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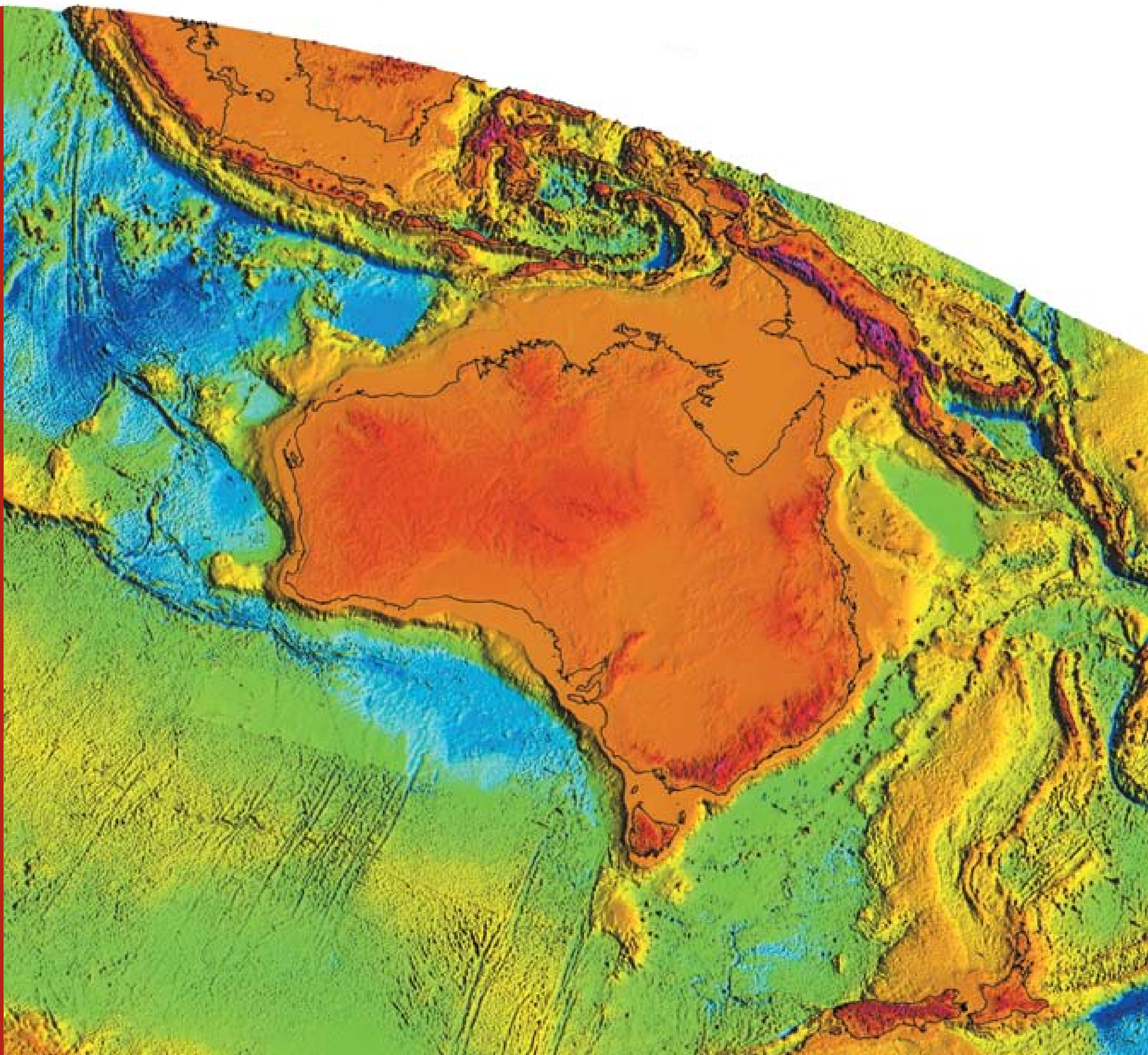

APPLYING GEOSCIENCE TO AUSTRALIA'S MOST IMPORTANT CHALLENGES

Tsunami Modelling Validation: The Impact of the 2004 Indian Ocean Tsunami on Geraldton, Western Australia

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RECORD 2010/01

by

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Contents

Executive Summary

In response to the devastating Indian Ocean Tsunami (IOT) that occurred on 26 December 2004, Geoscience Australia (GA) developed a framework for tsunami risk modelling. The outputs from this methodology have been used by emergency managers throughout Australia to prepare the community for such an event. For GA to be confident in the information that is provided to the various stakeholders, validation of the model and methodology is required.

While the huge loss of life from the tsunami was tragic, the IOT did provide a unique opportunity to record the impact of a tsunami on the coast of Western Australia. Eight months after the tsunami a post-disaster survey was conducted at various locations along the coast and maximum run-up was determined from direct observational evidence or anecdotal accounts. In addition, tide gauges located in harbours along the coast also recorded the tsunami and provide a timeseries of tsunami wave heights from which we obtain frequency information.

This study employs the tsunami hazard modelling methodology used by Geoscience Australia (GA) to simulate a tsunami scenario based on the source parameters obtained from the Indian Ocean earthquake of 2004. The model results are compared to observational evidence from satellite altimetry, inundation surveys and tide gauge data for Geraldton, a community on the Western Australian coast. The Western Australian coast provides a suitable location to validate the tsunami models for distant tsunami and compliments other work conducted at Geoscience Australia that has validated the models for near-source regions such as Patong Bay in Thailand.

Results show that the tsunami model provides good estimates of wave height in deep water and run up in inundated areas. Importantly, the model matches the timing of the first wave arrivals. However, the model fails to reproduce the timeseries data of wave heights observed by a tide gauge in Geraldton harbour. The model does, however, replicate the occurrence of a late arriving (16 hours after first arrival) wave packet of high frequency waves. This observation is encouraging since this particular wave packet was observed elsewhere in the Indian Ocean and caused havoc in harbours many hours after the initial waves had arrived and dissipated. This result has implications for tsunami warnings and response, as the initial waves may not be the most damaging in marine areas.

The results from this study demonstrate that GA's current methodology for modelling the hazard of tsunami for Australia is robust and credible. GA and its various stakeholders can be confident that the run up estimates are reliable, however precaution must be taken in interpreting waveform information in harbours which is less reliable.

To allow independent verification of the results from this study and to encourage further validation tests we have provided the necessary input data, supporting model scripts and all model outputs as a DVD appendix. This is inline with the open source philosophy of ANUGA and the creative commons licence encouraged by Geoscience Australia.

Introduction

The Indian Ocean Tsunami in 2004 highlighted to the world the widespread devastation that tsunamis can have, not only in communities proximal to an earthquake epicentre but also to ones lying thousands of kilometres away across vast stretches of ocean. In addition, the tsunami highlighted the inadequacies in Australia of understanding the risk and impacts such an event could cause to communities that lie along the Australian coastline, particularly in Western Australia.

In response, Geoscience Australia in conjunction with the Fire and Emergency Services Authority (FESA) of Western Australia developed a scenario based methodology for analysing the hazard of tsunamis to communities in Western Australia. The outputs of this work, mainly being GIS products, would allow emergency managers to mitigate against future events. In this partnership, GA provided the scientific expertise for natural hazard modelling and FESA provided high quality data critical to the modelling component and an understanding of the communities involved. A series of communities were selected based on probabilistic tsunami hazard assessments for Western Australia (Burbidge et al, 2008a) and the entire Australian coast (Burbidge et al, 2008b). The onshore tsunami hazard was then determined using a scenario based approach, utilising events from databases generated in the probabilistic offshore hazard assessment. The primary output is a map of maximum inundation depth and wave speed for a selection of events.

From 2005 to 2009 this methodology was applied, in collaboration with emergency managers, to model onshore tsunami impact at communities around Australia to help prepare for such an event.

GEOSCIENCE AUSTRALIA'S TSUNAMI HAZARD MODELLING METHODOLOGY

Developing a tsunami hazard model requires a three step process:

Step 1: Source Model

A source model is defined that is representative of a tsunamigenic source. This could be an earthquake, volcanic eruption, submarine landslide or meteor impact. Approximately 75% of historical tsunami observed in Australia have been generated by undersea earthquakes (Dominey-Howes, 2007). Therefore tsunami hazard modelling at Geoscience Australia has focussed predominantly on earthquake sources, building on existing seismic hazard capabilities. Earthquake source models determine vertical displacement of the seafloor to generate the initial wave for the tsunami.

Data Requirements: Earthquake source parameters

Step 2: Deep Water Propagation Model

The seafloor displacement model causes an initial displacement of the water column above the rupture, the deep water propagation model then simulates propagation of the tsunami from the source to the area of interest. This model solves the linear shallow water wave equation that is a function of the water depth obtained from bathymetric data. Hence the model is sensitive to source and water depth.

Data Requirements: Sea-floor displacement model, bathymetry

Step 3: Shallow Water Propagation and Inundation Model

As the tsunami enters shallow water and approaches and inundates a landmass its behaviour may increase in non-linearity and complexity. To model this behaviour an inundation model is required that solves the non-linear shallow water wave equation. The tsunami is modelled as it approaches the shoreline and begins to shoal (increase in wave height as it slows in shallow water). Again this

model is very sensitive to the resolution and quality of the bathymetry and topography data. This model simulates the run up of the tsunami onto land.
Data Requirements: Bathymetry, topography, timeseries of wave height and velocity components from the deepwater model at on offshore depth, such as the 100 m contour.

Once the inundation model is complete the results can be visualised and investigated further in three main ways:

- As an animation of the area of interest showing 'wet' and 'dry' regions
- As a timeseries of wave height or wave speed for any location within the model
- As a map of maximum inundation depth or wave speed.

The aim of this paper is to describe the specifics of Geoscience Australia's tsunami modelling methodology, to describe the nature of the input data and to compare the model results observational data. The accompanying DVD contains all the necessary input data and supporting model scripts to reproduce the results described here.

Model Descriptions

DEEP WATER PROPAGATION - URSGA

The deepwater propagation model is known as the URSGA model. This model was developed by URS and GA and incorporates the source model developed by Satake (1995). It has been extensively used by GA to simulate tsunami in the Indian and Pacific Oceans. The model uses a finite-difference grid, projected in spherical coordinates to solve the linear shallow wave equations. It requires input of bathymetry and seafloor displacement. It then solves the linear shallow water wave equation for wave height based on the height of the water column. Use of the linear shallow water wave equations and relatively coarse bathymetry allows modelling of tsunami propagation at ocean scales. This approach is considered valid to model the tsunami to the 100m water depth contour from where the output data is input into ANUGA for more detailed inundation modelling (Burbidge et al, 2008b).

SHALLOW WATER PROPAGATION AND INUNDATION - ANUGA

To simulate the propagation of tsunami waves from the 100 m water depth contour onto land, a detailed inundation model is employed. ANUGA is a free and open source hydrodynamic modelling program predominantly written in the Python programming language. ANUGA uses a finite-volume approach for solving the non-linear shallow water wave equations projected in Cartesian coordinates. The numerical scheme for computing internal fluxes is specifically designed for hydraulic jumps, or shock waves, that appear in complex flows typically seen with inundation scenarios (Jakeman et al, 2009). The study area is divided into an unstructured triangular mesh with nested mesh resolutions which allows a finer mesh resolution in areas of interest. Within each triangular cell, the water depth and horizontal momentum are calculated. When simulating distal tsunamigenic sources waves are introduced to the ANUGA model at the seaward boundary, typically at around the 100 m water depth contour. Wave timeseries are obtained from the URSGA model.

ANUGA has been validated using wavetank models that simulated the 1993 Okushiri Island tsunami off Hokkaido, Japan (Matsuyama and Tanaka, 2001). ANUGA performed well and matched both time series data of wave heights and also maximum run up observed within a valley in the study area (Nielson et al 2005). ANUGA is available for free download from the Source Forge website[1].

[1] http://sourceforge.net/projects/anuga/

One important factor in model performance is the choice of model boundary conditions. In this study input from the URSGA model provides a seaward boundary condition, however as this is defined at the 100 m contour there is no information on the side boundaries between the land and the URSGA boundary. A sensitivity study of possible side boundary conditions conducted as part of this project (Appendix 1) showed that application of a transmissive boundary condition is most appropriate. Other types of side boundaries may result in loss of water from the model or reflection of tsunami waves off the side boundary, leading to errors propagating from the side in to the model (see Appendix 1).

Data

One of the advantages of using a hydrodynamic model is that only few distinct data sets are needed, typically bathymetry and topography data. However, the models are highly sensitive to the quality and spatial resolution of the data. As this study is simulating the 2004 Indian Ocean Tsunami we also require source parameterisation for this particular event. All data described here is available on the accompanying DVD.

DEEP WATER PROPAGATION – URSGA

The source parameters used here are defined by Chlieh et al (2007). The model was determined by inversion of seismic data and was constrained by coseismic geodetic and coral reef uplift data. The rupture occurred along a 1500 km section of the subduction zone with a width of less than 150 km. The total moment release is 6.7-7.0 x 10^{22} Nm, equivalent to magnitude 9.15 (Figure 1).

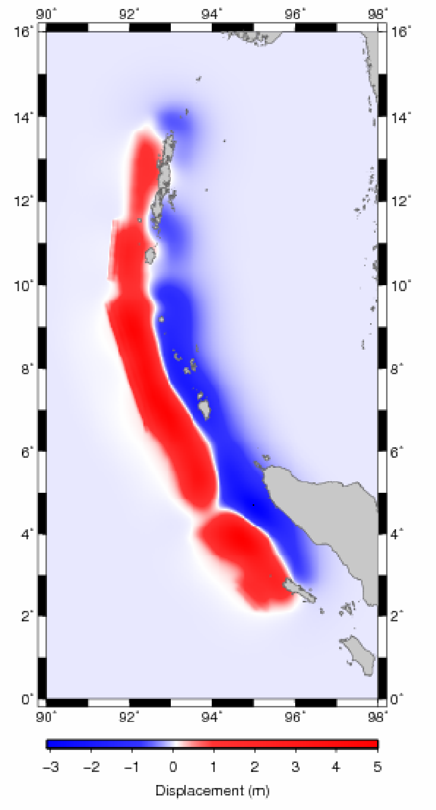


Figure 1: *Sea floor displacement model used for the tsunami source in the URSGA model from Chlieh et al (2007).*

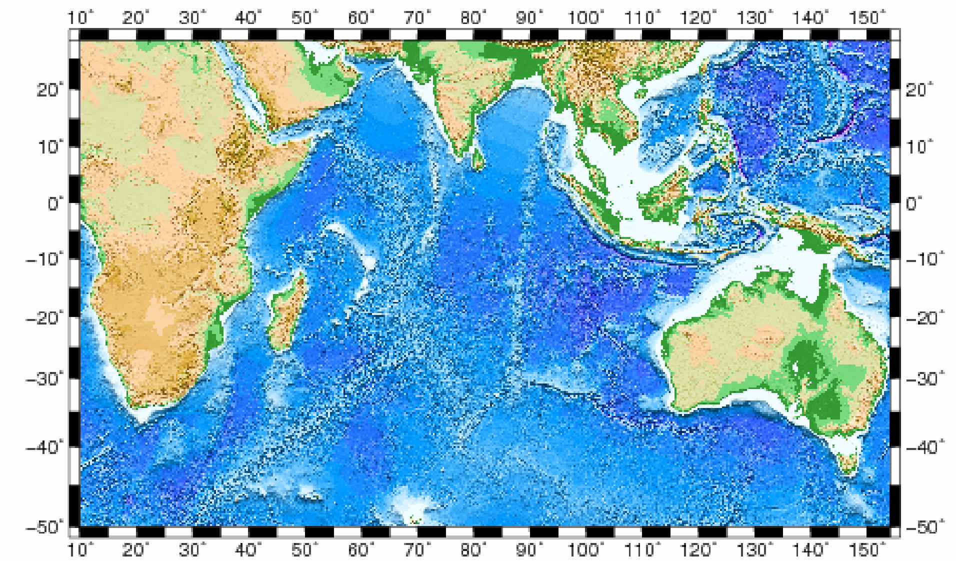


Figure 2: *GA-DBDB2 bathymetry data used in the URSGA model*

The bathymetry data used in the URS model is a combination of the 250 m Australian bathymetry and topography grid (Geoscience Australia, 2005) and the 1 minute resolution data set, DBDB2 (US Naval Research Laboratory[2]). The resultant bathymetry grid, GA-DBDB2, has a resolution of 1 arc minute. The URSGA model used a grid size of 2 arc minutes, which optimises the trade off between model detail and computational cost.

The model was run for the whole Indian Ocean (Figure 2; Table 1) for a time period of 80,000 seconds (22 hours). These parameters were chosen to accommodate for waves reflected from Africa and Madagascar that arrive in Western Australia ~15 hours after the earthquake. The model was also extended to 154°E because of model instabilities at cells that had steep topography and bathymetry and were adjacent to the edge of the model. This was resolved by extending the eastern boundary of the model so the model boundary did not intersect any land surfaces. Figure 3 shows the maximum wave heights obtained from the URSGA model.

Table 1: Model Boundary for URSGA model

E	ASTING	NORTHING
MIN	10°E	50° S
MAX	154°E	28° N

[2] http://www7320.nrlssc.navy.mil/DBDB2_WWW/NRLCOM_dbdb2.html

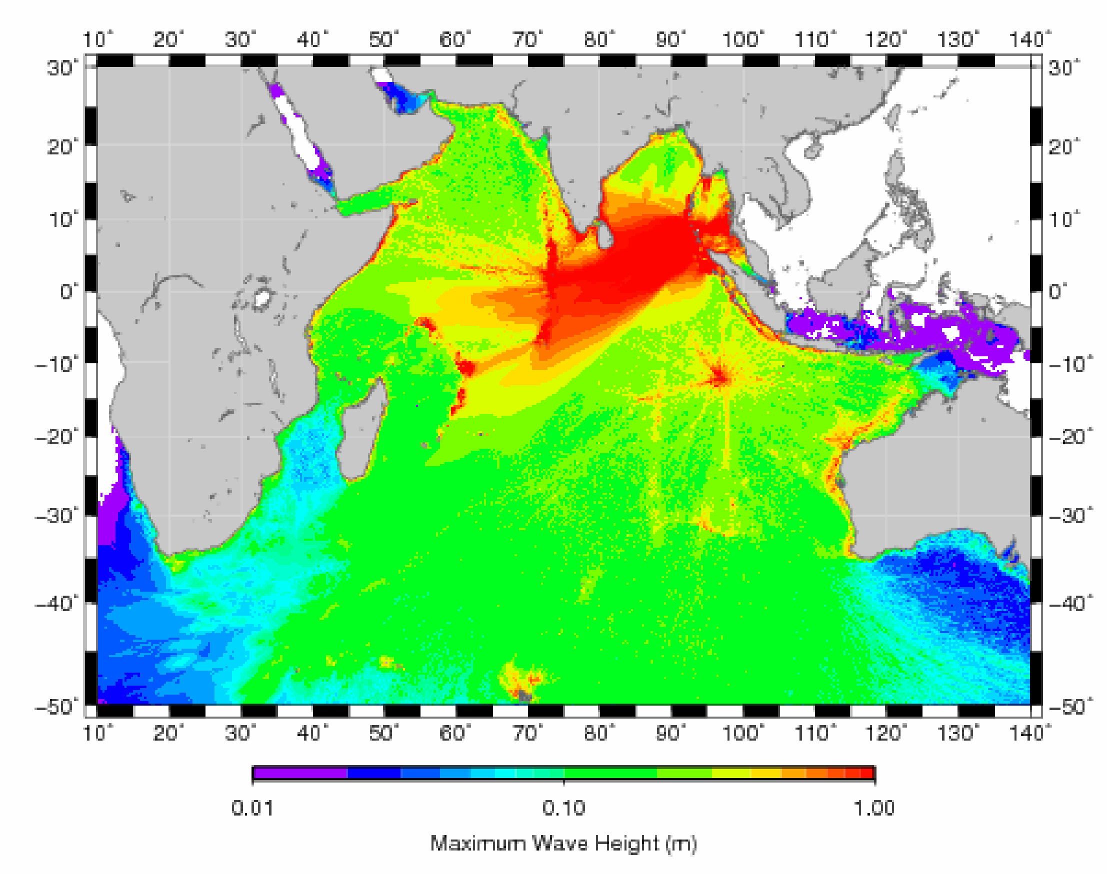


Figure 3: *Maximum wave heights obtained from the URSGA model.*

SHALLOW WATER PROPAGATION AND INUNDATION – ANUGA

The ANUGA model requires very few distinct data sets, only the incoming waves at the boundary provided by the URSGA model and a digital elevation data model based on near shore bathymetry and onshore topography. However, the model is very sensitive to the quality and the spatial resolution of the data. Available bathymetry was supplied by the Department of Transport in Western Australia and the onshore DEM (1 m resolution) was supplied by Land gate[3]. The bathymetry consists of various data sets, collected at different resolutions. Mesh resolution was increased in areas of interest near the coast, with data resolution and computational limitations providing a limit on fineness of the mesh. A maximum triangle area of 500 m^2 was chosen to balance model output accuracy and computational limitation. Figure 4 shows the bathymetry and elevation data and various mesh size resolutions. The ANUGA model was run for a simulation time of 80,000 seconds (22 hours) from the time that the first wave from the URSGA model arrives at the seaward boundary. The model was run for a fixed tide height of 0.4 m which was the tide height at the time of the first wave arrival (Department of Transport, WA). Inundation maps and time series of wave heights were extracted at locations for which observational data were available.

[3] This data is for non-commercial use only.

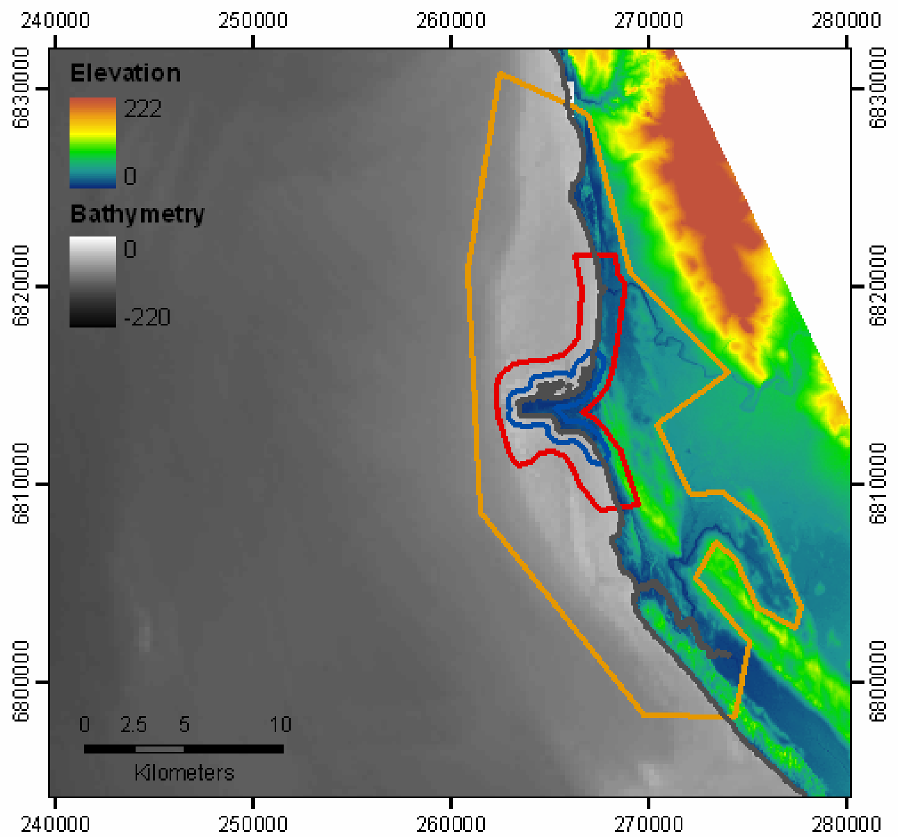


Figure 4: *Bathymetry and topographic data for the ANUGA model at Geraldton. The blue line shows the area where maximum mesh size is 500 m^2, red line is 1000 m^2 and orange line is 2000 m^2. The onshore elevation was supplied by Landgate and bathymetry is by the Department of Transport in Western Australia*[4].

Validation

This section presents the Indian Ocean Tsunami impact at Geraldton as a validation of the GA tsunami modelling methodology by comparing model outputs against observational data. The deep water propagation model is compared to satellite altimetry data and the shallow water propagation model is validated against tide gauge and run up observations.

DEEP WATER PROPAGATION – URSGA

Tsunami wave heights from URSGA are compared to altimetry data from the JASON satellite that coincidently passed over the Indian Ocean at the time of the tsunami. The satellite tracked from north to south and passed over the equator at 02:55 UTC on 26 December 2004, nearly two hours after the initial magnitude 9.15 earthquake (Gower, 2005). The satellite recorded the sea level anomaly compared to the average sea level from its previous five passes over the same region in the 20-30 days prior.

[4] This data is for non-commercial use only.

Figure 5 shows that the URSGA model replicates the amplitude and timing of the first wave but does not resolve the double peak of the first wave. This feature may have been generated by superposition of the initial waves from the rupture of two fault sections whereas the URSGA model simulates a single uplift displacement (Harig et al, 2008). The URSGA model also becomes out of phase with the JASON data at 3 to 7 degrees latitude. Chlieh et al (2007) also observe this misfit and suggest it is caused by a reflected wave from the Aceh Peninsula that is not resolved in the model due to insufficient resolution.

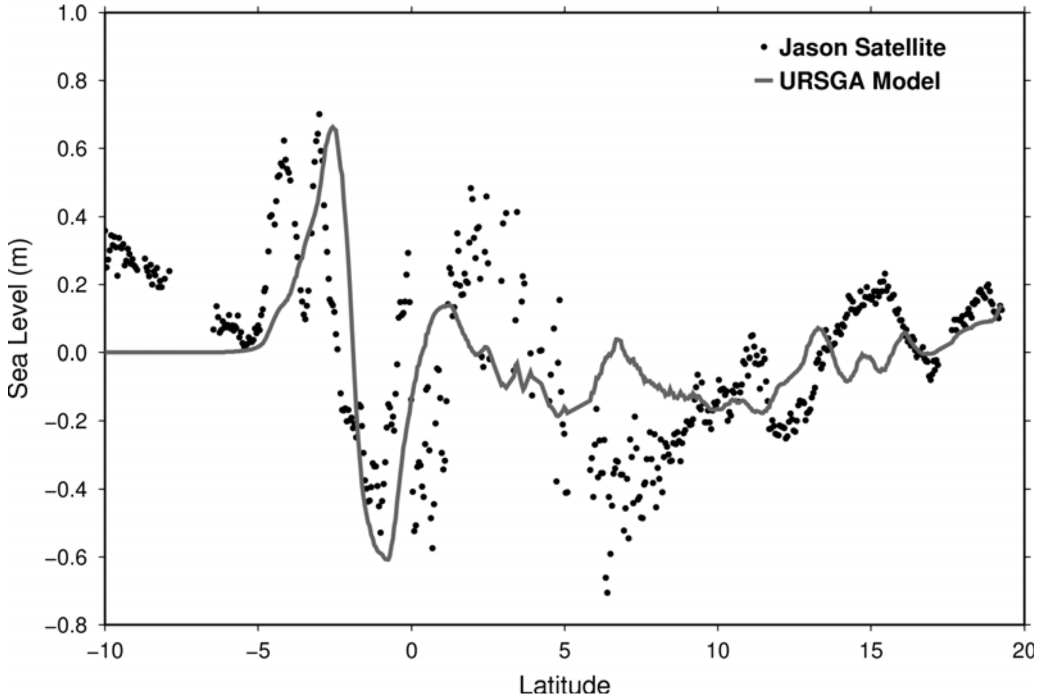


Figure 5: *Comparison of tsunami wave heights with satellite altimetry sea level anomalies from the JASON satellite.*

SHALLOW WATER PROPAGATION AND INUNDATION – ANUGA

Tide Gauge Data

The Department of Transport in Western Australia (WA) maintains a network of 11 tide gauges that are located in the ports or harbours of communities along the WA coastline. The Indian Ocean Tsunami (IOT) was recorded on a number of these tide gauges with wave heights ranging from 0.1m to 1.2 m. Although tide gauges are not designed for recording tsunami, 5 minute sampling intervals are sufficient to capture tsunamis which typically have wave periods of 10-30 minutes; thus the tide gauges provide a valuable timeseries of the tsunami. The Geraldton Port Authority maintains a WaveRider bouy offshore of Geraldton; however, the buoy is designed only to measure waves with periods less than 30 seconds, much too short to record the passage of a tsunami.

The recorded tide gauge signal at Geraldton is a mixture of tidal fluctuations and the tsunami signal (Figure 6). In order to extract the tsunami signal the tidal signal needs to be removed. This is accomplished by subtracting the predicted tide from the tide gauge recording. The predicted tide was obtained from XTide[5]; a tool that predicts the tide for any location on the globe. XTide uses the

[5] Available for free download from http://www.flaterco.com/xtide/

same algorithm as the National Ocean Service (NOS) in the USA. The resulting residual signal is representative of the tsunami (Figures 6 and 7).

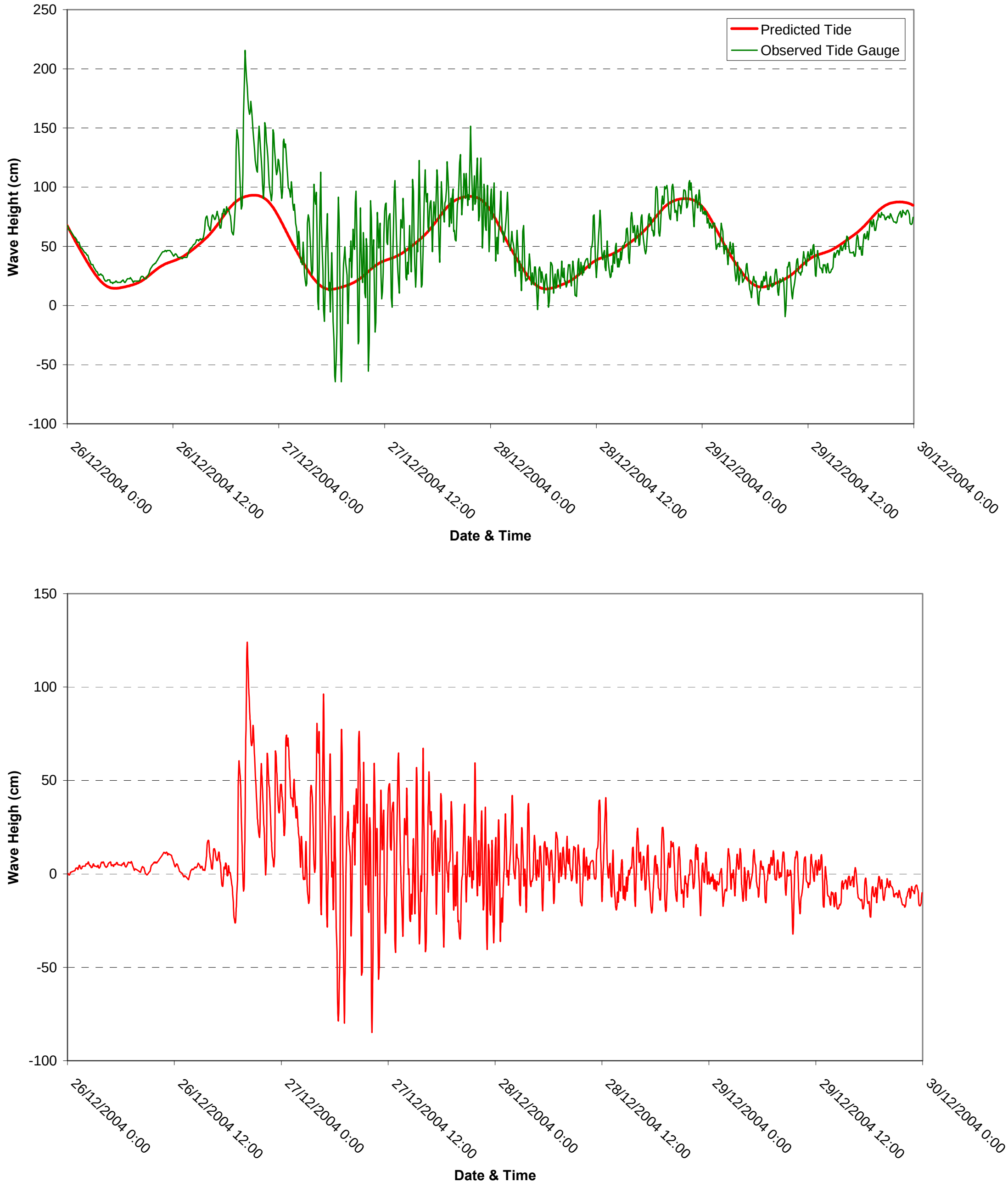


Figure 6: *Tidal corrections of tide gauge from Geraldton Harbour.* ***Upper panel:*** *The observed tide gauge signal provided by the Department of Transport, WA (green) and the predicted tidal fluctuations from XTide (red).* ***Lower panel:*** *The tsunami signal after the predicted tide has been subtracted from the observed tide gauge data.*

Once the tidal signal is removed, the first arrival of the tsunami can be seen at 15:24 local time (UTC+8) and 6:26 hrs after the onset of the earthquake. The four hours following the first arrival consists of waves with periods of ~40 minutes and wave heights of 10-20 cm. Approximately 11:10 hours after the earthquake and 4:45 hours after the first arrival the wave height increases dramatically to a maximum of 123 cm before reducing to a height of 30-70 cm with a period of 30-40 minutes. This pattern continues for a further 12 hours before tapering off, however the signal can be seen for four days following the first arrival.

In Figure 7 there is a wave packet of high amplitude waves that arrive 11 hours after the earthquake. This has been noted in other areas around the Indian Ocean notably, Oman, Reunion Island and the Mascarene Islands (Hebert et al, 2007). In these instances, tide gauges in harbours recorded high frequency waves with large amplitudes arriving 5-11 hours after the first wave arrival. At the Port of Salalah in Oman a 292 m long tanker broke its moorings and strong currents in the harbour prevented the ship from remooring. Anecdotal accounts from the ship's captain noted that this high energy wave activity continued for 3-5 hours and it started hours after the first tsunami waves arrived (Okal et al, 2006).

The high energy arrivals at Geraldton could be explained by high frequency wave packets that have been slowed due to dispersion or could alternatively be explained by reflections from Africa or islands in the West Indian Ocean such as Madagascar and Mauritius.

The Geraldton tide gauge is used here as a benchmark test for the GA tsunami modelling methodology. Figure 7 shows the observed tide gauge residual (blue) and the results of a synthetic tide gauge at the same location in the tsunami model (red). Three components are considered in this comparison of the tsunami model results with tide gauge data; timing, frequency and amplitude.

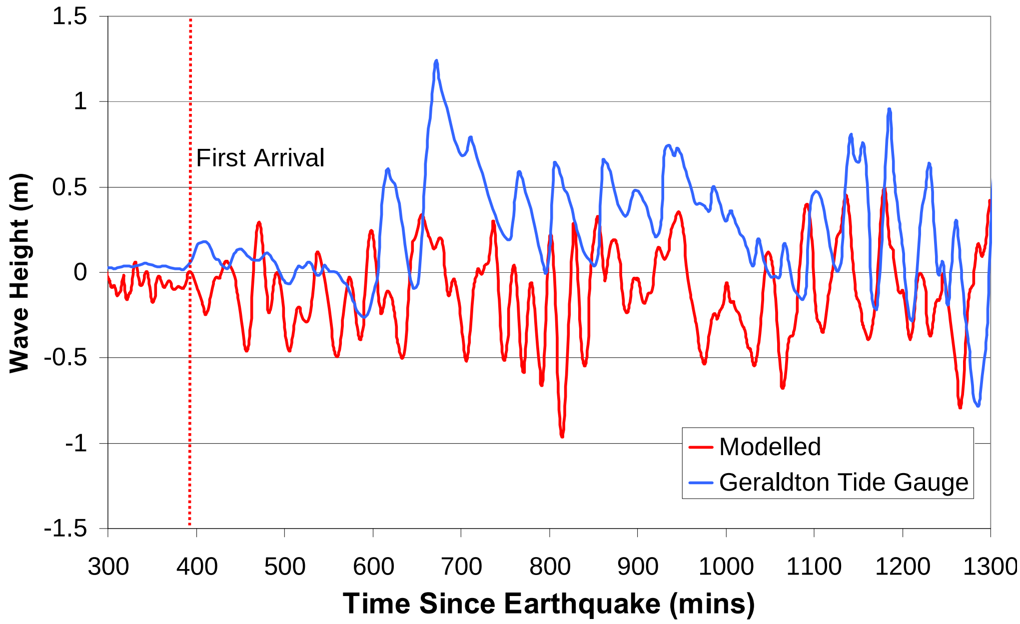


Figure 7: *Comparison of the Geraldton tide gauge residual with a synthetic tide gauge from the model at the same location. The Geoscience Australia model matches the timing of the first arrival but does not match the waveform, possibly due to complex harbour resonances. The red dashed line is the predicted first arrival from ray tracing (Pattiartchi & Wueratne, 2009).*

With respect to timing, the model matches the first arrival within a few minutes, a result that is consistent with other numerical models that predict the first arrival at 15:20 (Pattiartchi & Wueratne, 2009). However the amplitude of the first arrival is underestimated. The tsunami model also underestimates the amplitude of the peak wave height at around 6:30 hours after the earthquake. This wave is very large with respect to the maximum wave height at the boundary of the model. At the boundary the largest wave height that could coincide with this large arrival is 30 cm, and typically wave height may increase by a factor of 2-3 by the time it reaches land which would equate to a height of 60- 90 cm. Possible explanations for the large coastal amplitude include nearshore amplification and/or constructive interference (or resonance) inside the harbour. It must be noted that harbours are an inherently difficult area to model; for example, dredging may cause sharp changes in bathymetry. In Geraldton Harbour the elevation changes dramatically from +2 m to -13 m over a distance of a few metres creating near vertical 'walls'. Furthermore, obtaining data with a vintage consistent with the historical time of the event modelled is difficult.

When ANUGA creates a triangular mesh over the model area it attempts to fit the triangular surface to the topographic data points. If the resolution of the triangle is larger than the previously mentioned gradient in the real bathymetry then the triangles will have a slope less than that of the bathymetry. This creates different shaped surfaces that waves can reflect off, and if the model mesh is not identical to the steep changes in bathymetry then it is not possible to reproduce the same waveforms for tide gauges within harbours. A way to mitigate this effect is to use very high resolution bathymetry data in harbours, which often exists. For the model used in this study a 500m^2 mesh was used in the harbour area. When compared to previous models with a resolution of 1000m^2 the model fit improved significantly.

Approximately 18:20 hours after the earthquake the model starts to match the waveform of the tide gauge. This could be explained two ways; firstly it is coincidental that it has become synchronised or alternatively the resonances within the harbour that the model failed to resolve have subsided and it is accurately modelling the observed tsunami signal. If the latter is the case it is very encouraging because this particular part of the tsunami signal has a higher frequency content than the rest of the signal. This high frequency packet has been observed in other tide gauges around the Indian Ocean and has caused extensive damage in harbours many hours after the first tsunami waves arrived. This has important implications for tsunami hazard incorporated within warning bulletins. If waves arriving 12 hours after the first arrival are causing the most damage then bulletins need to include warnings that extend, especially for harbours, at least 12-18 hours after the first predicted wave arrival.

Post Tsunami Survey Data

Following the IOT, GA arranged for a consultant to conduct a post-tsunami survey in September 2005, nine months after the tsunami (see Gaul, 2005 for details). Given the time delay between the tsunami and the survey, most observational evidence was difficult to identify, hence the survey relies heavily on anecdotal evidence from residents of communities along the WA coastline. Anecdotal evidence, especially provided months after an event, must be scrutinised and compared to other lines of evidence in order to provide a reliable estimate.

Geraldton is one of the largest WA communities located north of Perth and as the wave heights there were larger than elsewhere, there is more anecdotal evidence than for other communities. Most of the accounts consist of residents recalling the height of run up relative to features such as jetty's, shop fronts or reefs.

During the survey the maximum run up height for each location was measured relative to the sea-level at the time of the survey. To obtain the run up height during the tsunami, this height was corrected to the height above sea-level at the time of the tsunami (first arrival) and also to mean sea level (AHD). The results from the survey are shown in Figure 8.

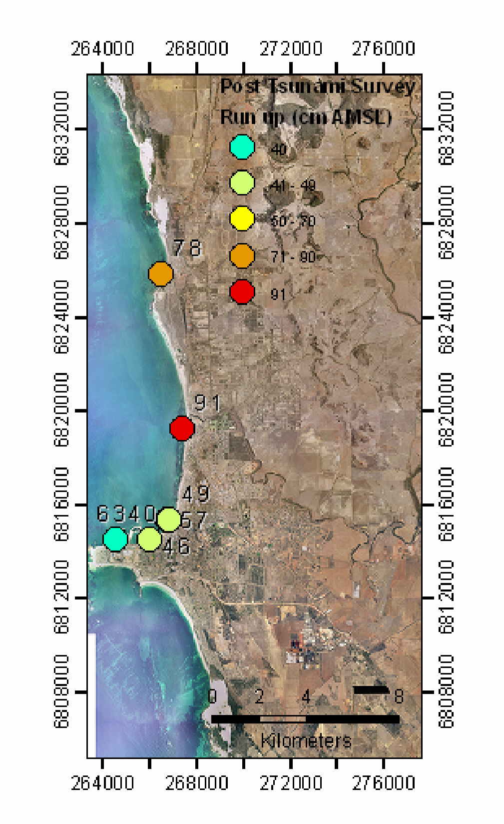


Figure 8: *Map of Geraldton with survey locations and the observed amount of run up (cm above MSL). The numbers shown are the Gaul site number. Imagery supplied by Landgate.*

Post-tsunami survey run up heights above MSL were compared to the maximum run up at the same locations in the model (Figure 9 & 10). Most of the locations are situated in the main harbour, port or a small recreational boat marina further north. There are also two locations at beaches around 5 and 10 km north of Geraldton CBD. There is a good agreement between the observed data and the model run up for the harbour, port and marina (Figure 9). However, the tsunami model overestimates the run up at the two beach locations. These locations were outside of the main area of interest in the model therefore had a coarser mesh with a triangle area of 5000 m^2. The model was rerun with a finer mesh of 500 m^2 in these locations, the same resolution as within the harbours, however the maximum run up height did not change significantly and there was still a misfit between model and observation. The most likely reason for this is errors in the elevation data and but could also be due accumulated errors from source model, propagation and inundation interacting differently with the bathymetry.

The post-tsunami survey data can be found in Appendix 2.

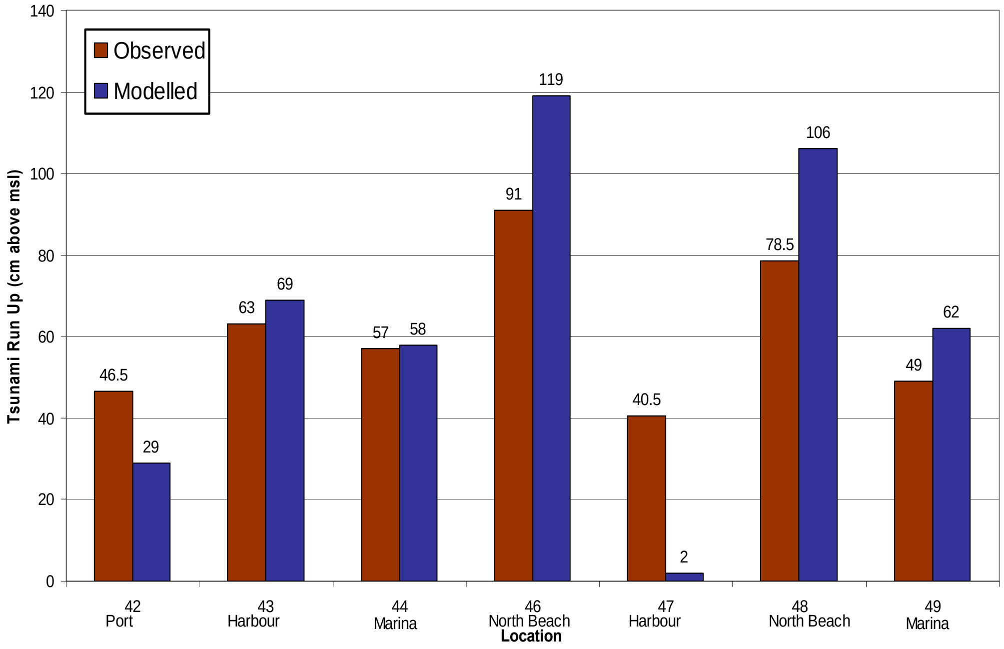


Figure 9: *Comparison of post-tsunami survey run up heights against run up heights in the tsunami model.*

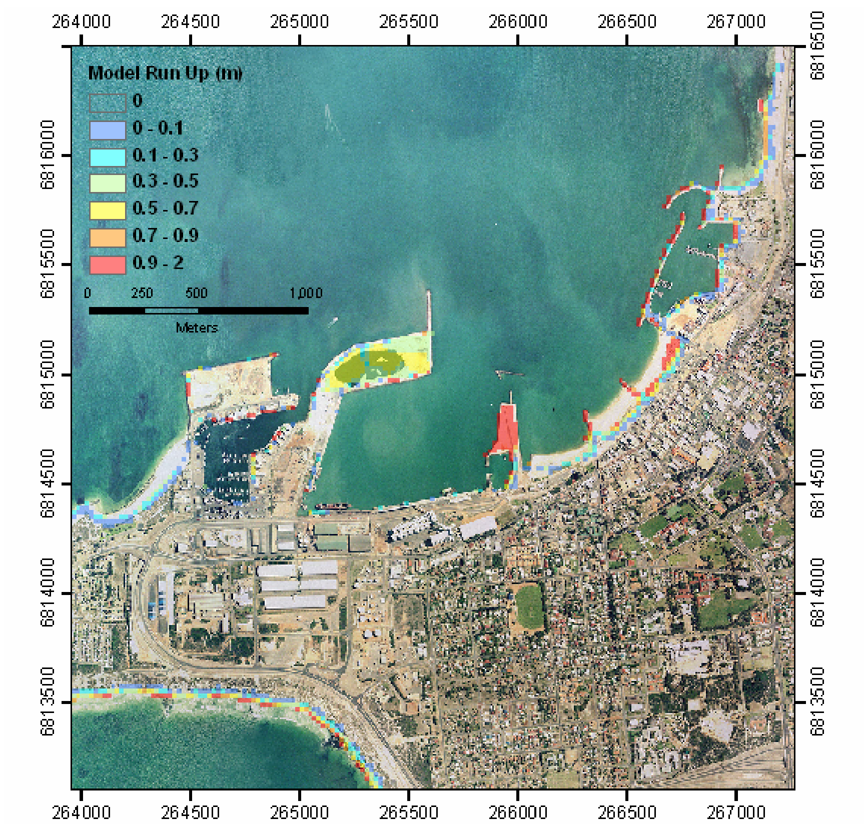


Figure 10: *Map of Geraldton Harbour with the maximum modelled run up height.*

Frequency Analysis with Wavelets

To compare the frequency content of the tide gauge and the model both waveforms were decomposed using wavelet analysis. Wavelet analysis allows a timeseries to be analysed for its frequency content at varying time and frequency scales. For this analysis a continuous wavelet transformation was performed using a Morlet wavelet (Mallat, 1999).

Figure 11 shows the wavelet coefficients for a URSGA boundary gauge, the Geraldton tide gauge and the modelled tide gauge at the same location. The URSGA boundary gauge shows long period waves arriving early followed by arrivals with shorter periods. Note that the grid size of the bathymetry controls the minimum frequency content of the data, which is around 50-100 minutes period in the deep ocean. If the grid was finer we would sample waves with shorter periods.

Since the Geraldton tide gauge is sampled at 5 minute intervals the Nyquist frequency is ~10 minute period therefore anything lower than this period could be aliased and should not be used in analysis. The high frequency packet of waves that begins around 1000 minutes after the earthquake and has a frequency content of around 15-20 minutes is thought to be real. This wave packet is also seen in the modelled data but at a slightly lower frequency. The first arrival in the model data is quite clear, occurring at 395 minutes the same as observed in the time series data. The first arrival is also marked in the Geraldton tide gauge, however it is less defined with low energy noise occurring prior to the first arrival shown by the transition from yellow to green intensity.

Recommendations

FUTURE WORK

The scope of the study was limited to one location and therefore it would be instructive to compare the onshore hazard results at other locations that have observational data along the Western Australian coastline. To support further study, the required outputs from URSGA have been stored at the 100 m water depth contour for the whole Western Australian coast. The URSGA output files and metadata can be found on the accompanying DVD.

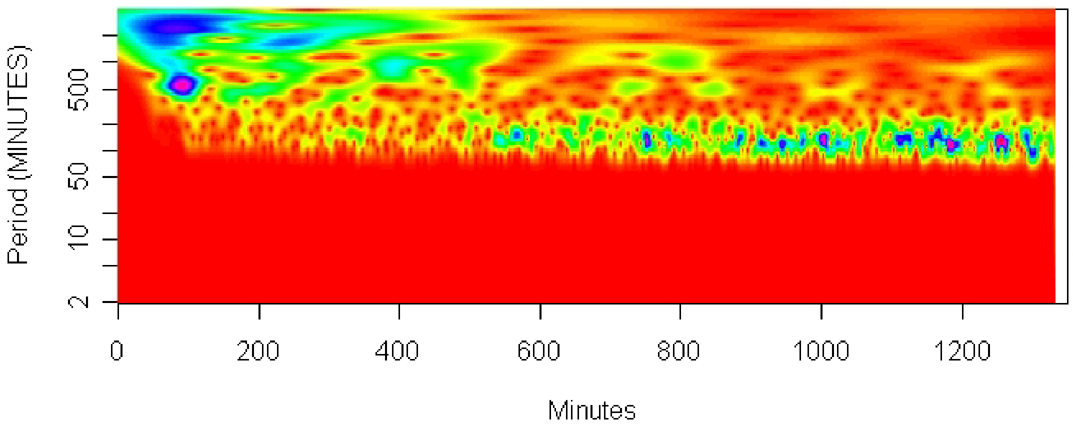
LIMITATIONS

Since the current tsunami methodology involves running two models that are linked together but mutually exclusive there are issues surrounding error propagation. It is difficult to validate both models independently because the models are inherently coupled. Attempts were made to try and independently validate the URSGA model using the satellite altimetry data from the JASON satellite. However the ANUGA model relies on input at the boundary from the URSGA model therefore the ANUGA results are dependent on the URSGA model and may inherit errors or misfits from URSGA. Whilst URSGA has an inundation component, GA has not used this in the tsunami modelling methodology. This is predominantly due to ANUGA's flexible unstructured mesh that allows the user to construct detailed models in the area of interest. ANUGA is restricted by its implementation in Cartesian coordinates and currently could model tsunami propagation from near field sources only. A number of models exist that can model the tsunami from source to shore. One example is TsunAWI that uses a finite element model and Harig et al (2008) has shown that it performs well at near source and far field distances.

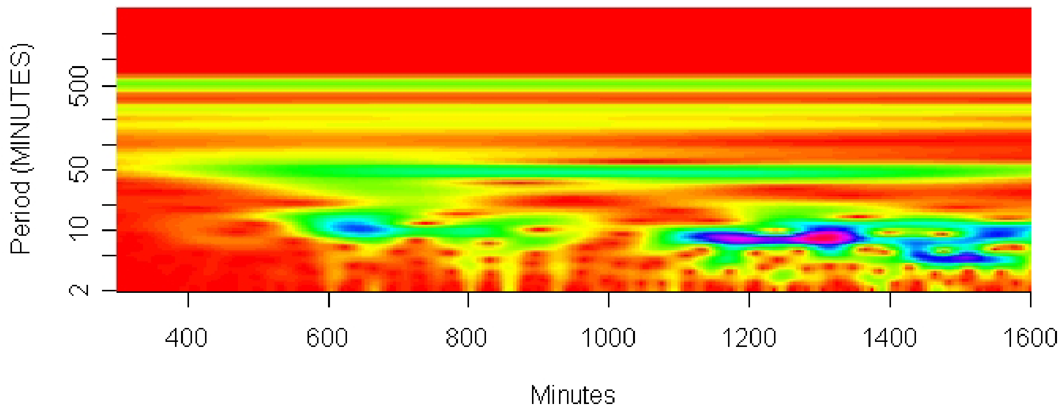
PHYSICAL DISPERSION IN URSGA MODEL

There is evidence from the Geraldton tide gauge and other locations around the Indian Ocean (Okal et al, 2006) that the presence of a late arriving packet of high frequency waves can cause significant damage in harbours hours after the first wave arrivals. These waves arrive much later due to physical dispersion. This is where waves of shorter periods arrive later since the speed of tsunami waves

A) URSGA Synthetic Tide Gauge at Boundary of Shallow Water Propagation Model



B) Observed Tide Gauge at Geraldton



C) Synthetic Tide Gauge from Model

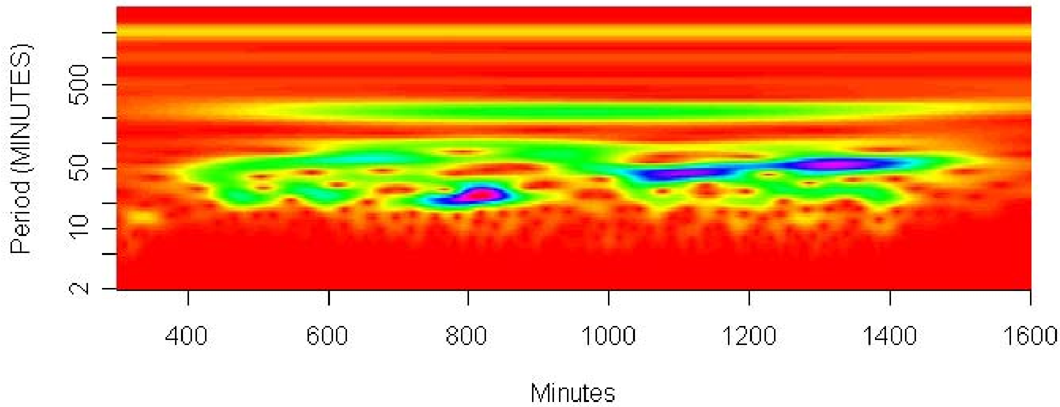


Figure 11: *Wavelet coefficients for tide gauge data.* ***Upper panel:*** *A synthetic tide gauge at the 100m water depth contour west of Geraldton from the URSGA model (2 second sampling). This is the seaward boundary input for the ANUGA model.* ***Middle Panel:*** *The tide gauge from Geraldton Harbour (5 min sampling).* ***Lower Panel:*** *A synthetic tide gauge from the GA model for the same location as the real Geraldton tide gauge. Note that the x-axis for A) is different from B) and C).*

across deep water is dependent on the wave period and water depth. At present the URSGA model does not account for physical dispersion and it is suggested that if possible this addition should be made to the code. This would allow the hazard posed by late high frequency wave trains to be accurately modelled. It is a common perception that the first waves of a tsunami are the most destructive. While this may be true for areas near the source it appears that later arrivals can cause the most destruction in areas distal to the source. It is advised then that warning systems be aware of the possibility of late arriving waves and extend there warnings – particularly for marine activities – out in time so that the public is aware of the hazard, some 12-18 hours after the first tsunami waves.

MESH RESOLUTION IN HARBOURS

Paradoxically most tide gauges are located in harbours so that they are protected from wave action and other noise. However, when using tide gauges in tsunami validation studies there is an added complexity since waves resonate within harbours complicating the waveform. This means that it is very difficult to accurately match the modelled waveform with a tide gauge. However there are means to address this problem. It was found in this study that when the mesh size was reduced by half, the detail of the model waveform was much higher. For the Geraldton harbour the bathymetry data was of sufficient resolution to allow the mesh size to be reduced to 500 m^2, however this did increase the computation time by three times. Therefore it is recommended that if comparisons are to be made with observational data or if stakeholders require accurate inundation models of harbours or ports then the mesh within the harbour be as fine as the bathymetry data allows.

TEMPORAL TIDAL FACTOR IN ANUGA

The URSGA model has no notion of tide so it must be added to the ANUGA boundary. However, at present ANUGA uses a tide factor that is not time dependent. This is valid for scenario based examples where maximum run up heights are required at the highest astronomical tide, however it provides limitations for models of observed events such as this study. This is due to the fact that tsunami signals can last days, which encompasses five or more tidal cycles, and the largest waves do not always arrive in the first few hours. In areas where the tidal height is large this could be the difference between an area being inundated or not. Therefore it is recommended that ANUGA be developed to include a time dependent tidal factor, where the tidal factor would be a time series of the predicted tide for the simulation date.

Conclusion

For Geoscience Australia to be in confident in the information on tsunami hazard that it provides to emergency managers around Australia and the region the methodology needs to be validated against observational results. This study has compared satellite altimetry, post-tsunami surveys and tide gauge observations from the 2004 Indian Ocean Tsunami to results obtained from the coupled URSGA and ANUGA model that Geoscience Australia uses to compute tsunami hazard.

Results show that the URSGA deep water propagation model reasonably reproduces the timing and amplitude of the first tsunami wave, but does not sufficiently reproduce near source reflections from Aceh Peninsula. In regard to detailed inundation models, the full hazard model coupling URSGA and ANUGA matches the timing of the first tsunami arrival at Geraldton but is unable to match the waveform of a tide gauge located in Geraldton harbour. When the run up heights are compared to wave heights from anecdotal evidence in a post-tsunami survey results it is shown that the model performs well. Misfits range from 1 cm – 17 cm for marinas and harbours in Geraldton to 28 cm along beach profiles located north of Geraldton. However, the beach survey data was from observational evidence some nine months after the tsunami so this data may be less reliable.

This study has also highlighted areas that could be improved in the current modelling methodology. These include adding the ability to model physical dispersion in the URSGA code and including a temporal tidal factor to ANUGA. This work has also laid the foundations for similar validation studies in other areas in Western Australia for the IOT event.

Acknowledgements

Data used in this study was supplied by the Western Australian Government. The Department of Transport supplied the bathymetry data and Landgate supplied the digital elevation model. The authors would also like to thank David Burbidge for assistance with the URSGA model and other colleagues at Geoscience Australia for feedback on a draft of this manuscript.

Appendix 1: Boundary Conditions in ANUGA

A small synthetic study was completed as part of this project to investigate the influence of different boundary conditions on ANUGA results. This was driven by the thought that the Dirichlet boundary conditions that have previously been used on the sides of the model, where no wave data is available, are causing the models to 'lose water', or in other words, that waves at the boundary are attenuated due to peaks being dragged towards the mean value applied applied by the Dirichlet boundary condition. In addition to Dirichlet boundary conditions, ANUGA allows the user to select transmissive, reflective or time dependent conditions. This study investigates the effects on the model using Dirichlet (Bd) and Transmissive (Bt) boundary conditions.

A simple beach run up model was set up that included a shallow sloping beach (in the x direction) which has two convex embayments that are designed to replicate headlands and cause some off axis reflections (Figure A1). Initially a model was run that has the y-axis 30 times longer than the x-axis. This is called the large model and is the benchmark model because the boundaries are so distant from the centre of the model that they should have no influence on the centre. A tide gauge is located between the two embayments to record wave heights. The two boundary conditions were used on the large model (Bd and Br) and produced identical results for the tide gauge located in the centre of the model, hence it is concluded that with a side boundary located some distance from the centre of the model that boundary conditions do not influence the centre of the model. The problem is that ANUGA models are typically computationally intensive and it is not feasible to have such a large model when modelling a typical tsunami scenario.

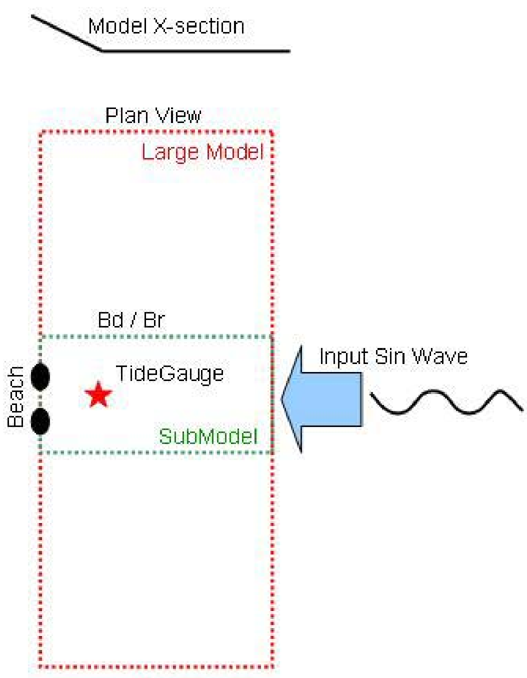


Figure A1: *Schematic of the model setup. The y-direction of the large model is 10 times as large as the submodel distance from the tide gauge.*

Next a series of smaller models were created that had the side boundaries located much nearer to the centre of the model. Three models were run, one for each of the boundary conditions.

The results from the tide gauge from each model were compared to the tide gauge from the large model (Figure A2). It is evident that the transmissive boundary of the small model best fits the large model that has no boundary influences whereas the Dirichlet boundary actually causes the model to have lower wave heights due to its inherent averaging. This shows that transmissive boundaries are the most suitable to use as they do not influence the model results. It is recommended that all future models use a transmissive boundary for the side boundaries where wave data is absent.

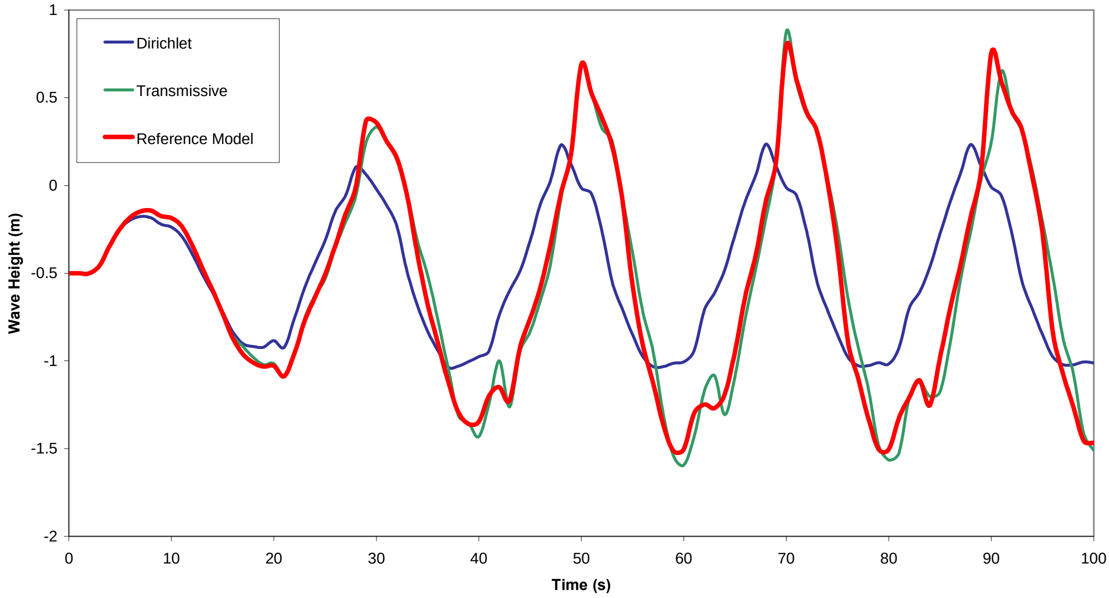


Figure A2: *Comparison of the effect of boundary conditions on a tide gauge located in the centre of the model. It is evident that a transmissive boundary best replicates the waveform from the large reference model, where boundary conditions do not influence the model.*

Appendix 2: DVD

The accompanying DVD contains all instructions for installing ANUGA as well as all data and scripts necessary to repeat the ANUGA inundation component of this validation study. Time series of the offshore tsunami from the URSGA model are also given for the entire Western Australia coast.

Data provided on the DVD includes:

- Geoscience Australia Record 2010/01 Tsunami modelling validation: the impact of the 2004 Indian Ocean Tsunami on Geraldton, Western Australia
- Field observations collected from the Western Australian coast following the tsunami
- Model outputs including:
    - Mux files containing time series of the tsunami for offshore Western Australia
    - CSV files containing time series of wave height and momentum for specific locations in the inundation model
- Combined elevation data used by the simulation. Bathymetry data was supplied by the Department of Transport in Western Australia and a 1 m resolution onshore DEM was supplied by Landgate. Data is provided for non-commercial use only.
- The Python scripts used to run the models.

If the DVD does not autostart and display a browser page, open the file index.html. contained on the DVD.

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