

Assessing vulnerability and adaptation  
to sea-level rise: Lifuka Island  
Ha'apai, Tonga

## C. Vulnerability and hazard assessment

### 1.0: Coastal hazards





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Jens Krüger and Hervé Damlamian

Secretariat of the Pacific Community  
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## List of technical reports for the Lifuka project: Assessing vulnerability and adaptation to sea-level rise: Lifuka Island, Ha'apai, Tonga

As part of the Australian Government's International Climate Change Adaptation Initiative (ICCAI), the Pacific Adaptation Strategy Assistance Program (PASAP) aims to assist the development of evidence-based adaptation strategies to inform robust long-term national planning and decision-making in partner countries. The primary objective of PASAP is: 'to enhance the capacity of partner countries to assess key vulnerabilities and risks, formulate adaptation strategies and plans and mainstream adaptation into decision making' (PASAP, 2011). A major output of PASAP is: 'country-led vulnerability assessment and adaptive strategies informed by best practice methods and improved knowledge'.

The Lifuka project was developed in conjunction with the Government of Tonga Ministry for Lands, Survey, Natural Resources, Environment and Climate Change (MLSNRECC), PASAP and the Secretariat of the Pacific Community (SPC) to develop an evidenced-based strategy for adapting to sea-level rise in Lifuka Island.

Many technical reports were written for the project on Lifuka Island. They are listed below. They complement, and should be read in conjunction with, the final report : Rising oceans, changing lives.

### **A: Final report:** Rising oceans, changing lives

### **B 1: Physical resources**

- 1.1: Shoreline assessment
- 1.2: Groundwater resources assessment
- 1.3: Oceanographic assessment
- 1.4: Benthic habitat assessment
- 1.5: Beach sediment assessment
- 1.6: Household survey to assess vulnerabilities to water resources and coastal erosion and inundation

### **B 2: Community assessment**

- 2.1: Community engagement strategy and community assessment manual
- 2.2: Community values and social impact analysis

### **C. Vulnerability and hazard assessment**

- 1.0: Coastal hazards
- 2.0: Coastal rehabilitation – Lifuka Island, engineering options report
- 3.0: Preliminary economic analysis of adaptation strategies to coastal erosion and inundation: Lifuka, Ha'apai, Kingdom of Tonga: Volume 1 – Least cost analysis
- 4.0: Preliminary economic analysis of adaptation strategies to coastal erosion and inundation: Lifuka, Ha'apai, Kingdom of Tonga: Volume 2 – Cost benefit analysis

### **D. Adaptation options and community strategies**

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## 1. Executive summary

The coastal hazard map presents the results of an assessment to determine the coastal erosion and inundation hazards for a hundred-year planning horizon (including an intermediate–high sea-level rise) for the western shoreline of Lifuka Island, Ha’apai, Tonga. The principal objective of the information presented here is to support the Lifuka community in making decisions to reduce the exposure of the built environment to climate change and variability.

The map shows three hazard areas that take into account both slow-onset hazards (e.g. sea-level rise and erosion) and rapid-onset hazards (e.g. extreme storm tides and inundation), which provide guidance for adaptation measures in the form of coastal setbacks, design standards, and living shorelines.

A coastal setback zone is a buffer space where permanent constructions are not allowed, defined by a specific distance from the shoreline. It protects human settlements from current and future coastal processes, and preserves natural assets, ecosystems and services. Critical infrastructure in this zone may have to be relocated.

Design standards refer to construction of residential buildings to make them more resistant to the damaging effects of inundation from the sea and associated wave action.

Living shorelines refer to management practices that restore or enhance coastal habitats, both terrestrial and marine. There will always be a residual risk, and the level of risk that is not offset by building siting and inundation-resistant design must be accepted by the community or owner of the building.

A historical shoreline-change assessment determined coastal setback distances of 25 m for Holopeka and Koula and 110 m for Pangai and Hihifo. Numerical modelling of a one-per-cent-annual-change extreme metocean event found that inundation and damaging waves can extend for long distances inland due to the low-lying nature of the western coastal plains. Areas above the six metre contour are deemed to be outside the hazardous coastal zones. The results of these modelled scenarios do not predict future changes, but describe future potential conditions to support decision-making.

In considering adaptation options, the community should not rely on future shoreline protection to compensate for poor location and design decisions. A reliance on hard structures (e.g. revetments) or beach nourishment to protect coastal sites and residential buildings is not a good substitute for proper siting and construction. Storms that exceed the design criteria of a revetment can lead to the overtopping of waves, leaving the people and buildings vulnerable to only the most severe events such as cyclones and tsunamis, and effectively increasing the risk to community and infrastructure. A managed retreat from the shoreline also favours a functional coastal ecosystem that is more resilient to climate change and variability and provides goods and services that are critical to livelihoods.

## 2. Background

The islands of Tonga lie west of the Tongan trench, which is an active subduction zone where the Pacific Plate is subducted beneath the Tongan and Indo-Australian Plate. Uplift and subsidence of the Tonga Ridge is influenced by faulting. Figure 1 shows that a series of transverse faults break the Tonga Ridge into at least a dozen discrete forearc blocks (Dickinson et al. 1999; Dickinson 2001).

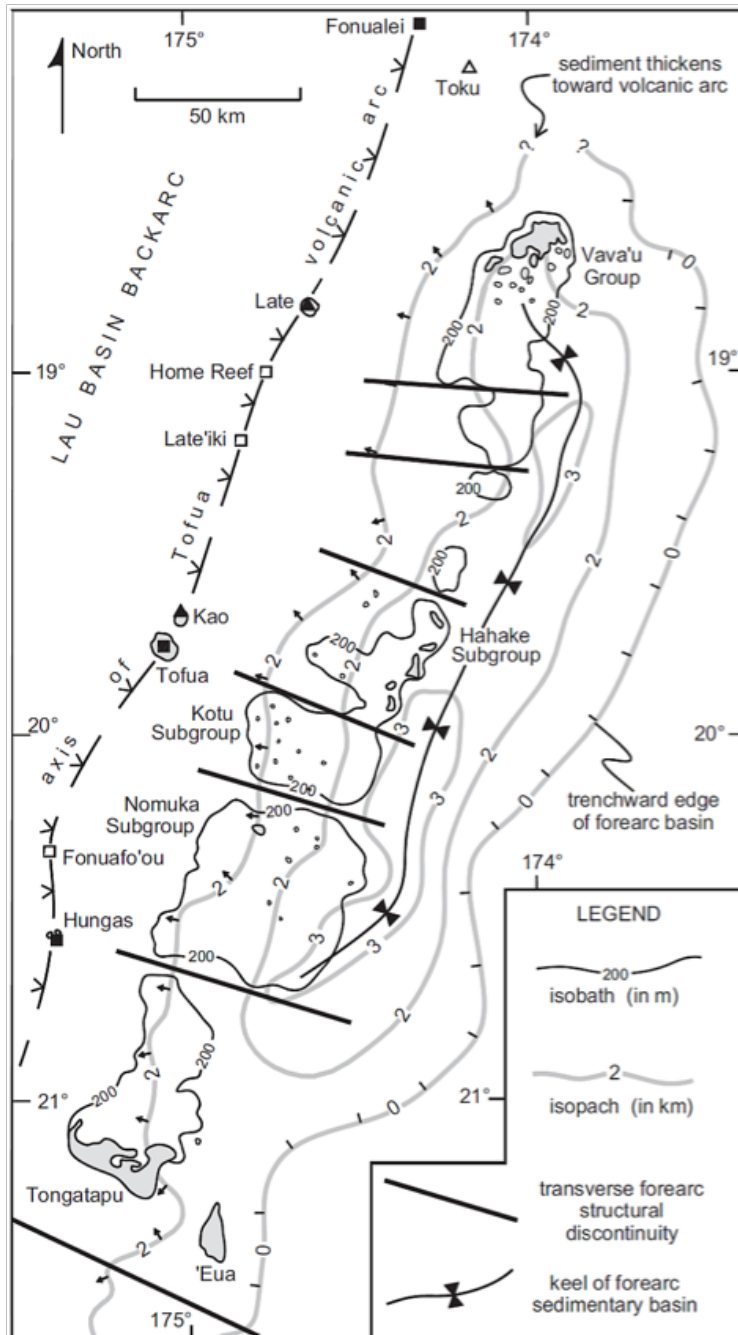


Figure 1: Map showing the geological setting of Tonga Group with Lifuka being part of the Hahake Subgroup (from Dickinson and Burley 2007)

Uplift along the Tonga Group was experienced in the late Pliocene to early Pleistocene, with the subduction of the Louisville Ridge crest on the Pacific Plate beneath the forearc (Dickinson and Burley 2007). Post-mid-Holocene drawdown of sea level was probably under way by the time of first human occupation of ~3 ka on Tongatapu (Dickinson 2003). Initial settlement on Tongatapu focused on the prograding mid-Holocene paleo-shoreline of the western coastline (Dickinson and Burley 2007). Today, Lifuka is a raised limestone island (maximum elevation of 17 m above mean sea level), and comprises a coastal plain of varying width (generally 200–500 m) along the western leeward shoreline (Figures 2 and 3). This sandy coastal plain has a presumed depth of some 15 m and acts as a reservoir of the island freshwater resource (Figure 4). Lifuka is the administrative centre for the Ha'apai Group, which consists of a series of 60 small, low-lying islands. Lifuka is home to 2,967 people, some 40% of the population of the Ha'apai Group, and houses the region's airport and main harbour. It comprises five main communities on the western leeward shore of the island (Figure 2). The island experienced relative sea-level rise in the order of 23 cm due to tectonic subsidence associated with the May 2006 earthquake (Cummins et al. 2006), and has since experienced increased erosion. The sea level changed because the underlying land fell with respect to the ocean surface. This is called relative sea level rise.

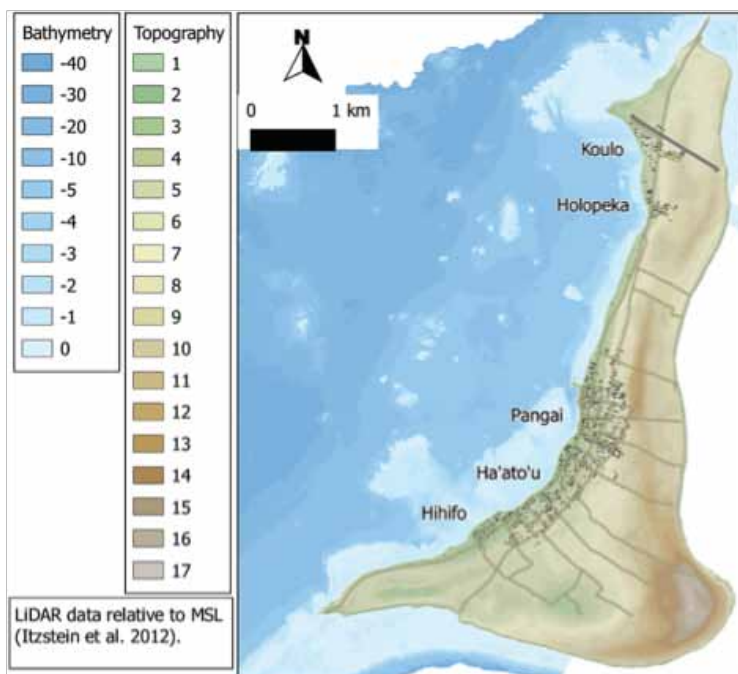


Figure 2: Coastal terrain model of Lifuka showing LiDAR bathymetry and topography collected under the PASAP project. The map also shows the location of major infrastructure such as houses, roads and the airport. Note that the majority of buildings are located on the low-lying western coastline.

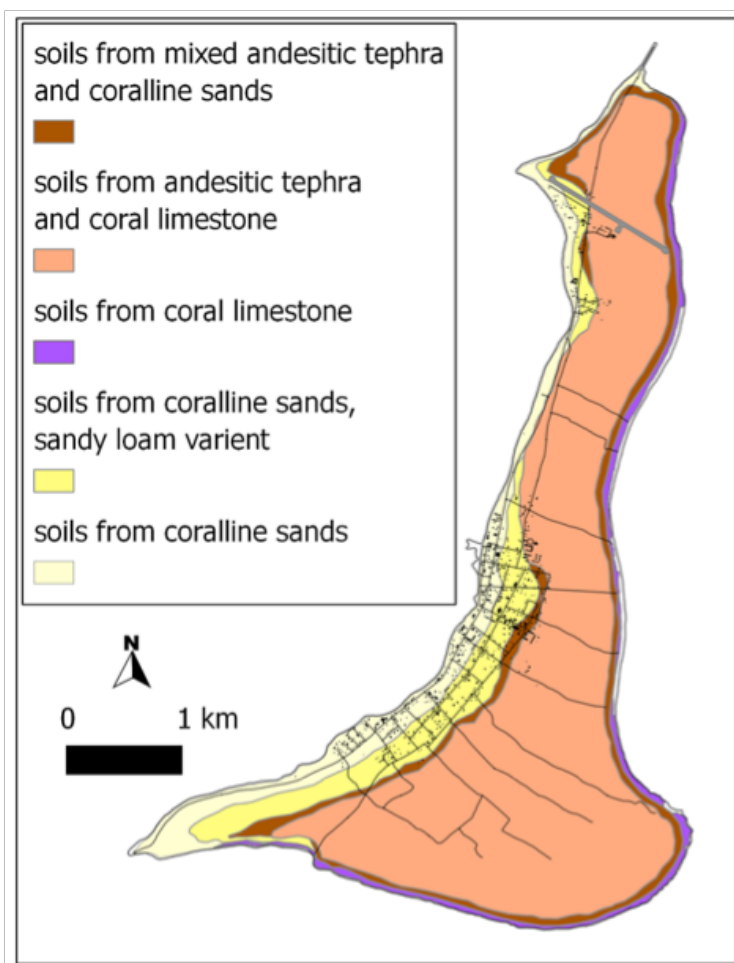


Figure 3: Soil map of Lifuka (redrawn from Wilson and Beecroft 1983) overlain with infrastructure (houses, roads, and airport). Note that the majority of buildings are situated on the sandy soils of the coastal plain. A hypothetical cross section through the Pangai area is shown in Figure 4.

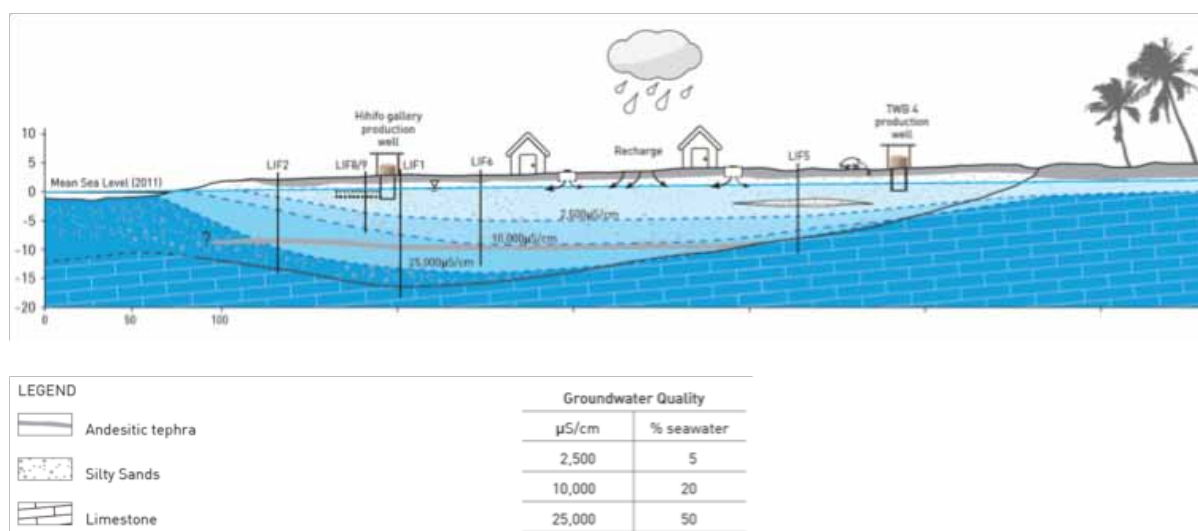


Figure 4: Conceptual diagram of groundwater resources, Lifuka. Note that the freshwater lens is largely confined to the unconsolidated sands of the coastal plains. For more details, please see the companion report B.1.2 Groundwater Resources Assessment.

## Objectives

Coastal erosion on Lifuka Island has been identified at the national and community level as a concern. The goal of the Lifuka project is to develop an evidence-based strategy for adapting to sea-level rise on Lifuka Island, which can be used as a case study to be applied in other parts of Tonga and the Pacific. The specific objectives of the Lifuka project are:

- to assess the impacts of seismic subsidence on the coastal zone and on the people of Lifuka;
- to analyse the vulnerability of the coastal zone and of the people of Lifuka to future rises in sea level;
- to propose and assess a range of adaptation strategies for adapting to sea-level rise on Lifuka;
- to support the capacity of the Government of Tonga and relevant NGOs to conduct assessments of coastal and social vulnerability and adaptation to sea-level rise in the future; and
- to design a system for monitoring ongoing changes in natural and social systems on Lifuka.

The outcomes of the Lifuka project will generate an informed basis for selecting appropriate adaptation response to future sea-level rise and storm surge on the western coastal zone of Lifuka.

In achieving this, the project considered the two major coastal hazards of coastal inundation and erosion. However, the existing repository of historical observational data (e.g. tropical cyclone winds, barometric pressure, high-water marks, wave conditions, pre- and post-storm beach profiles) is insufficient for use in predicting coastal inundation and erosion. As a result, this study relied heavily on the modelling of metocean conditions, water levels, and erosion rates to simulate coastal retreat and inundation depths for a 100-year planning horizon. This coastal hazards report details the results of the inundation modelling, as well as the historical shoreline change analysis that underpins the project's coastal hazard mapping activity.

## 3. Methodology

### 3.1 Coastal setback zone

A shoreline change analysis was carried out in order to define a coastal setback zone based on long-term erosion rates. A coastal setback zone is a buffer space where permanent constructions are not allowed, defined by a specific distance from the shoreline. It protects human settlements from current and future coastal processes, and preserves natural assets, ecosystems and services. Critical infrastructure in this zone may have to be relocated.

The Geology Department, the Lands and GIS Unit and online archives were searched and five suitable imagery sets were found (Figure 5) spanning a four-decade period. The 1968 and 1990 aerial photographs were scanned at 1,200 DPI and rotated to a north-up orientation in Gimp version 2.8 ([www.gimp.org](http://www.gimp.org)). The rotated images, as well as 2004 and 2008 satellite images, were then rectified against the 2011 digital orthophotomosaic (Itzstein et al. 2012), using Global Mapper version 12 ([www.globalmapper.com](http://www.globalmapper.com)) utilising a polynomial method with bilinear interpolation.

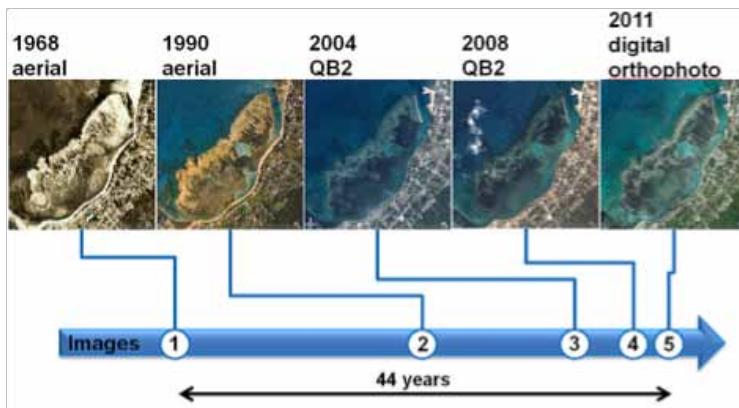


Figure 5: The five sets of imagery used in the shoreline-change analysis consisted of 1968 black and white and 1990 colour photography, 2004 and 2008 Quickbird-2 (QB2) imagery, as well as a 2011 orthophoto derived from digital imagery that was taken as part of the AAM LiDAR survey (Itzstein et al. 2012).

The shoreline feature that was digitised from each of the images was the base of the beach, also called the toe of the beach, and the uncertainties associated with this were estimated following Romine et al. (2009). They are summarised in Table 1.

Table 1: Shoreline uncertainties for Lifuka (RMS is root mean square). Note that the digitising error for the 1968 photo was relatively high (12 m) due to the poor contrast of the black and white photograph in certain areas. QB2 = Quickbird-2 satellite.

Uncertainty source	1968 air photo	1990 air photo	Satellite image (QB2)	2011 orthophoto
Digitising error	12	2	2	1
Pixel error	4	2	0.5	0.2
Seasonal error	4	4	4	4
Rectification error	4	2	2	0
Tidal error	3	3	3	1.5
Total positional error	27	13	11.5	6.7
RMS error	9	3	4	3

After digitising the shoreline, the historical shoreline change analysis was carried out using the Digital Shoreline Analysis System, DSAS v4.3 (<http://www.csc.noaa.gov/digitalcoast/tools/dsas>). DSAS is computer software that computes rate-of-change statistics from multiple historic shoreline positions residing in a geographic information system. At the time of the analysis, DSAS was freely available from the NOAA Coastal Services Centre website as an ArcGIS Desktop 10 plugin. DSAS is now a web application called DSASweb, which can be accessed online at <http://cida.usgs.gov/DSASweb/>.

Genz et al. (2007) discussed the various statistical methods to derive shoreline change rates and noted that most researchers prefer to use a linear regression method. For Lifuka, we decided to use the weighted linear regression method, placing more emphasis on the overall shoreline uncertainty (Figure 6).



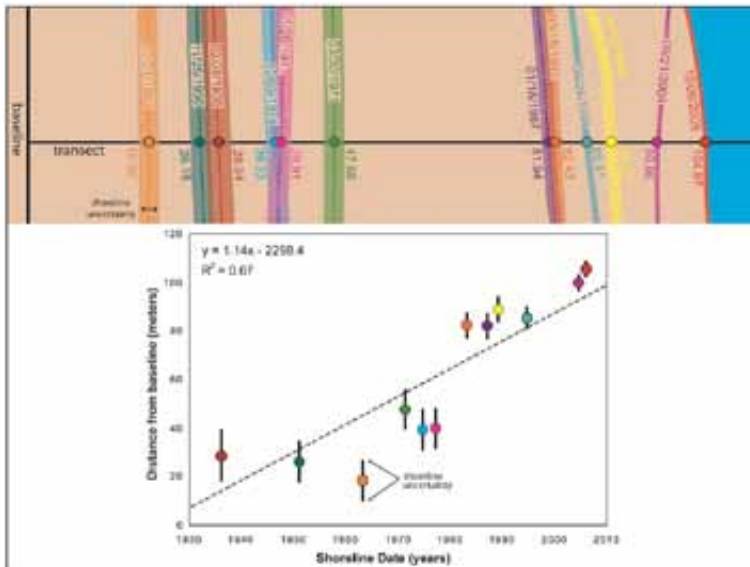


Figure 6: Example of how to determine the weighted linear regression rate by plotting the shoreline positions weight with respect to time. Measurement points with smaller positional uncertainty have more influence in the regression calculation because of the weighted component in the algorithm (Himmelstoss 2009). Note that in this example, older data sources have larger uncertainties. The uncertainties associated with the Lifuka shoreline dataset are listed in Table 1.

Transects were cast across the temporal shoreline data at 50 m intervals, and Excel was used to further analyse the resultant output from DSAS. Mean annual erosion rates were calculated for the coastal communities of Koulo, Holopeka, Pangai and Hihifo, and used to establish a distance to define the coastal setback zone using the following formula (Hwang 2005; Genz et al. 2007).

Setback Zone = (mean erosion rate + standard deviation) \* 100 + safety buffer where:

- the mean erosion rate is the arithmetic mean of the binned annual erosion rates. Results for transects 127 to 140 were averaged to derive an annual erosion rate for the shoreline north of the wharf (Koulo and Holopeka). Results for transects 45 to 80 were averaged to derive an annual erosion rate for the shoreline south of the wharf (Pangai and Hihifo). A minimum erosion rate of 0.03 m/year was used for shorelines with low annual erosion rates;
- the standard deviation is derived from the annual erosion rates for each of the transects;
- a 100-year planning horizon was used at the request of the Government of Tonga. The above-mentioned values were therefore multiplied by a factor of 100 in order to be able to project a coastal setback zone onto the western shoreline of Lifuka;
- the buffer was set at 6.1 m (20 feet). This is designed to partially compensate for method errors, storm erosion, and non-linear shoreline changes.

### 3.2 Coastal inundation

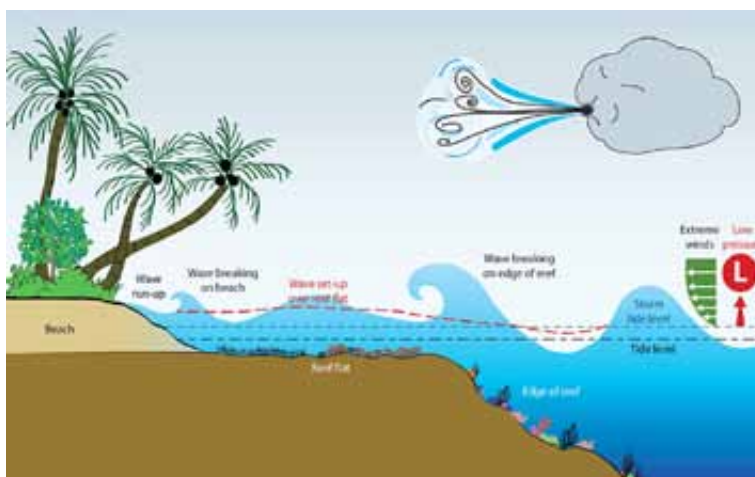
In order to map the coastal hazards associated with inundation, we considered extreme water levels due to the following:

- astronomical tides
- longer-term variations
  - interannual changes due to ENSO
  - sea-level rise

- storm surge
  - inverse barometer effect
  - wind stress
- wind-wave contributions
  - wave setup
  - wave runup

Tsunamis were not considered, as tsunami flooding typically has a longer recurrence interval than the one-per-cent-annual-chance flood event from a tropical cyclone.

For tides, the mean high-water spring (MHWS) level was considered, as determined from the temporary tide-gauge installation (see companion report B.1.1 Shoreline Assessment). Information on the interannual variability in water levels was taken from the Pacific Climate Change and Science Program (PCCSP, [www.pacificclimatechangescience.org](http://www.pacificclimatechangescience.org)) as shown in Figure 10. The PCCSP report also presents sea level projections for Tonga, where the high emissions scenario sea-level rise for 2030 is in the range 0.03–0.17 m; for 2055 the range is 0.09–0.31 m; and for 2090 it is 0.21–0.62 m. These levels are comparable to the intermediate-low scenario described in Parris et al. (2012) as shown in Figure 9. Figure 9 also includes significantly increased projected sea levels over the next century, namely the intermediate-high and highest levels, which were based on new research that improves our understanding of ice sheet movement and melting. This new research also influenced the sea level rise projections in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) that was released in September 2013 (<https://www.ipcc.ch/report/ar5/wg1/>; accessed 17 February 2014), bringing policy-makers and the public up to date with the state of climate science. The new projections included in the AR5 show an increase in projected sea levels in the range of 0.26–0.55 m by 2100 under a low emissions scenario and 0.52–0.98 m under the high emissions scenario, with the latter being comparable to the intermediate-high scenario of Paris et al. (2012). The sea level rise projections used as a baseline for this study therefore followed the intermediate-high scenario described in Paris et al. (2012) and defined as 1.2 m of global sea level rise above present day (the year 2011) conditions after four generations, or a planning horizon of 100 years (the year 2111), with little tolerance for risk. The contributions from storm surge and wind waves (Figure 7) were computed using a combination of various statistical, parametric and dynamic models. Inverse barometric effects and extreme winds were computed using the Tropical Cyclone Risk Model ([www.ga.gov.au](http://www.ga.gov.au)). The resulting synthetic cyclone data set was used in the Young and Burchell (1996) parametric model to derive extreme offshore wave conditions. The 100-year return interval values of these metocean parameters were used in the XBeach model (Roelvink et al. 2010) to assess and map coastal inundation during tropical cyclone conditions, including wave set-up and run-up. The methodology is further summarised as six modelling steps in Table 2.



*Figure 7: Conceptual diagram showing that the western coastline of Lifuka is vulnerable to impacts of waves, especially during tropical cyclone conditions. On steep reef-fringed shorelines, surface waves are the dominant contributors to coastal sea-level extremes via wave set-up. Adapted from a diagram by NIWA ([www.niwa.co.nz](http://www.niwa.co.nz)).*

Table 2: Summary of steps used to derive inundation maps for Lifuka

Step	Method	Reference
1	<b>Storm tracks</b> Input: Historical tropical cyclone record from the International Best Track Archive for Climate Stewardship (IBTraACS). See Figure 8 for an example of this kind of dataset. Description: Statistically modelled 1,000 years of storm tracks using the Tropical Cyclone Risk Model (TCRM) from Geoscience Australia. Output: Database of position, speed and direction, minimum pressure, maximum wind speed, and radius of maximum wind speeds for synthetic tropical cyclone positions within a 400 km radius of Lifuka.	<a href="http://www.ncdc.noaa.gov/oa/ibtracs/">http://www.ncdc.noaa.gov/oa/ibtracs/</a> <a href="http://www.ga.gov.au/hazards/our-techniques/modelling/our-models/what-is-tcrm.html">http://www.ga.gov.au/hazards/our-techniques/modelling/our-models/what-is-tcrm.html</a>
2	<b>Storm waves</b> Input: Dataset from Step 1. Description: Calculated significant wave height and period for each time step in dataset using Young's parametric wave model. Output: Dataset of surface wave parameters for synthetic tropical cyclone conditions.	Young (1988); Young and Burchell (1996) and Matlab script from Young (pers. comm.)
3	<b>Extreme conditions</b> Input: Dataset from Step 2 Description: Calculated annual exceedance probabilities of significant wave height, wave period, wind, and pressure for each generated tropical cyclone. Output: Annual exceedance probabilities, including 100-year return intervals (100 RI), for metocean conditions at Lifuka.	Coles (2001) and extreme value analysis implementation in the TCRM.
4	<b>Boundary scenarios</b> Input: 100 RI values from Step 3. Description: Used 100 RI output from above in combination with an intermediate–high sea-level rise scenario by 2111 (Figure 9), mean high-water spring-water level, elevated ENSO-condition water levels (Figure 10), inverse barometric pressure and wind contribution to storm surge conditions for use in the XBeach model. Output: Boundary conditions for the XBeach model.	Parris et al. (2012) Begg and Kruger (2013) BoM and CSIRO (2011)
5	<b>Inundation model</b> Input: Coastal terrain model from the LiDAR survey (Figure 2) and extreme offshore conditions from Step 4. Description: The XBeach numerical model was used to compute the nearshore processes during tropical cyclone conditions, including wave set-up and run-up. Output: XBeach output files of water depth, wave height, and velocities.	Itzstein et al. (2012) Roelvink et al. (2010) <a href="http://oss.deltares.nl/web/xbeach/">http://oss.deltares.nl/web/xbeach/</a>
6	<b>Inundation mapping</b> Input: Raster files from Step 5 Description: Raster files were combined to define a high hazard and a hazard area based on the V and A Zone definitions by the US Federal Emergency Management Agency (FEMA). Output: GIS shape files and maps, as well as an A0 poster on hazard zones.	<a href="http://www.fema.gov">www.fema.gov</a> <a href="http://www.qgis.org">www.qgis.org</a>

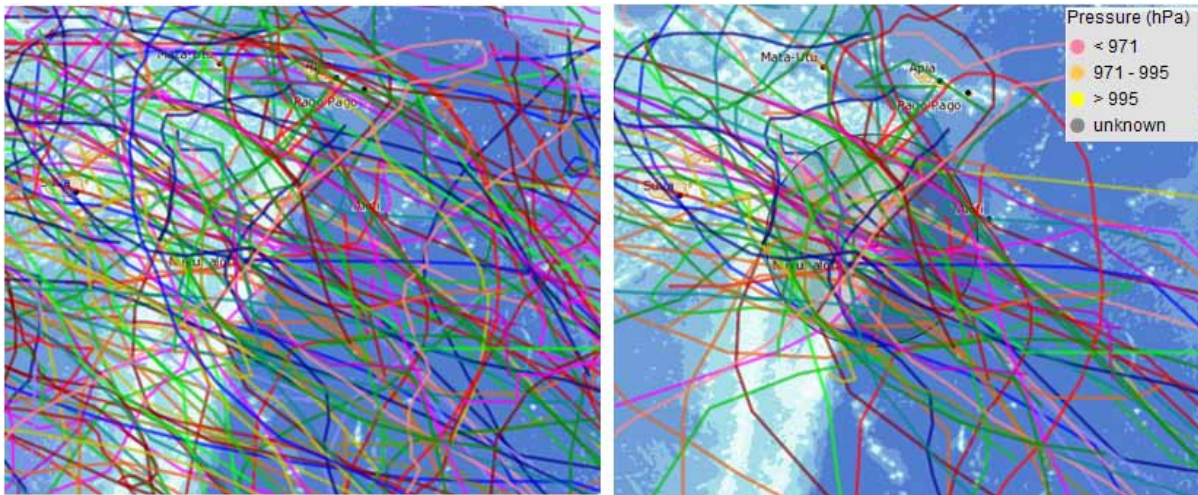


Figure 8: Left: There were 195 cyclones around Tonga from 1969 to 2010. Right: There were 70 cyclones within a 400 km radius of Lifuka (source: Pacific tropical cyclone data portal, [www.bom.gov.au](http://www.bom.gov.au)). TCRM generated 1,000 years' worth of tropical cyclone tracks and conditions using statistical sampling of this type of historical record.

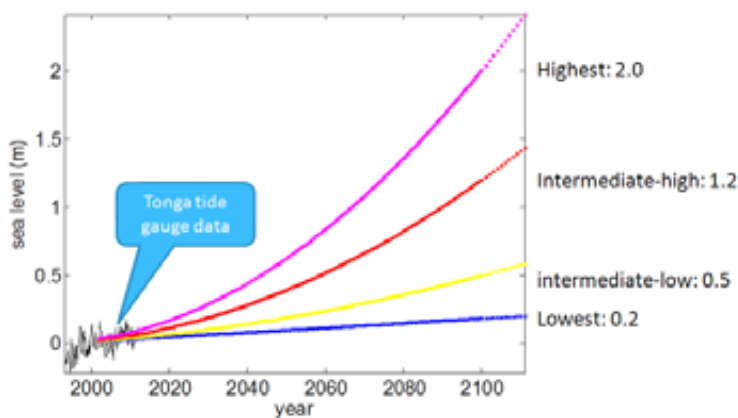


Figure 9: Global mean sea-level rise scenarios (using Parris et al. 2012). The intermediate-high scenario (red line) was used as a baseline for the inundation modelling. Also plotted are the observed tide gauge water levels (monthly means from 1993–2011). The relative sea-level trend in Tongatapu is 7.7 mm/year. This is compared to a global average since 1990 of 1.7 mm/year. (Source: [www.psmsl.org](http://www.psmsl.org) and [www.cacr.gov.au](http://www.cacr.gov.au)).

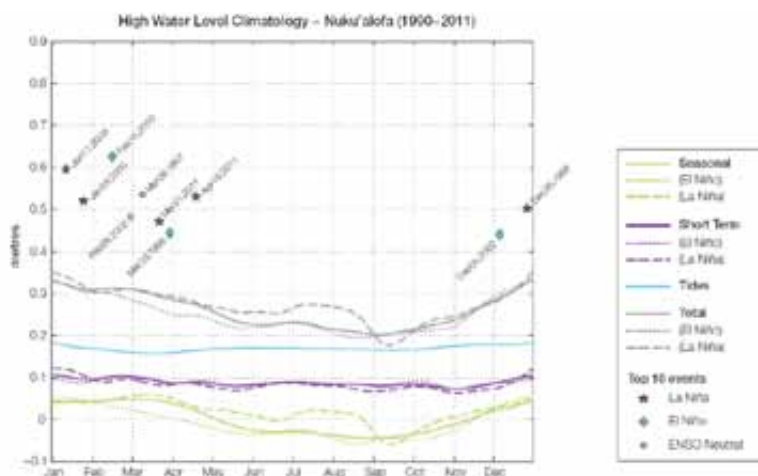


Figure 10: High-water level climatology for Nuku'alofa from 1990 to 2011. The maximum water level of 1.11 m (MSL 1990) on 15 February 2010 refers to Tropical Cyclone Rene. Interannual variability has been about 18 cm (5–95% range after removal of the seasonal cycles). From BoM and CSIRO (2011, Figure 14.7, p. 222).



## 4. Results

### 4.1 Shoreline change analysis

An example of the digitised shoreline dataset for the area of Hihifo is shown in Figure 11. Resultant annual erosion rates are shown in Figure 12.



Figure 11: Detail of the Hihifo area showing the digitised base of beach polylines for each of the five sets of imagery (dates are shown as mm/dd/yyyy) as well as the perpendicular transects (black lines) cast across the shorelines by DSAS to compute statistics on erosion rates. The backdrop is the 2011 digital orthophoto.

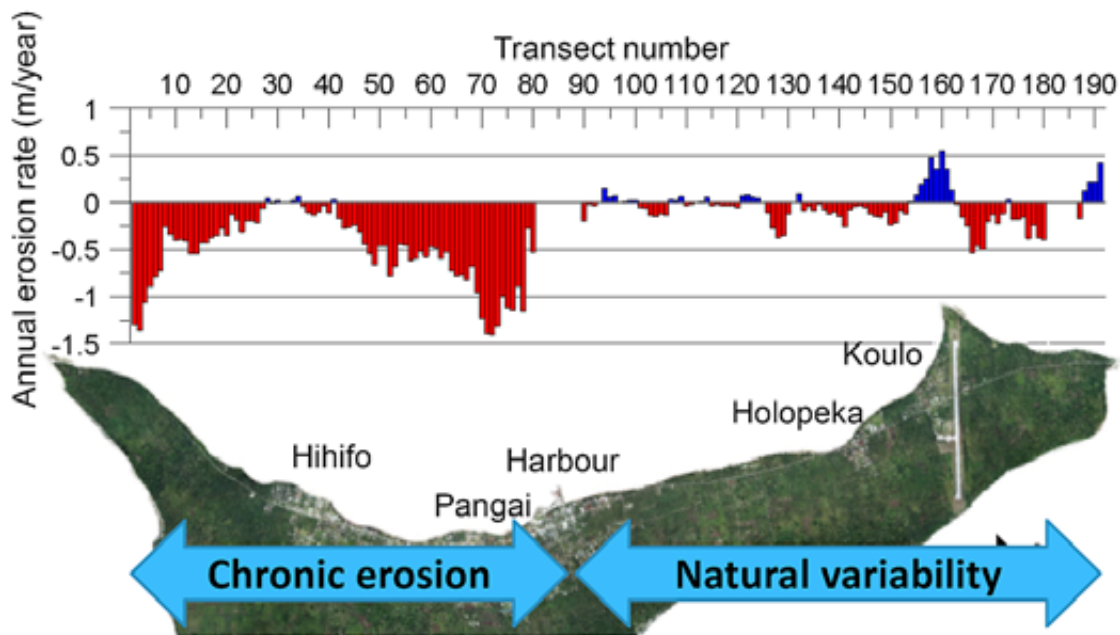


Figure 12: Bar chart of the annual erosion rate overlain on the 2011 orthophoto of Lifuka (north is to the right). The numbers on the x axis near the top refer to the transect numbers cast across the dataset of shorelines at 50 m spacing. The y axis on the bar graph refers to the annual erosion rate in m/year, with red bars indicating erosion and blue bars showing accretion. The analysis shows that the beaches north of Pangai Harbour are relatively healthy, exhibiting a natural variability over the decades. This is in contrast to the shoreline south of the harbour, which is experiencing chronic erosion.

The shoreline to the north of Pangai Harbour has experienced annual shoreline change rates that vary from +0.5 m/year (accretion) to -0.5 m/year (erosion). Accretion of the beach has occurred on the promontory extending into the lagoon westward of the runway at Koulo. This headland shows the growth of a small spit feature, which shows an incipient lateral protruding to the south, aligned obliquely with the dominant wave direction. This is further indication that the dominant longshore sediment transport is from the north to the south along this coastline. The highest erosion rates (-0.5 m/year) were noted immediately to the north of this sand spit, on the updrift coastline. Sand transported south from this part of the shoreline may be stored in the spit and can be released during short-term changes in the prevailing wave and wind conditions, such as during storms. This is part of the natural variability of a beach that is in dynamic equilibrium, and sediment supply is expected to improve with the planned reconstruction of the causeway linking Lifuka to the island of Foa in the north (Kitekei'aho and Ngaluafé 2010). The mean erosion rate for the communities of Holopeka and Koulo was assessed at 0.12 m/year, resulting in a setback zone of 25 m. The shoreline south of the harbour between Pangai and Hihifo has a mean annual erosion rate of 0.72 m/year. This shoreline has been heavily modified and is sediment-starved, leading to a coastal setback zone of 110 m. The stable section of shoreline near transect 30 has been pinned by an outcrop of beach rock.

The erosion rates and setback zones are not predictors and should not be taken to indicate that the shoreline at Pangai will continue to erode by some 70 cm per year, or a total of 110 m over the next 100 years. It might be less or more than this, and there may be significant variations between years due to variabilities in storm conditions or sediment supply. Still, the rates are useful as they give an indication of what has happened in the past in terms of shoreline erosion; the coastal setback zones take into account potential future conditions to support decision-making and adaptation planning.



Table 3: Coastal setback zone dimensions and summary of parameters.

	Pangai and Hihifo	Koulo and Holopeka
Mean erosion rate (m/year)	0.72	0.12
Standard deviation (m)	0.32	0.07
Safety buffer (m)	6.10	6.10
Resultant setback zone (m)	110	25

## 4.2 Coastal inundation

The results shown below follow subheadings as per the six steps summarised in Table 2.

### 4.2.1 Storm track

The TCRM computed 1,000 years of tropical cyclones, with a total of 7,012 individual cyclones and their tracks and associated data. A subset of tracks for the first 50 years is visualised in Figure 13. Further output examples from TCRM are shown in Figures 14 and 15.

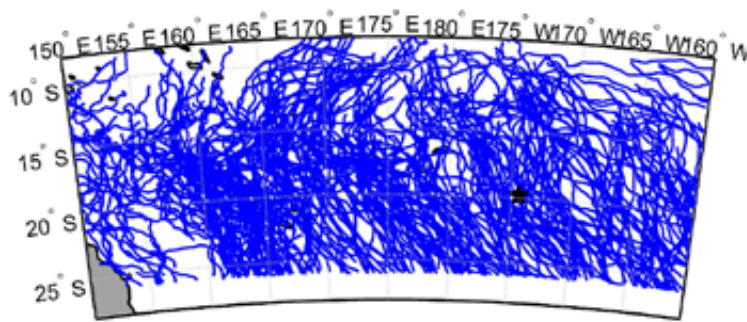


Figure 13: Map showing the synthetic cyclone tracks (blue) produced by TCRM. Only the first 50 years are shown for clarity. The location of Lifuka is indicated by the black star.

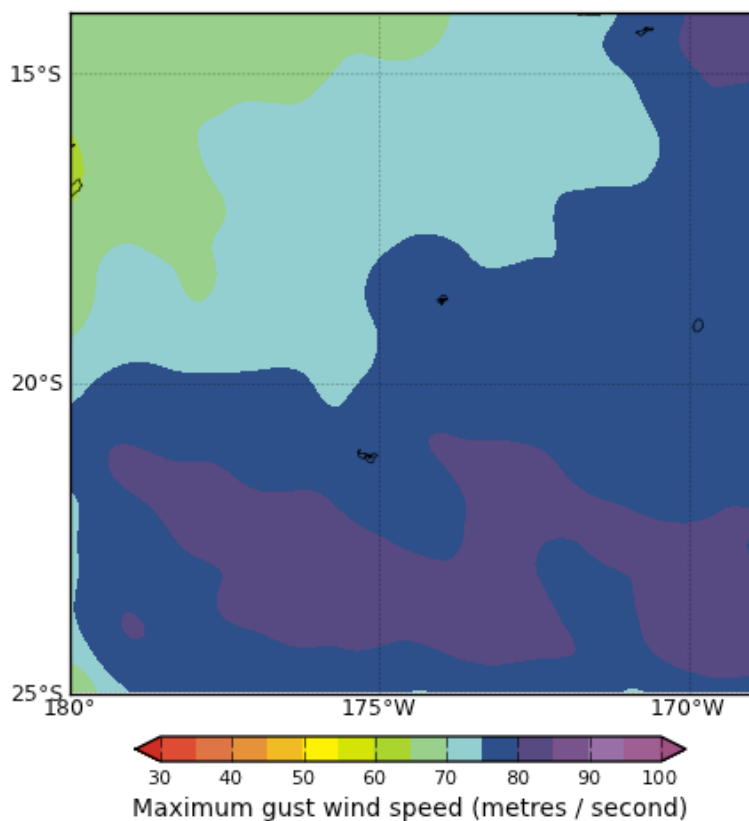


Figure 14: A 100-year return period cyclonic wind hazard map generated by TCRM centred on Lifuka. Note that the region south and southeast of Lifuka was modelled to experience greater wind gusts (90 m/s) than the area to the northwest, with wind gusts there at around 70m/s.

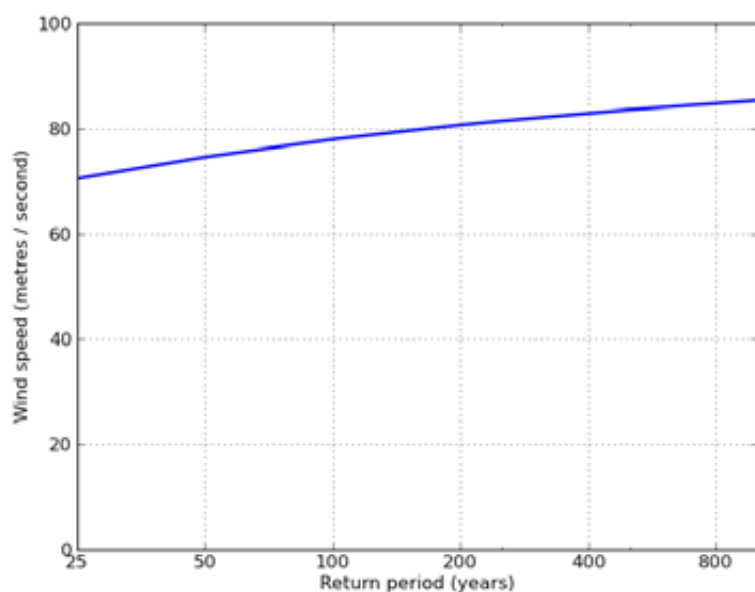


Figure 15: Return period wind speeds (m/s) at Ha'apai, Tonga (174.3W, 19.8S). The 100-year return wind speed is approximately 79 m/s.

#### 4.2.2 Storm waves

Significant wind-wave heights for the region around Lifuka are shown in Figure 16.

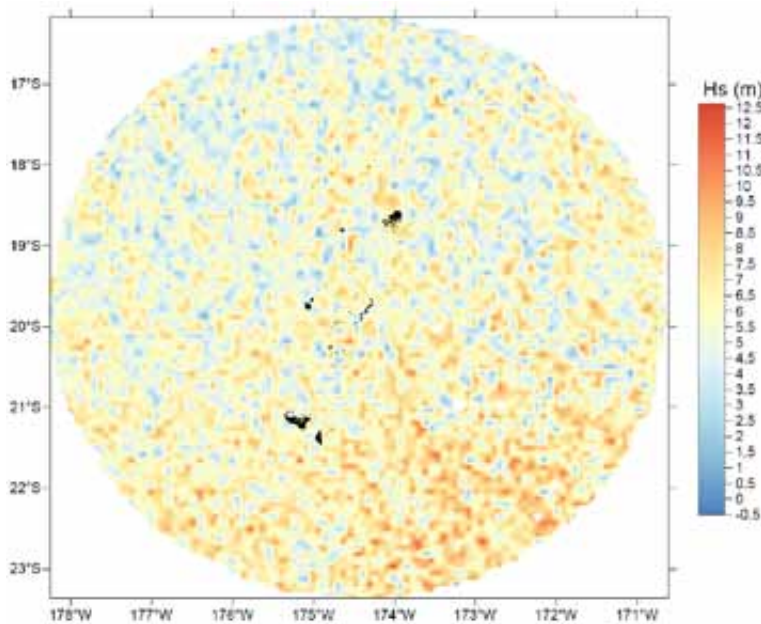


Figure 16: Significant wave height ( $H_s$ ) gridded over an area with a 400 km radius centred on Lifuka (land mass plotted in black) as modelled by the Young parametric wave model. Note that  $H_s$  is higher to the south and southeast of the region, corresponding to greater TCRM wind gusts in this area (c.f. Figure 14). Maximum wave heights ( $H_{max}$ ) of individual waves can be twice as high as  $H_s$ .

#### 4.2.3 Extreme condition

An example of the results of the extreme value analysis (EVA) for the tropical cyclone induced wave climate is shown in Figure 17.

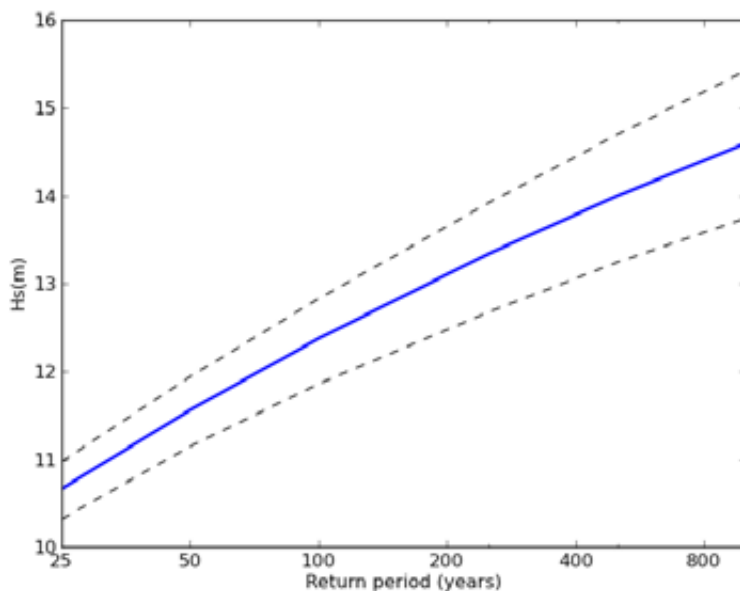


Figure 17: Return period significant wave heights ( $H_s$ ) for Lifuka. The 100-year return  $H_s$  is 12.3 m. The dashed lines indicate the 95% confidence interval.

A similar approach to compute return periods for waves was used by Scott Stephens, Coastal Modeller, National Institute of Water and Atmospheric Research NIWA, (pers. comm. July 2013). He found that extreme  $H_s$  depends more on the occurrence rate of tropical cyclones than on the track data. Using three

different wave parametric models, Stephens found the median 100-year return interval for Nuku'alofa to be 13.4 m (using Young 1988); 11.9m (after Cooper 1988); and 14.6 m (using Ross 1976). These results are similar to the value of 12.4 m for Lifuka used in this study (Figure 17), also considering that Lifuka is 180 km north-northeast of Nuku'alofa. It needs to be noted that none of these results incorporates land sheltering or topographic effects of any kind; the waves are generated on the assumption of deep, open-ocean conditions. The EVA analysis was carried out for all metocean parameters considered in this study and are summarised in Table 4. Wind speed and air pressure influence storm surge, and the wave heights contribute to inundation through the processes of wave set-up and run-up (c.f. Figure 7). The low air pressure during cyclones leads to the inverse barometric effect, whereby the water level rises by 1 cm/hPa. For example, if Tropical Cyclone Ofa, which struck the region in 1990, had passed directly over Lifuka, the water level due to the inverse barometric effect would have been around 0.88 m.

*Table 4: The 100-year return period values for metocean parameters considered in this study. The 100-year return period values have a one per cent chance of occurring in any one year, and are likely to occur or be exceeded within the anticipated life cycle of critical infrastructure (e.g. a hospital or power plant).*

Parameter	100-year return period value
Wind speed	244 km/h
Air pressure	70 hPa below ambient pressure
Wave height	12.3 m

#### 4.2.4 Boundary scenarios

The XBeach hydrodynamic model is configured using a collection of files that hold information on the bathymetry, boundary conditions, model settings, etc. Table 5 summarises some of the boundary conditions and their settings to simulate water levels, conditions and sea-level rise scenarios, in addition to the winds and waves described in the previous section. The final hazard map was produced using an intermediate-high scenario with a total water level of 2.1 m by the year 2111, in addition to the 100-year return level metocean conditions.

*Table 5: Lifuka sea-level scenarios. Sea-level rise scenarios do not predict future changes, but describe future potential conditions to support decision-making. The intermediate-high scenario was used for coastal inundation modelling to produce the final coastal hazard map.*

Contributing variable	Scenarios of sea-level change by 2111			
	Lowest	Intermediate-low	Intermediate-high	Highest
Global mean sea level	0.2	0.5	1.2	2.0
Vertical land movement	-	-	-	-
Interannual variability	0.18	0.18	0.18	0.18
Tide	0.71	0.71	0.71	0.71
Total water level	1.1	1.4	2.1	2.9

#### 4.2.5 Inundation model

Figure 18 shows the grid of the XBeach domain. This domain was run using the boundary conditions outlined in the sections above. A first run was made using only an MHWS tide level and a westerly wind perpendicular to the shoreline in order to investigate storm tide levels in the absence of waves and sea-level rise (Figure 19). The storm tide produced by the model was approximately 1.9 m at Pangai. In comparison,

water levels recorded at the Nuku'alofa tide gauge were 1.11 m during Tropical Cyclone Rene on 15 February 2010 (Figure 10).

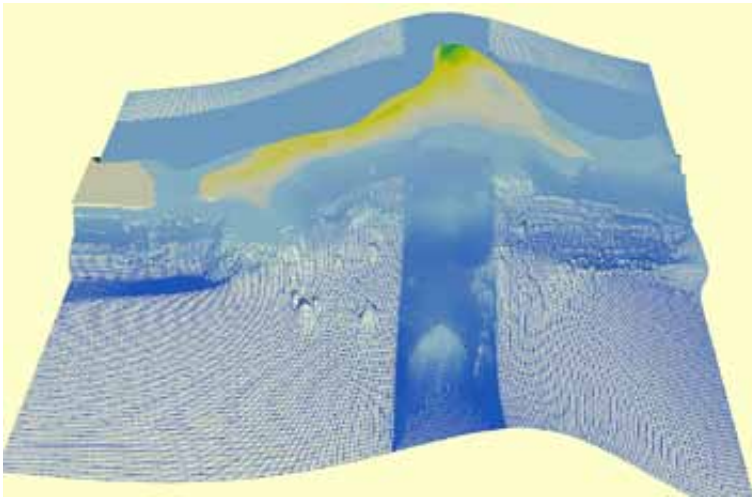


Figure 18: Curvilinear grid of the XBeach model domain. North is to the left. The offshore lagoon area to the west of Lifuka has grid sizes of approximately 30 m. The area around Pangai was modelled with a grid size of 5 m in the N–S direction and 10 m in the E–W direction. The bathymetry and topography used to construct the model is shown in Figure 2. Areas without LiDAR data were set to a water depth of 30 m.

A second preliminary model was run with only offshore wind waves. The results of this run are shown in Figure 20 and show that waves at the coastline can reach a maximum height of approximately 2 m.

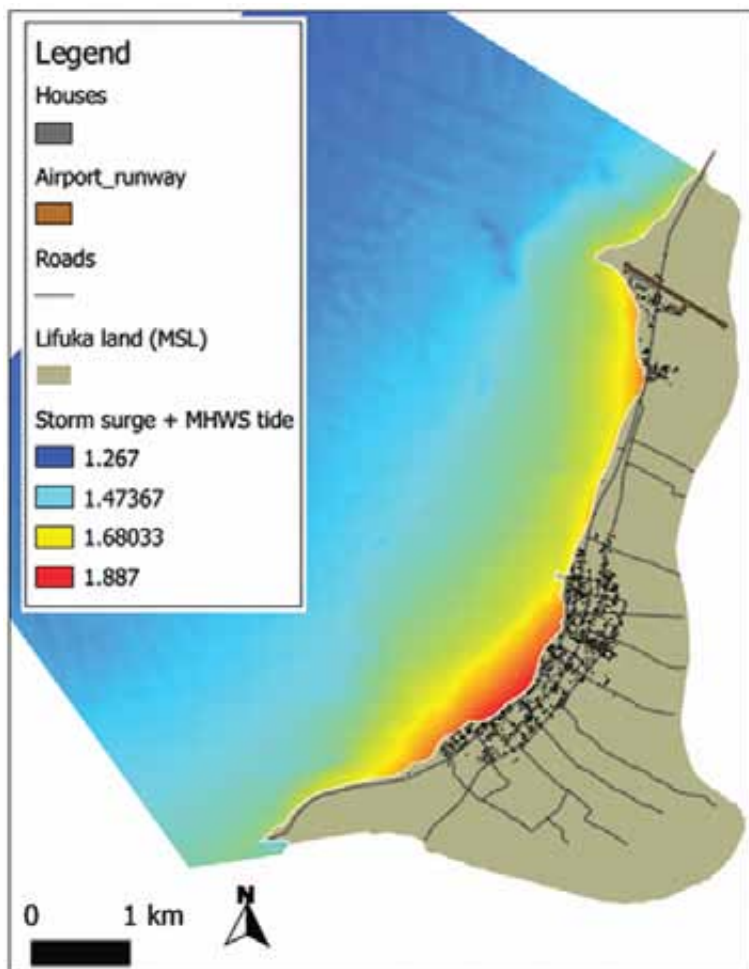


Figure 19: 100-year return period maximum storm tides. The resultant water level at the coast is about 1.9 m (MHWS plus storm surge).



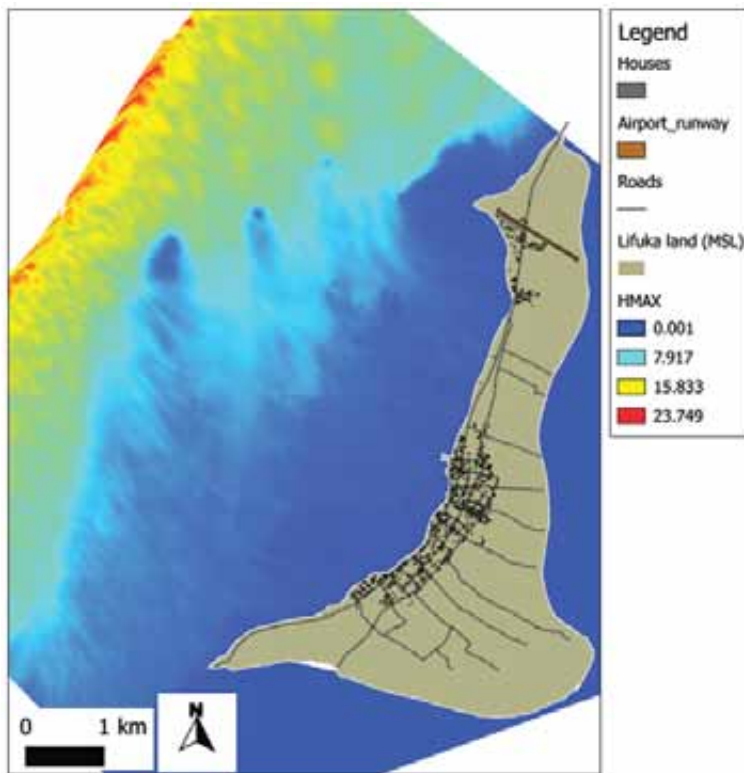


Figure 20: 100-year return period maximum wind-wave heights in metres as modelled by XBeach. Note that a wave field with significant wave heights of 12.3 m can have maximum wave heights of twice this value. These waves are attenuated as they travel into shallow waters towards the coast. The modelled nearshore wave height was approximately 2 m at Pangai.

In order to test simulated water levels and velocities output by the model, two runs were made using the metocean conditions from Table 4 in combination with: (i) total water level conditions for no sea-level rise (present day); and (ii) the highest sea-level rise scenario from Table 5. The results are mapped in Figures 21 and 22. Figure 21 shows the maximum combined water levels at the shoreline exceeding 4 m above MSL. Final runs for the purpose of hazard mapping were made using the intermediate-high sea-level rise scenario.



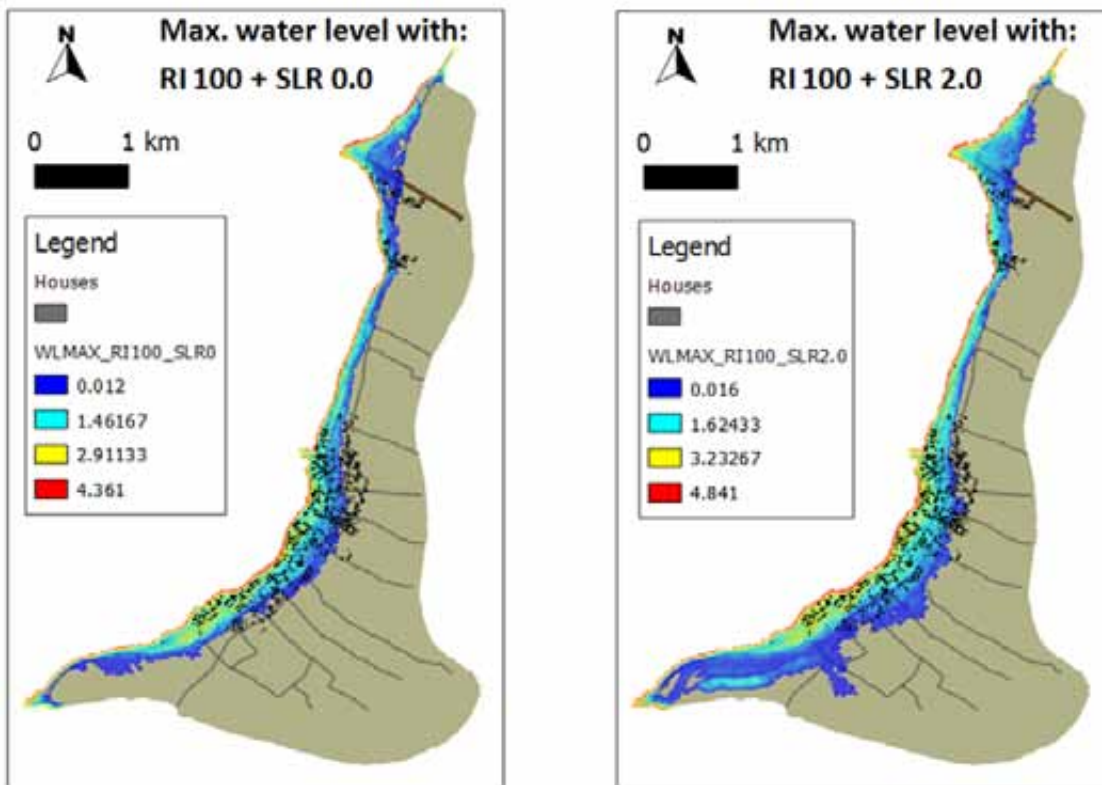


Figure 21: Maximum water levels in metres as simulated by XBeach for 100-year return interval (RI100) metocean conditions under present conditions with no sea-level rise (SLR 0.0) shown on the left, and a sea-level rise of 2 m (SLR 2.0) on the right.

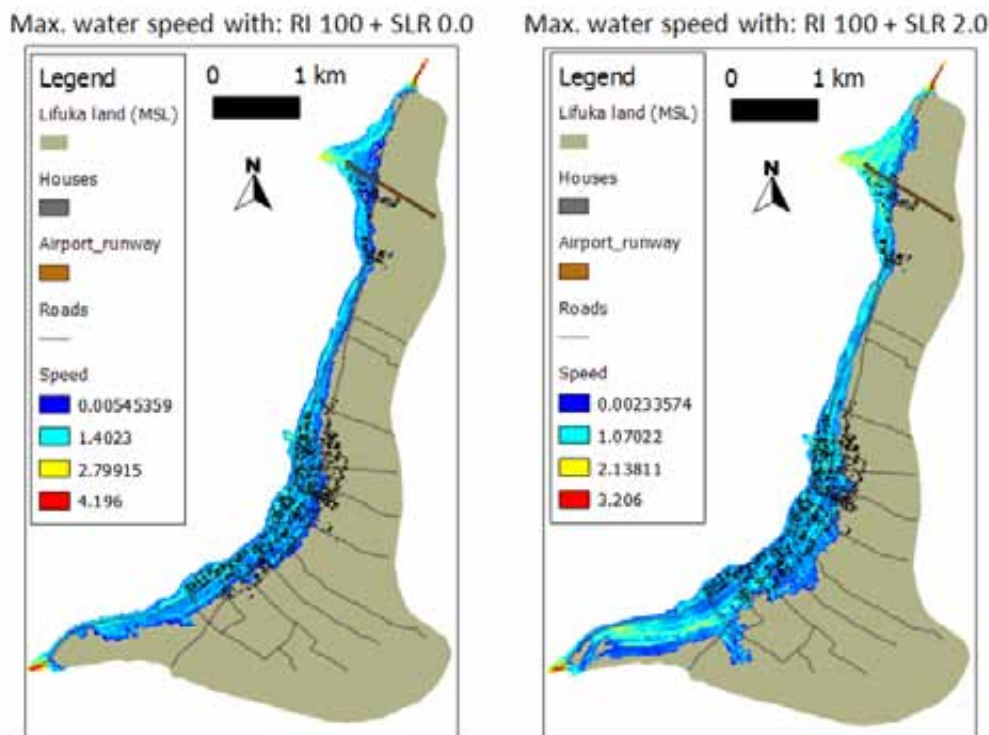


Figure 22: Maximum water speed in metres per second as simulated by XBeach for 100-year return interval (RI100) metocean conditions under present conditions with no sea-level rise (SLR 0.0) shown on the left, and a sea-level rise of 2 m (SLR 2.0) on the right.

#### 4.2.6 Inundation mapping

Final inundation maps were run using the XBeach model in conjunction with boundary conditions for metocean parameters using values from Table 4, in combination with the total water level as per the intermediate–high scenario from Table 5. Results are shown in Figures 23, 24 and 25, for Koulo and Holopeka, Pangai and Hihifo, respectively.



Figure 23: Inundation map for Koulo and Holopeka for the year 2100. The light shading indicates areas that are expected to flood under extreme one-per-cent-annual-chance storm tide conditions, an intermediate–high sea-level rise scenario, and an elevated regional sea level due to interannual variabilities (light shading). The darker shading indicates areas with additional hazards due to storm-induced wave action. The contours show depth of inundation, including wave effects, in metres above ground level.

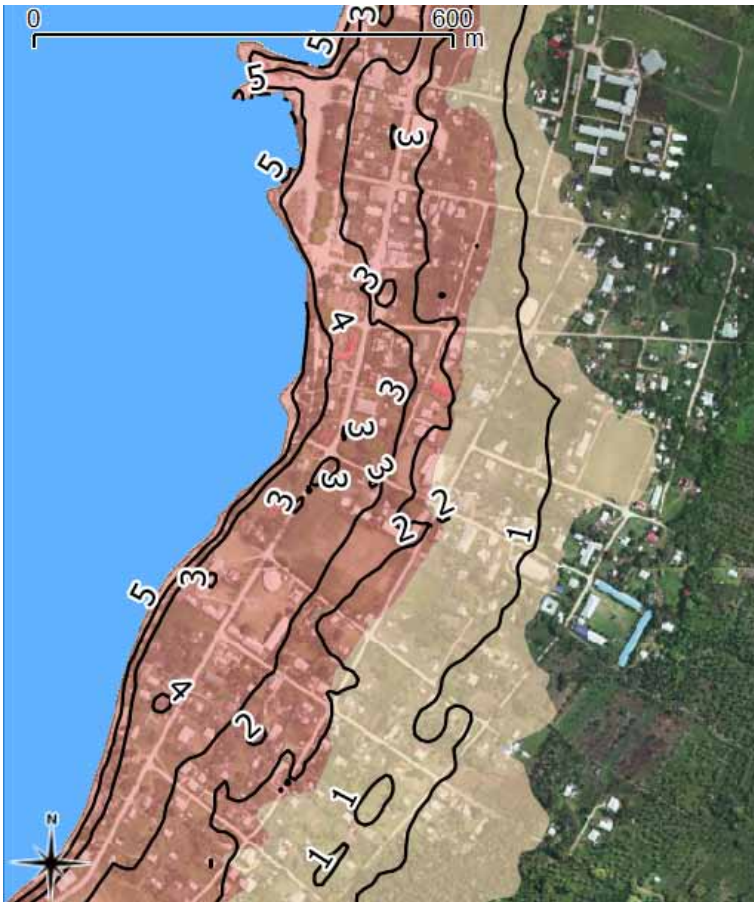


Figure 24: Inundation map for Pangai for the year 2100. The light shading indicates areas that are expected to flood under extreme one-per-cent-annual-chance storm tide conditions, an intermediate-high sea-level rise scenario, and an elevated regional sea level due to interannual variabilities (light shading). The darker shading indicates areas with additional hazards due to storm-induced wave action. The contours show depth of inundation, including wave effects, in metres above ground level.

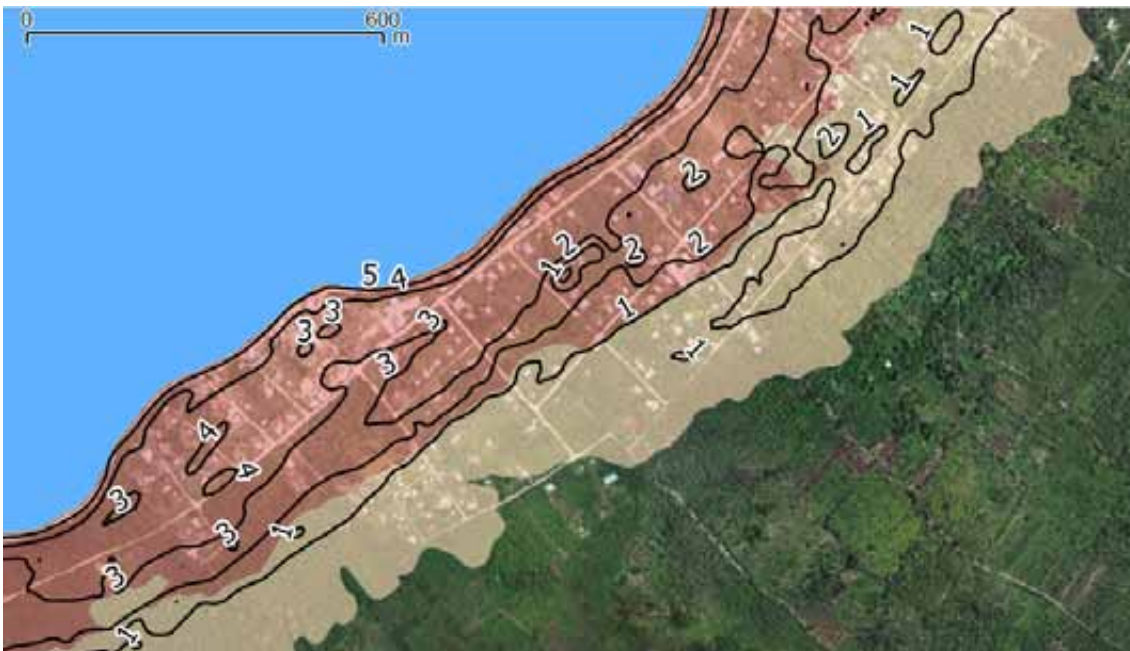


Figure 25: Inundation map for Hihifo for the year 2100. The light shading indicates areas that are expected to flood under extreme one-per-cent-annual-chance storm tide conditions, an intermediate-high sea-level rise scenario, and an elevated regional sea level due to interannual variabilities (light shading). The darker shading indicates areas that are subject to additional hazards due to storm-induced wave action. The contours show depth of inundation, including wave effects, in metres above ground level.



#### 4.2.7 Model validation

The existing repository of historical observational data (e.g. tropical-cyclone winds and barometric pressure, high-water marks, wave conditions, pre- and post-storm beach profiles) is very limited. This is one of the main reasons this project put a lot of emphasis on modelling of coastal hazards. However, the paucity of ground-truth data also means that the model could not be calibrated against a known extreme event. Tropical Cyclone Cyril passed through the area in February 2012, and a field visit was scheduled soon after to capture ephemeral data on the distance from base of beach to the debris line (inundation extent), and run-up levels, being the height of the debris line above base of the beach. The locations of these surveys are shown in Figure 26, and results are summarised in Table 6. For more information on this, please see the companion report *B.1.1 Shoreline assessment*. The horizontal extent of the inundation from the shoreline inland ranged from 13 m to 32 m, and the elevation of the ground at these locations above MSL ranged from 0.9 m to 2.0 m. The tropical cyclone was, therefore, not a large event in terms of inundation on Lifuka.

The XBeach model was then run for Cyril conditions taken from the IBTraACS repository. Wave heights were computed as  $H_s = 3.5$  m, the winds were assumed to be perpendicular to shore (westerlies), and the predicted high tide for the time of the storm was used. Upon checking the model output, it was found that the computed inundation did not penetrate more than two grid cells onto land. Given the grid cell size of the model domain is approximately 10 m in the east–west direction, this meant that land in the model domain was inundated up to a distance of about 20 m from the coast (MSL). Although this validation run did not provide conclusive results on the accuracy of the model, it did show that the simulation agreed with the ground-truthing data, given the limitations due to resolution, and did not overestimate inundation. Further ground-truthing data are required to increase confidence in the model results for Lifuka.



Figure 26: Survey locations for inundation and runup levels following TC Cyril

Table 6: Summary of land survey results following TC Cyril at the locations shown in Figure 26

Point name	Inundation extent (m) from base of beach	Elevation above MSL of inundation extent from LiDAR (m)
Holopeka 1	18	0.9
Holopeka 2	13	1.0
Pangai 1	19	1.5
Ha'ato'u 1	27	1.5
Ha'ato'u 2	22	1.2
Hihifo 1	31	2.0
Hihifo 2	32	1.4

In the Lifuka project's companion report *C.2.0 Coastal rehabilitation*, the SBEACH model was used to derive preliminary design parameters for the coastal protection structures. This is a nearshore wave transformation software, and was used to run a single one-dimensional profile line perpendicular to the Pangai coastline with the following boundary conditions:

- deepwater significant wave height of 8 m (as inferred from the ECMWF data for Cyclone Ofa in the open ocean in the vicinity of Lifuka Island);
- water level based on predicted astronomical tide during Cyclone Ofa in February 1990;
- a tidal anomaly based on the barometric set-up predicted from the MSL pressure information in the ECMWF data;
- an onshore wind speed of 23 m/s, as predicted by the ECMWF model during Cyclone Ofa.

The main findings were that the nearshore water level could reach 3.6 m above MSL at the shoreline, and that maximum wave heights could reach more than 2 m at the shoreline. Jones (1993) also mentions that wave set-up can cause combined water levels of up to 4.0 m on Lifuka. Although these results do not validate the XBeach model, they did provide an independent check for the XBeach modelling results.

### 4.3 Coastal hazard map

The results from the coastal setback and inundation assessments were combined into a coastal hazard map with three zones as defined in Table 7. A detail of the map for the Pangai area is shown in Figure 27.

Table 7: Definitions of Lifuka’s coastal hazard zones and recommended strategies for adaptation and risk reduction. ‘Buildings’ in this regard refers to new construction, substantial improvement, and repair of substantially damaged buildings. Technical guidance and recommendations concerning the construction of coastal residential buildings can be found in the Home Builder’s Guide to Coastal Construction ([www.fema.gov/library/](http://www.fema.gov/library/)).

Zone	Hazard	Recommendation
Long-term coastal erosion zone	This is the zone subject to erosion as well as the most intense natural forces from tropical cyclones and extreme storms with high-velocity wave action from damaging waves of 1 m or greater.	Any construction in this zone is to be avoided. All buildings must be located landward of the reach of the zone. Critical infrastructure in this zone should be considered for relocation. Removing sand or vegetation may increase potential flood damage and erosion. Instead, this zone should be vegetated and allowed to maintain its natural integrity.
Coastal high hazard area	This area is subject to inundation from tropical cyclones and extreme storms with high-velocity wave action from waves of 1 m or greater.	Building critical facilities in this area is to be avoided. All other buildings must be constructed on an open foundation (e.g. posts or columns) and the top of the lowest floor must be above the depth of inundation. Consider extra freeboard to add a margin of safety. Enclosed space below the lowest floor must be free of obstructions.
Coastal hazard area	This area is subject to inundation from tropical cyclones with wave characteristics that are sufficient to damage structures on shallow or solid-wall foundations.	Building critical facilities in this area is to be avoided. All other buildings must be constructed on an open foundation (e.g. posts or columns) and the top of the lowest floor must be above the depth of inundation. Enclosed space below the lowest floor of buildings may be used only for storage or parking and the walls must be of open design to allow entry and exit of water.

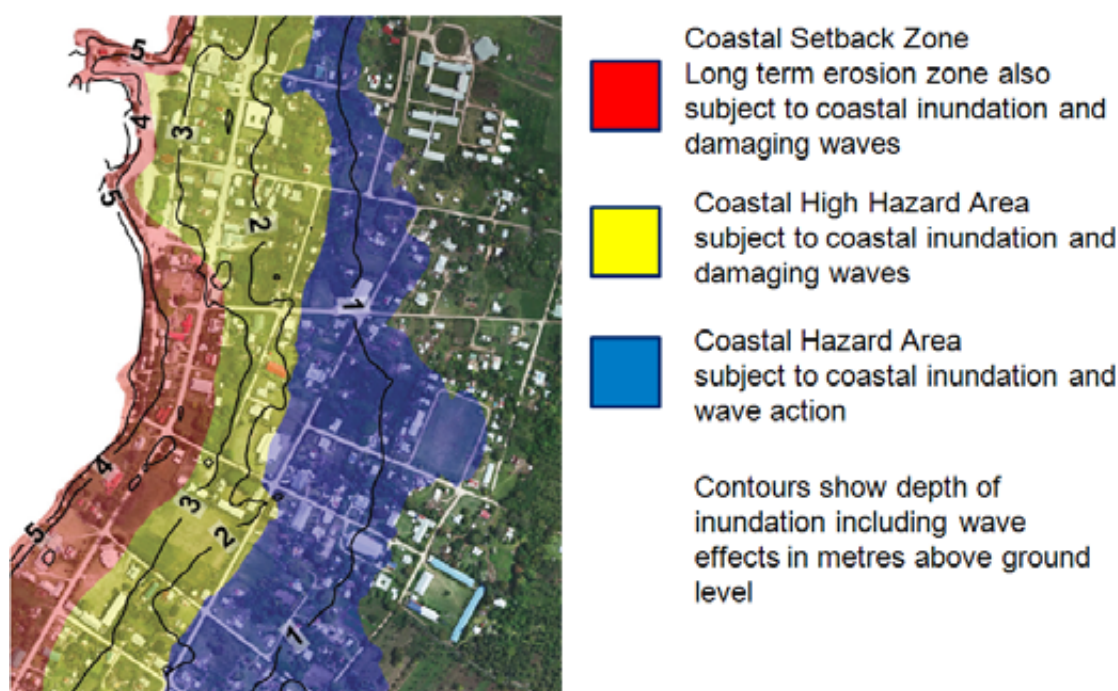


Figure 27: Detail of the coastal hazard map for the Pangai area. This map brings together the results of the inundation modelling as well as the shoreline change analysis.

A poster-sized (A0) map was created and used to disseminate findings and inform discussions with technical stakeholders (Figure 28). A simplified version in the Tongan language was also produced (Figure 29) and used extensively in community consultations on Lifuka.



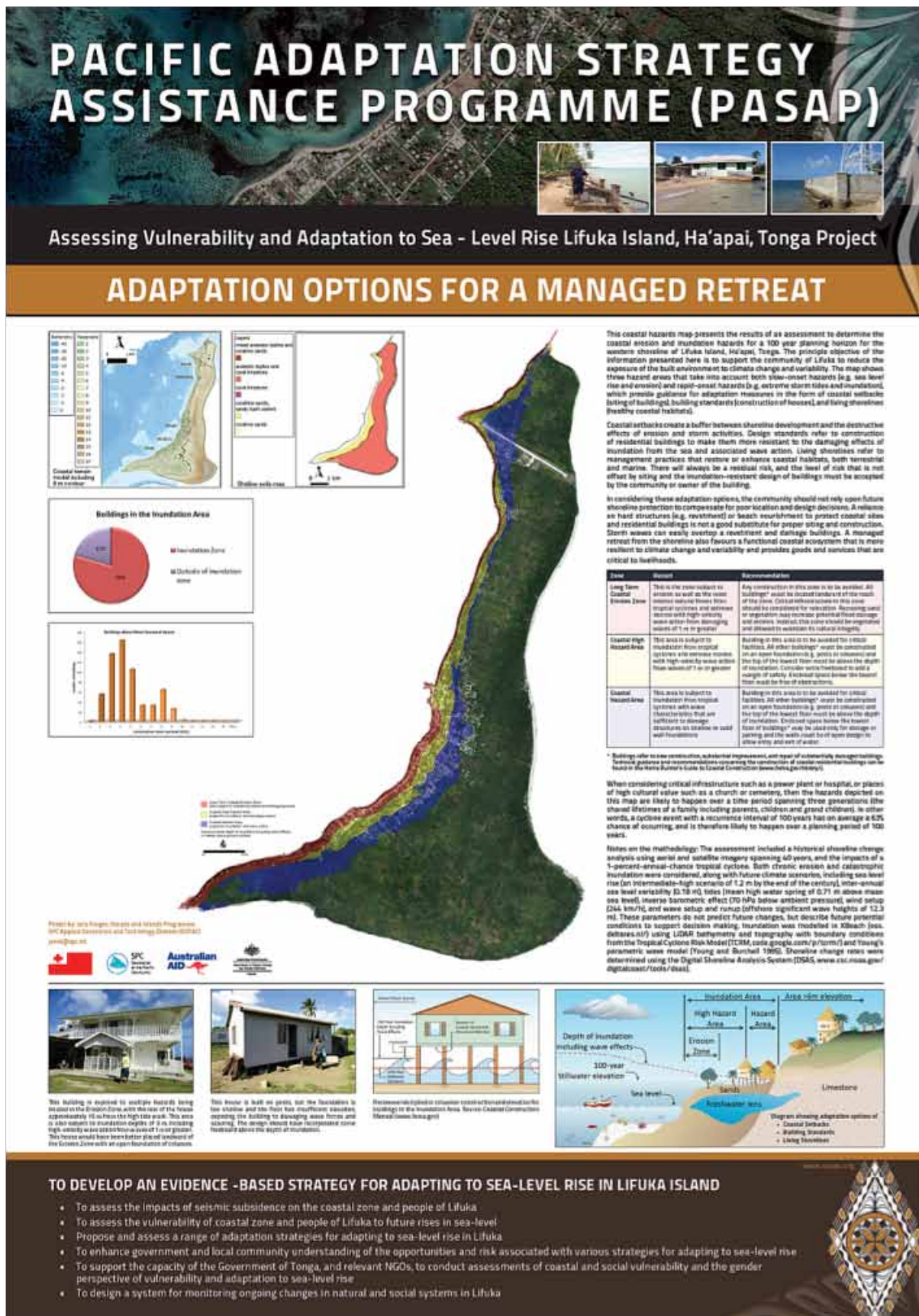


Figure 28: Coastal hazards poster used for government stakeholder consultations in Nuku'alofa, as well as project advocacy at meetings and technical workshops



# PACIFIC ADAPTATION STRATEGY ASSISTANCE PROGRAMME (PASAP)

Assessing Vulnerability and Adaptation to Sea - Level Rise Lifuka Island, Ha'apai, Tonga Project

ADAPTATION OPTIONS FOR LIFUKA/ NGA'AHU FOUNGA KE MATU'UAKI 'AKI 'A E PALOPELEMA 'I LIFUKA

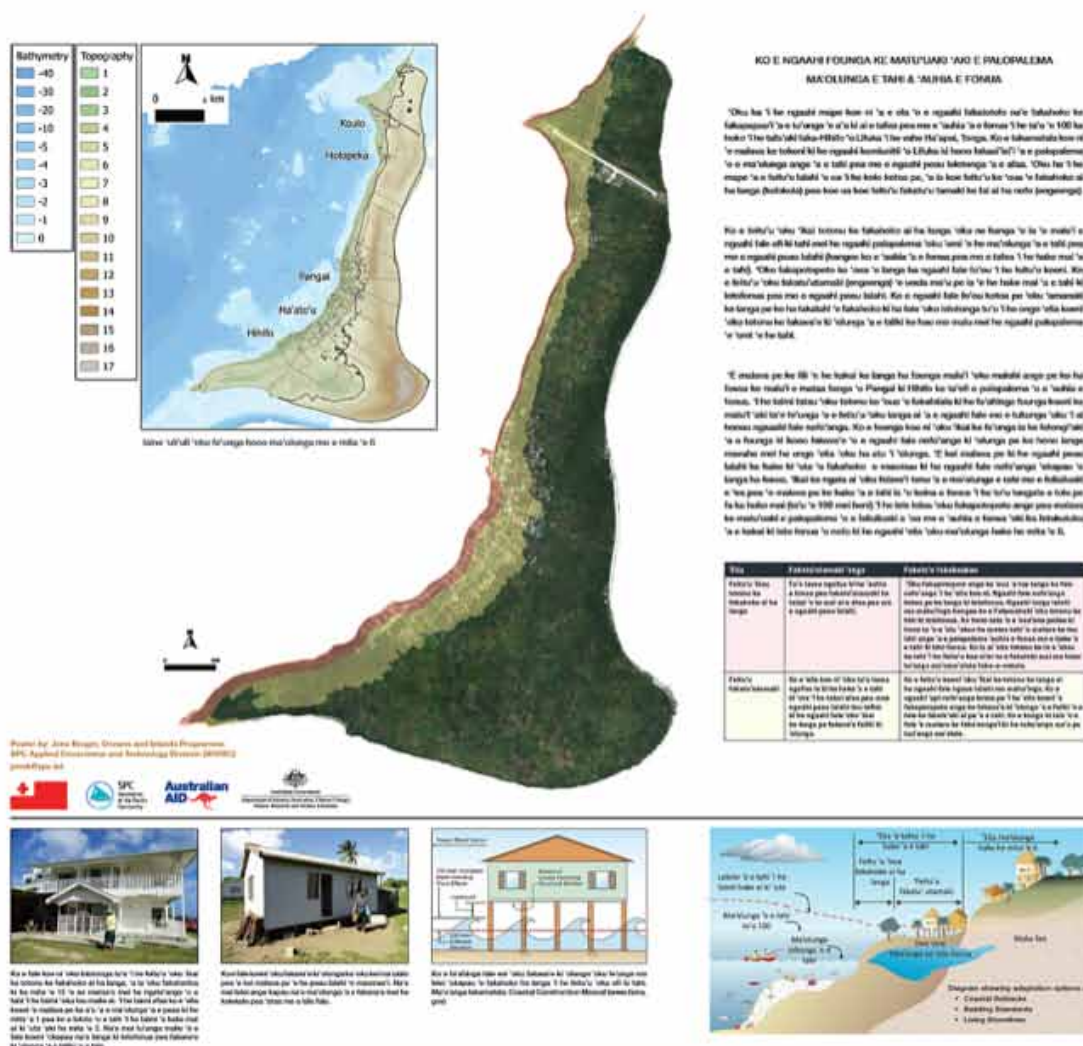
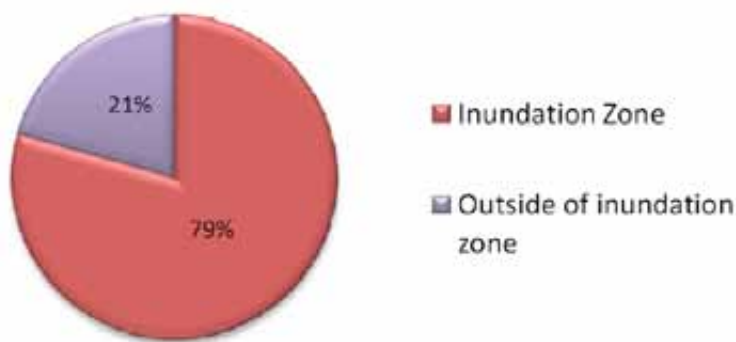


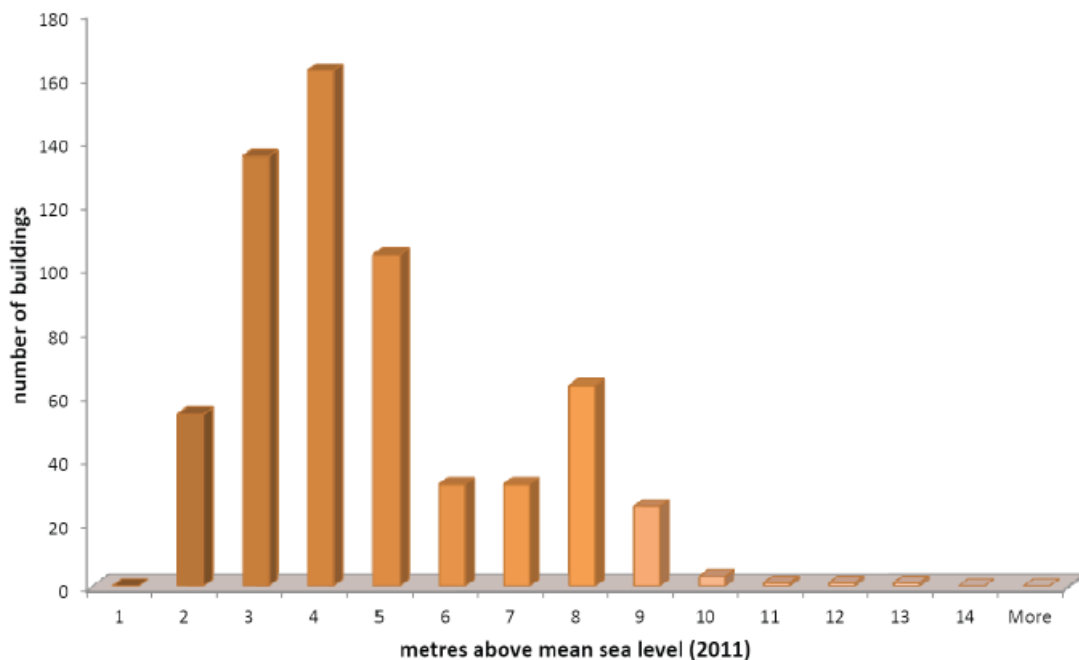
Figure 29: Tongan version of the coastal hazard poster. This version is a slightly simplified version with only two hazard zones (setback and inundation zones), and was widely used during the final community consultations on Lifuka.

## 5. Discussion and conclusion

GIS analysis of the hazard areas with digitised building footprints revealed that almost 80% of the houses are situated within the hazardous inundation zone (Figure 30). It has previously been illustrated that the majority of houses are situated within the low-lying coastal plains of the western shoreline (Figures 2 and 3), and further analysis of this dataset shows that most houses are situated in locations that are only 3–4 m above MSL (Figure 31) and in close proximity to the shoreline, leaving them highly vulnerable to coastal hazards.



*Figure 30: Percentage of buildings within the inundation zone identified by the hazard map. A large proportion (79%) of all the buildings on Lifuka are situated within coastal hazard areas subject to inundation.*



*Figure 31: Histogram of building elevation on Lifuka. The majority of buildings are below the 6 m contour identified as a minimum recommended elevation for new construction and siting of critical infrastructure.*

Since the first human occupation of Lifuka, the preferred areas for settlement have always been the low-lying coastal plains of the western shoreline (Marais 1990; Dickinson and Burley 2007). This has been aided by the fact that the plains comprise unconsolidated sands that prove to be much better reservoirs for freshwater than the porous limestones of higher elevation further inland (see companion report *B.1.2 Groundwater resources assessment*). However, it has only been in the last decades that these coastal margins have seen increasingly inappropriate development that has either placed infrastructure unnecessarily in harm's way (Figure 32), or negatively impacted on the natural functions of the coastal zone (Table 8).



Figure 32: Images showing the development of coastal areas in Hihifo. The left-hand image is a 1968 black and white aerial photograph overlain with the 2011 shoreline (in yellow). The right image is the 2011 digital orthophotomosaic overlaid with the 1968 shoreline (red). The development of this low-lying and eroding coastal area has seen infrastructure such as roads, water supplies, electricity lines and public assets such as the hospital (large building near the top right-hand corner) and private homes become increasingly exposed to coastal erosion and inundation.



Table 8: Summary history of harbour development in Pangai, Lifuka (Sources: Jones 1993; AusAID 1999)

Docking facility	Comment
Piled jetty	Until 1982 a jetty consisting of concrete piles and a timber deck was located inside the inlet.
Causeway jetty	In 1982 a stone causeway and ramp were constructed across the reef flat outside the entrance to the natural inlet, and coral heads in the area were blasted to provide a swing basin.
Pangai Harbour	<p>Design of the harbour was commissioned by the Australian International Development Assistance Bureau (AIDAB), and the present harbour opened in 1996.</p> <p>Three years after the completion of the harbour a study concluded that 'there are no reports of negative environmental impact due to the project since its completion (...) the harbour has deliberately been left open at the south and north ends to facilitate tidal currents and flushing of associated sediment loads. However, some accumulation of sediment is inevitable.'</p> <p>Construction of the harbour has effectively interrupted the longshore sediment transport, significantly reducing the sediment supply to the beaches south of Pangai Harbour, and contributing to chronic erosion in this area.</p>

Coastal hazards affecting the shoreline are likely to worsen with climate change. As the effects of the coastal hazards worsen, the ability of the community to maintain infrastructure in its current locations begins to decline. Eventually, if no action is taken, the structural integrity of coastal buildings will be compromised, and properties will be unsuitable for human habitation. As an adaptation option, living shoreline approaches that favour ecosystem services are generally recommended over hard structures (e.g. revetments). In the case of Lifuka, this can only be accomplished through a managed retreat guided by the hazard map in combination with the elevation of buildings (Figure 33).

However, the communities of Lifuka are paralysed by the complexity of the land tenure system and cost of relocation. They are, therefore, unable and unwilling to readily adopt managed retreat as an approach to adaptation. In fact, the majority are in favour of a revetment. Communities therefore need support with land rights issues in addition to guidance on building standards and appropriate siting. Only communities with the capacity to adapt are likely to be more resistant to impacts, or able to recover from extreme events.

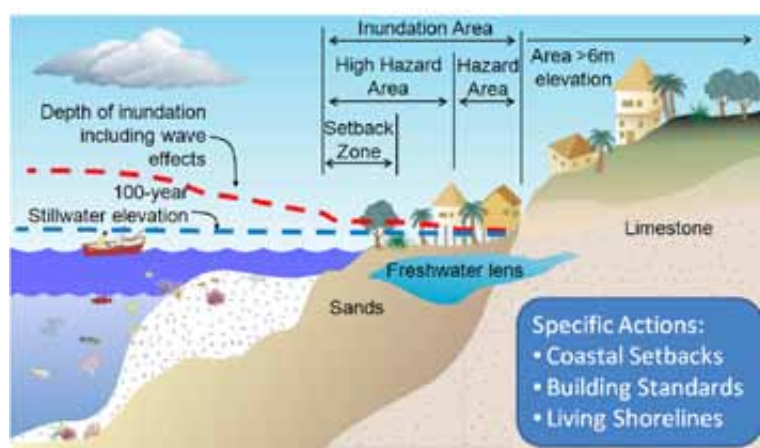


Figure 33: Conceptual diagram of coastal hazard map and adaptation options for Lifuka. The recommended adaptation option of managed retreat will include the elevation of houses in the inundation area outside of the setback zone, and preferential development of areas above the 6 m contour. The shoreline should be free of any obstructions that reduce its ability to adjust dynamically to changing forcing conditions. The 100-year stillwater elevation is the water level with a one-per-cent-annual-chance of being exceeded in a given year.



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