Risk Assessment and reduction: Earthquake and Tsunami Science Review, Tsunami Hazard and Risk

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GNS Science
Overview

1. Tsunami threats: recap
2. Science Review
3. Hazard and Risk Assessment
4. PTWS Plans and Strategy
Tsunami Source Categorisation

- **Distant Source** – travel time > 3 hours
  National Warning System

- **Regional Source** – travel time 1–3 hours
  National Warning System + Informal Evacuation

- **Local Source** – travel time less than 1 hour
  Self Evacuation (Natural Signs)
Tsunami Warning System in New Zealand- earthquakes

- **Local**: < 1 hr
- **Regional**: 1-3 hrs
- **Distant**: > 3 hrs
Tsunami Sources (1)

Events that are capable of generating tsunamis by suddenly displacing a large volume of water over a sufficiently large area include:

- **Earthquakes**

  Large submarine or coastal earthquakes in which significant uplift or subsidence of the seafloor or coast occurs.

- **Tsunami Earthquakes**

  ‘Slow’ earthquakes characterised by long rupture durations, slow rupture speeds and low angle thrust mechanisms that occur within 10-20 km of the subduction front at shallow depth.
Initiation, Propagation, Inundation
Tsunami Sources (2)

• Landslides

Underwater landslides and large landslides from coastal or lakeside cliffs, which may be triggered by an earthquake or volcanic activity.

• Volcanoes

Volcanic activity, for example, under-water explosions, eruptions or caldera collapse, pyroclastic flows and atmospheric air-burst over the ocean.

• Bolides (asteroids or comets)

Splashdown or an atmospheric air-burst over the ocean.
Tsunami Wave Speed & Shoaling

- Depth: 4000 m
- 213 km
- 23 km
- 50 m
- 10 m
- 10.6 km

<table>
<thead>
<tr>
<th>Depth (meters)</th>
<th>Velocity (km/h)</th>
<th>Wave length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7000</td>
<td>943</td>
<td>282</td>
</tr>
<tr>
<td>4000</td>
<td>713</td>
<td>213</td>
</tr>
<tr>
<td>2000</td>
<td>504</td>
<td>151</td>
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<td>200</td>
<td>159</td>
<td>48</td>
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<tr>
<td>50</td>
<td>79</td>
<td>23</td>
</tr>
<tr>
<td>10</td>
<td>36</td>
<td>10.6</td>
</tr>
</tbody>
</table>
Tsunami Intensity versus Earthquake Magnitude

Other factors:
Earthquake location
Earthquake depth
Earthquake mechanism
Based on shallow thrust assumption
Mwp=8.66 (initial PTWC Magnitude)

USGS (Gavin Hayes)
Wphase CMT: Mw=8.57 (Strike-slip)

The initial PTWC magnitude is larger than that of the USGS CMT magnitude, but the major difference between the two runs are focal mechanisms: thrust vs. strike-slip.
The Earthquake

Magnitude: $M_w$ 8.1
Location: 15.509°S 172.034°W
Depth: 18 km

185 km ENE of Hihifo, Tonga
190 km S of APIA, Samoa
710 km NNE of NUKU'ALOFA, Tonga
2700 km NNE of Auckland, New Zealand
Numerical simulation
Deep-ocean tsunami wave measurement (ocean floor pressure gauge) - model with a single normal fault

- Shaking of ocean floor by surface waves

Graphs showing observed and modelled data for different DART numbers.
Ocean floor tsunami recordings, with a model that uses both a normal fault and a thrust fault. A good fit.
A normal-faulting earthquake within the Pacific Plate and a nearly simultaneous thrust faulting earthquake on the interface between the subducting Pacific Plate and the Tonga microplate above.

Using land-based GPS measurements on an outlying Tongan Island, and tsunami wave measurements from ocean floor sensors in the Pacific Ocean, scientists have deduced that the tsunami that devastated Samoan and northern Tongan islands on 29 September 2009 was caused by two nearly simultaneous earthquakes, not one as previously thought.
Samoa
Greatest impact on Upolu
Max. runup: 12 m at Lalomanu
Max. flow depths: 4.5-5 m
Max inundation: 330 m
American Samoa

Max runup: 17.6 m at western tip of Tutuila
Max inundation: 500 m (up river valley) (Okal et al. SRL. Vol. 81, 2010).
Greatest flow heights recorded from the tsunami.

Inhabitants all on the leeward (western) side of the island. Tsunami flow heights decreased by ~½ and villages protected by 1km-wide reef.
Wallis & Futuna
Max. runup 4.5 m
Max. inundation 95 m
Max. flow depths 3.8 m
No warning
Minimal damage
(Lamarche et al., 2010, Marine Geology. Vol. 271, 297-302.)
Chile Tsunami: 27 February 2010

- Mw 8.8 earthquake (5th largest earthquake since 1900).
- Tsunami warning issued throughout the Pacific Ocean region.
- Tsunami caused substantial damage and loss of life in Chile where at least 800 people are reported dead.
- Wave of 2.6 m amplitude recorded on offshore tide gauge in Valparaiso, Chile.
- Rumours of very large waves on Juan Fernandez islands.
2010, Mw 8.8 – NOAA model
1960, Mw 9.5 – NOAA model
Numerical Model of the Tsunami from the Japan Earthquake

2011-03-11 Japan Tsunami (cGPS by Laura)
Quick Statistics

**Earthquake size and source:**  M8.9, near east coast of Honshu Japan

**Time of earthquake:** 1846 NZDT 11/03/2011

**First estimated tsunami arrival time in NZ:**  0623 NZDT 12/03/2011 (North Cape)

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### Tsunami Threat Level Map

**NOTE:**

1. The stated threat levels may apply to any one of the series of waves generated by the event and not necessarily to the first wave. The first wave is not always the largest or highest and waves are likely to continue for many hours.

2. The threat levels suggest the largest wave at any coastal point inside the zone. Wave heights will vary within a zone.

3. The amplitudes do not include the tidal state (sea level) at the time the wave reaches the shore.

4. The estimate is for the maximum expected wave amplitude at shore. Run-up can be up to twice as high on steep slopes onshore near the coast, i.e. a wave measuring 5m at shore can run-up as high as 10m on-shore near the shore.

5. The colours used to illustrate threat levels do not relate to the colours used for evacuation zones (red, orange, yellow – see Tsunami Evacuation Zones DGL003/08, MCDEM).

6. The expected wave amplitudes (crest to sea level) at the shore are likely to be different to measurements given in PTWC bulletins. PTWC measurements are taken at sea level gauges in the open ocean or at coastal points off shore from New Zealand. MCDEM information represents the official threat estimates.

<table>
<thead>
<tr>
<th>Maximum expected amplitude at shore</th>
<th>Threat definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20cm</td>
<td>No threat</td>
</tr>
<tr>
<td>20cm-1m</td>
<td>Threat to beaches, harbours, estuaries &amp; small boats</td>
</tr>
<tr>
<td>1m-3m</td>
<td>Minor land threat</td>
</tr>
<tr>
<td>3m-5m</td>
<td>Moderate land threat</td>
</tr>
<tr>
<td>5m-8m</td>
<td>High land threat</td>
</tr>
<tr>
<td>&gt;8m</td>
<td>Severe land threat</td>
</tr>
</tbody>
</table>

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Last updated: 0020 NZDT 12/03/2011
People rush to beaches and wharves for a good view of the expected tidal wave.

"I'll never get a shot like this again!"
Implications

- Recent large subduction zone earthquake have raised many questions about our understanding of how these systems work.
- Why do big subduction thrust earthquake break large areas of the plate interface, even through “non-locked” regions?
- Global seismology can usually work out the important details of a large earthquake very soon after it happens, but there are notable exceptions.
- How do we prepare for these very infrequent but very destructive tsunami?

- PTWS has plans and strategies built on “three pillars”, with matching Working Groups and Task Teams.
- It is important we get on preparing our communities and not wait for the “perfect” science answers!
Tsunami Risk

The graph illustrates the recurrence interval (years) of tsunami events versus the height of the tsunami in meters. Different sources of tsunami risk are shown:

- **Distant Earthquakes**
- **Local Earthquakes**
- **Volcanoes**
- **Landslides**
- **Asteroid Impact**

The recurrence interval decreases as the height of the tsunami increases for each category.
Potential Tsunami Threats to New Zealand

- Distant/Regional Earthquakes
- Local Earthquakes
- Landslide zones
- Volcanoes
Historical Tsunami in New Zealand

Maximum run-up:
- 10 m or more
- 6 m or more
- 4 m or more
- 2 m or more
- less than 2 m

LOCAL SOURCE:
- 1830s
- 1848
- 1855
- 1872
- 1874
- 1881
- 1882
- 1883
- 1913
- 1924
- 1929
- 1931
- 1947
- 1949
- 2009

DISTANT SOURCE:
- 1868
- 1877
- 1883
- 1912
- 1960
- 1964
- 1977
- 2001
- 2010

GNS Science
Potentially tsunamigenic events since 2001

On average two per year

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>Peru</td>
<td>8.4</td>
</tr>
<tr>
<td>2003</td>
<td>Fiordland</td>
<td>7.2</td>
</tr>
<tr>
<td>2004</td>
<td>Puysegur</td>
<td>7.1</td>
</tr>
<tr>
<td>2004</td>
<td>Macquarie Ridge</td>
<td>8.1</td>
</tr>
<tr>
<td>2004</td>
<td>Sumatra</td>
<td>9-9.3</td>
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<tr>
<td>2006</td>
<td>Tonga</td>
<td>8.0</td>
</tr>
<tr>
<td>2006</td>
<td>Kuril Islands</td>
<td>8.3</td>
</tr>
<tr>
<td>2007</td>
<td>Kuril Islands</td>
<td>8.1</td>
</tr>
<tr>
<td>2007</td>
<td>Peru</td>
<td>8.0</td>
</tr>
<tr>
<td>2007</td>
<td>Solomon Islands</td>
<td>8.1</td>
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<tr>
<td>2007</td>
<td>Auckland Islands</td>
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<td>2009</td>
<td>Fiordland</td>
<td>7.8</td>
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<td>8.3</td>
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<td>2009</td>
<td>Vanuatu</td>
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<tr>
<td>2010</td>
<td>Chile</td>
<td>8.8</td>
</tr>
<tr>
<td>2011</td>
<td>Japan</td>
<td>9.0</td>
</tr>
</tbody>
</table>
2010, Mw 8.8 – NOAA model
Three options for natural disaster risk reduction:

1. **Modify the process**
   - Restore dunes
   - (sea-walls for tsunami – **not recommended**)!

2. **Modify human activity**
   - Land-use planning and building codes
   - Can in theory remove **all** risk

3. **Accept the damage and warn people**
   - Still allows residual risk,
   - hard to achieve high effectiveness
   - **Permanently-sustained community preparedness is needed**
5 Steps to Effective Early Warning Systems within Resilient Communities

1. Early Warning System
   Hardware, electronics, communications and planning necessary to effectively detect a hazard, generate a warning message and transmit them to at-risk regions (including any use of public notification hardware). Multiple channels with consistent, officially-verifiable message.

2. Planning
   Decision-making tools: thresholds, evacuation routes and maps, inter-organisational relationships and communication channels.

3. Co-operation, Discussion & Communication
   Pre-planned and exercised communication between central government agencies, local emergency management agency staff, scientists, media and community representatives. Renewal of contacts must be regular and permanently sustained, to overcome common high staff turnover.

4. Education & Participation
   Public education, staff training, maps, and signs. Designed with the community.

5. Exercises
   Scenario development and simulations - table-top and preferably full, with observation and feedback.

Leonard et al. (2007)
Tsunami Inundation

• The water may recede before inundation takes place.

• The nature of inundation varies considerably according to both the shape of the approaching wave and the topography.
  – In some cases the water level just steadily rises,
  – in others there is a steep-fronted wave and a sudden torrent of water.

• Velocities can exceed 50 km/h (observations range from 10-75 km/h).

• There will be several waves (surges), the first is unlikely to the largest.

• Debris entrained in the flow can significantly affect the impact.
New Zealand evacuation mapping guidelines

Mangawhai: A starting map ready for local details and evacuation routes

Whananaki: A complete map with local details, evacuation routes and signs planned
Three coloured zones recommended as a guideline:

- **Red zone**: a shore-exclusion zone that can be placed off limits in the event of any expected tsunami.

- **Orange zone**: is intended to be evacuated in most if not all distant- and regional-source official warnings that extend beyond the red zone.

- **Yellow zone**: allows for all local-source expected events. It is very unlikely that an event will inundate much of this zone in a person’s lifetime.
Ladder of four ‘development rungs’ for improving evacuation zone boundaries over time

We should be looking to work our way up the ladder, improving development of boundaries over time:

- **Rung 1**: Bathtub inundation (ie. up to a specific elevation)
- **Rung 2**: Approximation by a rule (can be prepared in GIS) – allowing for drop-off inland from the coast. (see diagram below)
- **Rung 3**: Simulation model to do the below better, e.g. water is able to turn corners, slosh around
- **Rung 4**: An envelope around all inundations from multiple (many?) well-tested computer models
Rung 1: Bathtub

Sharp elevation +/- distance cut-off criteria

Zone continues if no distance cut-off is used ie. ‘Bathtub model’
Rung 2: GIS-calculated rule

Criteria that allow for attenuation

Line slope = 1m decrease inland every 200m (up river = 1m decrease every 400m)

Line slope = 1m decrease every 50m away from river edge
GIS-CALCULATED ATTENUATION RELATIONSHIP

(1) It is better to make maps that can be used now and improve them than wait for science to improve.
(2) We need to allow for all of the many sources, many characteristics for those sources, and uncertainty in models of source, deep water propagation, shallow water propagation and inundation.
(3) Current elevation datasets available are variable in accuracy and precision.
(4) A conservative approach is needed – zones need allow for a margin of safety and their boundaries can be redefined over time, but should only shrink over time.
Pillar 1: Risk Assessment and Reduction

- Internationally coordinated post-tsunami surveys are effective in providing data to understand impacts and calibrate forecast models.
- There is still a lot to learn about large subduction zone earthquakes and their potential to generate tsunami. If the “slow” subduction thrust had not been accompanied by the normal faulting event, would any warning have been given?
- Forecast models are becoming very important to tsunami response and impact estimation. The usual methods of estimating arrival times (e.g. TTT) can be a long way out because of the effects of deep ocean trenches and ridges.
- The various forecast models in use need to be rigorously compared to give confidence in their validity.
- Currently, risk estimates are based on too little history!
Pillar 2: Detection, Warning and Dissemination

- Detection, warning and dissemination all need to be improved, particularly for regional and local events.
- The SWP region needs more sensor sites. A PTWS Task Team (under WG2) is making progress on seismic sites. Do we need a similar effort for sea level?
- Warnings need to be faster and be based on forecast models (threat levels and coast zones). We need to both simplify and use newer technology for warning message content. This work is underway and progressing (a Task Team under WG2).
- Dissemination systems (particularly the last kilometre) remain a problem in the SWP region. A PTWS Task Team (under WG2) is working on this. How do we notify people at risk in varying situations (from large cities to remote islands)?
Pillar 3: Awareness and Response

- Recent tsunami demonstrated the success of public education campaigns, but also the reverse.
- The adoption of community based evacuation zones and routes (with sign posting) would greatly improve the effectiveness of tsunami response in the SWP region.
- This fits in well with the move to forecast model based threat levels for pre-defined coastal zones. This approach needs to be rolled out in the SWP region.
- Training must be an important part of the process of moving to a threat level based system using forecast models for coast zones (levels of threat from a particular event).
- How do we sustain the required high levels of awareness required over the long term?
PTWS WG1: Risk Assessment and Reduction ToR:

1. Review and report on existing arrangements with regard to tsunami hazard identification and characterization

2. Advise on credible seismic scenarios that need to be captured for numerical tsunami modelling e.g., location, magnitude, rupture, orientation, dip, and probability of occurrence

3. Review details on models that are currently used or in development and desirable standards of documentation (model inputs and outputs etc.)

4. Explore cooperation regarding coastal inundation models, including appropriate requirements for bathymetry

5. Develop guidance on mandatory metadata including details of bathymetry, hydrography and topography

6. Consider the issue of assessing hazard, vulnerability and risk, including the facilitation of access to models and mitigation measures

7. Liaise with Working Groups from the other ocean basins, as well as other working groups within ICG/PTWS to coordinate and ensure efficient and effective information for tsunami warning and mitigation.
<table>
<thead>
<tr>
<th>Actions in Risk Assessment and Reduction</th>
<th>Perform Indicators</th>
<th>Benchmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PTWS countries should complete their tsunami risk assessment taking into account existing information and data from other relevant studies.</td>
<td>Tsunami risk assessment report</td>
<td>By end of IP period, countries have completed at least 50% of this work</td>
</tr>
<tr>
<td>2. PTWS countries should provide tsunami event data to the World Data Center in order to improve the global tsunami historical database</td>
<td>Increase in amount of data</td>
<td>By end of IP period, countries affected by a tsunami have submitted data to WDC</td>
</tr>
<tr>
<td>3. PTWS countries should, or where applicable support, the update of existing or development of new tsunami inundation maps for vulnerable communities identified by risk assessment studies.</td>
<td>Inundation map</td>
<td>By end of IP period, at least 50% of countries with the need to have at least preliminary maps have maps in place.</td>
</tr>
<tr>
<td>4. Provide opportunities for countries to build their capacity to be able to conduct their own risk assessments. Such training could include, but is not limited to, tsunami numerical modeling and production of inundation maps. Based on identified needs, priority should be given to trainees from countries located in Central America, South West Pacific and South East Pacific, and South China Sea.</td>
<td>Number of trainings and trainees trained</td>
<td>By end of IP period, 50% of countries listed have had at least 5 personnel trained.</td>
</tr>
<tr>
<td>5. PTWS countries should continue to improve their tsunami hazard database through paleotsunami studies that can extend the historical tsunami record back in time. and with each tsunami, the conduct of post-tsunami field surveys to document the event. International collaboration to build national capabilities is encouraged.</td>
<td>Number of studies completed</td>
<td>By end of IP period about 30% to 50% of given number requested studies completed</td>
</tr>
</tbody>
</table>