9.4	7.6	14.9	Y	2
95	G26a				606465	5334799	gauge_G26a	11.5	2:41:42 AM	3:00:42 PM	4.2	3:41:42 AM	2.0	NC	3:38:42 AM	1.5	3.0	10.6	20.7	12.2	23.7	N	1
96	G27	Wine Glass Bay		Miscellaneous	607913.419	5330585.133	NA	5.4	2:09:42 AM	2:44:42 PM	7.5	2:12:42 AM	5.4	NC	2:34:42 AM	4.6	9.0	7.3	14.1	11.9	23.1	Y	1
97	G28	Triabunna		Map Sheet Hydrograph	574895.8073	5292426.482	NA	1.0	2:31:42 AM	3:35:42 PM	3.4	2:37:42 AM	2.4	NC	4:17:42 AM	3.1	6.0	3.2	6.2	6.3	12.2	Y	1
98	G29	Cygnet		Map Sheet Hydrograph	507073.5892	5219424.467	NA	3.2	3:01:42 AM	9:44:42 AM	2.1	3:10:42 AM	1.1	NC	3:20:42 AM	4.1	8.0	5.6	10.9	9.7	18.9	N	1
71	G2a				528851	5255408	gauge_G2a	8.5	3:03:42 AM	3:30:42 PM	4.9	3:08:42 AM	2.4	1080.0	5:53:42 AM	1.6	3.1	9.1	17.7	10.7	20.8	N	1
72	G3	Bellerive Yacht Club		Marina	529993.1637	5253143.453	NA	1.3	3:00:42 AM	3:15:42 PM	4.1	3:04:42 AM	2.8	NC	3:51:42 AM	1.7	3.2	3.6	6.9	5.2	10.2	Y	2
99	G30	Dover West		Map Sheet Hydrograph	501302.0433	5202970.165	NA	22.9	2:41:42 AM	12:59:42 PM	2.8	2:45:42 AM	1.6	NC	2:52:42 AM	0.5	0.9	15.0	29.1	15.5	30.1	N	1
100	G31	Dover East		Map Sheet Hydrograph	503405.485	5203930.605	NA	12.2	2:40:42 AM	12:57:42 PM	2.7	2:43:42 AM	1.6	NC	2:41:42 AM	0.6	1.2	11.0	21.3	11.6	22.5	N	1
101	G32	Bruny Island Neck North		Map Sheet Hydrograph	530027.5622	5209579.301	NA	16.3	2:23:42 AM	2:11:42 PM	10.9	2:26:42 AM	5.6	NC	2:31:42 AM	2.3	4.5	12.6	24.5	15.0	29.1	N	1
102	G33	Bruny Island Neck South		Map Sheet Hydrograph	526815.5141	5205457.085	NA	14.1	2:23:42 AM	2:56:42 PM	10.4	2:57:42 AM	6.0	NC	2:24:42 AM	2.1	4.1	11.7	22.8	13.8	26.9	Y	1
103	G34	Dunkels Beach		Map Sheet Hydrograph	526864.4622	5200534.502	NA	17.4	2:23:42 AM	3:33:42 PM	10.5	2:25:42 AM	4.1	NC	2:47:42 AM	2.1	4.2	13.1	25.4	15.2	29.5	N	1
104	G35	Granton - Bridgewater		Map Sheet Hydrograph	518849.6479	5267328.336	NA	1.7	3:45:42 AM	7:01:42 AM	2.1	3:49:42 AM	0.7	NC	3:52:42 AM	0.7	1.4	4.1	7.9	4.8	9.3	Y	1
105	G36	Bridgewater - Gagebrook		Map Sheet Hydrograph	521294.1697	5266105.297	NA	7.4	3:38:42 AM	6:53:42 AM	2.0	3:42:42 AM	0.6	NC	6:48:42 AM	0.5	0.9	8.5	16.5	9.0	17.5	N	1
106	G37	Austins Ferry - Old Beach		Map Sheet Hydrograph	521140.0496	5264777.086	NA	3.8	3:34:42 AM	10:22:42 AM	2.1	3:38:42 AM	0.8	NC	3:41:42 AM	1.8	3.5	6.1	11.9	7.9	15.4	N	1
107	G38	Dowsing Point - Otago Bay		Map Sheet Hydrograph	523929.2927	5259788.225	NA	4.8	3:13:42 AM	1:01:42 PM	2.5	3:17:42 AM	1.7	NC	3:37:42 AM	3.9	7.7	6.9	13.4	10.8	21.0	N	1
108	G39	Claremont		Map Sheet Hydrograph	522018.8733	5263010.425	NA	4.2	3:27:42 AM	11:38:42 AM	2.1	3:34:42 AM	1.0	NC	3:39:42 AM	1.6	3.2	6.4	12.4	8.0	15.6	N	1
72	G3a				529939	5253235	gauge_G3a	3.5	3:00:42 AM	3:15:42 PM	5.1	3:04:42 AM	2.8	1200.0	3:52:42 AM	2.4	4.7	5.8	11.3	8.2	16.0	Y	1
73	G4	Bellerive Jetty		Marina	529872.5134	5253121.228	NA	1.3	2:59:42 AM	3:28:42 PM	3.7	3:04:42 AM	2.8	NC	3:52:42 AM	2.8	5.4	3.5	6.8	6.3	12.2	Y	3
109	G40	Otago Bay		Map Sheet Hydrograph	523182.4777	5262088.464	NA	4.9	3:21:42 AM	11:33:42 AM	2.1	3:29:42 AM	1.2	NC	3:28:42 AM	1.9	3.7	7.0	13.5	8.9	17.2	N	1
110	G41	Rosetta/Montrose		Map Sheet Hydrograph	522024.6344	5259773.788	NA	3.5	3:18:42 AM	12:22:42 PM	2.3	3:22:42 AM	1.3	NC	4:14:42 AM	1.4	2.7	5.9	11.4	7.3	14.1	N	1
111	G42	Howrah		Map Sheet Hydrograph	532726.3176	5250584.508	NA	22.6	2:56:42 AM	2:05:42 PM	3.8	2:59:42 AM	2.2	NC	2:59:42 AM	0.9	1.7	14.9	28.9	15.8	30.6	N	1
112	G43	Bowen Bridge/Risdon		Map Sheet Hydrograph	525230.2516	5259367.802	NA	13.3	3:10:42 AM	1:59:42 PM	3.2	3:15:42 AM	1.6	NC	3:32:42 AM	2.9	5.6	11.4	22.2	14.3	27.8	N	1
113	G44	Bellerive		Map Sheet Hydrograph	530868.2797	5251985.309	NA	14.3	2:57:42 AM	1:15:42 PM	4.1	3:01:42 AM	2.3	NC	5:50:42 AM	0.9	1.8	11.8	23.0	12.7	24.8	N	1
114	G45	Tranmere		Map Sheet Hydrograph	533042.4953	5248498.264	NA	25.0	2:54:42 AM	1:36:42 PM	3.1	2:57:42 AM	1.7	NC	2:57:42 AM	1.2	2.4	15.7	30.4	16.9	32.8	N	1
115	G46	Taroona		Map Sheet Hydrograph	529699.4782	5245384.112	NA	20.6	2:50:42 AM	1:07:42 PM	3.2	2:53:42 AM	2.0	NC	3:08:42 AM	1.7	3.3	14.2	27.6	15.9	30.9	N	1
116	G47	Bonnet Hill		Map Sheet Hydrograph	528411.484	5242697.528	NA	15.9	2:47:42 AM	1:30:42 PM	4.8	2:50:42 AM	2.5	NC	2:50:42 AM	1.6	3.1	12.5	24.3	14.1	27.4	N	1
117	G48	Blackmans Bay		Map Sheet Hydrograph	527172.9669	5238603.092	NA	15.7	2:44:42 AM	1:05:42 PM	4.7	2:45:42 AM	2.6	NC	2:45:42 AM	1.8	3.4	12.4	24.1	14.1	27.5	N	1
118	G49	Tinderbox Hills		Map Sheet Hydrograph	528231.3024	5235553.763	NA	18.6	2:40:42 AM	2:26:42 PM	4.7	2:42:42 AM	2.7	NC	2:56:42 AM	1.7	3.3	13.5	26.3	15.2	29.6	N	1
73	G4a				529820	5253207	gauge_G4a	4.0	3:00:42 AM	3:15:42 PM	5.1	3:04:42 AM	2.7	1600.0	3:52:42 AM	3.7	7.1	6.3	12.2	10.0	19.4	Y	1
74	G5	Royal Yacht Club of Tasmania		Marina	527170.6438	5250426.579	NA	0.7	2:58:42 AM	3:15:42 PM	4.0	3:05:42 AM	2.6	NC	3:07:42 AM	1.0	1.9	2.7	5.2	3.7	7.1	Y	3
119	G50	Margate/Howden		Map Sheet Hydrograph	523244.9549	5236146.828	NA	13.4	2:49:42 AM	1:58:42 PM	2.7	2:52:42 AM	1.4	NC	3:03:42 AM	2.1	4.1	11.5	22.3	13.6	26.4	N	1
120	G51	Barretta/Electrona		Map Sheet Hydrograph	522705.8653	5233586.979	NA	19.6	2:47:42 AM	8:17:42 AM	2.1	2:49:42 AM	1.1	NC	5:31:42 AM	0.5	0.9	13.8	26.9	14.3	27.8	N	1
121	G52	Kingston Beach		Map Sheet Hydrograph	527533.7187	5240943.372	NA	21.6	2:45:42 AM	2:31:42 PM	5.0	2:48:42 AM	2.5	NC	2:47:42 AM	1.4	2.7	14.6	28.3	15.9	31.0	N	1
122	G53	Snug/Conningham		Map Sheet Hydrograph	522007.2232	5231514.265	NA	15.9	2:46:42 AM	12:28:42 PM	2.2	2:50:42 AM	1.2	NC	4:34:42 AM	0.6	1.3	12.5	24.3	13.1	25.5	N	1
123	G54	Kettering		Map Sheet Hydrograph	521795.1593	5225055.773	NA	19.1	2:52:42 AM	6:28:42 AM	1.6	6:26:42 AM	0.5	NC	5:52:42 AM	0.3	0.7	13.7	26.6	14.0	27.3	N	1
124	G55	Tinderbox Point		Map Sheet Hydrograph	527484.7706	5232200.331	NA	25.9	2:40:42 AM	1:47:42 PM	2.3	2:41:42 AM	1.4	NC	2:43:42 AM	1.5	3.0	15.9	31.0	17.5	34.0	N	1
125	G56	Dennes Point		Map Sheet Hydrograph	527663.3648	5231181.683	NA	18.0	2:40:42 AM	1:47:42 PM	2.3	2:42:42 AM	1.4	NC	2:42:42 AM	1.2	2.4	13.3	25.8	14.5	28.2	N	1
126	G57	Rokeby		Map Sheet Hydrograph	536262.3403	5248779.685	NA	4.7	3:00:42 AM	2:48:42 PM	3.7	3:05:42 AM	2.0	NC	3:54:42 AM	1.5	2.9	6.8	13.2	8.3	16.1	Y	1
127	G58	Seven Mile Beach		Map Sheet Hydrograph	542322.3691	5254538.088	NA	6.5	2:56:42 AM	3:34:42 PM	3.5	6:18:42 AM	2.3	NC	6:36:42 AM	1.2	2.4	8.0	15.5	9.2	18.0	N	1
128	G59			Map Sheet Hydrograph	544297.4876	5244120.098	NA	9.4	2:41:42 AM	3:23:42 PM	3.5	2:44:42 AM	2.1	NC	2:42:42 AM	1.7	3.2	9.6	18.6	11.2	21.9	N	1
74	G5a				527280	5250420	gauge_G5a	8.7	2:58:42 AM	2:59:42 PM	4.8	3:05:42 AM	2.5	700.0	3:07:42 AM	0.5	1.0	9.2	17.9	9.7	18.9	N	1
75	G6	Derwent Sailing Squadron		Marina	527176.9938	5250235.02	NA	0.8	2:58:42 AM	3:13:42 PM	3.5	3:05:42 AM	2.6	NC	4:01:42 AM	1.0	2.0	2.7	5.3	3.8	7.4	Y	3
129	G60	Roches Beach		Map Sheet Hydrograph	541227.6617	5250140.801	NA	6.1	2:52:42 AM	3:28:42 PM	3.2	8:15:42 AM	1.7	NC	3:09:42 AM	1.8	3.5	7.7	15.0	9.5	18.5	N	1
130	G61	Lauderdale East		Map Sheet Hydrograph	541285.0764	5248988.274	NA	4.9	2:51:42 AM	3:29:42 PM	3.9	3:12:42 AM	2.0	NC	3:10:42 AM	2.3	4.6	7.0	13.5	9.3	18.1	Y	1
131	G62	Lauderdale West		Map Sheet Hydrograph	538626.0086	5248551.71	NA	3.0	3:02:42 AM	12:01:42 PM	3.5	3:11:42 AM	1.7	NC	3:27:42 AM	3.4	6.5	5.4	10.6	8.8	17.1	Y	1
132	G63	Opossum Bay		Map Sheet Hydrograph	532506.4484	5240388.504	NA	11.6	2:45:42 AM	2:31:42 PM	4.7	2:48:42 AM	2.2	NC	3:04:42 AM	1.4	2.8	10.7	20.8	12.1	23.6	N	1
133	G64	South Arm		Map Sheet Hydrograph	533111.0226	5236570.03	NA	11.1	2:40:42 AM	2:21:42 PM	4.5	2:44:42 AM	2.3	NC	5:10:42 AM	1.5	2.9	10.4	20.2	11.9	23.1	N	1
134	G65	Lewisham		Map Sheet Hydrograph	550100.217	5256764.526	NA	9.1	3:01:42 AM	3:11:42 PM	2.2	6:21:42 AM	1.3	NC	3:05:00 AM	1.6	3.2	9.5	18.4	11.1	21.6	N	1
135	G66	Dodges Ferry		Map Sheet Hydrograph	550169.6702	5253202.565	NA	9.9	2:51:42 AM	2:49:42 PM	2.9	2:53:42 AM	1.5	NC	6:29:42 AM	1.3	2.6	9.9	19.2	11.2	21.7	N	1
136	G67	Oakwood		Map Sheet Hydrograph	570108.0486	5224711.117	NA	11.3	2:14:42 AM	2:13:42 PM	7.1	4:26:42 AM	3.4	NC	2:26:42 AM	5.3	10.4	10.5	20.4	15.8	30.8	N	1
137	G68	South Arm Neck		Map Sheet Hydrograph	537186.5317	5234570.208	NA	16.3	2:33:42 AM	2:40:42 PM	9.9	2:58:42 AM	4.5	NC	2:34:42 AM	1.5	3.0	12.7	24.6	14.2	27.6	N	1
138	G69	Calvert Beach		Map Sheet Hydrograph	540908.4329	5235817.06	NA	18.9	2:32:42 AM	3:37:42 PM	6.1	2:35:42 AM	4.0	NC	2:33:42 AM	1.5	2.8	13.6	26.4	15.1	29.3	N	1
75	G6a				527296	5250223	gauge_G6a	4.4	2:58:42 AM	2:59:42 PM	4.8	3:05:42 AM	2.5	700.0	5:42:42 AM	0.7	1.4	6.5	12.7	7.2	14.1	Y	1
76	G7	Margate Marina		Marina	521843.9091	5233696.148	NA	0.9	2:47:42 AM	12:30:42 PM	2.7	2:50:42 AM	1.5	NC	5:31:42 AM	0.8	1.6	2.9	5.7	3.8	7.3	Y	2
139	G70	Carlton		Map Sheet Hydrograph	551779.3901	5252338.867	NA	10.9	2:50:42 AM	3:09:42 PM	3.7	10:06:42 AM	1.7	NC	2:51:42 AM	0.8	1.6	10.3	20.1	11.2	21.7	NA	1
140	G71	Primrose Sands		Map Sheet Hydrograph	554011.155	5250370.892	NA	11.3	2:49:42 AM	3:36:42 PM	2.4	2:53:42 AM	1.3	NC	3:55:42 AM	0.8	1.5	10.5	20.4	11.3	21.9	N	1
141	G72	Connellys Marsh		Map Sheet Hydrograph	558710.9581	5250346.021	NA	9.4	2:54:42 AM	1:49:42 PM	2.7	6:46:42 AM	1.3	NC	8:17:42 AM	1.0	1.9	9.6	18.7	10.6	20.6	N	1
142	G73	Dunalley		Map Sheet Hydrograph	565309.6796	5249873.077	NA	4.0	3:10:42 AM	3:17:42 PM	3.7	7:00:42 AM	2.2	NC	6:55:42 AM	2.8	5.5	6.3	12.2	9.1	17.7	Y	1
143	G74	Nubeena		Map Sheet Hydrograph	558515.9876	5226605.474	NA	17.1	2:24:42 AM	3:08:42 PM	5.9	9:37:42 AM	3.1	NC	3:13:42 AM	2.2	4.3	12.9	25.2	15.1	29.4	NA	1
144	G75	Eaglehawk Neck		Map Sheet Hydrograph	576082.4762	5236820.494	NA	9.9	2:08:42 AM	2:45:42 PM	22.5	2:10:42 AM	12.7	NC	2:19:42 AM	8.5	16.5	9.9	19.2	18.4	35.7	Y	2
144	G75a				576703	5236781	gauge_G75a	17.3	2:07:42 AM	2:45:42 PM	20.3	2:08:42 AM	7.5	NC	2:16:42 AM	9.8	19.0	13.0	25.3	22.8	44.3	Y	1
145	G76	Port Arthur		Map Sheet Hydrograph	570544.4714	5222920.581	NA	26.2	2:12:42 AM	1:44:42 PM	6.7	2:13:42 AM	2.9	NC	2:24:42 AM	4.2	8.2	16.0	31.1	20.3	39.4	N	1
146	G77	Carnarvon Bay		Map Sheet Hydrograph	569836.7095	5221624.12	NA	13.4	2:13:42 AM	2:23:42 PM	10.5	2:19:42 AM	4.2	NC	2:25:42 AM	2.7	5.2	11.5	22.3	14.2	27.5	Y	1
147	G78	Bruny Island Neck Central		Map Sheet Hydrograph	528388.3245	5207647.477	NA	18.3	2:23:42 AM	2:15:42 PM	11.1	2:26:42 AM	4.9	NC	2:36:42 AM	2.3	4.5	13.4	26.0	15.7	30.6	N	1
148	G79	Adventure Bay		Map Sheet Hydrograph	527991.4487	5198928.116	NA	14.0	2:23:42 AM	3:35:42 PM	12.2	2:50:42 AM	5.6	NC	2:48:42 AM	3.8	7.3	11.7	22.7	15.5	30.1	Y	1
76	G7a				522205	5233570	gauge_G7a	15.7	2:47:42 AM	8:56:42 AM	2.2	2:50:42 AM	1.3	NC	5:31:42 AM	0.5	1.0	12.4	24.1	12.9	25.1	N	1
77	G8	Oyster Cove Marina		Marina	520310.9102	5225036.946	NA	2.4	2:52:42 AM	3:17:42 PM	2.4	6:28:42 AM	1.4	NC	3:43:42 AM	0.2	0.4	4.8	9.4	5.1	9.8	Y	2
149	G80	Shelly Beach		Map Sheet Hydrograph	573452.248	5287469.254	NA	6.4	2:27:42 AM	3:25:42 PM	5.6	2:33:42 AM	2.4	NC	2:47:42 AM	6.5	12.6	7.9	15.4	14.4	28.0	Y	1
150	G81	Orford		Map Sheet Hydrograph	572684.9548	5288031.494	NA	4.2	2:28:42 AM	3:26:42 PM	7.1	2:32:42 AM	3.1	NC	2:47:42 AM	5.3	10.3	6.4	12.5	11.7	22.8	Y	1
151	G82	Pittwater Bluff/Sorell Causeway		Map Sheet Hydrograph	542965.3079	5260374.808	NA	3.0	3:24:00 AM	1:38:42 AM	1.6	8:56:42 AM	0.3	NC	6:53:42 AM	1.6	3.0	5.5	10.6	7.0	13.7	Y?	1
152	G83	Midway Point/Sorell Causeway		Map Sheet Hydrograph	544460.2067	5261254.549	NA	2.0	3:22:42 AM	2:19:42 PM	2.0	6:37:42 AM	0.8	NC	6:54:42 AM	1.1	2.2	4.4	8.6	5.6	10.8	Y	1
153	G84			Miscellaneous	544367.6023	5262160.749	NA	1.6	3:24:00 AM	1:38:42 AM	1.6	6:40:42 AM	0.0	NC	6:40:42 AM	0.0	0.1	4.0	7.7	4.0	7.8	Y	1
154	G85	Sorell		Map Sheet Hydrograph	546348.0125	5261431.82	NA	1.7	3:18:42 AM	2:14:42 PM	1.9	6:35:42 AM	0.7	NC	6:30:42 AM	1.0	2.0	4.1	8.0	5.1	10.0	Y	1
155	G86	Southport Wharf		Map Sheet Hydrograph	498326.4467	5189649.522	NA	13.7	2:30:42 AM	2:32:42 PM	7.7	3:43:42 AM	3.3	NC	2:45:42 AM	6.0	11.6	11.6	22.5	17.6	34.1	N	1
156	G87	Cockle Creek/Catamaran		Map Sheet Hydrograph	491572.9437	5175110.638	NA	10.1	2:27:42 AM	2:55:42 PM	6.5	3:01:42 AM	3.6	NC	3:59:42 AM	2.1	4.1	9.9	19.3	12.0	23.4	N	1
157	G88	Hobart International Airport		Map Sheet Hydrograph	543820.6704	5255519.543	NA	8.2	2:56:42 AM	1:53:42 PM	3.0	6:17:42 AM	1.7	NC	8:17:42 AM	1.1	2.1	8.9	17.4	10.0	19.5	N	1
158	G89	Marion Beach Long Spit		Map Sheet Hydrograph	572192.9695	5257591.35	NA	12.1	2:16:42 AM	2:30:42 PM	13.4	2:19:42 AM	6.4	NC	2:33:42 AM	3.8	7.5	10.9	21.2	14.7	28.6	Y	1
77	G8a				520640	5225320	gauge_G8a	4.1	2:53:42 AM	2:24:42 PM	2.2	6:28:42 AM	1.2	NC	6:32:42 AM	0.8	1.6	6.4	12.4	7.2	13.9	N	1
78	G9	Kettering Jetty		Jetty or wharf	520949.0865	5225041.709	NA	6.6	2:52:42 AM	2:11:42 PM	1.7	6:28:42 AM	0.8	NC	6:31:42 AM	0.8	1.5	8.0	15.6	8.8	17.1	N	2
78	G9a				521398	5225162	gauge_G9a	14.2	2:52:42 AM	12:46:42 PM	1.6	6:28:42 AM	0.6	NC	6:31:42 AM	0.6	1.2	11.8	22.9	12.4	24.1	N	1
188	GA09_1		82	GA2009 Gauge	526875.1961	5257093.762	NA	19.6	3:05:42 AM	3:24:42 PM	5.1	3:11:42 AM	2.7	NC	3:25:42 AM	2.0	3.8	13.9	26.9	15.8	30.8	N	1
197	GA09_10		91	GA2009 Gauge	539708.6967	5218098.911	NA	46.7	2:20:42 AM	1:02:42 PM	5.1	2:22:42 AM	2.8	NC	2:22:42 AM	1.3	2.5	NA	NA	NA	NA	N	1
198	GA09_11		96	GA2009 Gauge	526611.8759	5177116.186	NA	61.7	2:12:42 AM	1:18:42 PM	7.4	2:14:42 AM	3.8	NC	2:14:42 AM	1.3	2.5	NA	NA	NA	NA	N	1

ID	SiteID	SiteName	Description	Type	Easting	Northing	DistAlongChannel (km)	Depth (m, hat)	Arrival time	End time	Max h (m)	MWH time	Max stage (ab HAT)	Wavelength first wave (m)	Time max current	Max current (m/s)	Max current (knots)	Wave speed (m/s)	Wave speed (knots)	Upper velocity (m/s)	Upper velocity (knots)	Turbulence	Reliability
199	GA09_12		97	GA2009 Gauge	582516.1998	5210452.273	NA	104.6	1:58:42 AM	1:35:42 PM	8.9	2:00:42 AM	6.3	NC	2:00:42 AM	1.3	2.4	NA	NA	NA	NA	N	1
200	GA09_13		98	GA2009 Gauge	578681.0747	5235970.606	NA	49.3	2:05:42 AM	1:55:42 PM	12.9	2:06:42 AM	5.8	NC	2:14:42 AM	2.9	5.7	NA	NA	NA	NA	N	1
201	GA09_14		99	GA2009 Gauge	565405.6416	5210599.778	NA	62.4	2:05:42 AM	1:41:42 PM	7.5	2:07:42 AM	3.9	NC	2:19:42 AM	1.6	3.1	NA	NA	NA	NA	N	1
202	GA09_15		100	GA2009 Gauge	543906.8152	5254961.85	NA	9.0	2:55:42 AM	1:52:42 PM	2.6	6:20:42 AM	1.7	NC	8:17:42 AM	1.1	2.1	9.4	18.2	10.5	20.3	N	1
203	GA09_16		101	GA2009 Gauge	553642.1328	5250315.449	NA	13.0	2:49:42 AM	3:35:42 PM	2.3	2:53:42 AM	1.3	NC	6:37:42 AM	0.9	1.8	11.3	21.9	12.2	23.7	N	1
204	GA09_17	Clifton Beach	102	GA2009 Gauge	543321.0757	5239857.303	NA	8.8	2:36:42 AM	3:33:42 PM	8.5	2:38:42 AM	4.7	NC	6:11:42 AM	2.0	3.8	9.3	18.1	11.3	21.9	Y	1
205	GA09_18		103	GA2009 Gauge	543920.3754	5243955.799	NA	6.4	2:42:42 AM	3:23:42 PM	4.0	4:15:42 AM	2.4	NC	2:42:42 AM	1.7	3.4	7.9	15.4	9.6	18.8	N	1
206	GA09_19		104	GA2009 Gauge	541193.0128	5249282.177	NA	5.3	2:51:42 AM	3:29:42 PM	3.7	3:12:42 AM	2.0	NC	3:09:42 AM	2.2	4.3	7.2	14.0	9.4	18.3	N	1
189	GA09_2		83	GA2009 Gauge	528504.4876	5252477.667	NA	25.2	2:59:42 AM	1:20:42 PM	3.6	3:04:42 AM	2.0	NC	3:17:42 AM	1.8	3.5	15.7	30.5	17.5	34.0	N	1
207	GA09_20		105	GA2009 Gauge	551134.0305	5252735.864	NA	12.3	2:50:42 AM	3:09:42 PM	2.9	2:53:42 AM	1.6	NC	8:32:42 AM	0.9	1.7	11.0	21.4	11.9	23.0	N	1
208	GA09_21		106	GA2009 Gauge	557450.2327	5226725.285	NA	20.1	2:23:42 AM	2:37:42 PM	4.4	6:08:42 AM	2.2	NC	3:03:42 AM	3.0	5.9	14.0	27.3	17.1	33.2	N	1
209	GA09_22		107	GA2009 Gauge	567971.7265	5236543.466	NA	15.3	3:24:42 AM	9:01:42 AM	1.8	7:08:42 AM	0.6	NC	7:26:42 AM	0.4	0.8	12.3	23.8	12.7	24.6	N	1
210	GA09_23		108	GA2009 Gauge	564507.6681	5248678.042	NA	7.7	3:46:42 AM	3:15:42 PM	2.1	7:02:42 AM	1.1	NC	6:54:42 AM	1.9	3.6	8.7	16.9	10.6	20.5	N	1
211	GA09_24		109	GA2009 Gauge	573389.8274	5257105.154	NA	18.4	2:15:42 AM	2:30:42 PM	9.4	2:17:42 AM	5.0	NC	2:41:42 AM	3.7	7.2	13.4	26.1	17.1	33.3	N	1
212	GA09_25		110	GA2009 Gauge	527862.8416	5199448.959	NA	19.2	2:23:42 AM	3:34:42 PM	10.6	2:52:42 AM	4.8	NC	2:48:42 AM	3.4	6.6	13.7	26.7	17.1	33.2	N	1
213	GA09_26		111	GA2009 Gauge	528072.8631	5207709.804	NA	13.0	2:23:42 AM	2:15:42 PM	12.8	2:26:42 AM	6.0	NC	2:36:42 AM	2.7	5.3	11.3	21.9	14.0	27.3	Y	1
214	GA09_27		112	GA2009 Gauge	536281.2754	5237704.994	NA	3.2	3:07:42 AM	7:03:42 AM	1.8	3:29:42 AM	0.8	NC	3:24:42 AM	1.3	2.5	5.6	10.9	6.9	13.4	N	1
215	GA09_28		113	GA2009 Gauge	536871.2947	5248030.331	NA	6.3	2:59:42 AM	11:11:42 AM	2.6	3:05:42 AM	1.4	NC	3:17:42 AM	1.9	3.7	7.8	15.2	9.7	18.9	N	1
216	GA09_29		114	GA2009 Gauge	570429.6509	5222543.968	NA	16.6	2:11:42 AM	1:43:42 PM	8.1	2:18:42 AM	2.8	NC	2:29:42 AM	8.6	16.6	12.7	24.8	21.3	41.4	N	1
190	GA09_3		84	GA2009 Gauge	531595.5245	5248900.591	NA	25.6	2:54:42 AM	10:25:42 AM	2.4	2:57:42 AM	1.5	NC	2:57:42 AM	1.1	2.1	15.8	30.8	16.9	32.9	N	1
191	GA09_4		85	GA2009 Gauge	531662.3021	5243902.583	NA	26.3	2:48:42 AM	12:08:42 PM	2.8	2:53:42 AM	1.6	NC	3:06:42 AM	1.3	2.6	16.1	31.2	17.4	33.8	N	1
192	GA09_5		86	GA2009 Gauge	529700.5304	5239787.546	NA	24.2	2:43:42 AM	1:03:42 PM	3.8	2:47:42 AM	1.8	NC	2:47:42 AM	1.3	2.6	15.4	29.9	16.7	32.5	N	1
193	GA09_6		87	GA2009 Gauge	530018.7453	5234913.089	NA	21.5	2:38:42 AM	2:24:42 PM	3.6	2:40:42 AM	1.8	NC	2:54:42 AM	1.6	3.1	14.5	28.2	16.1	31.3	N	1
194	GA09_7		88	GA2009 Gauge	532136.7232	5230645.958	NA	18.8	2:33:42 AM	2:31:42 PM	5.3	3:26:42 AM	3.1	NC	2:36:42 AM	1.8	3.5	13.6	26.4	15.4	29.9	N	1
195	GA09_8		89	GA2009 Gauge	535471.6778	5226925.359	NA	30.6	2:28:42 AM	2:11:42 PM	5.4	2:29:42 AM	2.5	NC	2:40:42 AM	1.6	3.1	NA	NA	NA	NA	N	1
196	GA09_9		90	GA2009 Gauge	538130.0366	5222843.153	NA	39.3	2:24:42 AM	2:13:42 PM	4.8	2:25:42 AM	2.6	NC	2:35:42 AM	1.5	2.9	NA	NA	NA	NA	N	1
35	HP1	Off Secheron Point	500m to the East	PRINCIPAL HOBART PORT AREA	528255.2066	5251249.492	NA	23.3	2:58:42 AM	1:43:42 PM	3.9	3:04:42 AM	2.2	800.0	3:13:42 AM	0.7	1.4	15.1	29.4	15.8	30.7	N	1
44	HP10	Centre of Constitution Dock		PRINCIPAL HOBART PORT AREA	527203.7012	5252165.993	NA	1.1	3:01:42 AM	3:38:42 PM	4.0	3:05:42 AM	2.2	950.0	3:01:42 AM	0.4	0.8	3.2	6.3	3.7	7.1	Y	2
45	HP11	Centre of Victoria Dock		PRINCIPAL HOBART PORT AREA	527308.7395	5252252.638	NA	1.9	3:01:42 AM	1:25:42 PM	3.9	3:05:42 AM	2.2	900.0	3:01:42 AM	0.7	1.3	4.3	8.3	4.9	9.6	Y	2
46	HP12	Macquarie Wharf 1	mid length	PRINCIPAL HOBART PORT AREA	527445.202	5252191.018	NA	2.8	2:58:42 AM	3:28:42 PM	3.1	3:05:42 AM	2.3	300.0	3:08:42 AM	0.4	0.8	5.2	10.2	5.6	11.0	Y	3
46	HP12a				527414	5252075	gauge_HP12a	10.0	2:59:42 AM	2:10:42 PM	4.4	3:05:42 AM	2.3	400.0	5:42:42 AM	0.4	0.8	9.9	19.3	10.3	20.0	N	1
47	HP13	Macquarie Wharf 2	mid length	PRINCIPAL HOBART PORT AREA	527671.1092	5252155.799	NA	5.1	1:38:42 AM	3:38:42 PM	3.8	3:04:42 AM	2.4	480.0	3:27:42 AM	0.6	1.1	7.1	13.7	7.7	14.9	Y	2
47	HP13a				527669	5252058	gauge_HP13a	16.7	2:59:42 AM	2:10:42 PM	4.2	3:04:42 AM	2.2	500.0	5:42:42 AM	0.6	1.1	12.8	24.8	13.4	26.0	N	1
48	HP14	Macquarie Wharf 3	mid length	PRINCIPAL HOBART PORT AREA	527799.589	5252181.266	NA	4.3	1:38:42 AM	3:38:42 PM	3.5	3:04:42 AM	2.2	600.0	3:27:42 AM	0.7	1.4	6.5	12.7	7.3	14.1	Y	2
48	HP14a				527804	5252090	gauge_HP14a	18.7	2:59:42 AM	2:10:42 PM	4.1	3:04:42 AM	2.2	NC	3:27:42 AM	0.9	1.7	13.5	26.3	14.4	28.0	N	1
49	HP15	200 m to the East of end of Macquarie Wharf 3 & 4		PRINCIPAL HOBART PORT AREA	528157.6504	5252211.458	NA	24.6	2:59:42 AM	1:43:42 PM	3.8	3:04:42 AM	2.1	660.0	3:17:42 AM	1.5	2.9	15.5	30.2	17.0	33.1	N	1
50	HP16	Macquarie Wharf 4	mid length	PRINCIPAL HOBART PORT AREA	527872.2664	5252381.635	NA	7.3	2:57:42 AM	3:29:42 PM	3.2	3:04:42 AM	2.1	730.0	3:13:42 AM	0.8	1.6	8.5	16.5	9.3	18.0	N	3
50	HP16a				527961	5252384	gauge_HP16a	25.8	2:59:42 AM	2:10:42 PM	3.7	3:04:42 AM	2.1	NC	3:13:42 AM	1.3	2.6	15.9	30.9	17.2	33.5	N	1
51	HP17	Macquarie Wharf 5	mid length	PRINCIPAL HOBART PORT AREA	527855.4642	5252507.854	NA	8.0	2:59:42 AM	3:15:42 PM	3.1	3:04:42 AM	2.1	660.0	3:13:42 AM	0.7	1.4	8.9	17.3	9.6	18.6	N	2
51	HP17a				527949	5252512	gauge_HP17a	24.1	2:59:42 AM	2:10:42 PM	3.6	3:04:42 AM	2.1	NC	3:14:42 AM	1.3	2.6	15.4	29.9	16.7	32.4	N	1
52	HP18	Macquarie Wharf 6	mid length	PRINCIPAL HOBART PORT AREA	527864.1599	5252698.821	NA	8.5	2:59:42 AM	3:14:42 PM	3.3	3:04:42 AM	2.0	1200.0	3:05:42 AM	1.0	2.0	9.1	17.7	10.1	19.7	N	2
52	HP18a				527939	5252693	gauge_HP18a	23.7	2:59:42 AM	2:10:42 PM	3.5	3:04:42 AM	2.0	NC	3:17:42 AM	1.4	2.8	15.2	29.6	16.7	32.4	N	1
53	HP19	200m to the East of Macquarie Point		PRINCIPAL HOBART PORT AREA	528100.3985	5252829.896	NA	25.8	2:59:42 AM	2:10:42 PM	3.3	3:04:42 AM	2.0	2500.0	3:17:42 AM	1.9	3.8	15.9	30.9	17.8	34.7	N	1
36	HP2	200m to the East of Battery Point		PRINCIPAL HOBART PORT AREA	528011.7986	5251711.005	NA	23.5	2:58:42 AM	1:43:42 PM	4.0	3:04:42 AM	2.2	600.0	3:14:42 AM	0.9	1.8	15.2	29.5	16.1	31.3	N	1
37	HP3	250 m to the North of Battery Point		PRINCIPAL HOBART PORT AREA	527707.8742	5251957.097	NA	18.7	2:59:42 AM	2:10:42 PM	4.1	3:04:42 AM	2.2	500.0	5:42:42 AM	0.6	1.1	13.5	26.3	14.1	27.4	N	1
38	HP4	CSIRO Wharf	mid length	PRINCIPAL HOBART PORT AREA	527653.6447	5251752.654	NA	7.0	2:58:42 AM	3:26:42 PM	3.6	3:04:42 AM	2.3	600.0	3:50:42 AM	0.6	1.2	8.3	16.0	8.9	17.3	N	2
38	HP4a				527694	5251883	gauge_HP4a	19.9	2:59:42 AM	2:10:42 PM	4.1	3:04:42 AM	2.2	NC	3:50:42 AM	0.6	1.2	14.0	27.2	14.6	28.4	N	1
39	HP5	Princes Wharf 2 & 3	mid length	PRINCIPAL HOBART PORT AREA	527443.1669	5251803.913	NA	5.4	1:38:42 AM	3:30:42 PM	3.1	3:05:42 AM	2.3	300.0	3:50:42 AM	0.5	1.0	7.3	14.2	7.8	15.1	N	2
40	HP6	Princes Wharf 1	mid length	PRINCIPAL HOBART PORT AREA	527236.064	5251821.505	NA	4.6	2:58:42 AM	3:29:42 PM	3.4	3:05:42 AM	2.4	300.0	3:50:42 AM	0.3	0.6	6.7	13.0	7.0	13.6	Y	2
40	HP6a				527477	5251935	gauge_HP6a	15.2	2:59:42 AM	2:10:42 PM	4.3	3:05:42 AM	2.3	300.0	3:50:42 AM	0.6	1.1	12.2	23.7	12.8	24.8	N	1
41	HP7	Between Brooke Street Pier and Ferry Pier		PRINCIPAL HOBART PORT AREA	527177.4075	5251939.337	NA	6.1	2:59:42 AM	2:44:42 PM	4.4	3:05:42 AM	2.4	200.0	3:07:42 AM	0.3	0.5	7.7	15.0	8.0	15.6	N	2
42	HP8	Elizabeth Street Pier	South side, mid length	PRINCIPAL HOBART PORT AREA	527240.608	5251979.064	NA	6.1	2:58:42 AM	3:26:42 PM	4.0	3:05:42 AM	2.4	150.0	3:07:42 AM	0.2	0.4	7.7	15.0	7.9	15.4	N	2
43	HP9	King Pier Marina entrance		PRINCIPAL HOBART PORT AREA	527369.512	5252009.757	NA	11.6	2:59:42 AM	2:10:42 PM	4.4	3:05:42 AM	2.3	200.0	3:50:42 AM	0.3	0.6	10.7	20.7	11.0	21.3	N	1
62	POW1	100m East of North end of INCAT slip		PRINCE OF WALES BAY WHARF AND D(	525504.1185	5258389.036	NA	8.0	3:09:42 AM	1:57:42 PM	3.8	3:14:42 AM	1.5	2232.0	3:29:42 AM	1.8	3.5	8.9	17.2	10.7	20.7	N	1
63	POW2	INCAT slip		PRINCE OF WALES BAY WHARF AND D(	525300.6986	5258396.338	NA	0.6	3:09:42 AM	1:58:42 PM	2.7	3:15:42 AM	1.5	2200.0	3:31:42 AM	0.9	1.7	2.5	4.8	3.4	6.5	Y	2
63	POW2a				525330	5258464	gauge_POW2a	4.4	3:09:42 AM	1:58:42 PM	3.7	3:14:42 AM	1.5	NC	3:28:42 AM	2.0	4.0	6.5	12.7	8.6	16.7	Y	1
64	POW3	100m East of INCAT jetty	North end	PRINCE OF WALES BAY WHARF AND D(	525182.744	5258506.484	NA	4.5	3:09:42 AM	1:58:42 PM	3.7	3:15:42 AM	1.5	2079.6	3:25:42 AM	2.1	4.0	6.6	12.8	8.7	16.9	Y	1
65	POW4	INCAT Jetty	mid length	PRINCE OF WALES BAY WHARF AND D(	525046.6395	5258459.341	NA	1.6	3:10:42 AM	1:59:42 PM	2.8	6:24:42 AM	1.5	1250.0	3:24:42 AM	1.4	2.7	4.0	7.7	5.4	10.4	Y	1
66	POW5	Prince of Wales Bay Marina wharf	mid length	PRINCE OF WALES BAY WHARF AND D(	524757.2958	5258235.407	NA	2.2	3:11:42 AM	3:01:42 PM	3.2	3:18:42 AM	2.0	NC	3:38:42 AM	3.7	7.2	4.7	9.1	8.4	16.3	Y	2
67	POW6	Prince of Wales Marine P/L dock facilities		PRINCE OF WALES BAY WHARF AND D(	524605.8401	5258304.576	NA	1.2	3:10:42 AM	3:29:42 PM	2.8	3:18:42 AM	2.0	NC	3:27:42 AM	2.6	5.0	3.4	6.6	6.0	11.6	Y	3
67	POW6a				524695	5258322	gauge_POW6a	5.7	3:11:42 AM	2:02:42 PM	4.3	3:18:42 AM	1.9	2346.0	3:26:42 AM	3.2	6.2	7.5	14.5	10.6	20.7	Y	1
68	POW7	Derwent Marine dock facilities		PRINCE OF WALES BAY WHARF AND D(	524478.6966	5258545.778	NA	0.8	3:11:42 AM	3:29:42 PM	3.1	3:19:42 AM	1.9	NC	6:16:42 AM	1.6	3.1	2.9	5.5	4.4	8.6	Y	2
68	POW7a				524572	5258507	gauge_POW7a	2.1	3:11:42 AM	2:02:42 PM	3.6	3:18:42 AM	1.9	1270.0	4:04:42 AM	0.9	1.8	4.5	8.7	5.4	10.6	Y	1
69	POW8	Pauline Point marina facilities		PRINCE OF WALES BAY WHARF AND D(	524651.213	5257987.265	NA	2.9	3:12:42 AM	2:03:42 PM	3.9	3:18:42 AM	2.2	NC	3:37:42 AM	2.6	5.0	5.3	10.3	7.9	15.3	Y	2
69	POW8a				524716	5257998	gauge_POW8a	4.6	3:12:42 AM	2:03:42 PM	4.2	3:18:42 AM	2.2	1500.0	3:37:42 AM	2.9	5.6	6.7	13.0	9.6	18.6	Y	1
1	PSC1	Off Iron Pot	mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	532170.5297	5231640.637	0.00	17.4	2:34:42 AM	1:44:42 PM	4.7	3:26:42 AM	2.6	NC	2:35:42 AM	1.7	3.3	13.0	25.4	14.7	28.7	N	1
10	PSC10	Off Ross Bay	on 353s leads (Tasman Bridge Channel)	PRINCIPAL SHIPPING CHANNEL; IRON	528214.3672	5253475.617	22.77	16.4	3:00:42 AM	1:59:42 PM	3.1	3:04:42 AM	1.8	3060.0	3:17:42 AM	2.5	4.8	12.7	24.7	15.1	29.4	N	1
10	PSC10a				528335	5253489	gauge_PSC10a	39.0	3:00:42 AM	1:59:42 PM	3.0	3:04:42 AM	1.7	3240.0	3:17:42 AM	2.5	4.8	19.8	39.3	22.3	44.1	N	1
11	PSC11	Off Montagu Bay	on 353n leads (Tasman Bridge Channel)	PRINCIPAL SHIPPING CHANNEL; IRON	528207.8641	5253821.89	23.12	23.2	3:00:42 AM	2:00:42 PM	3.2	3:06:42 AM	1.7	2882.1	3:17:42 AM	2.3	4.5	15.1	29.3	17.4	33.8	N	1
11	PSC11a				528287	5253804	gauge_PSC11a	32.9	3:00:42 AM	2:00:42 PM	3.1	3:06:42 AM	1.7	2748.5	3:17:42 AM	2.2	4.3	18.4	36.5	20.6	40.8	N	1
12	PSC12	Under Tasman Bridge	on 353T leads (Tasman Bridge Channel)	PRINCIPAL SHIPPING CHANNEL; IRON	528203.8409	5254115.739	23.41	26.9	3:01:42 AM	2:00:42 PM	3.4	3:07:42 AM	1.7	2670.4	3:17:42 AM	2.2	4.3	16.2	31.6	18.5	35.9	N	1
12	PSC12a				528252	5254107	gauge_PSC12a	28.5	3:01:42 AM	2:00:42 PM	3.3	3:06:42 AM	1.7	3103.0	3:17:42 AM	2.2	4.3	16.7	32.5	18.9	36.8	N	1
13	PSC13	Off Pavilion Point	on 353v leads (Tasman Bridge Channel)	PRINCIPAL SHIPPING CHANNEL; IRON	528186.5111	5254491.707	23.79	22.6	3:01:42 AM	2:00:42 PM	3.7	3:08:42 AM	1.9	2970.0	3:17:42 AM	1.9	3.6	14.9	28.9	16.7	32.5	N	1
14	PSC14	Off Rose Bay	on 353s leads (Tasman Bridge Channel)	PRINCIPAL SHIPPING CHANNEL; IRON	528186.8811	5255000.858	24.30	17.1	3:02:42 AM	2:01:42 PM	4.2	3:08:42 AM	2.1	2448.0	3:17:42 AM	1.4	2.6	13.0	25.2	14.3	27.8	N	1
15	PSC15	Off Lindisfarne Bay	on 353n leads (Tasman Bridge Channel)	PRINCIPAL SHIPPING CHANNEL; IRON	528164.8957	5255418.043	24.71	12.1	3:03:42 AM	2:50:42 PM	4.5	3:09:42 AM	2.3	1980.0	5:59:42 AM	1.5	2.9	10.9	21.2	12.4	24.1	N	1
16	PSC16	Off Beltana Point	on 135l leads	PRINCIPAL SHIPPING CHANNEL; IRON	527909.8952	5255658.833	25.06	10.7	3:03:42 AM	2:01:42 PM	4.6	3:09:42 AM	2.3	2310.0	5:59:42 AM	2.0	3.9	10.2	19.9	12.2	23.8	N	1
17	PSC17	Off Koomela Bay	on 135o leads	PRINCIPAL SHIPPING CHANNEL; IRON	527676.7043	5255882.091	25.39	13.5	3:03:42 AM	1:26:42 PM	4.7	3:09:42 AM	2.3	2112.0	5:59:42 AM	1.9	3.7	11.5	22.3	13.4	26.1	N	1
18	PSC18	Off Limekiln Point	on 135m leads	PRINCIPAL SHIPPING CHANNEL; IRON	527464.4365	5256069.389	25.67	18.0	3:04:42 AM	1:27:42 PM	4.8	3:10:42 AM	2.4	3468.0	6:00:42 AM	2.4	4.7	13.3	25.9	15.7	30.6	N	1
19	PSC19	Off Selfs Point Wharf South end	slightly East of mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	527312.9187	5256330.731	25.97	19.0	3:04:42 AM	3:23:42 PM	4.9	3:10:42 AM	2.5	2513.6	6:00:42 AM	2.1	4.2	13.6	26.5	15.8	30.7	N	1
2	PSC2	Off Johns Point	slightly East of mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	530892.4303	5234426.496	3.07	18.9	2:37:42 AM	1:44:42 PM	3.9	2:40:42 AM	2.0	2412.0	2:41:42 AM	1.8	3.5	13.6	26.5	15.4	30.0	N	1
20	PSC20	Off Selfs Point Wharf North end	mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	527161.5339	5256628.714	26.31	22.3	3:05:42 AM	3:24:42 PM	5.0	3:11:42 AM	2.6	2312.8	6:01:42 AM	2.0	3.8	14.8	28.7	16.7	32.5	N	1
21	PSC21	Off New Town Bay	mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	527013.7256	5256946.002	26.66	22.2	3:05:42 AM	3:24:42 PM	5.1	3:11:42 AM	2.7	2802.4	3:10:42 AM	1.8	3.5	14.8	28.7	16.5	32.2	N	1
22	PSC22	Off Shag Bay	mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	526884.3644	5257260.993	27.00	24.0	3:06:42 AM	3:24:42 PM	5.0	3:11:42 AM	2.7	2592.7	3:25:42 AM	1.8	3.5	15.3	29.8	17.2	33.3	N	1
23	PSC23	Off Stanhope Point	mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	526683.2792	5257630.007	27.42	23.3	3:06:42 AM	3:25:42 PM	4.7	3:11:42 AM	2.4	3000.0	3:26:42 AM	2.4	4.8	15.1	29.4	17.6	34.2	N	1
24	PSC24	Off Nyrstar Wharf South end	mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	526446.8528	5257953.732	27.82	18.8	3:07:42 AM	3:25:42 PM	4.5	3:11:42 AM	2.0	3400.0	3:13:42 AM	2.9	5.7	13.6	26.4	16.5	32.0	N	1
25	PSC25	Off Nyrstar Wharf North end	mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	526152.336	5258225.255	28.22	16.8	3:07:42 AM	3:25:42 PM	4.0	3:12:42 AM	1.6	4200.0	3:13:42 AM	3.2	6.3	12.8	25.0	16.1	31.3	N	1
26	PSC26	Off Store Point	mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	525813.5559	5258491.712	28.65	16.7	3:08:42 AM	1:57:42 PM	3.7	3:14:42 AM	1.4	3200.0	3:13:42 AM	3.0	5.8	12.8	24.9	15.8	30.6	N	1
27	PSC27	Off INCAT slip	on 308C leads	PRINCIPAL SHIPPING CHANNEL; IRON	525522.3362	5258717.333	29.02	16.6	3:09:42 AM	1:58:42 PM	3.8	3:14:42 AM	1.6	2448.0	3:14:42 AM	2.0	3.9	12.7	24.8	14.8	28.7	N	1
28	PSC28	Off Dowsings Point	midway between Dowsings Point and INCAT jetty	PRINCIPAL SHIPPING CHANNEL; IRON	525103.744	5258652.687	29.44	7.5	3:10:42 AM	1:58:42 PM	3.7	3:15:42 AM	1.6	2685.9	3:23:42 AM	3.5	6.9	8.6	16.7	12.1	23.5	N	1
29	PSC29	Entering Prince of Wales Bay	mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	524900.0696	5258591.796	29.65	7.6	3:10:42 AM	2:00:42 PM	3.8	3:17:42 AM	1.6	1800.0	3:24:42 AM	2.5	4.9	8.7	16.8	11.2	21.8	N	1
3	PSC3	Off Flowerpot Point	slightly East of mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	530517.0768	5238058.556	6.72	21.5	2:41:42 AM	12:59:42 PM	3.6	2:45:42 AM	2.0	1870.9	2:58:42 AM	1.4	2.7	14.5	28.2	15.9	30.9	N	1
30	PSC30	Entering Prince of Wales Bay	mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	524736.5394	5258487.113	29.85	6.5	3:11:42 AM	2:01:42 PM	4.0	3:18:42 AM	1.8	2100.0	3:24:42 AM	2.1	4.0	8.0	15.5	10.0	19.5	N	1
3	PSC3a				528214	5244485	gauge_PSC3a	22.9	3:01:42 AM	2:00:42 PM	3.7	3:08:42 AM	1.9	1922.8	3:17:42 AM	1.9	3.6	15.0	29.1	16.8	32.8	N	1
4	PSC4	Off White Rock Point	slightly East of mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	530225.2913	5241692.09	10.36	30.2	2:45:42 AM	1:03:42 PM	3.8	2:49:42 AM	1.9	1940.5	2:49:42 AM	1.2	2.2	17.7	35.1	18.9	37.4	N	1
5	PSC5	Off Trywork Point	slightly West of mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	530831.4667	5245756.148	14.47	28.4	2:50:42 AM	1:08:42 PM	2.8	2:54:42 AM	1.7	1350.0	3:08:42 AM	1.4	2.7	16.7	32.4	18.1	35.2	N	1
6	PSC6	Off Blinking Billy Point	West of Mid channel	PRINCIPAL SHIPPING CHANNEL; IRON	530557.3194	5248669.419	17.40	28.9	2:54:42 AM	8:23:42 AM	2.4	2:56:42 AM	1.4	NC	2:56:42 AM	1.2	2.3	16.8	32.7	18.0	35.0	N	1
7	PSC7	Off RYCT	South of Kangaroo Bluff	PRINCIPAL SHIPPING CHANNEL; IRON	529479.6724	5250388.499	19.43	24.8	2:56:42 AM	1:18:42 PM	3.1	3:02:42 AM	1.9	1100.0	3:59:42 AM	1.1	2.1	15.6	30.3	16.6	32.4	N	1
8	PSC8	Off Sullivans Cove	due South of Rosny Point	PRINCIPAL SHIPPING CHANNEL; IRON	528799.6671	5251988.146	21.16	22.9	2:58:42 AM	1:19:42 PM	3.6	3:03:42 AM	2.0	1080.0	3:16:42 AM	1.2	2.2	15.0	29.1	16.1	31.4	N	1
9	PSC9	Off Macquarie Point	on 353c leads (Tasman Bridge Channel)	PRINCIPAL SHIPPING CHANNEL; IRON	528377.4492	5252853.744	22.13	31.2	2:59:42 AM	2:10:42 PM	3.3	3:04:42 AM	1.9	NC	3:17:42 AM	2.1	4.0	18	35.7	20.1	39.7	N	1
58	RW1	100m South East of Nyrstar Wharf 2	South end	RISDON (NYRSTAR) WHARF	526360.4327	5257796.932	NA	11.8	3:07:42 AM	3:25:42 PM	4.5	3:11:42 AM	2.0	3400.0	3:13:42 AM	2.6	5.1	10.8	20.9	13.4	26.0	N	1
59	RW2	Nyrstar Wharf 2	mid length	RISDON (NYRSTAR) WHARF	526198.6151	5257907.152	NA	7.5	3:05:42 AM	3:38:42 PM	3.3	3:11:42 AM	1.8	3000.0	3:13:42 AM	2.7	5.2	8.6	16.7	11.3	21.9	N	2
59	RW2a				526244	5257965	gauge_RW2a	16.5	3:07:42 AM	3:25:42 PM	4.3	3:11:42 AM	1.8	NC	3:13:42 AM	3.1	6.0	12.7	24.7	15.8	30.8	N	1
60	RW3	Nyrstar Wharf 1	mid length	RISDON (NYRSTAR) WHARF	526081.4408	5258001.543	NA	5.4	3:05:42 AM	3:38:42 PM	2.7	3:11:42 AM	1.6	4000.0	3:13:42 AM	2.8	5.4	7.3	14.2	10.1	19.6	N	3
60	RW3a				526132	5258062	gauge_RW3a	17.0	3:07:42 AM	3:25:42 PM	4.1	3:11:42 AM	1.6	NC	3:13:42 AM	3.3	6.4	12.9	25.1	16.2	31.5	N	1
61	RW4	100m North West of Nyrstar Wharf facilities	North end	RISDON (NYRSTAR) WHARF	525885.6002	5258152.083	NA	8.7	3:08:42 AM	3:24:42 PM	3.8	3:12:42 AM	1.4	3000.0	3:13:42 AM	2.7	5.2	9.2	17.9	11.9	23.1	N	2
61	RW4a				525913	5258201	gauge_RW4a	17.2	3:08:42 AM	3:24:42 PM	3.8	3:12:42 AM	1.4	NC	3:13:42 AM	2.8	5.5	13.0	25.2	15.8	30.7	N	1
54	SPW1	100 m to the South of Selfs Point Wharf		SELFS POINT WHARF	527045.0706	5256167.106	NA	18.6	3:04:42 AM	3:22:42 PM	4.9	3:10:42 AM	2.4	2527.6	6:00:42 AM	2.1	4.0	13.5	26.2	15.6	30.3	N	1
55	SPW2	Selfs Point Wharf	mid length	SELFS POINT WHARF	527014.3476	5256375.551	NA	17.2	3:04:42 AM	3:23:42 PM	5.0	3:11:42 AM	2.5	2245.6	6:00:42 AM	2.4	4.7	13.0	25.2	15.4	30.0	N	1
56	SPW3	100m to the North of Selfs point Wharf		SELFS POINT WHARF	526974.7904	5256582.253	NA	16.0	3:05:42 AM	3:24:42 PM	5.1	3:11:42 AM	2.6	2332.4	3:09:42 AM	1.8	3.5	12.5	24.4	14.4	27.9	N	1
57	SPW4	Selfs Point Jetty	mid length	SELFS POINT WHARF	526890.4763	5256314.849	NA	6.9	3:04:42 AM	3:23:42 PM	4.9	3:11:42 AM	2.5	2280.7	4:01:42 AM	2.2	4.3	8.2	15.9	10.4	20.3	N	2
												bottom heavy	>2										
												top heavy	<2										
													2.0										

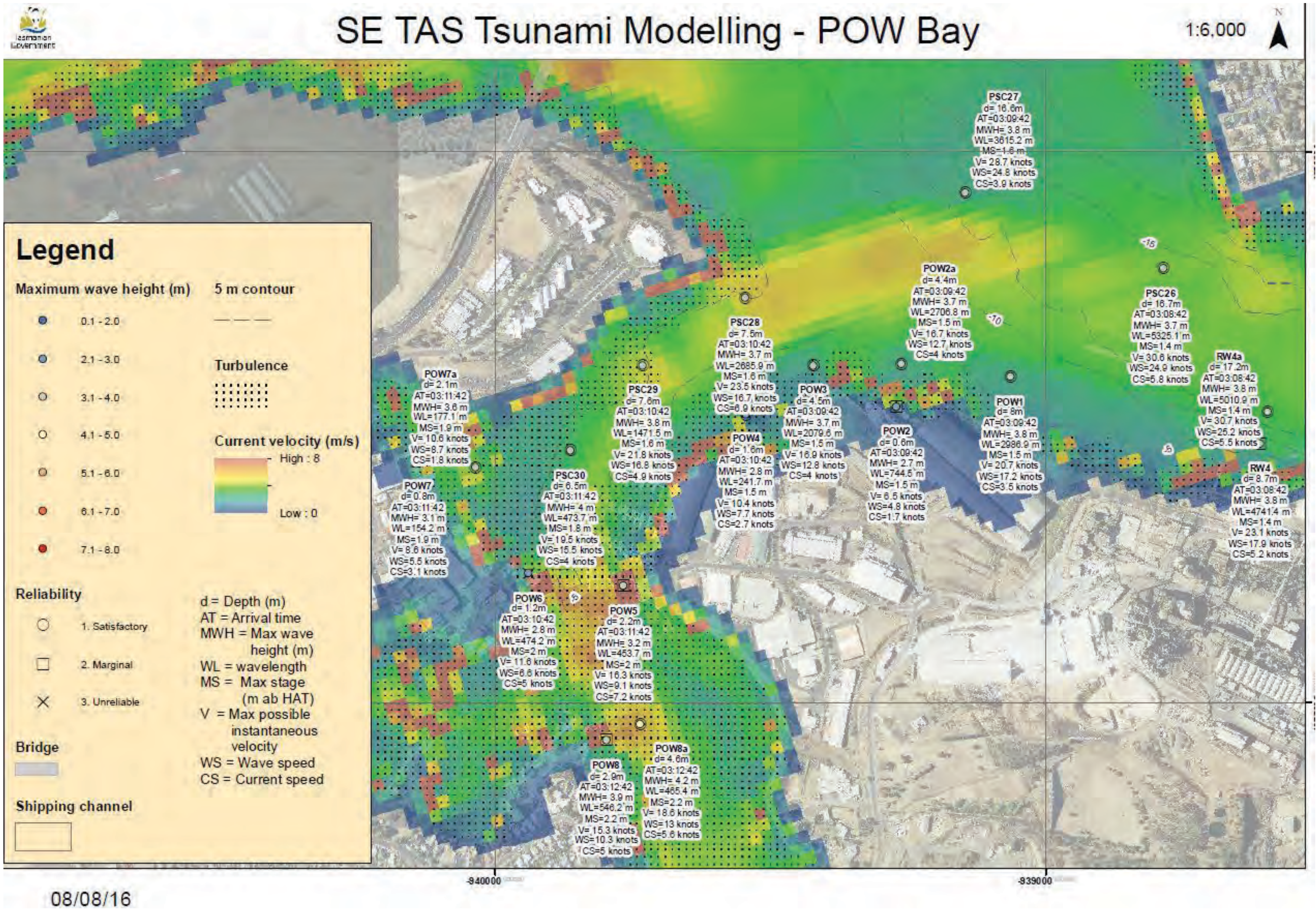
Appendix 5: Data Map Constitution Dock (HP 2-19)



Appendix 6: Data Map Risdon Wharf (RW 1-4)



Appendix 7: Data Map Prince of Wales Bay (POW 1-8)



TECHNICAL REPORT ON TSUNAMI INUNDATION MODELLING IN SOUTH EAST TASMANIA

Coastal Inundation Map Series

See accompanying volume

APPENDIX FOUR

Mineral Resources Tasmania
Department of State Growth

Tasmanian Government

TECHNICAL REPORT ON TSUNAMI INUNDATION MODELLING IN SOUTH EAST TASMANIA

Dune Erosion Impacts

Ted Rigby,
Rienco Consulting

APPENDIX FIVE

Mineral Resources Tasmania
Department of State Growth

Tasmanian Government

OBJECTIVES

This scenario was created to explore the level of protection afforded by the present (2015) Seven Mile Beach dune line, that separates Hobart Airport from the waters of Frederick Henry Bay, in the event of a major tsunami penetrating Frederick Henry Bay. Details of this tsunami are discussed elsewhere.

As a model was to be created capable of simulating erosion of these protective dunes at Seven Mile Beach, the opportunity was taken to investigate, at a lesser level of detail, the possible loss of protection at other potentially erosion prone sites in South Eastern Tasmania, as a guide to other sites that could warrant more detailed investigation in the future.

METHODOLOGY

Base Model

All scenarios in this review of Tsunami risk in South Eastern Tasmania share a common base model, developed by Rienco Consulting from an earlier model developed by Geoscience Australia (GA) in 2009. While sharing some content with the earlier GA model this new model included the latest available bathymetry and topography and added detailed spatially variable surface roughness data (Manning's n), in lieu of the single global value used in the earlier GA modelling. The domain boundary was retained, as used in the earlier GA modelling, but a more detailed distribution of mesh resolutions added in support of the various scenarios to be modelled. Details of this new base model (Scenario 2) are discussed elsewhere.

Scenario 5

As noted in the objectives, this Scenario was developed to explore erosion of the protective dune line along Seven Mile Beach during a major tsunami. As Anuga does not contain the necessary functionality to undertake this modelling, code in the form of an Anuga dune erosion operator was developed by Rienco Consulting to provide this functionality.

To enable this operator in the airport dunes, a polygon layer was created of the potential erosion zone. To provide the required level of detail near the airport, an extremely high resolution (10m triangles) area was added in the potential dune erosion zone and a very high-resolution zone (20m triangles) added as a rectangular plot window in the general vicinity of the airport and dunes to ensure plots obtained were of an appropriate resolution.

In all other areas of potential interest, polygons containing the potential erosion zones were added to the erosion polygons layer (to enable the erosion operator) but resolutions were not increased above the basic coastal zone level (50m). Therefore, erosion modelling in these areas can provide a guide to the likelihood of dune erosion in these areas but will need to be subject to more detailed modelling, if the consequences of such erosion are significant.

The locations of the full range of dune erosion zones investigated are shown in Fig 3

Runtime Performance

The Scenario 5 model was run from an SSD on a hex core I7 Ubuntu PC with 64GB of memory. Initially this model was run with the parameter store_vertices_uniquely=TRUE but this created a very large (72GB) output (sww) file that presented difficulties when trying to view results. When reset and re-run with store_vertices_uniquely=FALSE the output file dropped to 26GB in size, which eliminated earlier viewing problems. The calculations are identical in both cases, and this parameter merely affects how the output is stored.

Both model runs took about 72 hours to simulate a four hour tsunami event.

File Structure

All model input data, the model code, model results and post processed results were separately provided on a usb drive to MRT in November 2016.

The file structure on this drive is as follows;

CHECKS

(Various files created and stored during the run associated with sanity checking what has been read in by the model during execution)

DATA

(Input files read in by the model scripts while building the model)

RESULTS

(the output sww file)

SPATIAL

(Various asci grid files of surface elevation at different times and water depth)

TIMESERIES

(Various xy plots of stage or depth at particular gauge locations, versus time)

SCRIPTS

(All python scripts needed to run the model (from model_run.py) are in this directory.

The simulation scripts have been written to permit execution on multiple cores. A simulation is typically run from the scripts directory in a terminal window as 'mpirun -np xx python model_run.py', where xx is the number of available processors.

The post processing scripts are run (on a single processor without mpi) from the same terminal window as python model_results_....py.)

SUMMARY

(This summary only)

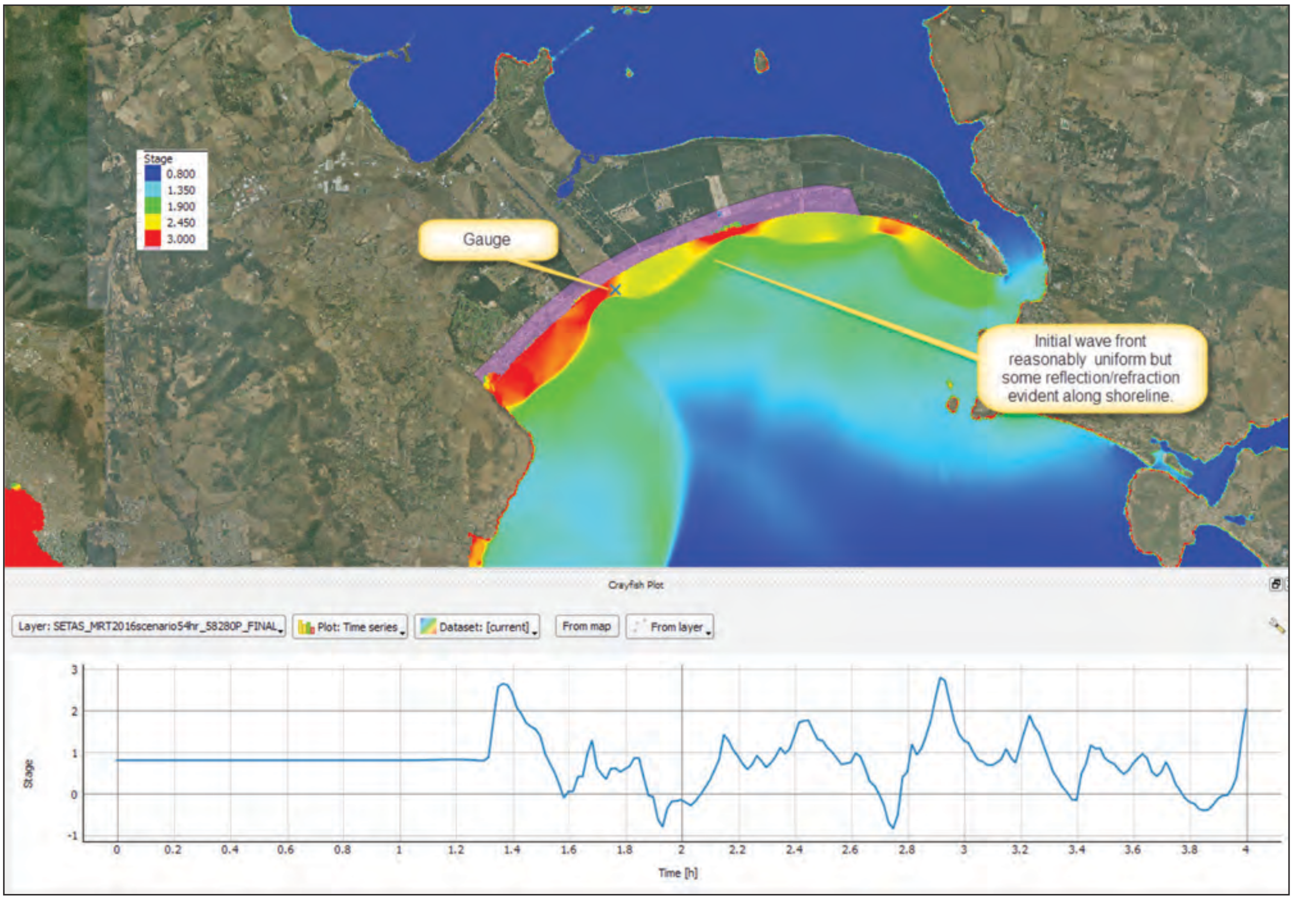
OBSERVATIONS

Airport Dune Protection

As will be apparent in the following plots, the dune line along Seven Mile Beach would provide effective protection for the runway and terminal buildings in a tsunami event up to the magnitude of that modelled. For the most part, this arises because of the considerable reduction in the tsunami wave height as it travels into and through Frederick Henry Bay.

In the following Fig 1, the stage timeseries at a gauge located off the beach in Frederick Henry Bay shows a series of approaching waves all peaking below 3mAHD. As most of the Seven Mile beach dune line is at or above that level there are no significant breaches simulated in the model. The plan graphic shows the spatial distribution of wave heights as the first wave front reaches the beach. Some reflection and refraction patterning of the front is already evident in this graphic.

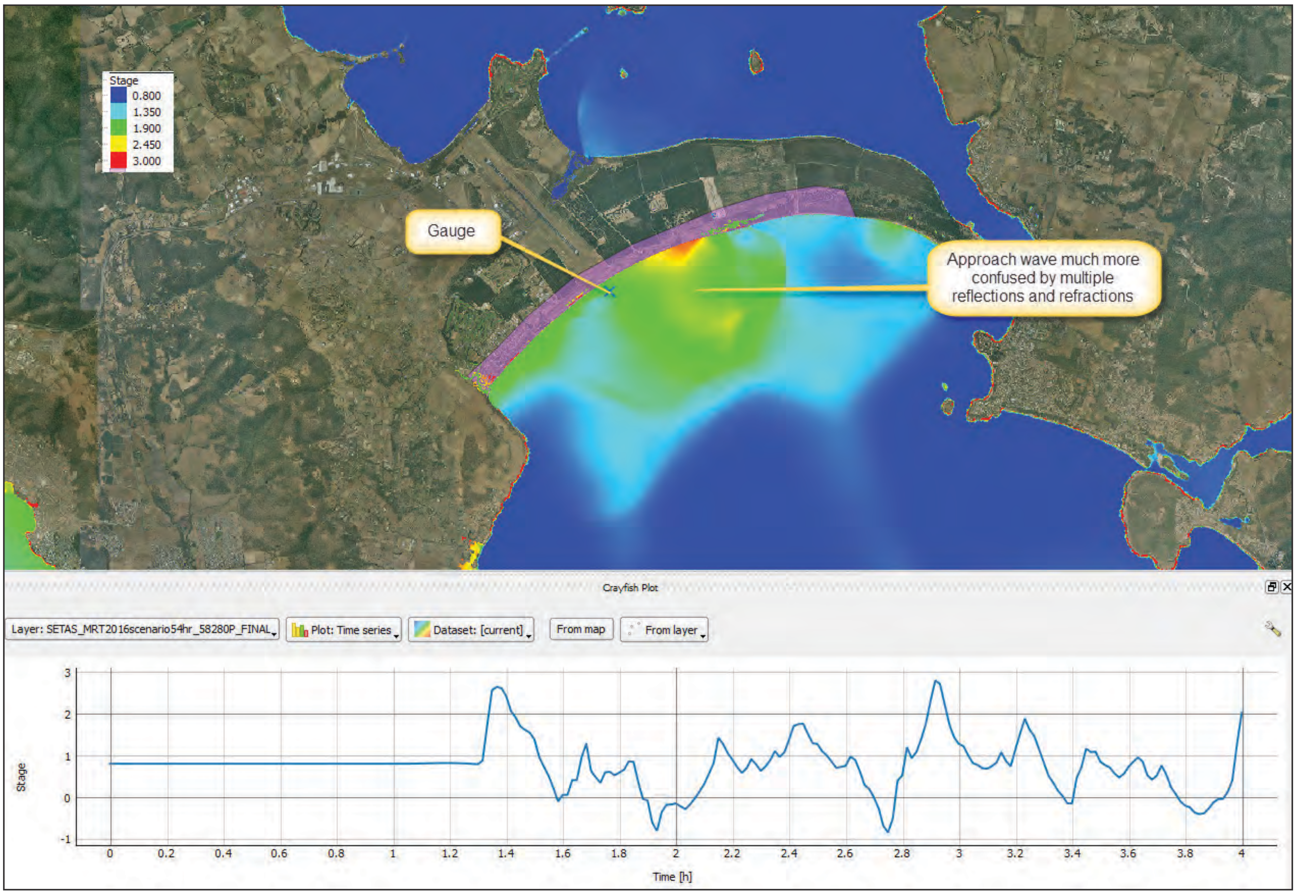
FIGURE 1: Airport Tsunami Stage Plot as First Wave Front Arrives



In Figure 2, the spatial disdtribution of wave heights is shown as the second highest wave front reaches the beach. As evident in this pattern, a considerably confused wave field now exists in the bay with little sense of an obvious front approaching the beach. There is considerable difference in the peak wave height at this instant along the beach but peak heights are again all below RL 3.00m AHD.

It is of importance to note, that significant portions of the dune line are however only marginally above the approaching wave run up height and relatively minor reduction in the dune height could create significant local breaches.

FIGURE 2: Airport Tsunami Stage Plot as Second Wave Front Arrives



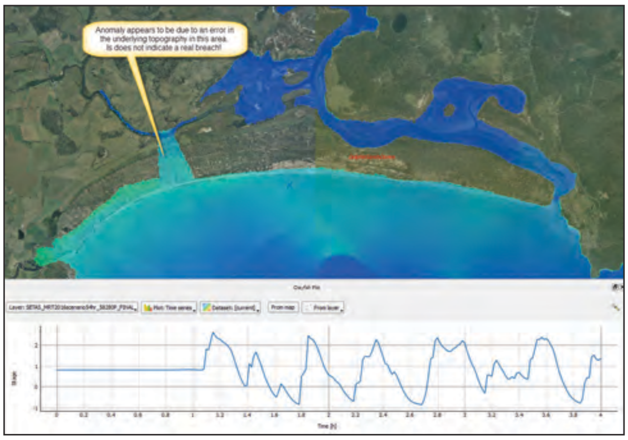
Other Dune Protection Areas

Generally

As noted in the Objectives, 12 other areas were included in this simulation to explore, in a preliminary manner, what other sites might exist on the South-East Coast that could be at increased risk from erosion of their protective dunes in a Tsunami. These additional sites were not modelled at the extremely high resolution that the Airport site was modelled at, creating modelling results that are therefore not as detailed as those available for the Airport site. They are however considered sufficient to highlight sites that may be worthy of further investigation.

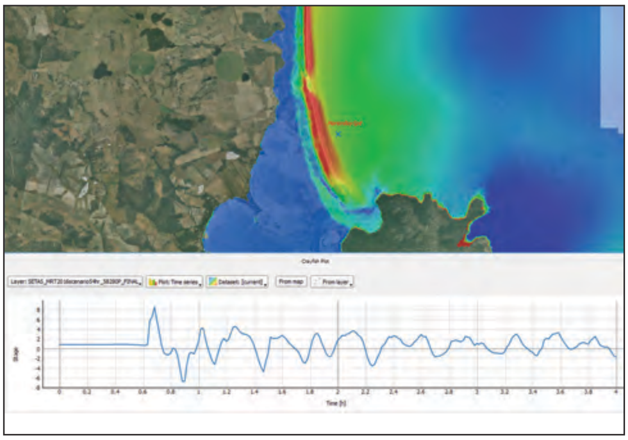
Each additional site is shown on Figure 3 and discussed further in the following.

FIGURE 3: Sites Modelled in Scenario 5



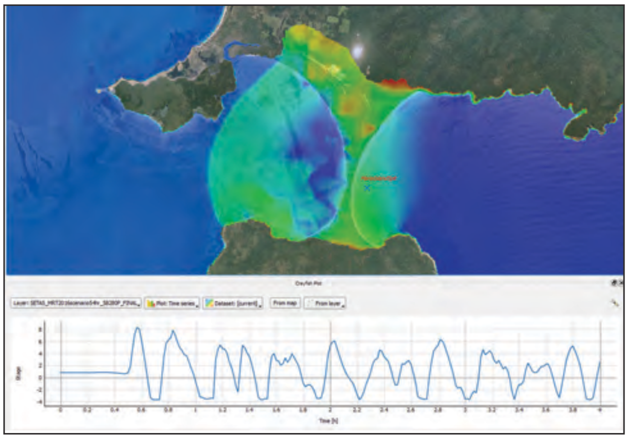
Dolphin Sands Beach Dunes

Dolphin Sands is a development located in the dunes at the northernmost extent of Great Oyster Bay and while a candidate for dune erosion is heavily protected from a tsunami by Freycinet Peninsula and Schouten Island. This is readily evident in the much-reduced tsunami wave heights off the beach at this location. While an error in the underlying topography has created an anomalous breach, a quick comparison of peak wave height and land height indicates that the developed spit would not be overtopped or scoured in such an event.



Marion Bay Spit Dunes

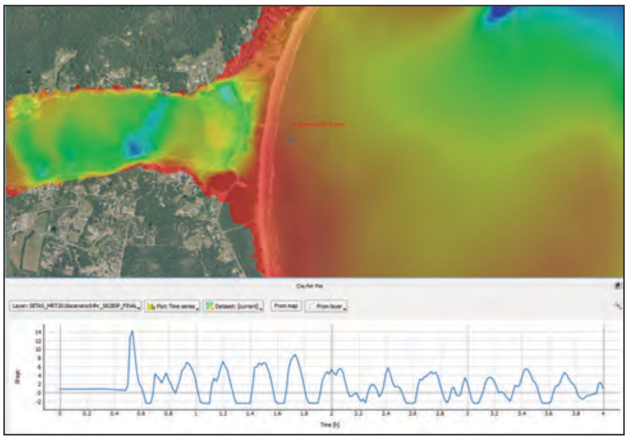
This modelling indicates that the tsunami would significantly overtop and erode the sand spit protecting Marion Bay, leading to elevated water levels in the Bay. While more detailed modelling will be required to confirm the resulting impacts, it seems likely that loss of the protective spit would increase the risk to residents and properties present on lower land around the bay's shore line. It is therefore considered prudent that tsunami impacts, including dune erosion, in this area be investigated in greater detail.

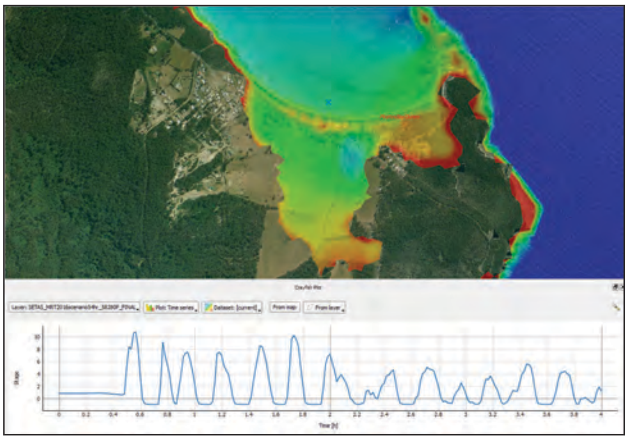


Maria Island Neck Dunes

The neck between north and south Maria Island provides the only land based access between the two island land forms.

While this modelling indicates that the interconnecting neck would be overtopped and significantly eroded by the simulated tsunami, the consequences of doing so would not be high as there is no infrastructure on the spit and minimal development on the shores of the embayment to the west of the spit that could be adversely impacted by raised water levels associated with scour of the neck.





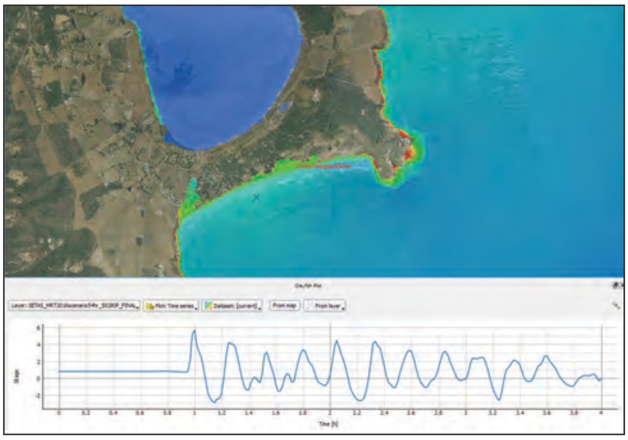
Eaglehawk Neck Dunes

Eaglehawk Neck provides the only road access to the Tasman Peninsula communities including the major tourist centre at Port Arthur. Loss of this access road would create considerable hardship for residents of the peninsula and loss of income from the present agricultural and tourist trade that the peninsula relies upon.

This modelling indicates that massive overtopping and erosion of these protective dunes is likely at this location. Given the extreme tsunami wave height at this location, it is most likely that the road would be destroyed during the event and the quantum of sand removed from the dunes would be such that the road (located on the lee side of the dunes) would be impassable for some considerable time. Given the consequences of such a road closure on access to and from the peninsula communities and damage to low lying properties along the otherwise protected waterway, it is also considered prudent that tsunami impacts, including dune erosion, in this area be investigated in greater detail.

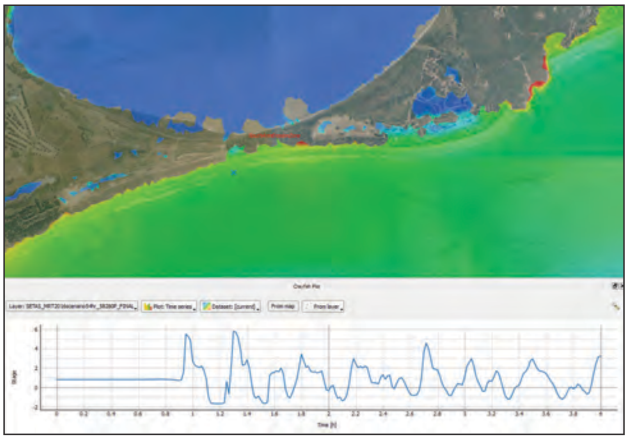
Pirates Bay Beach Dunes

This modelling indicates that the protective dune line would be substantially overtopped and all but removed by the tsunami, exposing the existing residents, dwellings and infrastructure to considerable risk, in respect to both loss of life and property damage. Given the consequences of this level of inundation, it is considered that tsunami impacts in this area, including the impact of dune erosion, be investigated in more detail. .



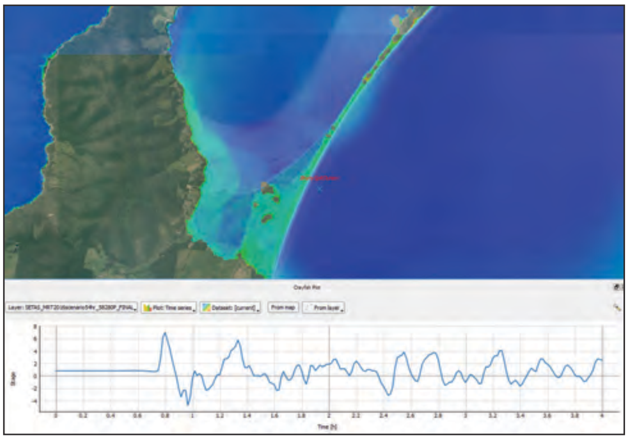
Cremorne Lagoon Beach Dunes

While the tsunami would inundate some properties behind Clifton Beach, this modelling indicates it unlikely that the land behind the beach would be overtopped. In addition, the area behind the beach is well vegetated reducing the likelihood of erosion of the underlying sands even if overtopped. Dune erosion is therefore unlikely to be a significant factor in respect to risk at this location.



South Arm Neck Dunes

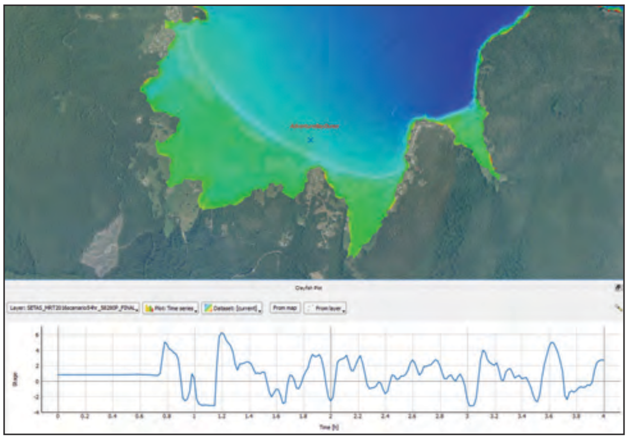
This modelling indicates that the dune line protecting the road between Lauderdale (to the north) and the villages of Opossum Bay and South Arm would likely be breached at a number of locations, depositing sand over the access road and raising the water level locally in Ralphs Bay above road level. As modelling does not indicate widespread overtopping of these dunes, overtopping will be heavily influenced by the actual (as distinct from modelled) dune topography. Since loss of road access to and from Opossum Bay and South Arm, for any length of time, would create many problems for the residents, it is recommended that tsunami impacts, including the impact of dune erosion, be investigated in more detail in this area.

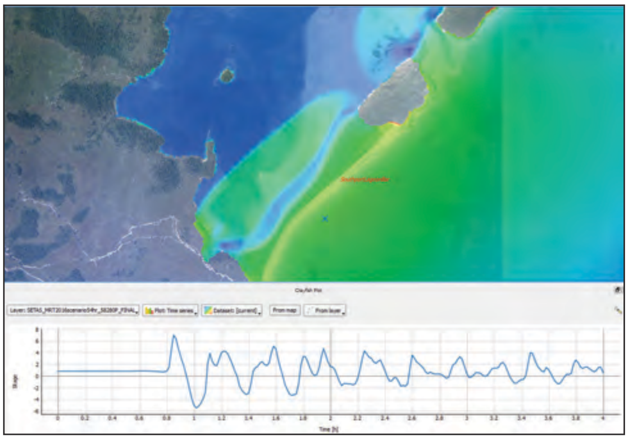


Bruny Island Neck Dunes

The only road connecting north and south Bruny has been constructed on the lee side of a sand spit that is protected by a continuous line of dunes. Loss of this access road would create considerable hardship for residents of the island and loss of income from the present agricultural and tourist trade that the island relies upon.

This modelling indicates that considerable overtopping and erosion of these protective dunes is likely, particularly in the southern half of the spit where dunes are lower. The quantum of sand removed from the dunes would be such that the road (located on the lee side of the dunes) would be impassable for some time, preventing access between the north and south of the Island. Given the consequences of such a closure, it is considered desirable that tsunami impacts, including dune erosion, in this area be investigated in greater detail.



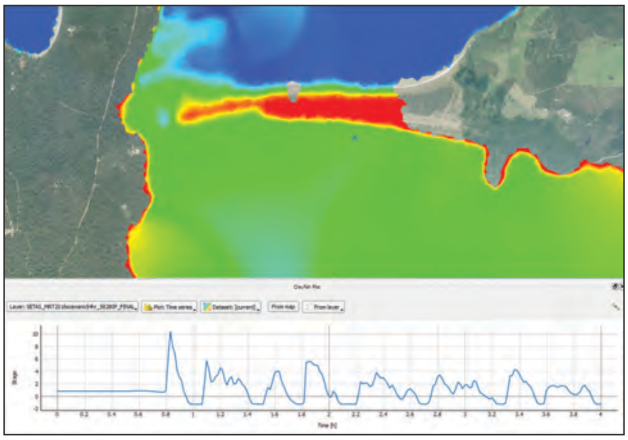


Adventure Bay Beach Dunes

This modelling indicates that the protective dune line would be substantially overtopped and all but removed by the tsunami, exposing the existing residents, dwellings and infrastructure to considerable risk in respect to both loss of life and property damage. Given the consequences of this level of inundation, it is considered desirable that tsunami impacts in this area, including the impact of dune erosion, be investigated in more detail in this area.

Southport Lagoon Spit Dunes

While this modelling indicates that there will be massive overtopping and scour of the low dune line protecting the lagoon, the consequences of doing so would not be high as there is no infrastructure on the protective dunes and minimal development on the shores of the lagoon itself. Such a level of overtopping and removal of the protective dunes and sand bar would however raise peak water levels in the lagoon during the tsunami and could significantly alter the protected nature of the lagoon and the ecosystems it supports.



Cloudy Bay Spit Dunes

While this modelling indicates that there will be significant high-level overtopping and scour of the dune line protecting the lagoon, the consequences of doing so would not be high as there is no infrastructure on the protective dunes and minimal development on the shores of the lagoon itself. Such a level of overtopping and scour of the protective dunes would however raise peak water levels in the lagoon during the tsunami and could significantly alter the protected nature of the lagoon and the ecosystems it supports.

CONCLUSIONS

When tsunami modelling is extended to include the impact of erosion of protective dunes on penetration of a tsunami, some areas initially considered not at risk from the tsunami can be demonstrated to be very much at risk.

This Scenrio5 was developed to explore where increased risk from erosion of a protective dune line, during a tsunami, might exist.in South Eastern Tasmania.

Hobart airport, an area protected by a low dune line behind Seven Mile Beach, was modelled in detail as an extension of the runway is currently under consideration. 12 other sites were modelled at a lesser level of detail to identify sites where a significant increase in risk from dune erosion appears likely.

With respect to the airport site, the modelling indicates that the dune line along Seven Mile Beach, as existing in 2016, would provide effective protection for the airport runway and terminal buildings in a tsunami event up to the magnitude of that modelled. For the most part, this arises because of the considerable reduction in the tsunami wave height as it travels into and through Frederick Henry Bay.

With respect to other sites, where erosion of protective dunes could elevate exposure and risk during a tsunami;

Sites that modelling indicates are exposed to increased risk as a result of erosion of protective dunes and are therefore recommended for more detail investigation include;

- Marion Bay Spit Dunes
- Eaglehawk Neck Dunes
- Pirates Bay Beach Dunes
- South Arm Neck Dunes
- Bruny Island Neck Dunes
- Adventure Bay Beach Dunes

Sites that modelling indicates are likely exposed to erosion but are not recommended for more detail investigation due to limited consequences arising from erosion include;

- Maria Island Neck Dunes
- Cloudy Bay Spit Dunes
- Southport Lagoon Spit Dunes

Sites that modelling indicates would not be overtopped and exposed to erosion by the simulated tsunami and are therefore not recommended for further investigation include;

- Dolphin Sands Beach Dunes
- Cremorne Lagoon Beach Dunes

Prepared for and on behalf of

RIENCO CONSULTING

E H Rigby BE, MEngSc, FIEAust, FASCE, CPeng, NER 481553

October 23rd 2016

TECHNICAL REPORT ON TSUNAMI INUNDATION MODELLING IN SOUTH EAST TASMANIA

Table of Data for Gauge Locations

Electronic file: see accompanying disc

APPENDIX SIX

Mineral Resources Tasmania
Department of State Growth

Tasmanian Government

TECHNICAL REPORT ON TSUNAMI INUNDATION MODELLING IN SOUTH EAST TASMANIA

Time Series Graphs of Water Levels at Gauges

Electronic file: see accompanying disc

APPENDIX SEVEN

Mineral Resources Tasmania
Department of State Growth

Tasmanian Government

TECHNICAL REPORT ON TSUNAMI INUNDATION MODELLING IN SOUTH EAST TASMANIA

Video Animations of Tsunami Simulations

Electronic file: see accompanying disc

APPENDIX EIGHT

Mineral Resources Tasmania
Department of State Growth

Tasmanian Government

TECHNICAL REPORT ON TSUNAMI INUNDATION MODELLING IN SOUTH EAST TASMANIA

Inundation Validation Site Visit Photographs

Electronic file: see accompanying disc

APPENDIX NINE

Mineral Resources Tasmania
Department of State Growth

Tasmanian Government

TECHNICAL REPORT ON TSUNAMI INUNDATION
MODELLING IN SOUTH EAST TASMANIA

Python Modelling Scripts and Post-processing R Scripts

Electronic file: see accompanying disc

APPENDIX TEN

Mineral Resources Tasmania
Department of State Growth

Tasmanian Government

TECHNICAL REPORT ON TSUNAMI INUNDATION
MODELLING IN SOUTH EAST TASMANIA

Development and Application of the Anuga Dune Erosion Operator

APPENDIX ELEVEN

Mineral Resources Tasmania
Department of State Growth

Tasmanian Government

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Experiences Developing and Applying an Anuga Dune Erosion Operator to Assess Risk from Loss of Dune Protection During a Tsunami

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In 2009, Geoscience Australia undertook modelling of tsunami impacts on the south-east coastline of Tasmania using the 2D hydrodynamic model ANUGA. At that time both bathymetric and topographic data were limited and the modelling was focussed on quantification of inundation extents in specific coastal villages considered at risk from a range of possible tsunamis. In 2016, Mineral Resources Tasmania (MRT) was requested to update this earlier work using currently available data and to additionally consider the impact of a worst-case tsunami on Hobart airport and on shipping and maritime safety in the Derwent estuary. In developing and running these updated models, it became clear that some low-lying areas of the coast were being protected from inundation by elevated frontal sand dunes. This raised questions as to the possibility of these dunes eroding during a tsunami, increasing the extent of inundation and risk in these otherwise protected rear dune areas. An ANUGA 'Operator' was therefore developed to allow dune erosion to be included in the model, so that a recommendation could be made as to the need to incorporate dune erosion in future modelling of these areas. This Operator in turn permitted any significant change in risk in these otherwise protected areas, to be assessed. This paper describes the development of this Operator, its incorporation into the ANUGA based tsunami model, and the results obtained from the erosion enabled model. ANUGA and the dune erosion Operator are both free and open source software.

1. INTRODUCTION

Modelling performed by Geoscience Australia in 2009 suggested that parts of the southeast Tasmanian coast could be significantly affected by a tsunami generated from a rupture of the Puysegur subduction zone, off New Zealand's southwest coast (van Putten et al., 2009). Since these results were published, emergency managers in Tasmania have sought greater detail regarding the impacts of such an event on key infrastructure and communities.

In 2015, a project to further quantify the likely impact of a major tsunami on coastal villages was commissioned by the State Emergency Services in Tasmania, and funded by a grant from the Natural Disaster Resilience Grants Program (Australian Government and Tasmanian Government), with the further support of Mineral Resources Tasmania.

A new Southeast Tasmanian (SETAS) tsunami model was created for this purpose, based on the advanced functionality available in ANUGA 2016. This project aimed to specifically address the danger to maritime activities in the Derwent estuary and to Hobart airport, as well as to populated areas and key transport routes close to the coast. The study area extended from West Cape to Bicheno (Figure 2) and covered an area of approximately 17,000 km^2.

The agreed modelling strategy comprised five scenarios, of which scenario 5 (SC5) involved consideration of the impact of dune erosion on coastal inundation limits and risk at Hobart airport.

SC1: Comparison of GA 2009 results with those from MRT's new model using the 2009 data

SC2: Comparison of GA 2009 results with those from MRT's new model using more recent data

SC3: Simulation of maritime hazards in the Derwent Estuary (13 hours simulation)

SC4: Simulation of coastal inundation and hazard at selected coastal sites (4 hours simulation)

SC5: Simulation of inundation and hazard at Hobart Airport (4 hours simulation)

MRT acquired and processed the required input data and provided reporting on the results obtained. Rienco Consulting was engaged as technical advisor to the project and to develop the new tsunami modelling scripts. Consultants Entura were engaged to execute the scripts for scenarios 1 to 4 and Rienco Consulting to execute the scripts for scenario 5.

In undertaking these simulations, it became clear that there were several locations within the modelled area where sand dunes could be providing some level of protection for property or assets behind the dune line. Hobart airport is one such location. To better understand and quantify the protection provided by these dunes, a new model was needed that could include consideration of erosion of the dunes, during the simulation process. At the time the study commenced, ANUGA had no such functionality but it did include tools, in the form of 'Operators', that could be developed for this purpose. This paper describes the development and incorporation of such an Operator into the South-East Tasmanian tsunami modelling scripts and its application to identify areas where more detailed modelling, incorporating dune erosion, might be needed to properly quantify risk.

2. THE DUNE EROSION OPERATOR

2.1. The Anuga Environment

ANUGA was developed by Dr Stephen Roberts of the Australian National University, together with Ole Nielsen, Duncan Gray and Jane Sexton from Geoscience Australia. It is currently being developed and maintained by Dr Stephen Roberts and Gareth Davies from Geoscience Australia. ANUGA is a free and open source software package, available and distributed under the terms of the GNU General Public Licence.

ANUGA is a hydrodynamic modelling library that allows users to construct models that realistically simulate complex depth averaged, two dimensional (2D) horizontal flow behavior. It was initially developed in 2005 to simulate near and on shore propagation of a tsunami, but in recent years has also found use as a general purpose flood model.

To run a simulation, a model specific set of Python scripts must be created by the user from the ANUGA library. Model inputs to these scripts include a variable mesh of triangular cells that fill the model domain, the domain topography and bathymetry, frictional resistance, initial values for water level (called stage within ANUGA), boundary conditions and ANUGA Operators such as rainfall, stream flows, wind-stress and pressure gradients.

When the Python scripts are run, ANUGA tracks the evolution of water depth and horizontal momentum within each cell over time, by solving the shallow water wave equation using a finite-volume approach. Most ANUGA library components are written in the object-oriented programming language Python.

Computationally intensive components of the library are written for efficiency in C, working directly with Python numpy structures.

An Operator class was added to the ANUGA library shortly after its initial release, to facilitate user control of the solution process at each computational time step. Operators permitted users to include spatially and temporally variable rainfall in their model scripts in a simple manner and to incorporate specialised structures such as culverts. As an Operator has direct access to the centroid values of a cell (stage, xmomentum, ymomentum, bed_elevation) during each computational step, it can provide a means of modifying the bed elevation at each computational step, to simulate dune erosion in user defined areas. The development and application of such a 'Dune Erosion Operator' is described in the following sections.

2.2. Development of The Dune Erosion Operator

2.2.1. Reviewing the Erosion Processes To Simulate

In preparing to code this Operator, it was necessary to decide whether it should include full erosion/transport/deposition functionality. Linked to this consideration was the further question as to whether a clear water or sediment laden approach would need to be simulated. As the prime objective of the dune erosion Operator was to quantify the potential increase in risk, from a tsunami scouring out a protective dune line, the focus was on the erosion process rather than the subsequent transport and deposition processes. With the specific intent of this modelling in mind, it was resolved to proceed with a simple, erosion only, Operator. While the approaching wave would likely include some sand in suspension, it was not considered quantifiable or high enough in level to warrant the use of non-clear water scour functionality in the Operator.

In general, three processes are involved in the removal of sand when water overtops the dune line.

- The detachment of sand by water flowing over the surface of the sand.
- The collapse of sand faces that have been steepened beyond the point of collapse by the erosion process.
- The fluidisation of sand in the rear face of the dune due to an elevated phreatic surface.

Of these three processes, detachment occurs first, closely followed by collapse of any faces steepened beyond their stable slope by the detachment process. These first two processes occur relatively instantaneously in response to the water flow and therefore require simulation to create a realistic response by the Operator.

The third process takes significantly longer, requiring penetration of water from the ocean side into and through the sand mass during the rising limb of the incoming wave (reversed as the wave recedes). Given the significantly longer time scale of this process, it was not deemed necessary to include it in this Operator.

2.2.2. Quantifying the Incorporated Erosion Processes

On the basis of the above, the erosion mechanism adopted assumed a clear water scour with no significant sediment entrained in the approaching wave that could impact detachment rates. It also assumed an environment where the detached sediment remained well within the transport capacity of the water column in the eroding area (viz. no deposition - only erosion within the target area).

The erosional relationships and parameters adopted in this application of the Operator are from the work by Dr David Froelich (2002) in which he investigated erosional rates associated with water flowing at different depths and velocities over different soils. While other relationships have been developed by other researchers, the relationships developed by Dr, Froelich are simple to apply and were considered more than adequate to establish whether or not dune erosion is a factor affecting inundation risk at some locations in the study area. Erosional parameters used in development of this Operator are;

Bed shear stress; $$\text{Tau\_bed} = \frac{Wd*G*n^2*m^2}{d^{2.333}} \text{ Pa} \qquad (1)$$

Where:

Wd is water mass density. (1000 kg/m^3)
G is acceleration due to gravity. (9.8 m/sec/sec)
n is Manning's n. (sand n = 0.025)
m is absolute momentum. ((mx^2+my^2)$^{0.5}$)
d is water depth. (ANUGA stage-elevation m)

Dr Froelich's work demonstrated that erosion occurs when the bed shear stress (Eq 1) is greater than the critical (detachment) bed shear stress (Tau_crit = 2.1 Pa for sand) and the detachment rate associated with this process when Tau_bed exceeds Tau_crit is (Eq 2);

Detachment Rate; $$Sk = \frac{Kd * (tau_{bed} - Tau_{Crit})}{Sd} \quad m^3/sec/m^2 \qquad (2)$$

Where:

Kd is the detachment rate. (0.0250 Kg/sec/m^2/Pa)
Sd is sediment mass density. (1800 kg/m^3)

It should be noted that while Dr Froelich's work provides erosional properties for other soils, this dune erosion Operator only uses parameters for, and is specific to, the erosion of sand.

The second process simulated by this Operator is the collapse, fluidisation and removal of sand from the dune system as a consequence of the erosion process creating face slopes that would be steeper than their angle of repose. This is applied in the Operator after the erosion computations for a particular timestep have been completed to compute a new stable surface. Each triangle within the specified erosion zone is checked to see if the elevation of the Center of Gravity (CG) of any neighbouring triangle lies above the angle of repose line from the lowest neighbour's CG. If so, then the neighbouring triangles CG elevation that is above the repose angle is adjusted to lie at the angle of repose relative to the lowest neighbour's CG. This adjustment is also made to the current triangle's CG, if it is also above the repose angle relative to the lowest neighbour's CG. A check is performed to prevent any reduction in elevation that would lower a triangle's CG below the specified no-scour base level. While this algorithm allows each triangle's elevation to be reviewed and adjusted up to three times in each timestep, it cannot guarantee all triangles will be fully adjusted back to a stable face. Given the multiple iterations at each time step and small size of each time step, the above was however considered adequate for the purposes of this study.

2.2.3. Coding the Dune Erosion Operator

The dune erosion Operator is coded in Python (2.7) and makes direct use of the Operator class defined in ANUGA. The Operator is spatially restricted to areas of interest by individual erosion zone polygons (shapefiles) created by the user. These polygons also set the level below which simulated scour cannot occur in each polygon. The erosion parameters are directly coded into the Operator as discussed in the preceding section. Coding is structured such that an alternative relationship for scour or collapse can be incorporated, if desired.

2.2.4. Testing the Dune Erosion Operator

A simplistic model was constructed for testing purposes, incorporating a notched dune 1.4 m high with 1:1 face slopes, followed by a level dune 1.0 m high, also with 1:1 face slopes. The notched dune no-scour base was set at 1.0 m with the level dune no-scour base at 0.3 m. The stable face slope was set at 34 degrees. While undertaken without field data to validate this simulation, the notched dune crest deepened and widened, maintaining the appropriate angle of repose and the level dune uniformly eroded in both a downward and rearward manner, all as properly expected. Manual spot checks on erosion rates confirmed that erosion was progressing in accord with the rates specified in the Operator. Images of the erosion part way into the simulation are reproduced in Figures 1a to 1c. Figure 1a shows the notched dune face scoured down to the no-scour base and the basin between the notched and level dunes starting to fill. Figure 1b shows the notched dune face further scoured and the interbasin water level rising. Figure 1c shows the interbasin area filled, the downstream level dune overtopped and uniformly scoured on the downstream face, to its no-scour base. Each graphic is reproduced with a 5:1 vertical exaggeration to more clearly show the scour geometry as time passes.

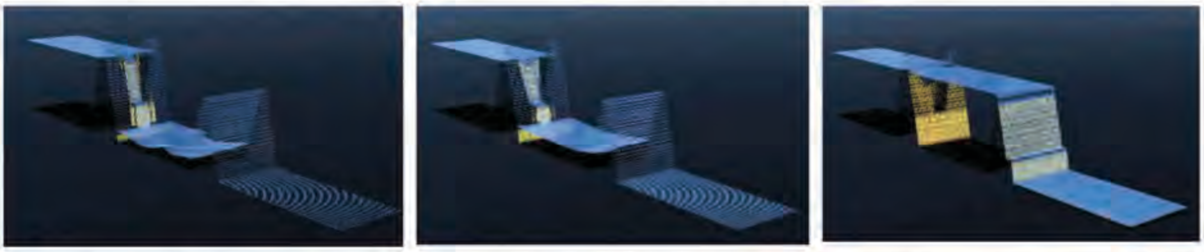

Figure 1a – t= 60 secs **Figure 1b – t=120 secs** **Figure 1c – t= 360 secs**

Figure 1 – Test of Dune Model Erosion Operator

The test model highlights the significant vertical components of flow that will occur in flow down a relatively steep surface such as those in the test model. The basic assumption that vertical components of flow in a 2D model will be minimal is clearly violated in such circumstances. Steep surfaces also present difficulties for erosion simulation in that shear forces no longer apply to a horizontally aligned surface and the true area of each surface element is significantly more than that of its horizontal projection. Notwithstanding these limitations, no solution to these limitations could be found without moving to a 3D model. Given the realistic response of the test model and the well correlated blind testing undertaken by Dr Froelich in 2002 of the underlying relationships used in this Operator, the 2D based dune erosion Operator was considered adequate for the purposes of this particular study, and adopted, recognising these limitations.

2.3. Integrating the Operator into the Tsunami Modelling Scripts

As several other scenarios had previously been modelled in the SETAS domain, a model was in place that could be extended to incorporate consideration of dune erosion. Integration of the Operator involved reading the erosion polygons with their no-scour base level into the model using a third party shapes.py library and adding code to call the Operator.

In adding the Operator to the SETAS tsunami model, a line of code was added for each of the 12 erosion zones in the model, as each erosion zone is independently managed by its own Operator. This line is required prior to the ANUGA evolve (simulation) loop to activate the Operator during the evolve loop. The call format is as follows.

```
# op6 – Dune Erosion Operator 6 (Dolphin Sands)

op6 = sanddune_erosion_operator( domainbase = nsbase_elev_c,
                                 polygon=model_data.erosion_polygons[6][0],
                                 verbose=model_ini.model_verbose)
```

As previously noted, each Operator references the associated erosion zone polygon and the no scour base level associated with that polygon. While an outwardly straightforward process, this integration step did not proceed smoothly due to the need to accommodate computation in a partitioned domain, but with some initial assignments in the global domain. At this point, Dr Roberts (one of the ANUGA developers) was consulted and an appropriate coding sequence established that overcame these difficulties.

In developing this additional model code, all dune erosion code was made conditional to facilitate switching between erosional and non-erosional simulations of otherwise identical models. This then permitted the relative impacts of dune erosion on inundation extents, depths and velocities to be easily quantified.

3. APPLICATION OF THE EROSION ENABLED MODEL

The modelled domain and locations of the 12 sites initially selected for review of the impact of dune erosion on risk during a major tsunami are shown in Figures 2 and 3. As in scenarios 1 to 4 (SC1 to

SC4), the modelled event was associated with hypothetical movements in the Puysegur trench, located to the immediate south of New Zealand, with an AEP of about 1:13000 (Geoscience Australia, 2009). Temporal wave data resulting from this hypothetical event, at about 100 m depth off the SE Tasmanian coast, was supplied by Geoscience Australia. The model domain is shown in red in Figure 2, with the stations at which temporal wave data were provided, as black dots. The inset in Figure 2 extracted from Hayes and Furlong (2010), shows the spatial relationship between the trench and the southeast coast of Tasmania, together with tsunami travel time contours from the Puysegur trench. As indicated in this graphic, travel time from the Puysegur trench to the south-east coast of Tasmania is a relatively short two hours.

Figure 2 – The SETAS Model Domain

Figure 3 – The Dune Erosion Zones

As the focus of Scenario 5 was initially in regard to the potential inundation of Hobart airport, this area was modelled at a relatively fine resolution (10 m triangles). Eleven other areas were modelled at the same resolution as the coastal strip (50 m triangles) as the purpose was only to establish if further, more detailed, modelling would be required in these areas, to quantify increased inundation levels from erosion of their protective dunes. Depending on location, a base no-scour elevation of 1 to 3 m AHD was set in these areas.

At the airport site, the dune erosion simulation indicated that peak wave height and dune height were comparable (as in previous scenarios), resulting in only minor erosion of the dune line at the western end of the beach, well away from the airport. In the immediate vicinity of the airport, this simulation showed that the existing dune line would remain intact.

Of the 11 other sites included in this simulation, the dunes at Dolphin Sands, Cremorne Lagoon and South Arm remained intact. All other sites suffered significant erosional dune loss during the simulated tsunami. While the consequences of loss of this protection varies, depending on the extent of property or infrastructure put at risk by this increased exposure, it is strongly recommended that all of the remaining 8 sites be modelled at increased resolution with locally specific erosion parameters, to quantify the impact of dune erosion, on risk at these sites.

The coastal holiday village of Doo Town fronts Pirates Bay on the east coast of the Tasman Peninsula. This is one of the sites at which the likely impact of dune erosion on inundation during a tsunami was investigated and provides a qualitative view of the consequences of loss of dune protection at that site.

Figure 4 shows the penetration of the tsunami at this site just after the first wave has peaked, together with the stage time series in the bay at the location indicated. Figure 5 shows the erosion rate of the protective dunes at the circled location, with most loss in two episodes, one at t = 0.5 hrs and the other at t = 1.7 hrs, some 72 minutes apart. The elevation time series of Figure 6 shows these two periods of greatest erosion occurred with the arrival of the first and sixth wave in the series, both waves having the greatest peak elevations in the series.

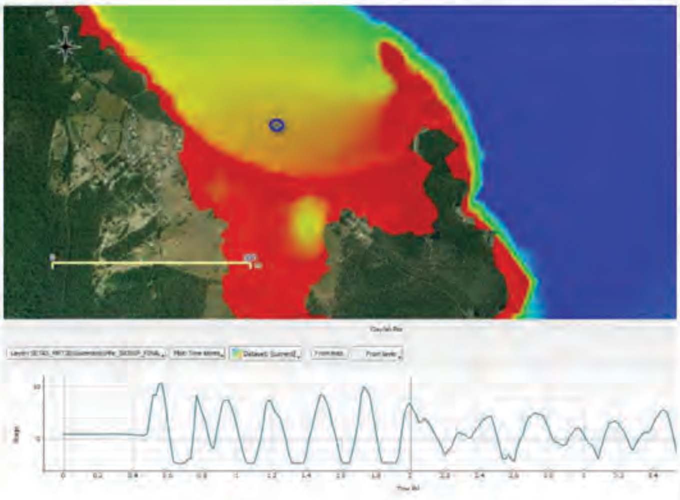

Figure 4 – Doo Town Inundation

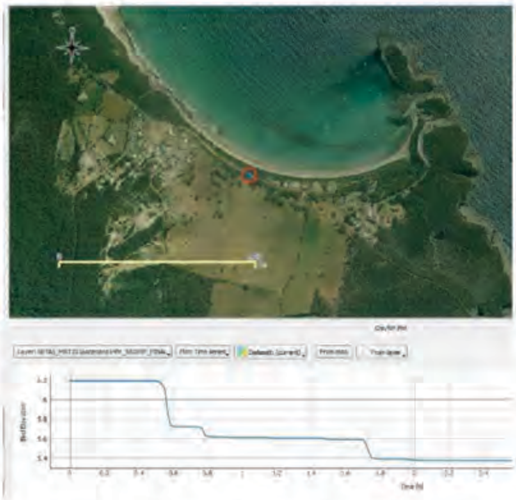

Figure 5 – Doo Town Dune Erosion

Figure 6 shows the erosional depth contours of the dunes after four hours of exposure to the tsunami. As expected, the greatest erosion depths are in and adjacent to the locations where the dunes are lowest. Approximately 240,000 m^3 of sand was removed from this dune line during this simulation.

Figure 7 shows the increased inundation levels in the rear dune area as a consequence of partial loss of the protective dune line. The maximum reduction in water surface elevation is on the ocean side of the area of greatest dune erosion and the maximum increase in elevation on the land side of that same location.

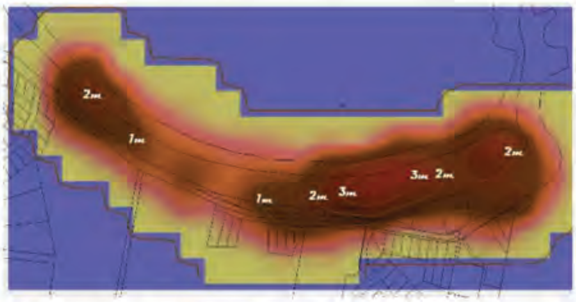

Figure 6 – Doo Town Dune Erosion Depths

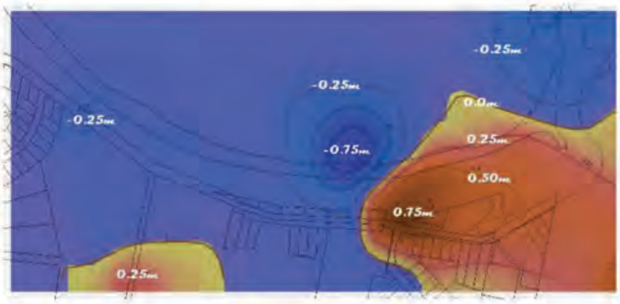

Figure 7 – Doo Town Inundation Impacts

While the results for this site appear sensible, it should be noted that they are from a model with a relatively coarse mesh in the area of interest (50 m triangles) and are based on the average erosional parameters adopted for all sites.

It is also noted that while the erosional parameters used in this modelling were developed from large scale testing by Dr Froelich, they do not distinguish between sand that is relatively bare, from sand that is well stabilised with grasses, shrubs and trees. It is therefore unclear as to what extent well stabilised dunes would, at least initially, lose material relative to the rates used in this modelling. Further investigation in this area is highly desirable before adopting any results in these potentially protected areas. Given the scale of topographic change in the dune field at all 8 sites and significant local differences in dune cover, it is recommended that the present element size be decreased to 20m or less in these areas and the model re-run with locally appropriate dune erosion parameters, to establish inundation extents suitable for input to the mapping process. Prior to undertaking this more detailed modelling, it would also be prudent to undertake f more deliberate testing of the Operator and to consider possible alternatives to the relationships proposed by Dr Froelich in the Operator.

4. CONCLUSIONS

1. Where partial erosion of a protective dune line during a tsunami could increase the level of risk for persons, property or other assets located behind this dune line, it is important to quantify that increased risk, as in some circumstances it can be very significant.

2. When augmented with an appropriate dune erosion Operator, the ANUGA library can be used to construct a hydrodynamic model capable of simulating the hydraulic impact of erosion of a protective dune line on inundation in the rear dune area and to assess any increase in risk this might present.

3. The ANUGA Operator described in this paper is provided as a free and open source tool to facilitate this analysis.

4. Modelling of tsunami impacts on the south-east coast of Tasmania using the ANUGA library with the above dune erosion Operator, has confirmed that the 2016 dune line protecting Hobart airport would not be breached by the simulated 1:13000 AEP tsunami event.

5. This modelling does however confirm that eight of the coastal sites included in the extended study are areas where erosion of their protective dune line could significantly increase the risk from inundation, by a tsunami of the magnitude simulated. It is recommended that the present model Operator be further tested to increase confidence in its use and the erosion enabled model re-run with increased resolution and locally relevant parameters in these potentially protected areas, to:

    a. more realistically simulate overtopping and erosion of the topographically variable dune line.
    b. more realistically reflect the impact of dune compositional and cover differences at each site, on detachment rates.
    c. permit a more realistic assessment of risk in these areas and to support development of appropriate inundation mapping and emergency management plans for these areas.

5. ACKNOWLEDGMENTS

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