Stage 4: Inundation Modelling and Evacuation Mapping Report for Samoa

Filling a critical gap in end-to-end tsunami warning in the Southwest Pacific: a pilot project in Samoa to create scientifically robust, community-based evacuation maps

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1.0 INTRODUCTION

Tsunami inundation modelling suitable for evacuation has been conducted during Stage four of the NZ Aid Programme funded Samoa tsunami evacuation planning project. Mapping has been undertaken in accordance with national guidelines developed in New Zealand for tsunami evacuation mapping. Zones are also been delivered as GIS datafiles on compact disc.

The objectives of this report are to:

1. define the method by which zones have been delineated;
2. explain the basis for elevations used to define those zones; and
3. document known limitations to the method and a recommended course for improvement over time.

2.0 WAVE HEIGHTS AT THE COAST

For the purpose of this study we need to derive evacuation zones suitable for two circumstances:

- A self-evacuation (‘yellow’) zone encompassing all areas believed to be at risk of tsunami inundation following a strongly-felt earthquake
- A warned evacuation (‘orange’) zone encompassing all areas believed to be at risk of tsunami inundation following earthquakes that are too far away to be strongly felt.

In practice there always exists the possibility of extreme, but rare, events larger than those considered here. While this is not a probabilistic study, the aim has been to consider events that may be considered a realistic threat on time frames of up to 2500 years.

In addition to the above a ‘red’ zone is drawn for the purposes of highlighting danger areas in the event of a smaller tsunami that poses only a ‘marine threat’.

For the purposes of our method for evacuation zoning we require estimates of the maximum realistic near-shore tsunami amplitude for each section of coast, or alternatively an estimate of the maximum potential onshore run-up height. We derive this information from both tsunami scenario models and historical analogy.

When considering tsunami scenario models it is important to bear in mind that the modelled scenarios only represent a few examples from a wide spectrum of possible scenarios. There is an important step of generalisation from the individual models to the distribution of maximum tsunami heights used to define the evacuation zones.

Report Two on Tsunami sources of relevance to Samoa, identified nine distant source scenarios, three regional (SW Pacific) source scenarios, and eight local source scenarios as of particular importance. Of these, the local scenarios were assumed to be accompanied by
strong-shaking and therefore contribute to the definition of the ‘yellow’ zone for self-evacuation; while the distant and regional scenarios provided examples of unfelt events used to define the ‘orange’ zone. Note that it is not certain whether or not large subduction zone earthquakes in the New Hebrides would be strongly felt in Samoa (see Report Two for location and distance), but it seems most likely that they would not, and this is the safer assumption.

2.1 Wave height modelling

Tsunami modelling was done with the COMCOT program. COMCOT models tsunami by solving the linear and non-linear shallow water equations on a system of nested grids. The nested grids allow for greater detail around areas of interest, in this case the islands of Samoa, while allowing a coarse grid to be used over the deep ocean to save computational time. Bathymetry data was combined from ETOPO digitised nautical charts and SOPAC survey data. Reefs were not incorporated due to a lack of high quality data, it was feared that incorporating poor quality reef bathymetry could lead to underestimation of tsunami hazard in the vicinity of unmapped reef channels.

The grid setup for the distant source scenarios is shown in Figure 1a, and that for the local and regional scenarios in Figure 1b. The nonlinear equations were solved within the innermost grid, and the linear shallow water equations in the outer grid layers. A vertical wall boundary condition was imposed at the shoreline.
Figure 1 Nested grid setup for a) Distant, and b) Local and Regional source scenarios. A finer grid is used within areas indicated by boxes.

For the distant source scenarios it was found that the maximum offshore wave amplitudes were up to 8m in the more severe scenarios. Moreover, the locations which showed the highest amplitudes varied considerably from scenario to scenario. Since we have not simulated a comprehensive set of all possible scenarios we need to assume that similar wave amplitudes may be reached in other areas from similarly large sources. The largest regional scenario, a Mw 9.4 earthquake on the New Hebrides trench, also produced maximum amplitudes of up to about 8m.

Two areas within the island of Savai’i did consistently show low amplitudes at the coast in our scenarios, but investigation of these coasts showed that they were in areas where our modelled bathymetry was extremely steep right up to the shoreline (it is unclear whether the actual bathymetry is truly like this, or that such steepness very close to the shore in the model is a result of the lack of chart data and consequent interpolation). In such circumstances the spacing of our finest grid still leaves the nearest offshore grid cell at depths from which further shoaling can take place. Hence we could not conclude that these areas were truly safer than other coasts from unfelt tsunami sources.

Of the local (i.e. strongly-felt) scenarios, it was those in the outer rise of the Tonga Trench (similar to the 1917 and 2009 earthquakes) that produced the largest wave amplitudes. The highest amplitudes were always found to be along the south coasts of Upolu and Savaii, with less impact on the north coast. The two most severe scenarios were ‘upscaled’ versions of the 1917 and 2009 earthquakes, and these most strongly impacted the western and eastern parts of the Samoan islands respectively. In drawing evacuation maps we need to bear in mind that these scenarios are part of a continuum of possible fault sources which could be oriented towards any particular part of the south coast. Hence we assume the maximum
heights from these scenarios could occur at any location on the south coast.

The scenarios provided by Report Two were based on the assumption of uniform slip. Variants of the ‘upscaled’ 1917 and 2009 scenarios were modelled in which the seismic moment was kept constant but the slip was concentrated into smaller sub-regions. It was found in these examples that non-uniform slip could increase maximum wave amplitudes by ~50% in some locations.

### 2.2 Historical analogies

Before discussing historical data we should clarify the assumed relationship between the maximum offshore wave amplitude and the maximum potential run-up. We assume that the maximum potential run-up is twice the maximum offshore amplitude. This is essentially a conservative assumption: in most situations we would not expect to find such a large increase, since the situations that lead to the greatest increase in run-up over shoreline height are rarely found. Since our model does not identify those locations, we assume they could occur anywhere, however our GIS technique does allow for the observation that run-up heights typically decrease with distance from the coast (Section 3.4; Appendix 1). We also note that high run-ups may also be caused by the effects of small-scale bathymetric features not present in our tsunami model.

The historical record for Samoa is relatively short compared to the recurrence time of the largest tsunamigenic earthquakes. In 1917 a tsunami originating from an earthquake south of Samoa, probably on the outer rise of the northern part of the Tonga Trench (Okal et al, 2011), had a maximum recorded run-up of 12.2m (NGDC database) on the south coast. In 1960 the great Mw9.5 Chilean earthquake produced maximum run-ups on Upolu of 4.9m (NGDC database), although it should be noted that the greatest tsunami energy from this event passed further north towards Hawaii and then Japan. In 2009 a pair of simultaneous Mw~8.0 earthquakes, one on the Tonga Trench subduction zone and one on the outer rise, caused a tsunami that most strongly affected the southeast corner of Upolu; the maximum reported run-up was 14.5m (NGDC database).

As it is intended that the evacuation zones should cover the largest events on a ~2500 year timescale it is appropriate to look beyond the Samoan historical record and consider historical events at other locations that we consider analogous to the most severe events that we believe could occur on Samoa over such a timeframe.

A useful analogue for the maximum distant source event comes from the impact of the 1960 Chile tsunami on Hawaii. Hawaii is close to the path of maximum energy in this event, which was caused by the largest instrumentally recorded earthquake (Mw 9.5) and produced arguably the most powerful recorded tsunami (Mt 9.4). Hawaii is also a good analogue since it is a cluster of volcanic islands of broadly similar size and shape to Samoa. Hilo, Hawaii, was the most strongly hit location; the maximum recorded water level was 10.7m (NGDC database). This was apparently a flow height rather than a run-up height (Eaton et al, 1961) – implying that when the water passed this point it still had some kinetic energy and so a higher run-up height may have been possible in a different topography. In most other parts of Hawaii the maximum recorded water levels were less than 5 m (NGDC database).

Hawaii is again useful when looking for analogues of regional source tsunami. Here we are looking for circumstances similar to those that Samoa would experience in a tsunami caused
by a Mw>9 New Hebrides earthquake. We propose the impact of the 1946 and 1957 Alaska-Aleutian tsunamis on Hawaii as near equivalents. The Aleutians are further from Hawaii than Samoa is to the New Hebrides, but this is counterbalanced by the lack of scattering bathymetric features in between, i.e. the bathymetry between the New Hebrides and Samoa has more islands and other bathymetric features that are likely to diffract the tsunami energy.

The source of the 1946 tsunami was an earthquake near Unimak Island in Alaska with Mw 8.1, but with Mt 9.3 (Abe, 1989) making this a ‘tsunami earthquake’ i.e. an earthquake that produced a particularly large tsunami for its magnitude. The maximum run-ups on the Hawaiian Islands were in the 16-17m range (NGDC database), with quite a wide geographical spread of locations experiencing run-ups in the 10-14m range (NGDC database).

The 1957 tsunami was caused by a Mw8.6 earthquake in the Andreanof Islands; the tsunami magnitude was Mt 9.0. The largest run-ups in the Hawaiian Islands were 16.2 m on the island of Kauai (NGDC database). While these maximum run-ups were comparable to the 1946 tsunami they were more localised: on islands other than Kauai the maximum run-ups were up to 10m (NGDC database).

For local source tsunamis a maximum run-up of 35 m is often assumed for coasts exposed to major subduction zones based on the distribution of run-up heights in past events. Situations where run-ups from seismic tsunami sources have exceeded 35m are rare exceptions, and appear to involve steep submarine v-shaped valleys close to the coast into which a tsunami becomes funnelled following the very largest events. In the 2004 Indian Ocean tsunami such a situation occurred at Riting in northern Aceh, Indonesia, where the tsunami passed over a saddle at an elevation of about 50m. A few examples of run-ups over 35m are emerging from the 2011 Japan tsunami in similar circumstances. However, these are very much the exception, occupying a very tiny fraction of the inundated area. These exceptions pose a dilemma for planners taking an empirical approach to evacuation zoning, as to accommodate them would result in a great increase in the total number of people displaced and the distance they would have to travel to evacuate.

In the case of Samoa the islands are not oriented in such a way as to receive the maximum tsunami impact from a putative Mw>9 Tonga Trench subduction earthquake. The largest events posing a threat to Samoa appear to come from outer rise events. Globally, the largest outer rise events do not appear to quite match the impacts of the largest subduction interface earthquakes – though care must be taken of the fact that the sample size of outer rise events is much smaller. The 1933 Sanriku tsunami was caused by an outer rise earthquake and had a maximum run-up of 28m.

Tsunamis caused by landslides should be given some consideration as they are frequently triggered by strongly-felt earthquakes, and may strongly affect coasts that are otherwise less vulnerable to conventional earthquake-caused tsunamis. Landslide tsunami sources are unfortunately a source of much uncertainty, as almost none are well understood and quantified. A recent tsunami widely believed to have been caused by a landslide is the 1998 Papua New Guinea (PNG) tsunami, which affected the north coast of PNG following a Mw7.1 earthquake. The Maximum water height reported in that event was 15m (NGDC database). For submarine-landslide generated tsunamis in a comparable geological setting to Samoa we again look at events in Hawaii, where tsunami believed to be predominantly generated by landslides occurred in 1868 and 1975, with maximum run-up heights of 13.7 and 14.3m.
respectively (NGDC database).

### 2.4 Combined assessment

The tsunami modelling and historical analogies were used to assess the maximum wave heights for different regions of the coast. In using the model results it was borne in mind that the provided scenarios represent only a sample of the range of possible events, and that non-uniform slip also contributes variability to the possible tsunami heights. The historical analogues were viewed as complementary to the tsunami modelling, and were generally consistent with it.

The assessment for unfelt distant and regional sources was that evacuation mapping for all parts of Samoa should assume an 8m amplitude wave just offshore, with potential run-up to 16m.

The assessment for felt local events is summarised in Figure 2.

![Figure 2](image)

**Figure 2** Assessment of maximum heights (m) for local source evacuation mapping – maximum offshore wave amplitudes, and maximum potential run-up heights in brackets.

### 3.0 INUNDATION ZONING

This report follows and updates the methodology as laid out in Leonard et al. (2008)

#### 3.1 Input data

The primary input data are:

- a Digital Elevation Model (DEM);
- natural feature coastline;
- Wave heights as described in Section 2.1;
- High tide value estimated from Nautical Charts; and,
- A river polygon digitised from Google Earth images and modified to fit the 2m contours.
The inundation modelling requires a good DEM in areas below 40m elevation but for display purposes a continuous elevation model across the four islands was derived. The DEM was produced as an ESRI format GRID with 10m horizontal grid spacing by using the Topogrid tool in ArcGRID. The input features for elevation modelling were contours, spot heights and coastline.

The dataset provided by the Ministry of Natural Resources and Environment (MNRE) consisted of 2m contours for majority of coastal area, 20m contours elsewhere, some spot height data and a coastline. The 20m contours were supplied without height attributes and these were added up to 120m elevation and used for generating DEM. Above 120m the input contours were derived from the initial DEM also supplied by MNRE.

The GPS data collected during the Stage Three fieldwork was used to check the existing contours. In some areas, where the differences between these were significant, contours were modified to fit the GPS data. Some GPS points collected on flats were also used as spot height input data to elevation modelling.

The coastline was used as a zero contour in the modelling of topography and it was slightly modified prior to modelling to fit the 2m contours.

In general, the Topogrid modelling method does not handle well the areas with missing data or flat areas where contours are far apart. To avoid artefacts in the model, areas below 40 m elevation and without 2 m contour data were identified. The contours were manually interpolated in these areas from the surrounding elevation data (Figure 3). Additional contours were also used in some areas with sparse contours to force better modelling of flat areas, especially near the coast.

Figure 3 Pink indicated areas below 40m elevation not covered by 2m-spaced contours. Contours were manually interpolated in these areas.

3.3 Methods for delineating zones
The National Disaster Management Office should be looking to improve the method by which their evacuation zones are delineated over time. This can be achieved by aiming to progress through the following stages as maps are revised and science improves:
3.3.1 Level 1 Bathtub inundation
This method creates a zone that covers all ground up to a specific elevation. This does not adequately allow for the way tsunami inundation drops in elevation inland.

3.3.2 Level 2 Approximation by a rule
Maps can be prepared in GIS, allowing for drop-off inland from the coast. This method relies on probabilistic wave heights at the coast. The method used here constitutes a variation on a ‘Level 2’ method as applied in New Zealand since a full probabilistic model was not used, and is detailed in Section 3.4. Future improvement could constitute using a Level 3 or 4 method (see below).

3.3.3 Level 3 A more robust, simulation model to do the above
This method would constitute a more complex hydrodynamic model than that used here. For example it would be an advantage to (a) allow for water moving laterally ‘around corners’ as it moves inland, and (b) allow for variations in roughness of the land surface. The input would still be zone heights derived from a probabilistic model of expected wave heights.

3.3.4 Level 4 An envelope around all expected inundation scenarios
Ideally evacuation zones should be an envelope around all of the expected inundation patterns, of all of the tsunami that can be expected (including the full range of source parameters such as varied magnitude and displacement), from all credible sources. This would require well-tested accurate and precise models of inundation from all sources. The character of tsunami generated at those sources would also need to be well understood. This stage is theoretically feasible, but requires:

- High quality bathymetry data close to the islands, including the reefs
- High quality topographic data
- A complete geophysical understanding of the full set of possible sources, especially the local sources
- A lot of computational resources

3.4 GIS-calculated attenuation relationship
This section defines the purpose and method for using GIS to calculate an attenuation relationship into evacuation zones (Level 2 as per Section 3.3.2). This is an interim method designed to provide zones that can be used now with the understanding that the method by which zones are defined is to be improved over time (Section 3.3). This principle is based on the following premises:

(1) It is better to make maps that can be used now and improve them, than to 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.
3.4.1 Attenuation from the coast over land
This relationship is 0.5% height attenuation by distance (i.e. the maximum attainable water level reduces by 1 m for every 200 m inland) based upon attenuation and testing outlined in Section 4.5 and Appendix 1.

3.4.2 From the coast up significant rivers and lakes
This relationship is 0.25% height attenuation by distance (i.e. the maximum attainable water level reduces by 1 m every 400 m up-river). One river was identified near Salani that was considered wide enough to warrant separate up-river modelling.

3.4.3 Over-banks across land from rivers
This relationship is 2% height attenuation by distance (i.e. the maximum attainable water level reduces by 1 m every 50 m across land away from a river).

3.4.4 GIS workflow
The input data for GIS modelling consisted of:
- A Digital Elevation Model (DEM) in ArcINFO grid format
- A river grid created from a river polygon
- A sea polygon coverage created from the coastline and then converted to a grid to be used as a source of inundation. The sea polygon used as source for generating the yellow zone was divided in three parts that were used as sources for each of the wave heights.

The GIS procedure was conducted in two steps. Firstly a DEM was generated using the contour, spot height data and coastline as explained in Section 3.1. The resulting DEM was used, together with sea and river polygons, as input to the inundation mapping.

In the second step, tsunami warning zones were developed by running two Arc Macro Language (AML) scripts with ArcGIS Workstation 9.1 followed by some manual editing and processing of the outputs in ArcMap 9.3.1.

The concept of inundation modelling and GIS procedures used are explained below.

1. AML for calculating sea inundated areas
- Calculate attenuated relationship from the coast until it intersects topography and output the intersection as a polygon coverage for each zone type (orange or yellow)
- AML script is run once for the orange warning zone and once for each of the wave run-ups used for defining the yellow zone. The AML calculates attenuation in two steps. Initially it creates an inundation area using the Euclidean distance function (the shortest distance from the coast). This function creates some inundated areas behind the high ground as they are low and close enough to the coast to satisfy the attenuation rule even though, in reality, the water would not be able to go over hills. In the next step the script uses that inundated area to limit the surface over which the water can travel when the GRID Pathdistance function is run again. This forces water to go around the hills that were not inundated in the first step instead of going over them.
- The detached polygons produced by running the script are removed manually.

2. AML for calculating inundation up and from rivers
- Calculate inundation depth up the significant rivers using adequate attenuation relationship. The water depth along the river was calculated as the difference
between inundation height and elevation of the river extracted from the DEM. The inundation distance was defined by the intersection of the attenuated inundation and topography.

- Calculate over-bank inundation by attenuating water step by step from the river. The processing finishes when the water elevation intersects the topography as read from the DEM.
- AML script is run once for the orange warning zone and once for each of the wave run-ups used for defining the yellow zone. The detached polygons produced by running the script are removed manually.

After the sea and river inundation zones were produced as ArclInfo coverages they were converted to shapefiles and merged together. For the yellow zone, the outputs for different parts of the coast that were modelled with different wave heights were merged together first and then the river inundation polygon was added to it.

As the warning (orange) zone polygons were created by converting grids to vectors, the smoothing of zone boundaries had to be done in ArcMap. The zones were checked against each other and some modifications were required in the areas were zones were supposed to have common boundaries (e.g. cliffs).

The red zone was created as a polygon between the coastline and reef edge. To make sure that beaches and reef edge were covered by red zone, the coastline and reef polygon were buffered by 50m.

After all of the zones were created they were merged together into one shapefile.

All the processing was done with the data in the Western Samoa Integrated Grid (WGS72) projection. The projection of the final outputs was then redefined to the projection used by the Samoa MNRE Mapping Office, (_MI_O projection) and the shapefiles were converted to MapInfo format as well.

### 3.4.5 Calibration and testing of the model

The GIS script and attenuation relationship has been calibrated against real data where possible. However, there is only limited data on the height and area inundated from historic tsunami and only a few real datasets provide enough information for adequate checking. Examples we have investigated (with varying degrees of utility) include:

1. Banda Aceh following the December 26th 2004 tsunami in the Indian Ocean – Inundation up to 6 km inland (e.g. McAdoo et al., 2007) over relatively flat flood plains, with up to 35m run-up (Tsuji et al., 2006) on steep coastal topography at the coast nearby. This was used to estimate the 1:200 overland attenuation rate. Subsequently, aerial images were used to test that the evacuation zone defined by this rule was appropriate at intermediate distances (Appendix 1.1).

2. Java following a tsunami in 2005 (Cousins et al., 2006) – Due to the generally flat topography of the areas surveyed it was difficult to determine how high the tsunami would have run-up had it encountered a steep slope close to the shore (this is a common problem with validation of this model). Nonetheless the 1:200 rule appears generally to be adequate even if inundation height is used instead of run-up height near
shore\(^1\) (Appendix 1.2).

(3) The general inundation pattern at the Solomon Islands (Fritz and Kalligeris, 2008).

(4) Published survey data for Sri Lanka (various data; Wijetunge, 2006; Fritz, 2005), (Appendix 1.3).

(5) Okushiri, Japan (12 July, 1993; 35m max run-up). The 35 m run-up in the Monai valley of Okushiri Island is a possible exception to the assumption that the maximum run-up height can be up to twice the wave height at the coast. However it is noted that in the near vicinity of the Monai valley the run-up heights are still very large (20-25m), so it is unclear to what extent the exceptional 35m run-up in the valley is a consequence of on-land effects versus a particularly large wave at the coast (Appendix 1.4). This event exposes some limitations of the stage 2 approach (Section 2.3) as only a detailed numerical model would be likely to predict the effect of near-shore bathymetry near the Monai valley.

(6) 1700 inundation at Tsugaruishi (Atwater et al., 2005; 5m near-shore offshore wave, and therefore \(~10m\) assumed potential run-up, \(~2km\) inundation across gently sloping topography)

(7) 1960 inundation at Tanabe (Atwater et al., 2005; 3.7m elevation at shore onshore open coast, <400m inland from coast inside harbour)

(8) 1983 Japan Sea tsunami (Kajiura, 1986). The maximum run-up height in the Minehama area was 15.5m measured on an open-coast near-shore dune. Maximum run-in distance in this area \(~1.25km\) (Appendix 1.5).

3.4.6 Summary of limitations and cautions

- The method outlined here can and should be improved upon over time (Section 2.3).
- The wave heights used to define the zone sizes can and should be refined over time, ideally in a probabilistic model. This will require at least the following: improved source models, better near-shore bathymetry, more calibration data from real tsunami, and possibly improved tsunami inundation models.
- As new tsunami inundation data becomes available we may be able to further test and refine the attenuation rates used here (drop off per distance inland).
- We may also be able to revise over time, with more field data, the cross-sectional model of attenuation, which is currently linear, i.e. a set drop off per distance inland (e.g. Appendix 1.7).
- The evacuation zones are designed to encompass the range of inundation patterns for many individual possible tsunamis. Any one tsunami will not inundate a zone fully.
- The GIS modelling can only be as good at the elevation data on which it is based.

3.5 Orange Zone

The estimated maximum wave amplitude from unfelt regional and distant sources was used to define the orange evacuation zone. This is the zone which we may reasonably expect there to be official warning for now or in the foreseeable future.

3.6 Yellow Zone

The estimated maximum wave amplitude from all sources, including strongly-felt local sources, (i.e. maximum credible event) was used to define the yellow evacuation zone. This zone must encompass all credible tsunami, including those for which there will only be

\(^1\) Inundation height (i.e. maximum water level not measured at the horizontal limit of inundation) is generally less than the maximum potential run-up height at the same distance from the coast.
enough time for natural or informal warning.

Zones are capped at 35m because inundations above this elevation are extremely rare from subduction zone sources, and to take this remote possibility into account would cause over-evacuation in the vast majority of situations. This is from discussion of the data gathered to-date internationally from the deposits and impacts of past tsunami.

### 3.7 Red Zone

For the purposes of village consultations a reef and foreshore ‘red zone’ has been drawn. This may be used in final maps if its value is shown from village consultations in Stage 5. If the red zone is included, careful planning as to the nature of the event that triggers evacuation of the red zone will be needed, because specific wave heights are not currently contained in PTWC warnings. It may be decided, for example, with the NDMO that tsunami watches trigger a warning for the red zone. Future changes to PTWC warnings may mean that wave heights are forecast and it may then be easier to pre-set criteria for evacuation of the red vs. orange zone.

### 4.0 EVACUATION MAPPING

#### 4.1 Framework

It was decided during workshops with the NDMO and presentation to the DAC during the inception visit (Report 1), following from discussion at all meetings, that the following elements would be taken to the pilot villages as a draft concept:

- Three coloured evacuation zones (red, orange, yellow) based on the same criteria as the New Zealand Evacuation Mapping Guideline\(^2\)
- Roads may be overlain on zones if those roads are not clear enough from the air photos
- The maps will contain tsunami evacuation information in both English and Samoan language, including the core action message: “In a natural or informal warning evacuate all zones; in an official warning evacuate the zone(s) stated in the warning”. It was emphasised that the message must make it clear that when the orange zone is evacuated the red must also be evacuated, and when the yellow is evacuated all three must be evacuated.

For the background it was planned to use 1999 aerial photographs at inception stage, however, Quickbird satellite imagery has been able to be obtained for US$3 per square kilometre for the purposes of tsunami evacuation mapping in Samoa. This is post-2009 tsunami and better represents the coastline as it is now.

In general the orange and red zones can be linked to official warnings from PTWC, whereas local sources should trigger evacuation of the full yellow, orange and red zones – where the yellow zone is present.

Ongoing discussion with the NDMO and villagers during Stage 5 will now refine the exact information to be displayed on village maps and map layout and design. It is recognised that with both English and Samoan language included, the area available for text is reduced so

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\(^2\) Tsunami evacuation zones (MCDEM, 2008)
the most important action messages will take priority.

Draft maps will be taken to the villages during Stage 5 to discuss evacuation routes, safe locations, local information needs and possible signage locations. These will be agreed with each village at the end of consultation and during Stage 6 the routes, safe locations and local information will then be added onto the maps for future stages.

It was agreed that tsunami evacuation maps and associated signs should be as seamless as possible with Coastal Infrastructure Management (CIM) plans, forming a basis for tsunami-specific CIM planning.

### 4.2 Maps

Orange and yellow zones are shown in Figure 4. These are GIS polygon vector digital files which will be trialled on in-country GIS systems during Stage 5. They can be plotted at scales from villages to the whole country.
Figure 4 An illustration of the coverage of the digital orange, yellow and red zones produced during Stage 4 for all of Samoa.

Zones are plotted over the satellite image, with roads and village annotation plotted over all of this. Examples to be used in the four pilot villages are shown in Figures 5 to 8.
Figure 5 Draft Satupaitea (Savai'i) village map for consultation, with examples of items that will be included on final maps (note the legend and text content will be bilingual and tailored to meet village needs).
Figure 6 Draft Faleu (Manono) village map for consultation.
Figure 7 Draft Poutasi Falealii (Upolu) village map for consultation.
Figure 8 Draft Mutiatele-Malaela (Upolu) village map for consultation.
4.3 Using maps

The blank draft maps shown in Section 4.2 will be taken to the village consultations during stage 5 for three main purposes. (1) to determine if the map layout and proposed content suits village and NDMO needs, (2) to map local features, evacuation routes, safe locations and signage locations as defined by villagers, (3) to define a long-term village roll-out process for villages Samoa-wide.

Natural (earthquake, unusual ocean noises and behaviour) and Informal warnings trigger an evacuation of all zones. Public education, and content and placement of maps, information boards and signage to maximise this message will be discussed with NDMO and villagers further during Stage 5. Official evacuations for sources further afield, especially from the Pacific Rim, are discussed in Section 4.3.2

4.3.1 Link to signage

During the inception visit it was agreed that draft ‘evacuation zone’, ‘evacuation zone map’, ‘evacuation route’ and possibly ‘safe location’ signs would be drawn up during Stage 4 in consultation with the NDMO, based on the New Zealand Signage Technical Standard (Figure 9). These will be taken to villages during Stage 5 for discussion as to the final sign style.

English and Samoan language signs have been prepared and will be taken to villages in Stage 5.
Figure 9 Agreed draft signage in various Samoan, Samoan-and-English, and English versions to be discussed in Stage 5 with NDMO and villages.

4.3.2 PTWC Warnings and calling official evacuations

Procedures for the triggering of evacuation in response PTWC warnings will be discussed further with NDMO during Stage 5.

Anticipated use:

The ‘yellow’ zone is expected to be used for self-evacuation in the event of strongly felt earthquake shaking or other recognised natural warnings. This is regardless of whether or not a PTWC warning is issued. People should self-evacuate as soon as possible after the shaking stops without waiting for official advice. An evacuation of the yellow zone also includes the orange and red zones.

The ‘orange’ zone is intended for evacuation in the event of a PTWC tsunami warning for Samoa that is not accompanied by strong earthquake shaking. If strong shaking is also felt the ‘yellow’ zone should be evacuated. An evacuation of the orange zone also includes evacuation to the red zone.

The ‘red’ zone is used to represent a ‘marine threat’ i.e. the forecast tsunami threat is confined to people and boats on beaches, reefs and harbours. It should only be used in situations where clear advice is received, in e.g. an advisory or phone call from PTWC, to indicate that only a marine threat exists. If in doubt the ‘orange’ zone should be used.

Currently (2011) PTWC do not issue conventionally issue ‘marine threat only’ messages. However this is likely to change in the next few years as PTWC moves towards a ‘threat level’ system. When this change occurs it will be important to seek clear advice regarding which threat level(s) correspond to only a marine threat.
5.0 REFERENCES

Abe, K., 1989. Quantification of tsunamigenic earthquakes by the Mt scale, Tectonophysics, Volume 166, Issues 1-3, 27-34.


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Pacific tsunami, July 2011, Pages 128-140.


APPENDIX 1  CALIBRATION PLOTS

A1.1  Comparison to measured inundation at Banda Aceh

The GIS script was run on an elevation dataset for the Banda Aceh area of Indonesia using 35m elevation at the coast. This zone (green line) for inundation from the west coast compared to the satellite image of damage from the tsunami is given in Figure 10. The damage wholly sits within the zone.

![GIS-modelled evacuation zone for a wave from the left, overlain on the real Banda Aceh damage satellite images (Google Earth).](image)

Note that the green zone is only modelled for inundation from the west coast, thus damage from inundation from the north coast is not included within a zone. This is because we have a good idea of the wave height and run-up elevation (input criteria for the GIS script) at only the west coast.
A1.2 Java survey results

The flat topography surveyed in Java (by Cousins et al, 2006) generally did not permit the estimation of maximum possible run-up heights on steep slopes near the coast. However, even if inundation heights near the coast are used in place of run-up heights it is generally found that the 1:200 attenuation rate is conservative (For example, Figure 11).

![Figure 11 Inundation images from Java and water elevation. The purple line represents the 1:200 attenuation relation based on an assumed maximum possible run-up at the coast of 10 m (which may be an underestimate). The maximum run-in distance was ~480 m at an elevation of ~2 m. The attenuation rule appears to be conservative for this tsunami.](image)

A1.3 Sri Lanka survey results

The published survey results of Wijetunge (Figure 12) do not contain all of the information required for a comprehensive calibration. The elevation at the maximum inundation distance is not recorded, though where this distance is a local maximum it seems reasonable to assume that this occurs close to waterways that are likely to be at low elevation given the generally flat topography. It is also unclear whether the tsunami height records are of run-up or inundation height, though again given the flat topography it seems reasonable to assume
that they are mostly inundation heights. This leads to the same issue as encountered in Java that we are unsure of the run-up height that would have been achieved had a steep slope been encountered.

Using the tsunami heights as (under-) estimates of the potential run-up, the rule would imply that heights of 5-8m would lead to inundation distances of 1-1.6 km which seems broadly consistent with the observations. Where the inundation distance is notably greater, e.g. ~3km around Kalkudah, it is noted that “In some areas, for instance, around Batticaloa and Kalkudah, the lagoons and other water bodies have certainly helped convey the tsunami surge large distances inland” so the 1:400 river attenuation rule is probably appropriate here.

Overall the data from Sri Lanka does not appear to directly contradict our rule, but is insufficient to act as a solid validation of it.

Figure 12 Inundation distance and Tsunami height measurements for the Sri Lanka east coast. From Wijetunge (2006).
Analysis of field survey and aerial-photography data (Titov, 2005) for the 1993 Okushiri island tsunami shows inconclusive results when used to validate the model described here. Refer to Figure 13 for the following discussion points:

In region A consistently high run-up values (20-25m) are seen which is believed to be due primarily to the focussing effect of the two offshore islands on the tsunami (only a detailed numerical model would be able to capture this effect). In one particular valley in this area a localised amplification effect has resulted in an exceptional 32m run-up.

In region B the maximum run-in distance is ~340m at which point the maximum water level is ~14m, approximately 2m lower than at points either side of the valley entrance. This is broadly consistent with our model.
However, in region C run-in distances of ~160m do not appear to have caused a verifiable drop in maximum water levels relative to surrounding coasts. So this does not validate our model, though the anticipated effect is small. We note that the beach area is wide here and the width may be sensitive to the state of the tide.

A1.5 1983 Japan Sea survey results

Figure 14 Run-up and inundation heights (m) as a function of the distance (m) from the shoreline on the Minehama coast (Kajiura, 1986). The superimposed red curve illustrates the envelope of points within the 1:200 attenuation curve, assuming a maximum possible run-up at the coast of 15.5m, the enveloped does not appear as a straight line because of the logarithmic scaling of the original plot.
Figure 15 GIS-modelled evacuation zone lines (black, representative lines labelled) compared to Camfield inundation zones (coloured). Top figure is Whananaki, Northland (legend colours slightly altered), bottom is Pegasus Bay, Canterbury.
A1.6 Comparison to modelled inundation

We ran a more-complex inundation model where we have detailed elevation data at Whananaki in Northland and Christchurch in Canterbury. The modelled inundation by the GIS script used here and a US Army Corps of Engineers model (Camfield, 1980) for the same wave height at coast are shown in Figure 7. The results are relatively similar and in general the GIS rule zone is larger and thus the more conservative option. It is important to note that the Camfield model and other wave-propagation models are no better tested against real tsunami data than the script used here.

A1.7 Comparison of linear relationship to logarithmic options

Experience of the impacts of the Indian Ocean tsunami in Sri Lanka and Thailand was expressed by Dr Hermann Fritz in terms of the height that someone would have to be to be safe at a given distance from the coast. It has been suggested that this could form the basis for defining evacuation zones (Meadows, draft), though this was not the original intention of Dr Fritz. Plotting of these ‘Fritz criteria’ suggests that there may be an exponential-decay relationship between decreasing inundation height and distance inland. The criteria are coarse-stepped and do not contain data points farther inland than 5 km. In a plot (Figure 8) of the relationship approximated as an exponential curve (equation 1) a 16 metre inundation at coast would go much further inland (light blue curve, Figure 8). The long-tail of the exponential curve would probably require some correction at large distances inland over flat terrain. While field data does not rule-out the exponential model, we have observed that it gives poor results (over-evacuation) when applied to areas where the topography data is based on interpolation of 0 and 20m contours. The linear relationship (green line for land, and red line for river, Figure 8, as used for modelling in this report) is therefore currently preferred.
Equation 1: Maximum Potential Run-up height = 2 * H * exp( - ln(2) / alpha * X )

where: 
H is the height at the shore (m) 
X is the distance from the shore (m) 
alpha is the distance (in meters) in which the wave height drops by half

On land assume alpha = 2000 (chosen so that a 32m potential run-up drops to 4m potential run-up in 6km)

On rivers assume alpha = 4000 (chosen to decay half as fast as on land) ln(2) is the natural logarithm of 2