Department of Science, Information Technology, Innovation and the Arts

Tsunami Modelling along the East Queensland Coast

Report 1: Regional Modelling

Coastal Impacts Unit

Great state. Great opportunity.

Australian Government
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Queensland Government

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Executive Summary

Following the 2004 Indian Ocean tsunami that devastated Indonesia, Thailand and Sri Lanka, the Australian Government through Geoscience Australia (GA) undertook a probabilistic assessment of tsunami hazard along the Australian coastline in terms of tsunami amplitude at the 100m depth contour. GA supplemented this with a national Nearshore Tsunami Hazard Assessment of Australia (NTHA) to examine the relative amplification of tsunami at 20m depth compared to the 100m depth contour for select locations. However that study did not include some locations such as the Sunshine Coast.

This study builds upon the earlier work of GA by utilising DHI's finite volume hydrodynamic modelling software (MIKE21FM) to examine the nearshore amplification at 10m depth along the entire east Queensland coast from Cooktown to the NSW border. A flexible mesh was developed using a high resolution 0.001 arc degrees digital elevation model (DEM) of the GBR and Coral Sea (known as the gbr100 DEM) that was developed by James Cook University.

Validation of the model against the 1 April 2007 Solomon Island tsunami demonstrates the ability of the DHI MIKE21FM software to replicate tsunami propagation. However, differences between the modelled and measured tsunami amplitude for some locations illustrates the sensitivity and need for accurate and representative bathymetric data, especially in depths less than 20m where the sea bed is the most dynamic and the tsunami amplitude is most sensitive to shoaling.

Modelling was undertaken adopting a methodology that is similar to that adopted for the NTHA, but more sites were considered and the results were extended to the 10m depth contour. This study further supports the conclusions provided in the former study. Specifically:

- The Great Barrier Reef and wider continental shelf from Fraser Island north provides protection to the coast by dissipating the tsunami. The influence of the GBR increases with increasing tsunami amplitude. The resulting amplification factors within the GBR lagoon are typically below 1, with the exception of Flying Fish Point.
- Regions where the continental shelf is the narrowest (i.e. south of Fraser Island) have the highest amplification factors in the order of 3 at 10m depth. Generally, the amplification factor increases with increasing tsunami amplitude.
- Large islands protect the adjacent mainland, generally producing amplification factors below 1.
- Complex bathymetry within the dynamic littoral zone (such as surf zone bars, nearshore or ebb shoals, etc.) that has not been sufficiently represented in the adopted DEM, may significantly affect amplification factors near the coast.

The communities identified in this study to have a higher tsunami hazard are in decreasing order of magnitude:

- Gold Coast
- Ocean side of Bribie, Moreton, and Stradbroke Islands
- Sunshine Coast
- Fraser Island
- Bundaberg
- Flying Fish Point
- Capricorn Coast

- Agnes Waters
- Hervey Bay

These conclusions are based on amplification factors at the 10m depth contour. They do not take into consideration the height of coastal dunes or the shoaling nature of the tsunami as it approaches the coast. It is possible that an amplification factor of less than 1 may still produce a tsunami that may cause inundation for north Queensland communities. Detailed inundation modelling would be required to assess the full risk for coastal communities.

The analysis has been based on three scenarios that are assumed constant along the boundary of each domain. In reality, wave characteristics will vary along the boundary. In addition each possible event will be unique in how it behaves in the nearshore due to differences in factors such as wave height, wave periods and individual wave interactions within the time series. Therefore analysis of a larger sample of events will provide more confidence that the amplification maps are representative of the tsunami climate for each region.

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Glossary

AEST	Australian Eastern Standard Time
ATWS	Australian Tsunami Warning System
BoM	Bureau of Meteorology
BPA	Queensland Beach Protection Authority
C	Chézy Coefficient
CofE	Coefficient of Efficiency
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute
EMA	Emergency Management Australia
EPA	Queensland Environmental Protection Agency
GA	Geoscience Australia
GBR	Great Barrier Reef
HAT	Highest Astronomical Tide
IofA	Index of Agreement
MSL	Mean Sea Level
NSW	New South Wales
NTHA	Nearshore Tsunami Hazard Assessment of Australia
PTHA	Probabilistic Tsunami Hazard Assessment of Australia
R^2	Coefficient of Determination
RMSE	Root Mean Square Error
SAG	Study Advisory Group
SEQ	South-east Queensland
TsuDAT	Tsunami Data Access Tool

1. Introduction

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

In addition, GA undertook a probabilistic assessment of tsunami hazard along the Australian coastline in terms of tsunami amplitude at the 100m depth contour (Burbidge et al, 2008). The study was intended to assist the relevant state government departments to assess the tsunami risk along the coast and to prioritise regions that require further detailed assessment. However the study was limited in that for Queensland, the 100m depth contour is offshore of the continental shelf and the Great Barrier Reef (GBR). Therefore, the influence of these significant features on tsunami propagation was uncertain.

To better understand the impact of the complex bathymetric features across the Australian continental shelf on tsunami propagation, GA undertook a Nearshore Tsunami Hazard Assessment of Australia (NTHA) to examine the relative amplification of tsunami at 20m depth compared to the 100m depth contour for select locations (Fountain et al, 2009b). The modelling was undertaken utilising ANUGA, a finite volume depth averaged hydrodynamic model that uses a flexible mesh on a cartesian coordinate system (Nielsen et al, 2005). The nearshore propagation was restricted to the 20m depth contour and adopted GA's 250m bathymetry and topography grid (Webster and Petkovic, 2005). A comparison by GA of modelling undertaken using the 250m grid against more detailed bathymetry in Western Australia found that although there were comparable results at 10m depth for some of the study sites, there was good comparison for all sites at the 20m depth contour. Models runs with different mesh configurations, but the same mesh sizes, also demonstrated discrepancies for depths less than 20m.

This study builds upon the work undertaken by GA utilising DHI's hydrodynamic modelling software to examine the nearshore amplification up to 10m depth along the entire east Queensland coast from Cooktown to the NSW border.

2. Scope

This study comprises two main stages:

- Stage 1: Develop, calibrate and validate hydrodynamic models of the east coast of Queensland for tsunami propagation modelling and determine amplification factors in the nearshore compared to the 100m depth contour.
- Stage 2: Undertake inundation modelling at one location to be determined from Stage 1 in consultation with the Study Advisory Group (SAG).

This report details the results for Stage 1 of the study.

As with GA's NTHA study (Fountain et al, 2009b) it is noted that the results of the nearshore modelling cannot be used to infer inundation levels over the land. Detailed bathymetry would be required to model with any confidence the propagation of the tsunami to shore and this process will be very sensitive to local bathymetric features.

This study has focused on the east coast of Queensland to examine the influence of the GBR on tsunami propagation. For a nearshore assessment of the Gulf of Carpentaria, please refer to the NTHA study (Fountain et al, 2009b).

3. Previous Studies

Prior to the 2004 Indian Ocean tsunami, tsunami research was confined to a small number of research institutes. Tsunami modelling was undertaken utilising purpose built numerical models. Three well known models include MOST (Method of Splitting Tsunami) (Titov and Gonzalez, 1997), COMCOT (Cornell Multi-grid Coupled Tsunami model) (Liu et al, 1994) and TSUNAMI2 (Goto et al, 1997). These models were developed using finite difference schemes for rectangular grids to solve the non-linear shallow water equations.

Research has shown that modelling tsunami propagation in the deep ocean can be successfully undertaken using a linear version of the shallow water equations, thereby greatly reducing computation time for oceanic basin scale extents. As the tsunami reaches shallow water near the coast, non-linear effects become important. Ideally, the Boussinesq type equations should be used in shallow water as they include both non-linear and frequency dispersion. Therefore they are capable of modelling the full wave transformation processes including non-linear wave-wave interactions, diffraction and partial reflection and transmission. However, these models are computationally demanding and so are only suited for small scale studies such as harbours where resonance is an important process. Application of the non-linear shallow water equations for inundation modelling has shown reasonable agreement with the sparse field data (Nielsen et al (2005) and Tang et al (2009)). These equations have traditionally been solved by explicit or implicit finite difference methods on either rectilinear or curvilinear grids. Of recent times, explicit finite volume methods have been used that allow for flexible or unstructured meshes. Finite Volume methods allow for better representation of complex coastlines and geomorphological features such as the Great Barrier Reef (Callaghan et al, 2007), but the explicit schemes can require much longer simulation times than the implicit finite difference schemes.

For the rectilinear finite difference approach, inundation levels are calculated by running the non-linear models through nested finer grids to adequately resolve the shorter wave lengths in shallow water and the shoaling behaviour over complex bathymetries. Tang et al (2009) adopted a three stage nesting for forecast inundation model testing comprising a regional grid of 2 arc minutes (approximately 3600m), an intermediate grid of 12 arc seconds (approximately 360m), and a nearshore grid of 2 arc seconds (approximately 60m). This was compared to a reference high resolution inundation model consisting again of three grids: 36, 6, and 1/3 arc seconds (i.e. approximately 1080, 180, and 10m). When compared to observations the reference model error was 6% compared to 18% for the forecast model. However the run time for the reference model was 8 hours compared to 10 minutes for the forecast model. Shuto et al. (1986) recommended that the tsunami wavelength should be covered by at least 20 grid points to diminish numerical dispersion (dissipation). Ramming and Kowalik (1980) found that 10 grid points per wavelength is sufficient if a 2% error in the phase velocity is acceptable.

Following the 2004 event, there has been an increased interest into tsunami science and numerical modelling for hazard assessment, mitigation, and forecasting for early warning systems (Cummins et al, 2008). This has also seen other numerical models traditionally used for river, coastal and ocean hydrodynamics being used for tsunami modelling. To address concerns of the growing number of models being developed that have not been adequately benchmarked for tsunami modelling, Synolakis et al. (2008) proposed model standards and procedures for validation and verification.

Two such models that are well known for hydrodynamic modelling are Delft3D (Deltares, 2012) and Mike21 (DHI, 2010a). Both models solve the non-linear shallow water equations using finite difference schemes on a rectilinear nested grid system. Both models have been used to model the 2004 Indian Ocean tsunami (Annunziato and Best (2005), Pedersen et al (2005)). DHI have also developed a finite volume version of their hydrodynamic software (Mike21FM) that utilises flexible meshes in either Cartesian or spherical coordinates(DHI, 2010b). Pedersen et al (2005) used DHI's Mike21FM global model to simulate the 2004 Indian Ocean tsunami. However it was concluded that the world model was to coarse to compensate for the damping that occurs with the fast travelling wave in combination with the explicit solution, causing the amplitude to dissipate too rapidly in the deep ocean. Luger and Harris (2010) also found the flexible mesh model to be too dispersive to accurately simulate tsunami propagation over large distances when considering offshore spatial resolutions of 6km. However it had the advantage of geographical coordinates, which was lacking in the classic nested rectilinear grid version. They also suggested that for the classic version, the grid spacing should be selected to ensure 20 to 30 grid points per tsunami wavelength. Mike21FM was also used to model tsunami and resonance response at Alberni Inlet, British Columbia following the 1964 Alaska tsunami (Barua et al, 2006).

In Australia, the development of the tsunami early warning system and tsunami hazard assessments on the national scale have been coordinated by the Bureau of Meteorology (BoM) and Geoscience Australia (GA).

The BoM have developed the T2 scenario database (Greenslade et al (2009), Greenslade et al (2011), and Simanjuntak et al (2011)) to support the tsunami warning service of the Joint Australian Tsunami Warning Centre (JATWC). The database, a revision to the original T1 database (Greenslade et al, 2007), provides over 2,000 individual scenarios as well as scaling methods for events not meeting the prescribed scenario conditions, to obtain the appropriate warning levels within the defined coastal zones during an event (Allen and Greenslade, 2010). The modelling was undertaken with the non-linear version of MOST and covers the entire Indian and Pacific Oceans for depths greater than 20m at a spatial resolution of 4 arc minutes. A comparison was also undertaken for deep water sites between the T1 database and the NOAA/PMEL system known as the Short-term Inundation Forecast for Tsunami (SIFT) (Greenslade and Titov, 2008). Both systems utilised the MOST model, but with differences in approaches in source implementation. Despite this, both approaches provided favourable comparison with the deep water records examined.

The T2 database extends to 20m depth, so while some portions of the GBR lagoon (those greater than 20m depth) are described by the T2 scenarios, the reef itself will not be adequately resolved at 4 arc min spatial resolution (about 6km to 7km across the GBR). So the tsunami amplitudes and currents from T2 within the lagoon are unlikely to be accurate. Note that the tsunami warnings issued by the JATWC and based on the T2 scenarios are derived through an impacts-based statistical technique (Allen and Greenslade, 2010) and so are not affected by this issue.

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

Although the PTHA provided a means of assessing the deep water hazard, it did not provide an understanding of the effects of complex bathymetric features associated with Australia's reefs and the continental shelf on tsunami propagation to the coast. To provide a better understanding of the nearshore hazard as a result of tsunami interaction with these features, GA (Fountain et al, 2009b) undertook the Nearshore Tsunami Hazard Assessment for Australia (NTHA). The study involved reassessing the tsunami hazard by determining amplification factors at 20m water depth for the tsunami maximum amplitude at the 100m depth contour. Modelling was undertaken using ANUGA (Nielsen et al, 2005), which employs a finite volume numerical scheme to solve the non-linear shallow water equations utilising an unstructured triangular mesh. The open source code was developed through collaboration with the Australian National University (ANU) and GA. The model has been validated against the 2004 Indonesian tsunami (Jakeman et al., 2010). The model uses Cartesian coordinates so model domains were chosen to meet this requirement. The study concluded:

- Areas with narrower shelves tend to result in an increase in wave height between deep water and nearshore areas. Wider shelves may act to attenuate tsunami, reducing wave heights;
- Offshore islands and reefs appear to provide significant protection to the mainland from tsunami, though this may have implications for communities living on these islands not investigated here;
- The protective effect of smaller islands is more variable, and in some cases can lead to locally increased wave heights. This behaviour is highly sensitive to the particular tsunami characteristics; and
- The response of tsunami to areas of complex seafloor features is variable and less predictable, demonstrating the need for accurate bathymetry data to underpin tsunami modelling.

The NTHA did not change the location of the highest hazard, being WA. It did however reduce the hazard ranking for locations within the GBR lagoon because of the protection offered by the reef structure. In Queensland, the three communities that demonstrated an increase in maximum tsunami amplitude were Bundaberg, Hervey Bay and Gold Coast.

On the state scale, a number of studies have been undertaken or are underway to assess tsunami hazard. GA has used the PTHA study to identify areas that are vulnerable along the WA coast (Burbidge et al, 2008b). A collaborative project between the Fire and Emergency Services Authority (WA) and GA undertook inundation modelling using ANUGA to assess tsunami impact on Broome, Port Hedland, Dampier, Karratha, Exmouth, Onslow, Carnarvon, Geraldton, Perth, and Busselton in WA (Hall et al, 2008). The University of Queensland undertook modelling with ANUGA for the NSW government to examine tsunami propagation within idealised embayment shapes typical of the NSW coast (Baldock et al, 2007). The study concluded that compared to an open coast beach, small embayments with a length in the order of 400m produced 50% to 200% higher run-up for shorter period waves and was dependent on the position of the still water level within the bay. For large embayments (length = 5000m), amplifications up to a factor of 6 were achieved for longer wave periods provide there was no wave breaking. Along the open coast, the run-up is typically 1 to 2 times the offshore amplitude at 20m depth, but can reach up to 4 times the offshore amplitude before breaking occurs (Somerville et al, 2009). The NSW government through the Office of Environment and Heritage and the State Emergency Services has also commissioned Cardno to undertake inundation modelling (Garber et al., 2011).

In Queensland, the primary source of information has been the PTHA and NTHA studies undertaken by GA as described above. In addition, GA undertook inundation modelling using ANUGA for the Gold Coast to illustrate the level of inundation that could occur (Fountain et al, 2009a).

Observations following the 2004 Indian Ocean tsunami have indicated that reefs offshore of Sri Lanka may have reduced the impact of tsunami on the coast (Fernando et al, 2005), whereas reefs closer to the source near Banda Aceh, Indonesia, where the tsunami amplitudes were large, made no significant difference (Adger et al, 2005). Kungel et al (2006) undertook modelling of an idealised circular island with a fringing reef to show that tsunami run-up on the island was reduced by 50% as a result of the protection offered by the reef. Baba et al (2008) examined the impact of the GBR on tsunami propagation by modelling the Solomon Island 2007 tsunami. A nested rectangular grid numerical model using a finite difference scheme to solve the linear shallow water equations was used and validated against water levels recorded by the Queensland Environmental Protection Agency (EPA, 2007). The GBR structure offshore of Cooktown was then removed from the model and the bathymetry smoothly interpolated. The results indicated that the GBR delays arrival time, reduces amplitude and increases tsunami period. However it was noted that a fully non-linear model would be required to test this conclusion for larger amplitude tsunami. The NTHA (Fountain et al, 2009b) also concluded that the GBR provides protection to the mainland, reducing tsunami amplitudes within the GBR lagoon.

4. Bathymetry

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

In 2006, an unstructured mesh of the Queensland coast and GBR was constructed for tidal modelling using DHI Mike21FM (Callaghan et al, 2007). The bathymetry used to create this mesh was based on the 1,000m DEM developed by GA (Petkovic and Buchanan, 2002) in conjunction with the 250m DEM of the GBR (Lewis, 2001).

In 2010, a high resolution 0.001 arc degrees (approximately 100m) DEM of the GBR and Coral Sea (known as the gbr100 DEM developed through Project 3DGBR) was developed by James Cook University (Beaman, 2010). The project was a collaboration of a number of state and commonwealth departments and organisations to develop a detailed 100m grid based on all available bathymetric data including ship-based multibeam and singlebeam echosounder surveys, airborne LiDAR bathymetric surveys, and satellite data, together with GA's 0.0025-arc degree (about 250 m) Australian Bathymetry and Topography Grid (Webster and Petkovic, 2005). Data coverage for this DEM is illustrated in Figure 1.

The gbr100 DEM was adopted for this study. The DEM extents are latitude 10˚ to 29˚ South, and longitude 142˚ to 160˚ East using WGS84 horizontal projection and Mean Seal Level (MSL) vertical datum. For outside this area, the GA 250m grid (GA, 2009) was adopted.

Although the DEM is based on rather detailed bathymetric data along certain areas such as the continental shelf and the numerous reef structures, the nearshore and coastal data is sparse and relies heavily on navigational chart data. Therefore, there is still uncertainty in the accuracy and detail within the coastal zone in depths less than 20m. To improve on this limitation, the gbr100 DEM was supplemented with available beach survey profiles collected by the Qld Beach Protection Authority (BPA) from the early 1970s to the mid-1990s (Figure 2). Transects were surveyed perpendicular to the coast seawards from the coastal dunes to a depth of 10 to 20m. These transect lines were spaced between 50m to 1000m along the coast. One survey date was used for each site that gave the most complete coverage. Details of the BPA surveys included into the DEM are provided in Table 1.

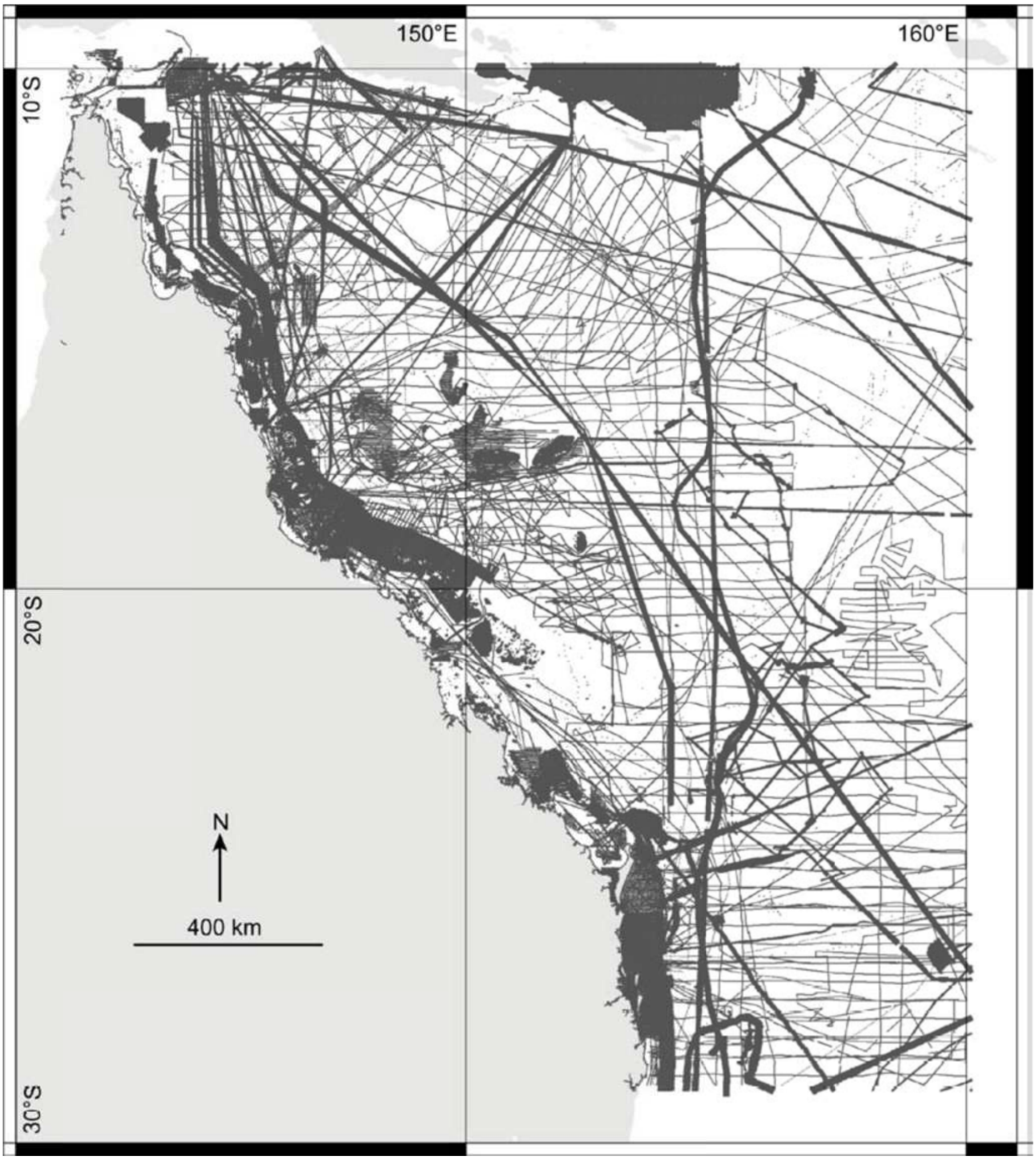

Figure 1 - Bathymetric data used for the gbr100 DEM (Beaman, 2010)

Table 1 - Details of BPA surveys.

Site	Year	Extent of survey				Depth (m AHD)	Data Count
		Latitude	Longitude	Latitude	Longitude		
Airlie	1997	-20.28347	148.68333	-20.26597	148.78511	-11.2	2238
Amity	1984	-27.40526	153.42653	-27.391504	153.43984	-22.7	346
Bowen	1995	-20.00945	148.0801	-19.86476	148.28732	-17.9	5370
Burrum	1998	-25.31483	152.83904	-25.23946	152.94761	-13.2	4333
Cairns	1994	-16.87705	145.67102	-16.73313	145.84233	-13.4	10379
Cardwell	1994	-18.27128	146.01661	-18.22727	146.0672	-22.5	830
Douglas	1999	-16.68253	145.40498	-16.333	145.6436	-18.7	4938
Gold Coast 1	1989	-28.16721	153.52113	-28.15587	153.54653	-14	617
Gold Coast 2	1995	-28.19960	153.49701	-28.13679	153.58251	-29.2	1755
GoldCoast 3	1994	-28.1433	153.435	-28.02564	153.50296	-21.3	1687
Gold Coast 4	1994	-28.0254	153.42875	-27.42371	153.55718	-21.5	683
Hervey Bay	1992	-25.28370	152.87509	-25.27916	152.8892	-2.4	549
Hay Point	1986	-21.31059	149.29261	-21.27399	149.33897	-16.1	824
Isis	1986	-25.17688	152.55073	-25.03301	152.67194	-15.5	1264
Johnstone	1994	-17.50953	146.07604	-17.47761	146.12532	-18.2	1909
Kings Beach	1989	-26.81307	153.13573	-26.8032	153.15607	-15	13645
Livingstone	1996	-23.48850	150.74964	-22.82605	150.93533	-21	15002
Lucinda	1994	-18.54716	146.33205	-18.51068	146.35736	-15.1	1160
Mackay	1992	-21.20965	149.15631	-20.91029	149.34438	-23	7889
Moreton Island	1977	-27.86168	153.32573	-26.98313	153.59258	-62.5	4050
North Coast 1	1988-93	-27.08385	153.1294	-26.82026	153.22673	-20.4	1048
North Coast 2	1993	-26.813	153.12222	-26.68226	153.1596	-19.7	1011
North Coast 3	1975	-26.68269	153.09247	-26.38451	153.14772	-33.9	1082
North Coast 4	1992	-26.38665	153.0866	-26.38187	153.09368	-7.1	266
Point Lookout	1991	-27.44696	153.53766	-27.437889	153.55945	-21	241
Townsville	1983	-19.25286	146.71552	-19.09819	146.88583	-14.2	1783

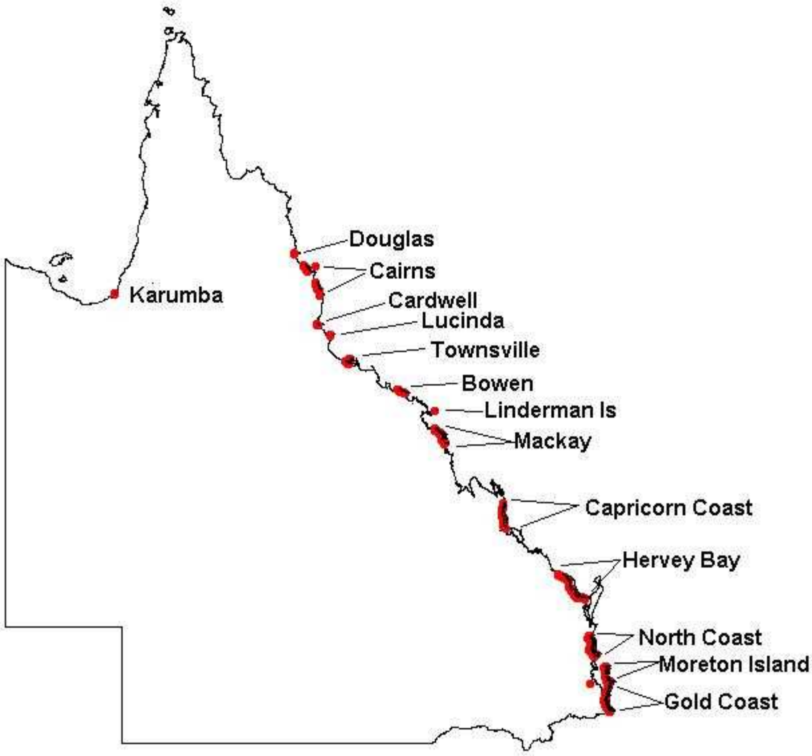

Figure 2 - Location of major concentrations of BPA beach profile lines.

5. Model Implementation

The modelling was undertaken using release 2011 of DHI's MIKE21 flexible mesh hydrodynamic model (MIKE21FM). The hydrodynamic model is based on the numerical solution of the two-dimensional (depth averaged) shallow water equations (DHI, 2010). The model solves the continuity and momentum equations using a cell-centred finite volume method. Unstructured meshes can be generated comprising both triangular and quadrilateral elements in either Cartesian or spherical coordinate systems. An explicit scheme is adopted for time integration.

Despite the limitations described in section 3 for finite volume methods in regards to numerical dispersion and long simulation times, this approach was adopted as it provided the best flexibility for accurately describing the complex Queensland coastline and the GBR as well as handling large model domains due to the inclusion of spherical coordinates.

The solution method is similar to ANUGA (Nielsen et al, 2005) in that both software systems solve the non-linear shallow water equations using the finite volume approach with Riemann solvers. MIKE21FM has the ability to handle larger regional extents given that it can be utilised in either Cartesian or spherical coordinates, whereas ANUGA currently only works in Cartesian coordinates. However, MIKE21FM has the limitation that the mesh generator is 32 bit and so has memory restrictions in terms of the number of mesh elements.

The model domain was chosen to provide reliable results along the east coast of Queensland between Cooktown in the north to Gold Coast in the south. A triangular mesh was adopted to best represent the complex geometry of the GBR and the Queensland coastline. Mesh resolution was adjusted to provide detailed resolution across the GBR and in the nearshore while maintaining reasonable computation times as well as balancing the memory limitations of the software.

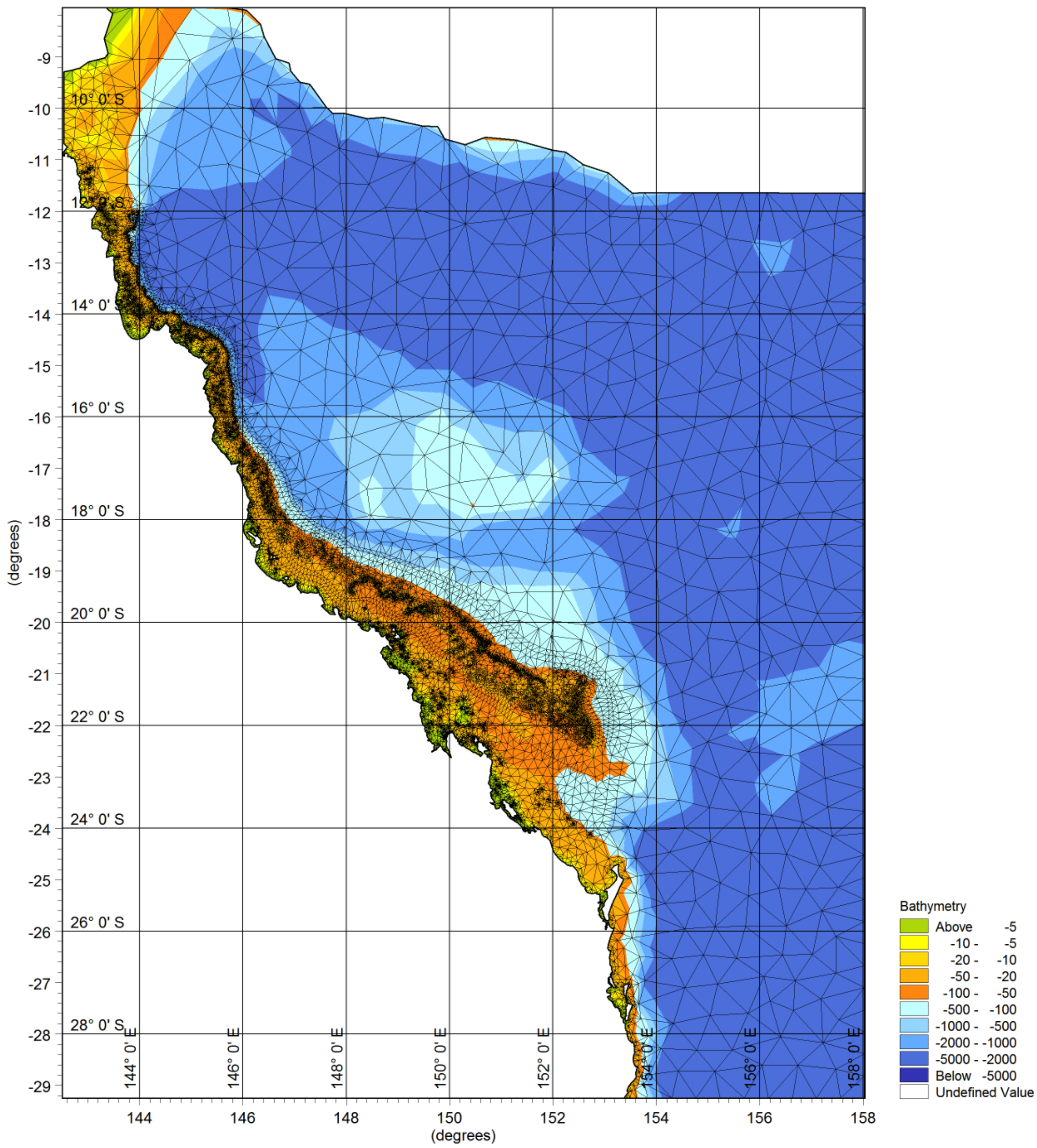

Figure 3 - Original ocean tidal mesh developed in 2006.

The mesh developed for this study is the result of further refinement of an existing mesh of the east Queensland coast produced in 2006 for modelling tides (Callaghan et al, 2007 - refer Figure 3). To optimise computation time by minimising the occurrence of unnecessarily small mesh elements, a process was developed with the original mesh creation to simplify the representation of the numerous small islands along the Queensland coast. The following approach was implemented:

- Islands of less than 1.2 hectares were removed as they had negligible influence on oceanic scale tides but significantly increased computation time;
- Schematised equilateral triangular shapes when island area is less than 10^{-5} °²;
- Schematised rectangular shapes when island area is in the range 10^{-5} °² and 0.001°²; and
- As surveyed when island area exceeds 0.001°².

Given that tsunami modelling requires a finer mesh than for tidal modelling given the shorter periods, mesh development involved refining the representation of the coastline, islands with area greater than 0.001°², and the GBR based on the gbr100 DEM. Given that there are over 750 identified islands along the Queensland coast, there was no further adjustment of the smaller islands. This approach was considered appropriate given the regional nature of this study. However tsunami inundation modelling would require consideration of all geomorphological features.

6. Model Calibration

The mesh developed for tidal modelling (Callaghan et al, 2007) was originally assessed against predicted tides at 72 locations along the east Queensland coast using a number of skill scores being the Index of Agreement (IofA) (Wilmott, 1981), the Mean Error normalised by Highest Astronomical Tide (HAT), the Coefficient of Determination (R^2) (Kreyszig, 1999), and the Coefficient of Efficiency (CofE) (Nash and Sutcliffe, 1970). The skill score classification that was adopted is reproduced in Table 2.

Table 2 - Skill score classification (Callaghan et al, 2007)

Skill score		Skill score classification			
Description	**Range**	**excellent**	**satisfactory**	**Poor**	**reject**
Index of agreement	0–1	>0.95	0.85–0.95	0.5–0.85	<0.5
Mean Error normalised by HAT	-∞–∞	absolute value <2%	absolute value 2–5%	absolute value 5–30%	absolute value >30%
Coefficient of Determination (R^2)	-1–0–1	>0.925	0.85–0.925	0.5–0.85	<0.5
Coefficient of Efficiency	-∞–0–1	>0.85	0.6–0.85	0.4–0.6	<0.4

The skill scores provide a statistical measure of agreement between the observed and modelled data. For the original tidal mesh, verification was undertaken for two spring/neap cycles in January 2000. Tidal constituents provided by the National Tidal Centre define the open boundaries offshore of the coastline and in the Torres Strait. The assessment indicated a satisfactory to excellent reproduction of the predicted tides. About 10% of the model results were considered a poor representation of the predicted tides.

To improve the accuracy, further refinement of the original mesh was undertaken against the gbr100 DEM. This involved refining the coastline and larger island polygons to a regular 500m internode spacing. Care was also taken to improve the representation of channels, passages and bays such as Moreton Bay. The representation of the GBR was manually refined against the finer gbr100 data (refer Figure 4 and Figure 5).

The mesh was again calibrated against tides using 39 days from January to February 2011. The IofA and CofE were used to assess the model, along with the Root Mean Square Error (RMSE) normalised to the amplitude of the Highest Astronomical Tide (HAT) (i.e. HAT - Mean Sea Level (MSL)). The Coefficient of Determination was not used in this study as it can produce an incorrect result for systematic errors (such as consistently over or under-estimating) and is oversensitive to outliers (Dawson et al, 2005). The normalised RMSE criteria adopted was within 10% for excellent agreement, 20% for satisfactory agreement, 30% for poor agreement, and over 30% for rejected.

As expected for tides, the sensitivity of the model related to the representation of the continental shelf, GBR and particularly passages between the reefs, as well as larger scale geomorphological features. Testing of the sensitivity of the tidal modelling to mesh size showed an initial improvement, but further mesh reduction only provided small improvements to the results compared to considerable increase in computation time. This is an expected outcome considering that the modelling is being undertaken on a large regional scale and so small scale features such as tidal inlets and harbours are not included. Larger passages such as Hinchinbrook Channel and the Great Sandy Strait were not calibrated or validated as there was no available data in these regions for comparison.

Calibration therefore concentrated on the roughness parameter and refinement of coastal and bathymetric features such as the GBR.

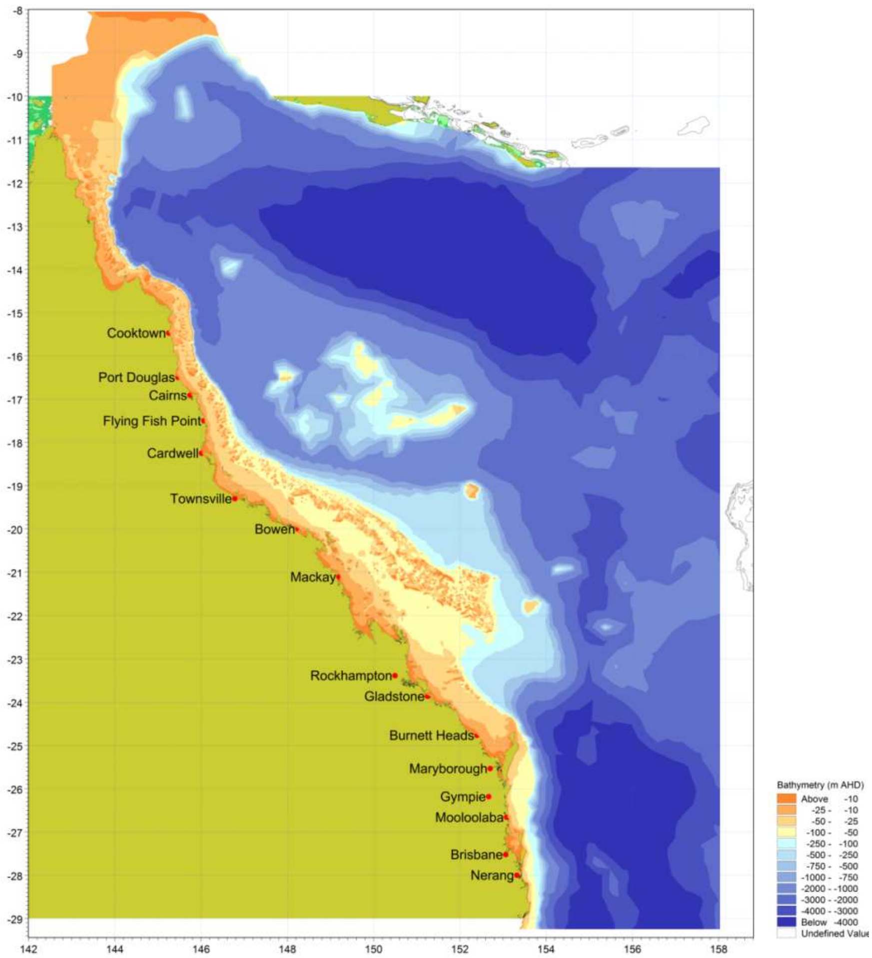

Figure 4 - Bathymetry along the east coast of Queensland adopted for Tidal Model.

The calibration process showed that north of Bowen where the coastal lagoon narrows, the influence of friction on the tidal range is minor compared to correctly representing the tidal exchange through the GBR. However the results compare slightly better with higher friction (i.e. lower Chézy Coefficient, C) in the far North, which is outside the area of interest for this study. The tidal range between Bowen and Hervey Bay, where the continental shelf is the widest, is more sensitive to the friction factor, with the calibration suggesting a higher value of C=60 (i.e. less friction). The Gold Coast region, where the continental shelf is the narrowest, did not show much sensitivity to friction.

Following a number of adjustments to the mesh and friction parameters, the results of the final calibration are summarised in Table 3 and detailed in Appendix A. Given the improved mesh resolution, the number of locations was increased to 83 to include regions that were previously not represented well within the mesh. This is based on a C=30 m$^{1/2}$/s on the GBR, and C=60 m$^{1/2}$/s elsewhere.

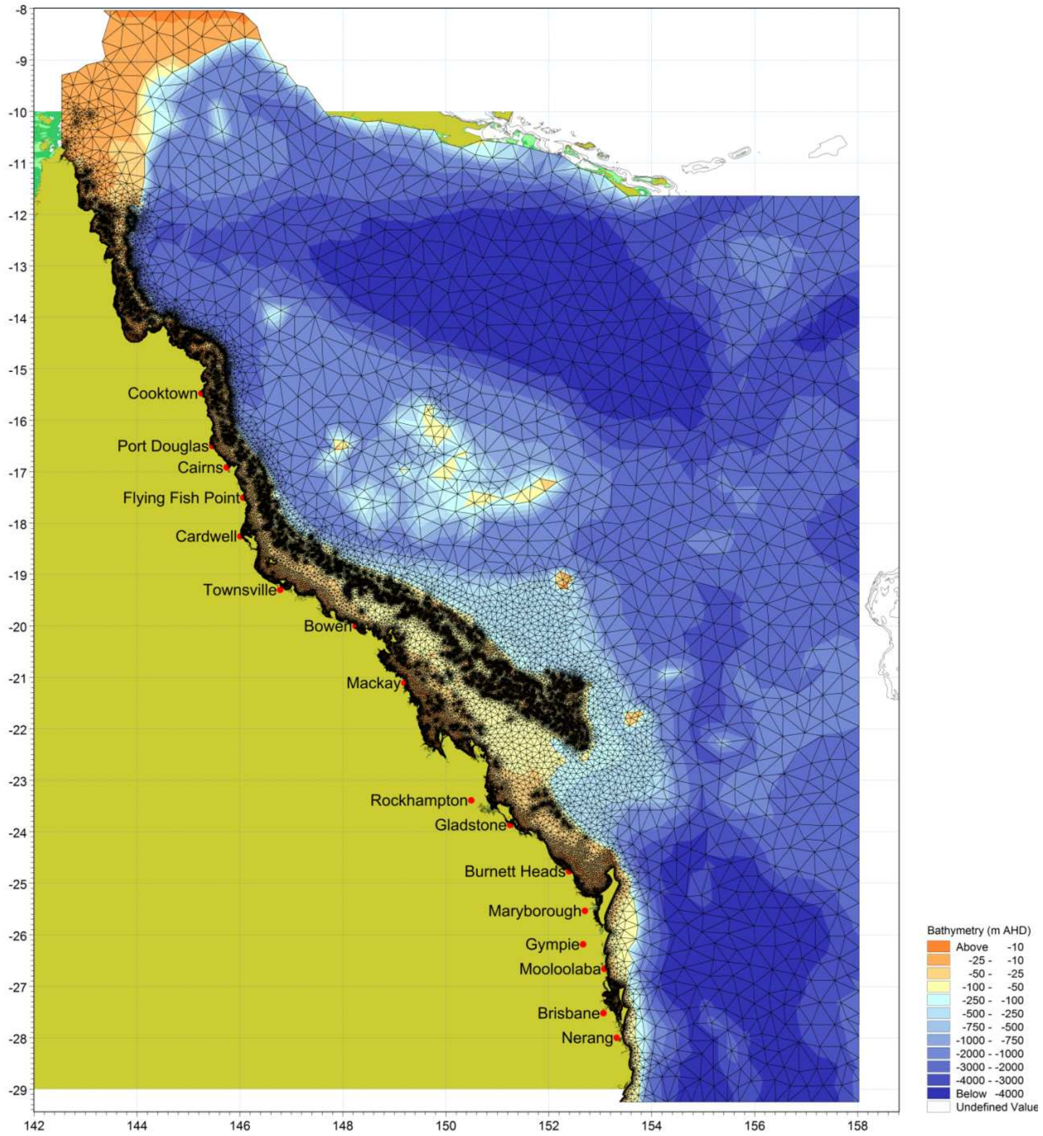

Figure 5 - Mesh used for tidal calibration.

Table 3 - Skill score classification summary for the predictions at 83 locations along the Queensland Coastline.

Classification	Percentage of each classification obtained at the calibration points [%]		
	Norm RMSE	IoA	CofE
reject	0	0	0
poor	0	0	1.2
satisfactory	7.1	2.4	7.1
excellent	92.9	97.6	91.7

As a further assessment of the mesh's ability to predict tides, the major tidal constituents (i.e. O1, K1, N2, M2, and S2) for a number of locations were calculated and compared to the constituents from the measurement gauges. The constituents were calculated with the DHI Mike21 toolbox using the IOS method. Although the constituents calculated from the model results are for a much shorter record length than those from the measuring gauges, they compare well. The main differences occur in the M2 tide for locations north of Bowen, which again indicates that tidal exchange with the GBR is of primary importance in this region. However as these differences are still relatively small and conservative, no further calibration was undertaken as there seemed no merit to artificially adjusting reef structures without understanding the impact on tsunami propagation.

7. Model Validation – 2007 Solomon Islands Tsunami

To examine the validity of using the developed mesh for tsunami application, a tsunami event was modelled and compared to measured water levels along the Queensland coast. Although there is little captured data in Queensland during these events given their rarity of occurrence, the then Queensland Environmental Protection Agency (EPA) were able to update their Storm Tide Monitoring network from 10min to 1min sampling rates during the 2007 Solomon Islands tsunami event.

On Monday 2 April 2007, at about 0640 AEST, an 8.1 magnitude earthquake occurred at Latitude 8.481º South and Longitude 156.978º East as a result of the subduction of the Australia, Woodlark and Solomon Sea plates beneath the Pacific plate. The epicentre of the quake was about 43km south southeast of Gizo in the Solomon Islands, and approximately 540km west northwest of the capital Honiara (EPA, 2007). The tsunami that was generated devastated the local islands resulting in 52 deaths and leaving more than 7,000 Solomon Islanders homeless. Over three hours later, the tsunami started to reach the Queensland coastline. The waves that were measured by a number of tide gauges were of much smaller magnitude. Amplitudes along the east coast of Queensland were typically less than 0.1m with the exception of Clump Point and Rosslyn Bay, which recorded in the order of 0.25m.

The north-eastern boundary of the mesh was adjusted to be more parallel with the wave crest (refer Figure 6). As the tsunami was generated from an earthquake some 500km north of the north-east corner of the mesh, boundary conditions in the form of a varying water level time series along the open eastern boundaries was provided courtesy of GA and consists of a maximum leading wave ranging between 0.7m in the north and 0.05m in the south. The land boundary was defined as a stationary solid boundary with the normal velocity component set to zero. Although the land boundary was based on a GIS shapefile polyline representing 0m AHD, the depths along the boundary interpreted from the gbr100 DEM varied between -1.5m and -15m AHD.

It became apparent through the validation process that as fine a mesh that was feasible was required over the model domain to adequately model the tsunami propagation and to minimise numerical dispersion as described in section 2. Given the 32 bit memory limitation of the mesh editor within the DHI software, a number of combinations of mesh resolutions for the offshore, GBR, nearshore, and inshore regions were examined to obtain the best comparison to the measured maximum tsunami amplitude at the storm tide gauge locations. The finer meshes required better representation of the numerous islands and the GBR structure, given that a number of the rectangular and triangular idealised island shapes were now more significant in the finer mesh.

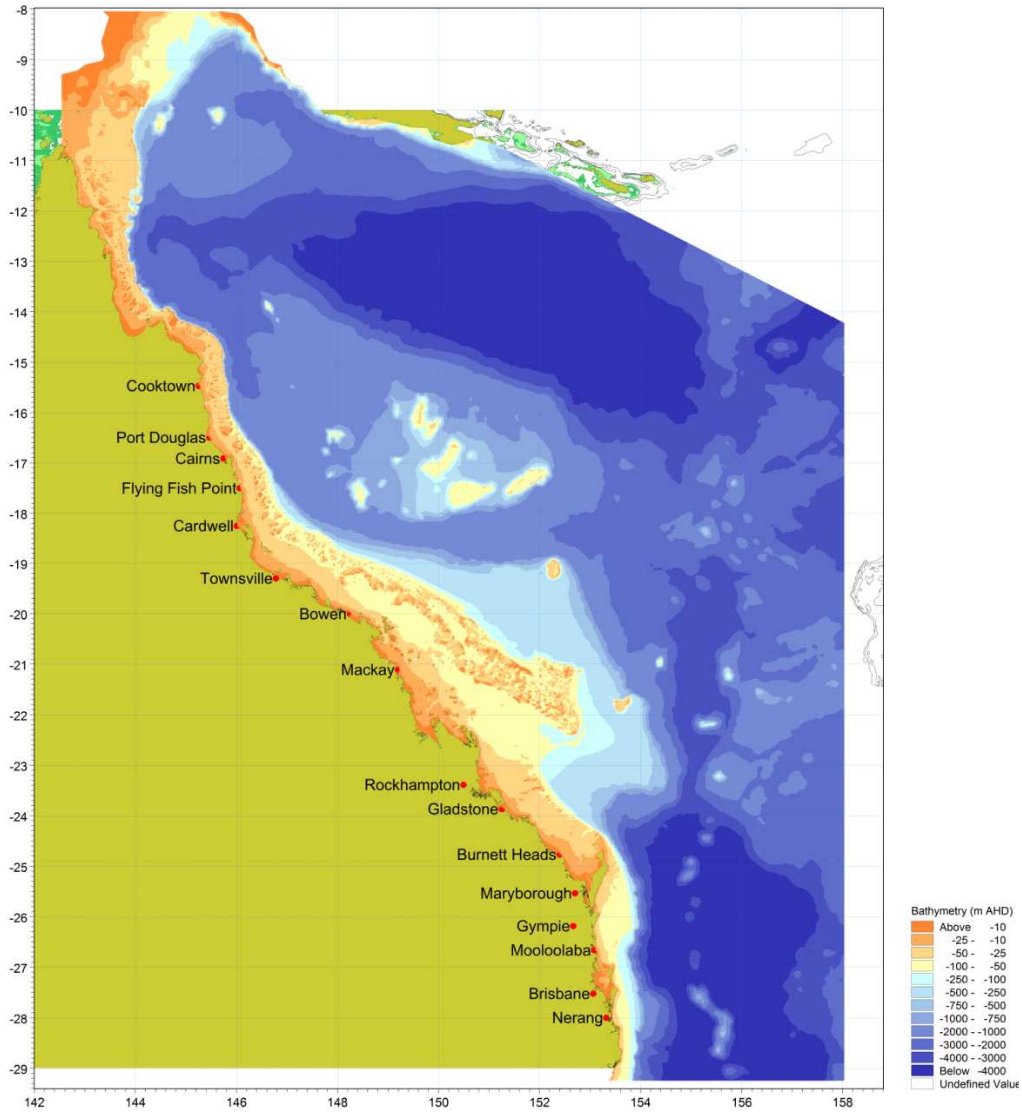

Figure 6 - Mesh domain for 2007 Solomon Islands Tsunami model validation.

Although the mesh editor is limited by the 32 bit memory size, the MIKE21 hydrodynamic engine is 64 bit and so has the capacity to handle much larger meshes. Courtesy of DHI, a Matlab toolbox was utilised that is capable of bisecting the mesh faces, generating four triangle elements to each element in the original mesh. The final mesh was a combination of generating the finest mesh possible given the limitations of the software and bisecting this, resulting in 1,179,240 triangular elements with areas generally ranging from 17km^2 offshore to 31,000m^2 near the coast. This equates approximately to a maximum equivalent spatial resolution of 6km offshore to 250m along the coast. Finer meshes with equivalent spatial resolutions down to 50m were incorporated in the vicinity of storm tide gauge locations. An example of the mesh is provided in Figure 7. The modelling was undertaken with a constant still water level at mean sea level (MSL). To consider the impacts of the stage of tide given the variation in arrival time along the coast, the modelling was also undertaken for MSL + 1m. As the modelling utilises an explicit numerical scheme, the computation time based on a dual 4 core 3.07 GHz Xeon processor took 25.8hrs to simulate 12hrs of prototype time.

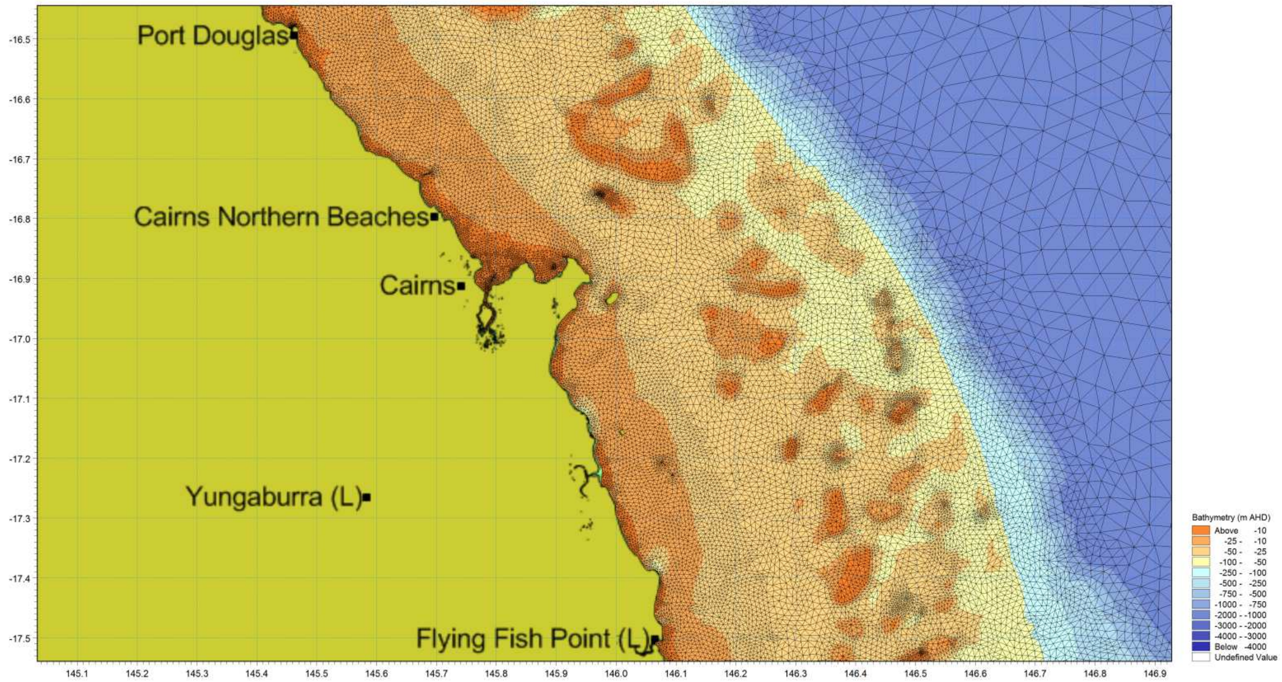

Figure 7 - Mesh geometry near Cairns.

The results of the validation are provided in Appendix B and are summarised in Table 4 in terms of the maximum amplitude and Table 5 for arrival times. As described in Table 4, the tide gauges are located within shallow water, with a number of them situated within waterways and harbours. The tsunami propagation will be more sensitive than tides to the complex bathymetry associated with these coastal features. The nearshore zone is a dynamic environment that continuously adjusts to meteorological conditions. The bathymetry adopted in the model is not of fine enough resolution or high accuracy in the nearshore zone to effectively capture these small scale features such as surf zone bars and ebb shoals or the interaction of the tsunami with semi-enclosed harbours. There is also some uncertainty associated with the boundary water level time series as there were no offshore measurement sites in the Coral Sea to validate against, and as described in Pedersen et al (2005) and Luger and Harris (2010), it is possible that there may be some numerical dispersion with a 6km offshore mesh resolution. Sensitivity testing demonstrated that the model became too dispersive when the offshore mesh resolution was increased.

Despite these limitations, the modelled results provide good agreement with the measured data in terms of arrival times, wave periods, and the maximum amplitude for the majority of sites that were compared. Figure 8 provides an example of the measured and modelled water level time series for Cooktown. As can be seen, the modelled leading wave compares well with the measurements. However for this and a number of other sites (refer Appendix B), the maximum modelled amplitude occurs from a subsequent wave. Given the leading wave is the largest along the forced boundaries; it is possible that the boundary conditions may have introduced wave reflections and/or resonance into the model results.

The sites that experienced the largest underestimation of the maximum amplitude were the two sites that recorded the highest tsunami wave height: Clump Point and Rosslyn Bay. The Rosslyn Bay tide gauge is located within a semi-enclosed boat harbour and so the differences could be associated with interactions with this structure. The Clump Point site, like Bowen and Shute Harbour, is an open coast site suggesting that the bathymetry adopted for the mesh does not fully represent the actual condition at this site.

Table 4 – Maximum amplitude for select tide sites following the 2007 Solomon Islands tsunami.

Site	Location	Measured Maximum Amplitude (m)	Model (MSL) (m)	Model (MSL+1m) (m)
Cooktown	Railway wharf, Endeavour River entrance	0.14	0.17	0.18
Mossman River	Newell Beach Public Jetty, Mossman River	0.11	0.15	0.16
Port Douglas	Port Douglass Marina, Packers Creek	0.11	0.16	0.15
Cairns	Cairns Harbour, Trinity Inlet	0.09	0.13	0.23
Mourilyan Harbour	Mourilyan Harbour Wharf, Moresby River	0.11	0.06	0.06
Clump Point	Clump Point Jetty on the open coast	0.24	0.10	0.09
Cardwell	Cardwell Jetty on the open coast.	0.06	0.11	0.08
Lucinda (Offshore)	Lucinda Point wharf on the open coast.	0.08	0.05	0.08
Townsville	Within Townsville Harbour	0.13	0.07	0.09
Cape Ferguson	Cape Ferguson jetty on the open coast	0.11	0.09	0.09
Bowen	Main cargo wharf on the open coast	0.10	0.15	0.17
Shute Harbour	Within Shute Bay	0.06	0.15	0.13
Mackay Outer Harbour	Within Mackay Outer Harbour on Pier No 1	0.07	0.06	0.05
Hay Point	Hay Point wharf on the open coast	0.06	0.06	0.06
Rosslyn Bay	Within Rosslyn Bay boat harbour	0.28	0.16	0.17
Port Alma	Port Alma cargo wharf, Raglan Creek	0.07	0.07	0.13
South Trees Wharf	Within Port Curtis protected by Facing Island	0.03	0.11	0.09
Burnett Heads	Within Burnett Heads boat harbour	0.09	0.12	0.10
Urangan	Within Urangan Boat Harbour, Great Sandy Strait	0.06	0.06	0.06
Mooloolaba	Pilot jetty within Mooloolah River	0.12	0.10	0.13
Gold Coast Seaway	Within the Broadwater	0.10	0.04	0.05
Gold Coast Seaway Entrance	Model point on the open coast near Seaway entrance	-	0.12	0.11

Table 5 provides the measured and modelled arrival times relative to the time of the earthquake for a number of the tide sites. The arrival time is defined as the time when the leading edge of the tsunami deviates by more than 1cm from MSL. Determination of the recorded arrival times for some of the measured sites was complicated by the tsunami amplitude being comparable in magnitude to the background meteorological fluctuations preceding the event. Given the limitations described above, the modelled arrival times compare well with the measured times, with differences averaging 4 minutes.

Table 5 – Tsunami arrival times following the 2007 Solomon Islands earthquake for select tide sites.

Site	Measured Arrival Time (h:min)	Model (MSL) Arrival Time (h:min)
Cooktown	3:27	3:27
Cairns	3:50	3:49
Clump Point	3:50	3:53
Cardwell	4:46	4:42
Townsville	4:49	4:46
Cape Ferguson	4:34	4:32
Bowen	4:49	4:50
Mackay Outer Harbour	5:17	5:24
Rosslyn Bay	5:58	5:54
South Trees Wharf	5:36	5:30
Urangan	5:38	5:26
Mooloolaba	4:11	4:09
Gold Coast Seaway	4:28	4:20

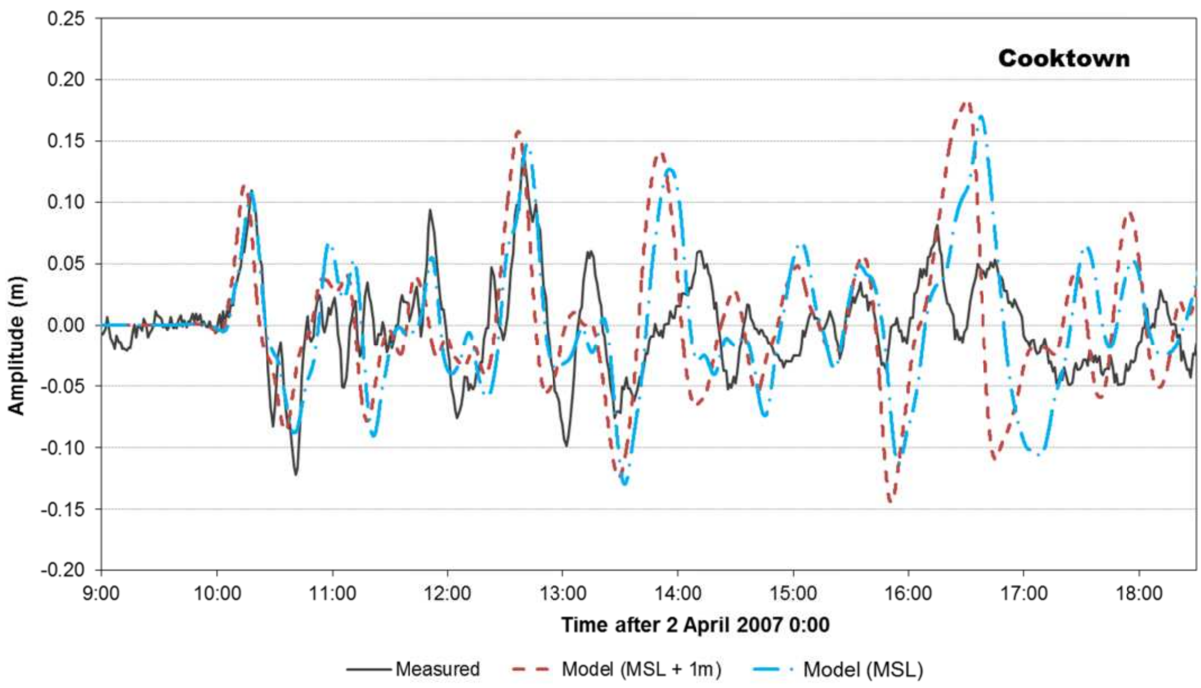

Figure 8 - Comparison of measured and modelled tsunami amplitude for Solomon 2007 event at Cooktown Storm Tide Gauge.

Seven cross-sections were extracted from the model runs to examine the tsunami propagation in terms of the maximum amplitude. An example is provided in Figure 9 for a section extracted just north of Townsville. All seven sections are provided in Appendix B. As the offshore amplitude is only small (less than 6cm), there is no notable influence of the GBR other than fluctuations in the amplitude as the waves travel over the complex bathymetry. For all sections, most of the shoaling occurs in depths less than 25m. But again, this was a small event on the Queensland coast and so no generalised conclusions can be made on the influence of the GBR on tsunami propagation.

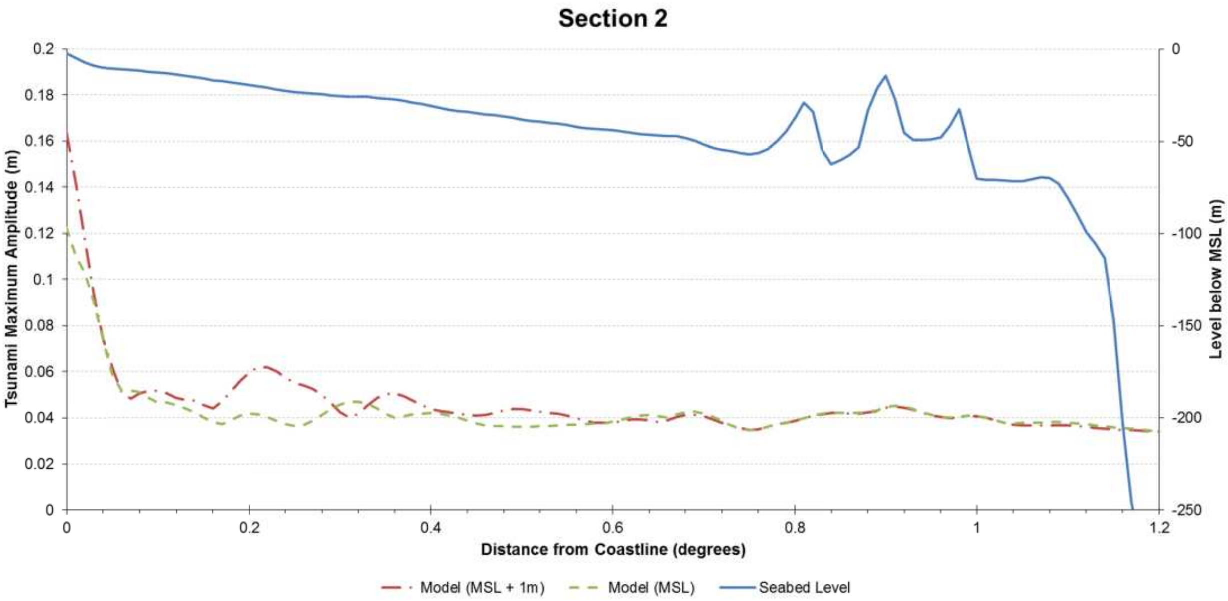

Figure 9 - Modelled maximum tsunami amplitude for the Solomon 2007 event along a profile north of Townsville.

In general, the validation exercise for the 2007 Solomon Island tsunami event supports the use of MIKE21FM and the developed mesh for tsunami propagation studies along the east coast of Queensland. Taking into consideration the findings of this validation, the final regional meshes will be of finer mesh resolution and the results will not extend shallower than 10m depth. It is noted though that this validation has relied solely on one event.

8. Tsunami Nearshore Amplification

The validation process highlighted that a fine mesh is required in the nearshore to fully model tsunami shoaling over the GBR and within the complex bathymetry of the GBR lagoon. To optimise mesh resolution, two model domains were developed representing the two distinctly different bathymetric regions along the east Queensland coast. The first domain (GBR mesh) represents the GBR from Cooktown in the north to Hervey Bay in the south (Figure 10). The second domain (SEQ mesh) represents the narrower continental shelf region of south-east Queensland from Fraser Island to the Queensland and NSW border (Figure 12).

The GBR mesh comprised 1,021,088 triangular elements with areas ranging from 600,000m^2 offshore to 30,000m^2 near the coast or a spatial resolution of 1km to 250m. The SEQ mesh comprised 337,854 triangular elements with areas ranging from 110,000m^2 offshore to 60,000m^2 near the coast or a spatial resolution of 470m to 350m. Offshore of the Sunshine Coast, the mesh was limited to a maximum area of 50,000 m^2 or an equivalent length of 320m. These mesh resolutions were considered appropriate based on tsunami wave periods ranging between 10 and 30 minutes.

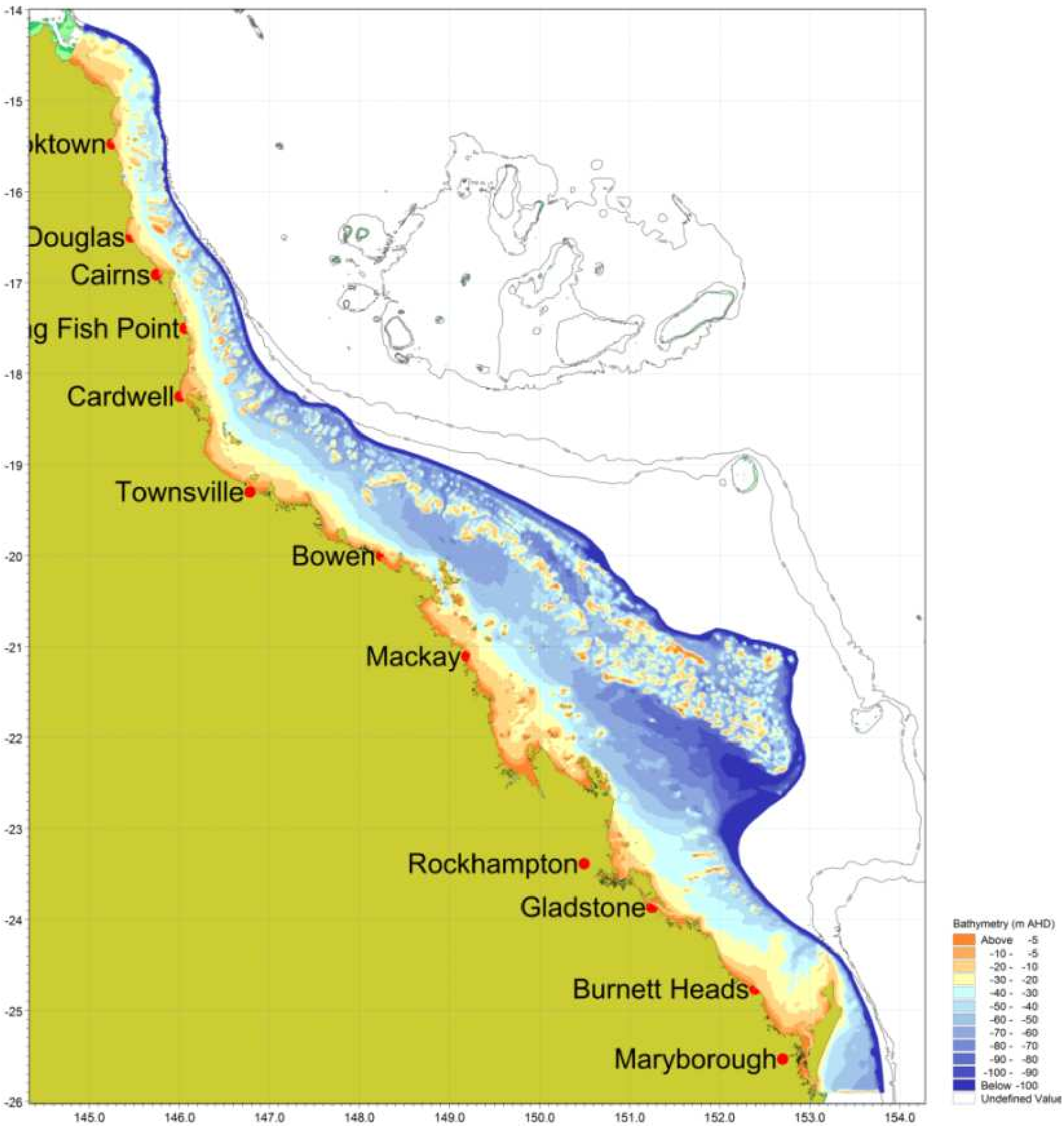

Figure 10 – GBR mesh.

Two finer meshes were also created for Hervey Bay, being the region of transition from the GBR mesh and the SEQ mesh, and the Gold Coast, being the region where the continental shelf is the narrowest. The Hervey Bay mesh extends from Curtis Island to Caloundra (Figure 11) with 275,085 triangular elements ranging from 110,000 m^2 (about 470m) to 60,000 m^2 (about 350m). The Gold Coast mesh (Figure 13) extends from Mooloolaba to Evans Head with 147,939 triangular elements ranging from 50,000 m^2 (about 320m) to 40,000 m^2 (about 280m).

As previously described, the NTHA undertaken by GA (Fountain et al, 2009b) limited the nearshore results to 20m depth contour based on discrepancies in shallower water between model results from using the GA 250m grid compared to more detailed survey data in WA. As this model has used a finer DEM and based on the promising validation results, amplification factors have been extended to the 10m depth contour.

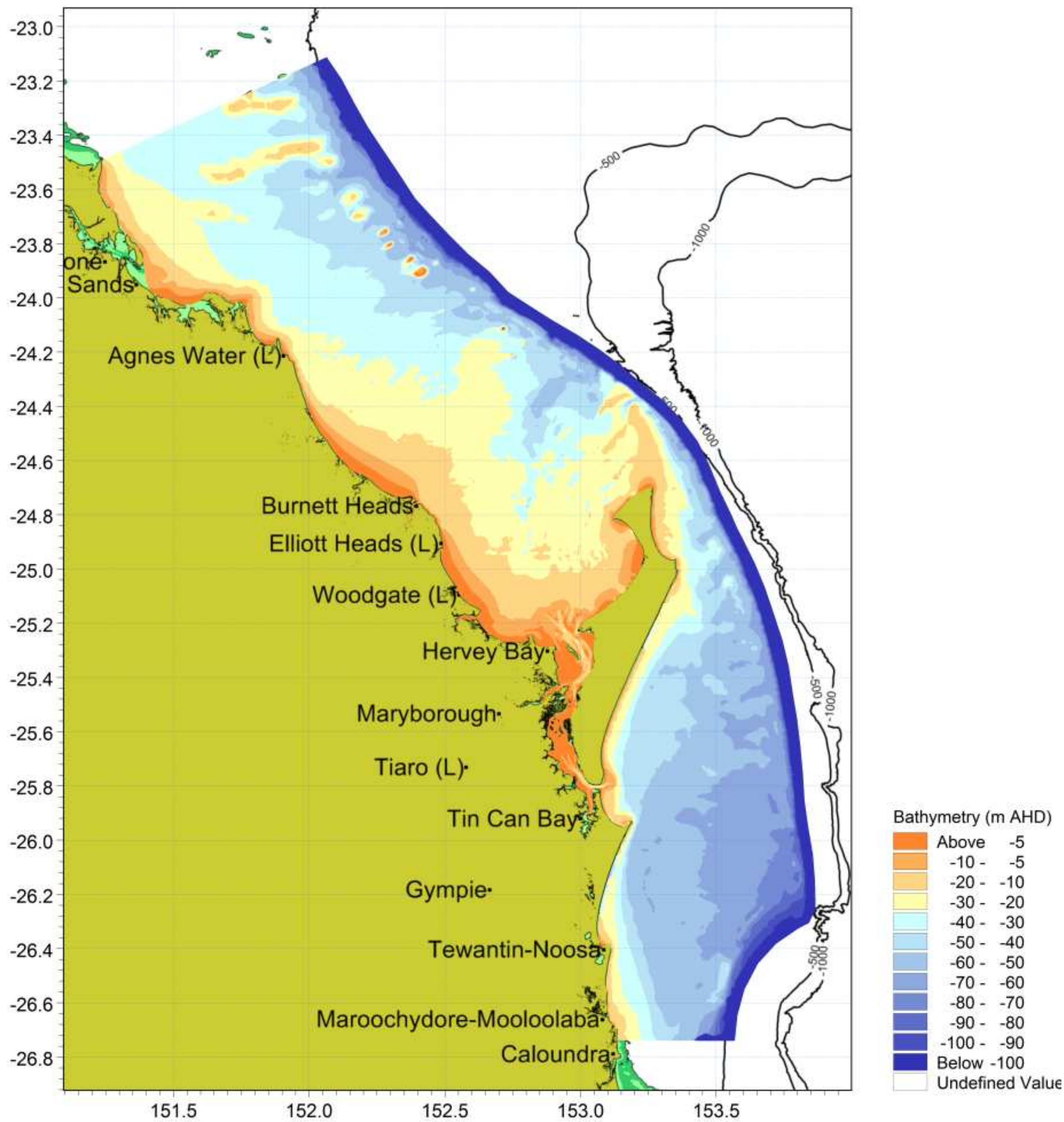

Figure 11 - Hervey Bay mesh.

The inshore boundary was limited to 3m depth in the GBR model and 5m depth in the SEQ model to avoid wetting and drying processes that would increase simulation times given the size of the mesh. This approach was considered reasonable given that the results would be limited to the 10m depth contour. There is potential for reflected waves with this approach but such affects would potentially provide for a more conservative result. Given the uncertainties associated with model validity with larger events, this assumption seemed plausible.

The methodology adopted follows the approach provided in the NTHA study (Fountain et al, 2009b). The following extract from the NTHA study describes the methodology. *"Three synthetic events were simulated for each model; that is, they were altered from the modelled events in the PTHA so are no longer "real" events. Where tsunami events from the PTHA generate an irregular wave at the ocean boundary of the model (that is, with varying wave heights and momentum* *across the ocean boundary), the synthetic events used were altered so that they had a uniform wave across the ocean boundary (i.e. a uniform wave height and momentum). The events were generated by applying a single waveform from an event selected from the PTHA uniformly across the whole ocean boundary, thus providing a standardised synthetic wave with frequency and momentum characteristics of a real tsunami event. This method was chosen to isolate the effects of the continental shelf on tsunami propagation, as any variations in wave height obtained within the model must be due to effects of the shelf bathymetry, rather than from propagation effects between the earthquake source and the 100 m contour, which normally leads to an irregular incoming wave."*

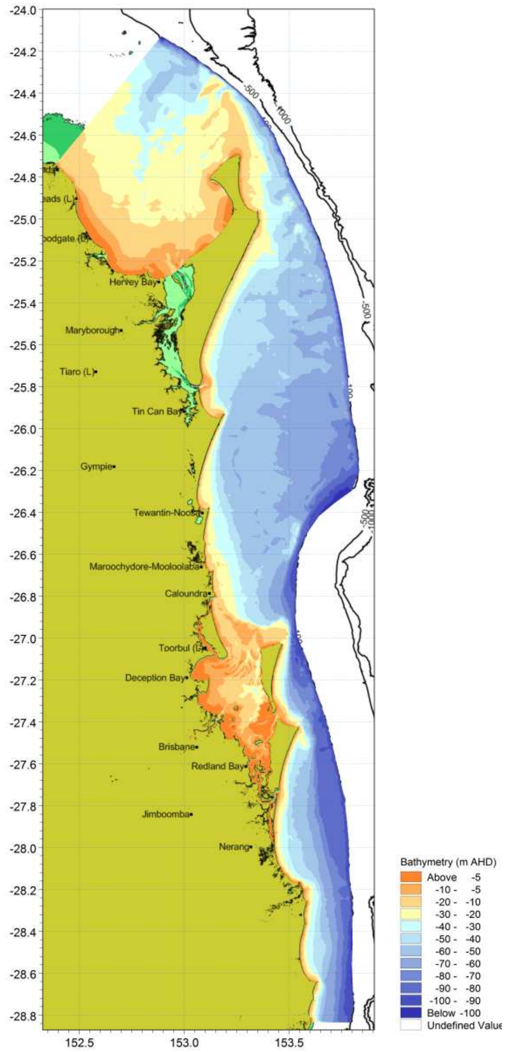

Figure 12 - SEQ Mesh.

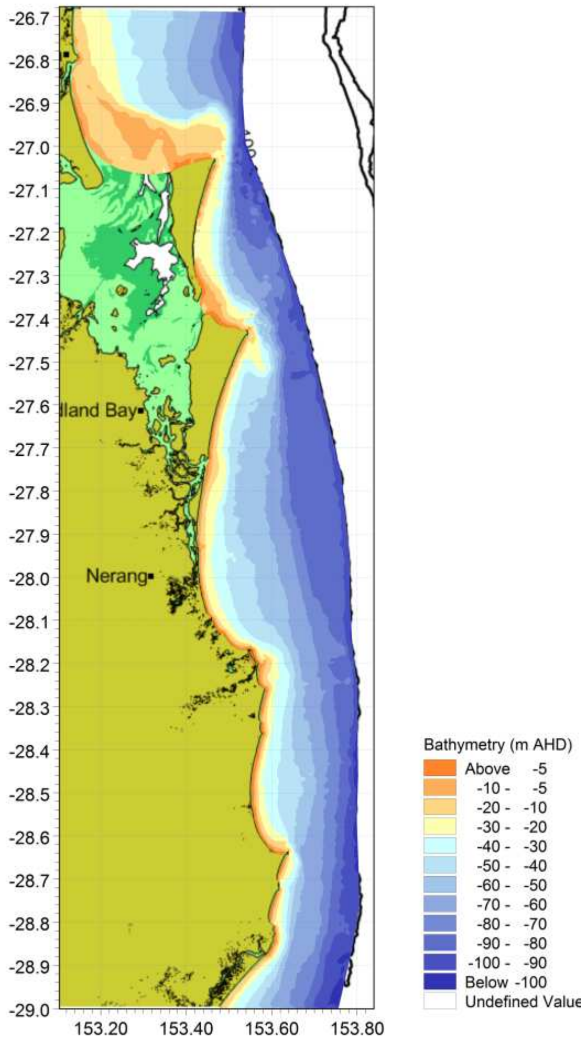

Figure 13 – Gold Coast mesh.

The offshore boundary was set along the continental shelf at 100m depth to correspond to the output locations for the deep-water PTHA by GA (Burbidge et al, 2008a). Boundary conditions were obtained for three events for each of the GBR and SEQ meshes. The scenarios were determined from TsuDAT, a tool created by GA (2010) to allow for the extraction of synthetic events from the PTHA at defined hazard points along the 100m depth contour based on user defined criteria of area of interest, average recurrence interval (ARI), and subduction zone. As the probabilistic assessment varies for each hazard point, one hazard point within the area of interest was selected to define the return period statistics for event selection. For this study, a hazard point approximately mid-way along the GBR and SEQ mesh was selected (longitude 149.55° east, latitude 19.3° south for the GBR mesh and longitude 153.567° east, latitude 26.6° south for the SEQ mesh).

Examination of TsuDAT showed that the pre-defined sub-faults along the South East Solomons Trench have the highest contribution to the hazard at the selected GBR mesh hazard point (refer Figure C- 1), and the New Hebrides Trench has the highest contribution to the hazard at the selected SEQ mesh hazard point (refer Figure C- 3). The location of these trenches is shown in Figure 14.

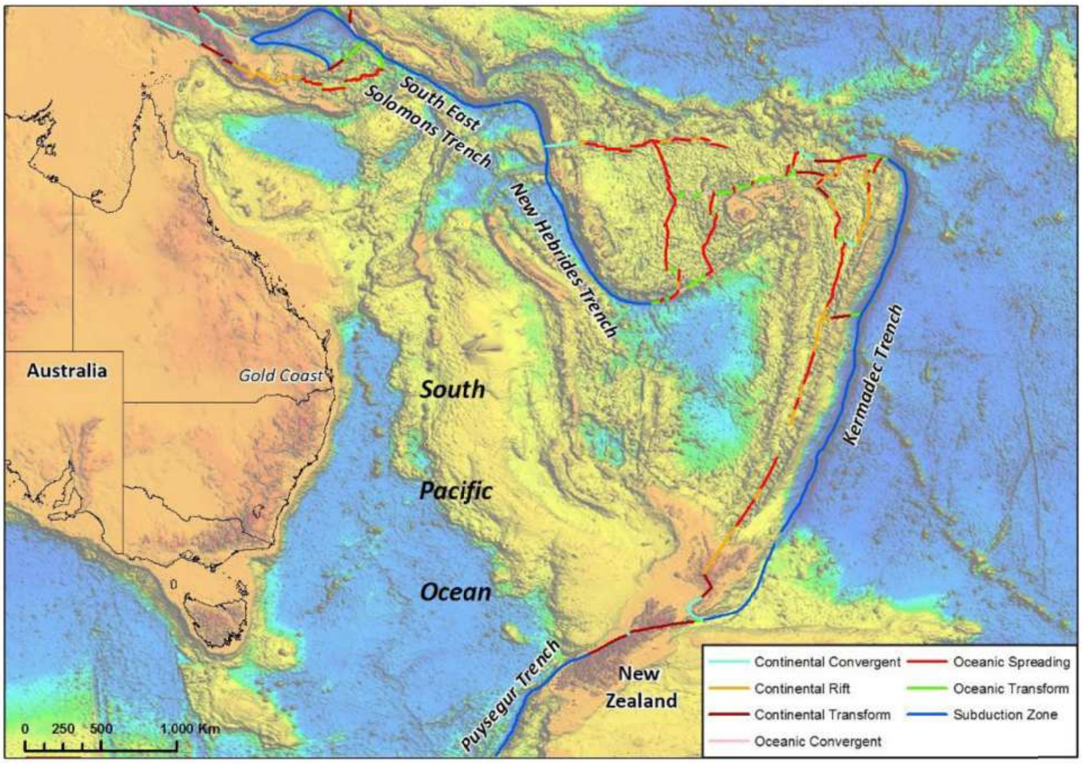

Figure 14 – Location of subduction zones influencing the east Queensland coast (Burbidge et al, 2008a).

TsuDAT provides a time series of water level and momentum along the two major axes (uh and vh). Three synthetic events were arbitrarily selected for each model domain representing a range of return periods for the selected hazard point (refer Table C- 1 and Table C- 2). The water level time series were then applied uniformly along the boundary so that the modelled amplitudes would be influenced only by the nearshore bathymetry and not by variations in the continental shelf along the boundary. This approach therefore provides a simple mechanism to normalise the resulting maximum amplitude maps to produce amplification factors. The momentum component from TsuDAT was not incorporated into the boundary condition as a uniform value along the full domain was not considered representative given the changing orientation of the continental shelf along the model domain. The tsunami return periods provided in Table C- 2 are based on the given maximum amplitude at MSL.

An amplification factor map of the maximum amplitude across the model domain was then produced for each event, normalised to the maximum amplitude in the boundary time series. These three maps were then averaged to produce an overall amplification factor map for each model domain.

Initial testing of the models showed a rapid attenuation of the tsunami time series a short distance from the boundary for the GBR model domain. This issue did not appear in the SEQ model domain, suggesting that it was a result of the boundary being located on the very steep offshore edge of the GBR. The offshore boundary for the GBR model domain was therefore extended a further 4 km offshore and a constant bed level was set with a transition zone to the 100m depth contour. This approach stabilised the offshore boundary so that there was minimal change in the tsunami amplitude at the 100m depth contour.

The model results are provided in Appendix C and are summarised in Table 6 and Figure 16 to Figure 23. As with the validation stage, seven cross-sections were extracted from the model runs to examine the tsunami propagation in terms of the maximum amplitude. An example is provided in Figure 15 for a section extracted just north of Townsville. All seven sections are provided in Appendix C. For all sections, the shoaling occurs in depths less than 20m with the greatest amplification in depths less than 5m to 10m. For all sections within the GBR domain (i.e. sections 1 to 5), the GBR effectively dissipates the tsunami so that the amplification factors are below 1 along the 10m depth contour. The sections also demonstrate a slight decrease in the amplification factor with increases in the boundary tsunami amplitude suggesting that the dissipating influence of the GBR increases with increasing tsunami height. This is particularly so when we consider the results of the validation stage which suggests amplifications factors above 2 in the GBR region for small offshore amplitudes of less than 0.1m that can propagate over the GBR with little disturbance.

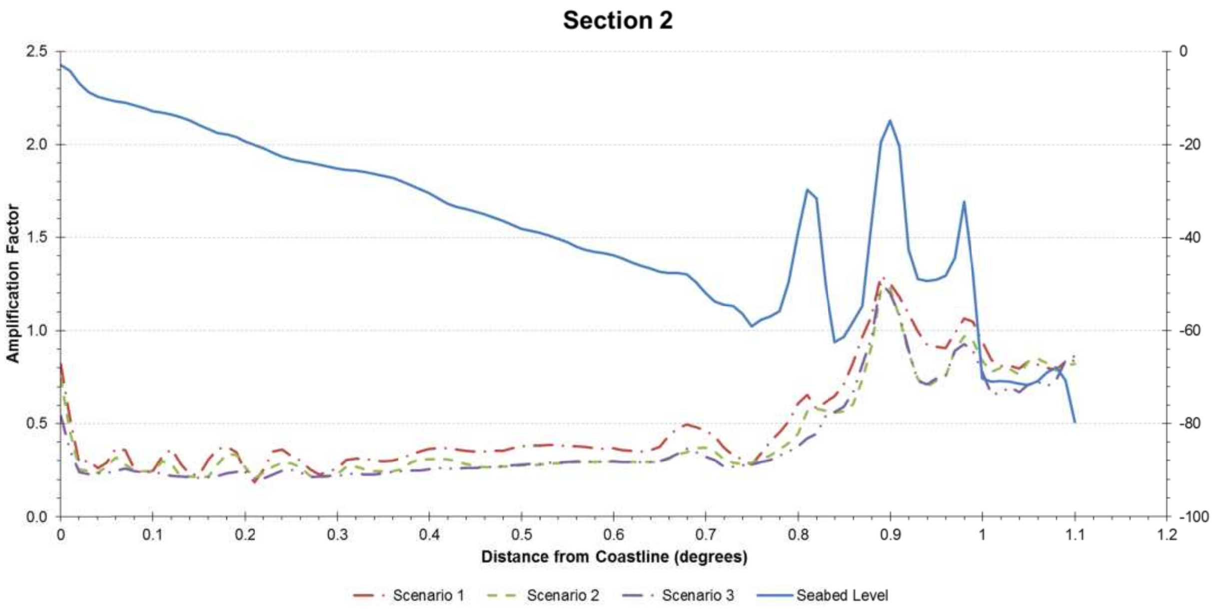

Figure 15 - Amplification Factor for Section 2, north of Townsville.

Conversely, the sections within the SEQ model domain show an increase in the amplification factor with increasing tsunami amplitude. The amplification factors are also above 1, with the largest factors occurring from Moreton Island south.

Table 6 provides the range of amplification factors for a number of regional centres along the coast. The table is based on extracting the amplification factors at approximately 100m spacing along the 10m and 20m depth contour for a stretch of coastline that represents the region of interest for each of the three scenarios. An overall minimum, maximum and average was then calculated.

When comparing the 20m depth amplification factors in this table to table 1 in the NTHA (Fountain et al, 2009b), Table 6 provides a wider range of factors for each site. There are also differences in the magnitude of the amplification factors for a number of locations with this study providing smaller amplification factors for Lucinda, Mackay, Gladstone and Hervey Bay, and higher amplification for Cooktown and Flying Fish Point (Innisfail). These differences could be attributable to a number of factors including differences in: the bathymetric data sets used; the mesh resolution; the boundary time series; and the regional extents for extracting the amplification factors for each location.

Table 6 – Maximum amplification Factors for all Modelled Scenarios.

Site	Arrival Time* (h:min)	Amplification Factor at 10m depth (m)		Amplification Factor at 20m depth (m)	
		Range	Average	Range	Average
Cooktown	0:54	0.3 to 0.4	0.4	0.2 to 0.5	0.4
Port Douglas	1:00	0.1 to 0.4	0.4	0.1 to 0.3	0.3
Cairns	0:49	0.2 to 0.4	0.4	0.1 to 0.4	0.4
Flying Fish Point / Etty Bay	0:53	0.3 to 0.8	0.6	0.2 to 0.6	0.4
Cassowary Coast (Mourlyan to Tully)	1:02	0.1 to 0.4	0.3	0.2 to 0.6	0.4
Cardwell	1:10	0.1 to 0.4	0.3	0.1 to 0.3	0.3
Lucinda	1:09	0.2 to 0.5	0.4	0.2 to 0.3	0.3
Townsville	1:35	0.1 to 0.4	0.4	0.1 to 0.4	0.4
Bowen	1:34	0.2 to 0.4	0.3	0.2	0.2
Airlie Beach	1:36	0.1 to 0.3	0.2	0.1 to 0.2	0.2
Laguana Quays	2:29	0.1	0.1	0.1	0.1
Mackay	2:30	0.1 to 0.3	0.3	0.1 to 0.2	0.2
Hay Point	2:38	0.2 to 0.3	0.3	0.1 to 0.3	0.3
Capricorn Coast	1:51	0.1 to 0.6	0.5	0.1 to 0.5	0.5
Gladstone / Tannum Sands	1:36	0.1 to 0.3	0.2	0.1 to 0.3	0.3
Seventeen Seventy	1:00	0.2 to 0.6	0.5	0.2 to 0.4	0.4
Bundaberg	1:19	0.2 to 1.1	0.8	0.2 to 1.0	0.8
Hervey Bay	1:24	0.1 to 0.5	0.4	0.1 to 0.5	0.5
Fraser Island	0:50	0.6 to 2.3	1.7	0.5 to 2.0	1.6
Sunshine Coast	0:34	0.6 to 1.9	1.5	0.6 to 1.4	1.2
Bribie Island	0:40	0.4 to 1.4	1.1	0.5 to 1.1	0.9
Moreton Bay	0:59	0.1 to 0.5	0.5	0.1 to 0.4	0.3
Moreton Island	0:11	0.6 to 2.4	1.9	0.6 to 2.0	1.6
Stradbroke Islands	0:12	0.9 to 3.0	2.4	0.9 to 2.5	2.0
Gold Coast	0:21	0.9 to 2.3	2.1	0.8 to 2.0	1.9

*Arrival time refers to the average time it takes the leading wave (defined as a deviation of 1cm from MSL) to travel from the 100m depth contour to the 10m depth contour.

In most cases, this difference has minimal influence on the resulting hazard given in most cases it is a reduction in tsunami amplitude. However, the differences in results for Hervey Bay and Flying Fish Point (Innisfail) could benefit from further investigation as to the reason.

Table 6 also provides amplification factors at the 10m depth contour for each site. When compared to the factors for the 20m depth contour, generally there is little change to the amplification factor within the GBR domain (less than a 0.1 increase). South of Fraser Island, the amplification factor increases by up to 0.4 in some locations. However as mentioned above, the sections analysed suggest that shoaling occurs in depths less than 10m.

Appendix C also provides indicative estimates for the amplification factor of specific points at 5m depth. This data has been included to provide an indicative increase to the amplification factor close to the coast. However, care should be taken in using this data given that the accuracy and resolution of the bathymetric data may not sufficiently represent the complex conditions that can exist in the surf and nearshore zone as demonstrated with the validation results for Clump Point and Rosslyn Bay. In addition, the data provided in Appendix C is only for a specific point within the model domain. As Table 6 has demonstrated, the modelled amplification factor can vary substantially along the coast. Generally, the 5m depth amplification factors show further shoaling of the tsunami with small increases in the amplification for locations within the GBR lagoon, and more notable increases south of Fraser Island. Of particular note for the GBR domain would be Flying Fish Point where the amplification factor increases to 1.2. For SEQ the increase reached an amplification factor of 3.5.

Moreton Bay is the one exception for SEQ. The protection offered by Moreton and Stradbroke Island as well as the extensive shoals between Moreton and Bribie Islands serve to attenuate the tsunami amplitude within the bay. The amplitude is reduced the most in the southern extent of the bay, with less dissipation northwards such that Redcliffe indicates an amplification factor of 0.8 in 5m depth.

The arrival times provided in Table 6 are indicative of the time it takes the leading wave to travel from the 100m depth contour to the 10m depth contour. According to shallow wave theory, the speed of the wave is proportional to water depth according to the relationship $c = \sqrt{gd}$ where c is wave celerity, g is gravitational acceleration and d is water depth. The shallow nature of the GBR lagoon substantially slows down the tsunami with travel times in the order of 50 minutes in the north to up to 2 hours 38 minutes around Hay Point where the continental shelf is the widest. Outside the GBR lagoon where the continental shelf is narrower and deeper closer to shore (i.e. SEQ) the arrival times are 10 to 20 minutes. However this analysis is based on synthetic events that are assumed to reach the continental shelf at the same time along the entire Queensland coast. In reality the time the tsunami reaches the 100m depth contour will vary along the east Queensland coast and is dependent on the source location for the earthquake.

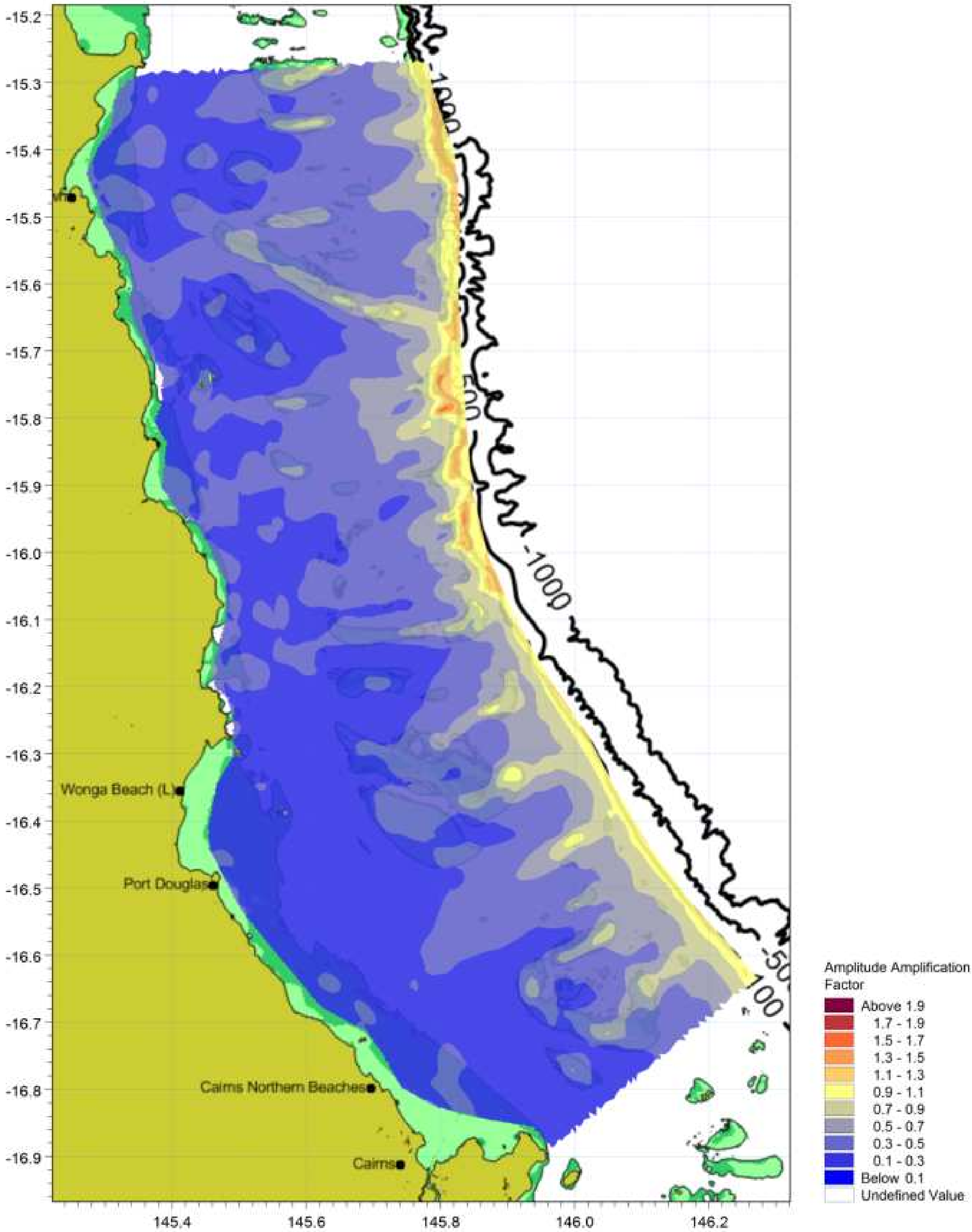

Figure 16 Amplification factor (average of all Scenarios) below 10m depth for Cooktown to Cairns.

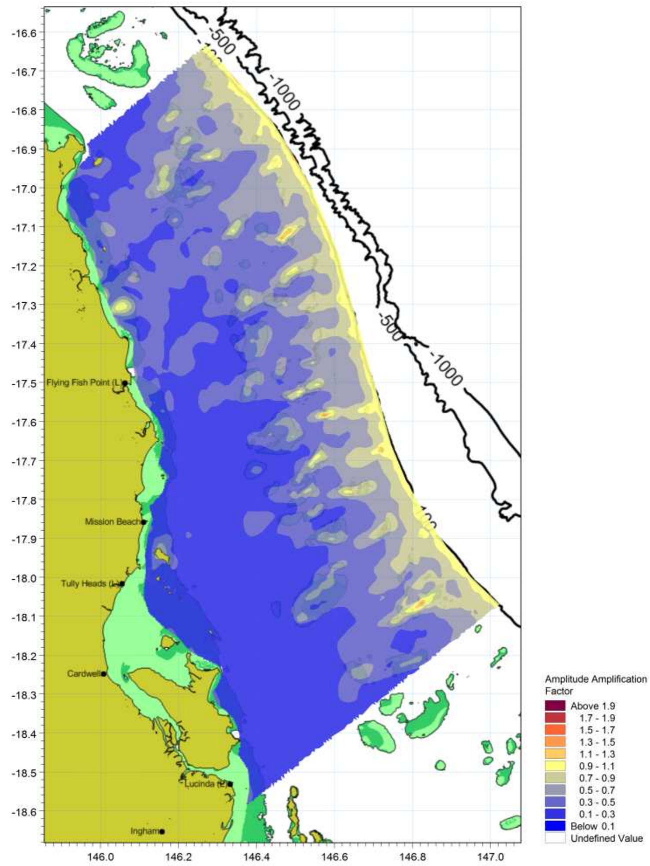

Figure 17 Amplification factor (average of all Scenarios) below 10m depth for Cairns to Lucinda.

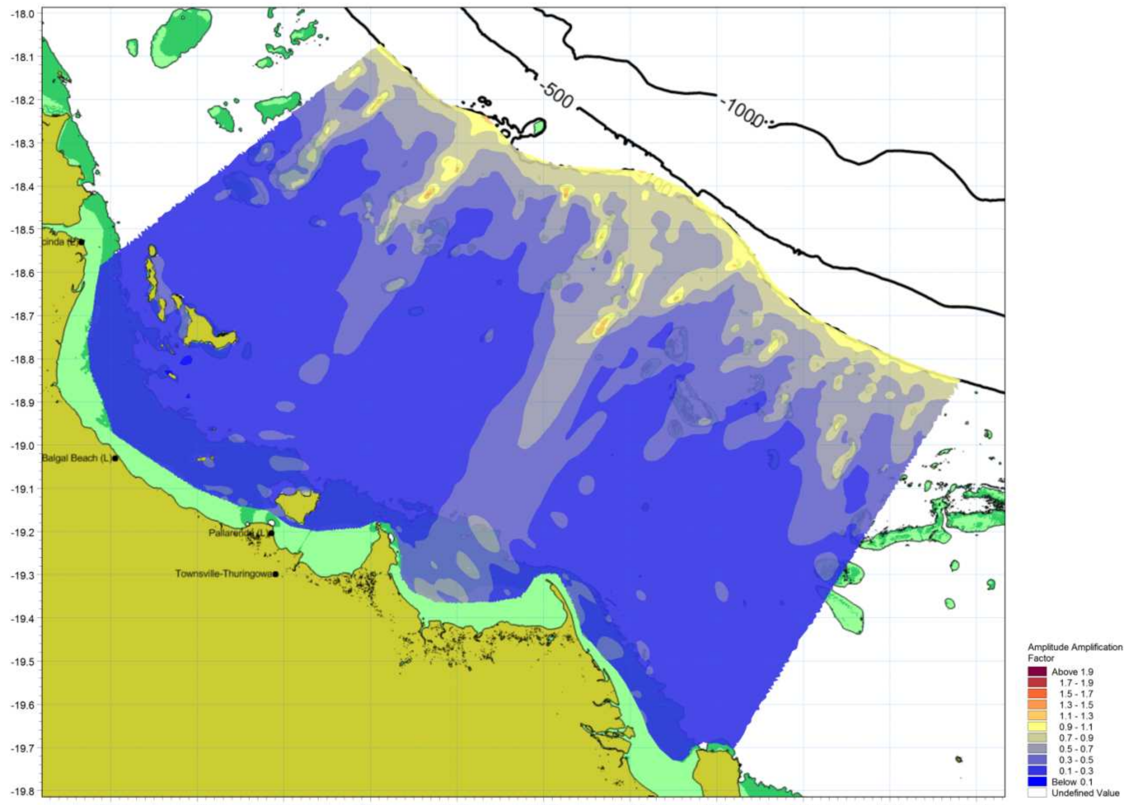

Figure 18 Amplification factor (average of all Scenarios) below 10m depth for Lucinda to Ayr.

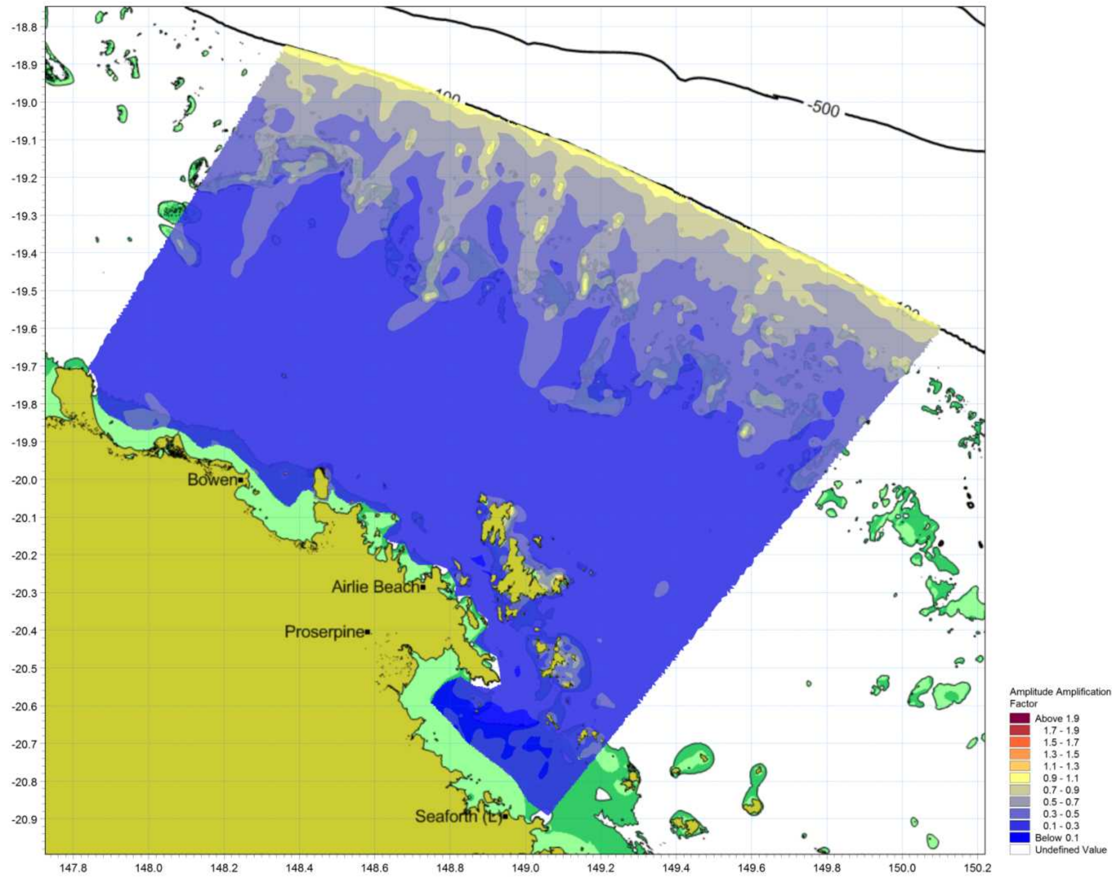

Figure 19 Amplification factor (average of all Scenarios) below 10m depth for Ayr to Seaforth.

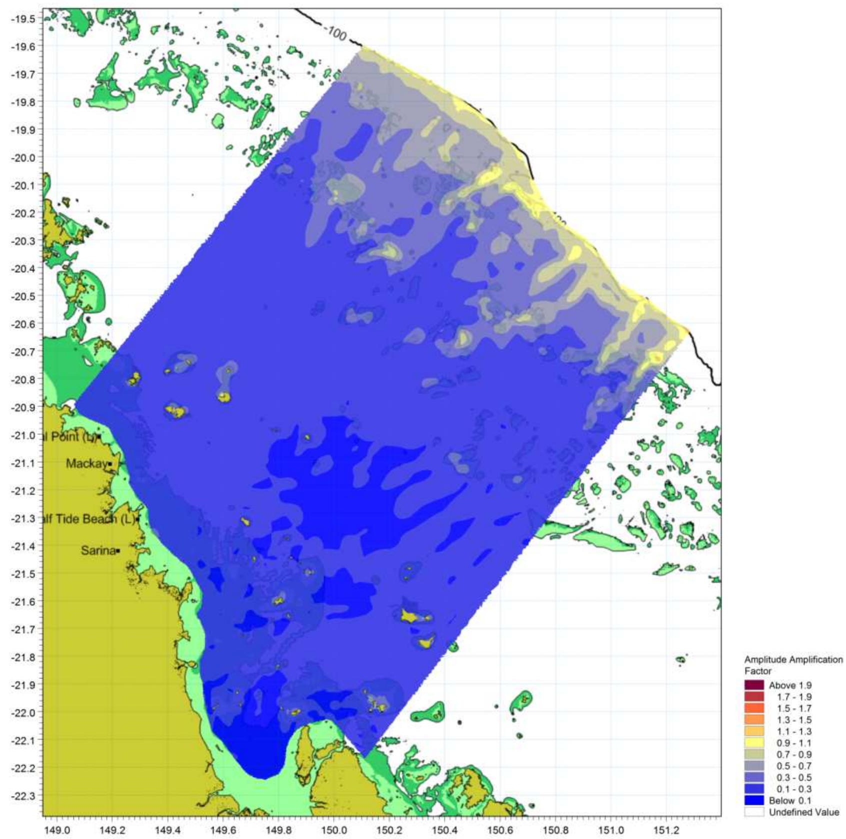

Figure 20 Amplification factor (average of all Scenarios) below 10m depth for Cape Hillsborough to St Lawrence.

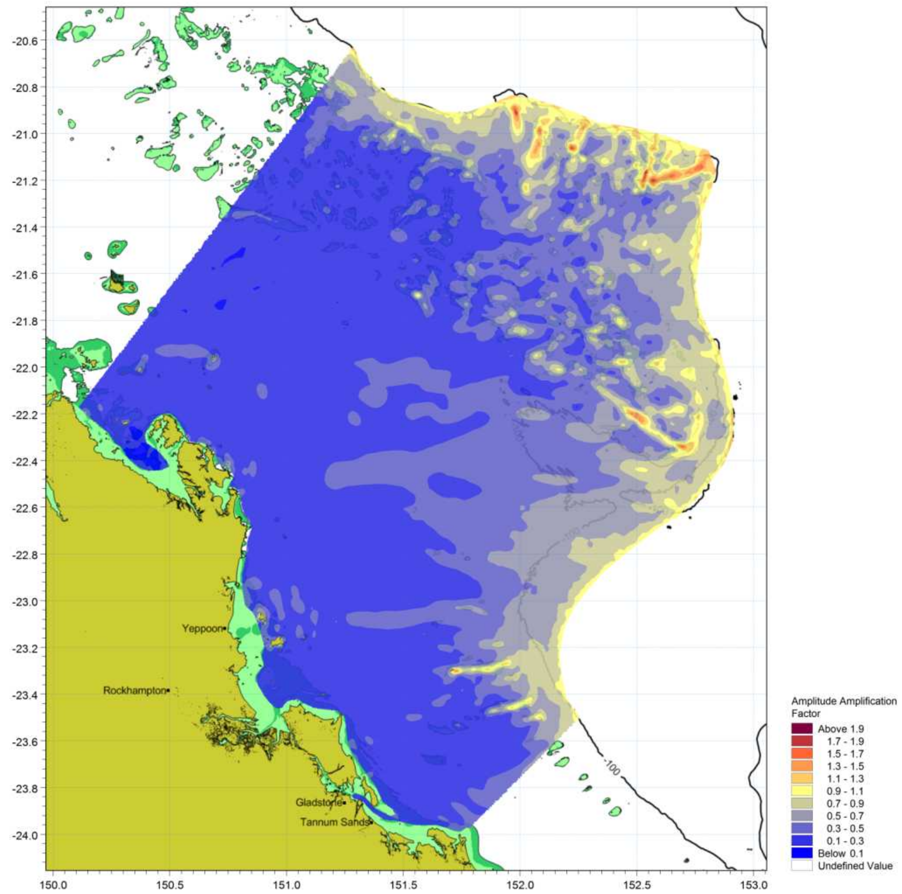

Figure 21 Amplification factor (average of all Scenarios) below 10m depth for Stanage to Bustard Head.

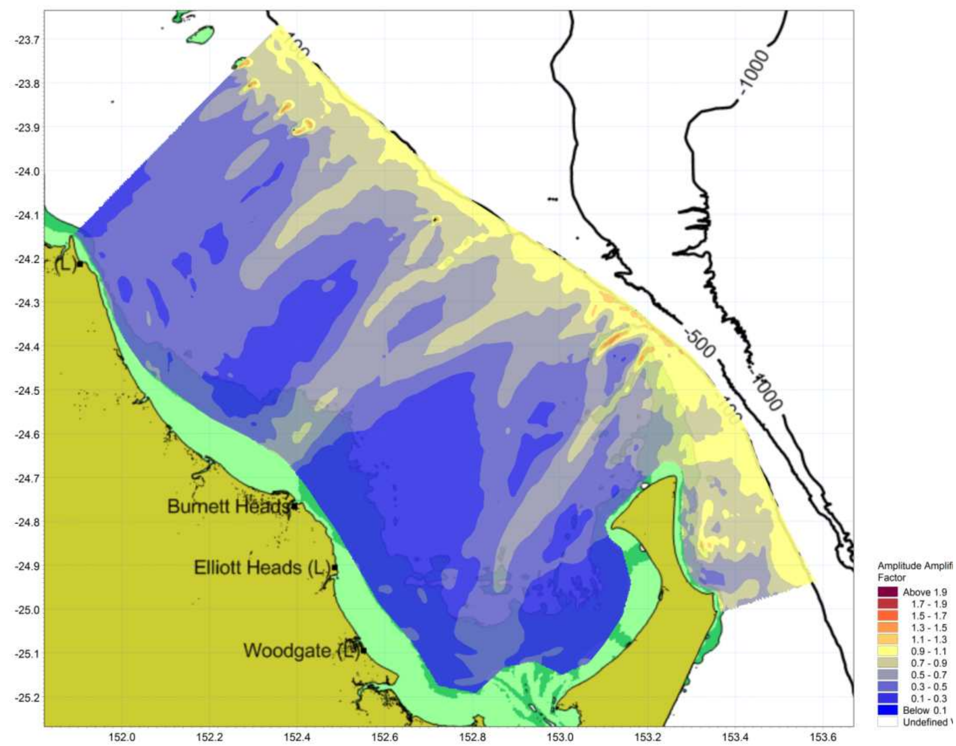

Figure 22 Amplification factor (average of all Scenarios) below 10m depth for Town of Seventeen Seventy to Hervey Bay.

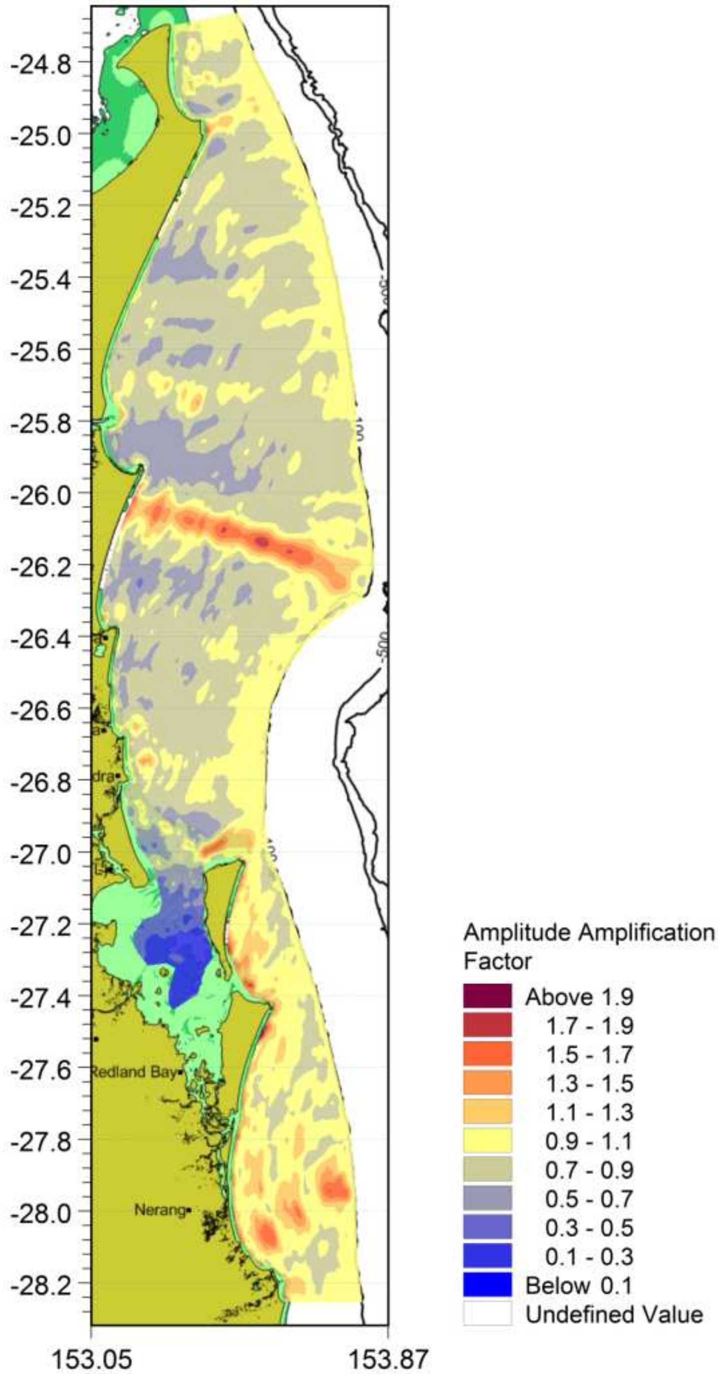

Figure 23 Amplification factor (average of all Scenarios) below 10m depth for Fraser Island to Gold Coast.

9. Conclusions

Validation of the model against the 1 April 2007 Solomon Island tsunami demonstrates the ability of the DHI MIKE21FM software to replicate tsunami propagation. However, differences between the modelled and measured tsunami amplitude for some locations illustrates the sensitivity and need for accurate and representative bathymetric data, especially in depths less than 20m where the sea bed is the most dynamic and the tsunami amplitude is most sensitive to shoaling.

Modelling was undertaken adopting a methodology that is similar to that adopted for the NTHA (Fountain et al, 2009b), but more sites were considered and the results were extended to the 10m depth contour. This study further supports the conclusions provided in the former study. Specifically:

- The Great Barrier Reef and wider continental shelf from Fraser Island north provides protection to the coast by dissipating the tsunami. The influence of the GBR increases with increasing tsunami amplitude. The resulting amplification factors within the GBR lagoon are typically below 1, with the exception of Flying Fish Point.
- Regions where the continental shelf is the narrowest (i.e. south of Fraser Island) have the highest amplification factors in the order of 3 at 10m depth. Generally, the amplification factor increases with increasing tsunami amplitude.
- Large islands protect the adjacent mainland, generally producing amplification factors below 1.
- Complex bathymetry within the dynamic littoral zone (such as surf zone bars, nearshore or ebb shoals, etc.) that has not been sufficiently represented in the adopted DEM, may significantly affect amplification factors near the coast.

The derived amplification for SEQ also supports the findings of Somerville et al (2009) for idealised open coast beaches typical of NSW, in that the amplification is typically between 1 and 2 but may increase up to a factor of 4 before breaking. The greatest amplification factors occurring along the Gold Coast where the continental shelf is at its narrowest.

The communities identified in this study to have a higher tsunami hazard are in decreasing order of magnitude:

- Gold Coast
- Ocean side of Bribie, Moreton, and Stradbroke Islands
- Sunshine Coast
- Fraser Island
- Bundaberg
- Flying Fish Point
- Capricorn coast
- Agnes Waters
- Hervey Bay

These conclusions are based on amplification factors at the 10m depth contour. They do not take into consideration the height of coastal dunes or the shoaling nature of the tsunami as it approaches the coast. It is possible that an amplification factor of less than 1 may still produce a tsunami that may cause inundation for north Queensland communities. Detailed inundation modelling would be required to assess the full risk for coastal communities.

The analysis has been based on three scenarios that are assumed constant along the boundary of each domain. In reality, wave characteristics will vary along the boundary. In addition each possible event will be unique in how it behaves in the nearshore due to differences in factors such as wave height, wave periods and individual wave interactions within the time series. Therefore analysis of a larger sample of events will provide more confidence that the amplification maps are representative of the tsunami climate for each region.

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Appendix A - Calibration

Table A- 1 Major harmonic constituents from measured tides.

Name	K1		O1		S2		M2		N2	
	Amplitude (m)	Phase (degrees)	Amplitude (m)	Phase (degrees)	Amplitude (m)	Phase (degrees)	Amplitude (m)	Phase (degrees)	Amplitude (m)	Phase (degrees)
Cooktown	0.3117	190.76	0.1475	153.09	0.3193	246.94	0.5355	277.07	0.1784	256.70
Port Douglas	0.3075	190.22	0.1508	152.68	0.3301	246.26	0.5614	275.33	0.1864	254.15
Cairns	0.3123	190.97	0.1530	153.72	0.3403	248.12	0.5782	276.71	0.1928	255.79
Mourilyan Harbour	0.3158	190.13	0.1559	153.53	0.3335	248.68	0.5775	277.42	0.1900	256.14
Clump Point SS	0.3215	189.17	0.1563	152.75	0.3578	247.68	0.6169	276.82	0.2033	255.43
Cardwell	0.3377	192.27	0.1620	155.51	0.4308	255.20	0.7455	283.20	0.2393	263.14
Lucinda (Offshore)	0.3327	189.15	0.1607	152.91	0.4012	248.48	0.6895	278.06	0.2254	256.37
Townsville	0.3386	188.24	0.1638	152.23	0.4265	247.78	0.7400	278.08	0.2392	256.27
Bowen	0.3464	189.82	0.1726	152.73	0.3120	271.30	0.7587	302.47	0.2188	278.70
Laguna Quays	0.3862	191.97	0.1924	152.97	0.5096	320.27	1.4457	326.35	0.3679	307.01
Mackay Outer Harbour	0.3902	186.87	0.1956	147.41	0.6092	320.84	1.6634	322.01	0.4146	304.58
Hay Point	0.3942	185.91	0.1979	146.46	0.6532	321.01	1.7675	321.24	0.4348	303.69
Rosslyn Bay	0.3012	160.09	0.1565	120.55	0.4896	277.37	1.3126	270.36	0.3008	253.94
South Trees Wharf SS	0.2615	158.20	0.1367	116.73	0.4066	272.23	1.1469	261.14	0.2583	248.26
Gladstone Port Gauge	0.2643	160.50	0.1429	119.36	0.4220	278.48	1.1916	265.84	0.2666	253.22
Bundaberg	0.2206	158.50	0.1166	118.09	0.2925	258.52	0.8696	245.41	0.1888	231.46
Burnett Heads SS	0.2201	158.28	0.1153	118.00	0.2895	257.70	0.8586	244.77	0.1881	231.07
Urangan	0.2371	164.03	0.1202	123.78	0.3467	273.77	1.0554	255.87	0.2240	244.34
Mooloolaba	0.1899	154.67	0.1051	118.62	0.1627	252.73	0.5390	234.97	0.1151	221.28
Caloundra Head	0.1940	152.90	0.1120	116.40	0.1600	251.20	0.5320	234.40	0.1120	217.00
Brisbane Bar	0.2129	170.90	0.1174	131.10	0.1911	301.53	0.7028	274.19	0.1378	264.19
Gold Coast Seaway	0.1779	145.13	0.1009	104.44	0.1442	256.34	0.5115	236.94	0.1056	223.19
Point Danger	0.1728	141.70	0.0991	100.20	0.1460	252.50	0.5124	232.10	0.0981	219.70

Table A- 2 Modelled major harmonic constituents.

Name	K1		O1		S2		M2		N2	
	Amplitude (m)	Phase (degrees)	Amplitude (m)	Phase (degrees)	Amplitude (m)	Phase (degrees)	Amplitude (m)	Phase (degrees)	Amplitude (m)	Phase (degrees)
Cooktown	0.3599	199.27	0.1556	144.84	0.3565	260.97	0.6835	263.74	0.1920	243.73
Port Douglas	0.3644	198.54	0.1572	144.20	0.3735	260.11	0.7163	262.95	0.2005	242.73
Cairns	0.3625	198.16	0.1564	143.95	0.3689	259.43	0.7097	262.31	0.1984	242.07
Mourilyan Harbour	0.3646	198.68	0.1572	144.58	0.3842	262.33	0.7439	264.77	0.2062	244.66
Clump Point SS	0.3694	199.23	0.1591	145.26	0.4098	264.13	0.7918	266.32	0.2186	246.36
Cardwell	0.3780	203.25	0.1628	151.09	0.4866	272.80	0.9299	273.24	0.2570	254.96
Lucinda (Offshore)	0.3768	200.36	0.1625	146.85	0.4532	267.02	0.8737	268.91	0.2392	249.44
Townsville	0.3851	200.70	0.1669	147.42	0.4842	267.72	0.9368	269.78	0.2550	250.85
Bowen	0.3960	204.31	0.1755	150.01	0.3649	290.24	0.8855	293.36	0.2266	275.17
Laguna Quays	0.4443	207.35	0.1976	151.30	0.5621	338.81	1.5955	321.49	0.3868	308.02
Mackay Outer Harbour	0.4444	200.81	0.1956	143.57	0.6074	336.13	1.7127	315.01	0.4025	301.74
Hay Point	0.4458	200.38	0.1963	143.07	0.6363	336.81	1.7824	314.77	0.4174	301.89
Rosslyn Bay	0.3656	172.47	0.1580	114.09	0.5190	292.12	1.4011	263.97	0.3115	251.38
South Trees Wharf SS	0.3246	169.63	0.1391	110.77	0.4342	284.33	1.2035	253.04	0.2646	241.63
Gladstone Port Gauge	0.3277	171.55	0.1410	112.22	0.4504	288.95	1.2467	256.68	0.2750	246.01
Bundaberg	0.2767	164.33	0.1180	105.74	0.3069	264.01	0.8774	232.70	0.1903	219.36
Burnett Heads SS	0.2766	164.32	0.1180	105.72	0.3067	263.97	0.8770	232.67	0.1902	219.33
Urangan	0.2895	169.50	0.1227	111.34	0.3769	278.27	1.0724	242.58	0.2324	232.14
Mooloolaba	0.2264	153.72	0.0879	102.21	0.1815	255.02	0.5657	221.38	0.1211	206.78
Caloundra Head	0.2255	154.29	0.0878	103.30	0.1815	256.88	0.5684	223.05	0.1215	208.40
Brisbane Bar	0.2386	170.86	0.0980	119.52	0.2261	302.73	0.7498	258.80	0.1564	250.51
Gold Coast Seaway	0.2154	149.43	0.0957	113.81	0.1711	254.99	0.5499	220.27	0.1211	205.48
Point Danger	0.2124	149.40	0.1023	113.45	0.1688	255.40	0.5448	220.50	0.1207	205.46

Table A- 3 Comparison of Modelled tides against predicted tides.

Site	RMSE (m)	Norm. RMSE	IofA	CofE
Albany Island	0.16	5%	0.99	0.95
Turtle Head Island	0.24	8%	0.98	0.89
Cairncross Island	0.35	11%	0.95	0.76
Shelbourne Bay	0.30	12%	0.95	0.76
Portland Roads	0.18	10%	0.97	0.87
Ham Reef	0.16	9%	0.97	0.87
Night Island	0.14	7%	0.98	0.92
Morris Island	0.14	7%	0.98	0.92
Pipon Island	0.13	7%	0.98	0.93
Cape Melville	0.16	8%	0.98	0.89
Normanby River	0.20	8%	0.98	0.88
Lizard Island	0.13	7%	0.98	0.92
Cape Flattery	0.15	8%	0.98	0.90
Cape Bedford	0.18	10%	0.97	0.86
Cooktown	0.14	7%	0.98	0.92
Bailay Creek	0.19	12%	0.97	0.83
Mossman River	0.20	9%	0.97	0.83
Port Douglas	0.15	7%	0.98	0.91
Palm Cove	0.16	8%	0.98	0.90
Cairns	0.14	7%	0.98	0.93
Swallows Landing	0.12	5%	0.99	0.96
Green Island	0.15	8%	0.98	0.90
Fitzroy Island	0.15	7%	0.98	0.92
High Island	0.16	8%	0.98	0.90
Russell Island	0.20	10%	0.97	0.82
Mourilyan Harbour	0.16	7%	0.98	0.91
Dunk Island	0.20	9%	0.97	0.87
Clump Point	0.17	8%	0.98	0.91
Goold Island	0.21	9%	0.97	0.87
Cardwell	0.19	7%	0.98	0.92
Lucinda (Offshore)	0.18	7%	0.98	0.91
Albino Rock	0.15	7%	0.99	0.94
Townsville	0.19	7%	0.98	0.92

Site	RMSE (m)	Norm. RMSE	IofA	CofE
Cape Ferguson	0.17	7%	0.98	0.92
Abbot Point	0.15	6%	0.99	0.94
Bowen	0.16	6%	0.99	0.94
Square Reef	0.19	6%	0.99	0.96
Double Bay	0.14	6%	0.99	0.96
Hayman Island	0.12	5%	0.99	0.97
Molle Island	0.15	6%	0.99	0.96
Cid Harbour	0.14	5%	0.99	0.97
Hook Island	0.11	5%	0.99	0.98
Shute Harbour	0.16	5%	0.99	0.96
Dent Island	0.18	6%	0.99	0.96
Thomas Island	0.20	6%	0.99	0.96
East Repulse Island	0.21	6%	0.99	0.96
Laguna Quays	0.37	9%	0.97	0.89
Blacksmith	0.19	5%	0.99	0.97
Mackay Outer Harbour	0.18	4%	0.99	0.98
Hay Point	0.19	4%	0.99	0.98
McEwan Islet	0.41	7%	0.99	0.95
Osborn Island	0.17	4%	1.00	0.99
Marquis Island	0.20	4%	1.00	0.98
Reef Point	0.20	5%	0.99	0.98
Port Clinton	0.15	4%	0.99	0.98
Peaked Island	0.14	4%	1.00	0.98
Rosslyn Bay	0.13	4%	1.00	0.98
Middle Island	0.18	6%	0.99	0.97
Port Alma	0.16	4%	0.99	0.98
Heron Island	0.11	5%	0.99	0.97
Tryon Islet	0.12	5%	0.99	0.97
Gatcombe Head	0.15	5%	0.99	0.97
South Trees Wharf	0.13	4%	0.99	0.98
Gladstone Port Gauge	0.15	5%	0.99	0.97
Clews Point	0.10	5%	1.00	0.98

Site	RMSE (m)	Norm. RMSE	IofA	CofE
Lady Musgrave Island	0.10	5%	0.99	0.96
Lady Elliot Island	0.10	5%	0.99	0.96
Bundaberg	0.10	4%	0.99	0.98
Burnett Heads	0.09	4%	1.00	0.98
Waddy Point	0.10	6%	0.99	0.94
Urangan	0.12	4%	0.99	0.98
Ungowa	0.17	6%	0.99	0.96
Boonlye Point	0.17	7%	0.99	0.94
Elbow Point	0.12	8%	0.98	0.93
Noosa Head	0.08	5%	0.99	0.96
Mooloolaba	0.08	6%	0.99	0.96
Caloundra Head	0.06	4%	1.00	0.98
Tangalooma Point	0.19	12%	0.96	0.84
Bongaree	0.12	8%	0.98	0.93
Brisbane Bar	0.11	6%	0.99	0.96
Runaway Bay	0.23	18%	0.90	0.47
Gold Coast Seaway	0.09	6%	0.99	0.95
Point Danger	0.08	6%	0.99	0.96
Tweed River	0.11	8%	0.98	0.91

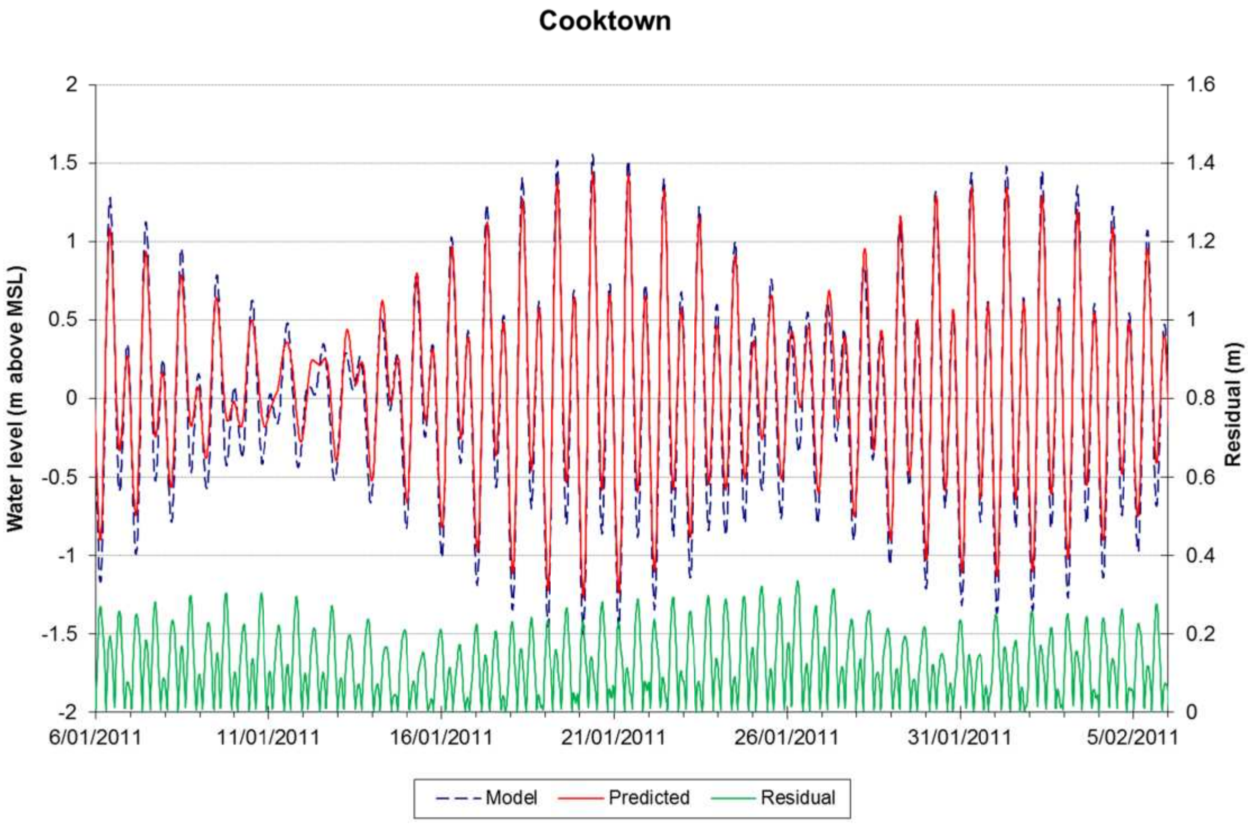

Figure A- 1 Comparison of modelled and predicted tides for Cooktown.

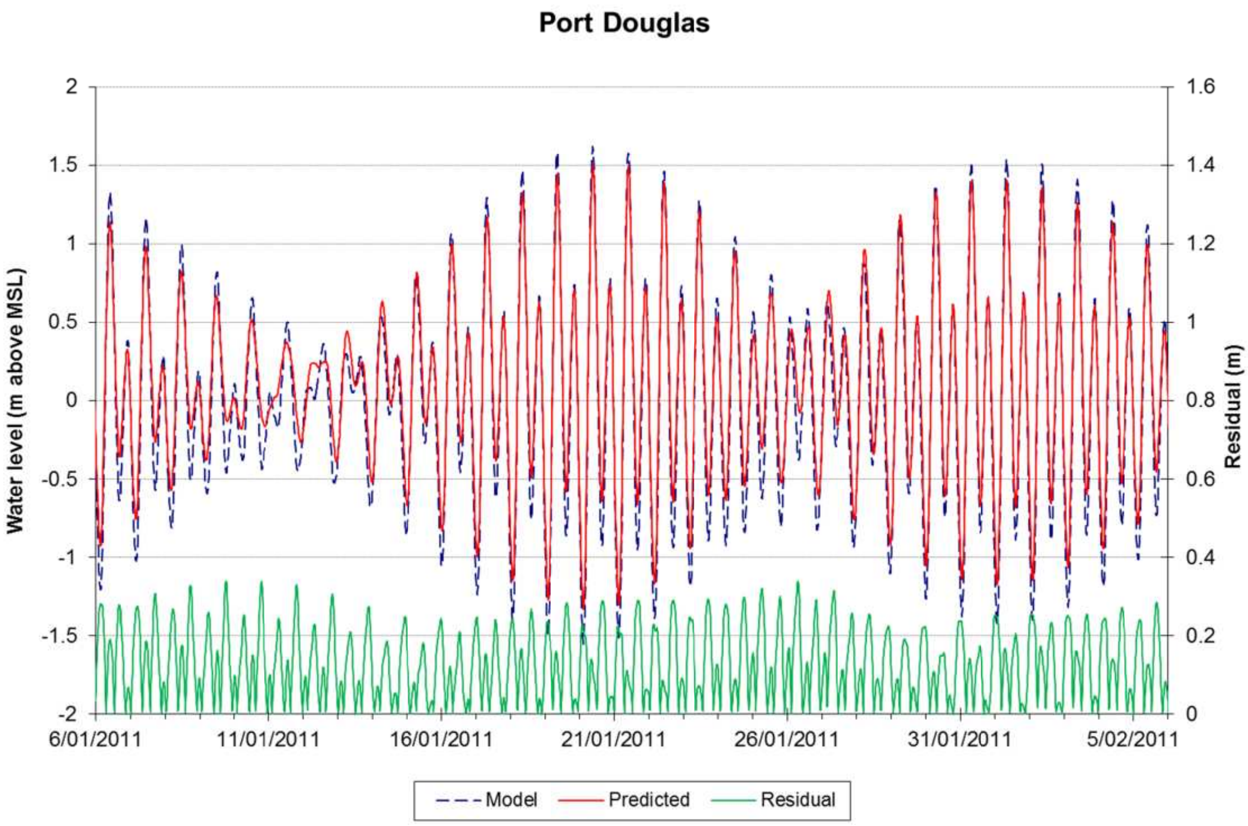

Figure A- 2 Comparison of modelled and predicted tides for Port Douglas.

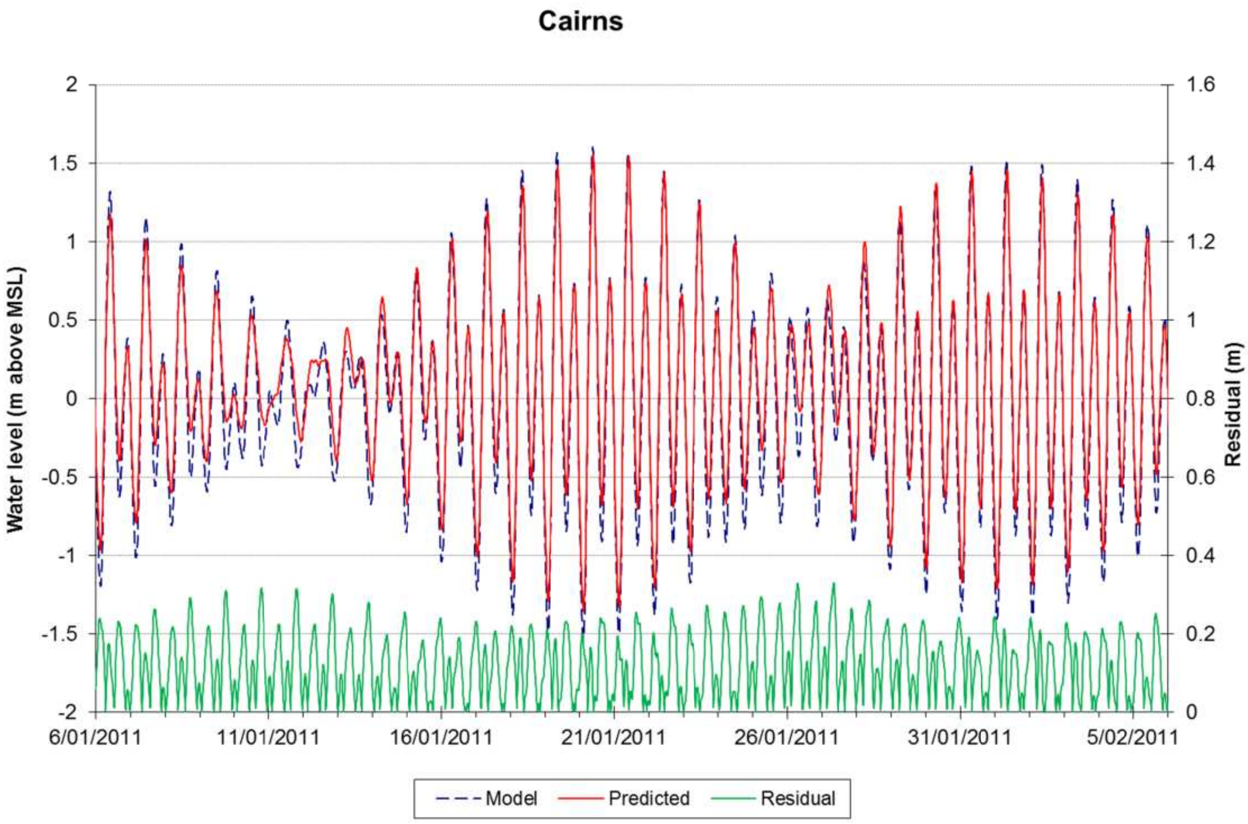

Figure A- 3 Comparison of modelled and predicted tides for Cairns.

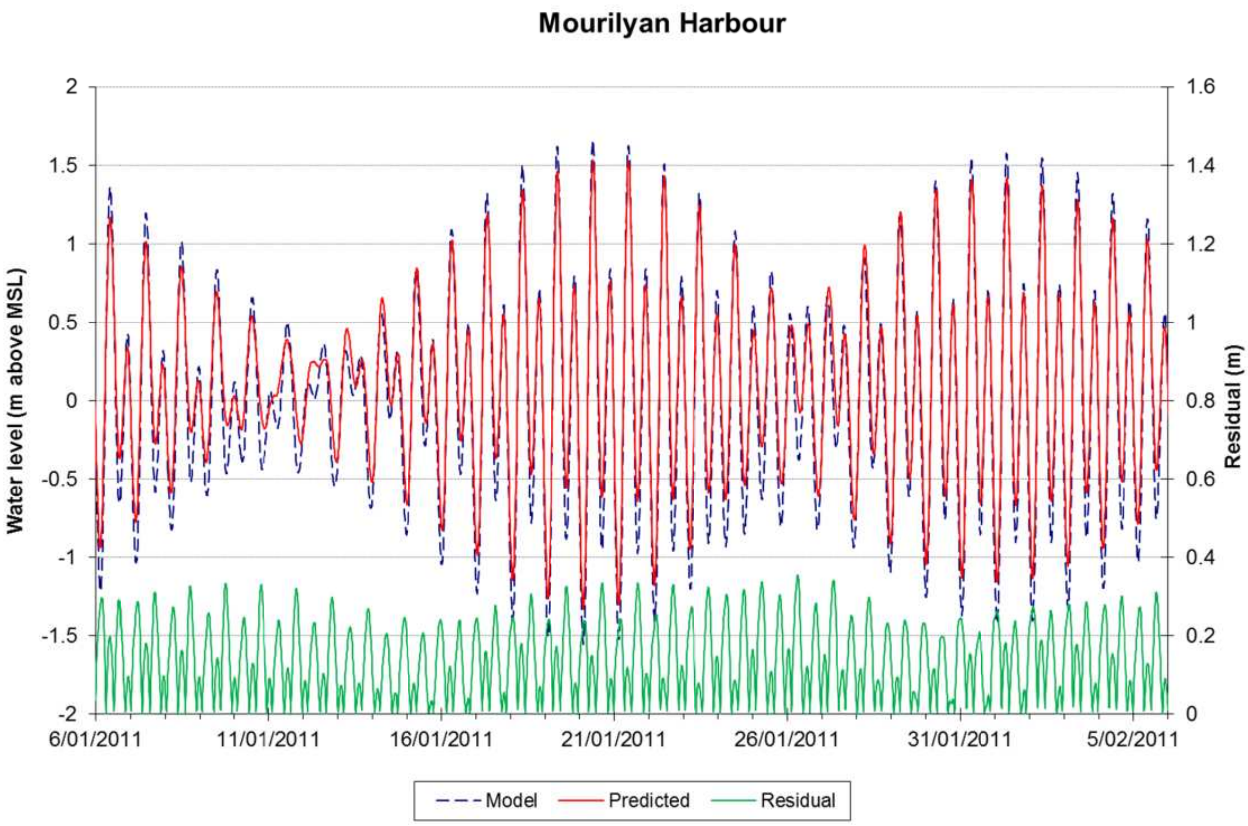

Figure A- 4 Comparison of modelled and predicted tides for Mourilyan Harbour.

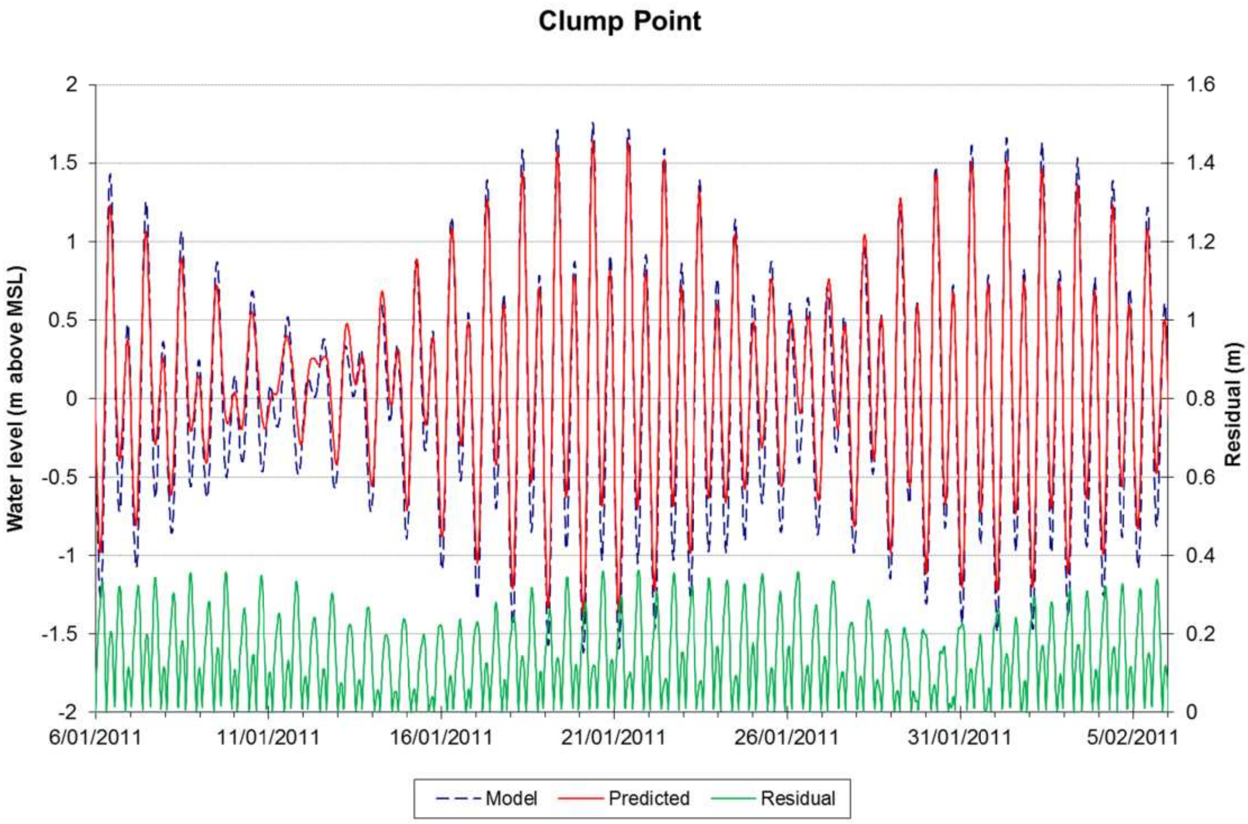

Figure A- 5 Comparison of modelled and predicted tides for Clump Point.

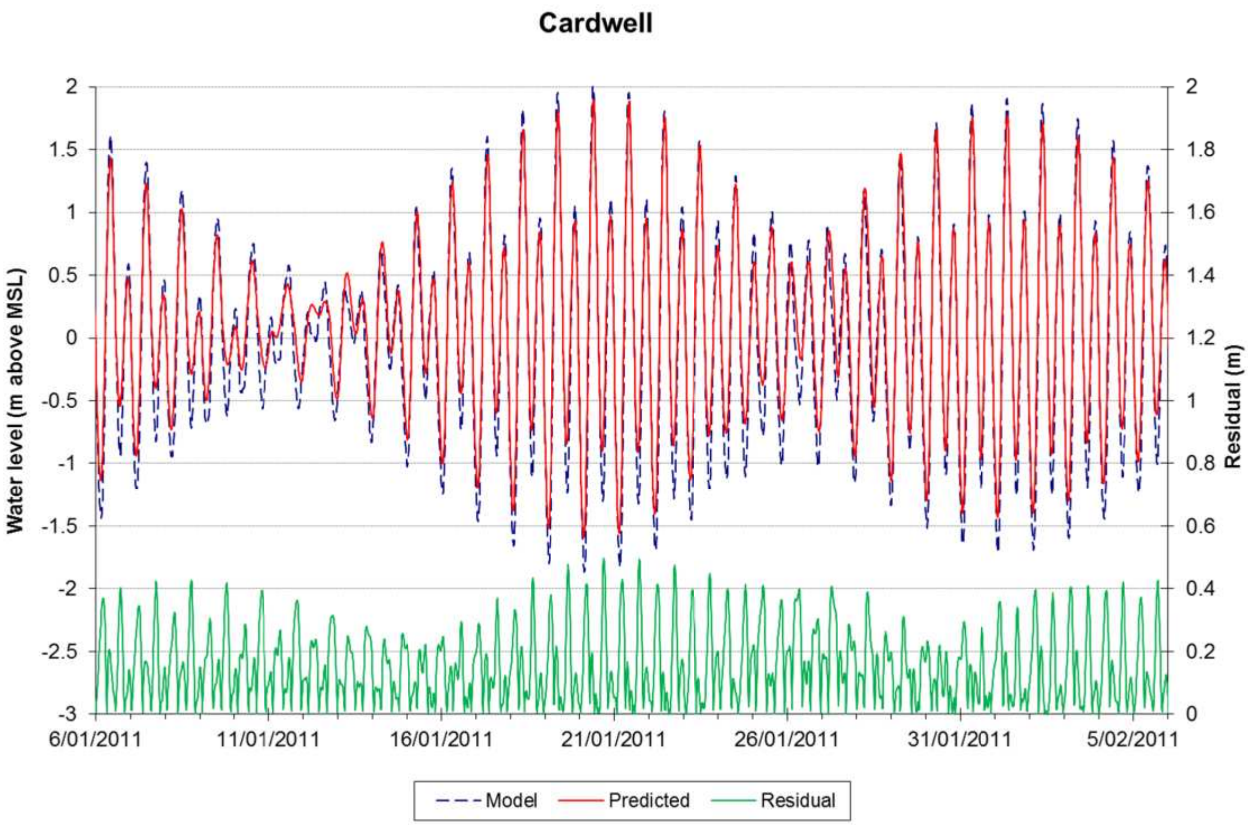

Figure A- 6 Comparison of modelled and predicted tides for Cardwell.

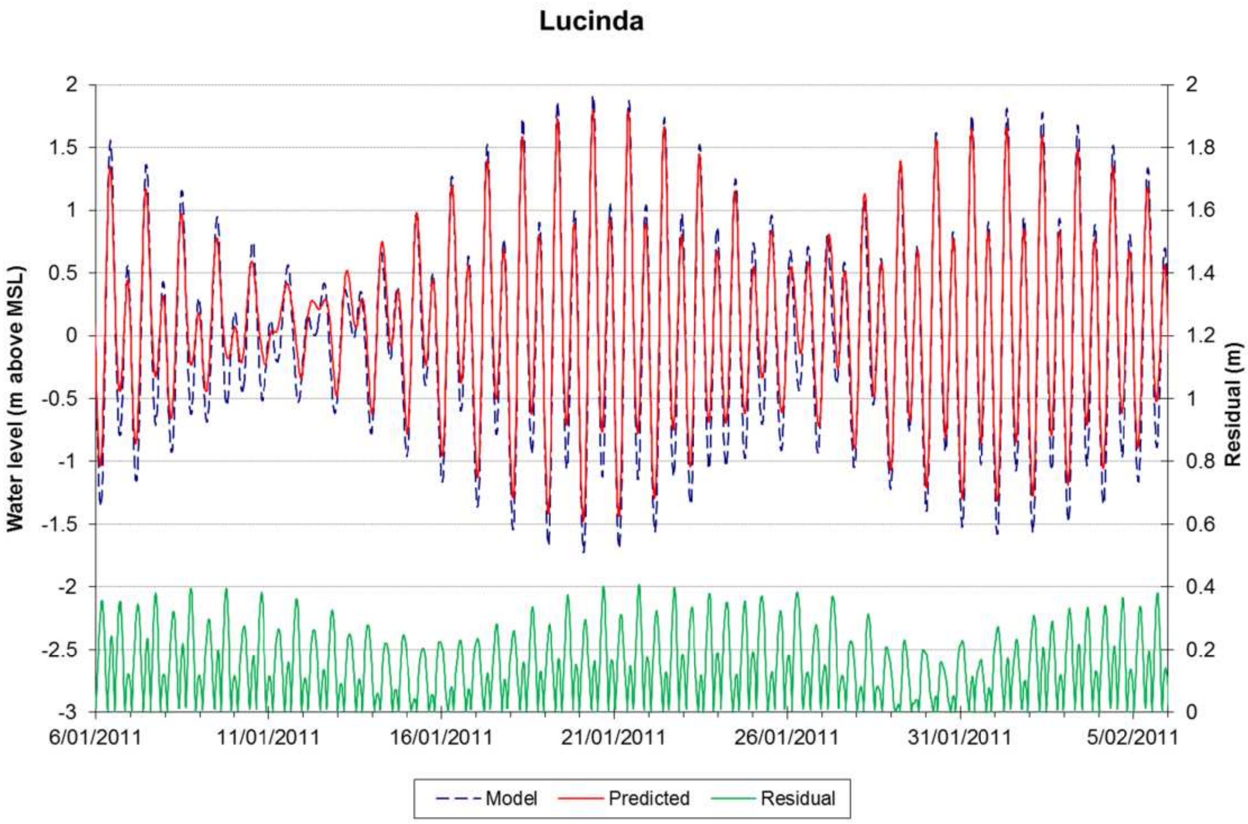

Figure A- 7 Comparison of modelled and predicted tides for Lucinda.

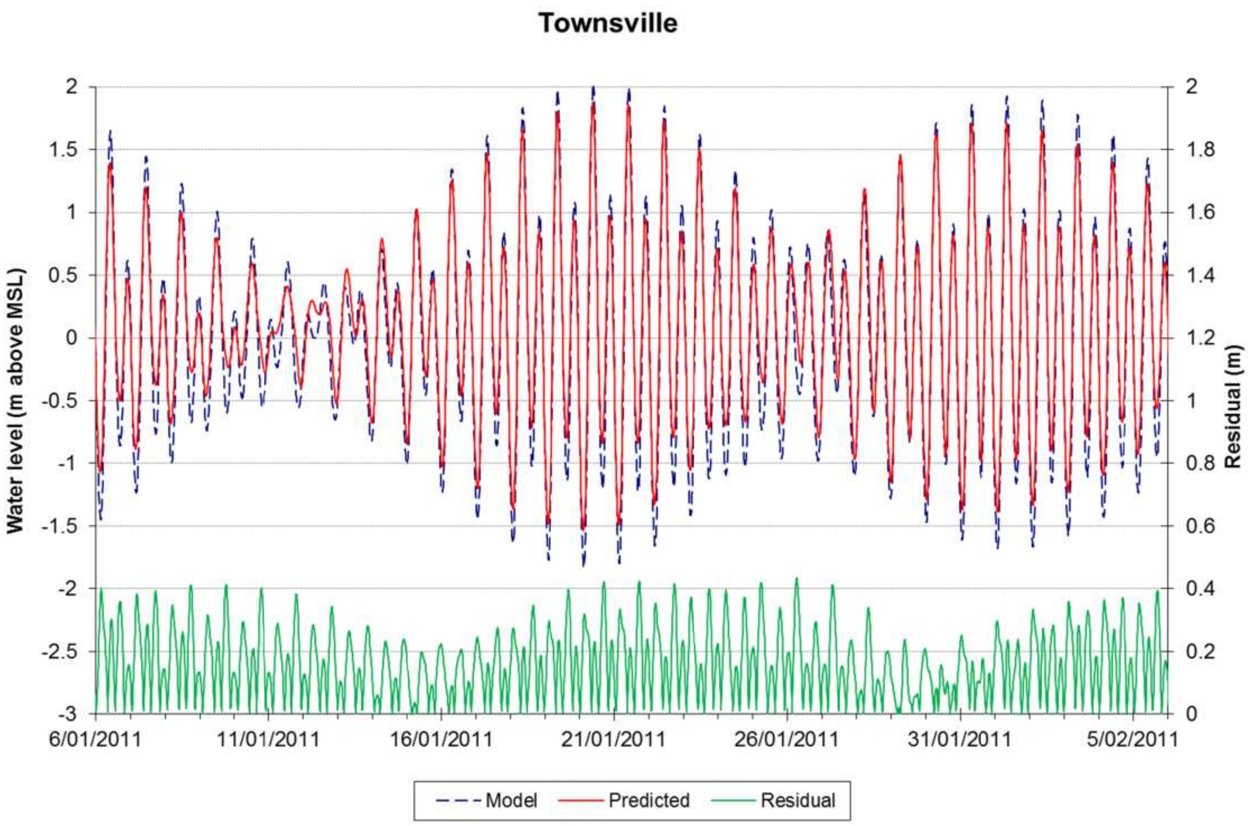

Figure A- 8 Comparison of modelled and predicted tides for Townsville.

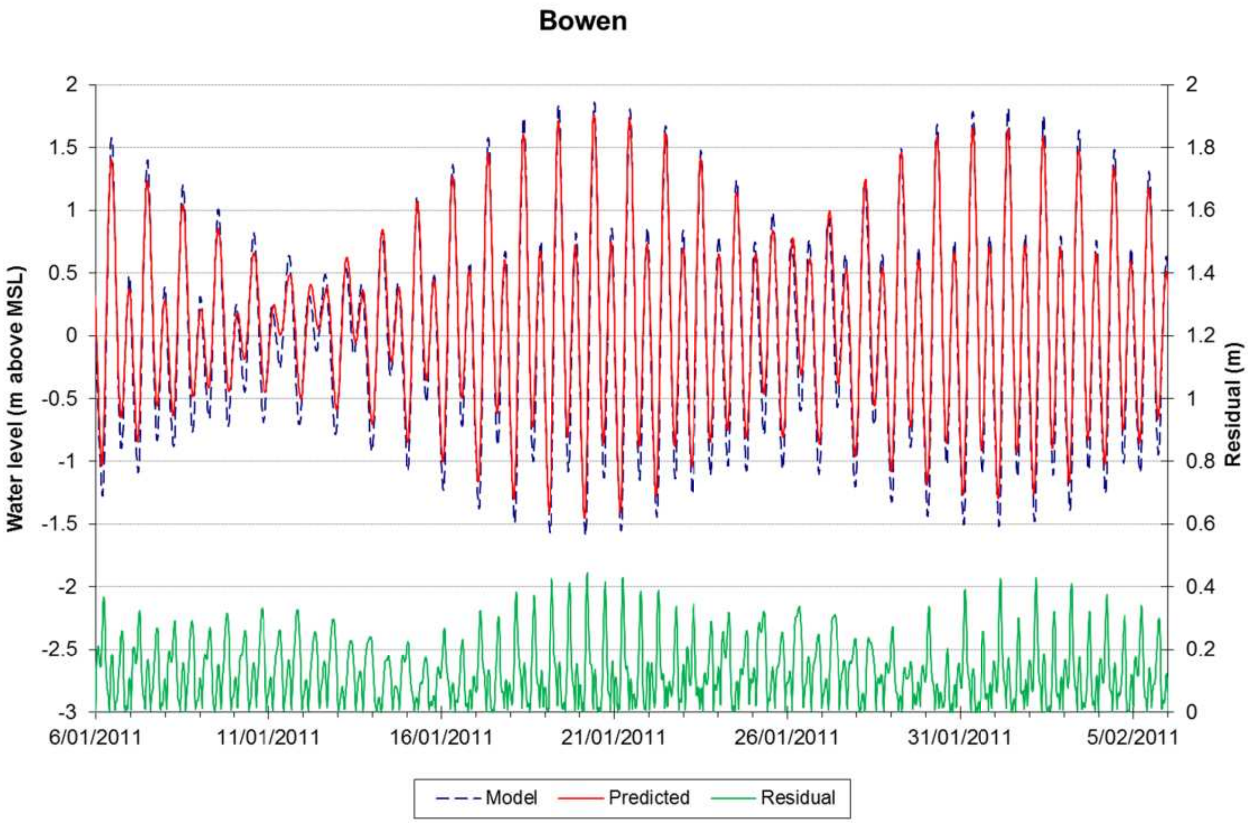

Figure A- 9 Comparison of modelled and predicted tides for Bowen.

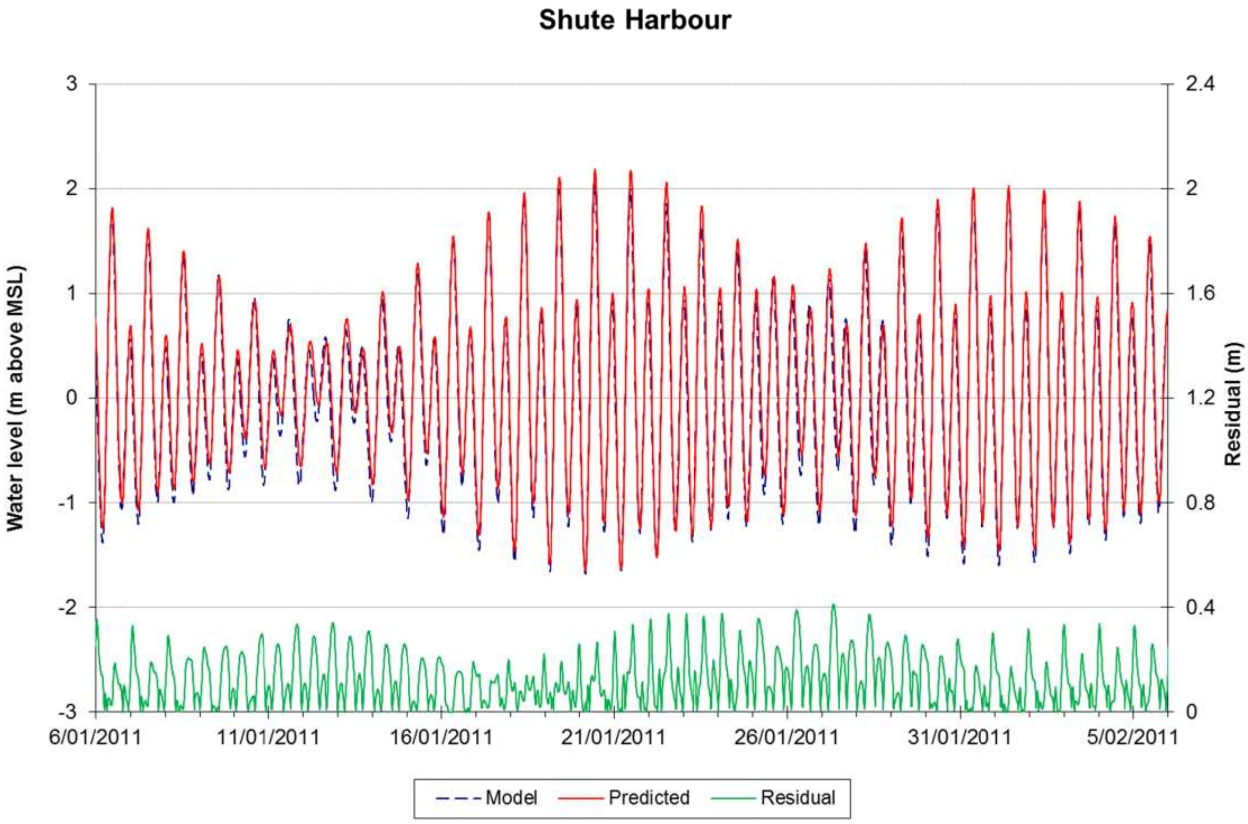

Figure A- 10 Comparison of modelled and predicted tides for Shute Harbour.

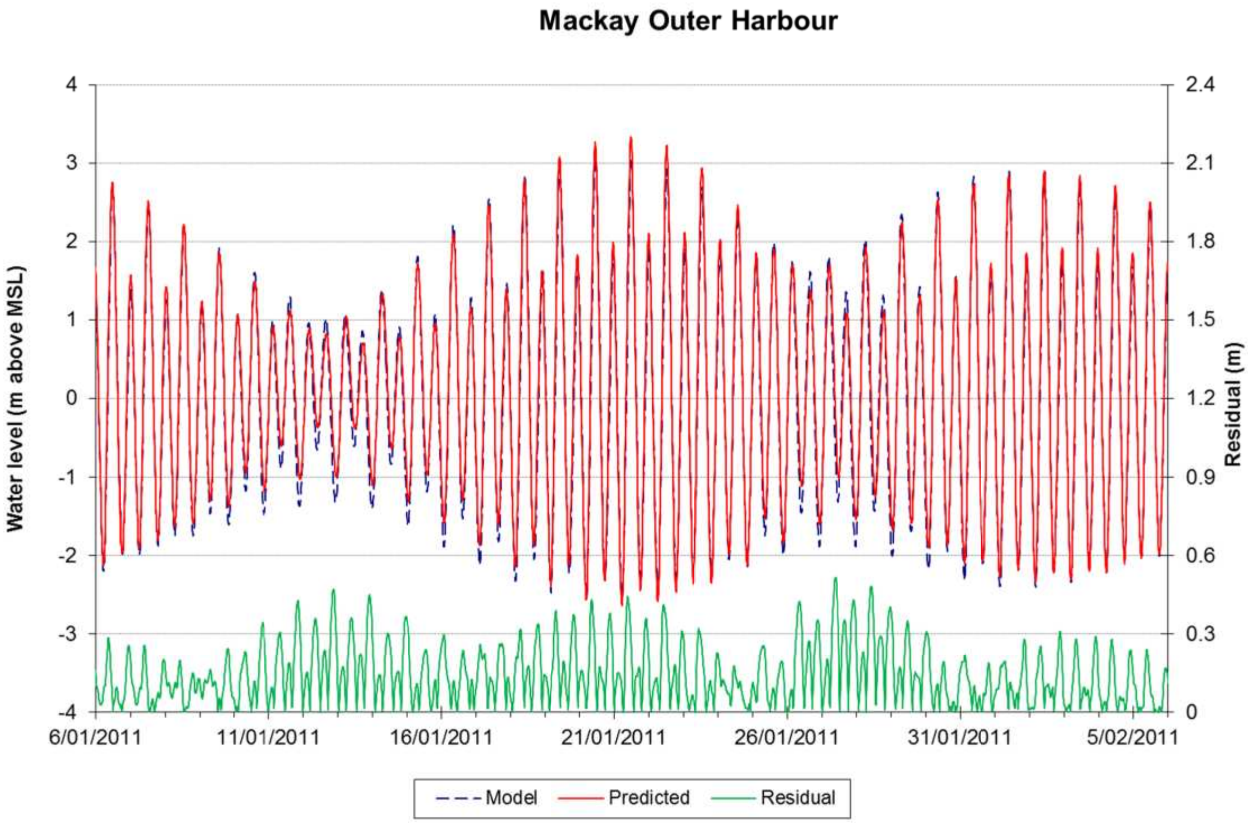

Figure A- 11 Comparison of modelled and predicted tides for Mackay.

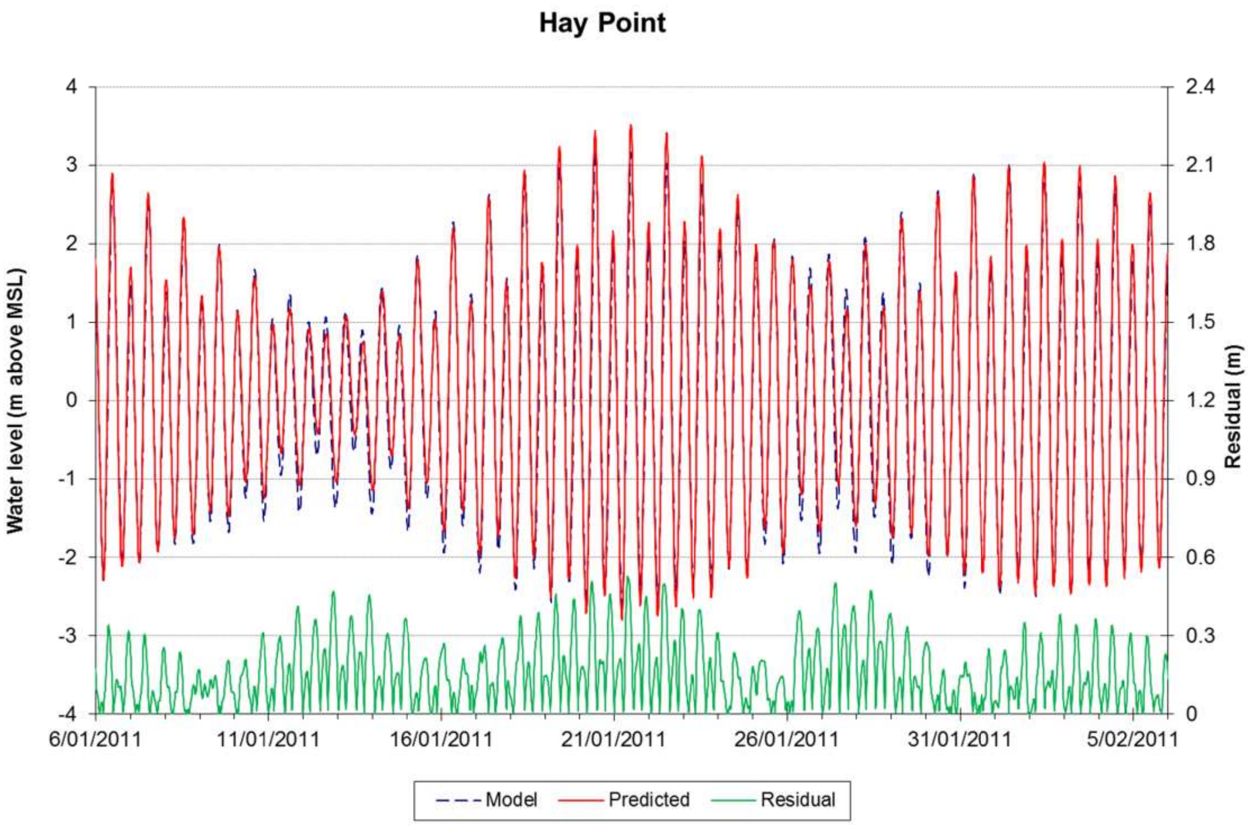

Figure A- 12 Comparison of modelled and predicted tides for Hay Point.

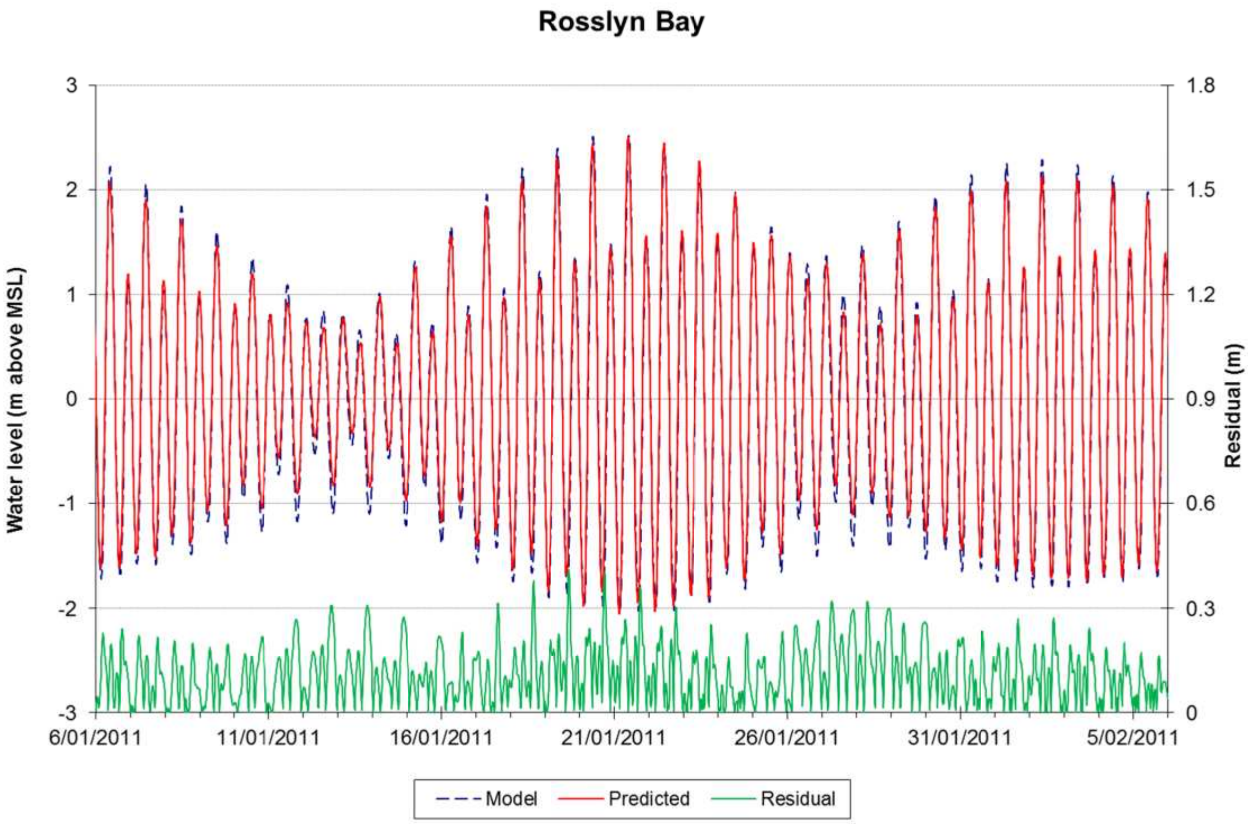

Figure A- 13 Comparison of modelled and predicted tides for Rosslyn Bay.

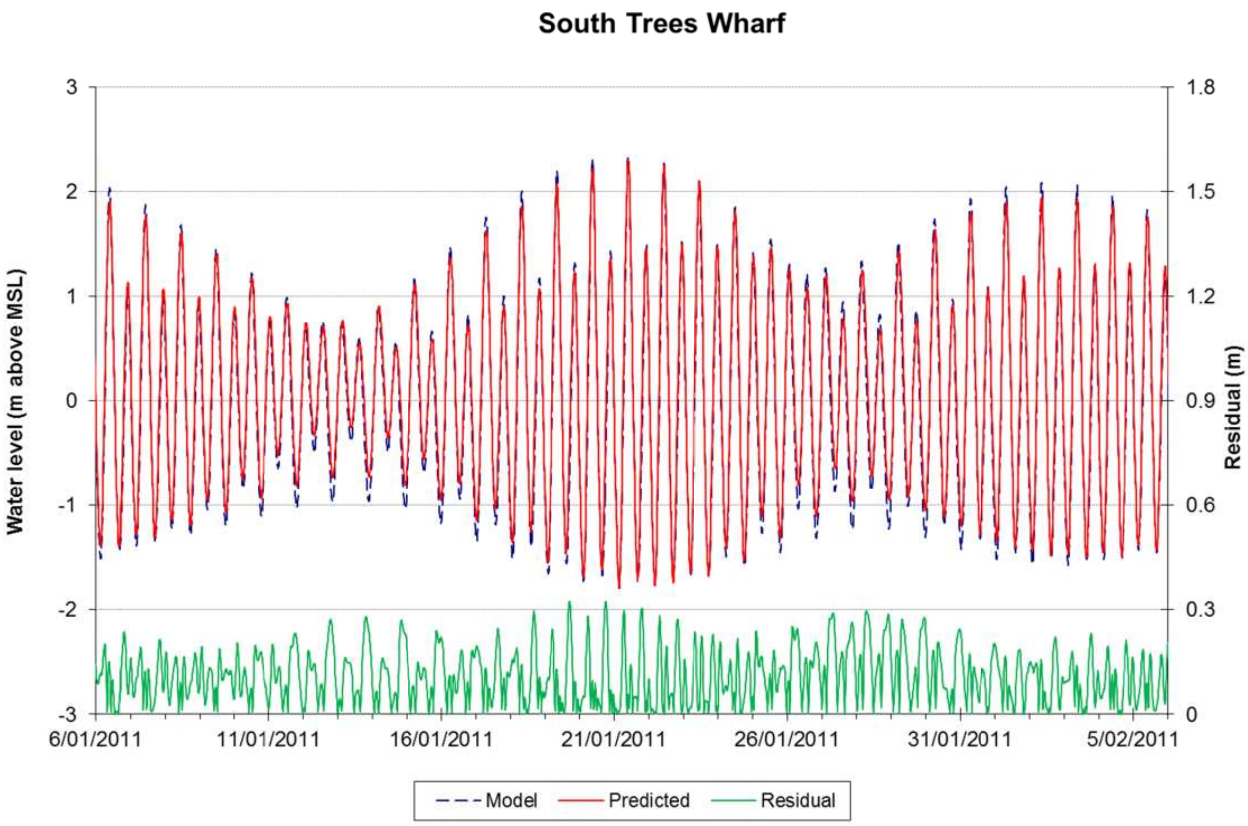

Figure A- 14 Comparison of modelled and predicted tides for South Trees.

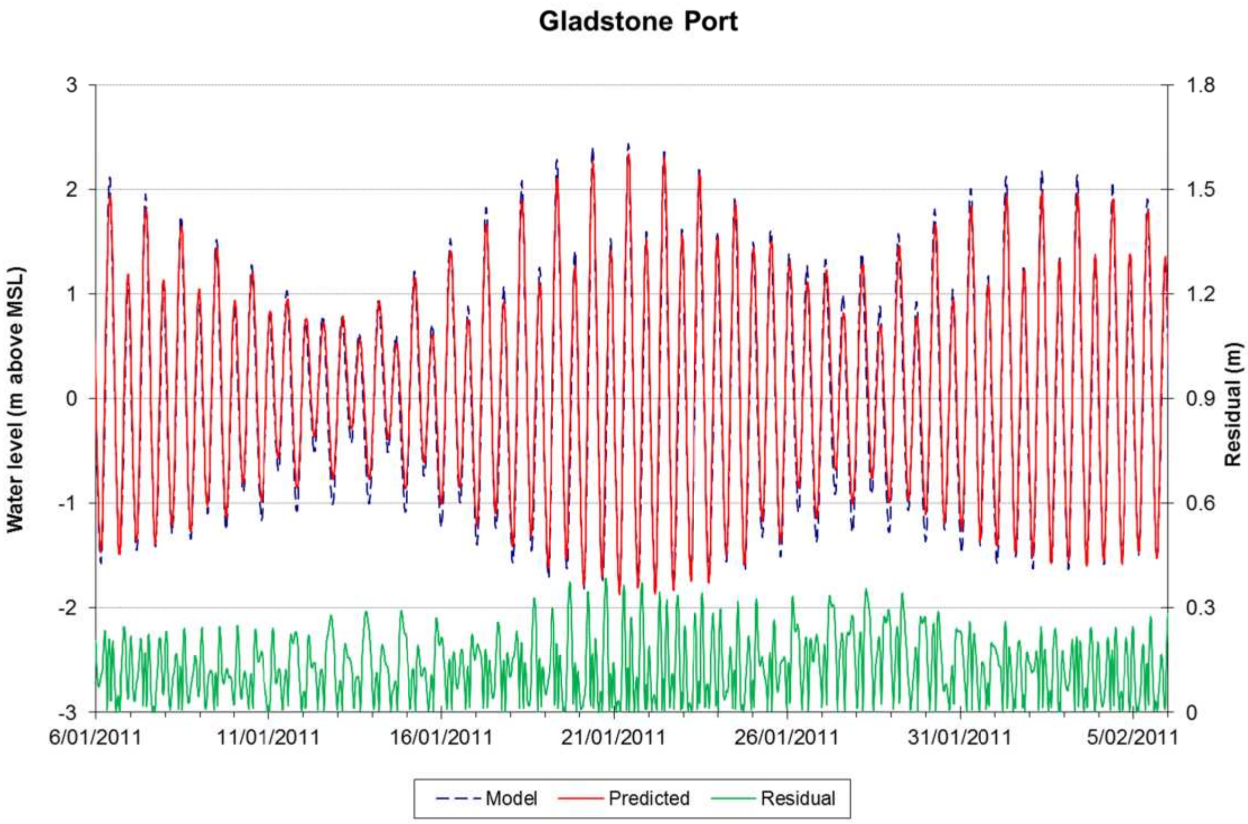

Figure A- 15 Comparison of modelled and predicted tides for Gladstone.

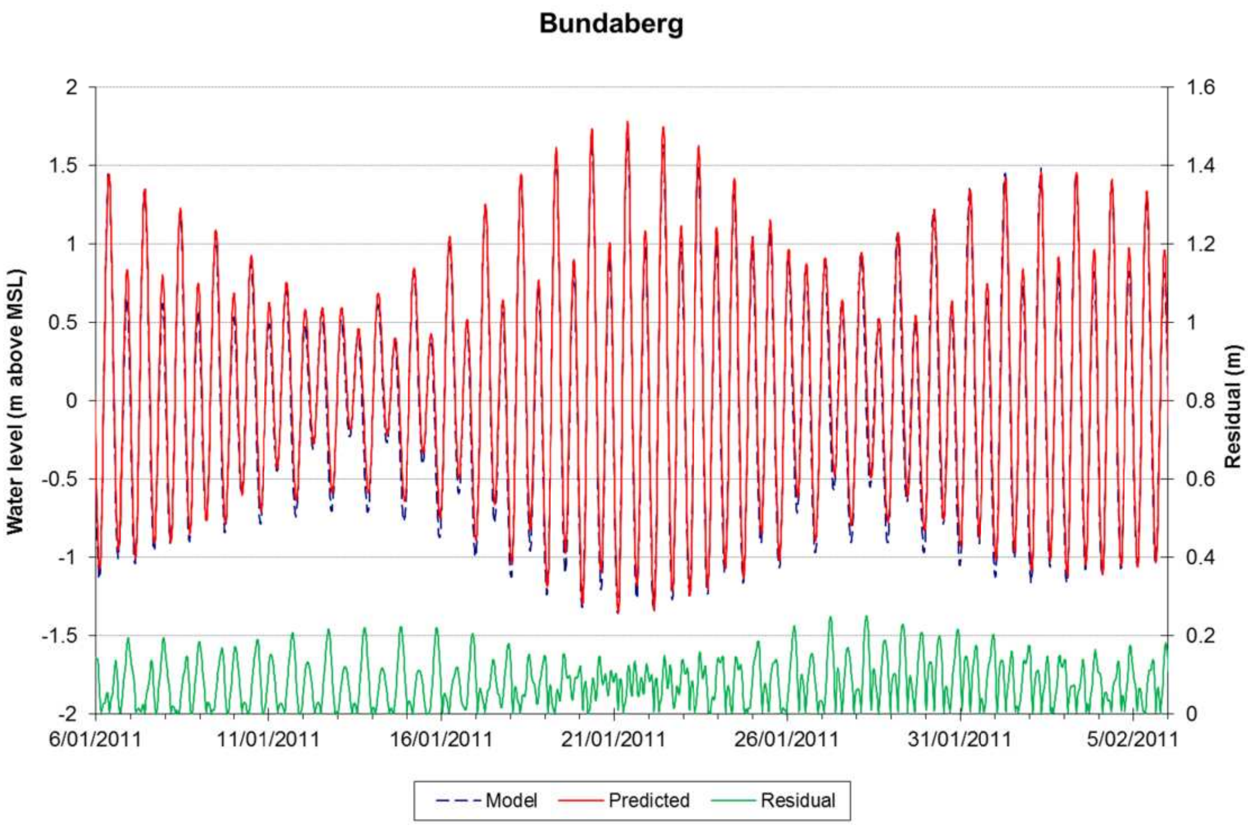

Figure A- 16 Comparison of modelled and predicted tides for Bundaberg.

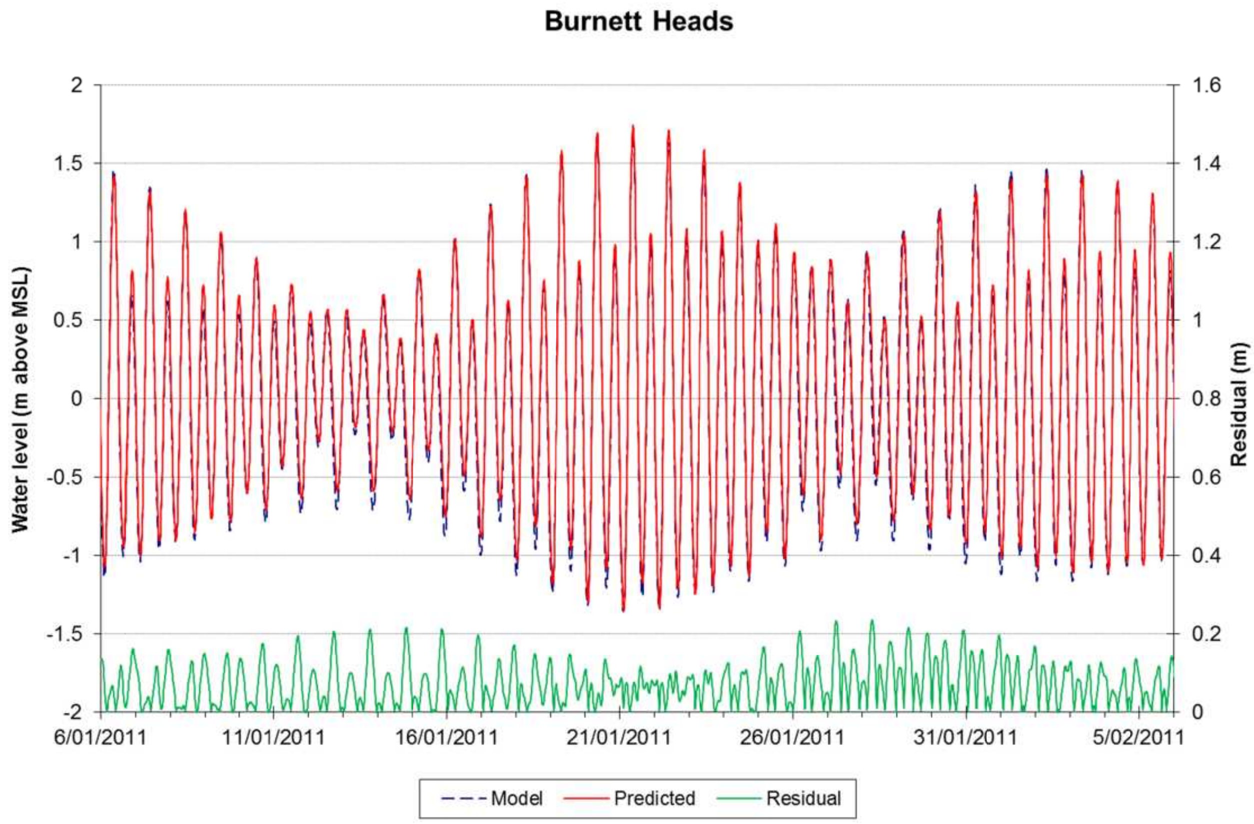

Figure A- 17 Comparison of modelled and predicted tides for Burnett Heads.

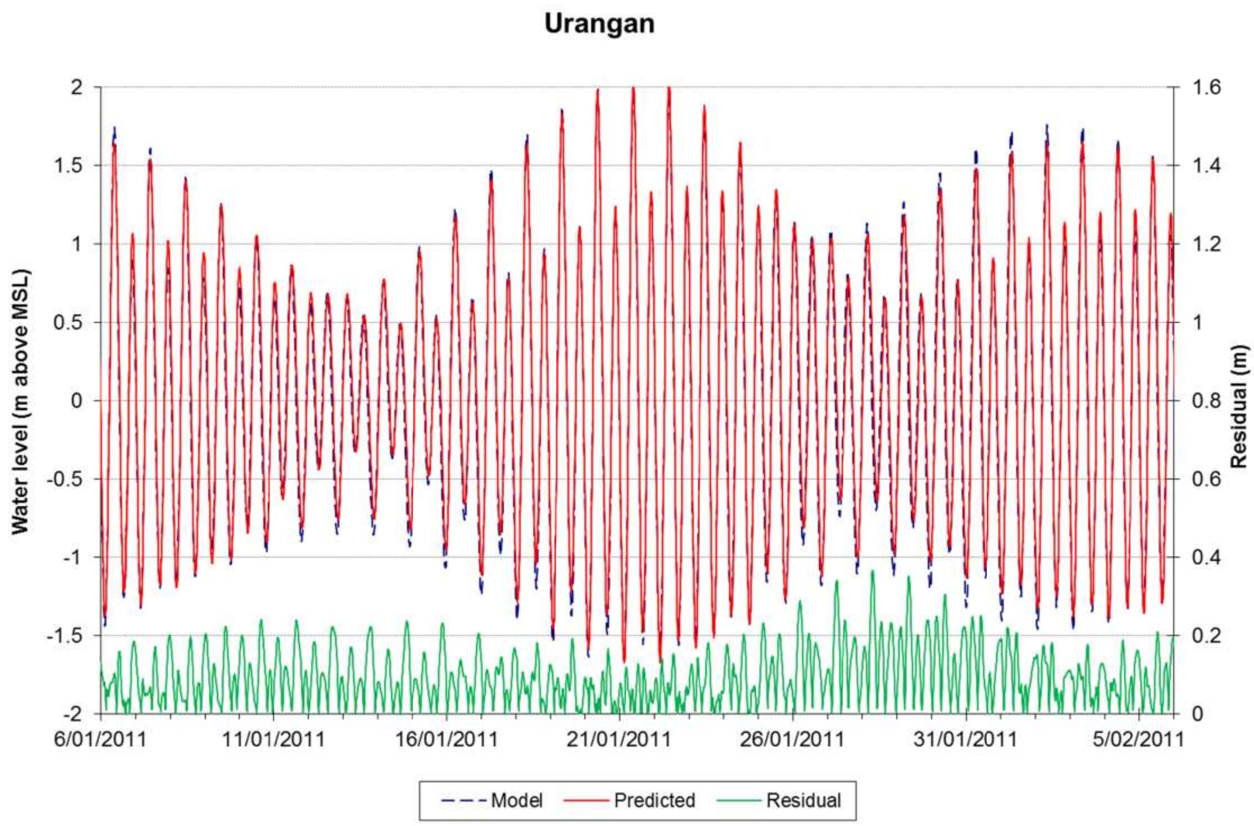

Figure A- 18 Comparison of modelled and predicted tides for Urangan.

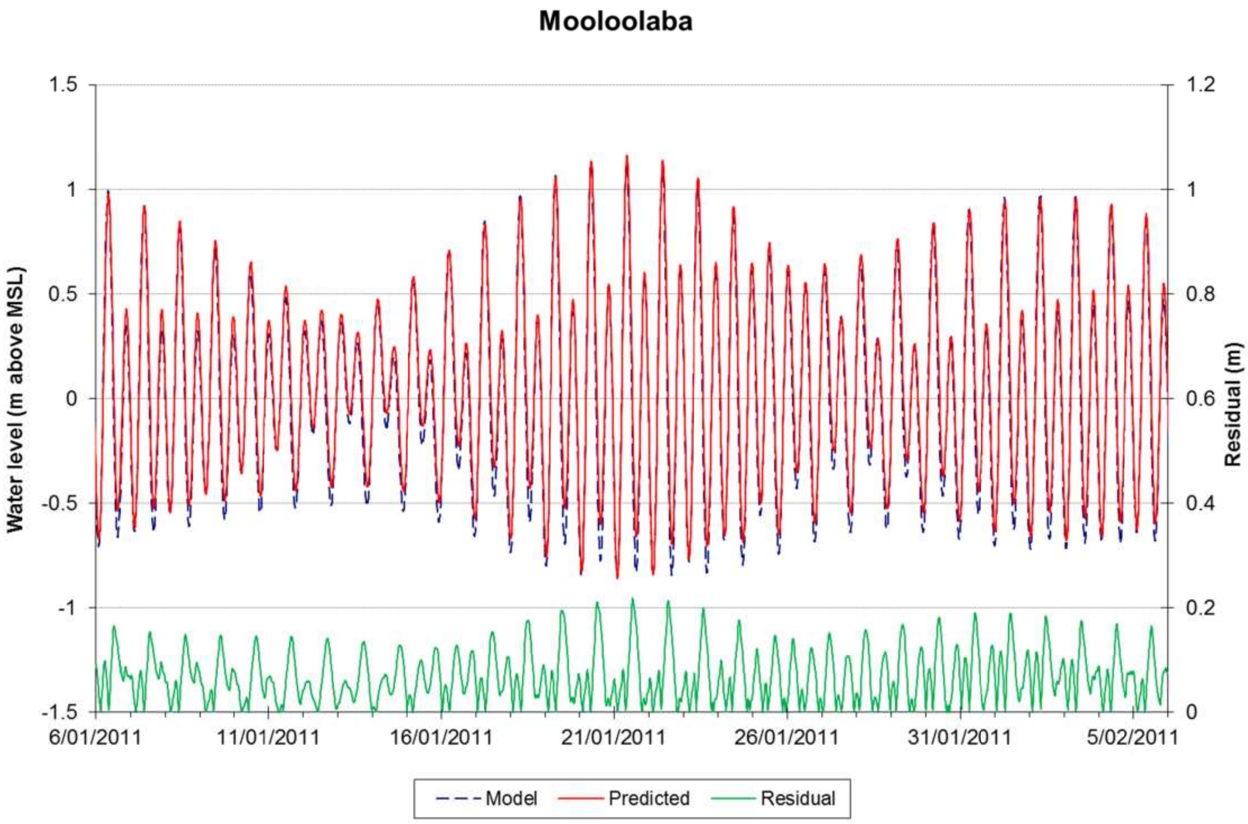

Figure A- 19 Comparison of modelled and predicted tides for Mooloolaba.

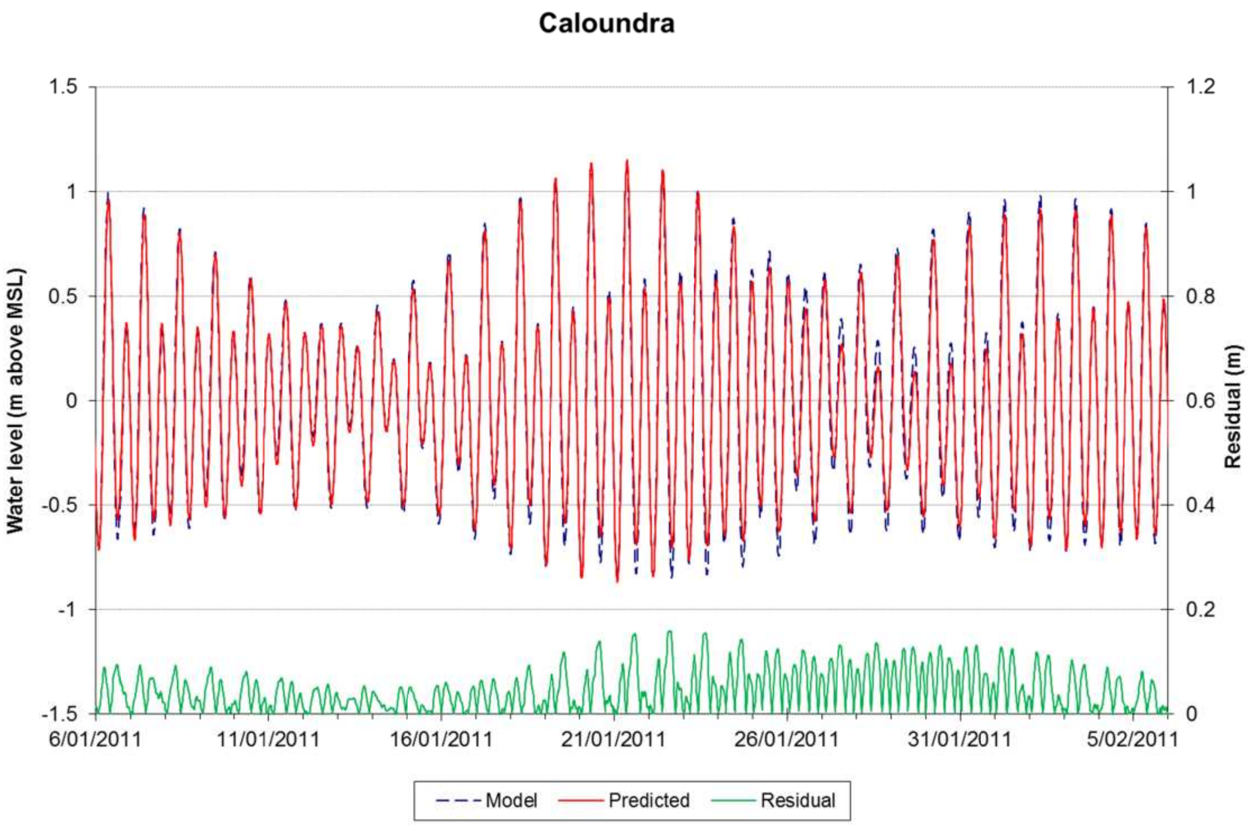

Figure A- 20 Comparison of modelled and predicted tides for Caloundra.

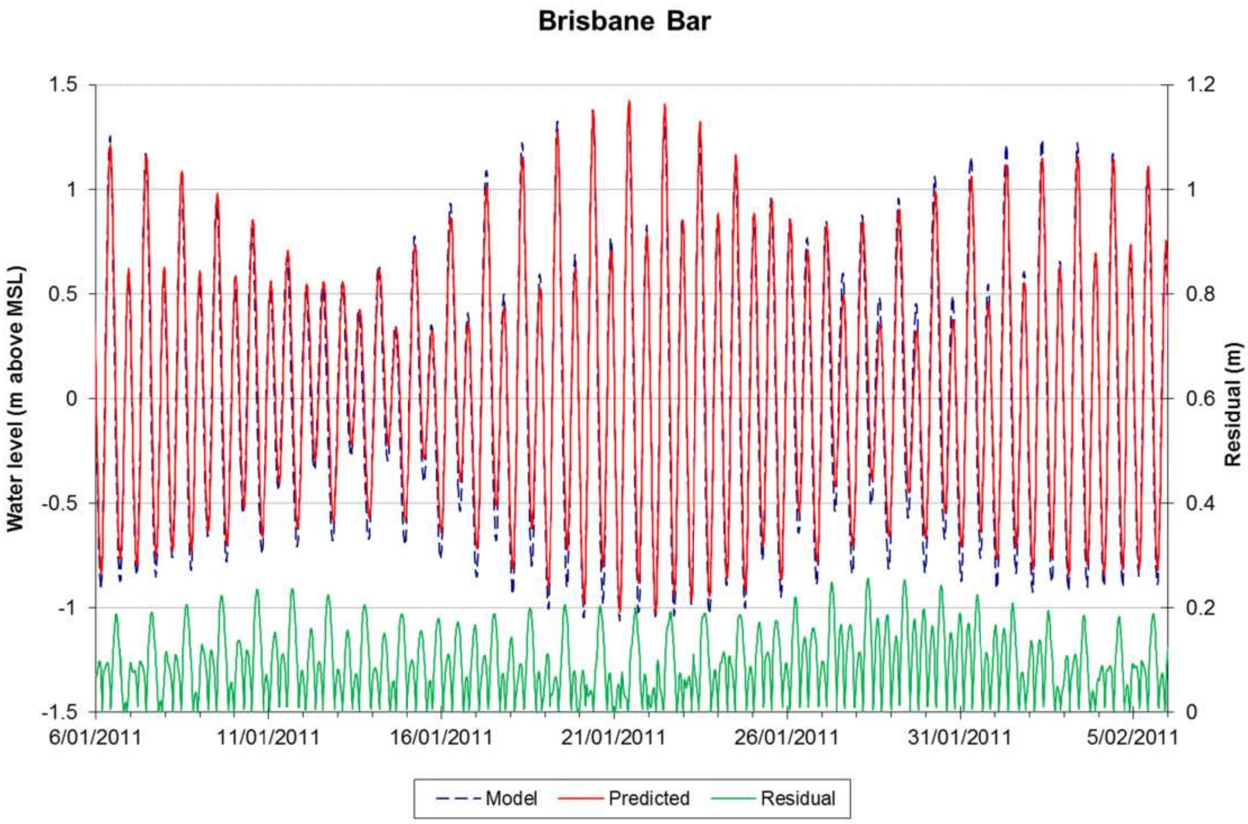

Figure A- 21 Comparison of modelled and predicted tides for Brisbane Bar.

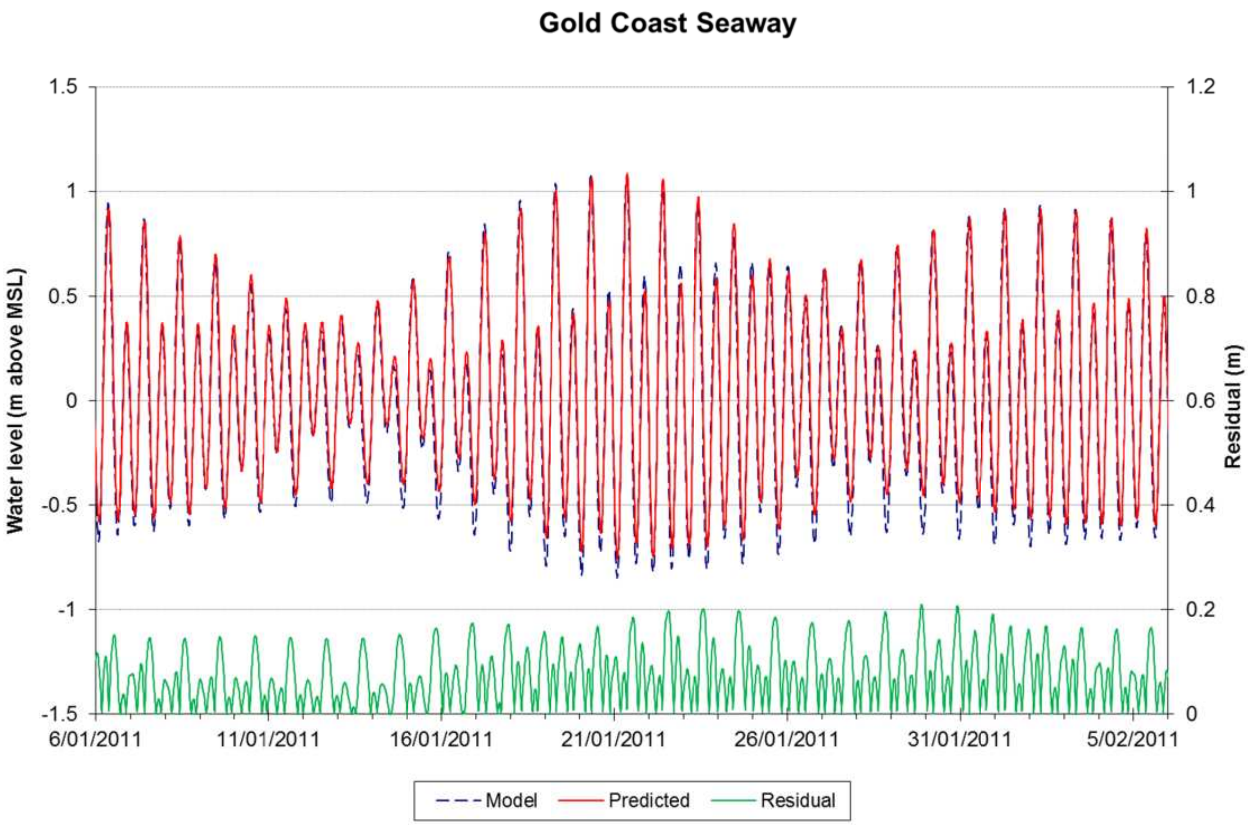

Figure A- 22 Comparison of modelled and predicted tides for Gold Coast Seaway.

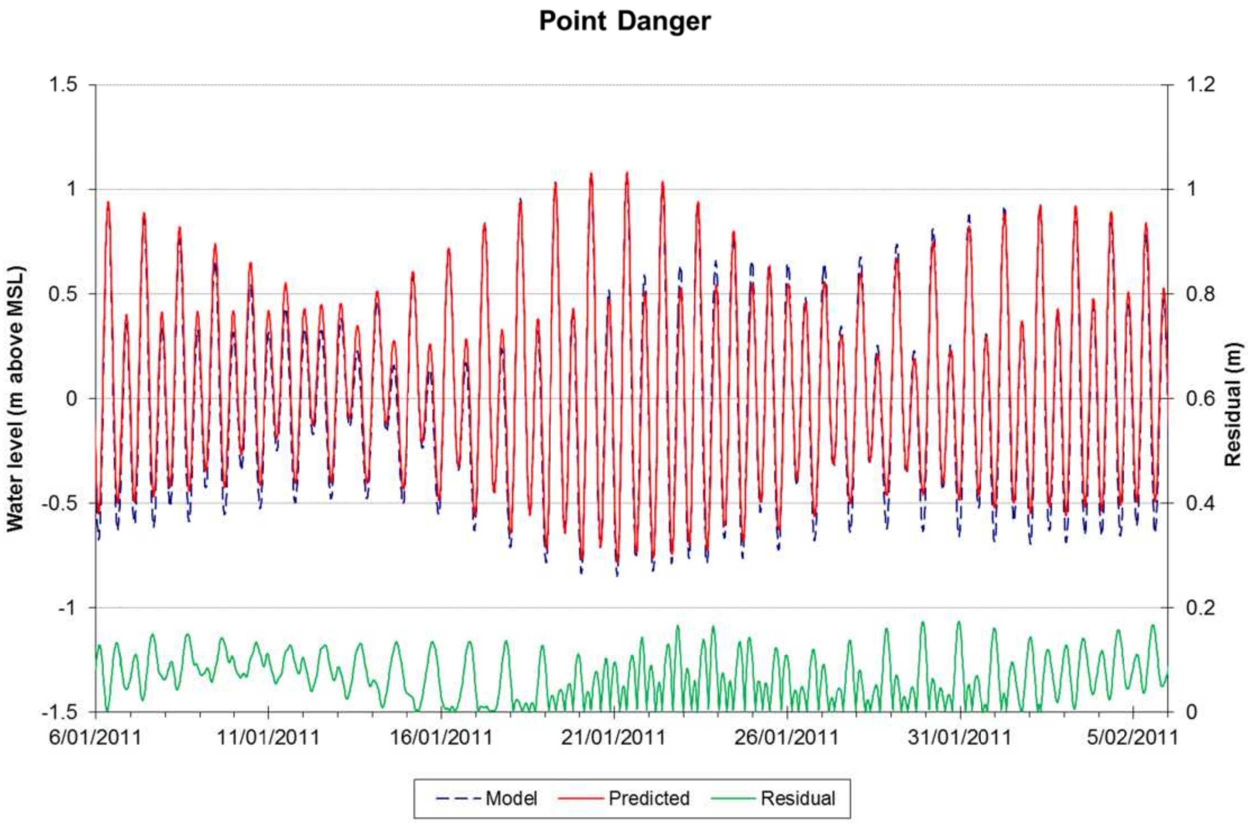

Figure A- 23 Comparison of modelled and predicted tides for Point Danger.

Appendix B - Solomon Islands 2007 Tsunami

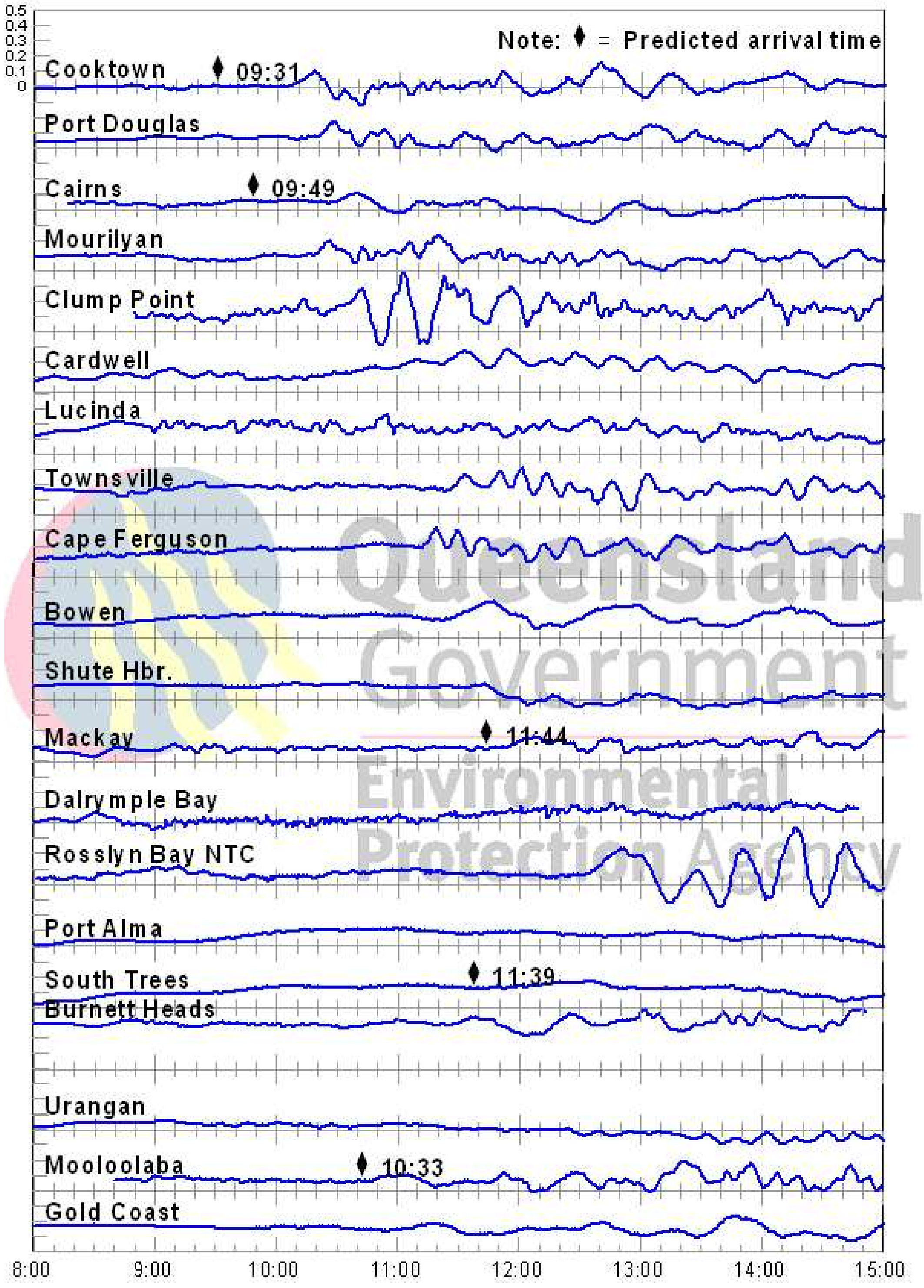

Figure B- 1 Measured water levels on 2 April 2007 (AEST) following the Solomon Islands submarine earthquake.

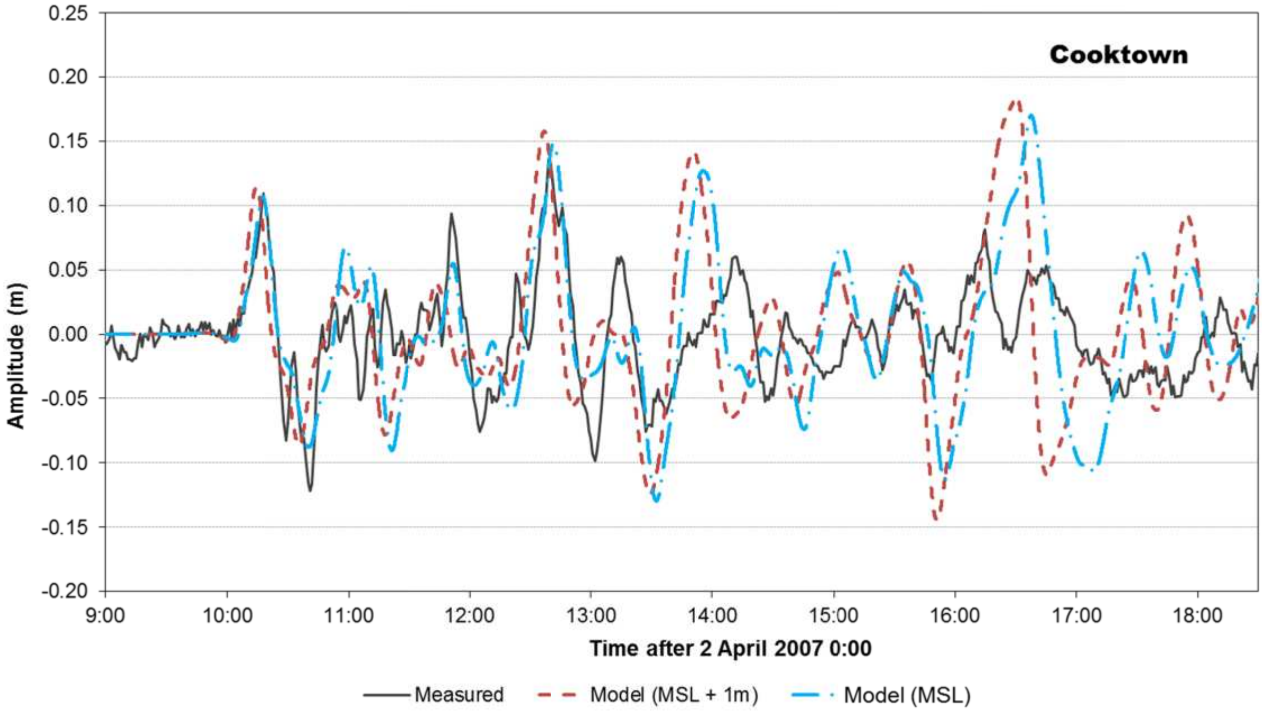

Figure B- 2 Solomon Is 2007 tsunami as measured and modelled for Cooktown.

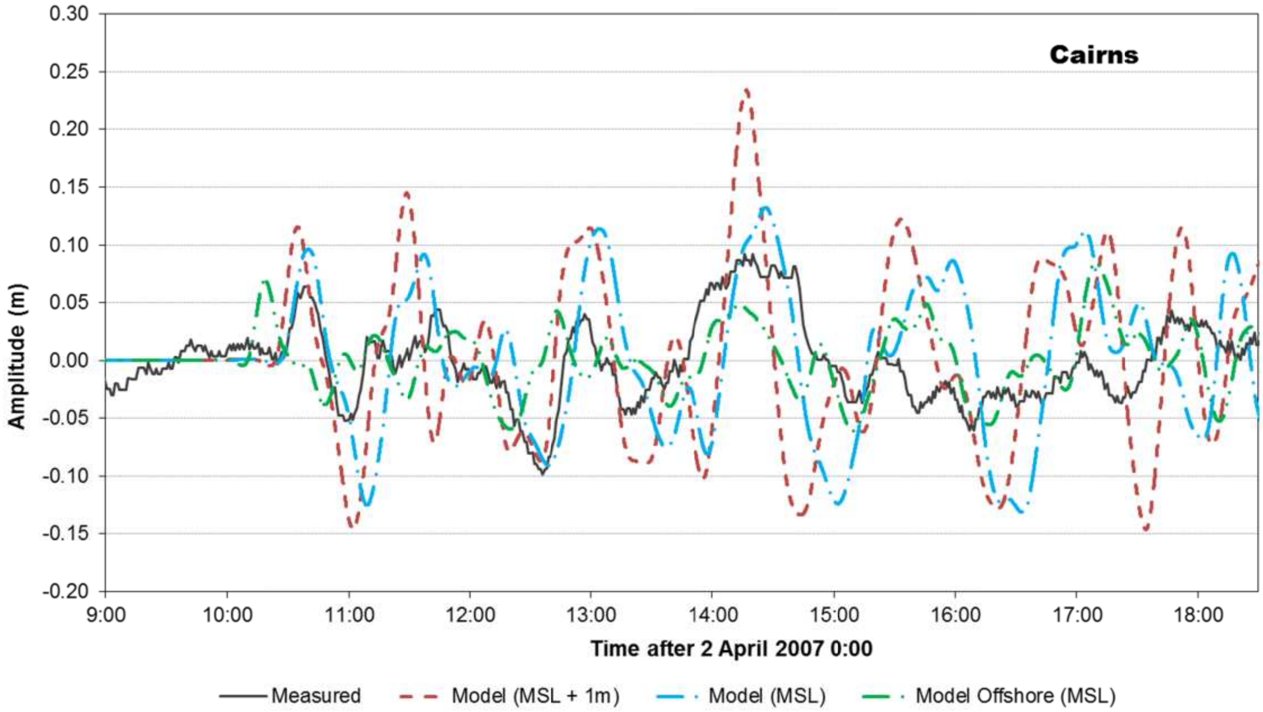

Figure B- 3 Solomon Is 2007 tsunami as measured and modelled for Cairns.

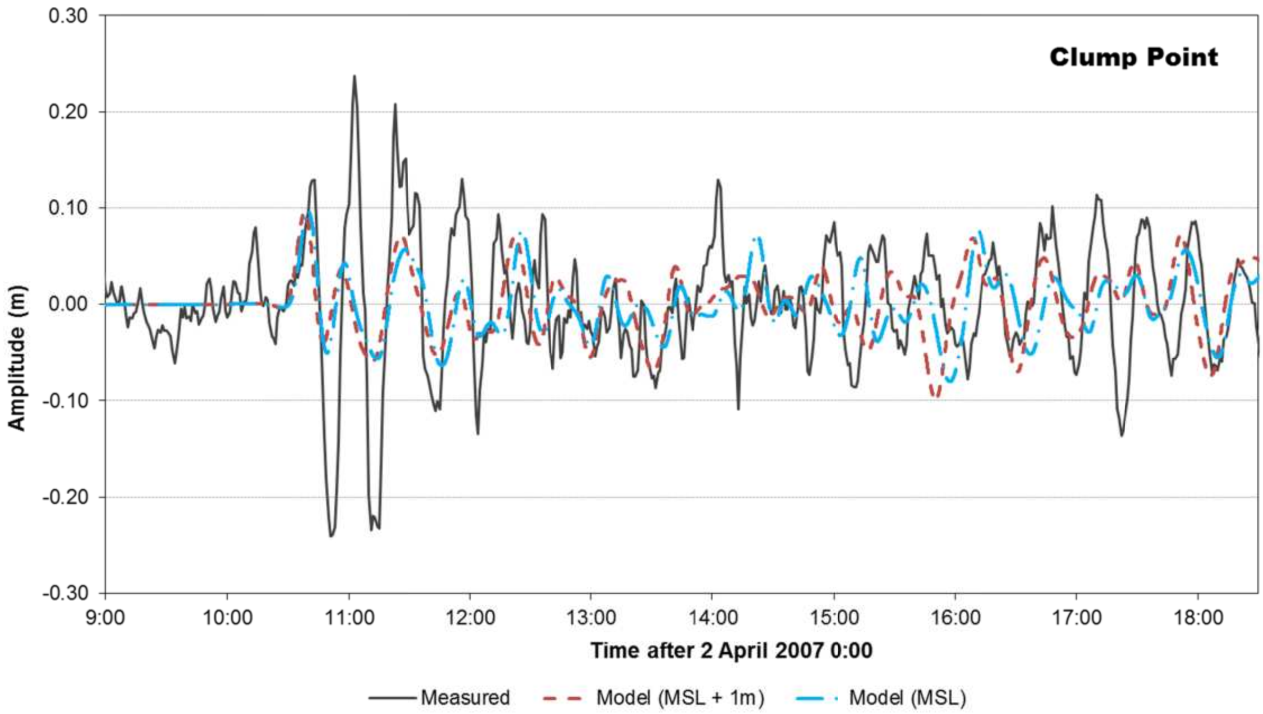

Figure B- 4 Solomon Is 2007 tsunami as measured and modelled for Clump Point.

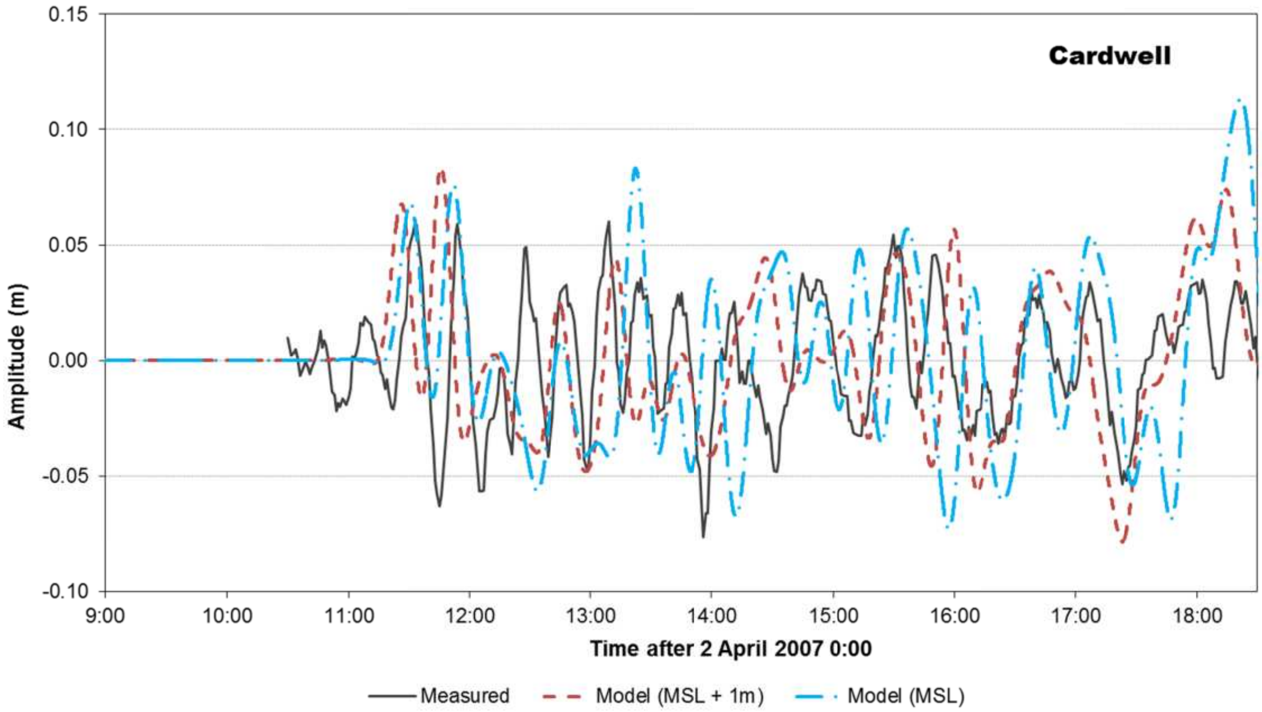

Figure B- 5 Solomon Is 2007 tsunami as measured and modelled for Cardwell.

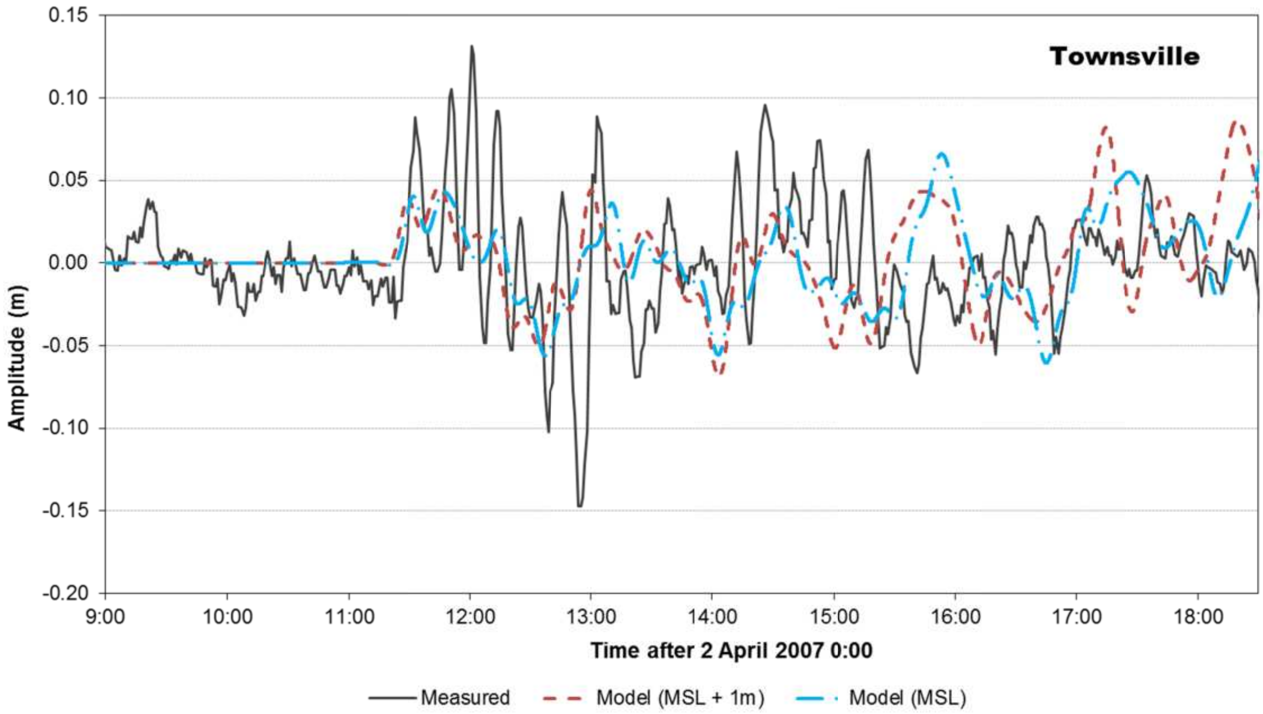

Figure B- 6 Solomon Is 2007 tsunami as measured and modelled for Townsville.

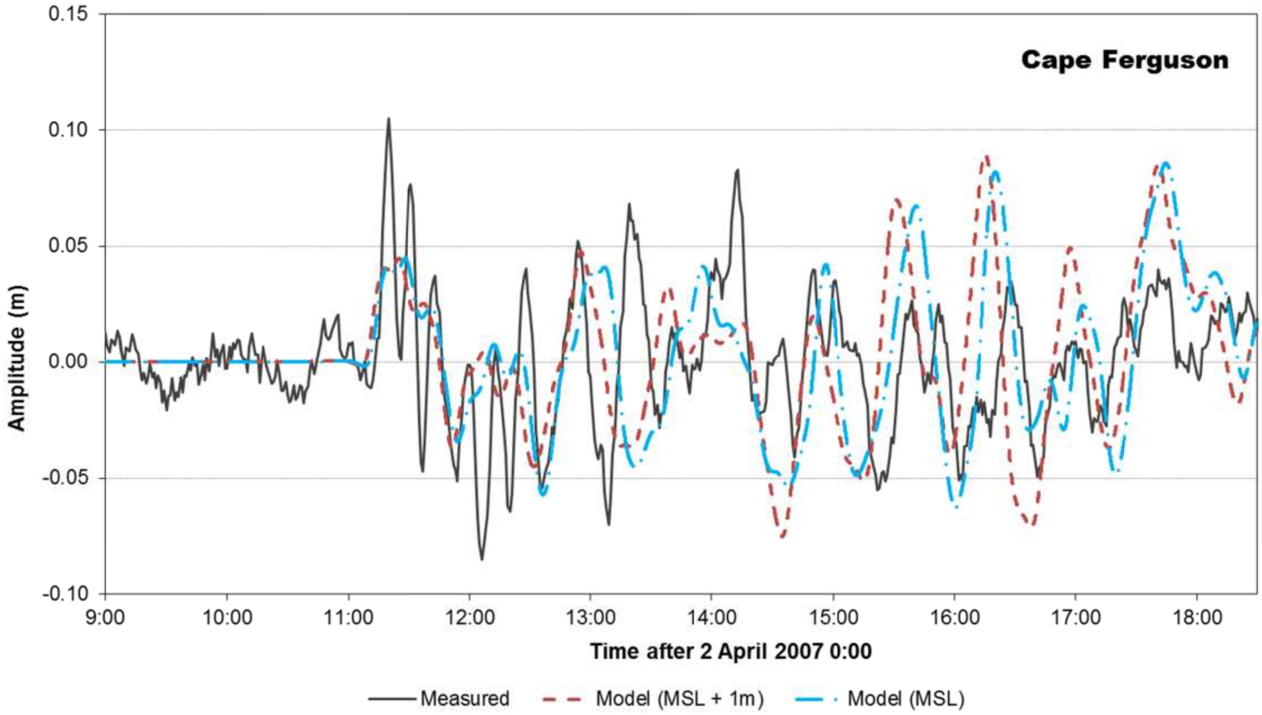

Figure B- 7 Solomon Is 2007 tsunami as measured and modelled for Cape Ferguson.

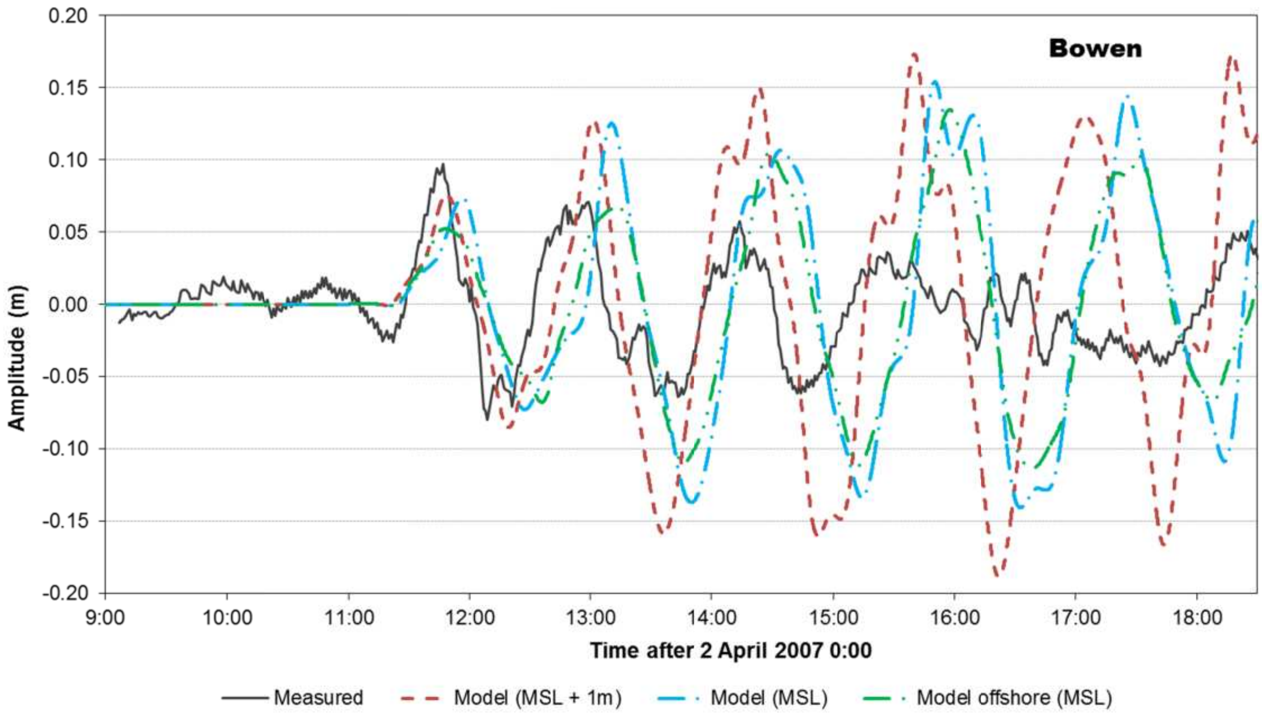

Figure B- 8 Solomon Is 2007 tsunami as measured and modelled for Bowen.

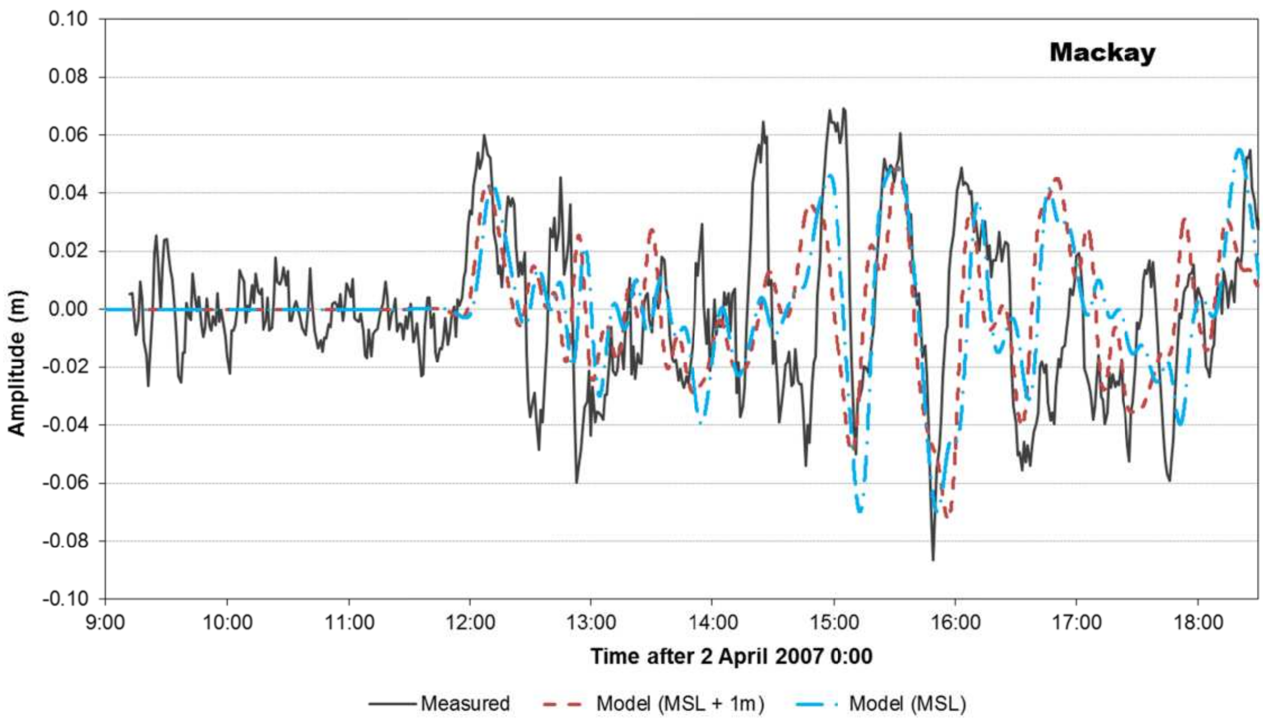

Figure B- 9 Solomon Is 2007 tsunami as measured and modelled for Mackay.

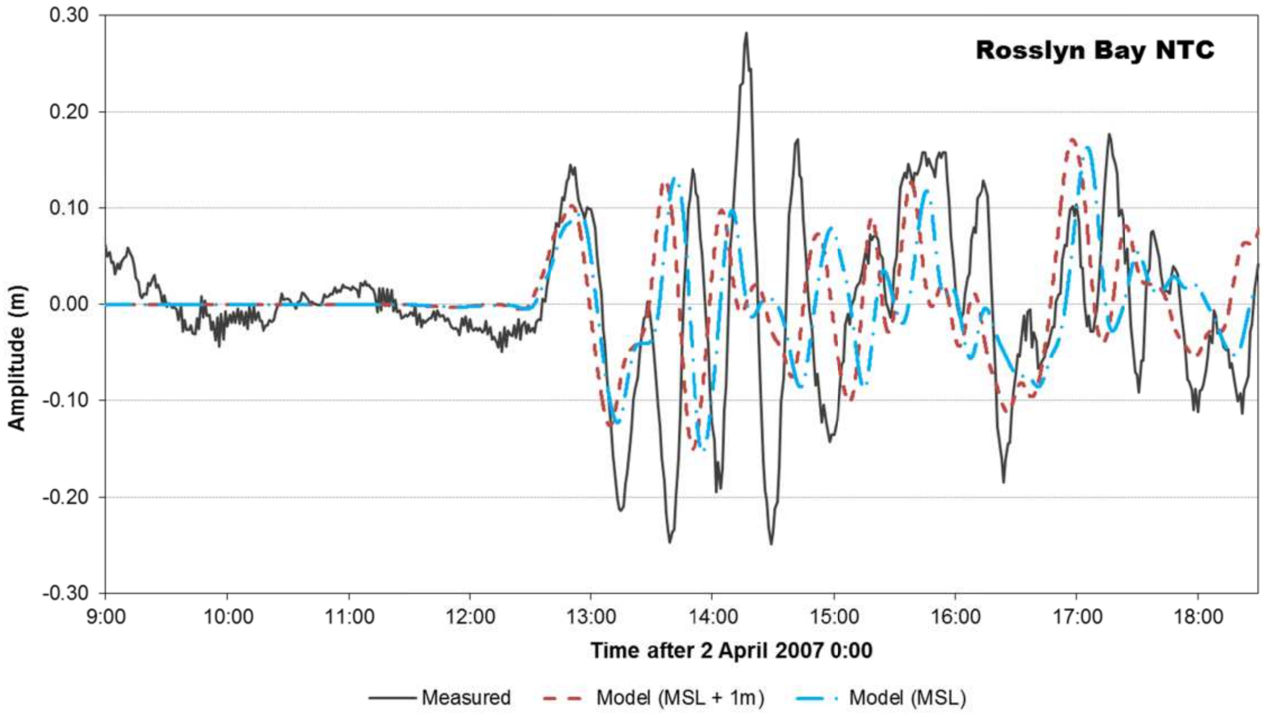

Figure B- 10 Solomon Is 2007 tsunami as measured and modelled for Rosslyn Bay.

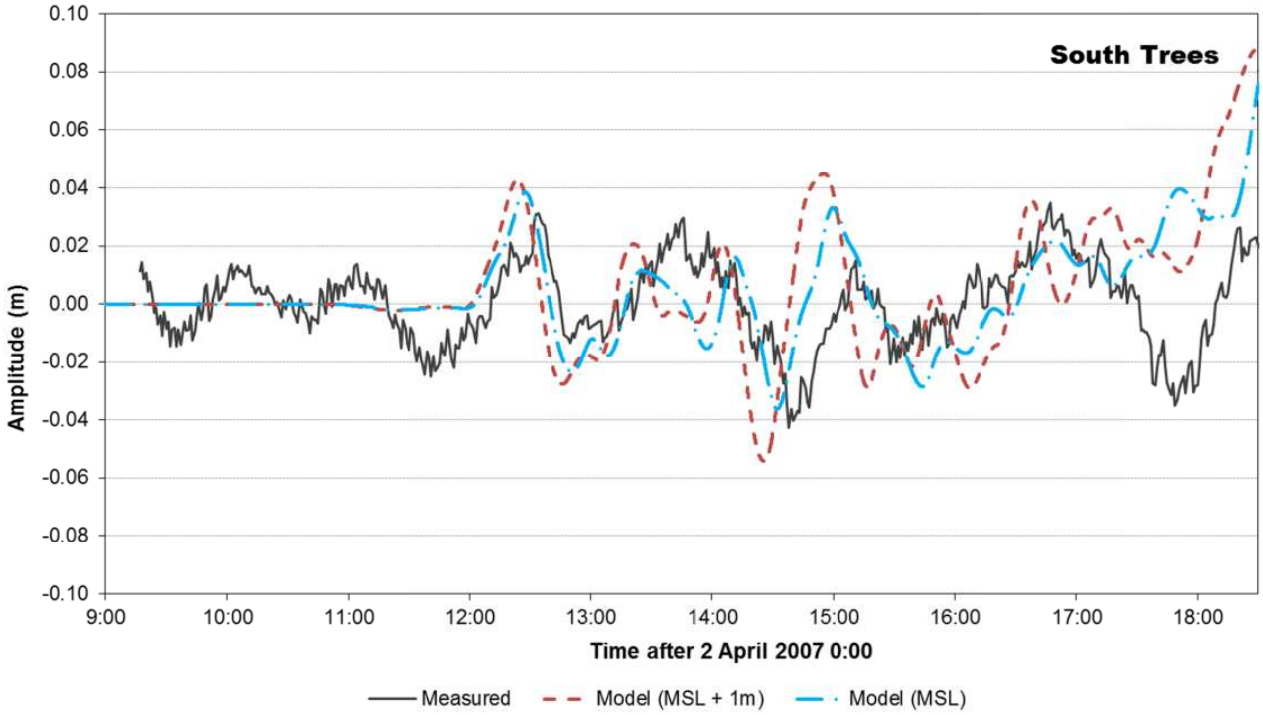

Figure B- 11 Solomon Is 2007 tsunami as measured and modelled for South Trees.

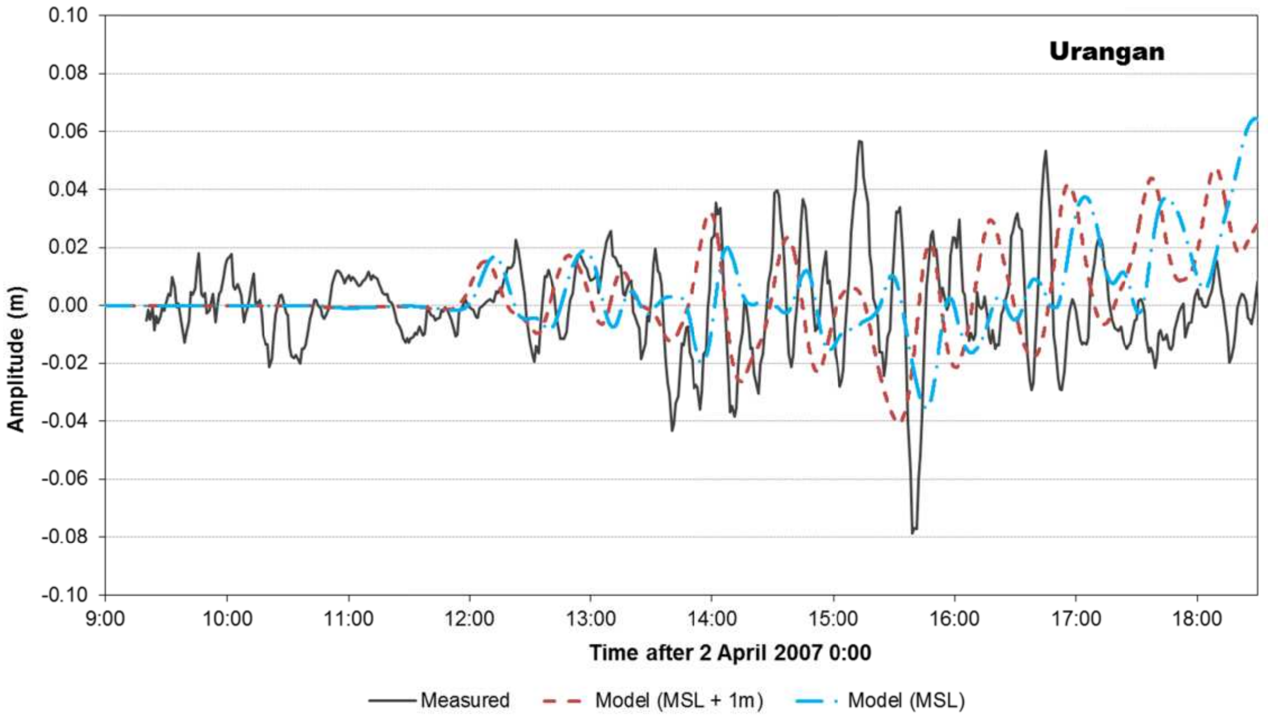

Figure B- 12 Solomon Is 2007 tsunami as measured and modelled for Urangan.

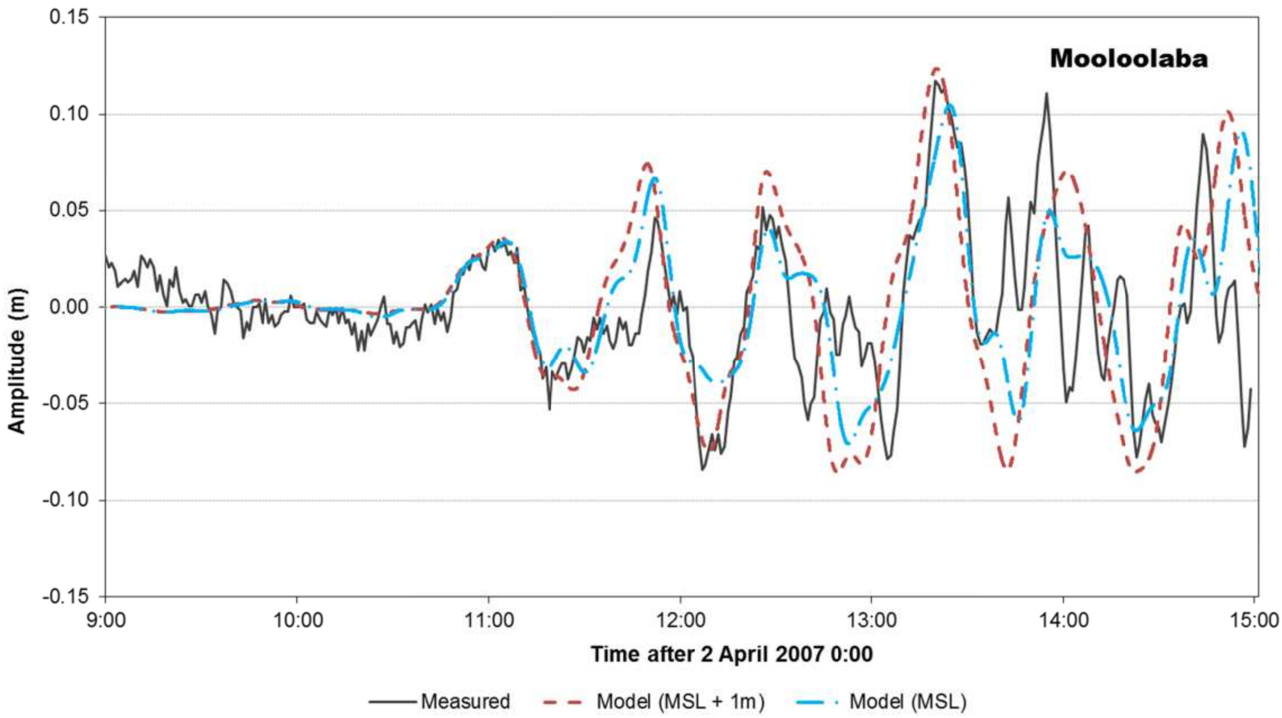

Figure B- 13 Solomon Is 2007 tsunami as measured and modelled for Mooloolaba.

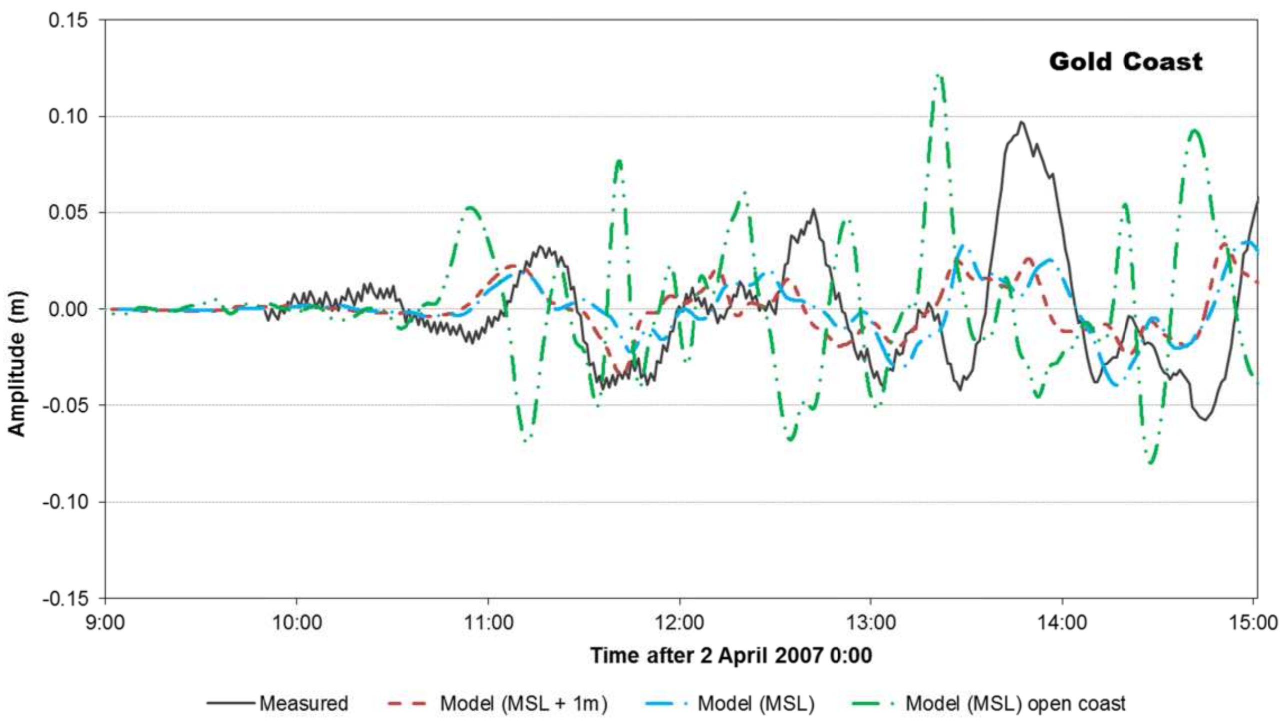

Figure B- 14 Solomon Is 2007 tsunami as measured and modelled for Gold Coast.

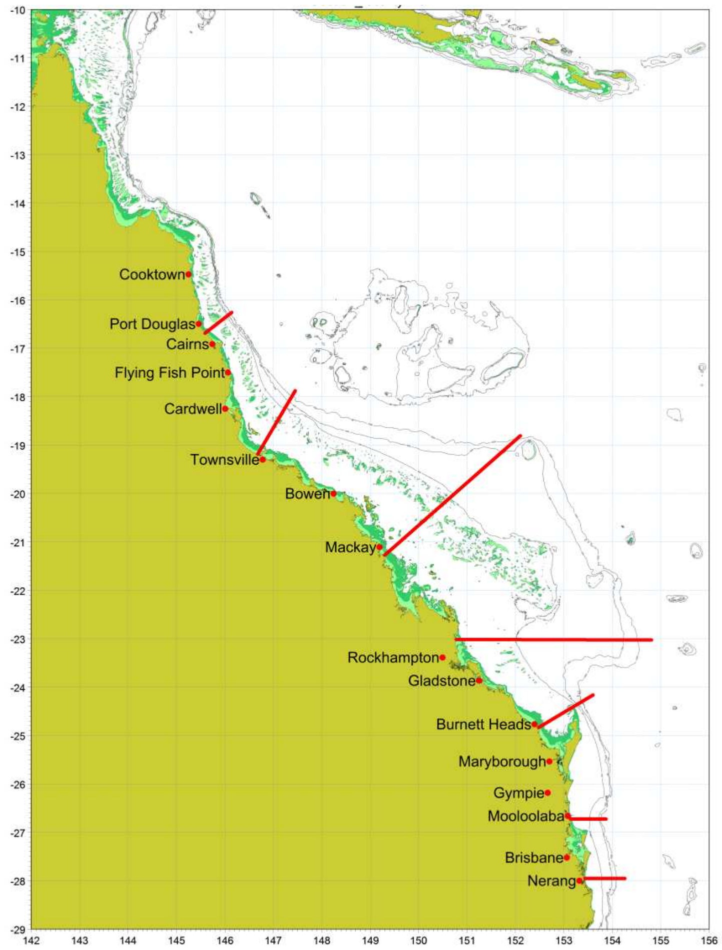

Figure B- 15 Location of extracted profiles 1 to 7.

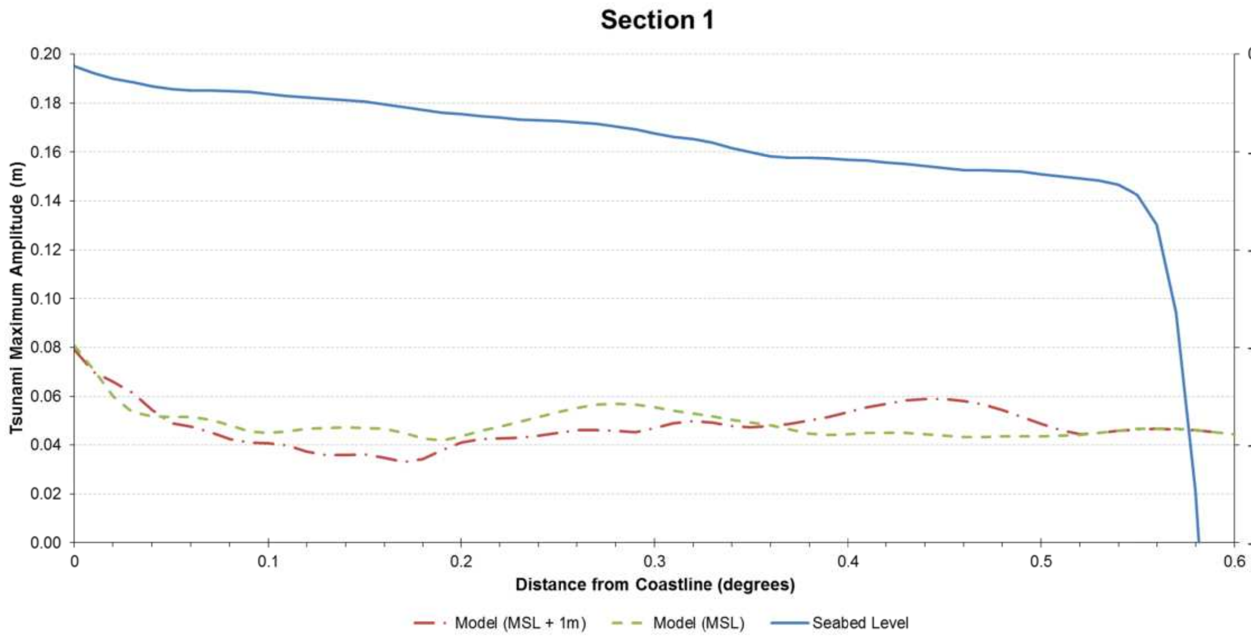

Figure B- 16 Modelled maximum tsunami amplitude along Section 1 north of Cairns.

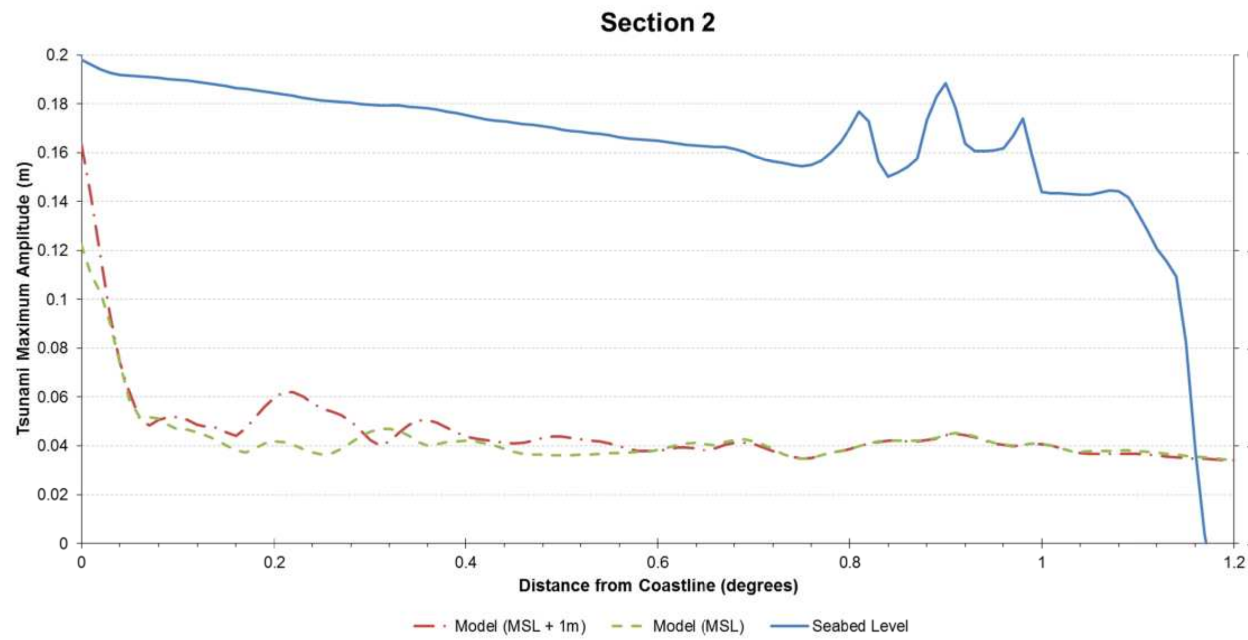

Figure B- 17 Modelled maximum tsunami amplitude along Section 2 north of Townsville.

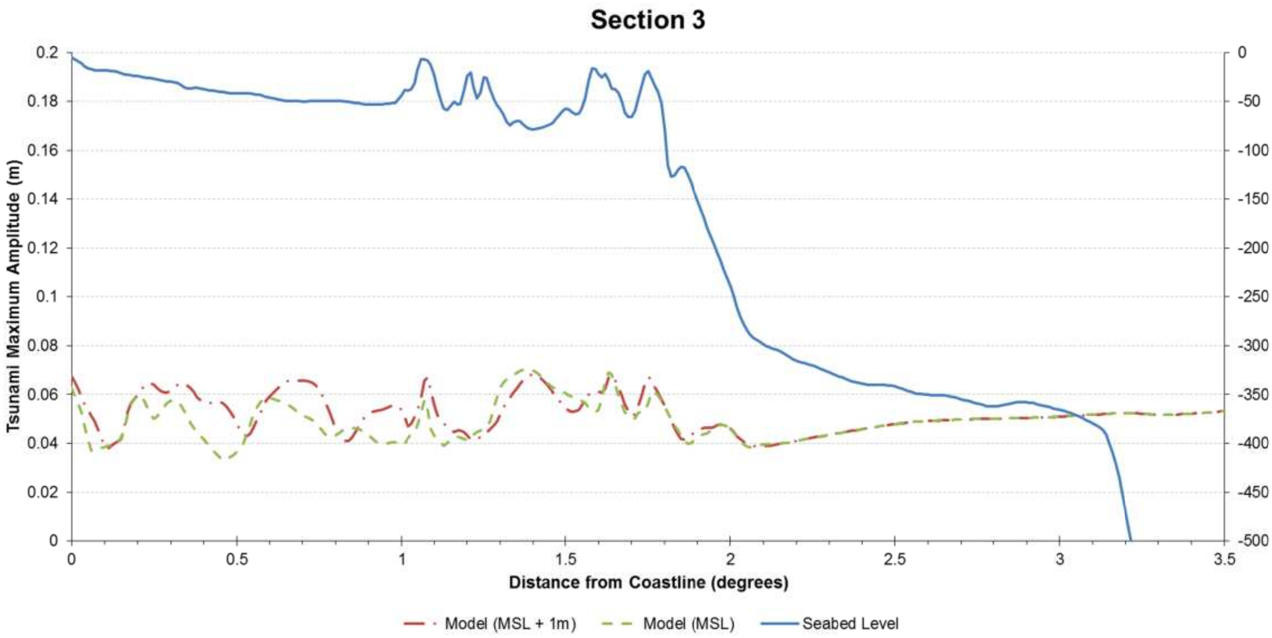

Figure B- 18 Modelled maximum tsunami amplitude along Section 3 near Hay Pt.

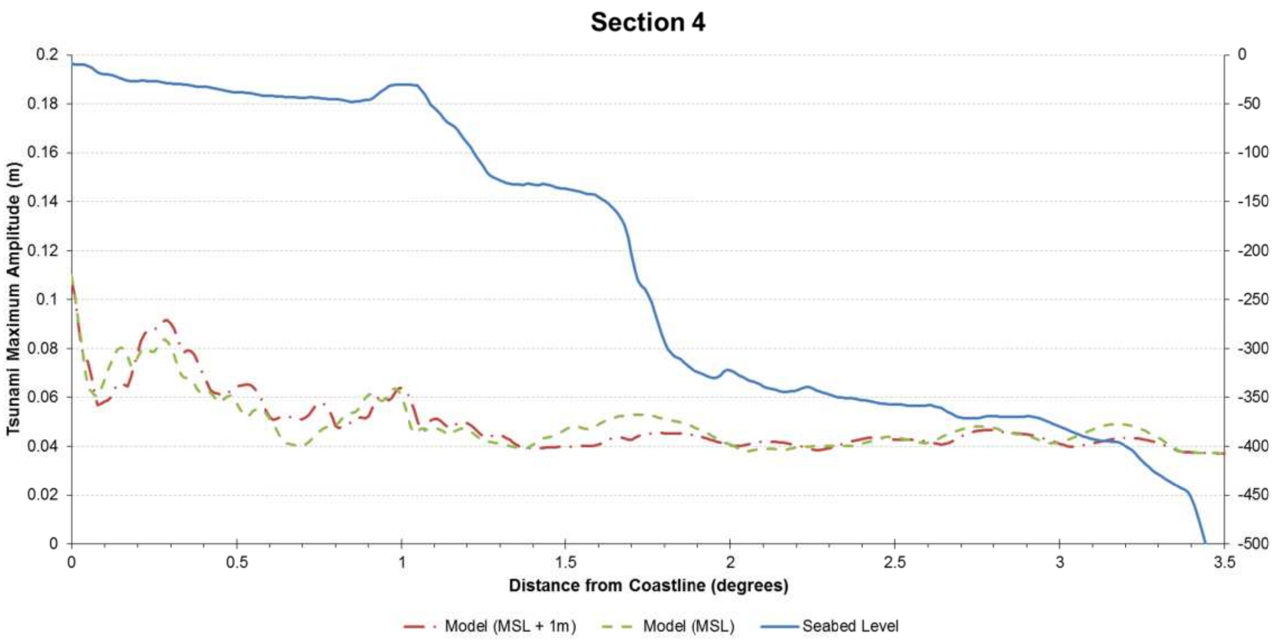

Figure B- 19 Modelled maximum tsunami amplitude along Section 4 north of Yeppoon.

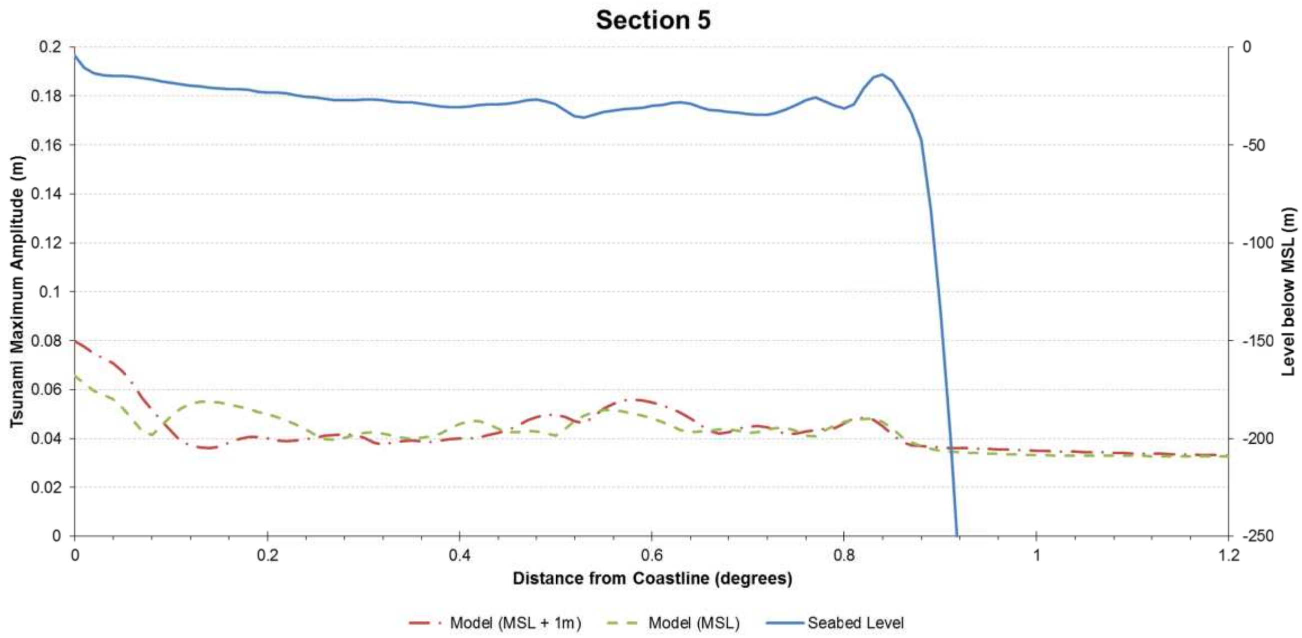

Figure B- 20 Modelled maximum tsunami amplitude along Section 5 north of Elliott Heads.

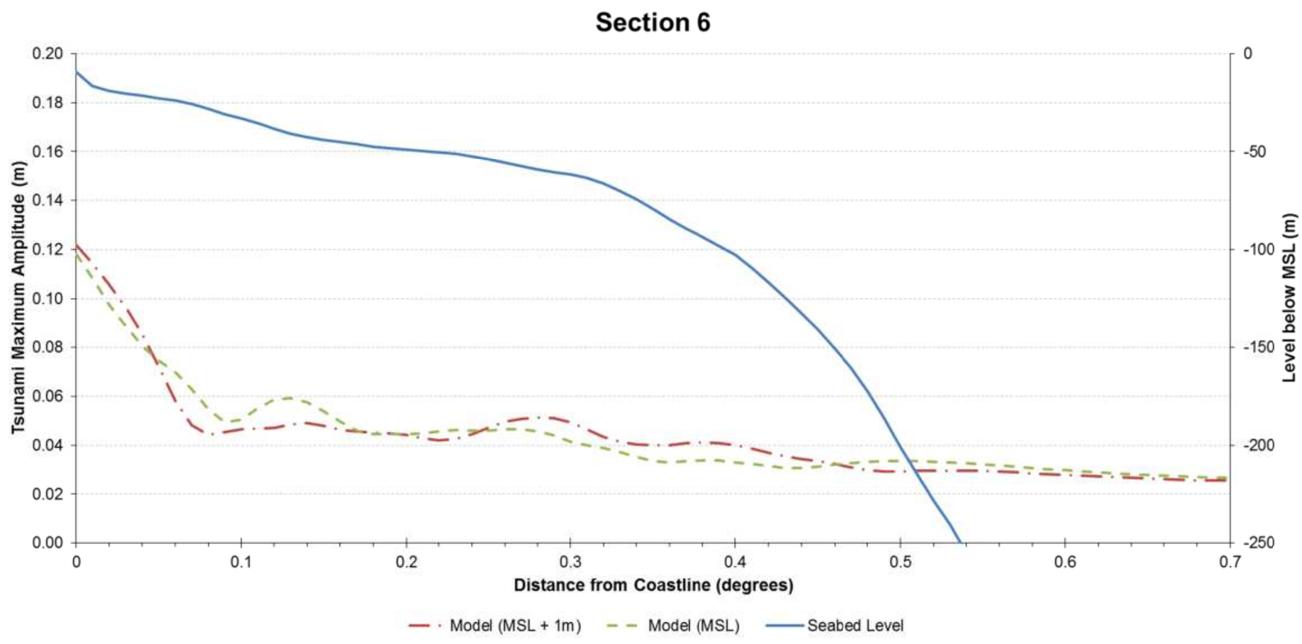

Figure B- 21 Modelled maximum tsunami amplitude along Section 6 south of Mooloolaba.

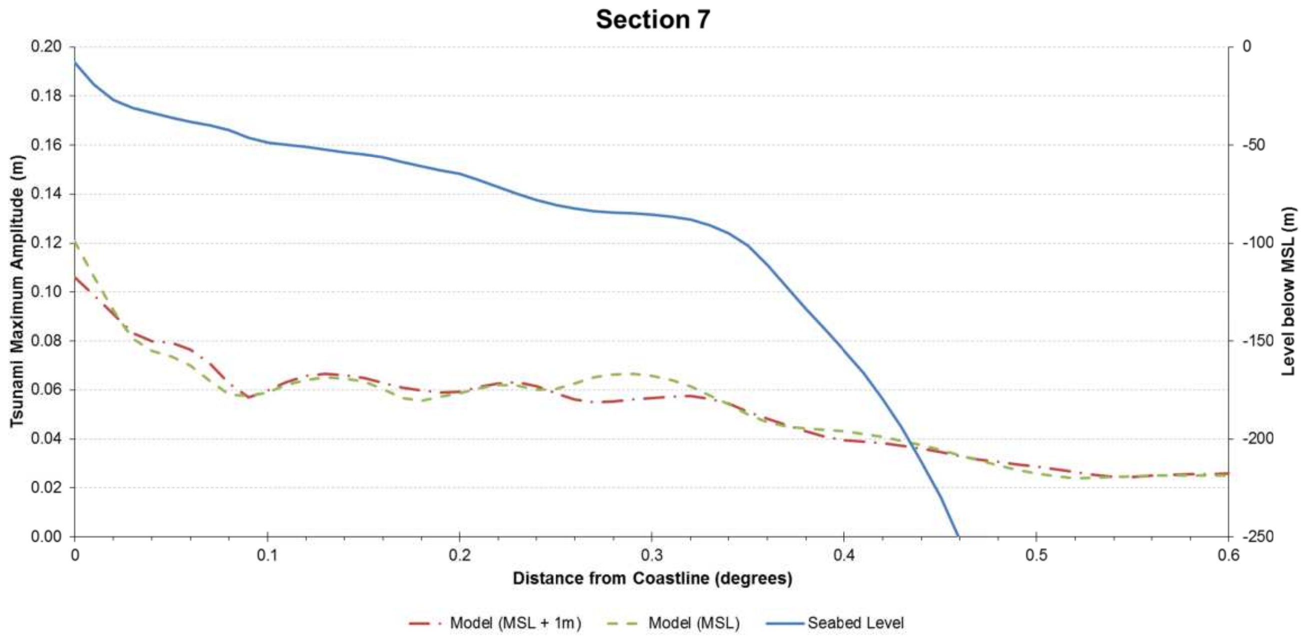

Figure B- 22 Modelled maximum tsunami amplitude along Section 7 at Main Beach, Gold Coast.

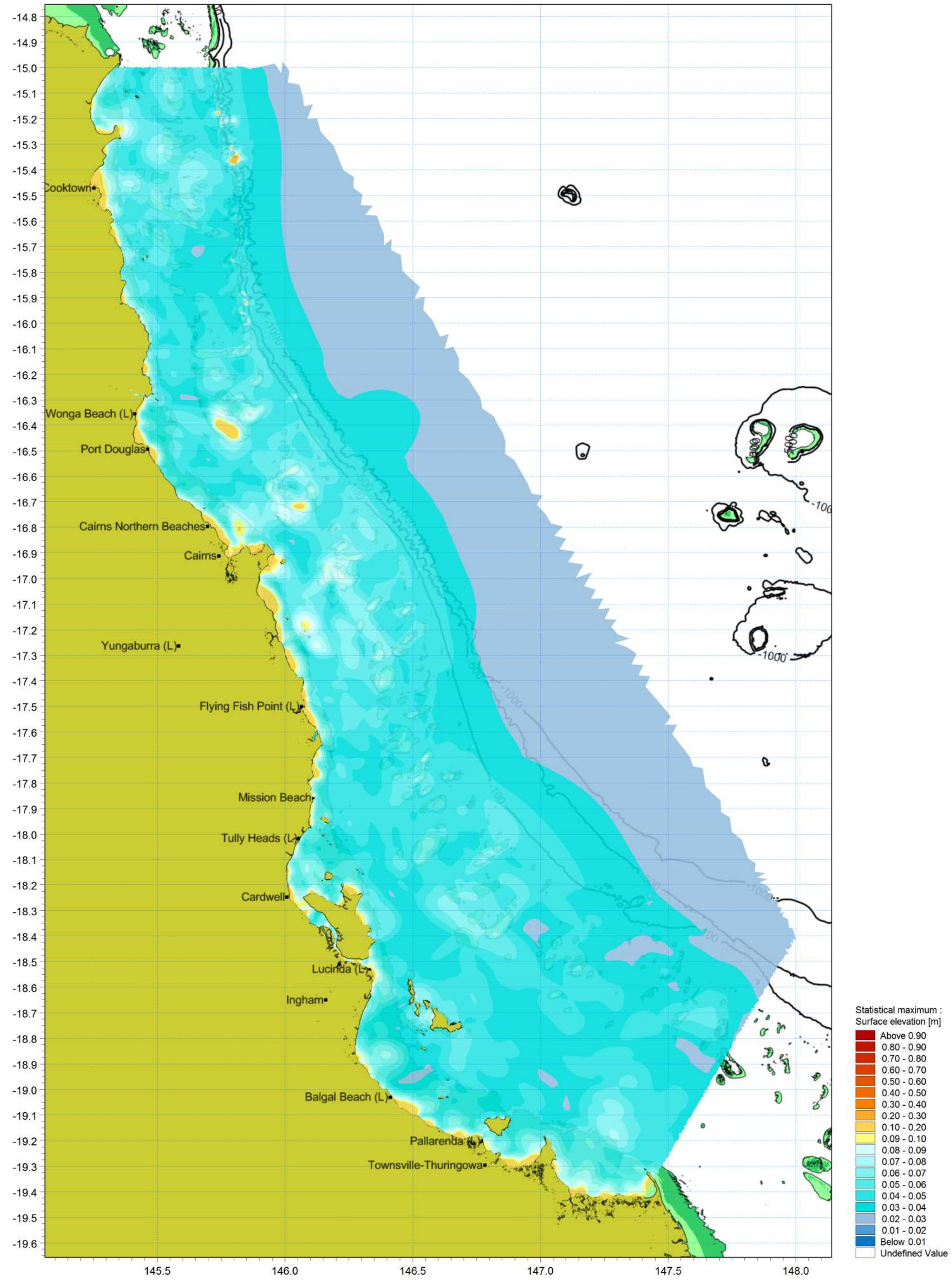

Figure B- 23 Solomon Is 2007 tsunami maximum amplitude from Cooktown to Townsville.

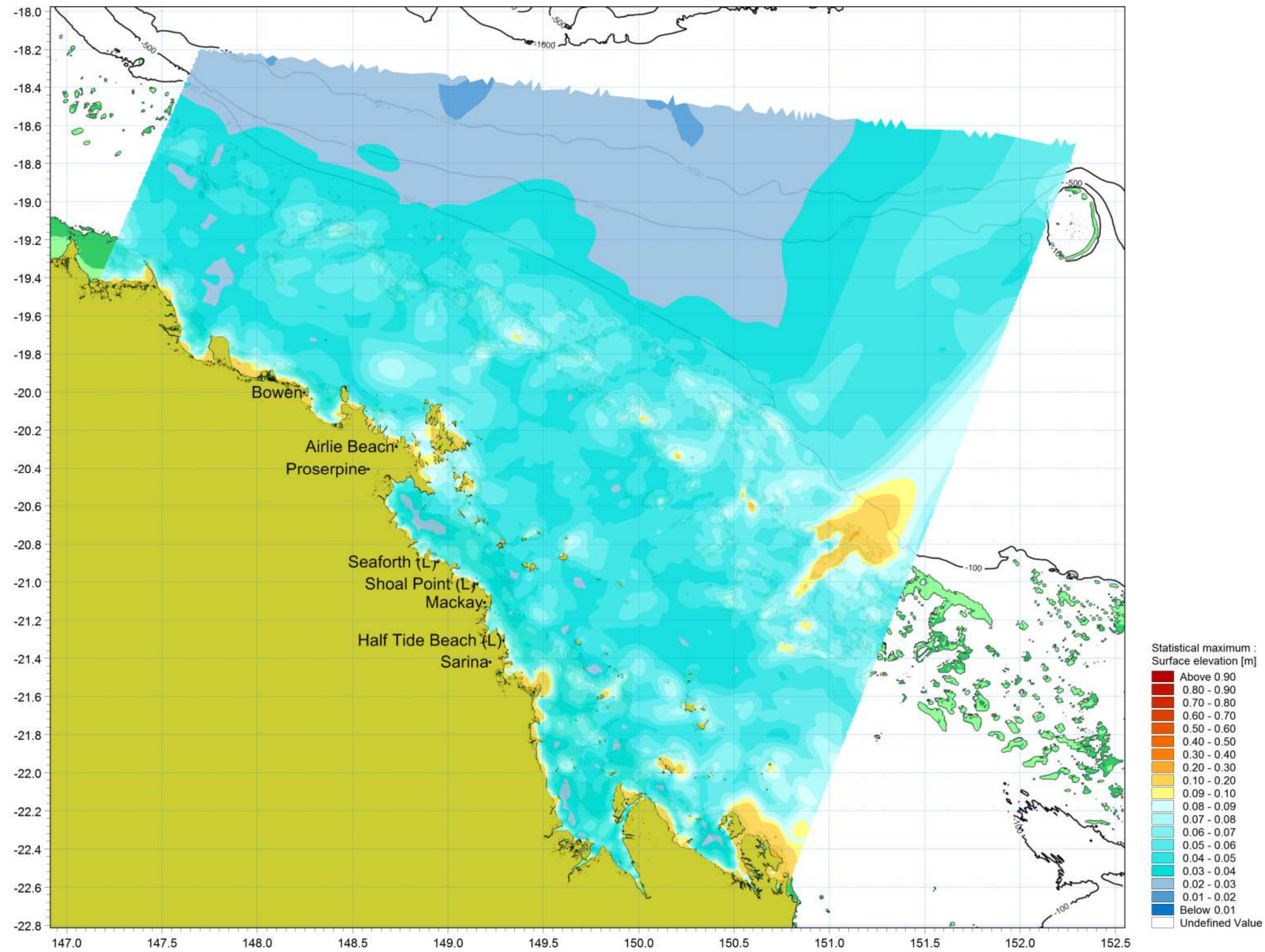

Figure B- 24 Solomon Is 2007 tsunami maximum amplitude from Cungulla to Shoalwater Bay.

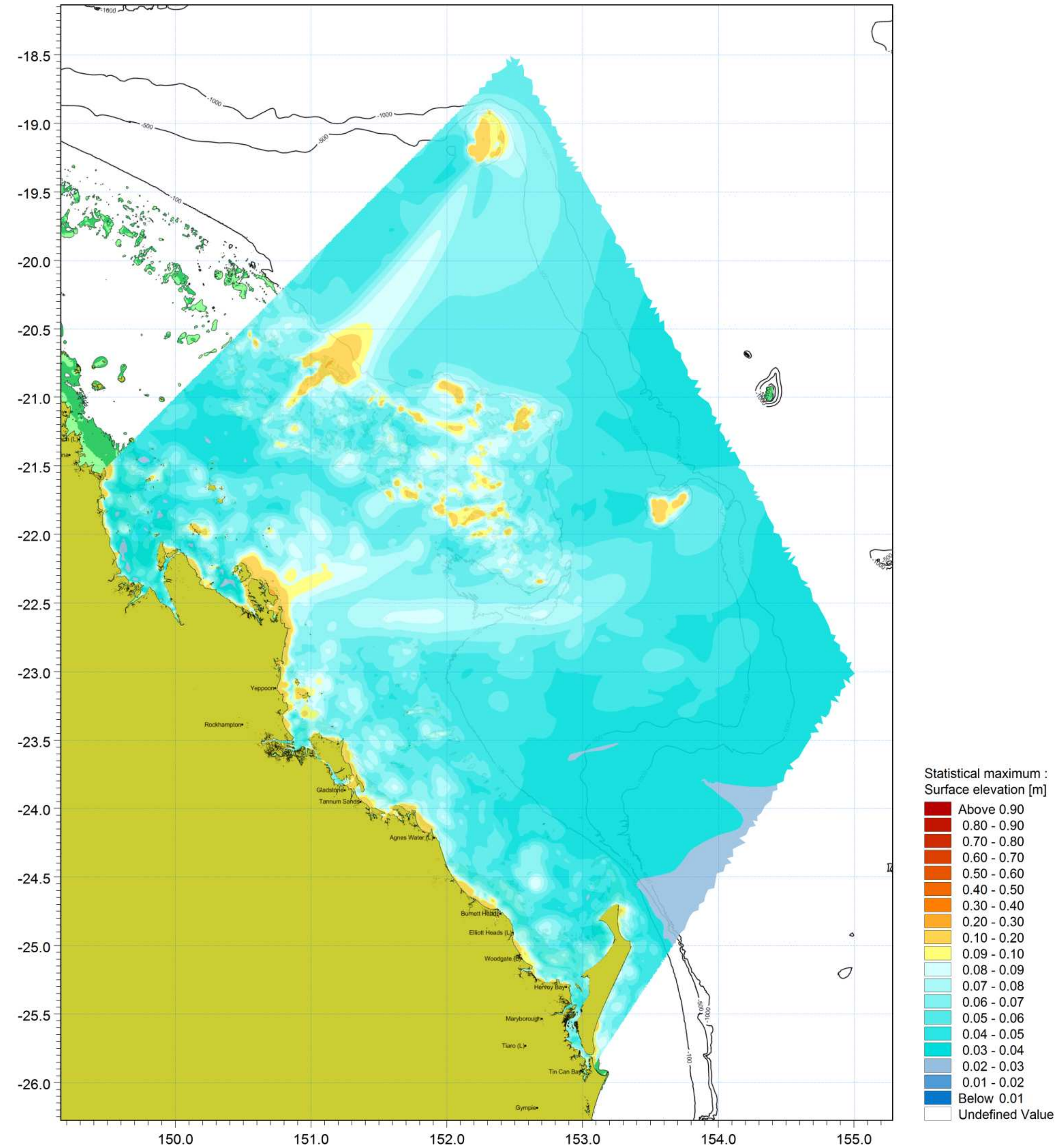

Figure B- 25 Solomon Is 2007 tsunami maximum amplitude from Shoalwater Bay to Fraser Island.

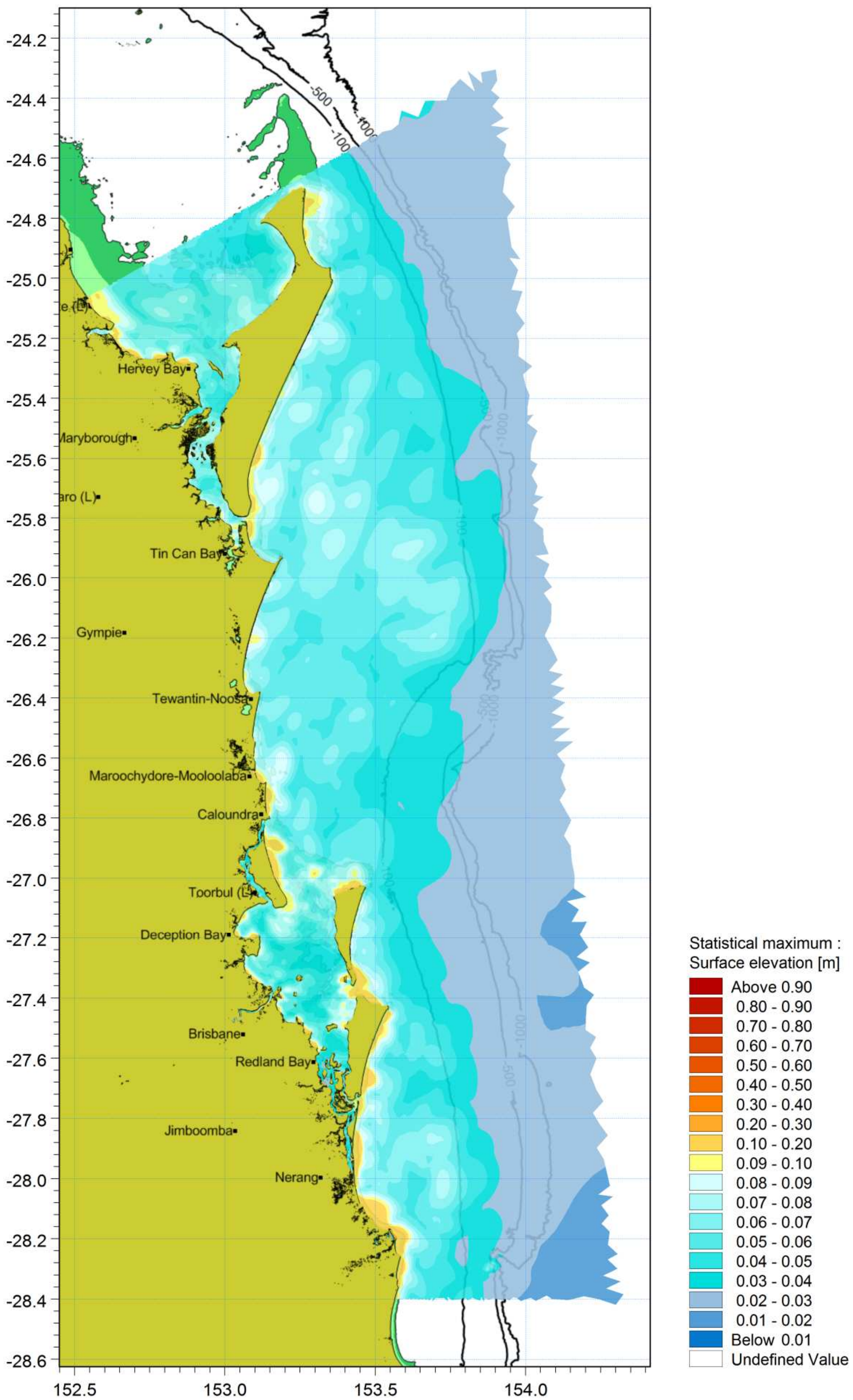

Figure B- 26 Solomon Is 2007 tsunami maximum amplitude from Fraser Island to Gold Coast.

Appendix C - Amplification Factors

Table C- 1 TsuDAT details for selected scenarios.

Scenario	Hazard Point				Source Earthquake Information			
	Output ID	longitude	latitude	Description	Event ID	Subduction Zone	Magnitude	Slip (m)
1	2701	149.55	-19.3	Offshore Whitsundays	64047	SE Solomon	8.5	11.834
2	2701	149.55	-19.3	Offshore Whitsundays	64161	SE Solomon	8.8	7.629
3	2701	149.55	-19.3	Offshore Whitsundays	64223	SE Solomon	9.1	24.273
4	3466	153.533	-26.917	Offshore Bribie Is	49931	New Hebrides	8.8	7.629
5	3466	153.533	-26.917	Offshore Bribie Is	50156	New Hebrides	9.3	13.882
6	3466	153.533	-26.917	Offshore Bribie Is	50101	New Hebrides	9.2	27.36

Table C- 2 Tsunami details for selected scenarios from TsuDAT.

Scenario	Tsunami Details			Model Domain
	Return Period (yrs)	Min Amplitude (m)	Max Amplitude (m)	
1	750	-0.47	0.50	GBR and Hervey Bay
2	3000	-0.96	1.01	GBR and Hervey Bay
3	15000	-2.10	1.97	GBR and Hervey Bay
4	750	-0.45	0.55	SEQ and Gold Coast
5	3000	-0.80	1.13	SEQ and Gold Coast
6	6000	-1.43	1.32	SEQ and Gold Coast

Table C- 3 Indicative amplification factors for specific points at 5m depth.

Site	Range	Average
Cooktown	0.5	0.5
Port Douglas	0.2 to 0.4	0.3
Trinity Beach	0.5 to 0.7	0.6
Cairns	0.4 to 0.6	0.5
Bramston Beach	0.5 to 0.6	0.6
Flying Fish Point	0.6 to 1.2	0.9
Mourilyan	0.4 to 0.5	0.4
Mission Beach	0.5 to 0.6	0.5
Cardwell	0.1 to 0.3	0.2
Lucinda	0.3 to 0.5	0.4
Saunders Beach	0.3 to 0.4	0.3

Site	Range	Average
Townsville	0.2 to 0.3	0.2
Bowen	0.4 to 0.5	0.4
Airlie Beach	0.3	0.3
Laguana Quays	0.1	0.1
Blacks Beach	0.3	0.3
Mackay	0.4 to 0.6	0.5
Hay Point	0.2 to 0.3	0.2
St Lawrence	0.1 to 0.2	0.1
Byfield	0.4	0.4
Yeppoon	0.4 to 0.6	0.5
Emu Park	0.3	0.3
Tannum Sands	0.3	0.3
Seventeen Seventy	0.3 to 0.5	0.4
Agnes Waters	0.7 to 1.1	0.9
Burnett Heads	0.3	0.3
Elliott Heads	0.2 to 0.3	0.2
Urangun	0.2 to 0.3	0.3
Fraser Island	1.4 to 2.2	1.9
Rainbow Beach	0.8 to 1.1	1.0
Noosa	1.2 to 1.8	1.5
Peregian Beach	1.2 to 1.5	1.4
Coolum Beach	1.3 to 2.0	1.7
Twin Waters	1.2 to 1.6	1.4
Mooloolaba	1.1 to 1.5	1.3
Dicky Beach	1.3 to 2.2	1.8
Woorim	0.8 to 1.1	1.0
Deception Bay	0.2 to 0.3	0.2
Redcliffe	0.6 to 0.7	0.7
Bramble Bay	0.3 to 0.5	0.4
Manly	0.2 to 0.4	0.3
Point Lookout	1.9 to 3.3	2.6
Nth Stradbroke Is	1.8 to 2.4	2.1
Main Beach	2.1 to 2.6	2.3
Mermaid Beach	1.9 to 3.3	2.4

Site	Range	Average
Burleigh	2.1 to 3.4	2.6
Tugun	1.6 to 2.9	2.3
Coolangatta	1.4 to 1.8	1.7
Letitia Spit	1.6 to 1.9	1.8
Kingscliff	1.6 to 1.8	1.7

Table C- 4 Indicative amplification factors for tides sites.

Site	Range	Average
Cooktown	0.5 to 0.6	0.6
Mossman River	0.2 to 0.4	0.3
Port Douglas	0.3	0.3
Cairns	0.3 to 0.5	0.4
Mourilyan Harbour	0.4 to 0.5	0.5
Clump Point	0.4 to 0.5	0.5
Cardwell	0.2 to 0.3	0.2
Lucinda (Offshore)	0.2	0.2
Townsville	0.3 to 0.4	0.3
Cape Ferguson	0.7 to 0.8	0.8
Bowen	0.2 to 0.3	0.2
Shute Harbour	0.2 to 0.3	0.3
Mackay Outer Harbour	0.3	0.3
Hay Point	0.3 to 0.4	0.4
Rosslyn Bay	0.5 to 0.6	0.6
Port Alma	0.2 to 0.3	0.3
South Trees Wharf	0.1 to 0.2	0.1
Burnett Heads	0.4	0.4
Urangan	0.2 to 0.3	0.3
Mooloolaba	1.3 to 1.7	1.5
Gold Coast Seaway	1.3 to 2.1	1.7
Nerang River	1.8 to 2.1	2.0

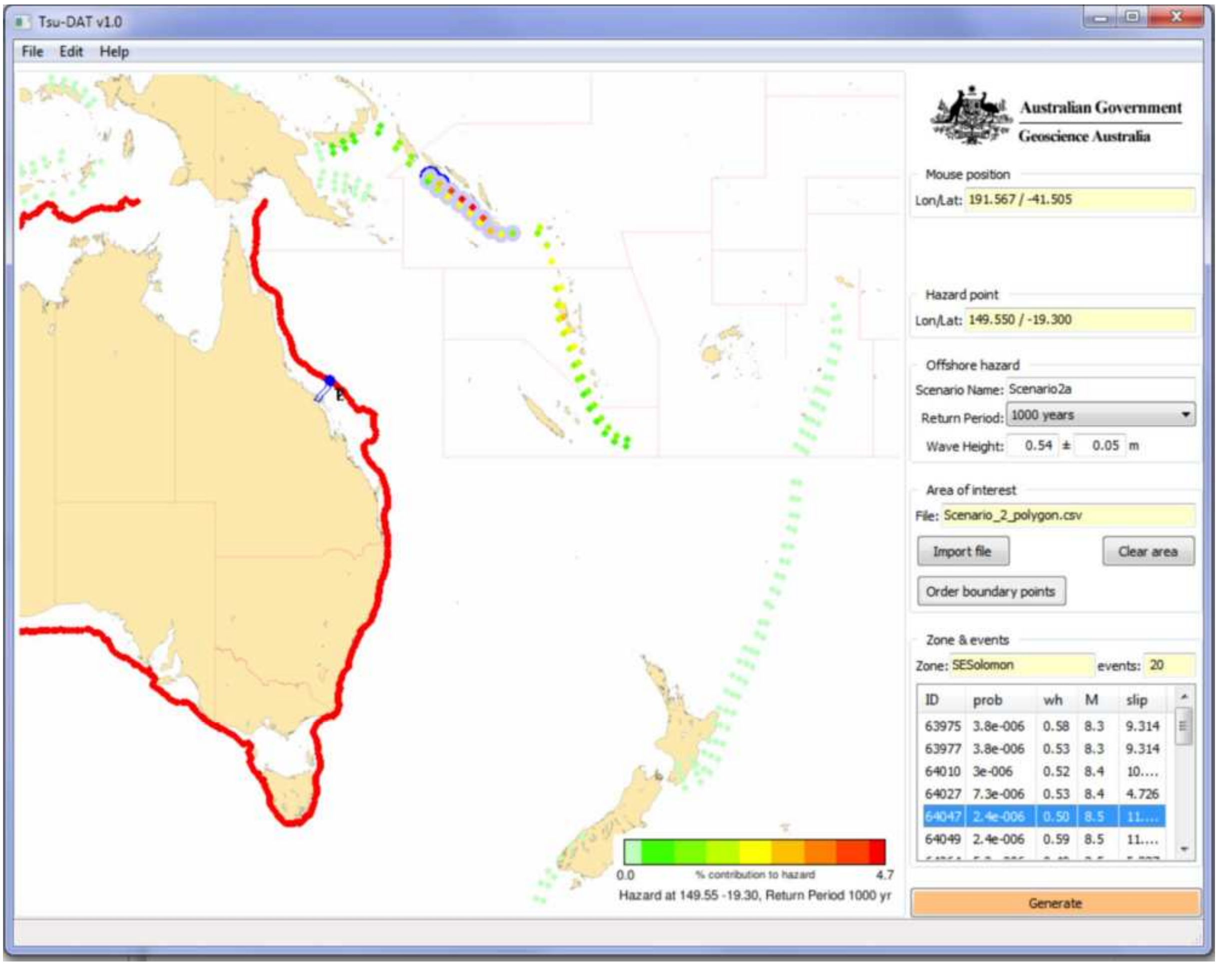

Figure C- 1 TsuDAT input for Scenario 1 (GBR mesh).

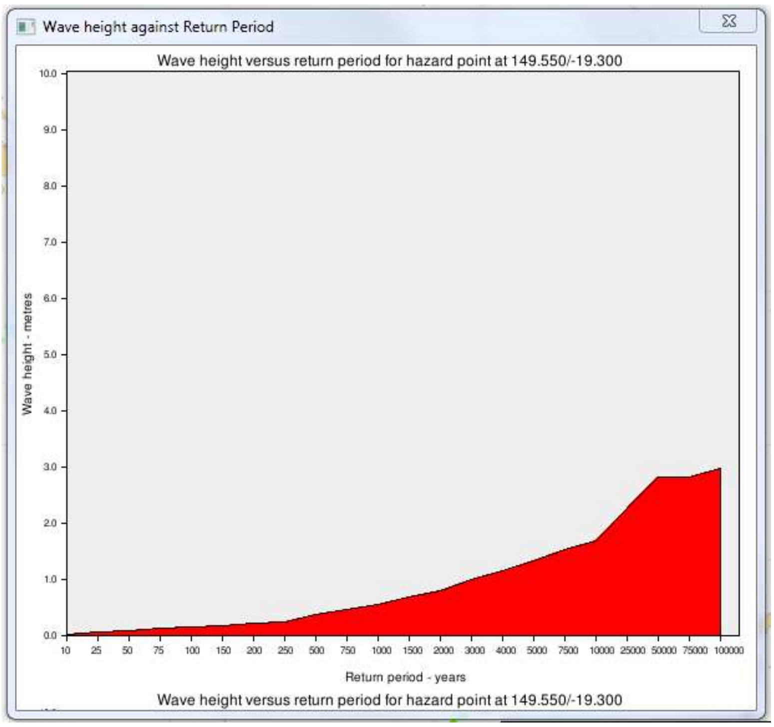

Figure C- 2 Return Period of tsunami amplitude for TsuDAT hazard point used in GBR model.

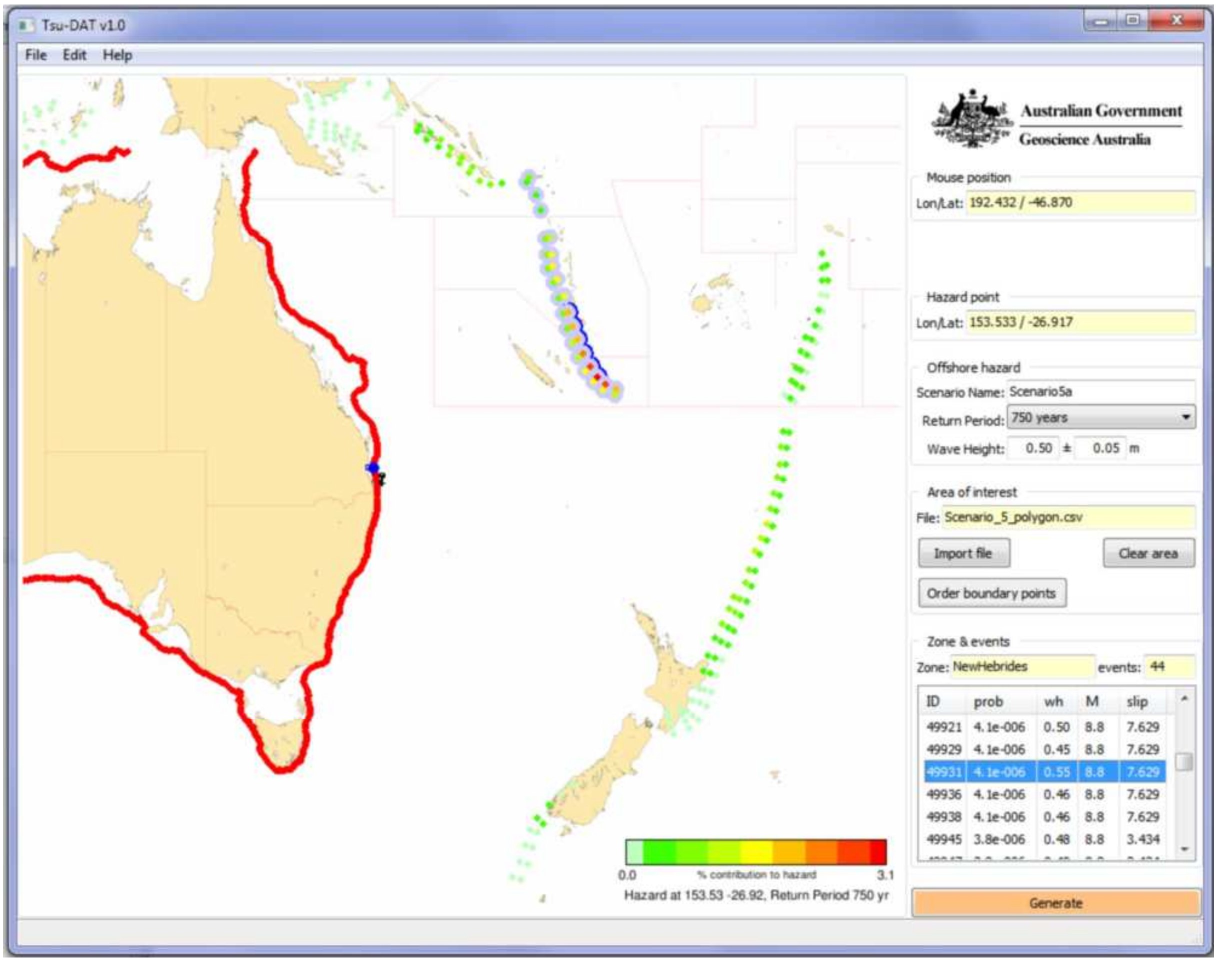

Figure C- 3 TsuDAT input for Scenario 4 (SEQ mesh).

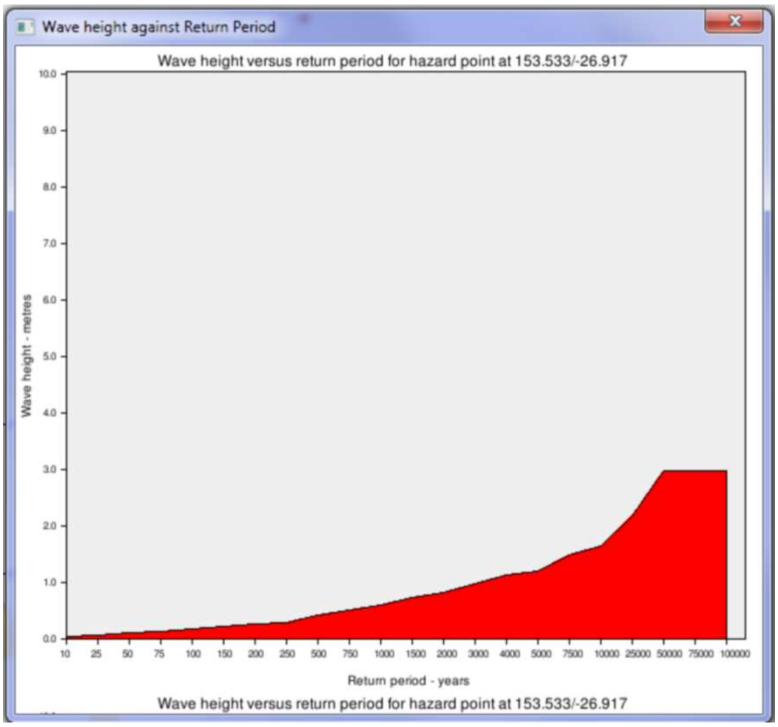

Figure C- 4 Return Period of tsunami amplitude for TsuDAT hazard point used in SEQ model.

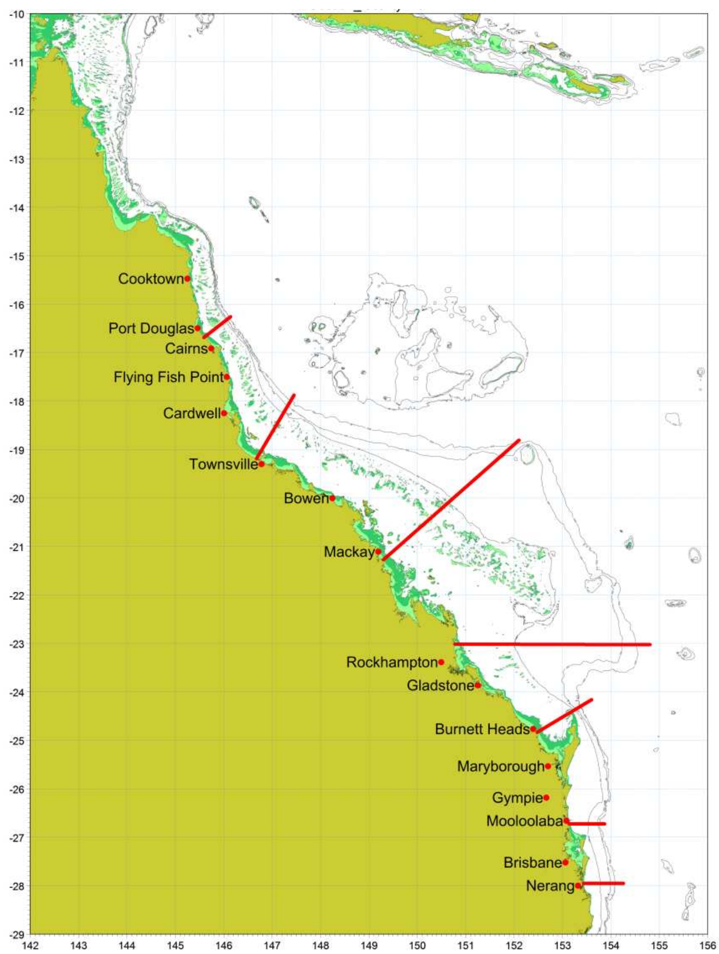

Figure C- 5 Location of extracted profiles 1 to 7.

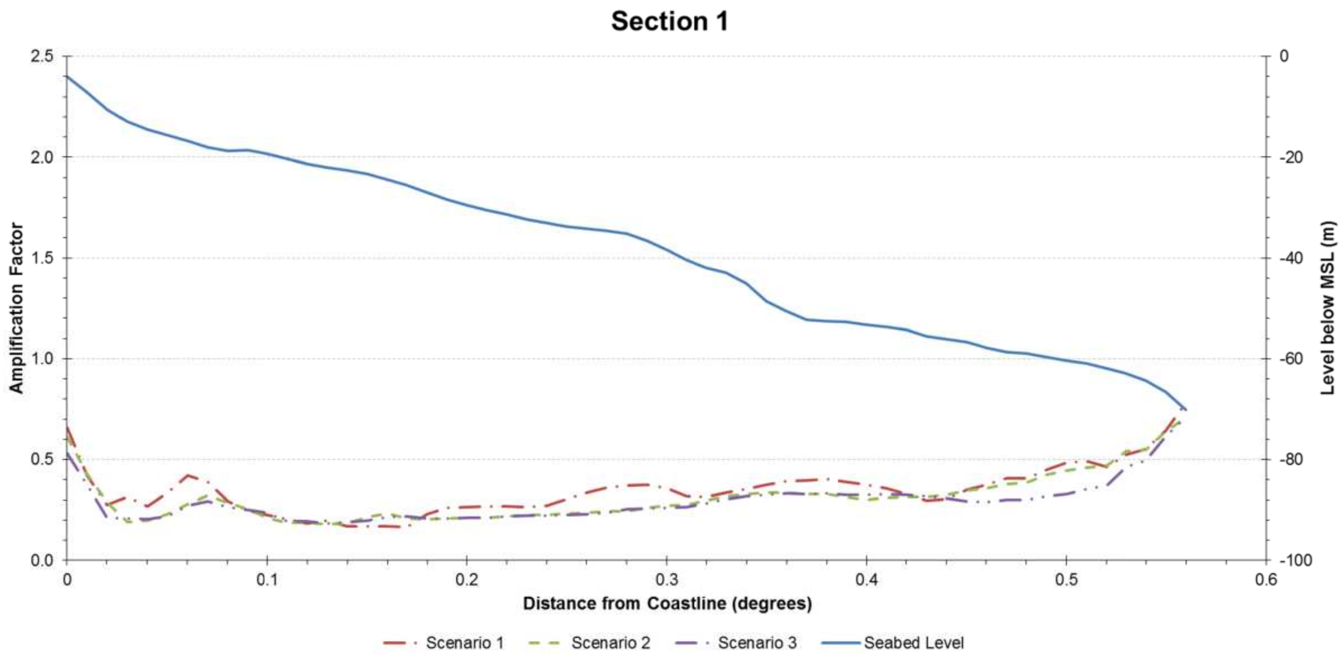

Figure C- 6 Amplification factors along Section 1 north of Cairns.

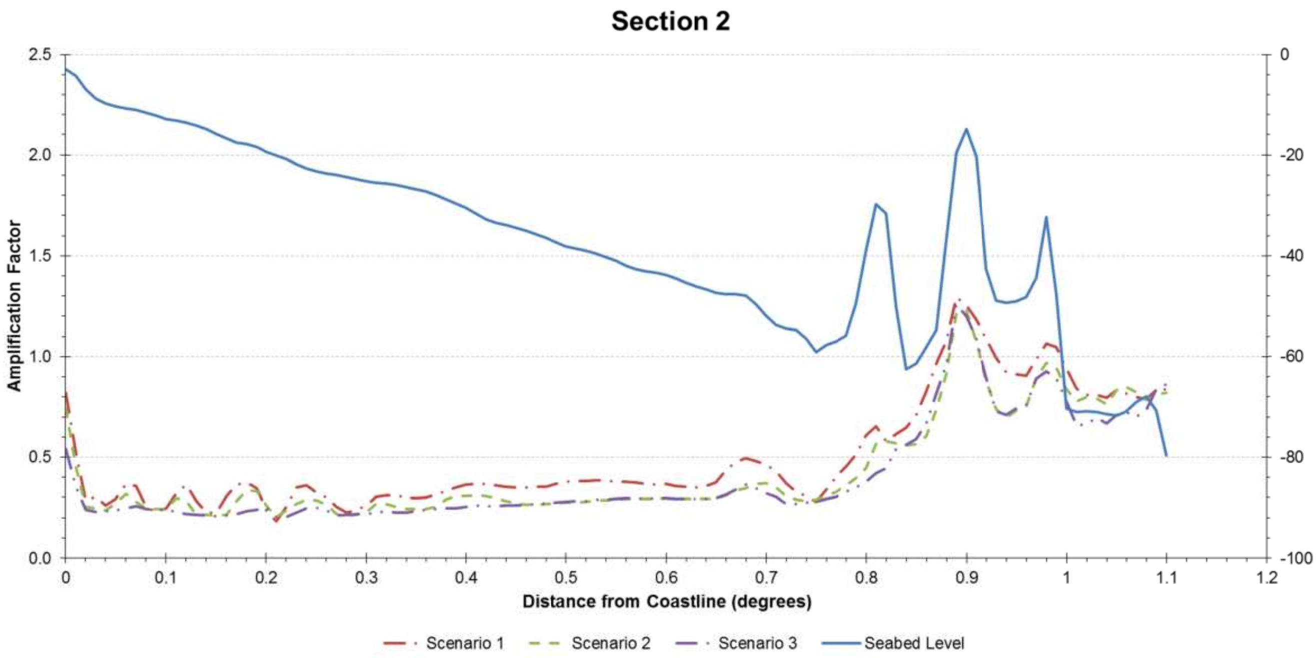

Figure C- 7 Amplification factors along Section 2 north of Townsville.

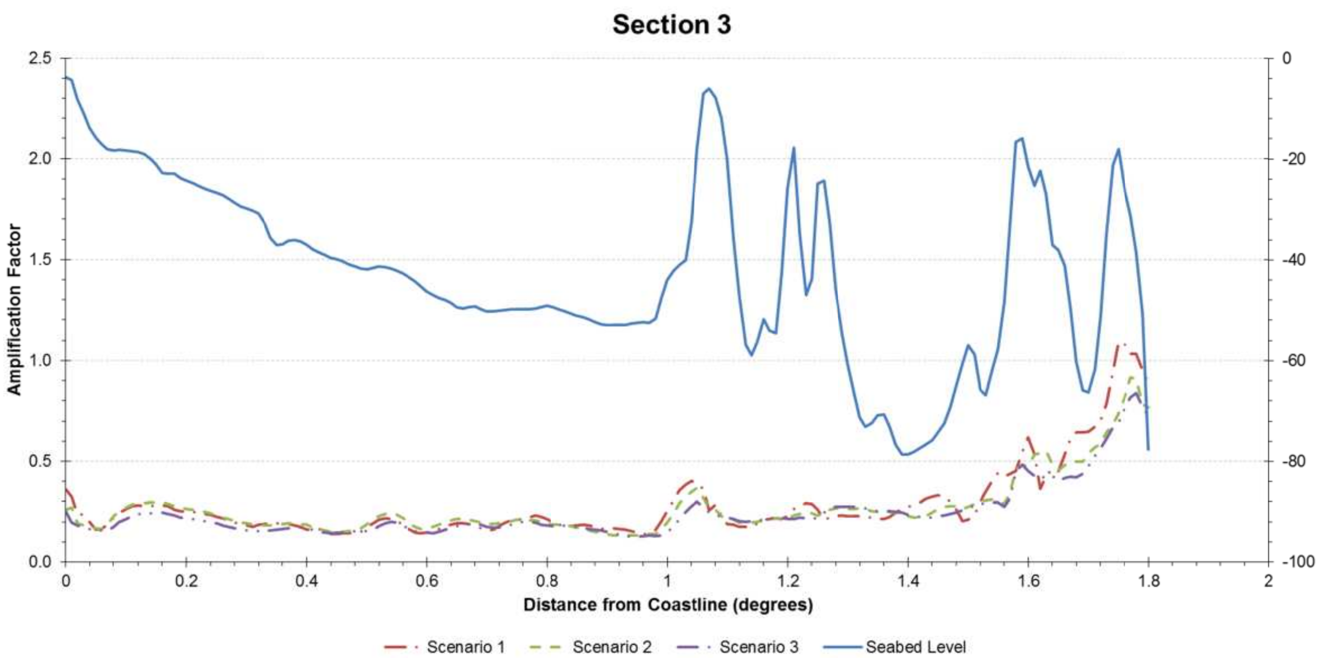

Figure C- 8 Amplification factors along Section 3 near Hay Pt.

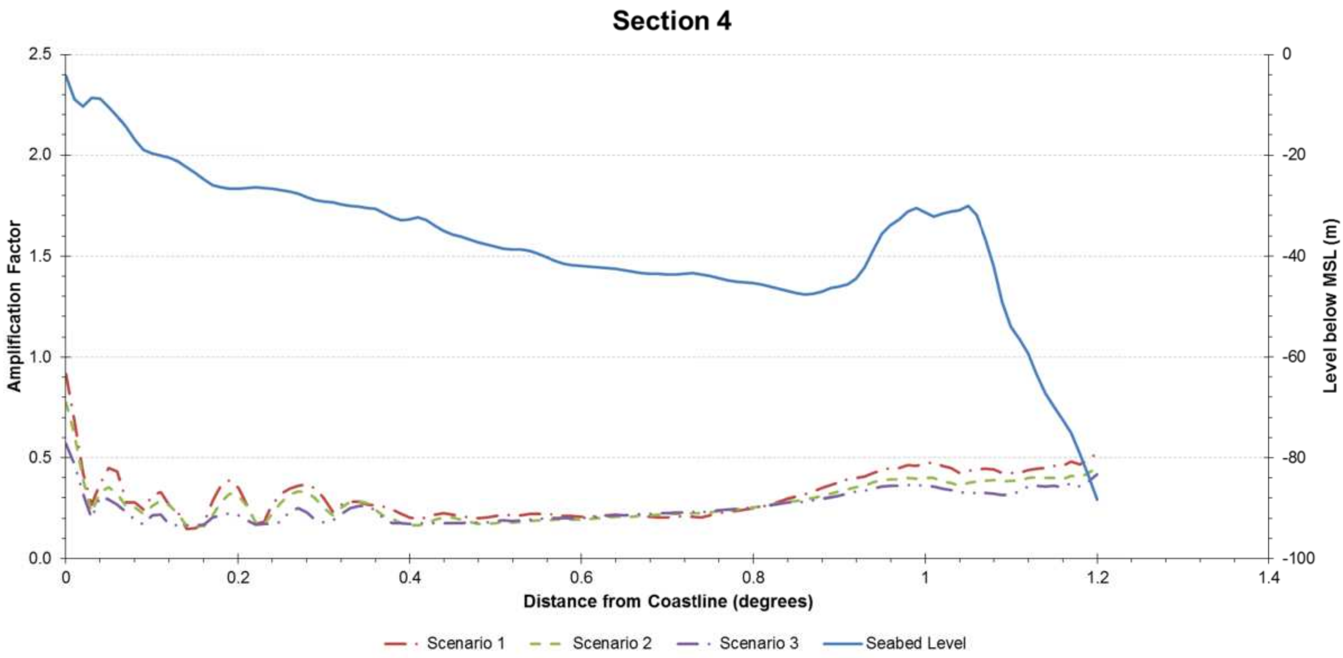

Figure C- 9 Amplification factors along Section 4 north of Yeppoon.

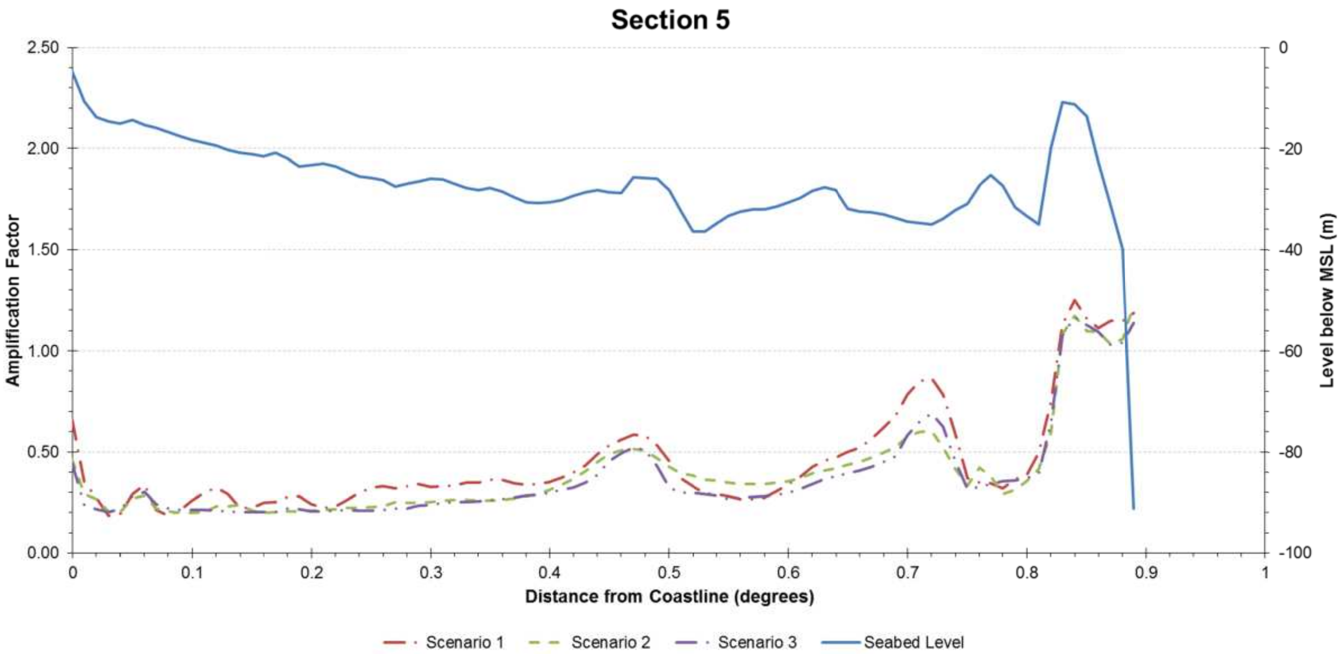

Figure C- 10 Amplification factors along Section 5 north of Elliott Heads.

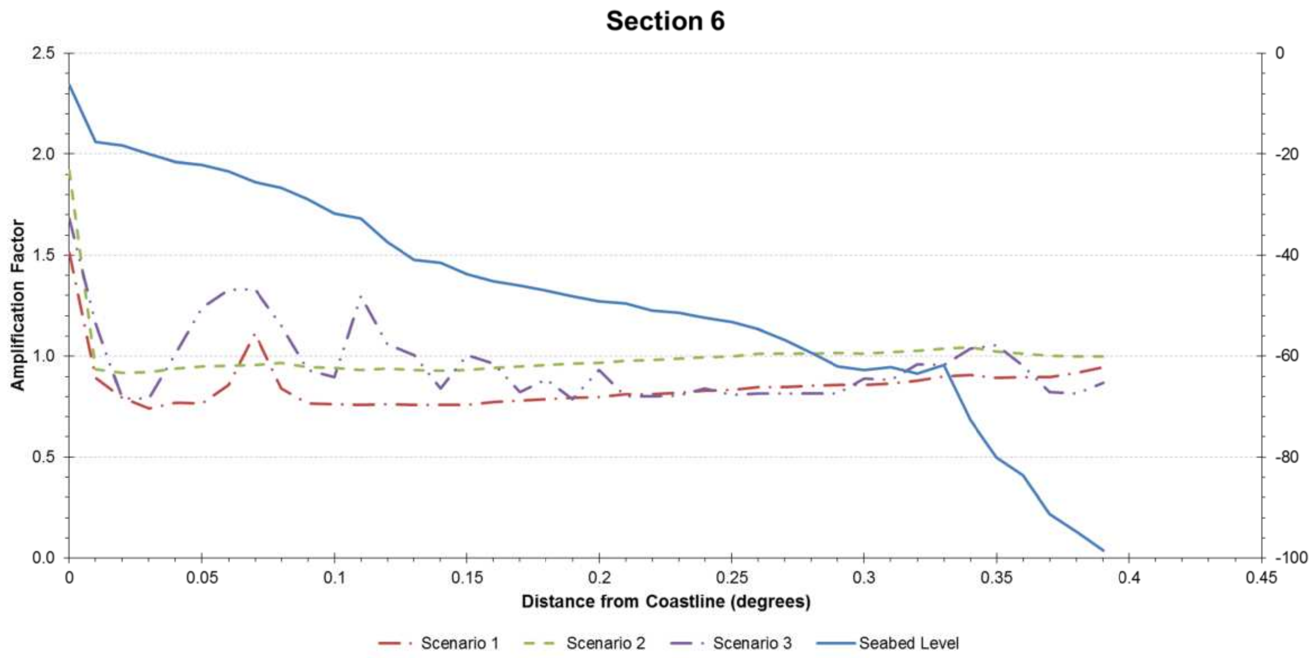

Figure C- 11 Amplification factors along Section 6 south of Mooloolaba.

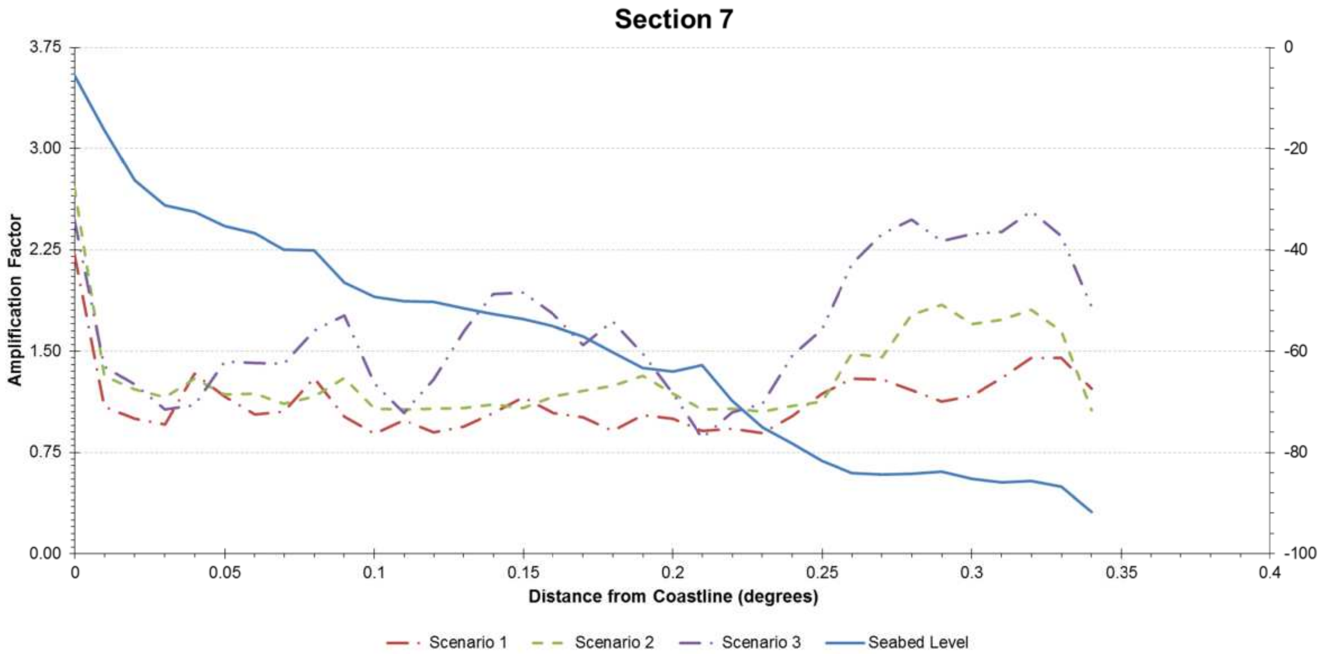

Figure C- 12 Amplification factors along Section 7 at Main Beach, Gold Coast.

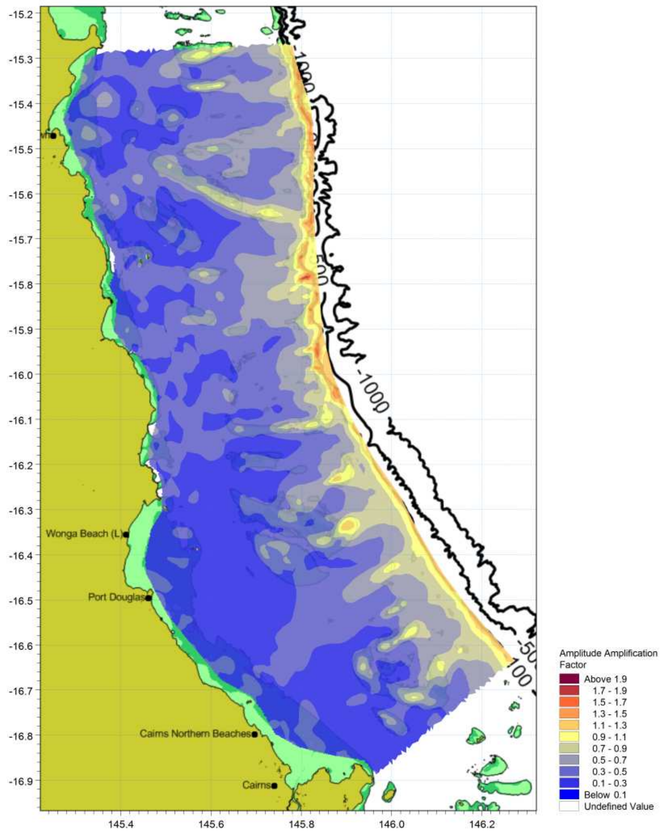

Figure C- 13 Scenario 1 amplification factor map below 10m depth for Cooktown to Cairns.

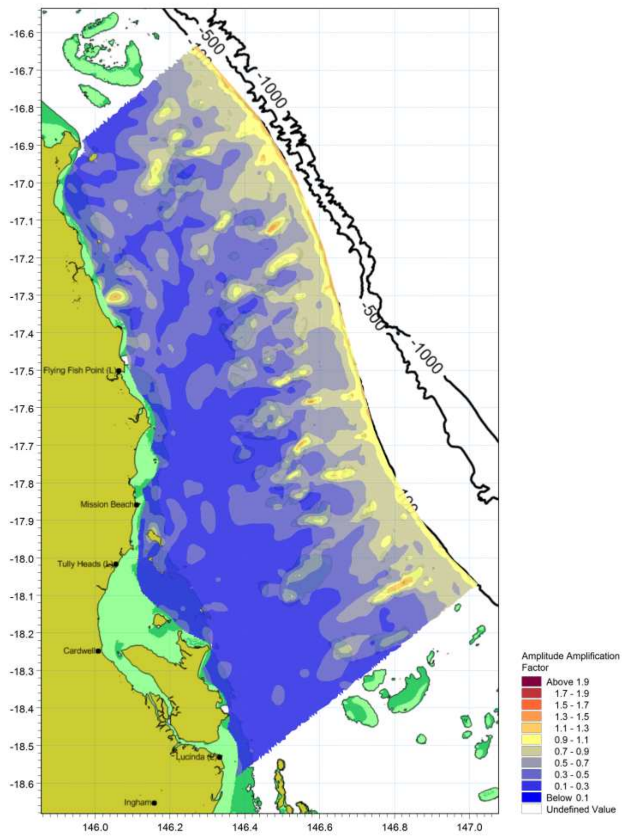

Figure C- 14 Scenario 1 amplification factor map below 10m depth for Cairns to Lucinda.

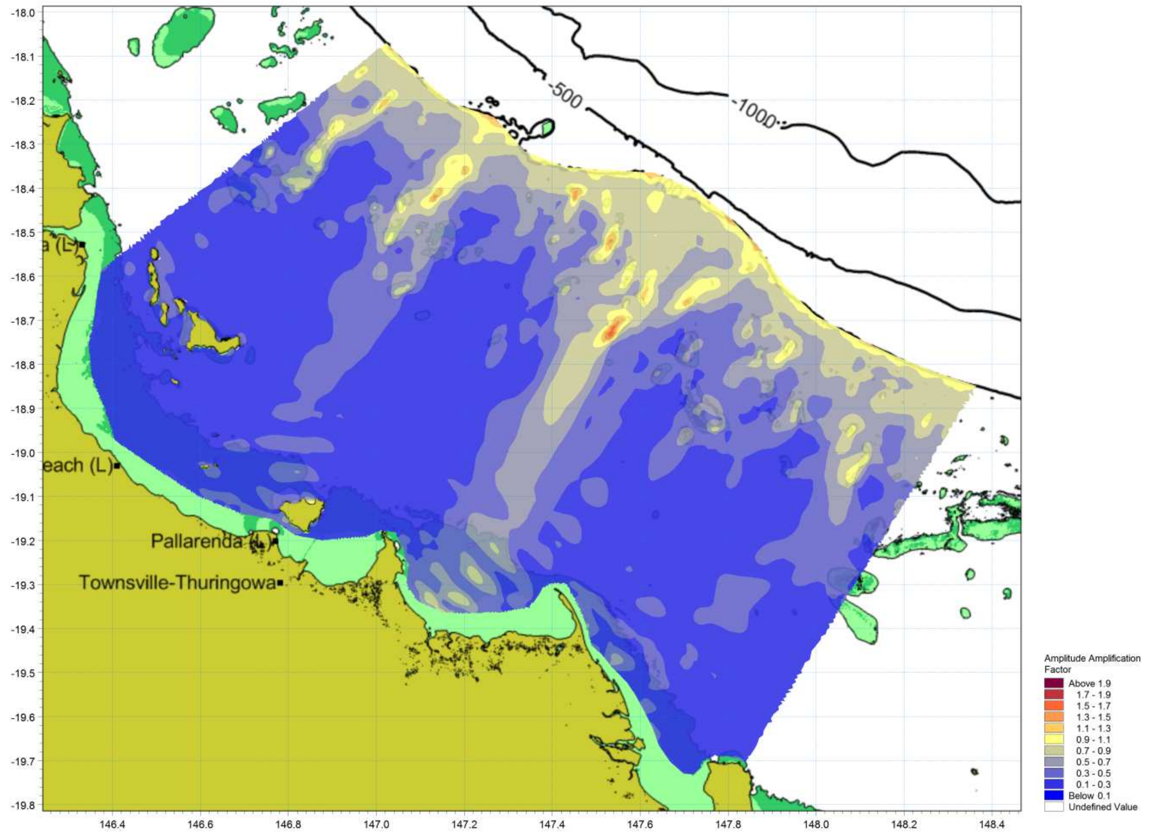

Figure C- 15 Scenario 1 amplification factor map below 10m depth for Lucinda to Ayr.

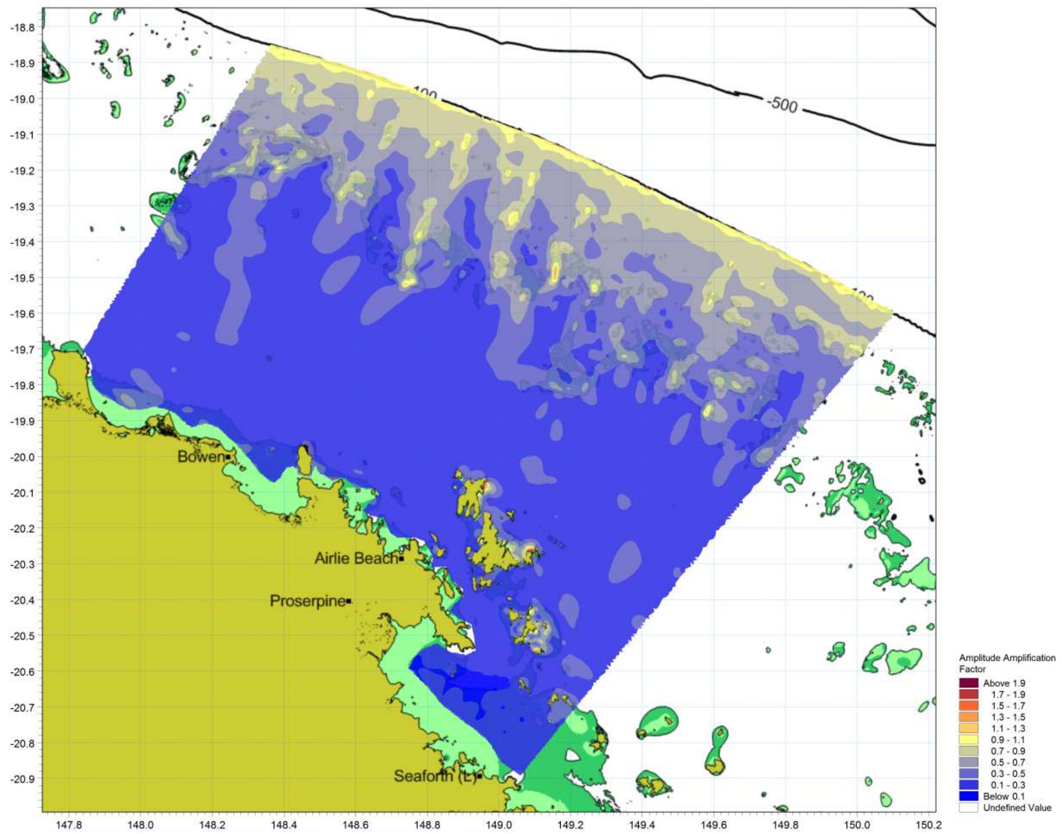

Figure C- 16 Scenario 1 amplification factor map below 10m depth for Ayr to Seaforth.

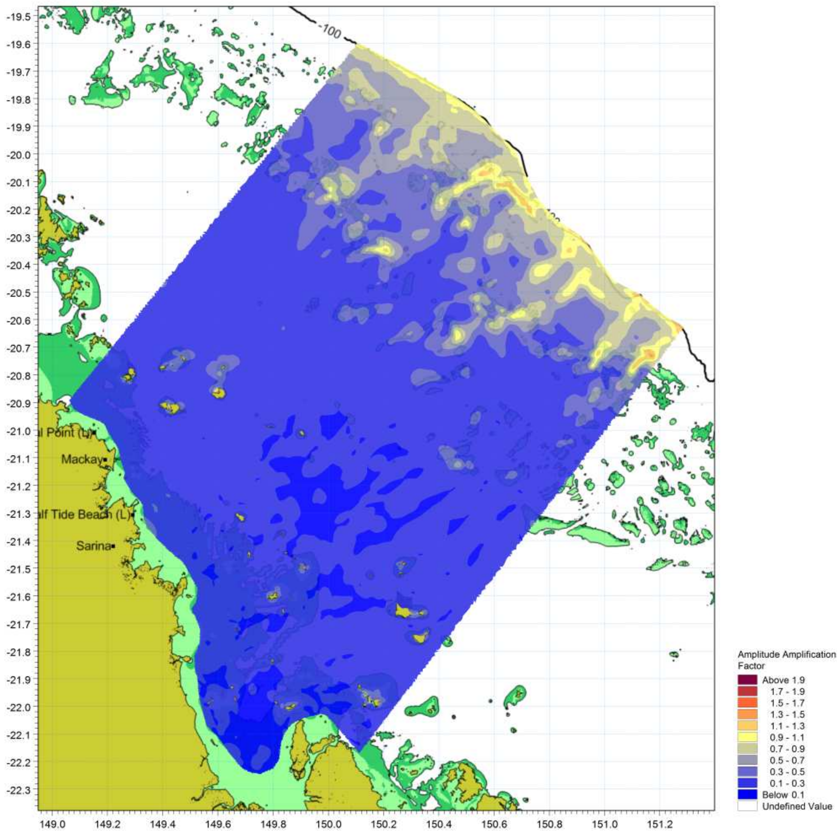

Figure C- 17 Scenario 1 amplification factor map below 10m depth for Cape Hillsborough to St Lawrence.

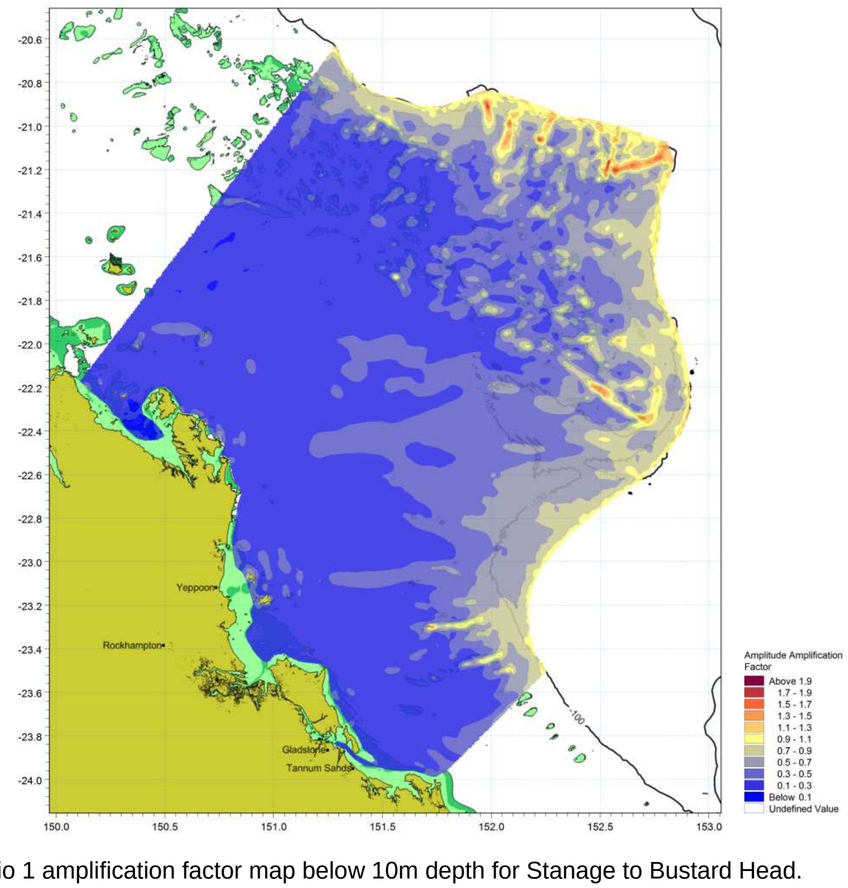

Figure C- 18 Scenario 1 amplification factor map below 10m depth for Stanage to Bustard Head.

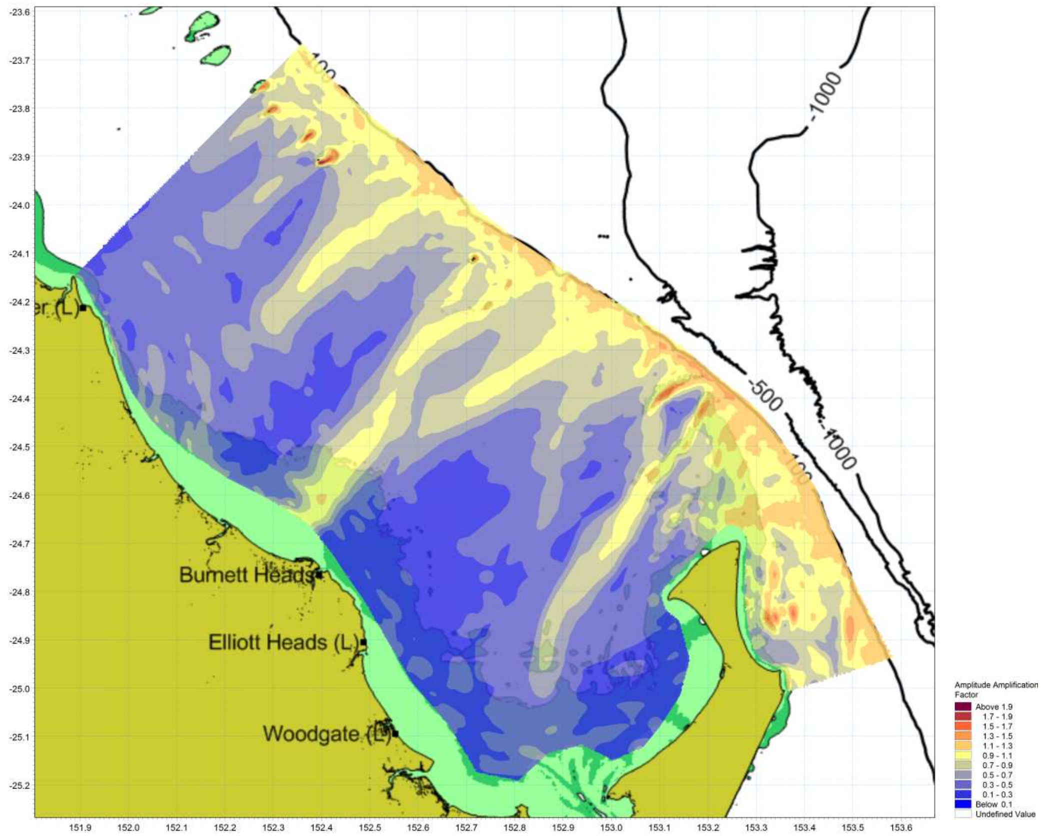

Figure C- 19 Scenario 1 amplification factor map below 10m depth for Seventeen Seventy to Hervey Bay.

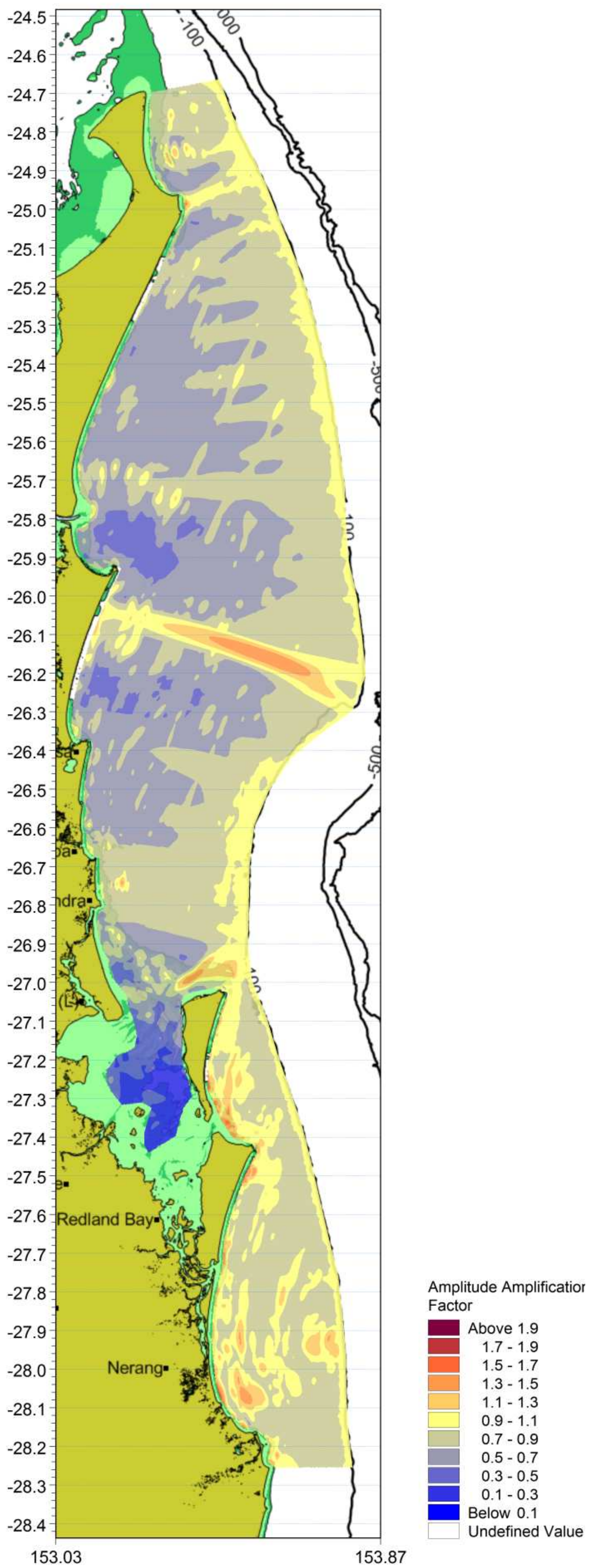

Figure C- 20 Scenario 4 amplification factor map below 10m depth for Fraser Island to Gold Coast.

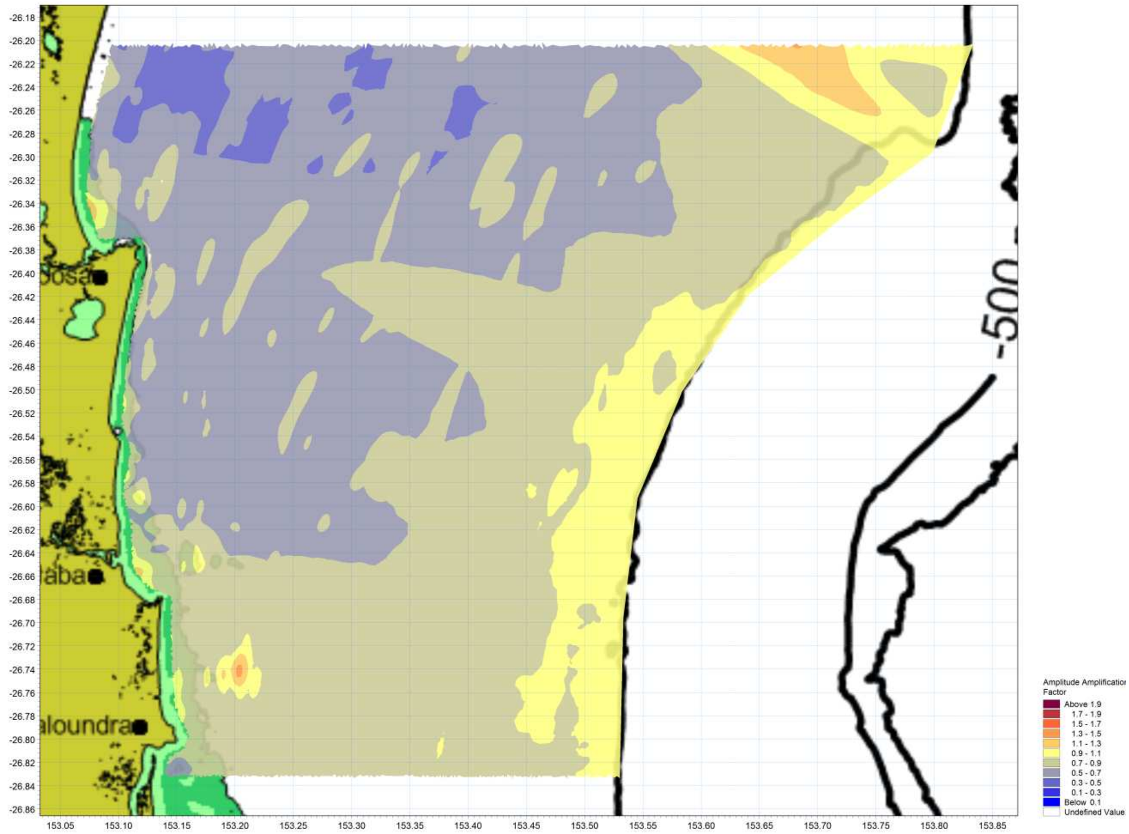

Figure C- 21 Scenario 4 amplification factor map below 10m depth for Sunshine Coast.

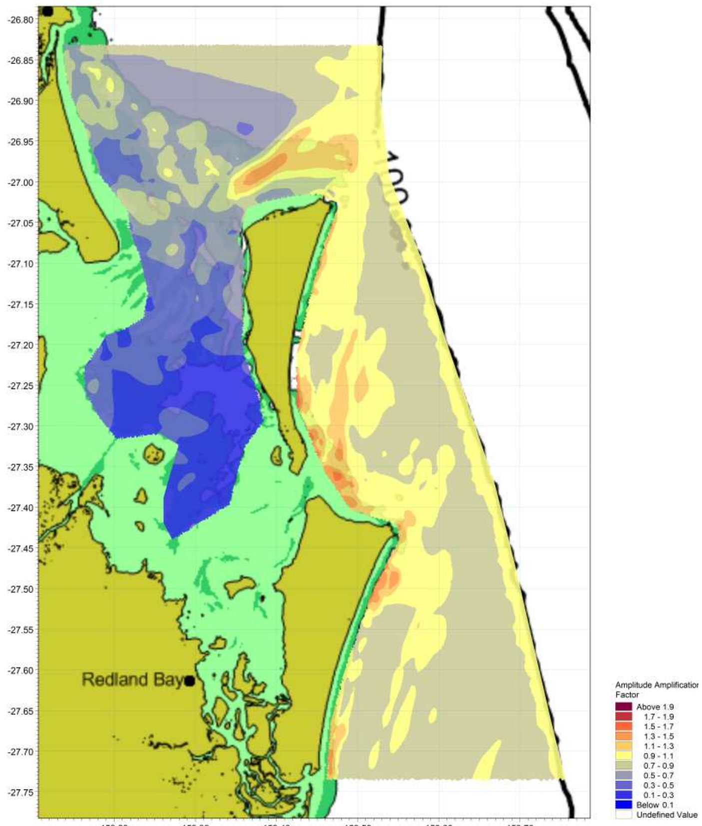

Figure C- 22 Scenario 4 amplification factor map below 10m depth for Moreton Bay.

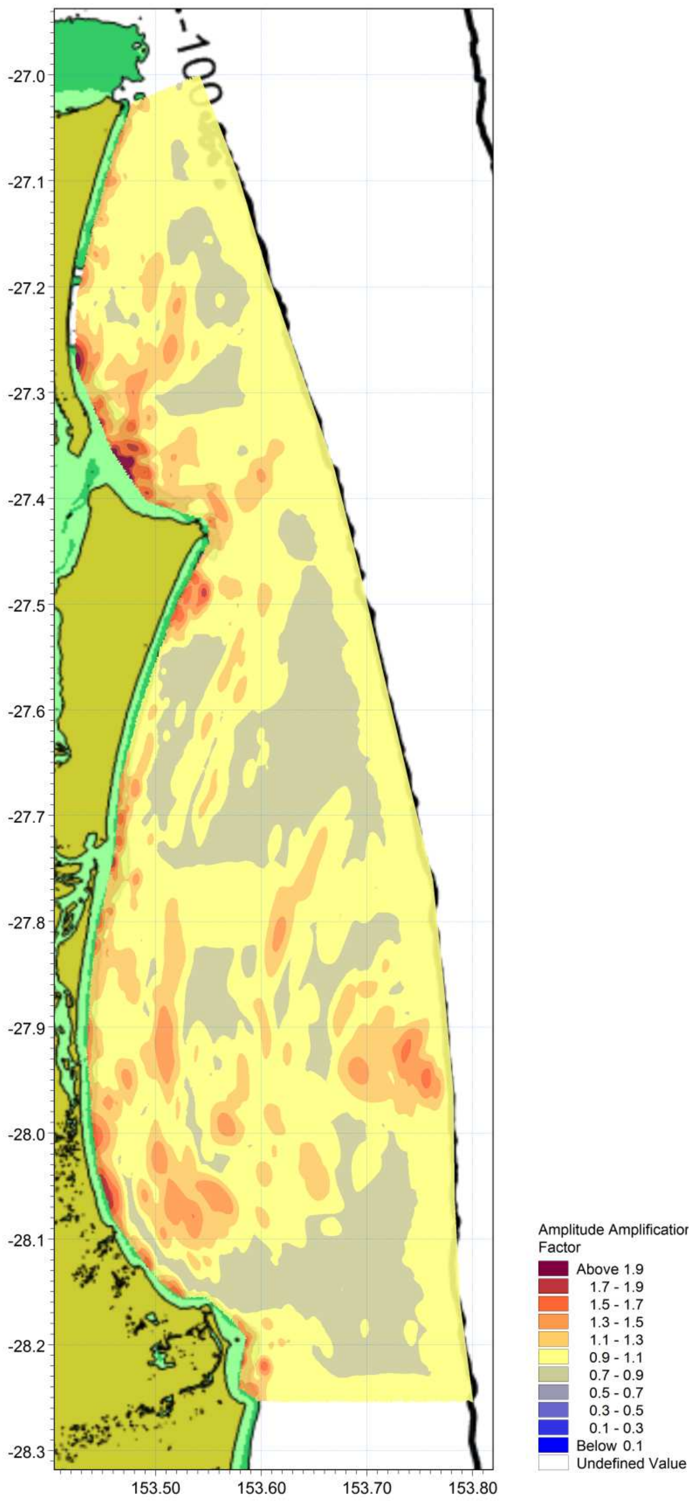

Figure C- 23 Scenario 4 amplification factor map below 10m depth for Gold Coast

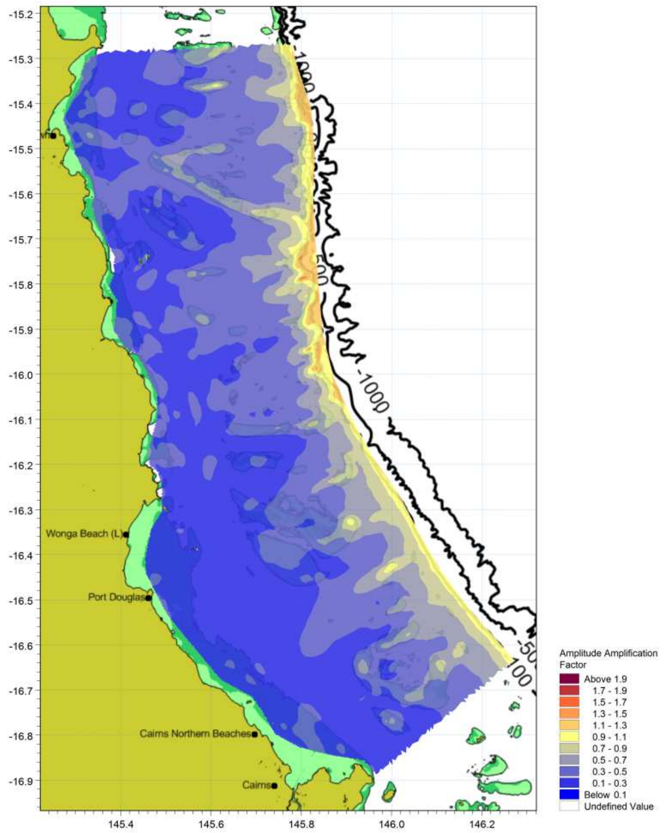

Figure C- 24 Scenario 2 amplification factor map below 10m depth for Cooktown to Cairns.

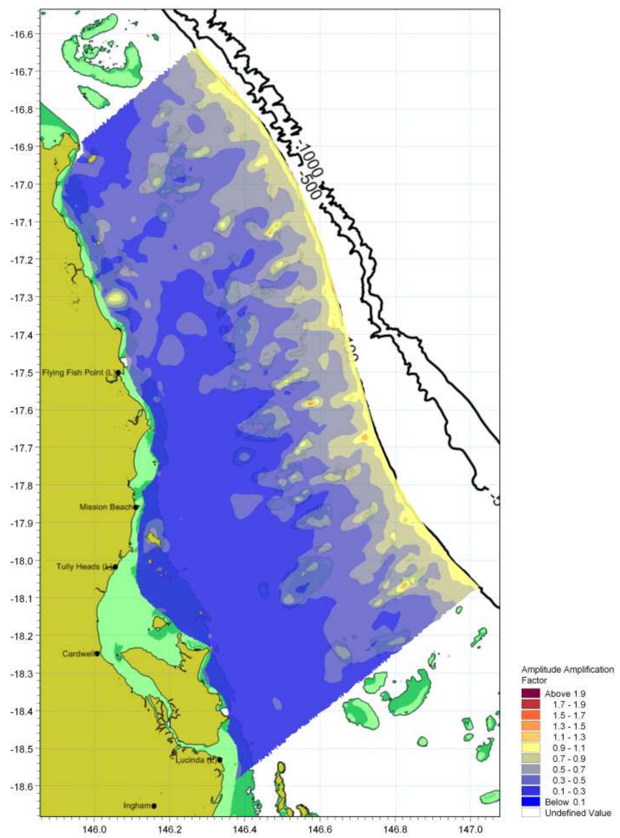

Figure C- 25 Scenario 2 amplification factor map below 10m depth for Cairns to Lucinda.

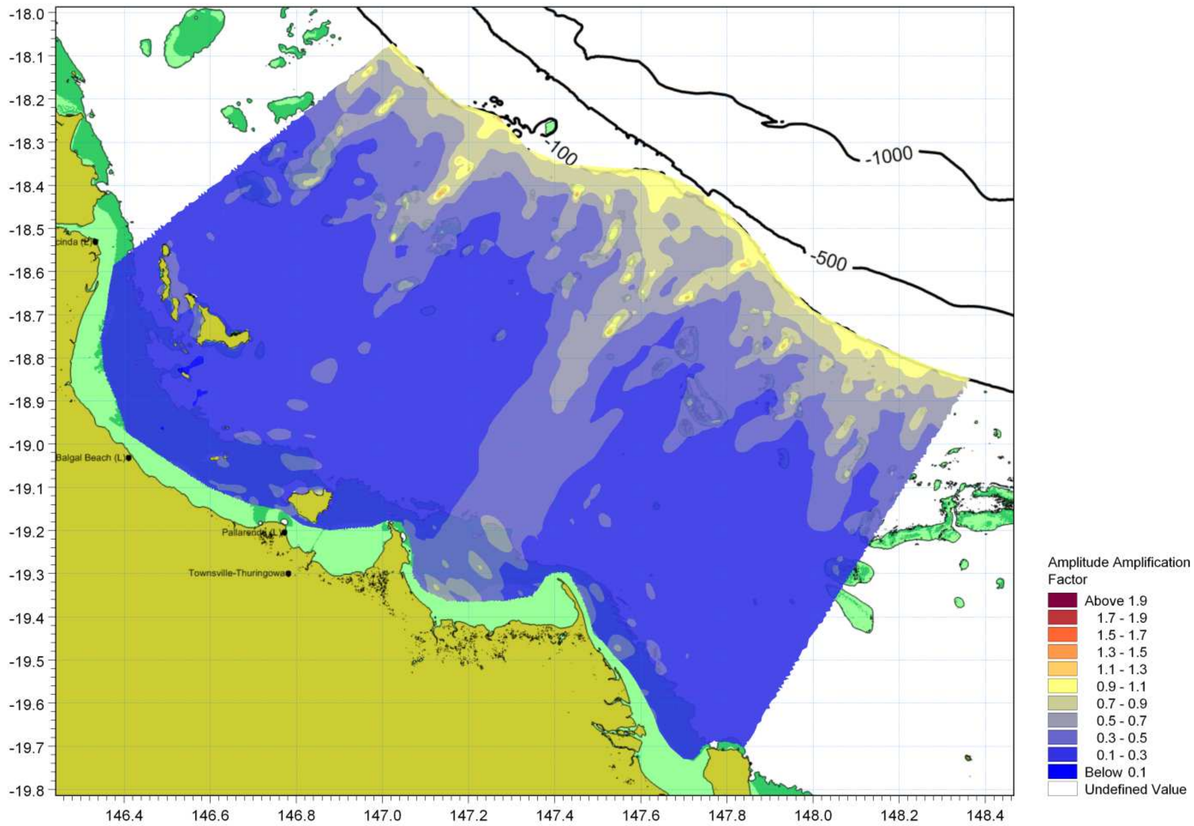

Figure C- 26 Scenario 2 amplification factor map below 10m depth for Lucinda to Ayr.

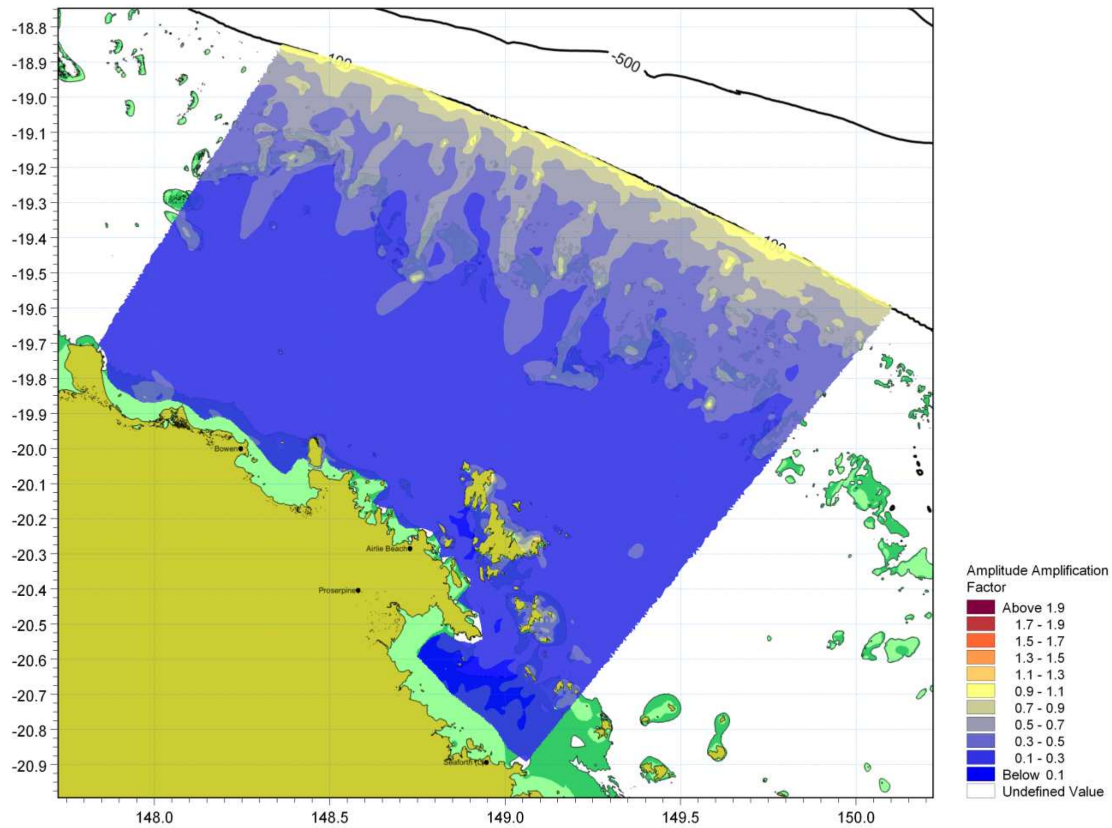

Figure C- 27 Scenario 2 amplification factor map below 10m depth for Ayr to Seaforth.

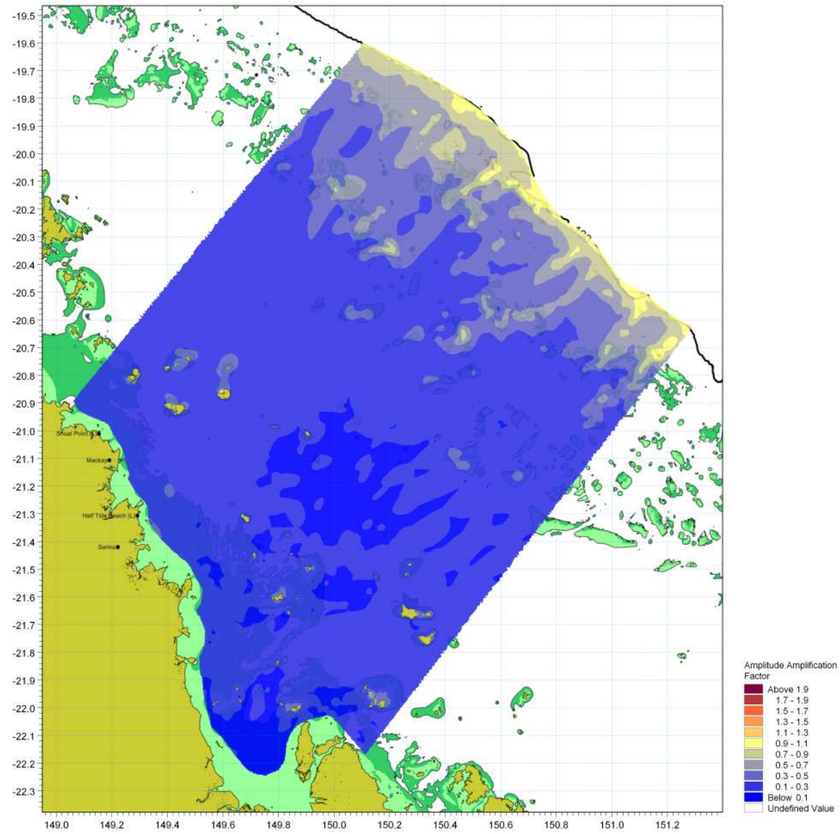

Figure C- 28 Scenario 2 amplification factor map below 10m depth for Cape Hillsborough to St Lawrence.

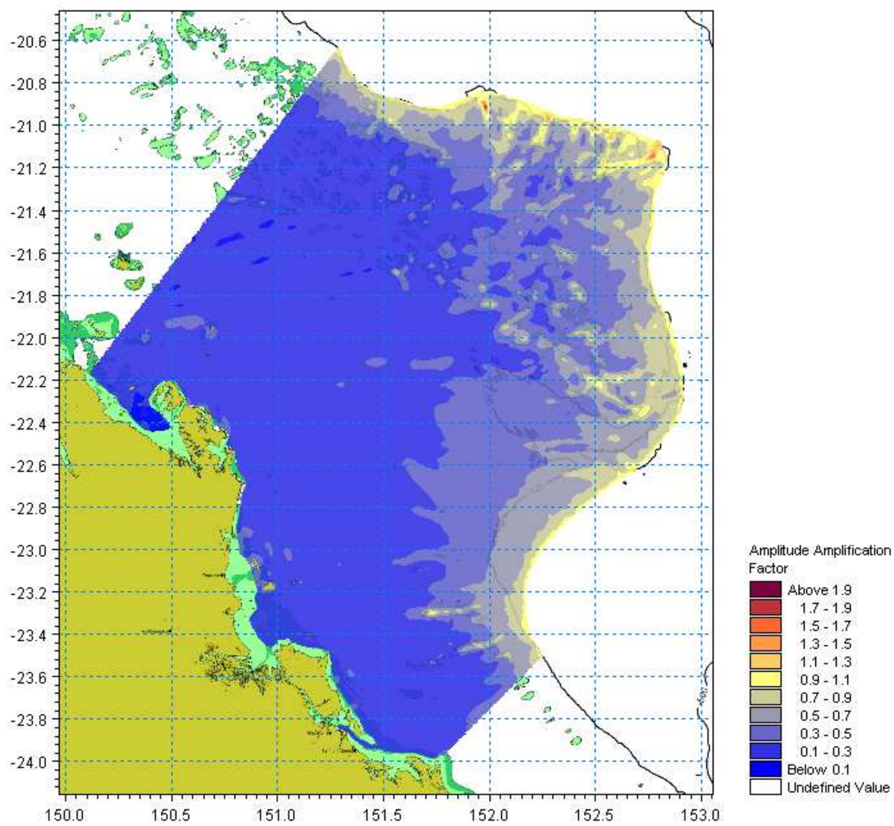

Figure C- 29 Scenario 2 amplification factor map below 10m depth for Stanage to Bustard Head.

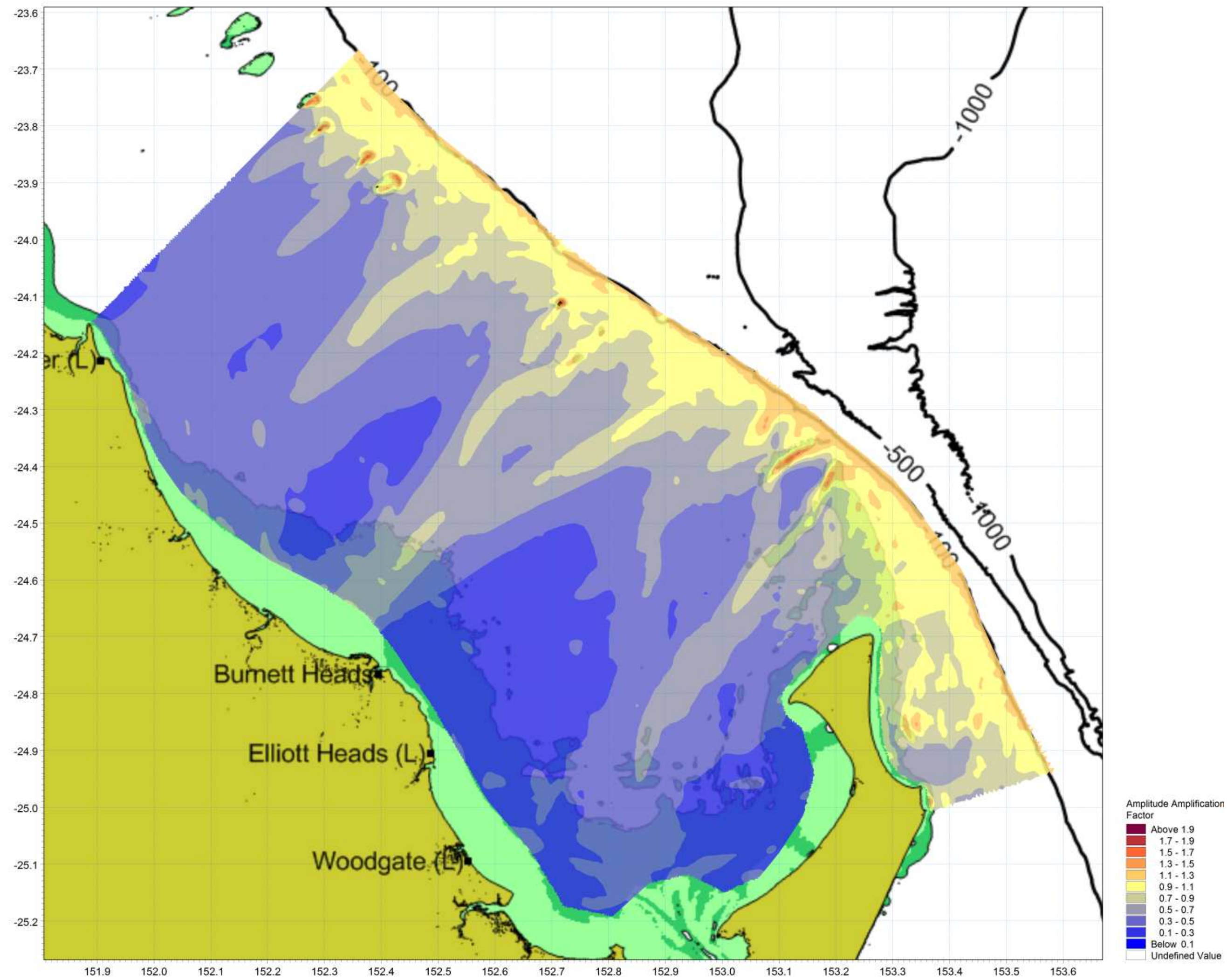

Figure C- 30 Scenario 2 amplification factor map below 10m depth for Seventeen Seventy to Hervey Bay.

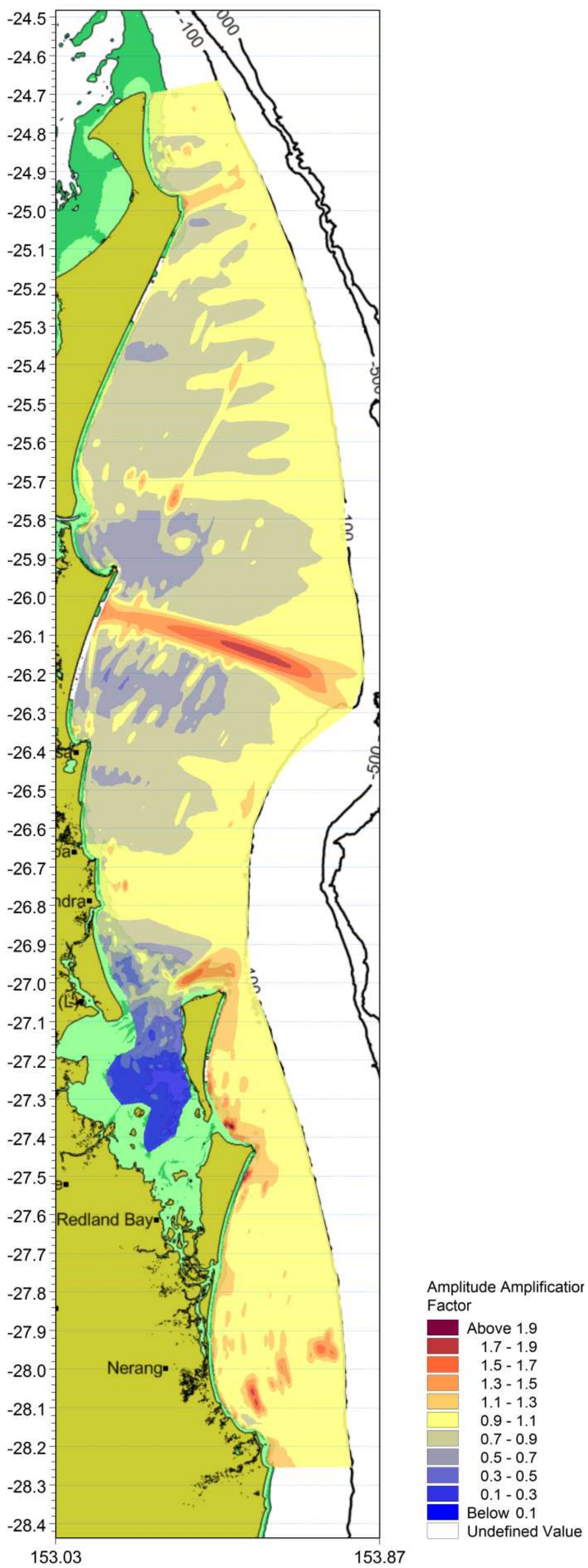

Figure C- 31 Scenario 5 amplification factor map below 10m depth for Fraser Island to Gold Coast.

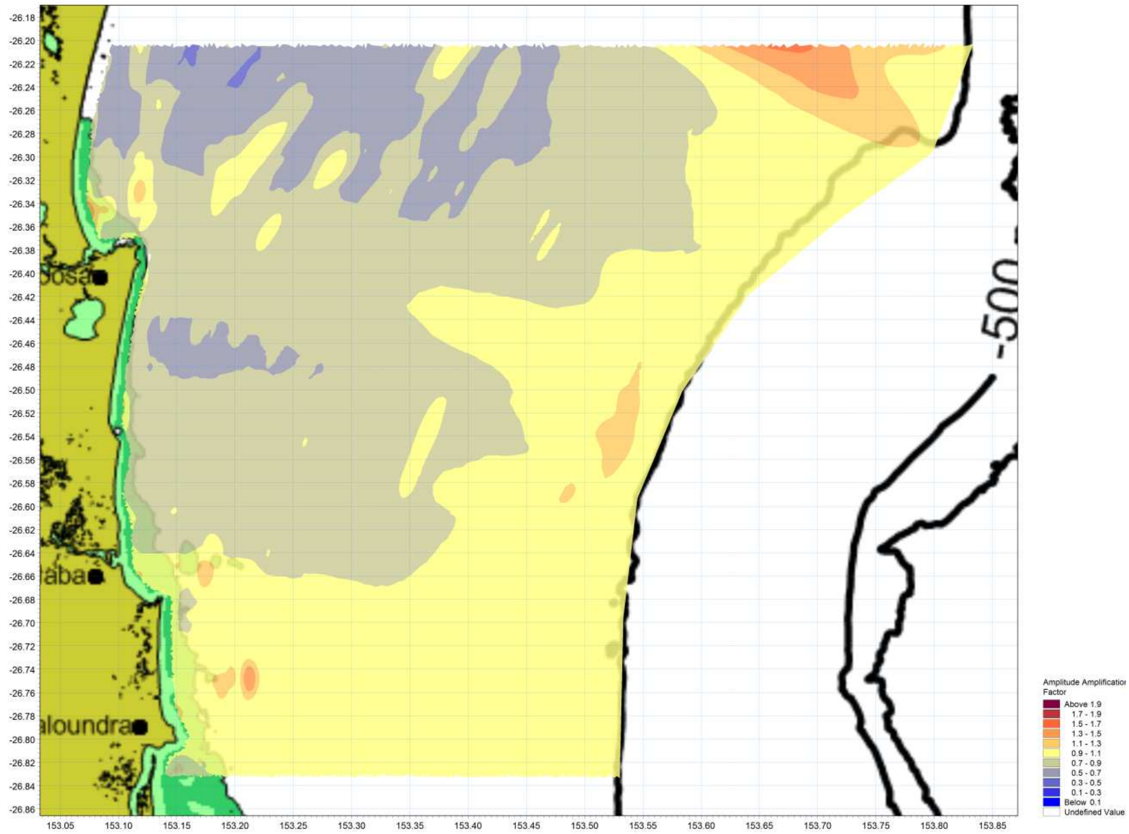

Figure C- 32 Scenario 5 amplification factor map below 10m depth for Sunshine Coast.

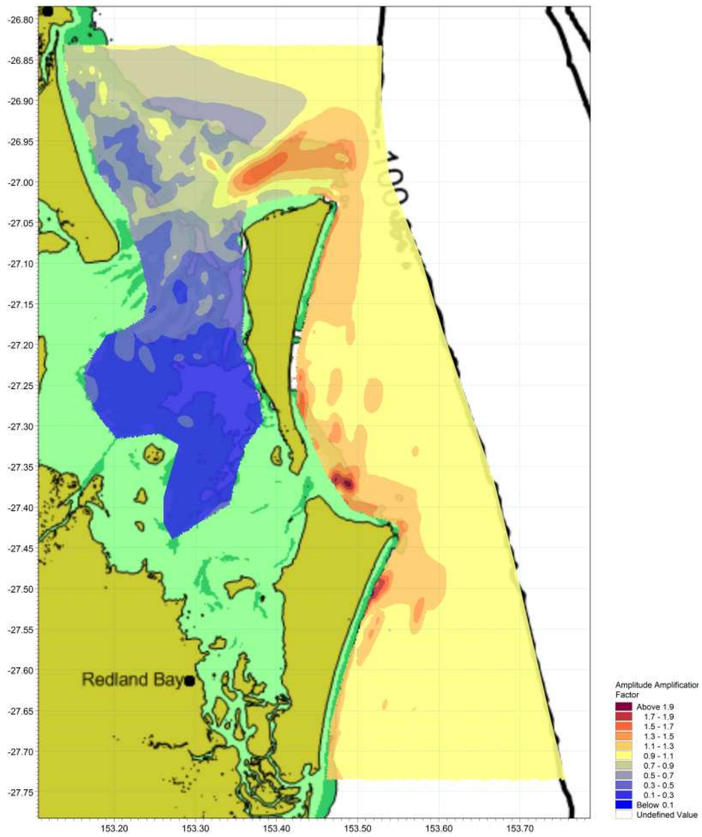

Figure C- 33 Scenario 5 amplification factor map below 10m depth for Moreton Bay.

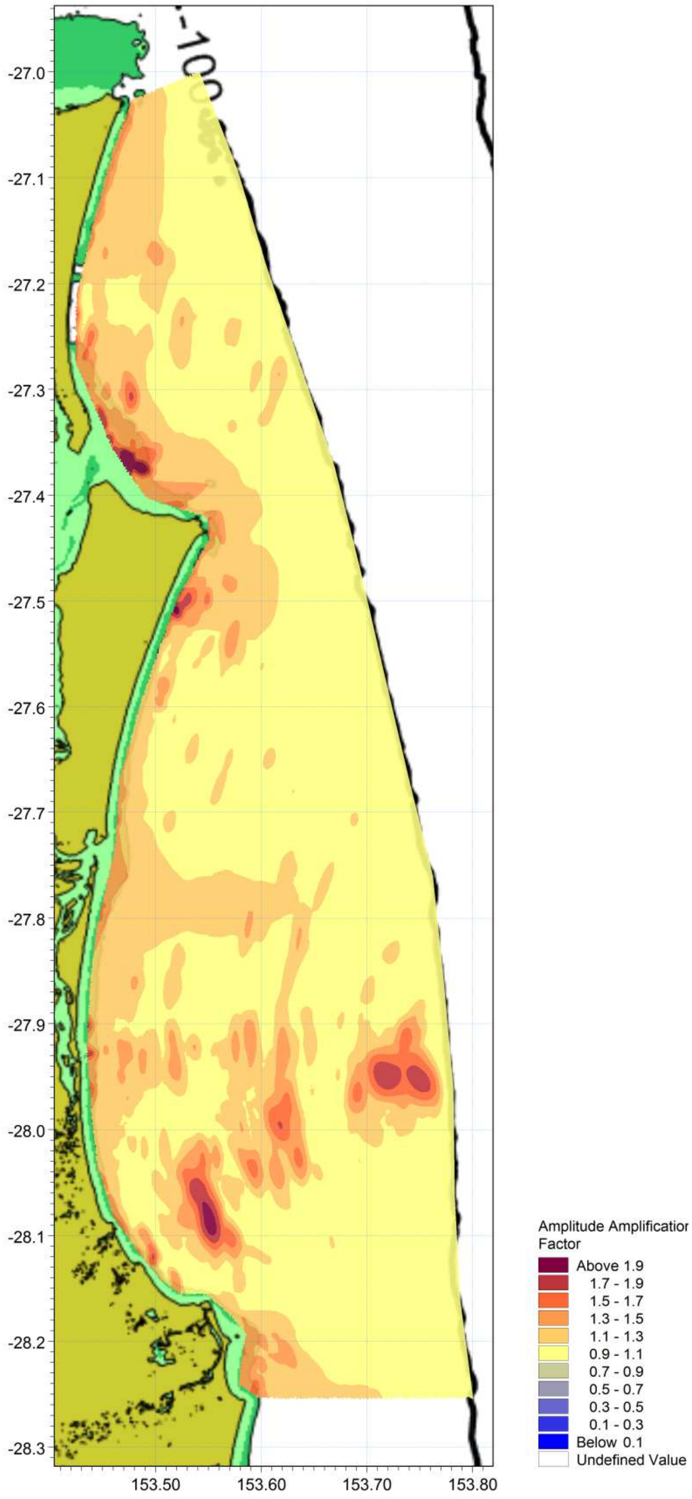

Figure C- 34 Scenario 5 amplification factor map below 10m depth for Gold Coast

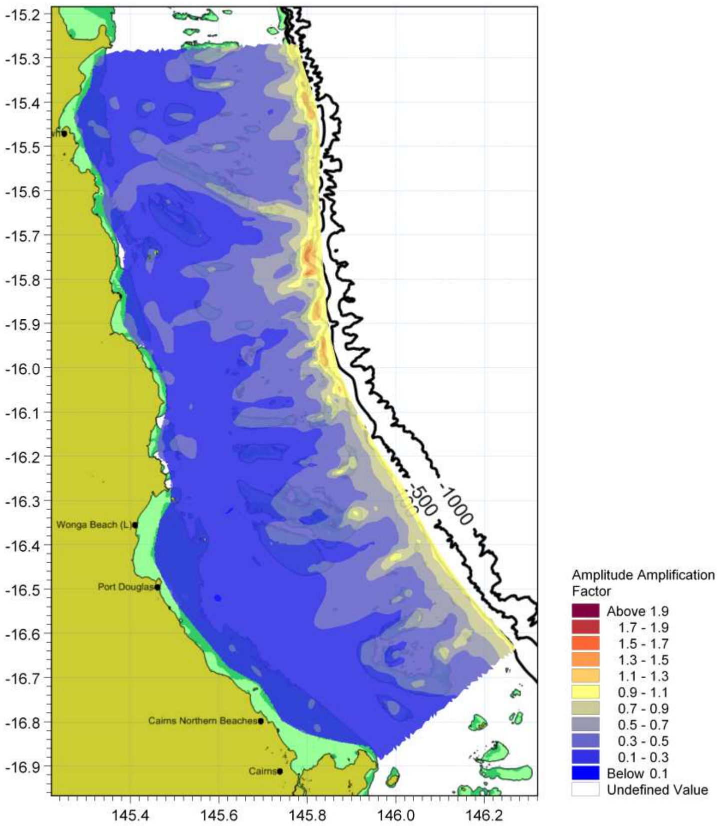

Figure C- 35 Scenario 3 amplification factor map below 10m depth for Cooktown to Cairns.

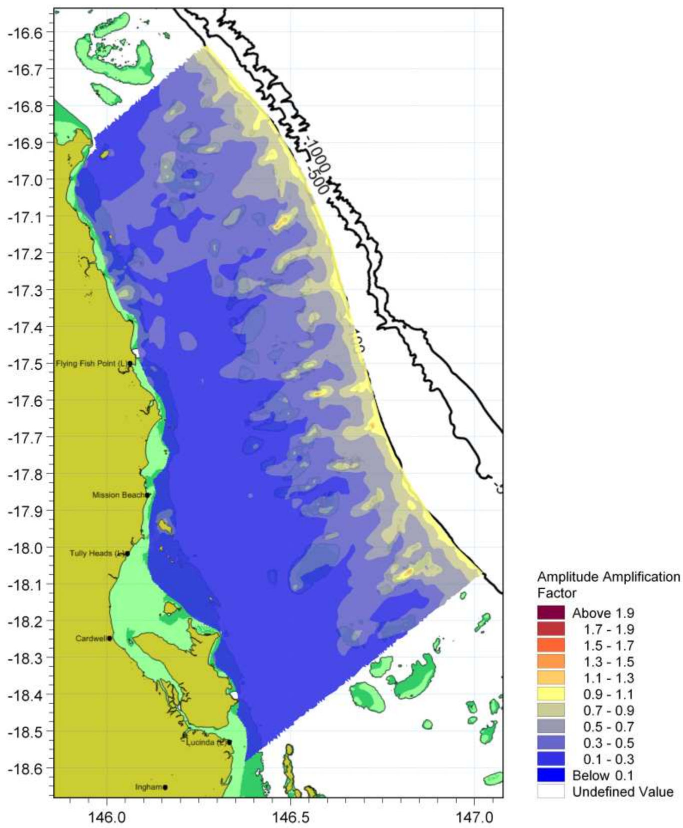

Figure C- 36 Scenario 3 amplification factor map below 10m depth for Cairns to Lucinda.

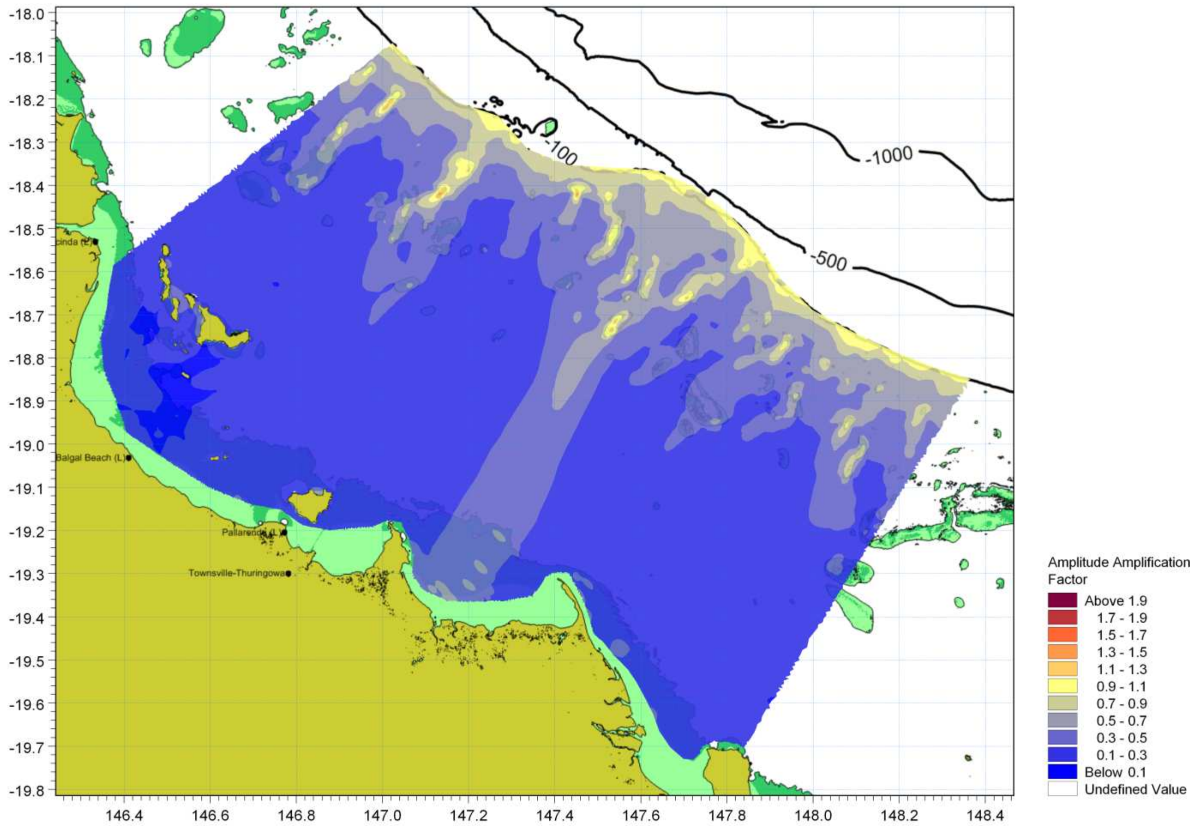

Figure C- 37 Scenario 3 amplification factor map below 10m depth for Lucinda to Ayr.

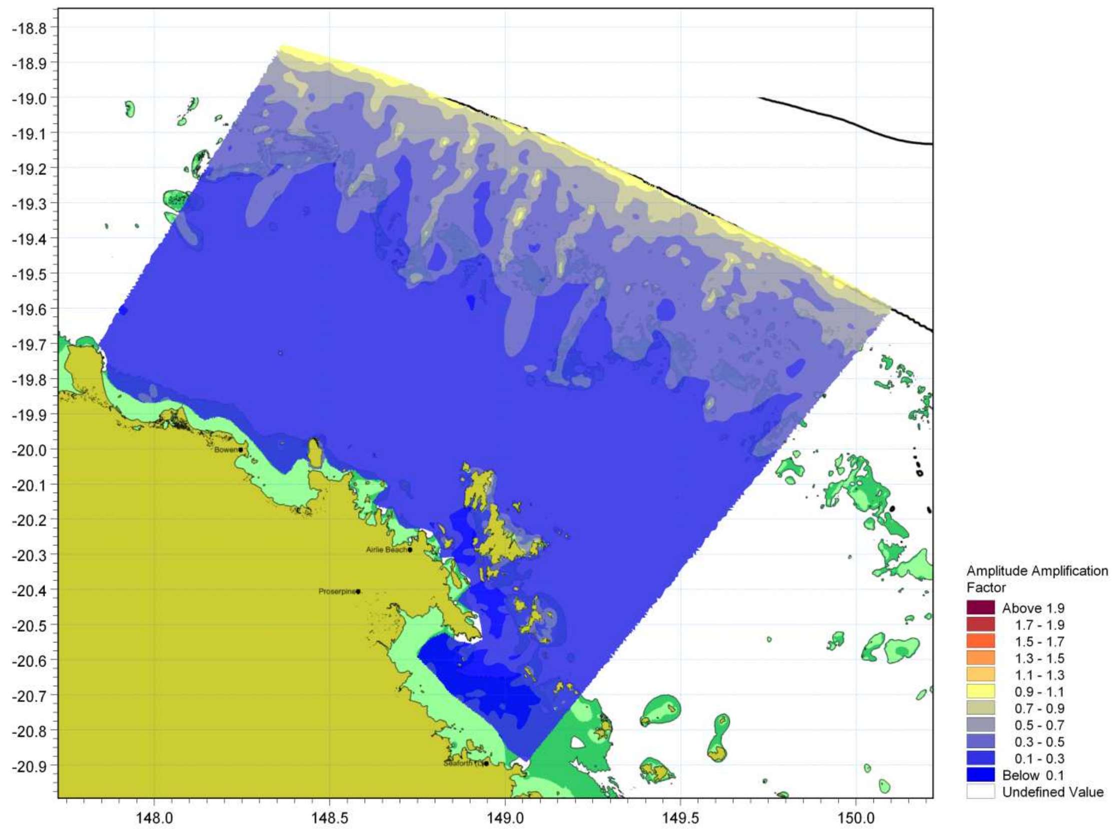

Figure C- 38 Scenario 3 amplification factor map below 10m depth for Ayr to Seaforth.

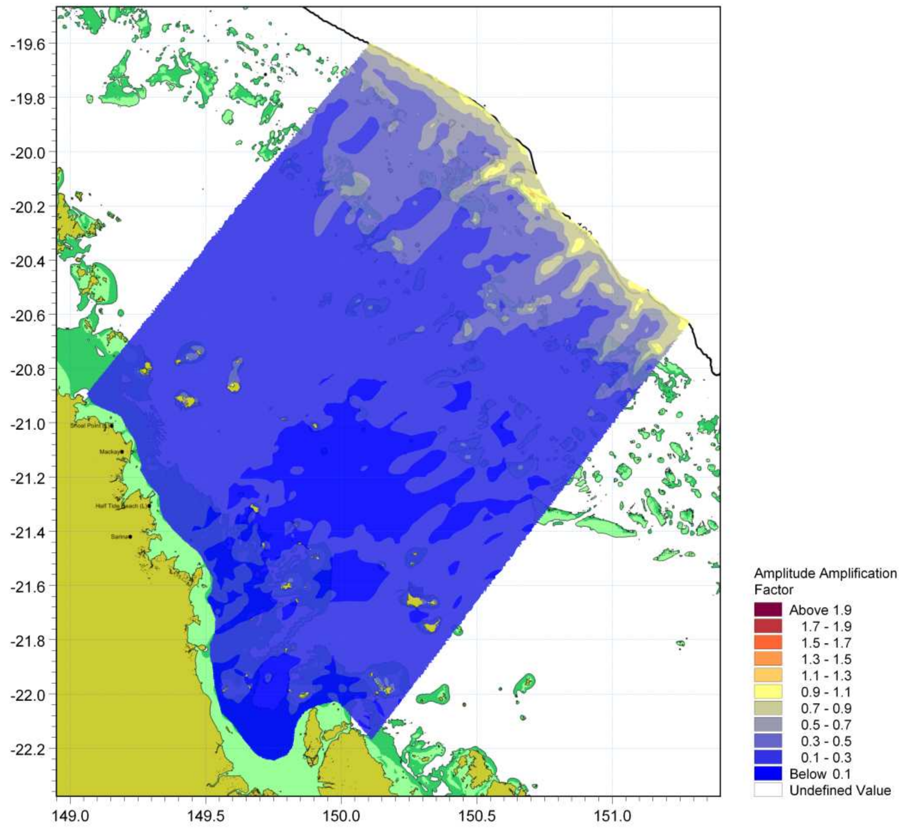

Figure C- 39 Scenario 3 amplification factor map below 10m depth for Cape Hillsborough to St Lawrence.

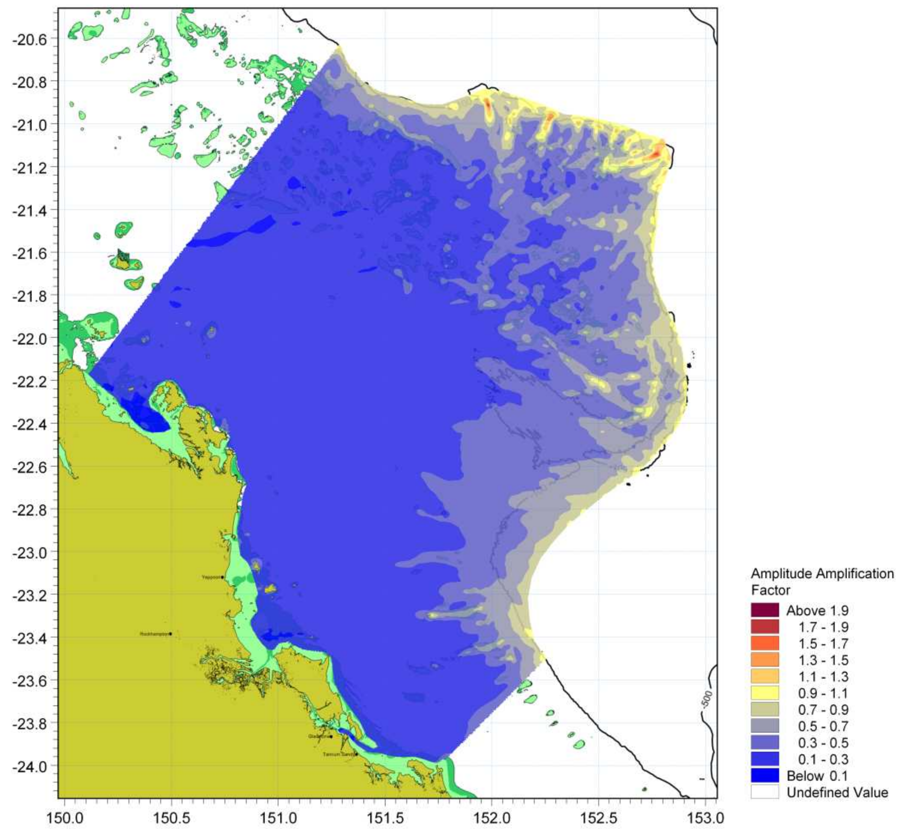

Figure C- 40 Scenario 3 amplification factor map below 10m depth for Stanage to Bustard Head.

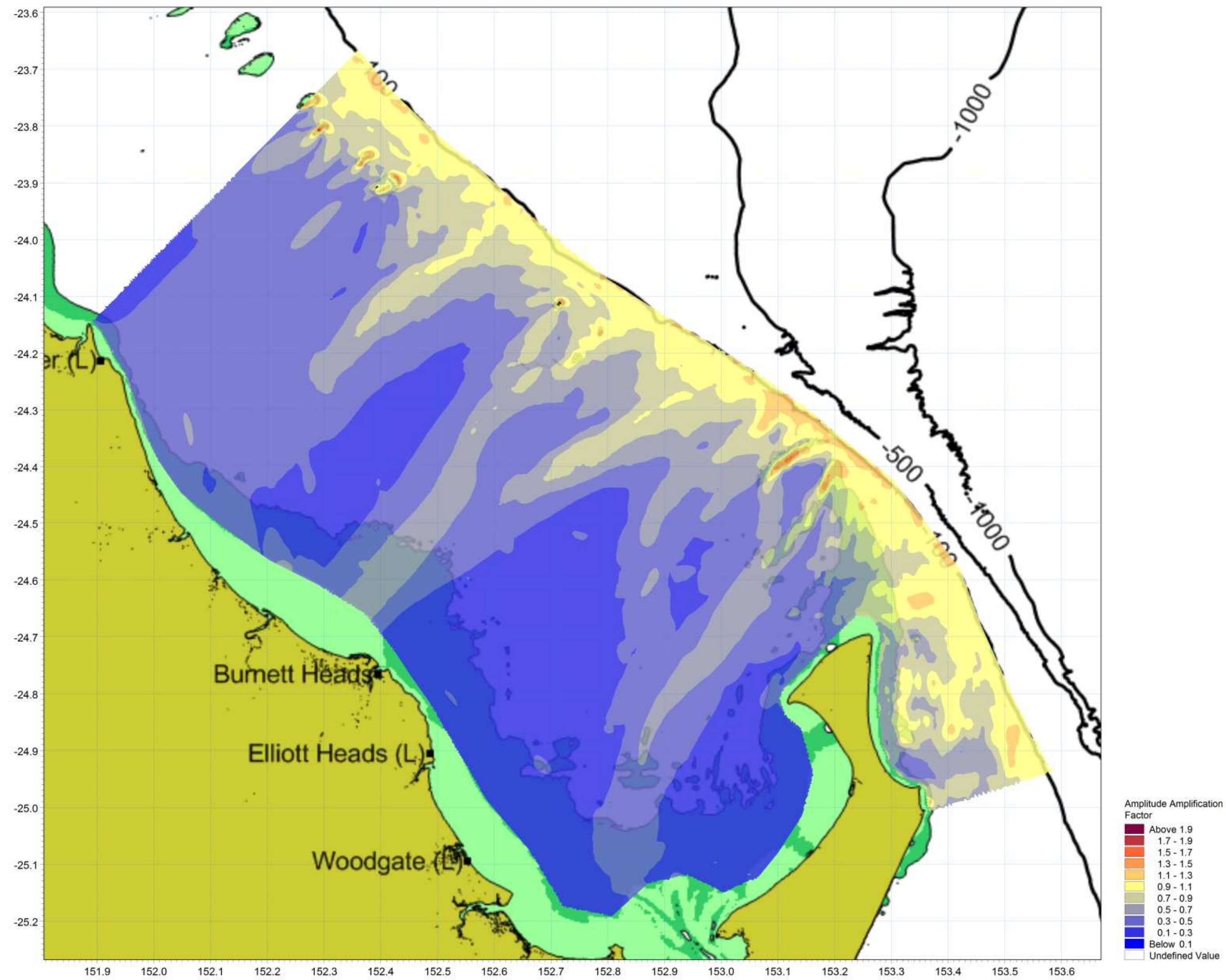

Figure C- 41 Scenario 3 amplification factor map below 10m depth for Seventeen Seventy to Hervey Bay.

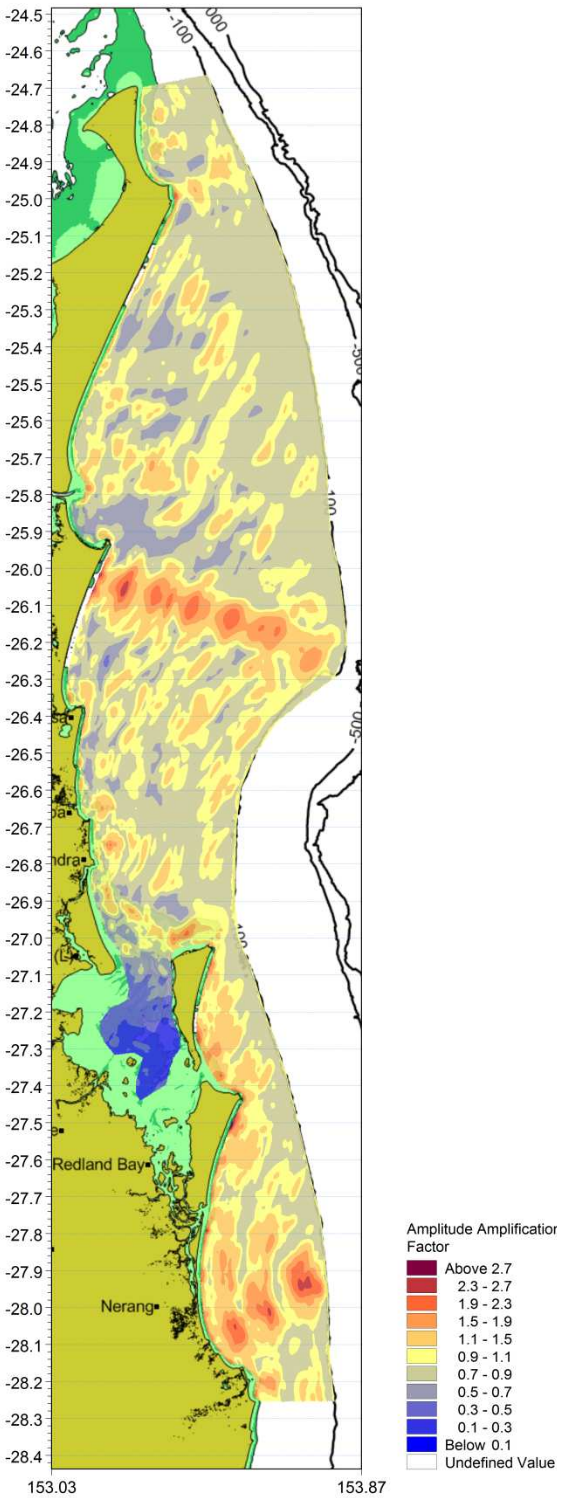

Figure C- 42 Scenario 6 amplification factor map below 10m depth for Fraser Island to Gold Coast.

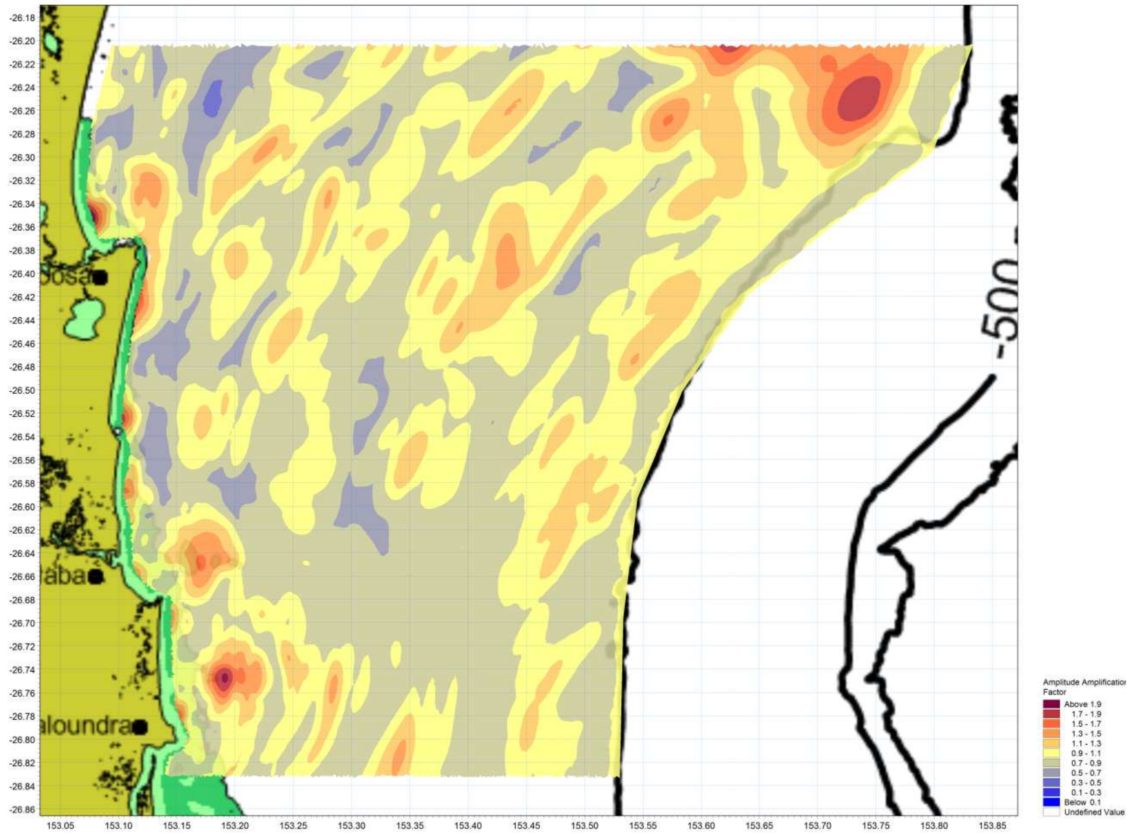

Figure C- 43 Scenario 6 amplification factor map below 10m depth for Sunshine Coast.

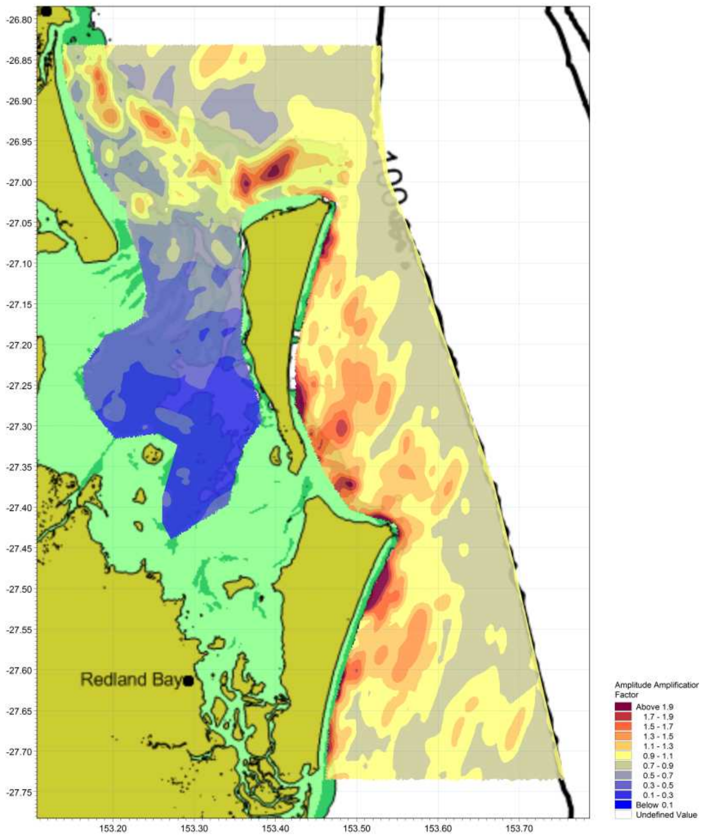

Figure C- 44 Scenario 6 amplification factor map below 10m depth for Moreton Bay.

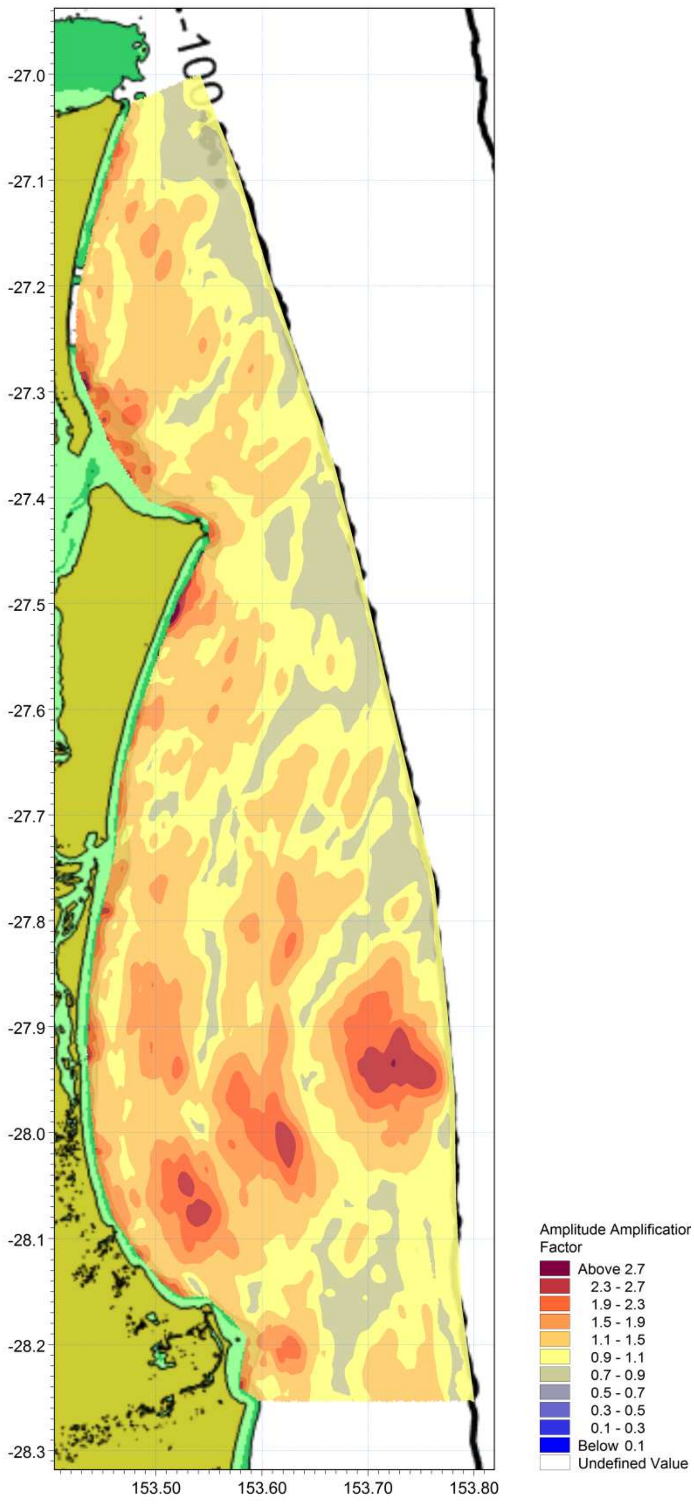

Figure C- 45 Scenario 6 amplification factor map below 10m depth for Gold Coast.

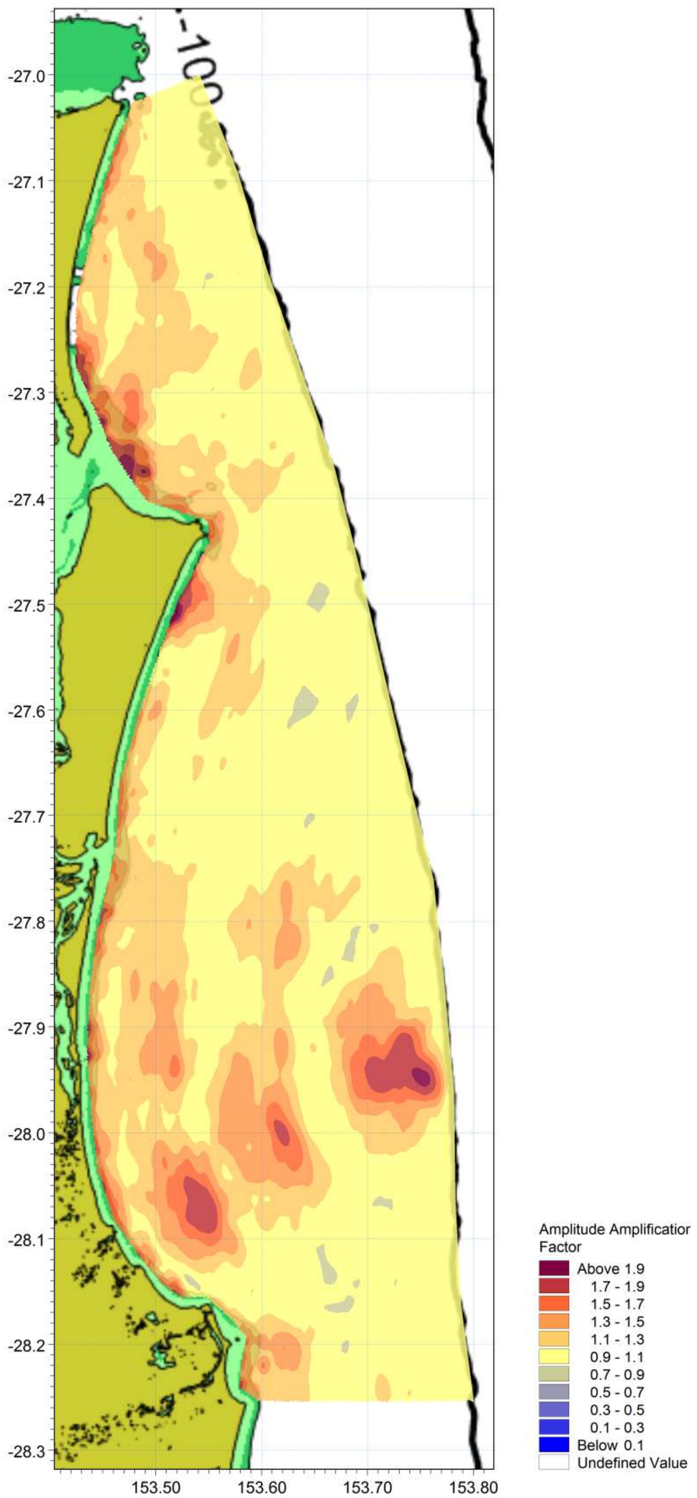

Figure C- 46 Amplification factor map (average of all Scenarios) below 10m depth for Gold Coast.