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Probabilistic cyclone and swell-driven inundation hazard assessment: Lenakel, Tanna, Vanuatu

Geoscience, Energy and Maritime Division of the Pacific Community

KFW

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EXECUTIVE SUMMARY

Coastal hazards such as tsunami, storm tides and wave-driven flooding frequently challenge coastal settlements, infrastructure and ecosystems in the Pacific region. Climate variability and change, including sea-level rise trends and changes in weather patterns, are also likely to add pressure on coastal communities. If not planned for, coastal processes can damage public and private assets and facilities. Local governments and municipalities often carry the burden of managing such risks.

The report of the post-disaster needs assessment (Esler 2015) carried out for Vanuatu after Tropical Cyclone (TC) Pam in 2015 highlighted the need for multi-hazard mapping of urban areas and for action plans to identify safe areas for future growth. The report also emphasised the importance of having a sound scientific basis for predicting hazards.

In 2016, the Pacific Community (SPC) started working on a component entitled *Multi-hazard mapping to inform improved resilience of coastal communities, Lenakel* under the SPC TC Pam Recovery Project funded by the German Development Bank (KfW). This component was designed to develop coastal hazard maps to identify vulnerable areas in Lenakel, Tanna, and provide tools and training for the dissemination of the information, both at the central and provincial government level.

Sound and robust methodologies, combining stochastic, parametric, dynamic and meta-modelling, have been implemented to assess the inundation hazard from tropical cyclones and from the co-occurrence of swell and high-water level.

This study highlights the relatively low vulnerability of Lenakel to a metocean-driven inundation hazard. However, the risk assessment exercise undertaken by Vanuatu central and provincial government stakeholders during a coastal hazard and planning workshop stressed that key assets, such as the wharf and the market, were facing a high risk.

The results of the study should guide future development plans of Lenakel so that the number of assets within the hazard prone areas remains relatively low.

I. INTRODUCTION

I.1 Background

In December 2015, the Government of the Federal Republic of Germany, through the KFW Banking Group, signed an agreement with SPC for the delivery of a project designed to provide support to Pacific Islands affected by TC Pam.

The project, SPC Recovery Support for Tropical Cyclone Pam, is implemented through 42 packages involving a mix of advisory services, field activities and investments to support recovery from the cyclone in affected parts of Vanuatu, Tuvalu, Kiribati and Solomon Islands. The project is structured in two phases. Phase 1 comprises technical capacity support for damage assessments in the immediate aftermath of the cyclone. Phase 2 is significantly longer, involving implementation of a combination of multi-sector activities targeted at specific recovery needs identified by each country.

I.2 Project objectives and activities

Vanuatu is highly vulnerable to natural hazards either from geophysical or hydro-meteorological hazards. The post-disaster needs assessment (PDNA) report (Esler 2015) emphasises that a mid- to long-term reconstruction effort is to be driven by improving resilience in all sectors.

The PDNA highlights the need for multi-hazard mapping of urban areas and action plans to identify safe areas for future growth. The report also mentions the importance of having a sound scientific basis for predicting hazards and a reliable forecasting system.

The Geoscience, Energy and Maritime Division of SPC proposed to assist the multi-hazard mapping effort already under way in Port Vila and Luganville (World Bank MDRR project) by undertaking a similar activity in an appropriate location, Lenakel, Tanna (population of about 14,000 people). The study aims to identify the probable risk of coastal inundation from tsunamigenic earthquake, cyclone and the co-occurrence of large swell with possible high storm tide level. The study also investigates the possible exacerbation of the inundation risk inherent from sea-level rise. Community members were engaged to provide information and data, and to participate in the development of response plans.

Through this project SPC aimed to deliver:

- geospatial baseline data used in cross-sector activities, e.g. topography, bathymetry;
- hazard maps to identify low hazard-prone land suitable for future growth;
- tools and training for the dissemination of the information, both at the central and provincial government level; and
- a support response plan for the municipality and adjacent communities.

I.3 Purpose of this report

This report describes the methodology and results of the probabilistic swell-driven inundation hazard assessment undertaken for Lenakel, Tanna Island, Vanuatu. The report also outlines the training that was conducted in August 2018 to promote the use of hazard information to support planning decisions.

II. Cyclone-driven inundation probabilistic hazard assessment

II.1 Vanuatu cyclone threat profile

According to the annual world risk report published by the United Nations University's Institute for Environment and Human Security, Vanuatu has been considered, for four years running, the most disaster-prone country in the world as it is highly exposed to a wide range of hazards, such as earthquakes, tsunami and cyclones.

Vanuatu is located at the centre of the Pacific tropical belt, which is known for the frequent occurrence of tropical cyclones driving damaging winds, rains and extreme ocean conditions, leading to inundation events. Between 1990 and 2011, Vanuatu experienced at least twenty tropical cyclones: almost one each year (Pacific Catastrophe Risk Assessment and Financing Initiative [PCRAFI], Country Risk Profile, 2011).

PCRAFI (2011) reports that Vanuatu is expected to incur, on average, USD 48 million worth of damage per year due to earthquakes and tropical cyclones. In March 2015, TC Pam caused widespread damage across the country. According the post-disaster need assessment damage, loss and needs in the aftermath of TC Pam was estimated at USD 450 million; 64% of Vanuatu's GDP.

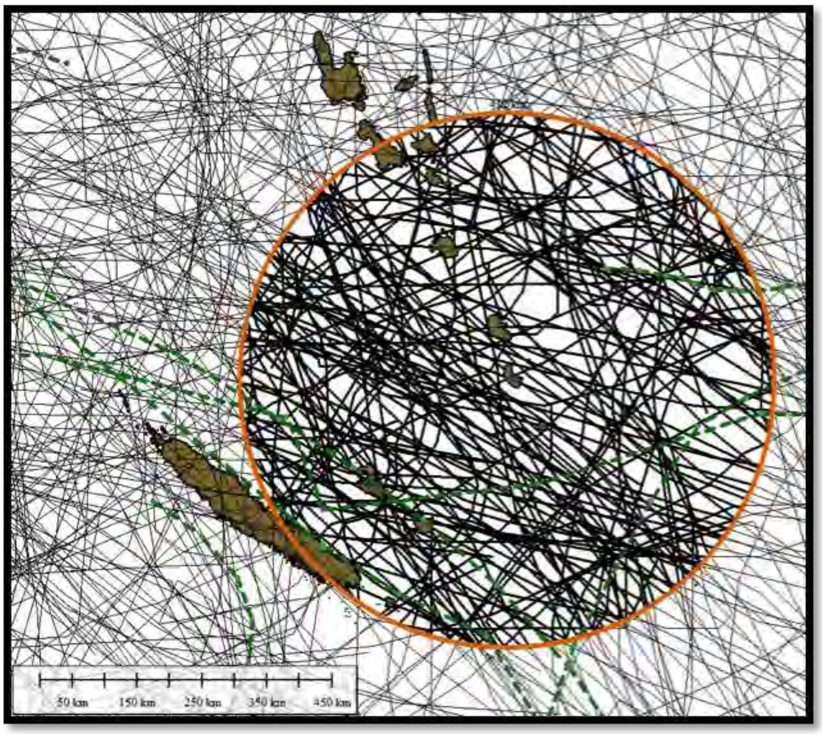

Figure 1: Historical tropical cyclones that passed within 4 degree (~400 km) of Lenakel between 1916 and 2016 (source: IBTrACS database https://www.ncdc.noaa.gov/ibtracs). The orange circle represents the 4-degree radius centered on Lenakel. The cyclone tracks are represented in grey lines and thick black lines for tracks outside and inside the 4-degree radius respectively. The green tracks represent the paths of the 1956 cyclones.

Lenakel town has experienced numerous cyclones over the last hundred years. According to the International Best Track Archive for Climate and Stewardship (IBTrACS, https://www.ncdc.noaa.gov/ibtracs/), 151 tropical cyclones passed within a 4-degree radius (~400 km) from Lenakel between 1916 and 2016 (**Error! Reference source not found.**). Witness accounts and landmarks of past tropical cyclones can easily be found (Figure 2) in Lenakel. However, their use in this study is limited due to: (i) the lack of understanding of local seismic activity over the last 100 years, which potentially led to a significant uplift of the coastal zone; and (ii) the potential inaccuracy of the historical hazard information. The landmark from the 1956 tropical cyclone event represents, on today's topography, a run-up greater than 15 m. The most damaging cyclone that passed near Tanna Island in 1956 was a category 2 cyclone named Agnes (as per IBTrACS). It is unlikely that a cyclone of category 2 generated the necessary extreme ocean condition to drive an inundation run-up of 15 m. For comparison, TC Pam, a category 5 cyclone, generated a run-up as high as 7 m northeast of Efate (Damlamian 2017).

Figure 2: Landmark in Lenakel representing inundation extent from 1956 tropical cyclone (with a 15–20 m run-up)

II.2 Methodology

Various methodologies are being used to assess inundation hazard from tropical cyclones.

II.3 Inundation hazard based on an extreme historical event

One of the simplest methodologies consists of assessing tropical cyclone hazard solely by investigating known historical events. The limitation of such a methodology resides in the relative short tropical cyclone historical records compared to the high variability of tropical cyclone genesis and behaviour.

As part of the EU-funded project – Supporting Disaster Risk Reduction in Pacific Overseas Countries and Territories – the French Polynesia government requested SPC to map cyclone wave inundation models for five atolls in the Tuamotu Archipelago, with the aim of including this information in future development plans and risk prevention solutions (Damlamian et al. 2013). To ensure consistency in the French Polynesia's risk prevention plans, SPC was required to focus on a predefined characteristic cyclone event, based on the most extreme event experienced during the last 25 years. A 12 m wave height, combined with a 1 m storm surge occurring at spring high tide, characterises the ocean condition generated by tropical cyclone Nisha-Orama in 1983 off Anaa atoll. It completely wiped out the village.

This methodology limits the usability of the hazard data, as the likelihood of the predefined characteristic event is unknown. The produced inundation hazard being extreme, a risk reduction solution would require major investment. Without perspective on the likelihood of such a disaster, the information is unlikely to become actionable.

II.4 Stochastic, parametric and dynamic modelling approach

As part of the Australian funded project, Assessing Vulnerability and Adaptation to Sea-level Rise: Lifuka Island, Ha'apai, Tonga, under the Pacific Adaptation Strategy Assistance Programme, SPC undertook a probabilistic tropical cyclone-driven inundation hazard assessment for Lifuka island (Kruger 2013).

The methodology for the assessment can be summarised as shown below:

- generation of a large number of synthetic cyclone tracks (1000 years of cyclone) based on a stochastic approach;
- estimation of the ocean condition for each track using a parametric wave modelling;
- development of probabilistic scenarios; and
- inundation hazard mapping using dynamic modelling.

The primary limitation inherent to this methodology resides in the use of a parametric wave model to estimate the offshore wave condition generated by each cyclone. While dynamic wave modelling can provide satisfying offshore cyclone wave information, the required computational time to simulate thousands of cyclones was deemed unpractical and fell outside the project timeline. Therefore, the Young parametric wave model (Young & Burchell 1996), a widely used and computationally efficient model to estimate cyclone wave in open ocean, was used, despite its inability to account for geomorphological interference (shallow bathymetry features, sheltering of islands, etc.).

II.5 A new methodology

The challenge in assessing the likelihood of tropical cyclone-driven inundation hazard resides in:

- the high variability of cyclone events characterised by a range of parameters, such as its origin, its potentially complex path, the changing minimum barometric pressure and cyclone forward speed;

- the small historical database relative to the variability and occurrence of cyclone events which prevents the direct use of historical data to define the probability of extremes (i.e. looking at the last 50–100 years of historical events does not provide reliable access to 25 years, 50 years or 100 years return period event).
- the likelihood of the inundation event should be assessed as a compound event, depending not only on the cyclone characteristics driving wave height, period and direction and on storm surge (wind set-up and inverted barometric pressure) but also on the tide and the mean level of the sea;
- the probability of an inundation hazard event should not be based on offshore ocean condition but on the inundation hazard itself (i.e. flood depth); and
- the high uncertainty of the changing behaviour of cyclones under climate change.

A new and innovative methodology, tailored to fronted reef shoreline, was developed as part of this project. This methodology was largely inspired by the hazard mapping work being carried out under the project Advancing Best Practices for the Analysis of the Vulnerability of Military Installations in the Pacific Basin to Coastal Flooding under a Changing Climate by the University of Cantabria and the United State Geological Survey as part of the US Department of Defence project.

The methodology that combines stochastic, parametric and dynamic and meta-modelling can be broken down into eight primary steps (Figure 3).

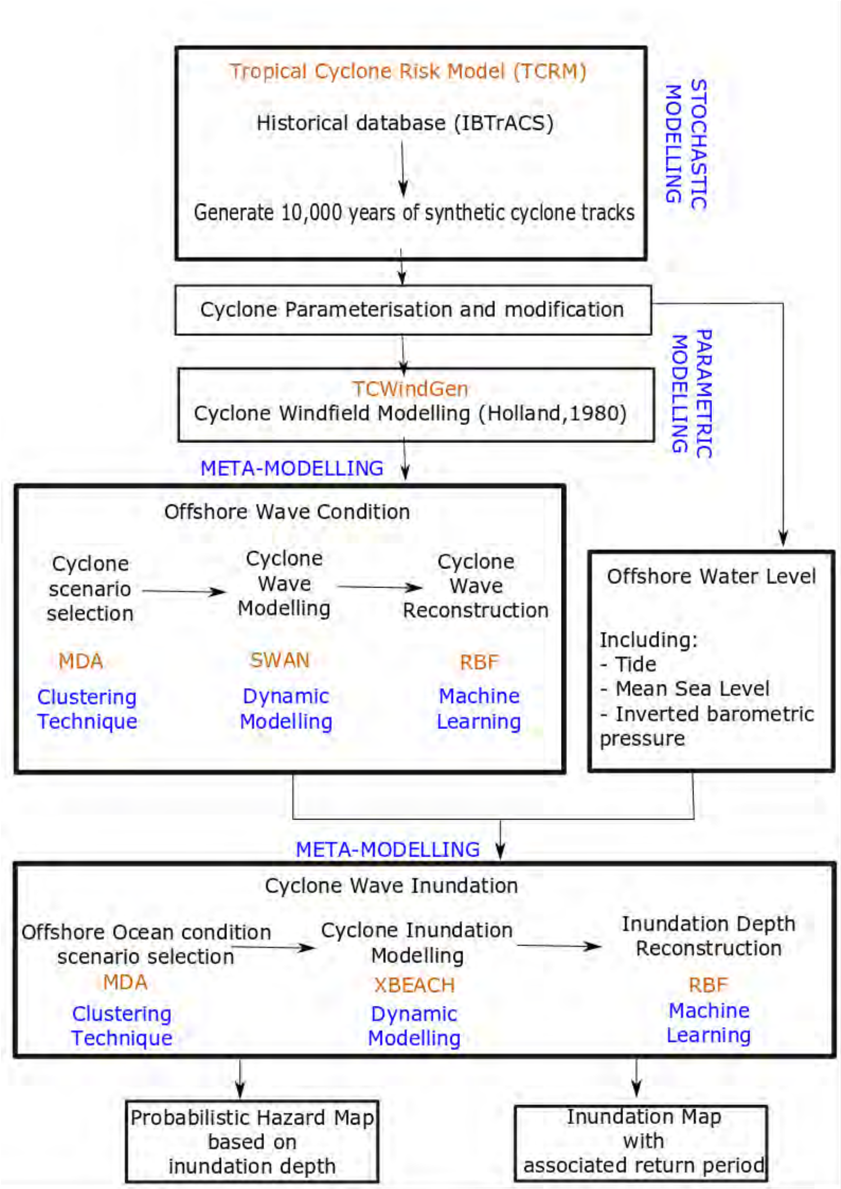

Figure 3: New methodology to assess cyclone inundation hazard, with techniques in blue and tools in orange

II.5.1 Stochastic modelling

As mentioned above, the historical tropical cyclone database cannot be used directly to assess the return period of a tropical cyclone hazard. In order to increase the robustness of the statistical analysis, the historical database needs to be expanded. Following a stochastic approach (Emanuel et al. 2006, Rumpf et al. 2007) a large number of synthetic tropical cyclone events are generated using Geoscience Australia open source Tropical Cyclone Risk Model. The main steps of this process are listed below.

- Analyse the statistical behaviour of historical cyclones (extracted from the International Best Track Archive for Climate Stewardship (IBTrACS), described via the means, variance and autocorrelation of the following parameters: intensity and location information, speed, bearings and genesis locations (Figure 5, Figure 6). The study considered historical tropical cyclones from 1950 to 2018 based on data quality analysis of the IBTrACS database (Figure 4).

- Generate 10,000 years of cyclone tracks (>16,000 cyclones) that share the same statistical behaviour as the 1950–2018 dataset.
- Generate the wind field for each of the 10,000 years of tropical cyclone tracks using Holland's parametric wind model (Holland 1980).
- Generate a probabilistic hazard map based on the 10,000 years of ttropical cyclone wind by fitting a generalised extreme value distribution at each grid point across the domain (Figure 7, Figure 8).

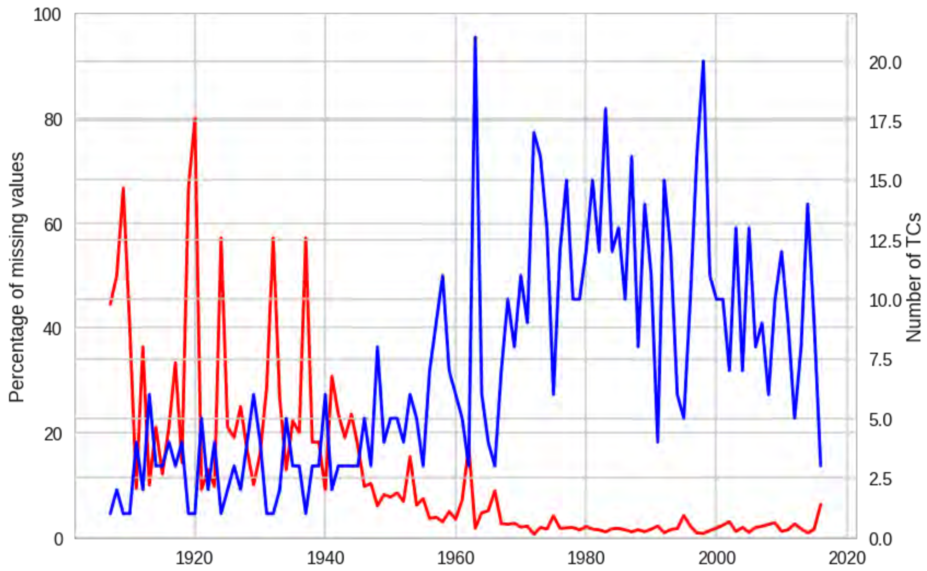

Figure 4: IBTrACS data quality. The figure shows the percentage of missing data (red) and number of cyclone tracks in the historical database (blue) since 1900.

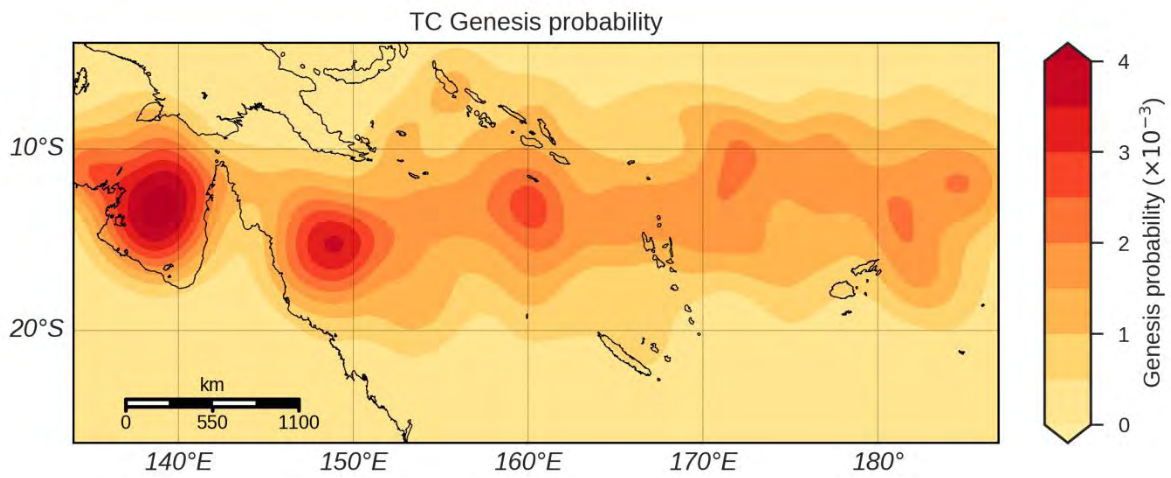

Figure 5: Tropical cyclone genesis probability generated by TCRM for Lenakel, Tanna

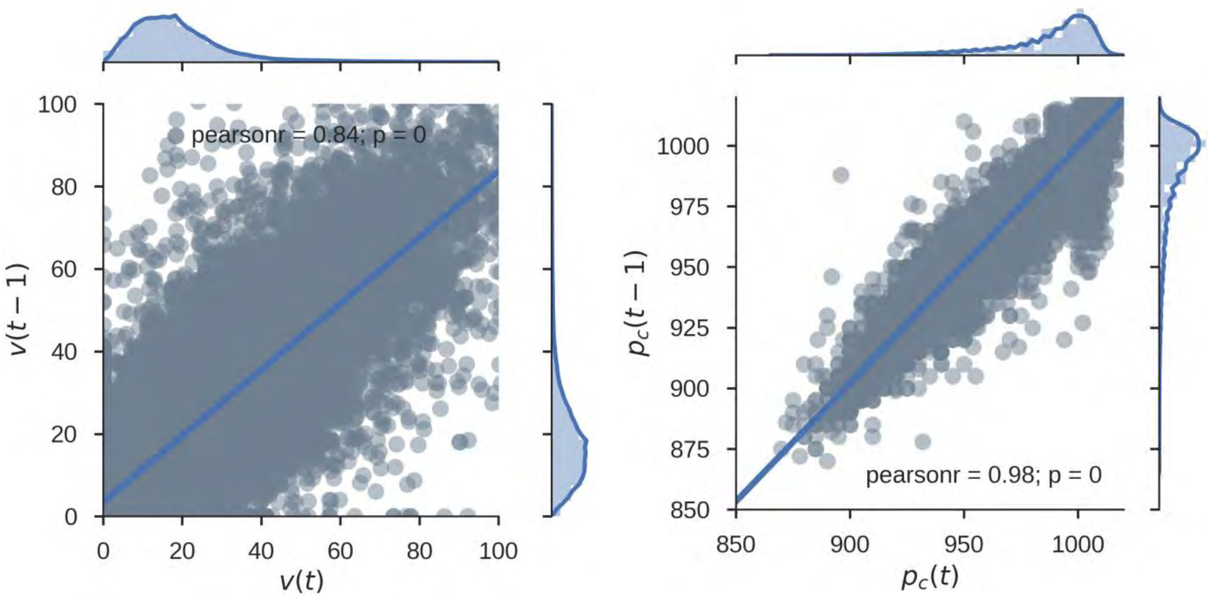

Figure 6: Correlation between tropical cyclone forward speed (right) and central pressure (left) between time=t-1 and time=t based on tropical cyclone events around Lenakel from 1950 until 2017

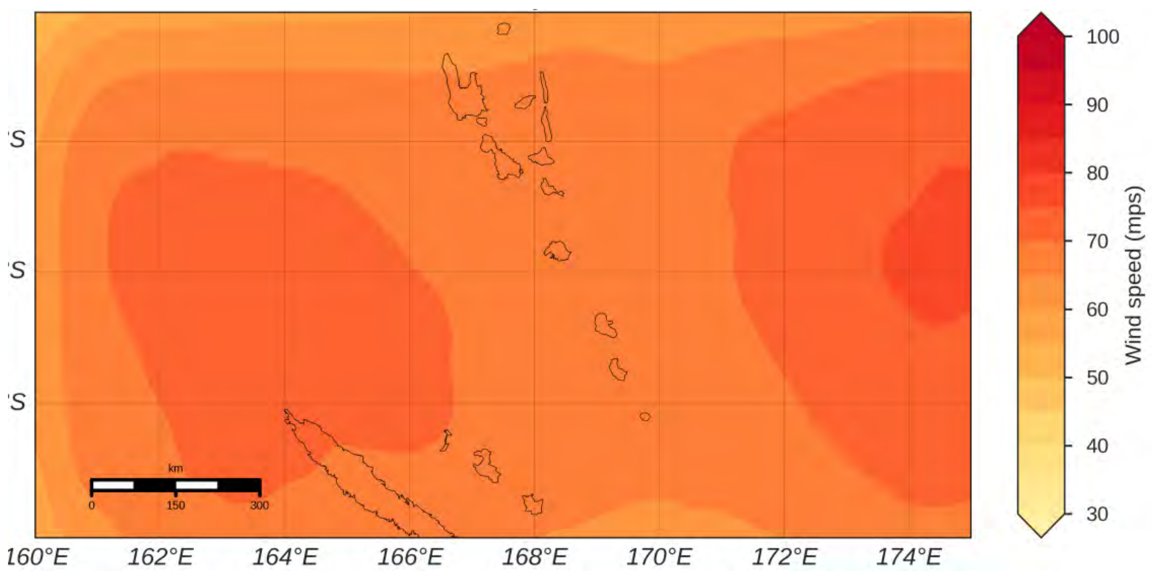

Figure 7: 100-year return period cyclonic wind hazard for Vanuatu, based on 10,000 years of synthetic tracks

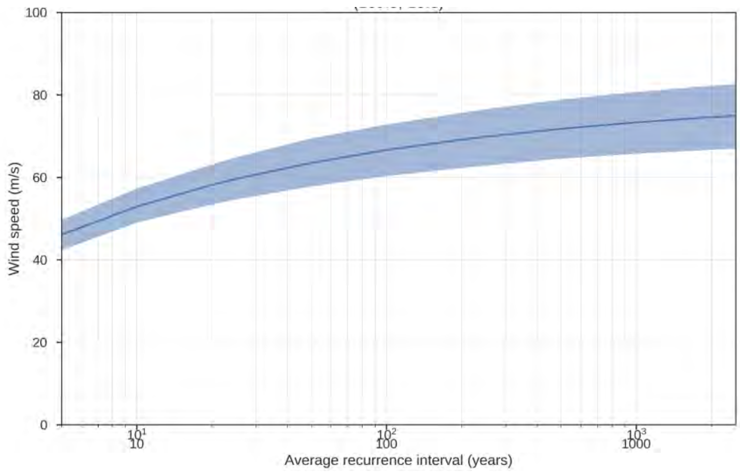

Figure 8: Extreme value analysis of tropical cyclone wind speed at Lenakel, Vanuatu, based on 10,000 years of synthetic tracks. The result does not consider effect from the topography and land cover.

II.5.2 Tropical cyclone parameterisation and modification

The primary difference between the methodology used for mapping tropical cyclone hazard in Lifuka Island in 2012 (II.4) and this study resides in how the large cyclone database (10,000 years of tracks) is dealt with. Instead of estimating offshore wave with an inadequate cyclone parametric model, the methodology is based on a recent but already widely used technique in physical oceanography named meta-modelling. The reliability of this technique, which is detailed in (II.5.4), lies in the ability to select representative scenarios.

To organise the cyclone database, tracks passing within four degrees of Lenakel are parameterised, following Mendez et al. 2017 (Figure 9). The four parameters describing each cyclone are:

- P_{min}: minimum central pressure, the minimum pressure along the track while the cyclone is within a 4-degree radius of Lenakel;
- v: forward speed, the mean forward speed of the cyclone within a 4-degree radius of Lenakel;
- γ: azimuth, the angle defined, based on the track entrance point into and exit point from the 4-degree circle centred on Lenakel. For cases where either the entrance point or the exit point does not exist (tropical cyclone initiates or ends within a 4-degree of Lenakel), the mean track direction within the 4-degree radius is used;
- δ: angle of entrance into the 4-degree circle centred on Lenakel.

This parameterisation leads to significant modification of the cyclone tracks (**Error! Reference source not found.**) with a constant minimum pressure, forward speed and direction within the area of interest, as well as a necessary adjustment in temporal space.

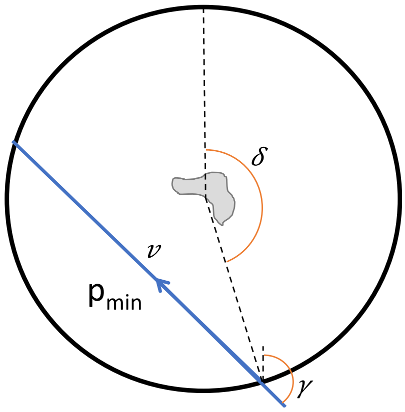

Figure 9: Cyclone parameterisation following Mendez et al. 2017 with γ: azimuth, δ: angle of entrance, v: forward speed, and P_{min}: minimum pressure

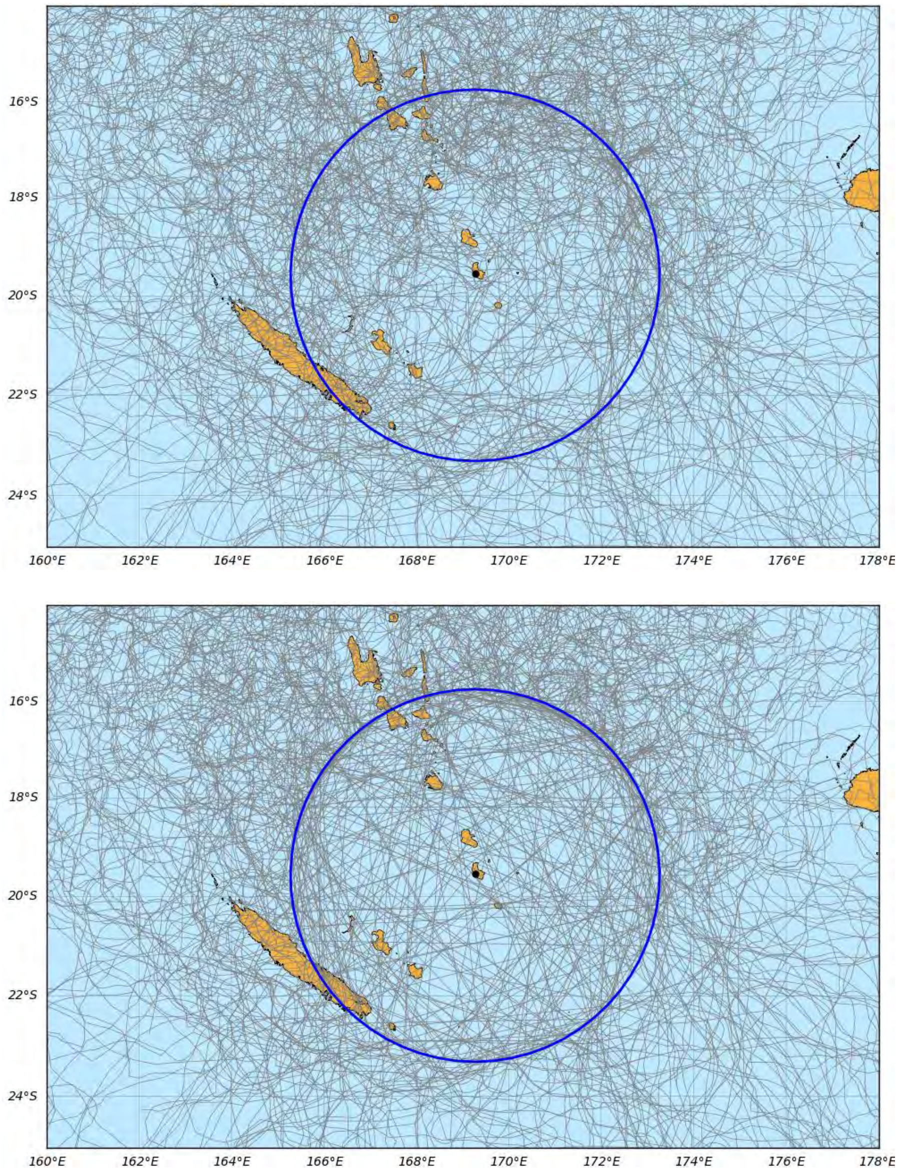

Figure 10: Cyclone track modification. The figure shows an example of 300 cyclone tracks before (top) and after parameterisation (bottom).

II.5.3 Cyclone wind field modelling

For each modified tropical cyclone track, a time-varying two-dimensional wind and pressure fields is calculated, based on a cyclone wind parametric model (Holland 1980). In 2016, SPC allocated programme funds into the in-house development of TCwindgen; an open source and computationally efficient tool to generate a cyclone wind field (https://github.com/CyprienBosserelle/TCwindgen) and export it as a wave model formatted input.

The parametric model was set up to generate a wind field with a 0.04 degree resolution and a 30-minute timestep. A batch file was created to loop through all the tracks, format the input files (modified tracks and parameter files) and generate wind input files to SWAN via TCwindgen.

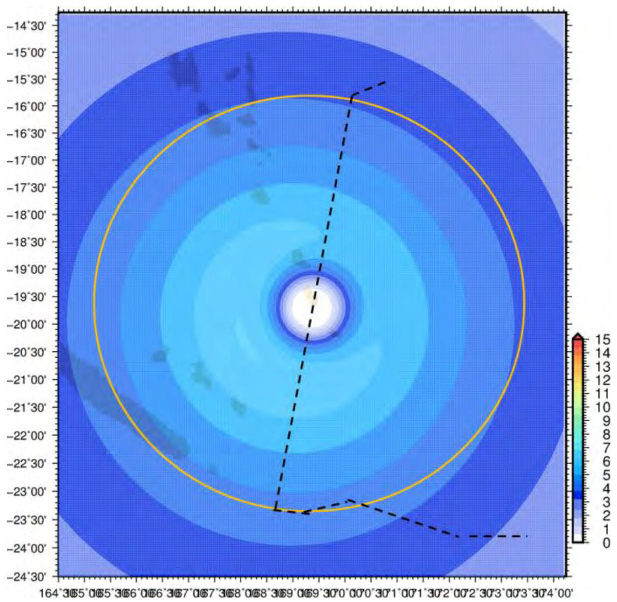

Figure 11: Snapshot of the wind field generated by a synthetic cyclone using Holland's parametric model (Holland 1980). The yellow circle represents the 4-degree radius centred on Lenakel. The dashed line represents the associated (modified) cyclone track.

II.5.4 Meta-modelling of cyclone offshore wave condition

Because physical process-based models are computationally intensive, their use in computing offshore wave condition for a large sample of events (>16,000 cyclone tracks) raises practical challenges (Gouldby et al. 2014). Meta-models (or models of models) are being increasingly used in the physical oceanography field (Camus et al. 2011a; Camus et al. 2011b ; Camus et al. 2014; Gouldby et al. 2014 ; Rueda et al. 2016 ; Rueda et al. 2019) as an alternative to overcome these challenges.

The meta-model to estimate offshore cyclone wave off Lenakel for 10,000 years of tropical cyclone is composed of a four-variable predictor (P_{min}, v, γ, δ) and a three-variable predictand (Hs, Tp, Theta). The development of the meta-model can be described in three steps (Figure 12).

1. The careful selection of representative scenarios (or designed points) from the entire cyclone database. Based on the investigation of the performance of various clustering technics (K-Means, Self-Organising Map, Maximum Dissimilarity Algorithm [MDA]) found in Camus et al. 2011, 500 cyclone tracks where selected, using an MDA. The performance of the meta-model is highly dependent on the selected scenarios. The benefit of the MDA resides in its ability to select points within the population data covering the edge of the domain, in turn making it highly efficient for interpolating in spaces of high dimensionality.
2. The physical process-based modelling of the selected scenarios. Offshore wave is computed for the selected representative cyclone events using SWAN, a third-generation spectral wave model developed by Delft University of Technology (Booij et al. 1999). SWAN has been used in non-stationary mode, forced by the moving wind field (varying in space and time) predicted by the Holland wind field model (previous section). The resolution of the wave model is about 2 km.
3. The reconstruction of predictand (Hs, Tp, Theta) for the 10,000 years of tropical cyclone. Following Camus, 2011 and Gouldby et al. 2014, the relationship between the set of representative predictors (i.e. P_{min}, v, γ, δ) and their predictand (i.e Hs, Tp, Theta) is approximated by a radial basis function (RBF). The trained RBF is then used to reconstruct the offshore wave condition for the 10,000 years of cyclone events.

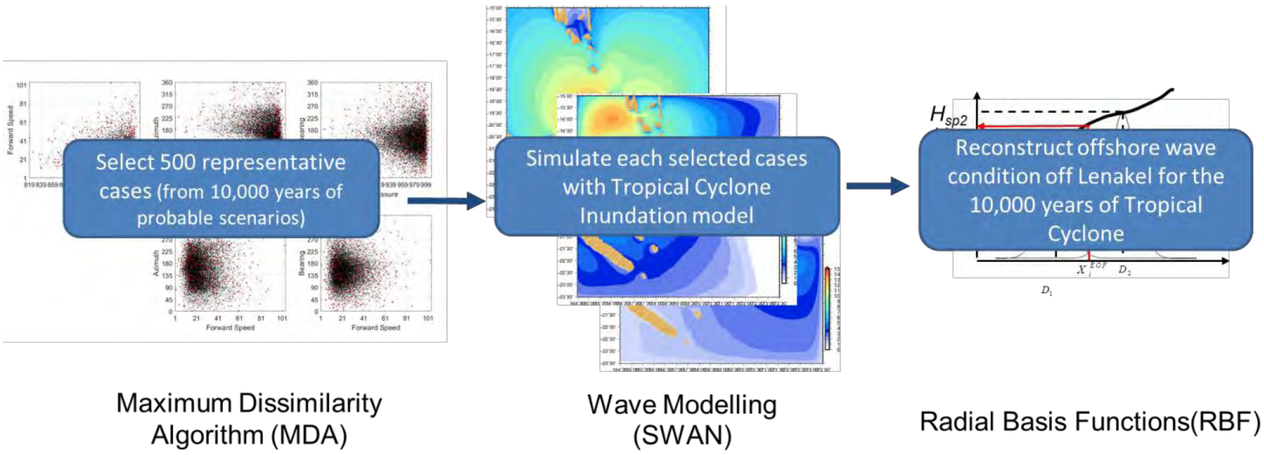

Figure 12: Meta-model to approximate 10,000 years of cyclone-driven offshore wave condition off Lenakel

II.5.5 Offshore water level

Cyclone-driven inundation needs to be assessed as a compound event. The inundation event is not only dependent on the wave and storm surge (inverted barometric pressure and wind set-up) induced by the cyclone but is also modulated by the tide and the mean level of the sea (MLoS). In this study, the offshore water level for each synthetic cyclone is defined as a combination of the inverted barometric pressure, a tide level and an MLoS.

II.5.5.1 *Inverted barometric pressure*

Inside a cyclone, the barometric pressure at the ocean surface can drop to extremely low levels. As a result, the ocean surface responds hydrostatically and rises. This phenomenon is called the inverted barometric pressure.

As the cyclone central pressure is set to constant within a four degree radius from Lenakel, the inverted barometric pressure is calculated for each cyclone as follow (Eum & Series 2016):

$$Inverted\ Barometric\ Pressure = -9.948 * (Pmin - Penv)$$

II.5.5.2 *Tide level*

A tide level was given to each synthetic track following these steps:

- tide gauge data analysis; a permanent tide gauge was set up in Lenakel by the Japan International Cooperation Agency in 2016. The tide gauge data were used to:
  - extract tidal harmonics from the tide gauge data using MATLAB T_TIDE toolbox (https://www.eoas.ubc.ca/~rich/#T_Tide);
  - predict long-term tidal level for Lenakel (100 years);
- map the monthly empirical tidal level distribution for Lenakel;
- retrieve what month each synthetic tropical cyclone passes near Lenakel from the database; and
- attribute a random tidal level to each synthetic tropical cyclone following the monthly empirical tidal level distribution.

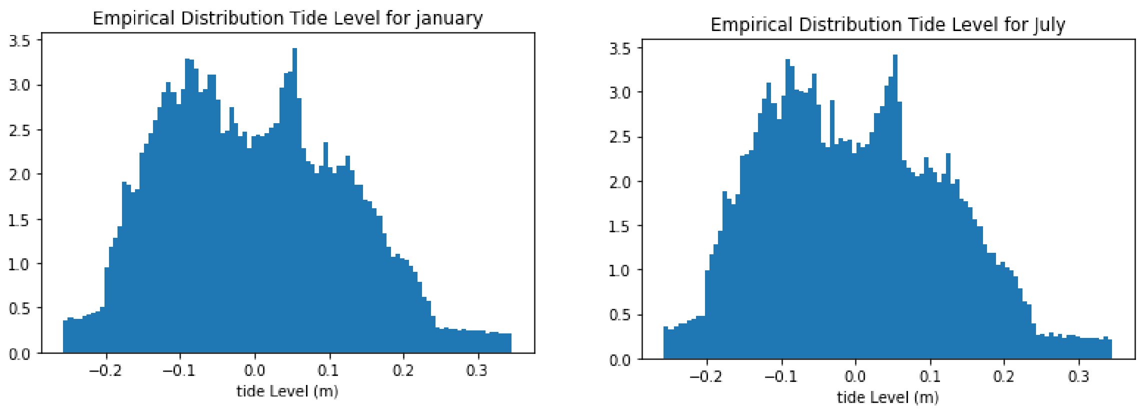

Figure 13: Empirical distribution of Lenakel tide level for the month of January

II.5.5.3 *Mean sea level*

As the Lenakel tide gauge record goes back only two years, the in situ mean level of the sea (MLoS) recorded does not provide adequate information on the range of anomalies that can be induced by climate variability (e.g. ENSO) or mesoscale eddies.

MLoS information off Lenakel was extracted from HYCOM (Chassignet et al. 2007) re-analysis global hindcast model, providing ocean surface elevation at 0.08 degree resolution from 1992 to 2012 (20 years). The 20 years hindcast data are analysed to map the monthly empirical MLoS distribution. A random MLoS is then attributed to each synthetic tropical cyclone following its monthly empirical distribution.

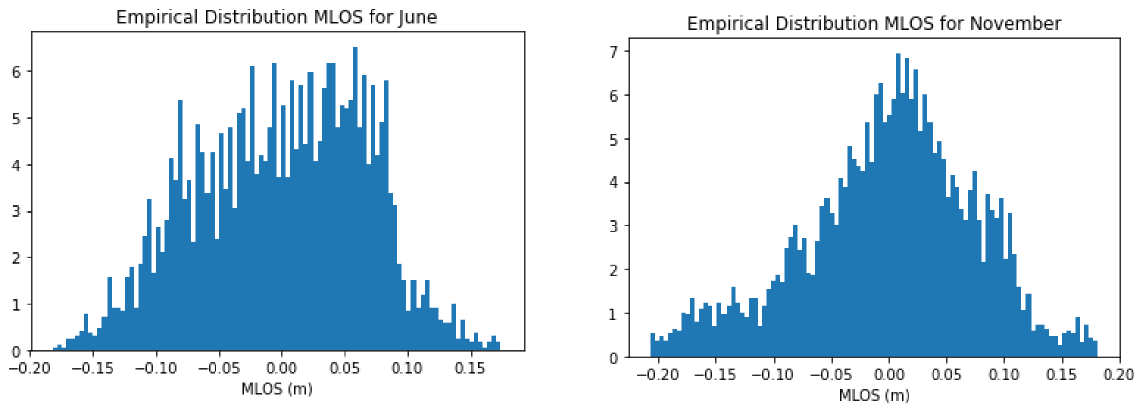

Figure 14: Monthly empirical distribution of the mean sea level off Lenakel, based on HYCOM 20 years hindcast for June (right) and November (left)

II.5.6 Meta-modelling of cyclone driven inundation

Following a similar process to that in II.5.4, a meta-model is created to approximate inundation depth from the 10,000 years of cyclone-driven offshore ocean condition off Lenakel. The meta-model is composed of a six-variable predictor (Hs, Tp, Theta, Wspd, Wdir, offshore water level) and a predictand (inundation depth) every 10 m within coastal zone (Figure 15).

Five hundred representative cyclone-driven sea states are selected via the MDA. A 10 m resolution XBEACH-GPU model (https://github.com/CyprienBosserelle/xbeach_gpu), calibrated using in situ wave and water level data, is used to simulate inundation for the 500 representative scenarios. Finally, an RBF is used to reconstruct the 10,000 years of cyclone-driven inundation depth for each 10 m grid cell on land.

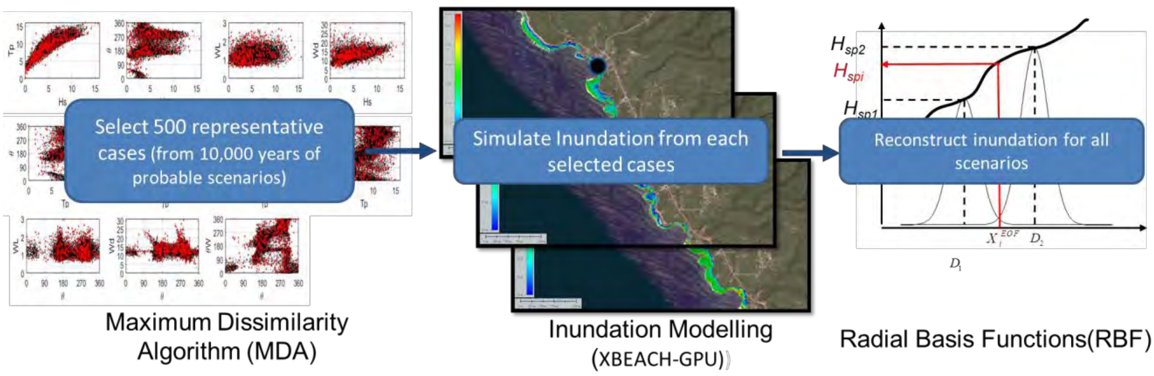

Figure 15: Meta-model to approximate 10,000 years of cyclone driven inundation based on ocean offshore condition (Hs, Tp, Theta, Uwind, Vwind, WL)

II.5.7 Inundation map with associated return period

One advantage of this methodology resides in the ability to quantify the likelihood of a tropical cyclone-driven inundation event based on the actual hazard (i.e. inundation depth) instead of the driver (i.e. the offshore ocean condition).

As inundation depth is expected to vary across the coastal zone. The estimated return period of the inundation hazard can vary, depending on the area of the coastal zone the analysis focuses on. The analysis can be performed in at least two ways;

- by performing an extreme value analysis on an appropriately selected grid cell; and
- by creating a simple inundation depth response function (i.e. weighted average of inundation depth from a set of grid cells) and performing an extreme value analysis on the response function's output.

In this study, a single grid cell to estimate the likelihood of the inundation hazard was considered. An extreme value analysis (EVA) was undertaken, based on 10,000 years of inundation depth information generated on the beach in front of Lenakel's market.

The EVA consists of : (i) selecting the maxima using a peak over threshold (Figure 16); and (ii) fitting the selected maxima to a generalized pareto distribution (Figure 17).

For each return period (RP) (i.e. 20 year RP, 50 year RP, 100 year RP, 200 year RP), a range of inundation depth is selected, following the 95% confidence interval as shown in Figure 17. The range of inundation depth is linked, via the meta-model descried in II.5.6, to a set of tropical cyclone-driven ocean conditions (Hs, TP, Theta, Wspd, Wdir, WL). For each RP, the corresponding set of ocean conditions is used to force the XBEACH-GPU model of Lenakel.

The resulting maximum inundation depth for each ocean condition is then aggregated into an inundation hazard map with an associated return period.

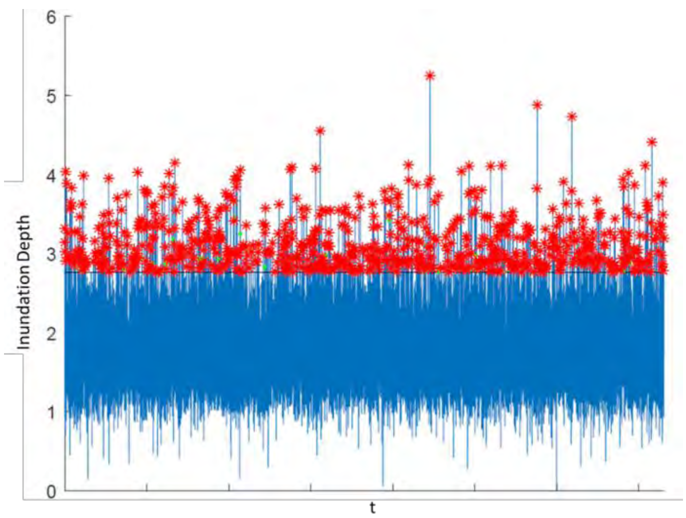

Figure 16: Peak over threshold on the 10,000 years of inundation depth data generated on the beach in front of Lenakel's market

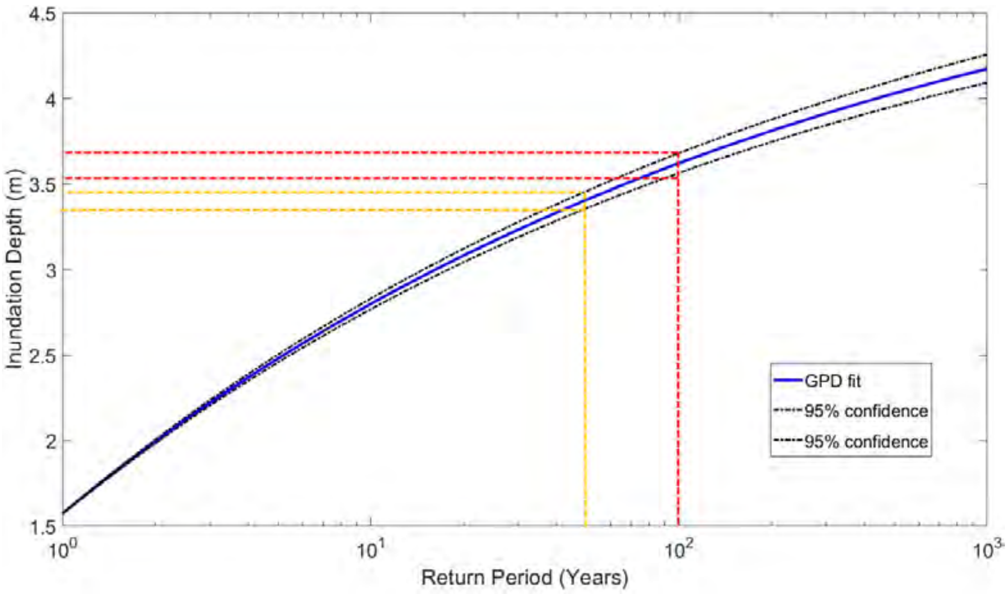

Figure 17: Return period for tropical cyclone-driven inundation depth (m) along the beach in front of Lenakel market. The yellow dashed line shows the range of inundation depth attributed to a 50 year return period event within a 95% confidence interval. The red dashed line shows the range of inundation depth attributed to a 100 year return period event within a 95% confidence interval.

II.5.8 Hazard under climate change

The *Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC 2013) provides projections of future changes for four greenhouse gas concentration trajectories, called Representative Concentration Pathways (RCPs).

The RCPs are labelled according to the range of radiative forcing values in the year 2100 relative to pre-industrial values:

- RCP2.6 applies a radiative forcing value of +2.6 W/m2 and represents a low forcing level;
- RP4.5 and RCP6 apply radiative forcing values of +4.5 and +6.0 W/m2 and represent stabilisation scenarios; and
- RCP8.5 applies a radiative forcing value +8.5 W/m2 and represents a high forcing level.

AR5 predictions of changes in tropical cyclone statistics show:

- The total annual frequency of tropical storms to potentially decrease (between 0 and 60%); and
- The annual frequency of high intensity cyclones (Category 4 and 5) to globally increase between 0 and 30%. There is, however, not enough supporting data in the South Pacific region for a specific prediction.

With little confidence in the projected behaviour of cyclones around Vanuatu, this study only considers climate change-driven potential exacerbation of the inundation hazard in relation to sea-level rise (SLR).

The study considered an SLR of 0.64 m: the 2090 projected SLR for Vanuatu under RCP8.5 scenario (BOM and CSIRO 2014). The scenarios associated with each return period are re-computed after increasing the water level at the model offshore boundary by 0.64 cm.

The cyclone-driven inundation hazard maps with and without SLR are shown in ANNEX A.

II.5.9 Probabilistic hazard map based on inundation depth

In II.5.7, probabilistic inundation hazard is characterised by the inundation depth mapped for a fixed likelihood (e.g. 20, 50, 100 years return period). This is the standard output from a probabilistic inundation hazard assessment.

With meta-modelling, however, this study gives access to a database of 10,000 years of inundation map, in turn providing an opportunity to map for the probability in any place on land of experiencing an inundation depth exceeding a given threshold. This new packaged hazard information can prove to be more adequate to support decision makers on urban planning and other risk prevention solutions.

For each grid cell on land, the 10,000 years of inundation depth data are used to compute the probability of exceeding a given inundation depth (e.g. 0.25 m, 0.5 m, 1 m) (Figure 18).

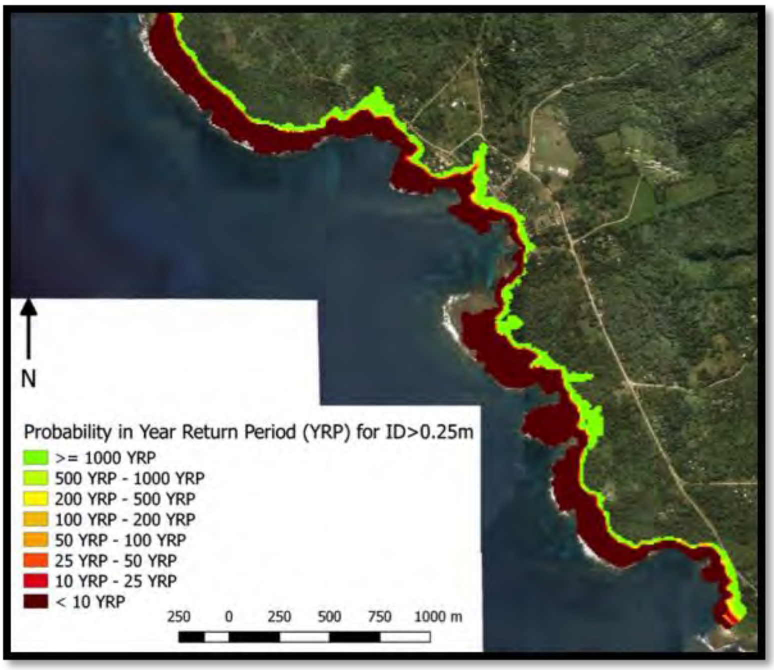

Figure 18: Probabilistic inundation map showing the likelihood of Lenakel experiencing inundation depths greater than 0.25 m.

II.6 Model calibration

An XBEACH-GPU model was calibrated, using in situ oceanographic data. Six oceanographic instruments were deployed in Lenakel (Figure 19) recording data for a four- to six-month period (from February 2017 to July 2017). It includes:

- two RBR*virtuosos*, recording continuously at 1 Hz;
- three RBR TWRs, recording 2048 seconds burst at 1 Hz every three hours; and
- one AWAC, recording 2048 seconds burst at 1 Hz every three hours.

Over the deployment period, two wave events with wave height exceeding three metres (Hs>3 m) were recorded (Figure 20). Four events were selected to carry out the calibration process. These events are characterised by a high wave (Hs>3m) with offshore water level ranging from mid to high level.

Pressure data were processed into an hourly wave set-up, wave height and wave period for short and infragravity waves.

More than 400 XBEACH_GPU runs were computed during the calibration process, with varying friction coefficient (Cf, fw), eddy viscosity (nuh) and the wave breaking parameter (gamma).

The best overall performance was achieved with Cf=0.01, fw=0.25, gamma=0.55 and nuh=0.25, giving a root mean square (RMS) error across the four selected events of:

- 0.09 m for the wave set-up,
- 0.02 m for the Infragravity wave height, and
- 0.055 m for the short wave height.

It is to be noted that the RMS error is only indicative and might not reflect the modelling error when simulating extreme waves (Hs>10 m).

Figure 19: Oceanographic instrument deployment's location (Red: Virtuoso, Blue: TWR, Orange: AWAC).

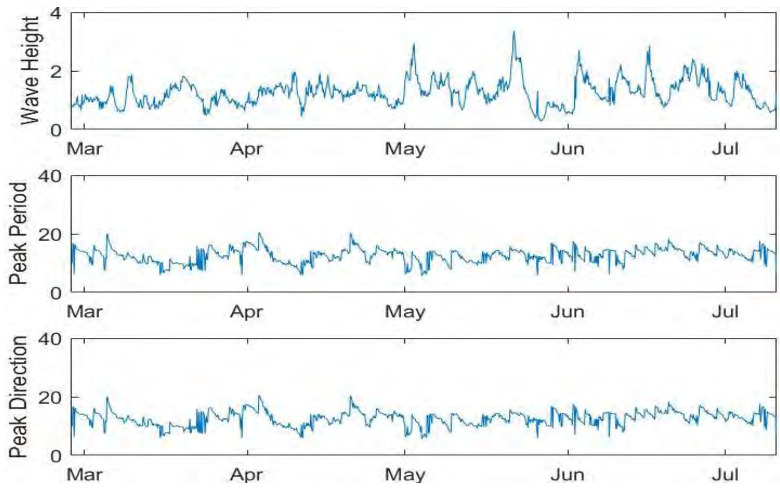

Figure 20: Wave data recorded by the AWAC off Lenakel

III. Swell-driven inundation hazard assessment

III.1 Background

The island of Tanna in the southern part of Vanuatu is exposed to the ocean swells. The mean wave condition map in Figure 21 shows large waves generated by extra-tropical storms within the southern ocean storm belt, between -40° and -60° latitude. As these high waves travel away from the storm, they become swells characterised by a long wave period and, in turn, a high wave power. Swell events in Tanna Island can be relatively severe, with a 99th percentile wave height greater than 3.5 m (Figure 22).

Under the European-funded Wave and Coast in the Pacific (WACOP) project, a wave climate report based on hindcast wave model data from Trenham 2013 was developed for Lenakel for an offshore location. The wave climate offshore Lenakel is moderate and dominated by southern swells (Hs=1.3, Tp=12.58s, Dm=188°) with the most energetic swells reaching Lenakel between March and August (Bosserelle C. et al. 2015).

Swells can travel long distances across the Pacific and can cause high impact inundation events on the coastal zone, as described in Hoeke et al. 2013. An inundation event is triggered by the non-linear interaction between the offshore wave condition, the offshore water level condition and the coastal geomorphology. Thus, a probabilistic swell-driven inundation hazard assessment requires investigation of the possible offshore ocean conditions (wave and water level), as well as the translation of these offshore conditions into inundation run-up information.

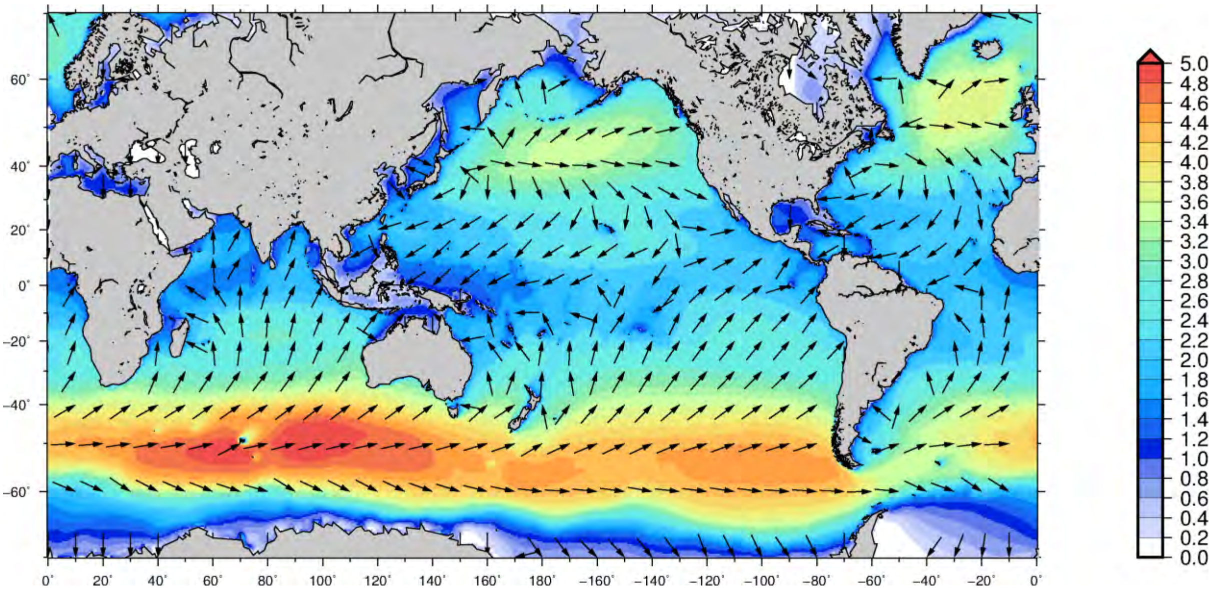

Figure 21: Mean wave height (colour-coded) and direction (black arrows) based on 30 years global wave hindcast developed with BoM (ref. SPC WACOP website: http://wacop.gsd.spc.int)

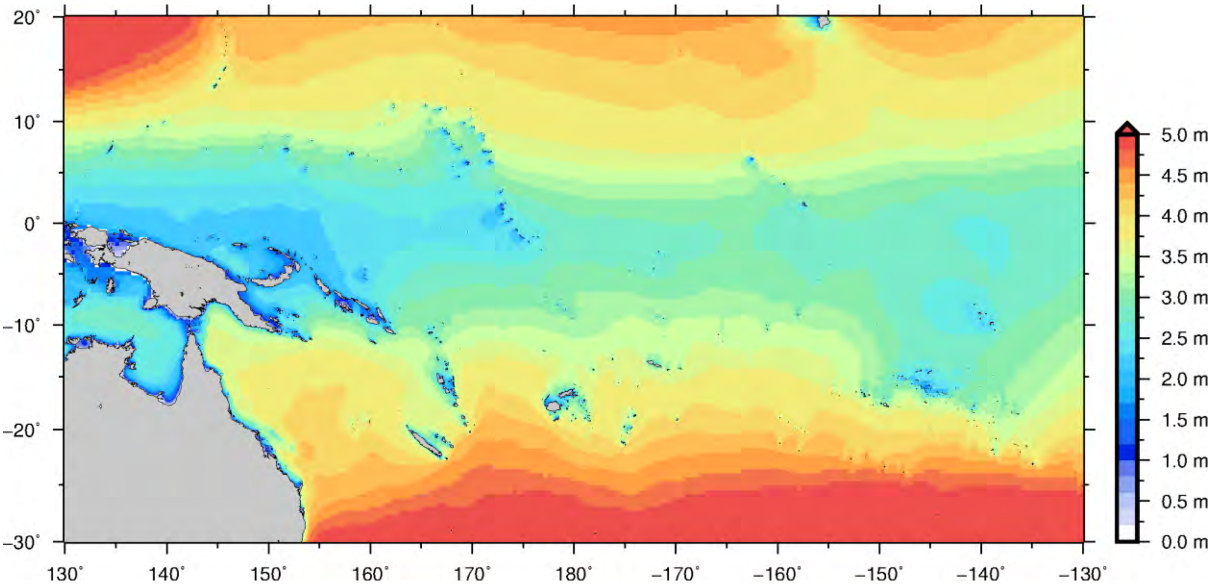

Figure 22: 99th Percentile wave height across the pacific region based on ~30 years hindcast wave information developed by BoM – ref. SPC WACOP website: http://wacop.gsd.spc.int).

III.2 Methodology

In recent years, methodologies used for inundation hazard assessment (Figure 23) in the Pacific region have been restricted to quantifying the likelihood of an offshore ocean condition characterised by the co-occurrence of two variables; usually wave height and total water level (Stephens & Gorman 2010; Damlamian et al. 2015). While this methodology is commonly used, it can lead to an underestimation of extreme events. Using a single variable to characterise offshore total water level means that the extreme values are heavily biased towards the historical co-occurrence of its independent components (tide, storm surge and the mean level of the sea. Similarly, for the wave, this methodology characterised an extreme ocean wave condition using wave height (a representative wave period and wave direction can be predefined).

The methodology implemented as part of the KfW project was initially designed by Heffernan & Tawn 2004 and adapted and extended by Gouldby et al. 2014 for coastal inundation application (Figure 24). The method was introduced to the Oceanography Team of SPC during a one-week collaboration workshop with the University of Cantabria (UoC) in December 2016 and tested with data previously collated for Bonriki (Kiribati, Tarawa atoll) under the Bonriki Inundation Vulnerability Assessment project using a 1D inundation model.

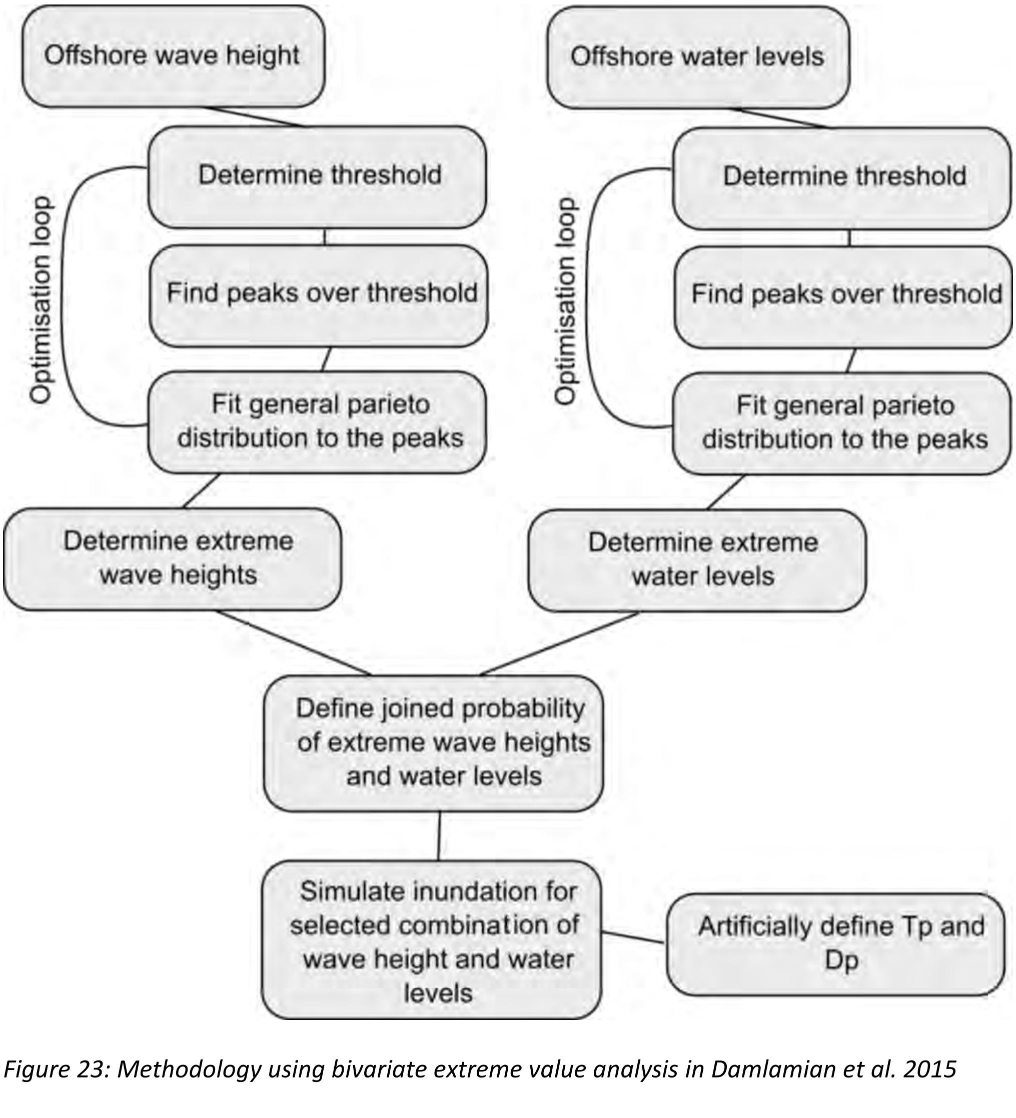

Figure 23: Methodology using bivariate extreme value analysis in Damlamian et al. 2015

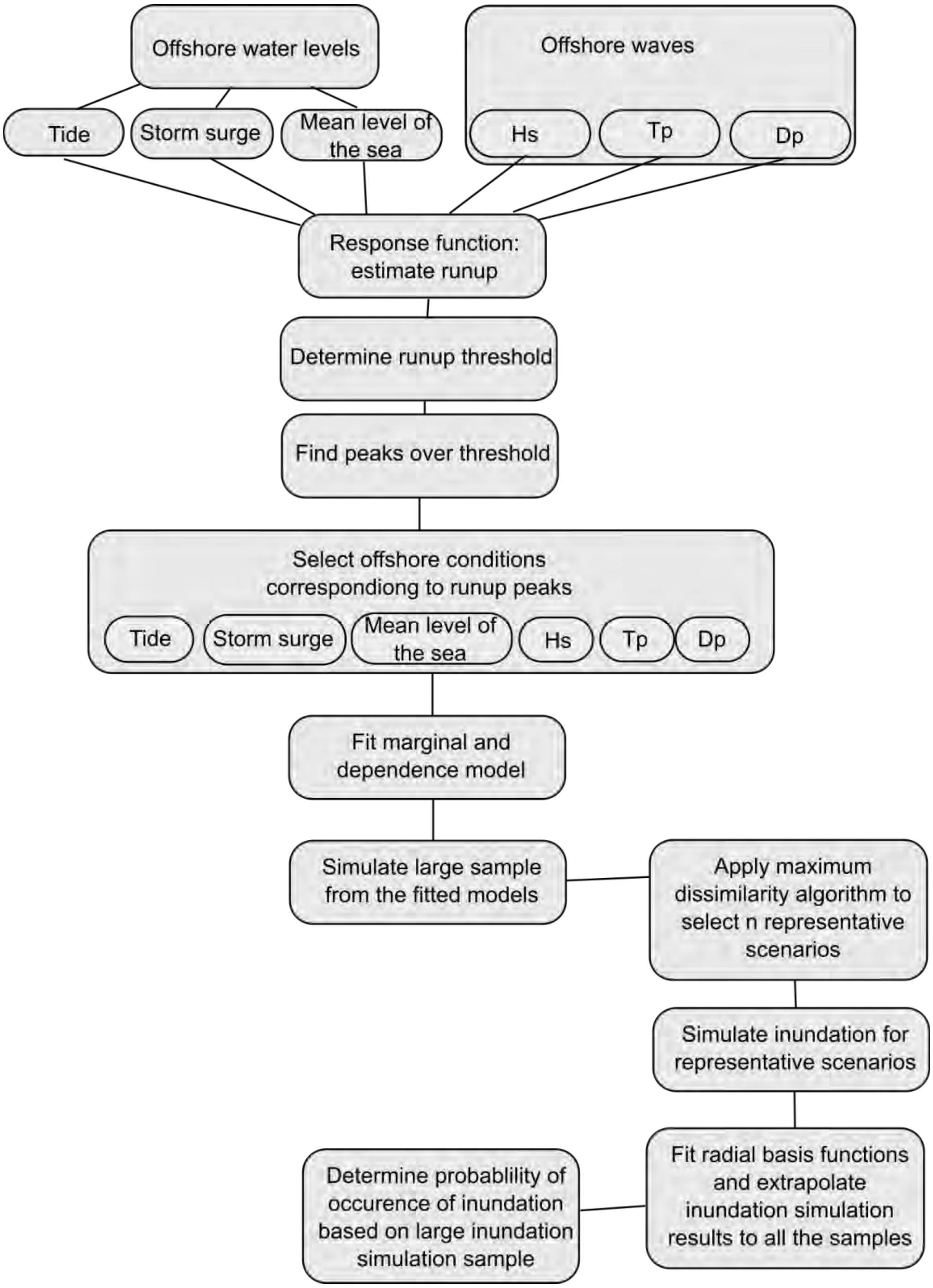

Figure 24: New methodology based on multivariate extreme value analysis and meta-modelling, adapted from Gouldby et al. 2014

III.2.1 Generate past ocean conditions off Lenakel.

Past ocean conditions are characterised by six variables: wave height, wave period, wave direction, tide, storm surge and the mean level of the sea.

III.2.1.1 *Wave condition*

A 500 m resolution wave model centred on Tanna Island and including the islands of Eromango, Anatom, Futuna and Aniwa was created using the open source SWAN model (Booij et al. 1999). The model was nested onto a global hindcast wave model (Trenham 2013) to produce 38 years of high resolution wave information from 1979 to 2016 around Tanna Island (Figure 25).

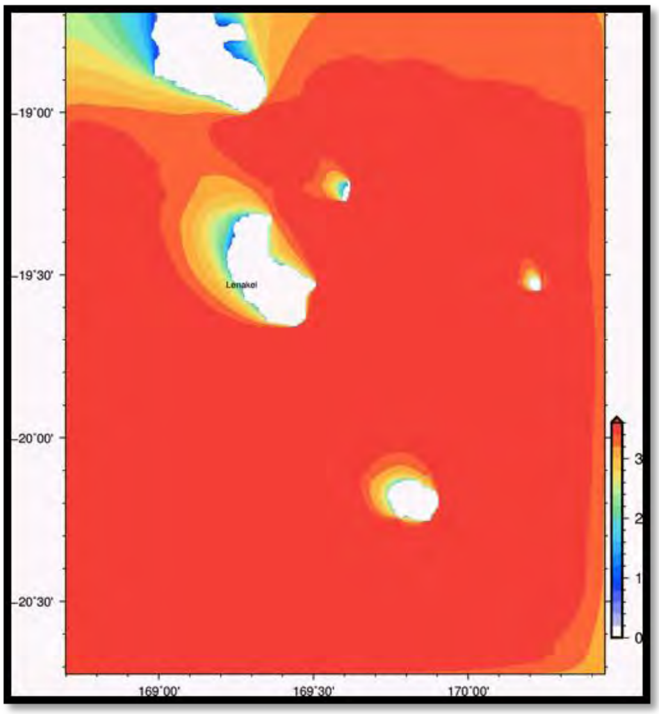

Figure 25: Snapshot of the 500 m resolution hindcast wave model of Tanna during the May 1996 swell event

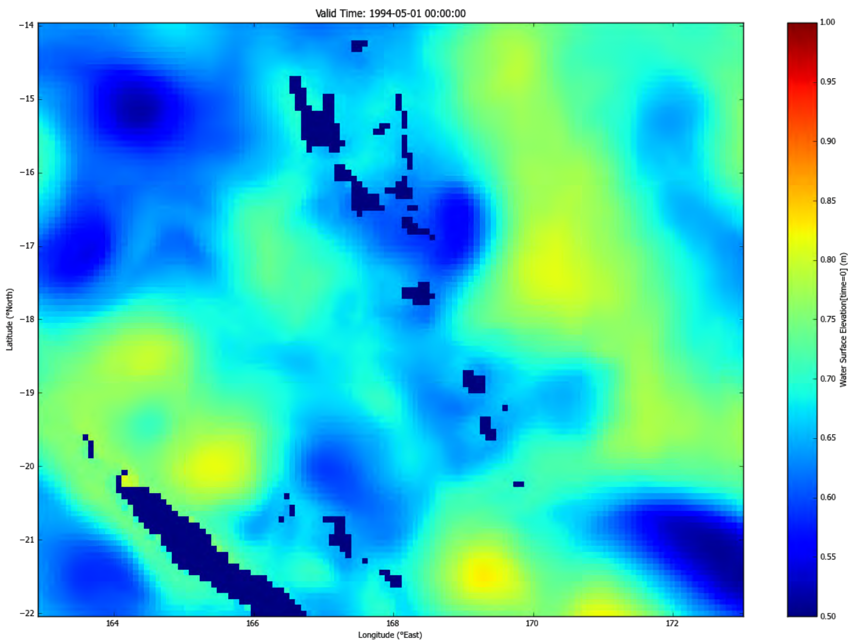

Figure 26: Snapshot of the HYCOM global circulation model hindcast zoomed around Vanuatu

III.2.1.2 *Offshore water level condition*

Tidal harmonics were extracted, based on an analysis of the tide gauge records at the Lenakel wharf (Figure 27). As the tide gauge in Lenakel was recently installed (2016), a longer record of mean level of the sea and storm surge (i.e. inverted barometric pressure) offshore Lenakel was extracted from a 20-year hindcast circulation model: HYCOM (Chassignet et al. 2007) (Figure 26).

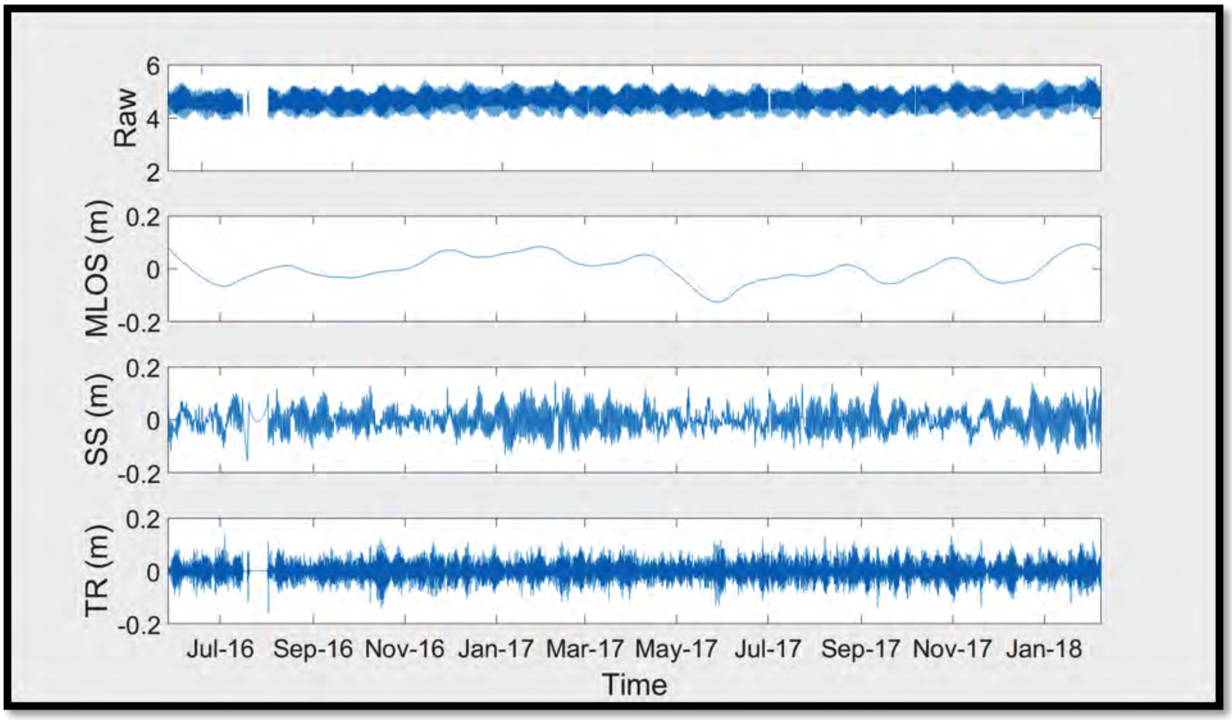

Figure 27: Analysis of the water level record at the Lenakel tide gauge. Raw data were used to extract tidal harmonics and tidal residual using T_Tide. The tidal residual was decomposed into storm surge and mean level of the sea using an orthogonal wavelet filter.

III.2.2 Multivariate extreme value analysis

A response function (Stockdon et al. 2006) was used to estimate run-up from the hindcast ocean condition constructed by combining wave and water level data offshore Lenakel. It is to be noted that the response function used to convert ocean condition into run-up is not appropriate to a reef-fronted island environment. While a tailored response function should be used in the future, such as HYCREWS (Rueda et al. 2019), the run-up information is used only to separate the 30% highest historical run-up events from the ocean condition time series.

The selected 30% historical events are then de-clustered into their six components: wave height, wave period, wave direction, tide, storm surge and mean level of the sea.

The statistical behaviour of each variable and their inter-dependency are mapped to drive a Monte Carlo simulation. The Monte Carlo simulation was used to generate 10,000 years of high sea state ocean condition off Lenakel.

III.2.3 Meta-modelling for swell inundation scenario

As physical-based dynamic inundation modelling is computationally expensive, it is impractical to attempt simulating a large sample (10000 years) of inundation events. Thus, as described in **II.5.6**, a meta-model following Camus et al. (2011) is created. The meta-model for Lenakel's swell-driven inundation estimates inundation depth according to offshore ocean conditions characterised by four variables; wave height, wave period, wave direction and the total water level (sum of the tide, mean level of the sea and storm surge). The model was trained using 500 inundation scenarios simulated with Xbeach-GPU.

III.2.4 Inundation map with associated return period

Following the process described in II.5.7, a swell-driven inundation map was computed for 20-year, 50-year, 100-year and 200-year return periods.

Wave projection for Vanuatu under the changing climate was computed by BOM & CSIRO 2014 for the years 2035 and 2090. The 2090 projected change under RCP8.5 shows a mean change in wave height of 0.1 m for the December-March season and no change for the June-December season. The projected wave climate also shows no significant change in terms of wave period (decrease of 0.1s 0.2s) and wave direction. Thus, similar to II.5.8, climate change-driven exacerbation of Lenakel's swell inundation hazard is only considered in relation to sea level rise (SLR). An SLR of 0.64 m is used and represents the projected SLR for Vanuatu by 2090 under RCP8.5.

The swell-driven inundation hazard maps with and without SLR are shown in ANNEX A.

IV. Coastal hazard and town planning workshop

This component of the KfW project was designed to develop coastal hazard maps to identify vulnerable areas in Lenakel, Tanna, and provide tools and training for the dissemination of the information, both at the central and provincial government level.

In July 2018, SPC organised a two-day workshop on managing coastal hazards, with a focus on town planning and zoning in Lenakel, Vanuatu.

Expected outcome

The focus of this training workshop was on professional development and was designed to improve the understanding of coastal dynamics and impacts on settlements, infrastructure and ecosystems, and to develop skills for the application of coastal hazard information to town planning and coastal development.

It is anticipated that the workshop will contribute toward identifying the development of a coastal hazards strategy for the municipality of Lenakel by applying the ISO 31000 risk assessment framework to coastal zone management.

A simple risk assessment methodology following a semi-qualitative approach was introduced to provincial and central government officers as a tool to convert hazard data into actionable information. The methodology, based on the settlement planning work undertaken by Haines P. (2015) in Taro, Solomon Islands, starts by defining the likelihood scale (i.e. rare, possible, almost certain, etc.) and consequence scale (i.e. low, medium, high, etc.) using a participatory approach. By overlaying printed inundation maps with transparent paper, participants identified hazard information and the likelihood category for each key asset (Figure 28). Through group discussion, a level of impact (from the consequence scale) was qualitatively estimated for each key asset. Finally, a risk category was attributed as a function of the likelihood of the hazard and its consequence (Figure 29). The primary limitation resides in the qualitative estimation of the level of impact. SPC and regional partners, such as NIWA and GNS, are working towards the implementation of regionally tailored vulnerability function in order to harmonise and improve risk assessment work in the region.

The risk assessment provides a risk category for each key asset. Such information can support the government to prioritise its risk reduction action. For each asset, three choices are presented: (i) accept the risk; (ii) reduce the likelihood of the hazard; or (iii) reduce the consequence on the asset.


Figure 28: Vanuatu stakeholders undertaking risk assessment by identifying key assets and hazard zones, using transparent paper overlayed on a probabilistic inundation map

		CONSEQUENCE				
		Insignificant	*Minor*	*Moderate*	*Major*	*Catastrophic*
LIKELIHOOD	Almost Certain	Low	Medium	High	Extreme	Extreme
	Possible	Low	Low	Medium	High	Extreme
	Rare	Low	Low	Low	Medium	High

Figure 29: Risk matrix

V. Conclusion

This report outlines SPC's new methodologies to tackle inundation hazard assessment from tropical cyclones and swells and showcase the continued effort to provide high quality regional technical service to Pacific Island countries.

Some of the benefits of these methodologies described below.

- Meta-modelling provides a practical way to assess inundation from a large sample of tropical cyclone events (e.g. 10,000 years of tropical cyclone events were modelled in this study).
- By partially removing constraints on computational time (e.g. the methodology still requires the dynamic modelling of a few hundred scenarios to ensure some convergence of the meta-model solution), the inundation hazard can be assessed as a compound event, looking at the possible combination of each forcing: tide, mean level of the sea, and the metocean condition-related forcings (wave and storm surge).
- The methodologies also provide a more accurate probabilistic hazard assessment, as the likelihood is not estimated, based on the forcing, i.e. cyclone intensity (Haines et al. 2015) and the offshore ocean condition (Damlamian et al. 2015) but on the response (i.e. inundation depth).
- The inundation hazard maps are not based on a single characteristic event for each likelihood but on the aggregated inundation depth from a set of events.
- Based on the computed 10,000 years of inundation maps, these methodologies offer the possibility of generating a probabilistic inundation hazard map, giving the likelihood for a given inundation depth to be exceeded for each grid cell.

Finally, these methodologies open a new window onto the development of an inundation forecast system in the Pacific region. Meta-modelling can be used as a powerful forecasting tool, offering a great compromise between accuracy and computational time. SPC is currently developing a swell-driven inundation forecast system in Fiji (Coral Coast) as part of the WMO Coastal Inundation Forecast Demonstration Project, which is based on the creation of a similar meta-model described in III.2.3. The forecast system was successfully used by the Fiji Meteorological Office in 2018 to issue two inundation warnings (May and Nov 2018).

To date, there is no tropical cyclone inundation forecast system in Pacific Island countries. The complexity of cyclone-driven inundation forecasting resides in the fact that the event is sub-regional and requires high resolution computation in the order of a kilometre in order to accurately transfer energy from the wind field into the waves. Furthermore, the resulting inundation should be assessed as a compound event, driven by the wave, storm surge, the tide and MLoS and their non-linear interaction. For this reason, high computational power would be required to dynamically forecast cyclone inundation, which is not available in the region. Another challenge resides in the instability of the inundation models when simulating large waves propagating and breaking on fringing reef environment.

The meta-models developed as part of the tropical cyclone-driven inundation hazard assessment link cyclone track parameters to an inundation map. They could potentially offer an exciting advancement in the development of a tropical cyclone inundation forecast system, providing rapid and robust detailed inundation information to governments for warning purposes and to support enhanced first response coordination and prioritisation. The use of meta-models for tropical cyclone inundation forecasting should be further investigated.

SPC will continue strengthening the new probabilistic tropical cyclone inundation hazard assessment methodology described in this report. The mean level of the sea attributed to each synthetic tropical cyclone is currently based on its monthly distribution. Further improvement should include the investigation of the potential interdependence between sea level anomalies and tropical cyclone. Furthermore, climate change driven tropical cyclone behaviour is not addressed as explained in II.5.8. SPC, in partnership with university of Cantabria, will address these current limitations under the coastal hazard assessment study for Majuro, Republic of Marshall Islands, funded under the World Bank funded Pacific Resilience Programme (PREP-2).The inundation hazard assessment highlights the relatively low vulnerability of Lenakel to swell and cyclone-driven inundation hazards. Hazard-prone areas are limited to the areas nearest to the shore. However, key assets such as the wharf, the market and the road are within the hazard prone areas. During the KfW coastal hazard and planning workshop, stakeholders attributed a high-risk category to the wharf and the market (Figure 30).

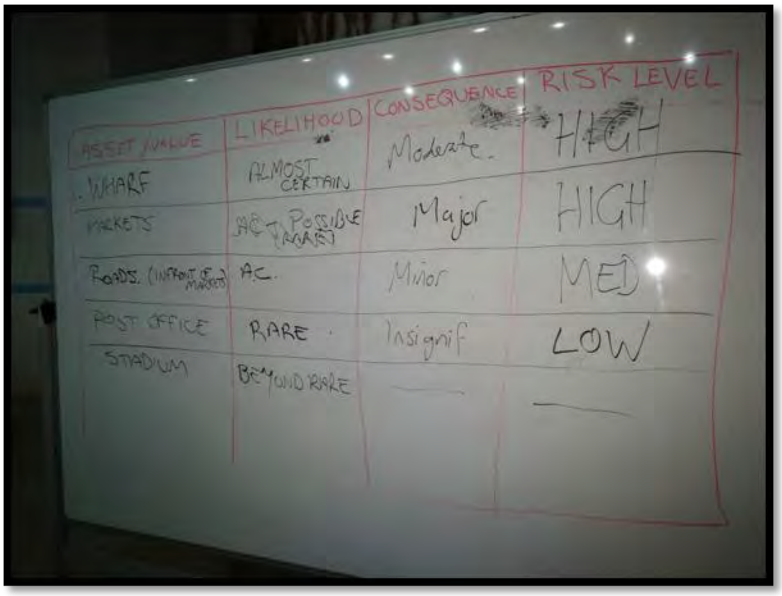

Figure 30: Risk category attributed to some key Lenakel assets, July 2018 Coastal Hazard Workshop

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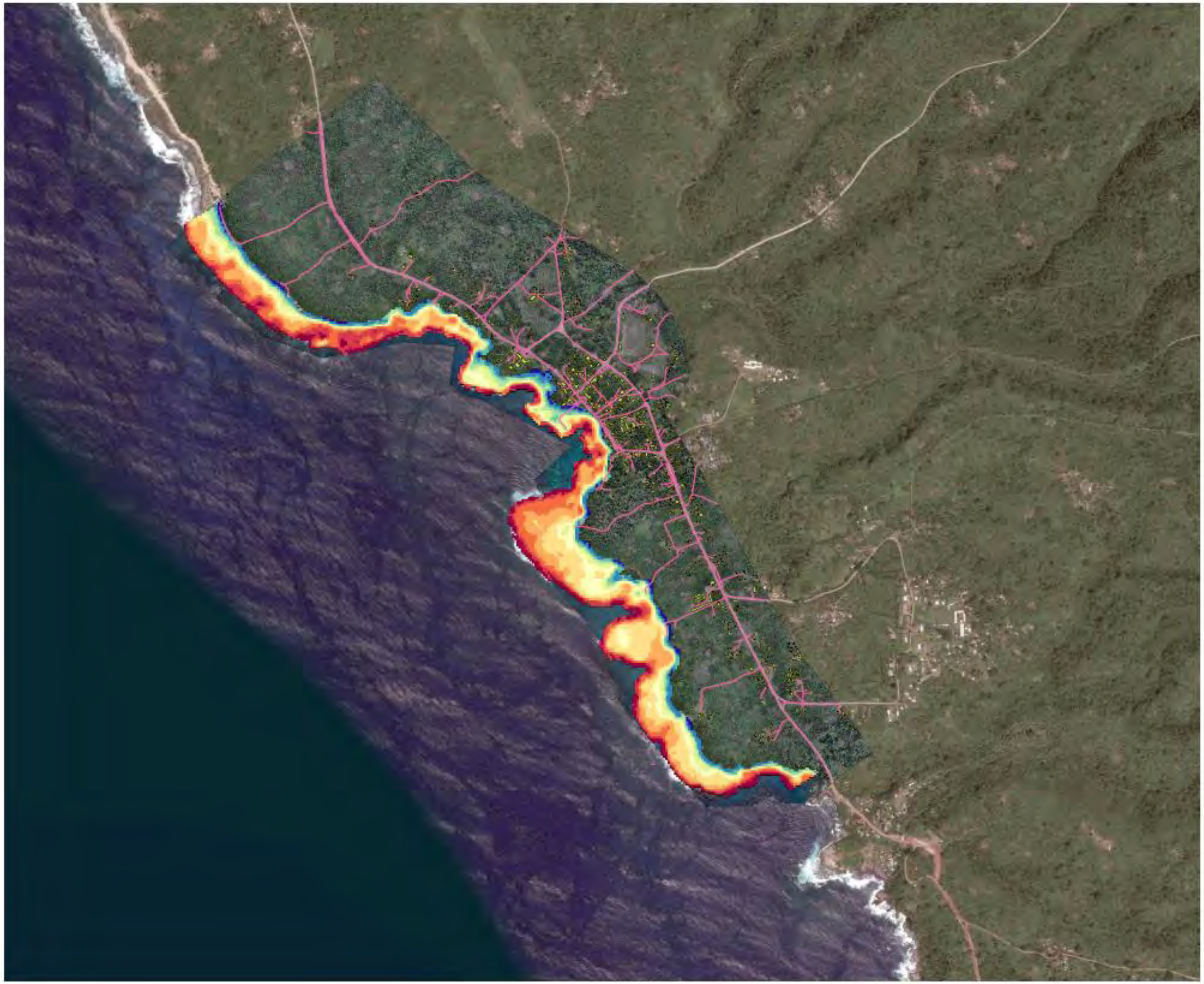
VII. ANNEX A: Tropical cyclone-driven inundation hazard maps

Tropical Cyclone Inundation Map
25 year Return Period
Lenakel, Tanna Island - Vanuatu



Legend

Max - Inundation depth (m)

- <= 0.156
- 0.156 - 0.541
- 0.541 - 0.925
- 0.925 - 1.31
- 1.31 - 1.69
- 1.69 - 2.08
- 2.08 - 2.46
- 2.46 - 2.85
- 2.85 - 3.23
- 3.23 - 3.62
- 3.62 - 4

Sea level rise scenario:

SLR: 0m (present day)

Projection:

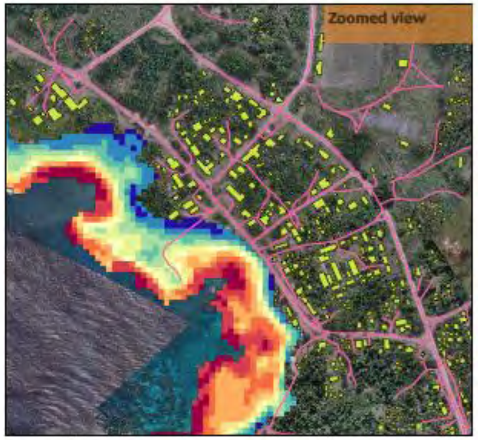
Coordinate system: GCS WGS 1984 (zone 59 South)

Other data sources:

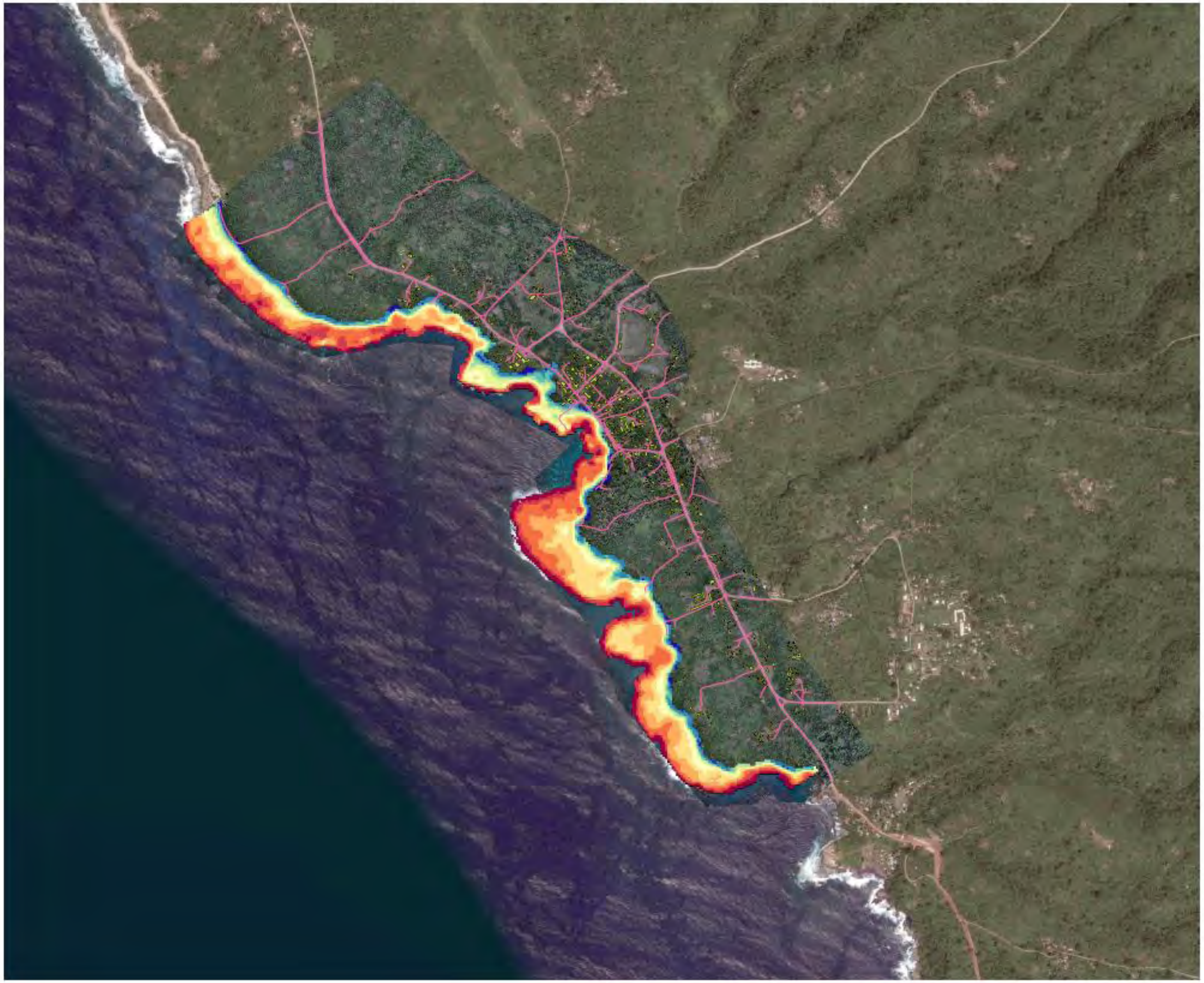
Orthophoto 2007
Orthophoto 2016 (from UAV survey)
Building layer & Roads digitised from UAV orthophoto acquired from the UAV survey 2016

Scale:1:10,000 @ A2

0 100 200 300 400 500 m



Tropical Cyclone Inundation Map
25 Year Return Period with SLR
Lenakel, Tanna Island - Vanuatu



Legend

Max - Inundation depth (m)

- <= 0.111
- 0.111 - 0.557
- 0.557 - 1
- 1 - 1.45
- 1.45 - 1.89
- 1.89 - 2.34
- 2.34 - 2.79
- 2.79 - 3.23
- 3.23 - 3.68
- 3.68 - 4.12
- 4.12 - 4.57

Sea level rise scenario:

SLR: 0.64m (2090 projection - RCP 8.5)

Projection:

Coordinate system: GCS WGS 1984 (zone 59 South)

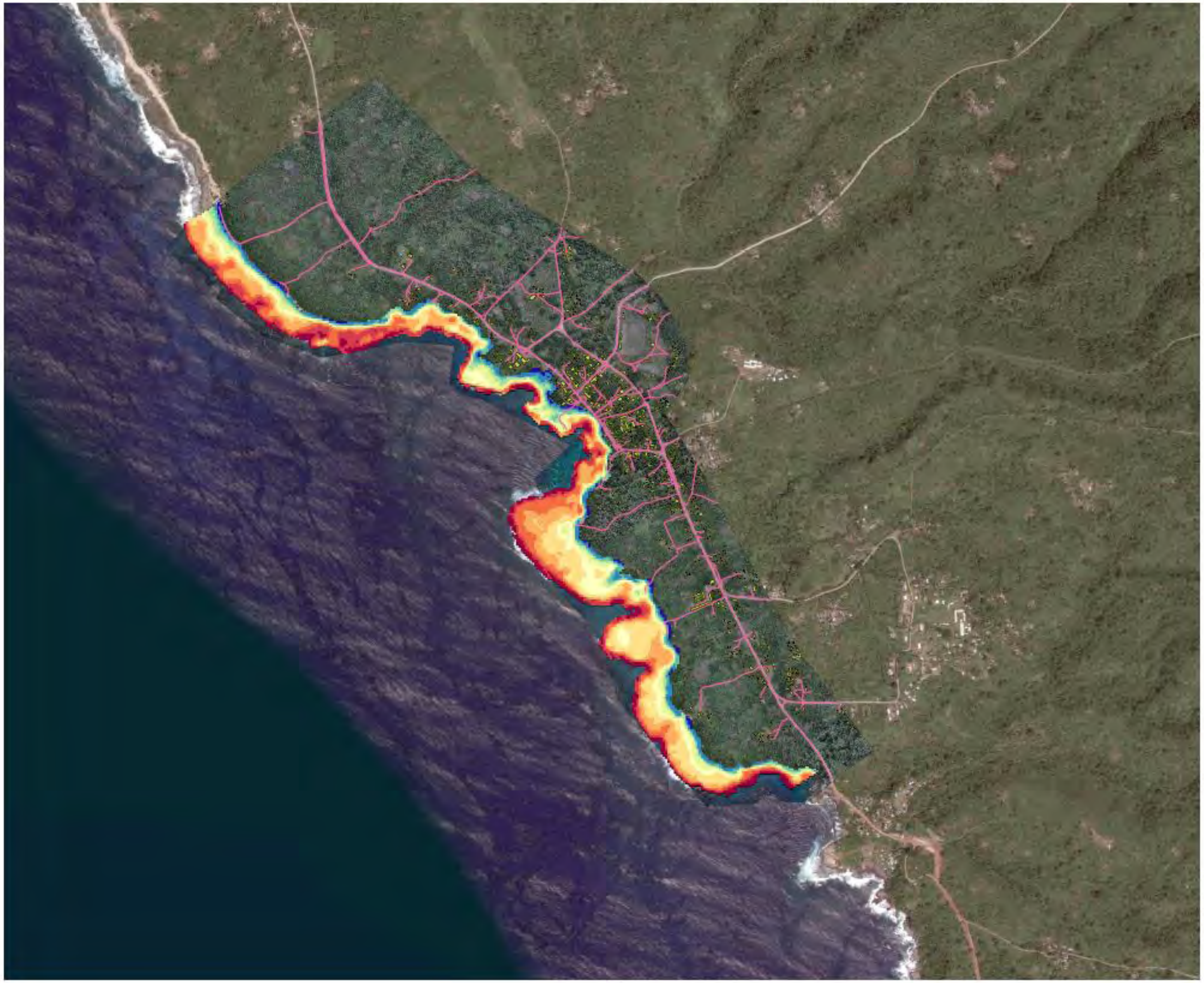
Other data sources:

Orthophoto 2007
Orthophoto 2016 (from UAV survey)
Building layer & Roads digitised from UAV orthophoto acquired from the UAV survey 2016

Scale:1:10,000 @ A2

0 100 200 300 400 500 m

Tropical Cyclone Inundation Map
50 year Return Period
Lenakel, Tanna Island - Vanuatu



Legend

Max - Inundation (m)

- <= 0.488
- 0.488 - 0.878
- 0.878 - 1.27
- 1.27 - 1.66
- 1.66 - 2.05
- 2.05 - 2.44
- 2.44 - 2.83
- 2.83 - 3.22
- 3.22 - 3.61
- 3.61 - 4
- > 4

Sea level rise scenario:

SLR: 0m (present day)

Projection:

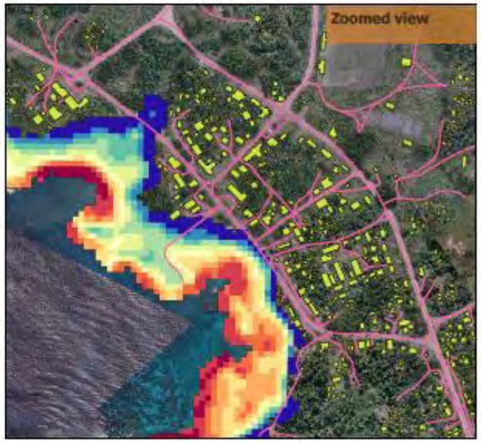
Coordinate system: GCS WGS 1984 (zone 59 South)

Other data sources:

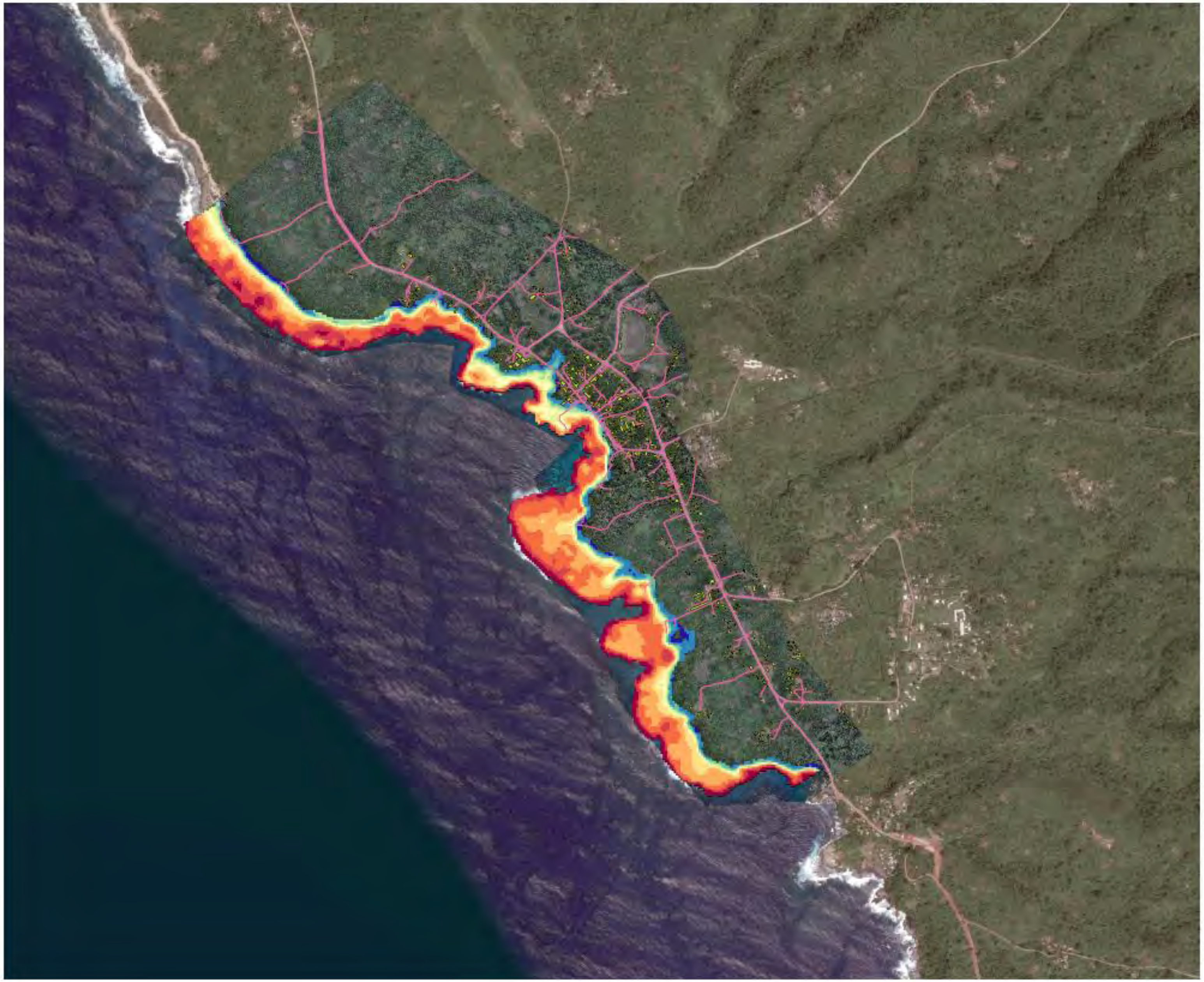
Orthophoto 2007
Orthophoto 2016 (from UAV survey)
Building layer & Roads digitised from UAV orthophoto acquired from the UAV survey 2016

Scale:1:10,000 @ A2

0 100 200 300 400 500 m



Tropical Cyclone Inundation Map
50 Year Return Period with SLR
Lenakel, Tanna Island - Vanuatu



Legend

Max - Inundation depth (m)

- <= 0.0831
- 0.0831 - 0.571
- 0.571 - 1.06
- 1.06 - 1.55
- 1.55 - 2.03
- 2.03 - 2.52
- 2.52 - 3.01
- 3.01 - 3.5
- 3.5 - 3.98
- 3.98 - 4.47
- 4.47 - 4.96

Sea level rise scenario:

SLR: 0.64m (2090 projection - RCP 8.5)

Projection:

Coordinate system: GCS WGS 1984 (zone 59 South)

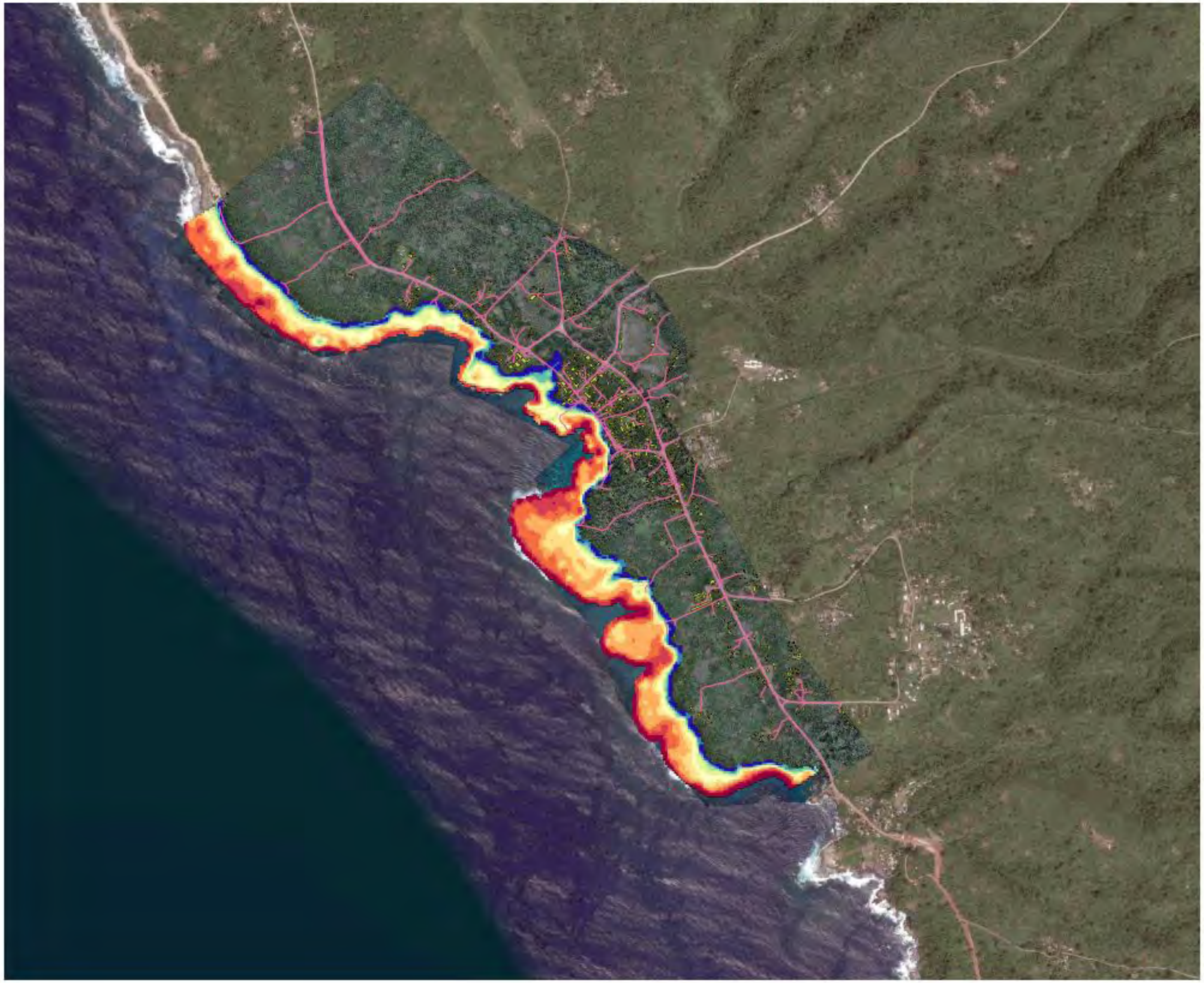
Other data sources:

Orthophoto 2007
Orthophoto 2016 (from UAV survey)
Building layer & Roads digitised from UAV orthophoto acquired from the UAV survey 2016

Scale:1:10,000 @ A2

0 100 200 300 400 500 m

Tropical Cyclone Inundation Map
100 year Return Period
Lenakel, Tanna Island - Vanuatu



Legend

Max - Inundation (m)

- <= 0.488
- 0.488 - 0.878
- 0.878 - 1.27
- 1.27 - 1.66
- 1.66 - 2.05
- 2.05 - 2.44
- 2.44 - 2.83
- 2.83 - 3.22
- 3.22 - 3.61
- 3.61 - 4
- > 4

Sea level rise scenario:

SLR: 0m (present day)

Projection:

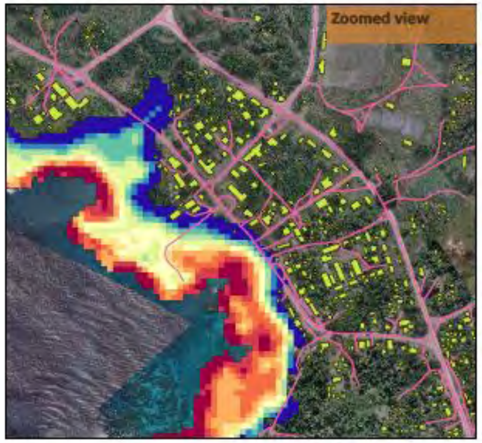
Coordinate system: GCS WGS 1984 (zone 59 South)

Other data sources:

Orthophoto 2007
Orthophoto 2016 (from UAV survey)
Building layer & Roads digitised from UAV orthophoto acquired from the UAV survey 2016

Scale:1:10,000 @ A2

0 100 200 300 400 500 m



Tropical Cyclone Inundation Map
100 Year Return Period with SLR
Lenakel, Tanna Island - Vanuatu

Legend

Max - Inundation depth (m)

- <= 0.55
- 0.55 - 0.997
- 0.997 - 1.44
- 1.44 - 1.89
- 1.89 - 2.34
- 2.34 - 2.79
- 2.79 - 3.23
- 3.23 - 3.68
- 3.68 - 4.13
- 4.13 - 4.57
- > 4.57

Sea level rise scenario:

SLR: 0.64m (2090 projection - RCP 8.5)

Projection:

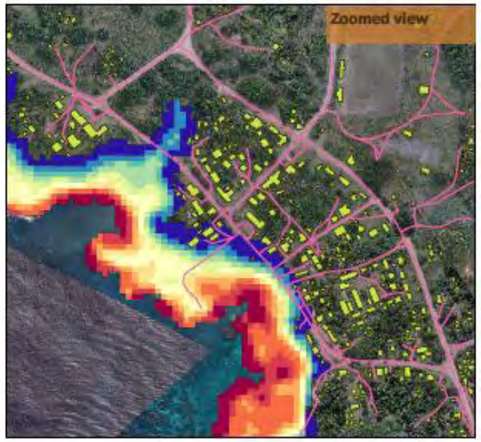
Coordinate system: GCS WGS 1984 (zone 59 South)

Other data sources:

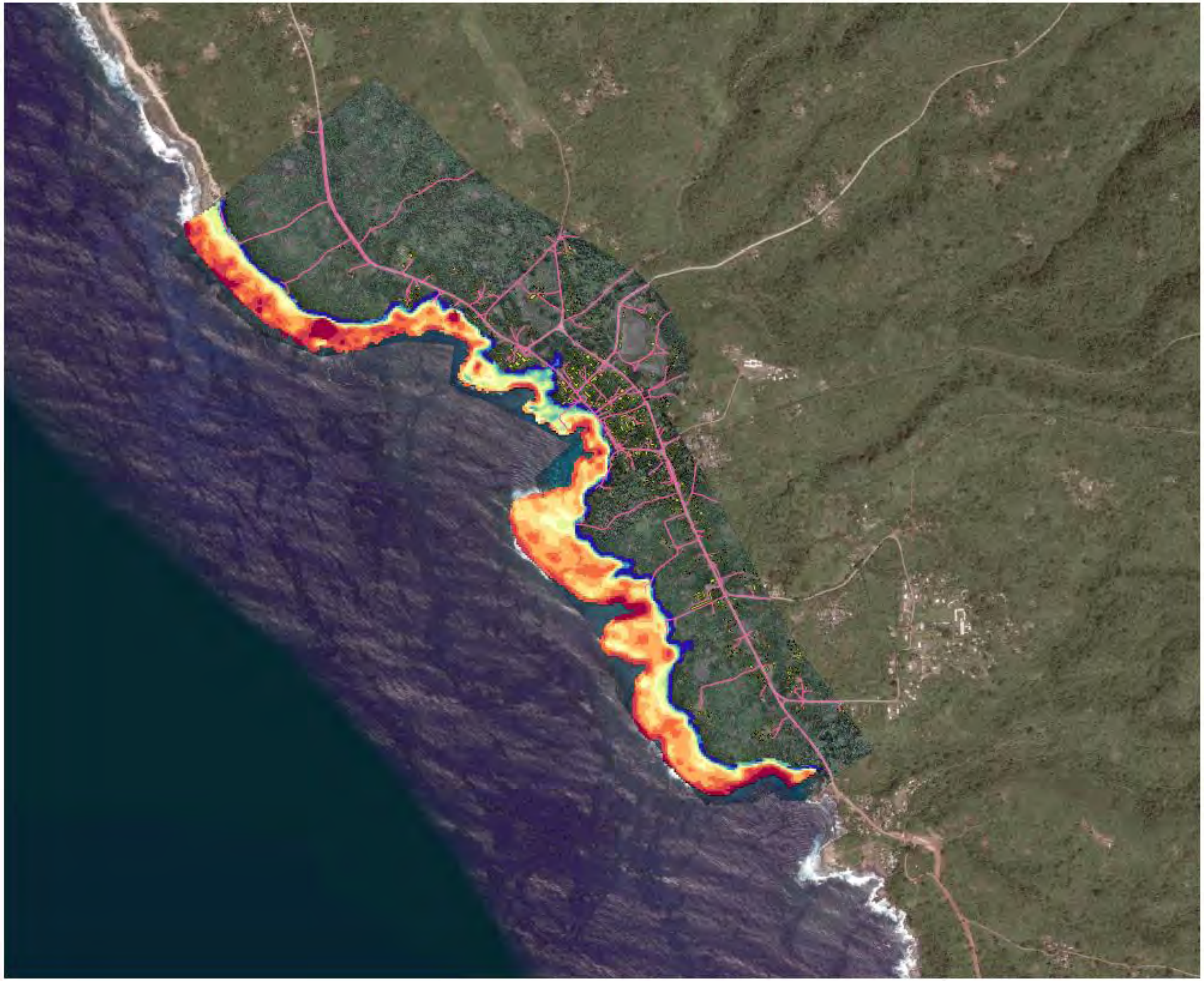
Orthophoto 2007
Orthophoto 2016 (from UAV survey)
Building layer & Roads digitised from UAV orthophoto acquired from the UAV survey 2016

Scale:1:10,000 @ A2

0 100 200 300 400 500 m



Tropical Cyclone Inundation Map
200 year Return Period
Lenakel, Tanna Island - Vanuatu



Legend

Max - Inundation depth (m)

- <= 0.526
- 0.526 - 0.955
- 0.955 - 1.38
- 1.38 - 1.81
- 1.81 - 2.24
- 2.24 - 2.67
- 2.67 - 3.1
- 3.1 - 3.53
- 3.53 - 3.96
- 3.96 - 4.39
- > 4.39

Sea level rise scenario:

SLR: 0m (present day)

Projection:

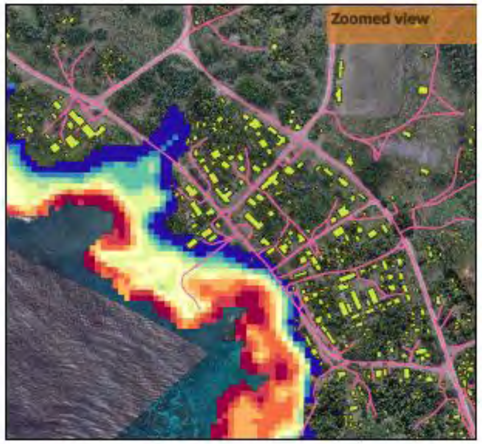
Coordinate system: GCS WGS 1984 (zone 59 South)

Other data sources:

Orthophoto 2007
Orthophoto 2016 (from UAV survey)
Building layer & Roads digitised from UAV orthophoto acquired from the UAV survey 2016

Scale:1:10,000 @ A2

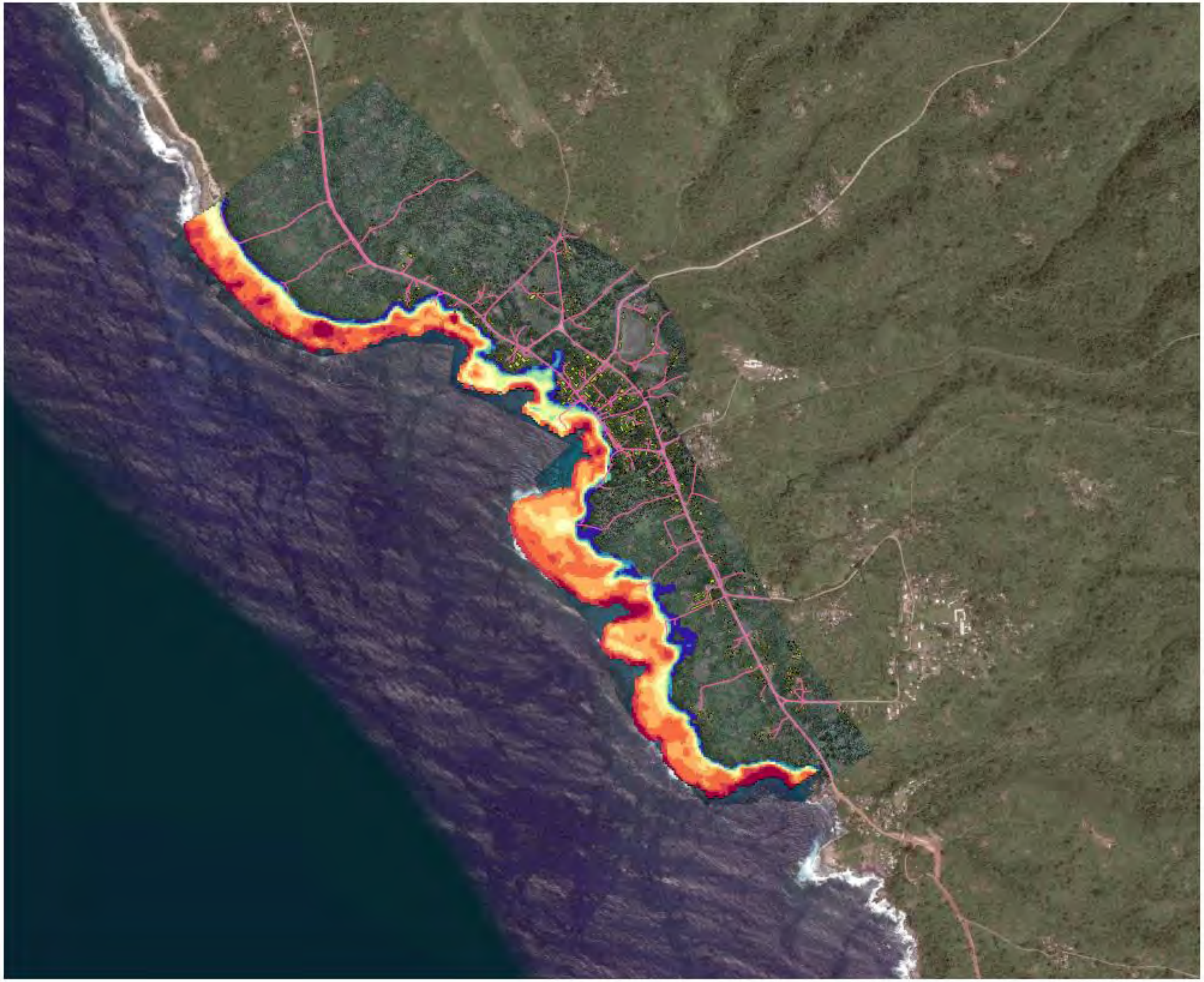
0 100 200 300 400 500 m



NEW ZEALAND
FOREIGN AFFAIRS & TRADE

Tropical Cyclone Inundation Map
200 Year Return Period with SLR
Lenakel, Tanna Island - Vanuatu

Pacific Community
Communauté du Pacifique



Legend

Max - Inundation depth (m)

- <= 0.572
- 0.572 - 1.03
- 1.03 - 1.5
- 1.5 - 1.96
- 1.96 - 2.42
- 2.42 - 2.88
- 2.88 - 3.34
- 3.34 - 3.81
- 3.81 - 4.27
- 4.27 - 4.73
- > 4.73

Sea level rise scenario:

SLR: 0.64m (2090 projection - RCP 8.5)

Projection:

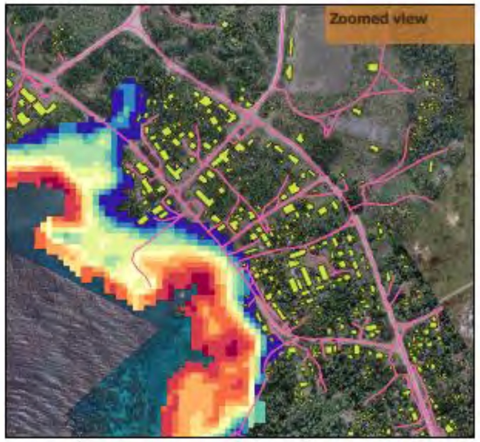
Coordinate system: GCS WGS 1984 (zone 59 South)

Other data sources:

Orthophoto 2007
Orthophoto 2016 (from UAV survey)
Building layer & Roads digitised from UAV orthophoto acquired from the UAV survey 2016

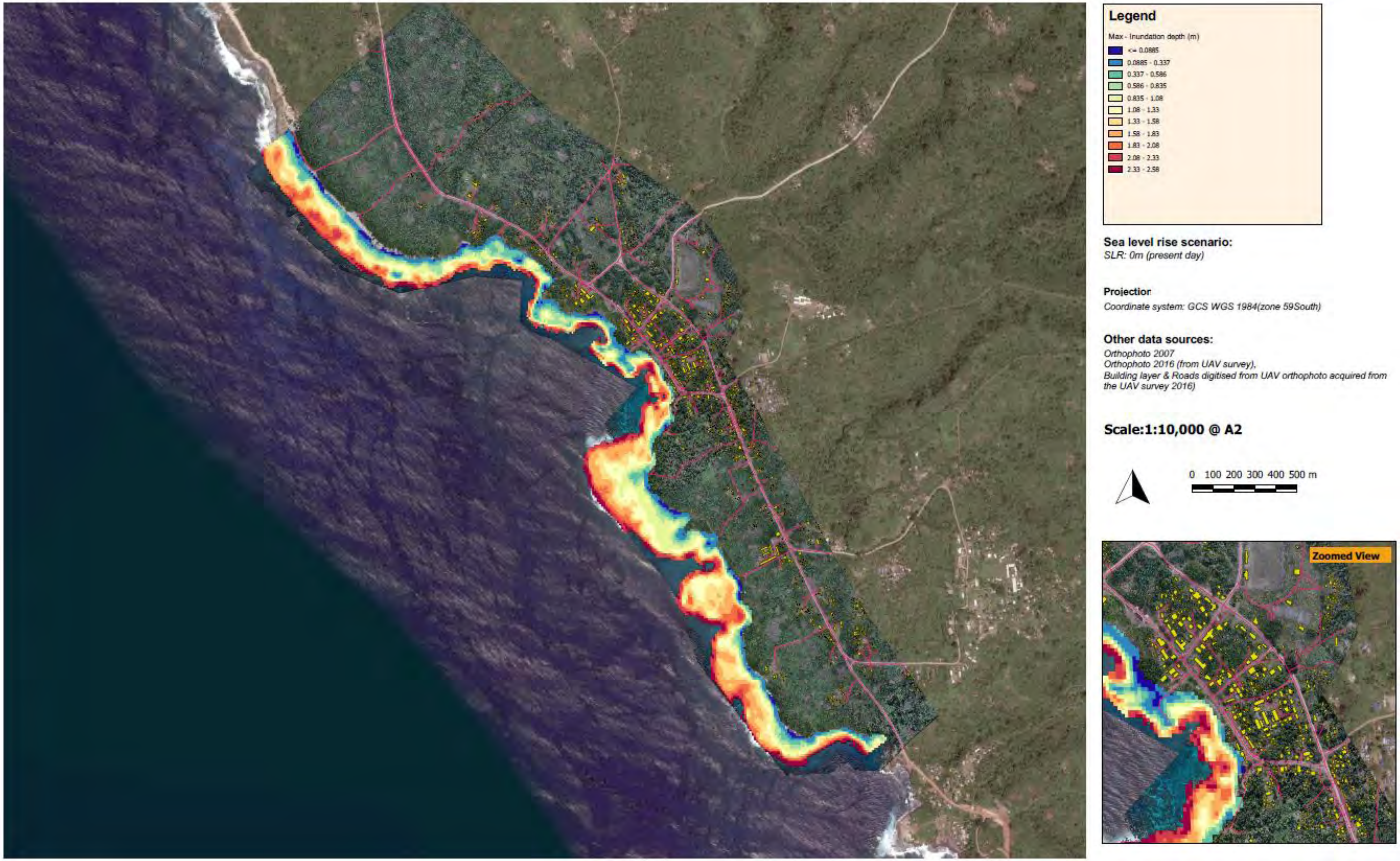
Scale:1:10,000 @ A2

0 100 200 300 400 500 m

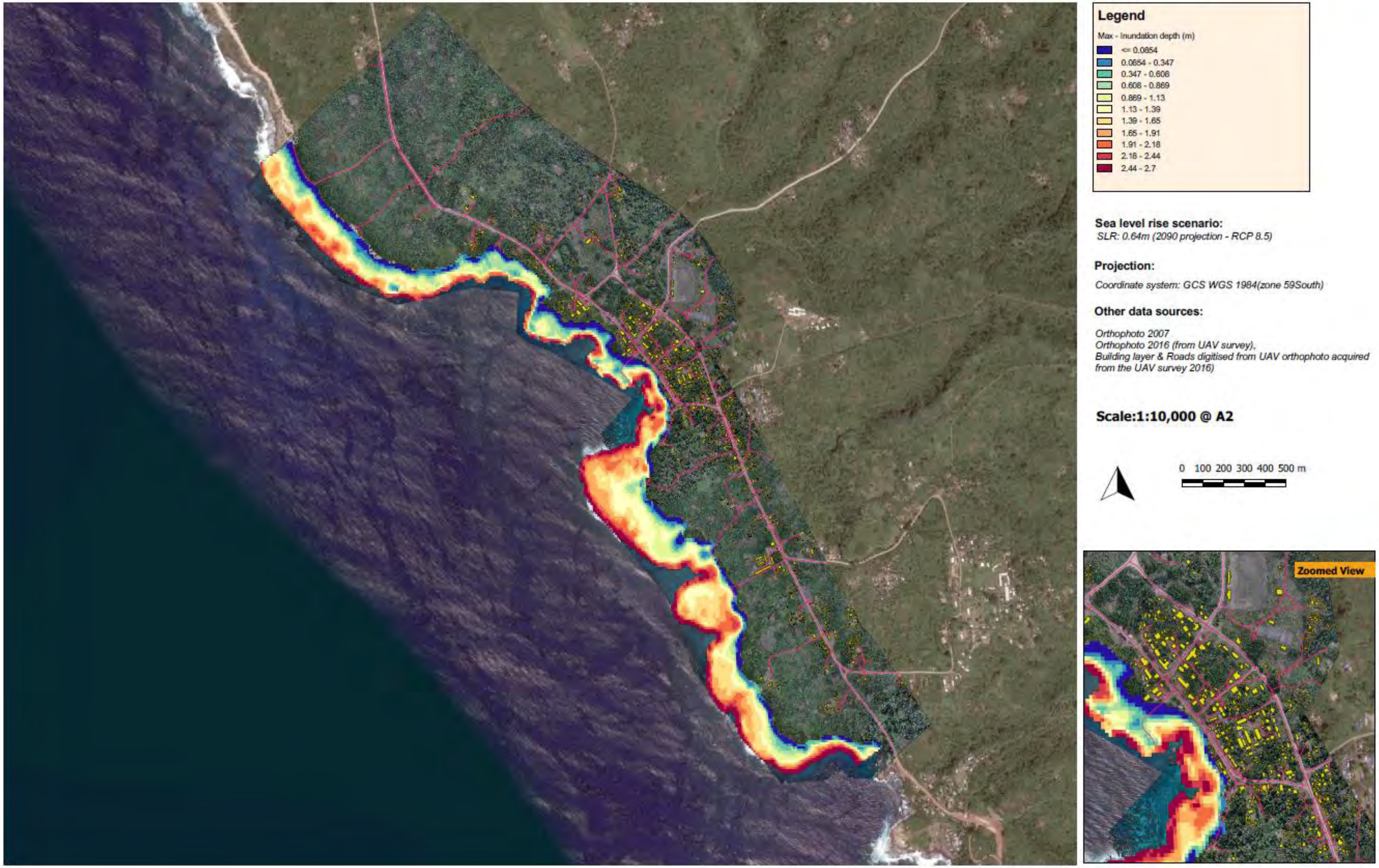


VIII. ANNEX B: Swell-driven inundation hazard maps

Swell Inundation Map
25 year Return Period
Lenakel, Tanna Island - Vanuatu



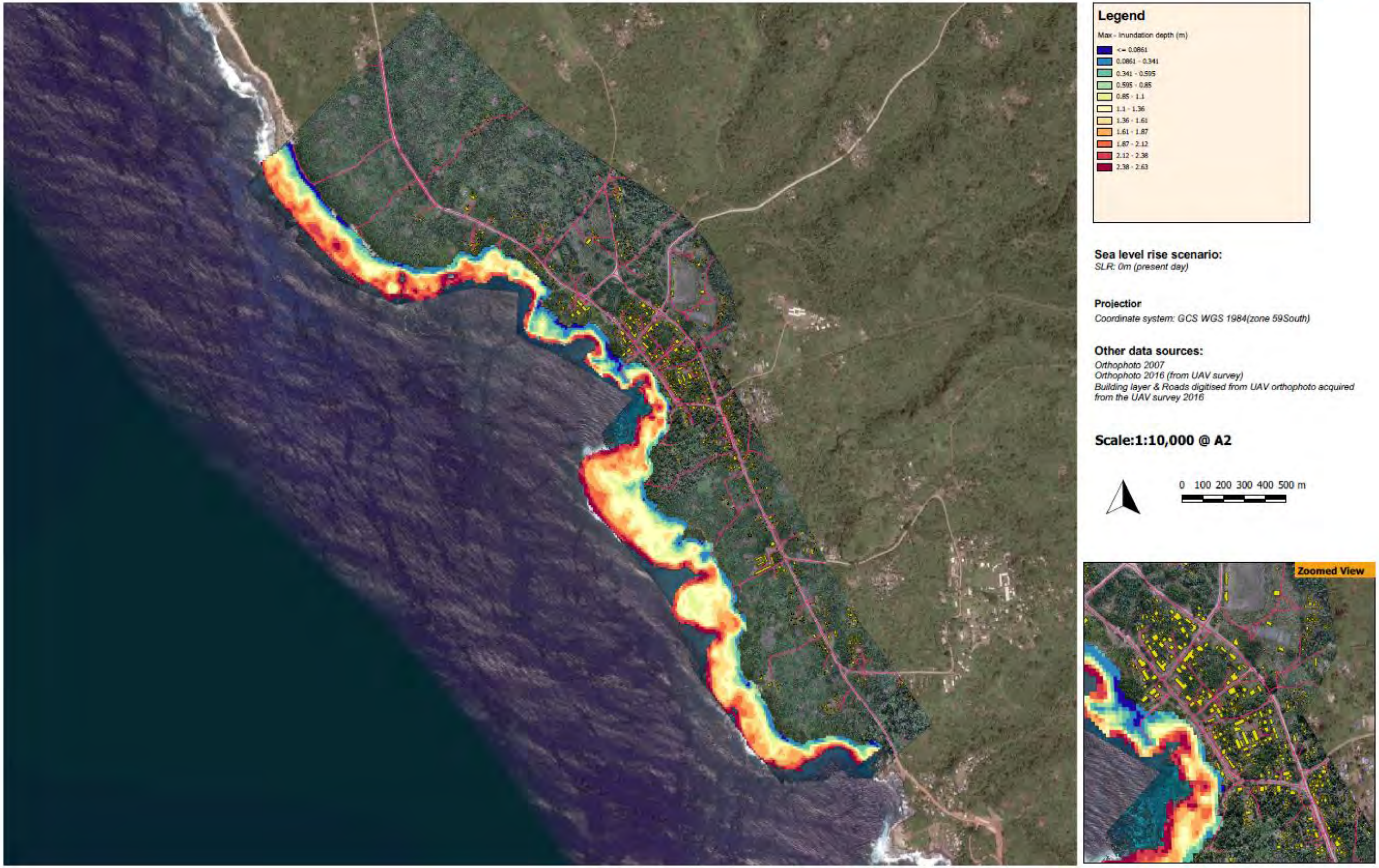
Swell Inundation Map
25 year Return Period with SLR
Lenakel, Tanna Island - Vanuatu



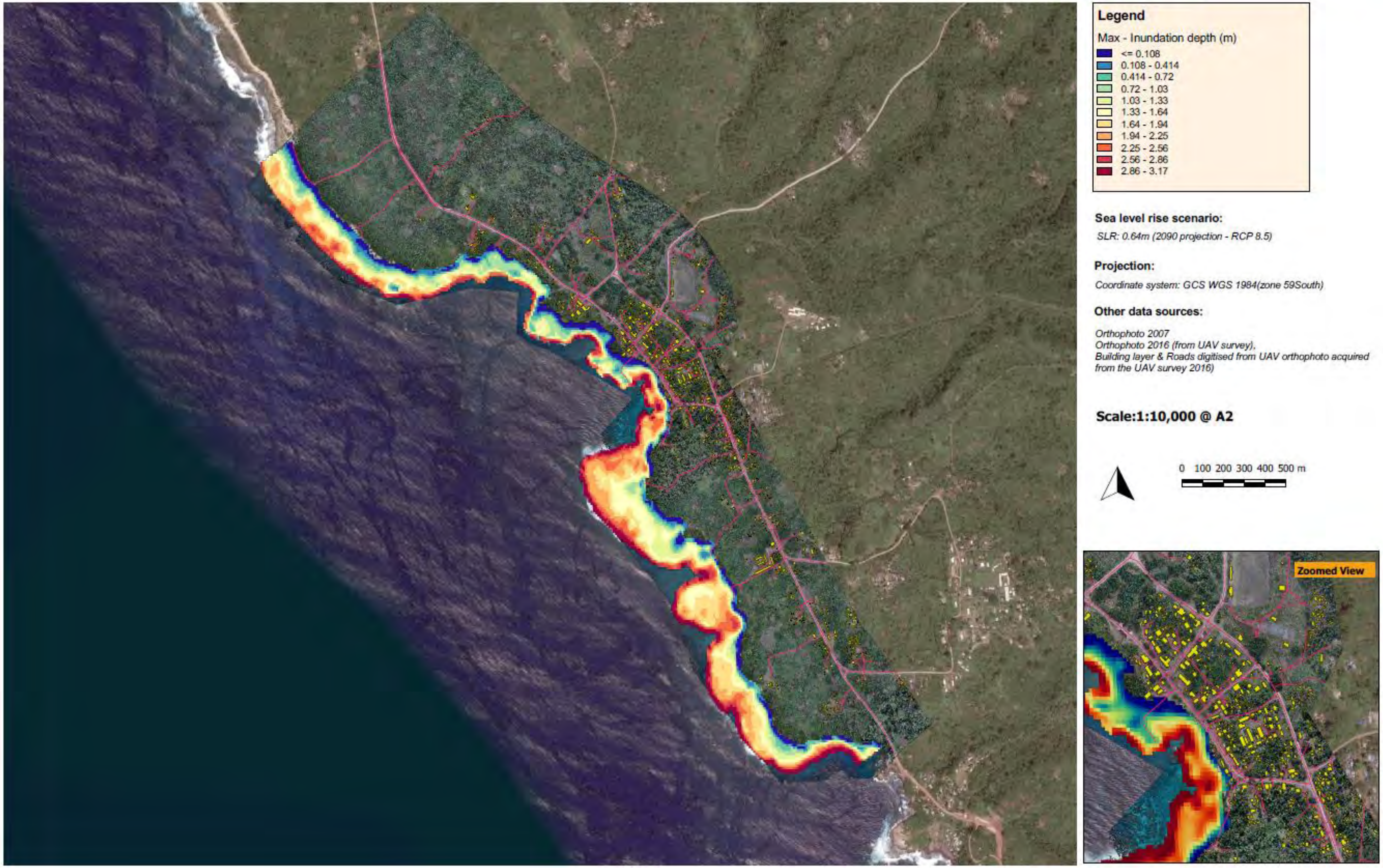
NEW ZEALAND
FOREIGN AFFAIRS & TRADE

Swell Inundation Map
50 year Return Period
Lenakel, Tanna Island - Vanuatu

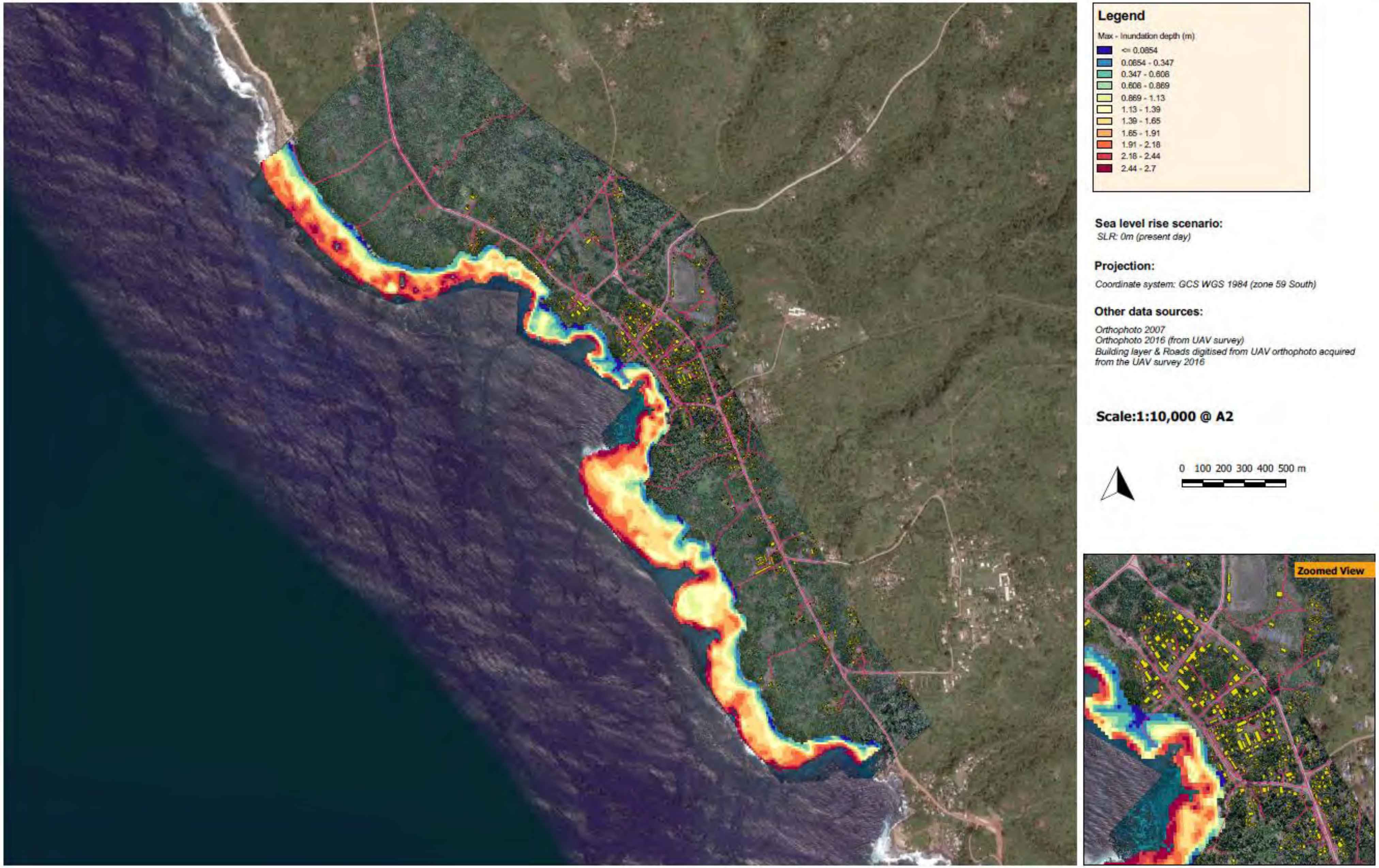
Pacific Community
Communauté du Pacifique



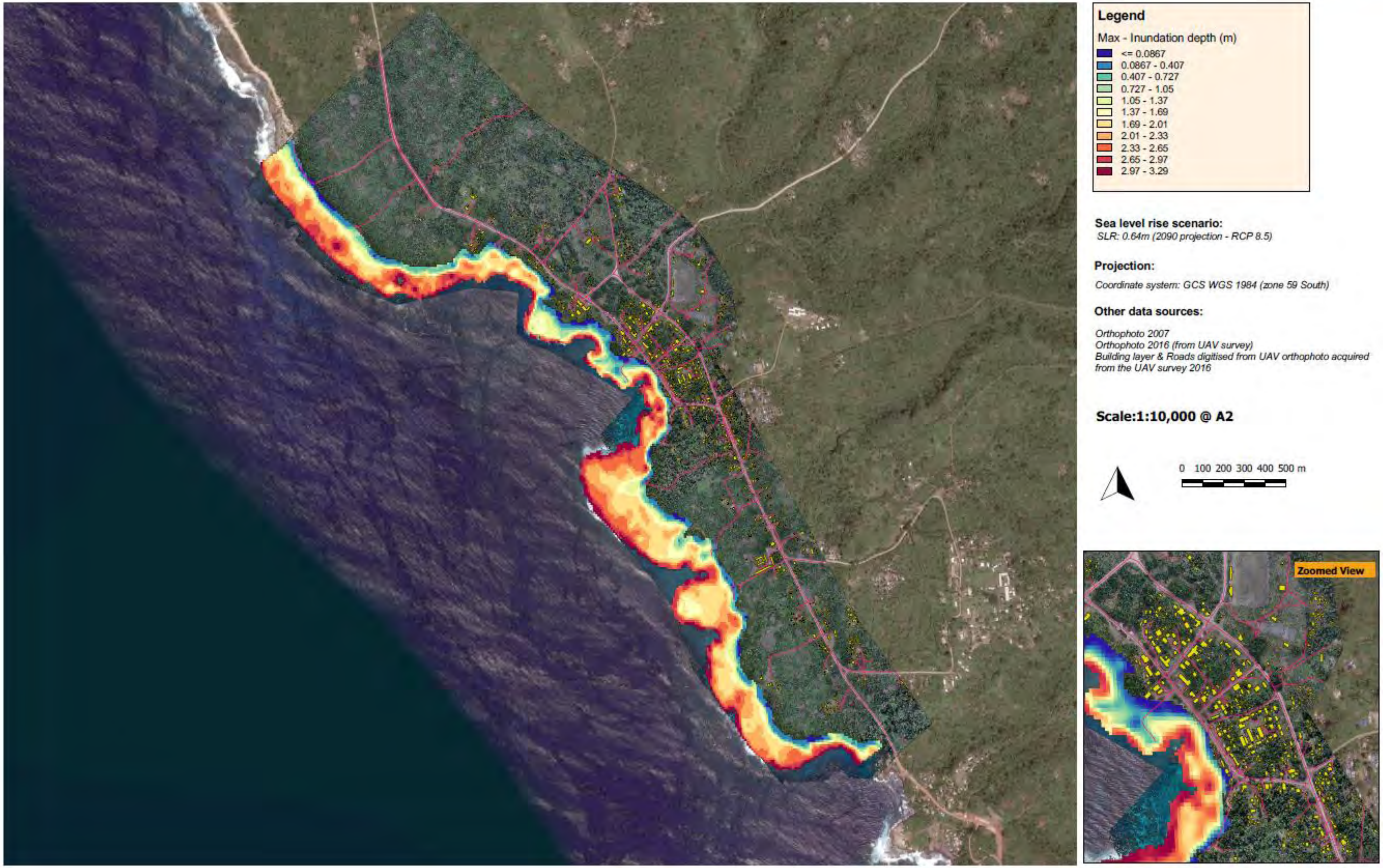
Swell Inundation Map
50 year Return Period with SLR
Lenakel, Tanna Island - Vanuatu



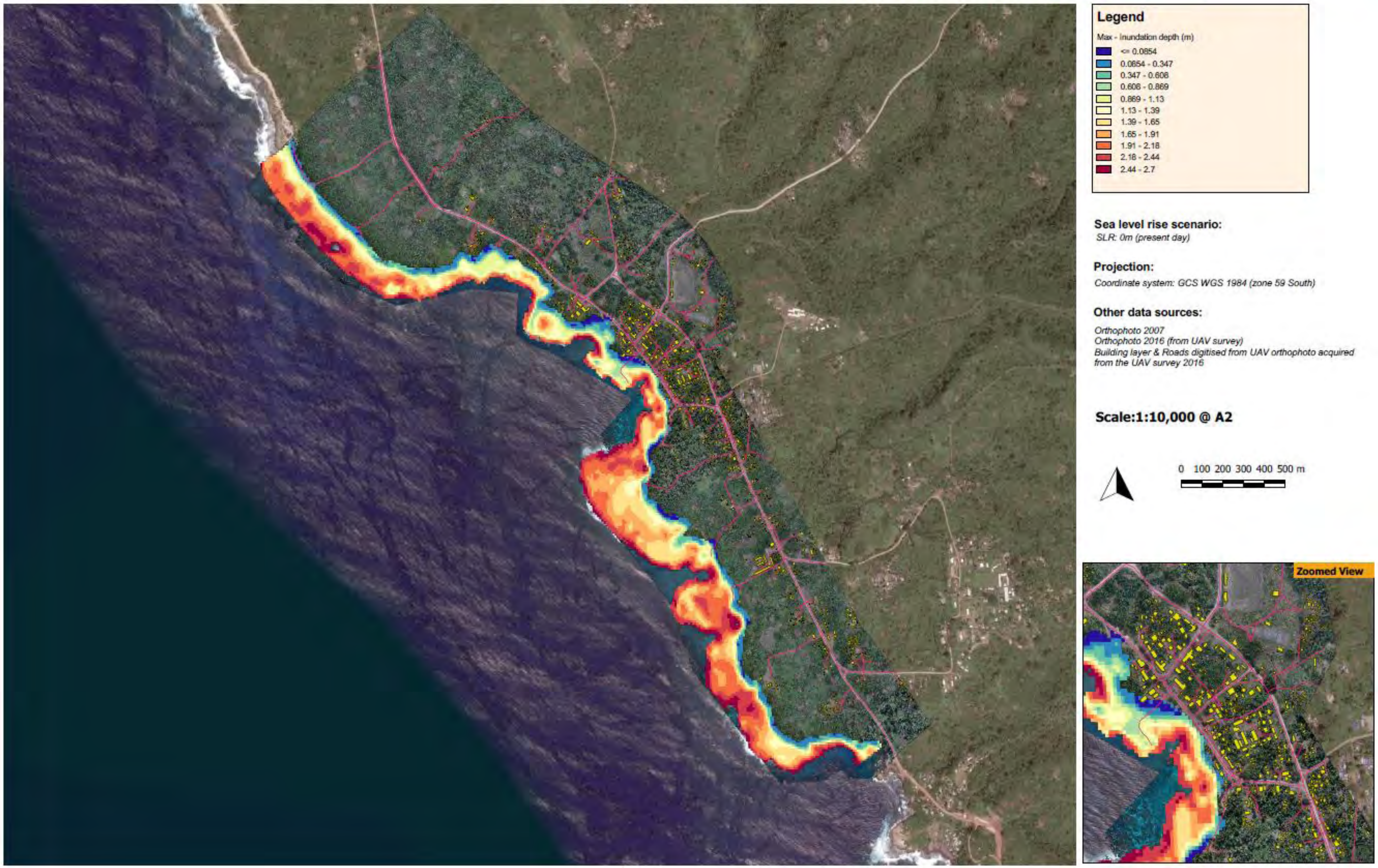
Swell Inundation Map
100 year Return Period
Lenakel, Tanna Island - Vanuatu



Swell Inundation Map
100 year Return Period with SLR
Lenakel, Tanna Island - Vanuatu



Swell Inundation Map
200 year Return Period
Lenakel, Tanna Island - Vanuatu



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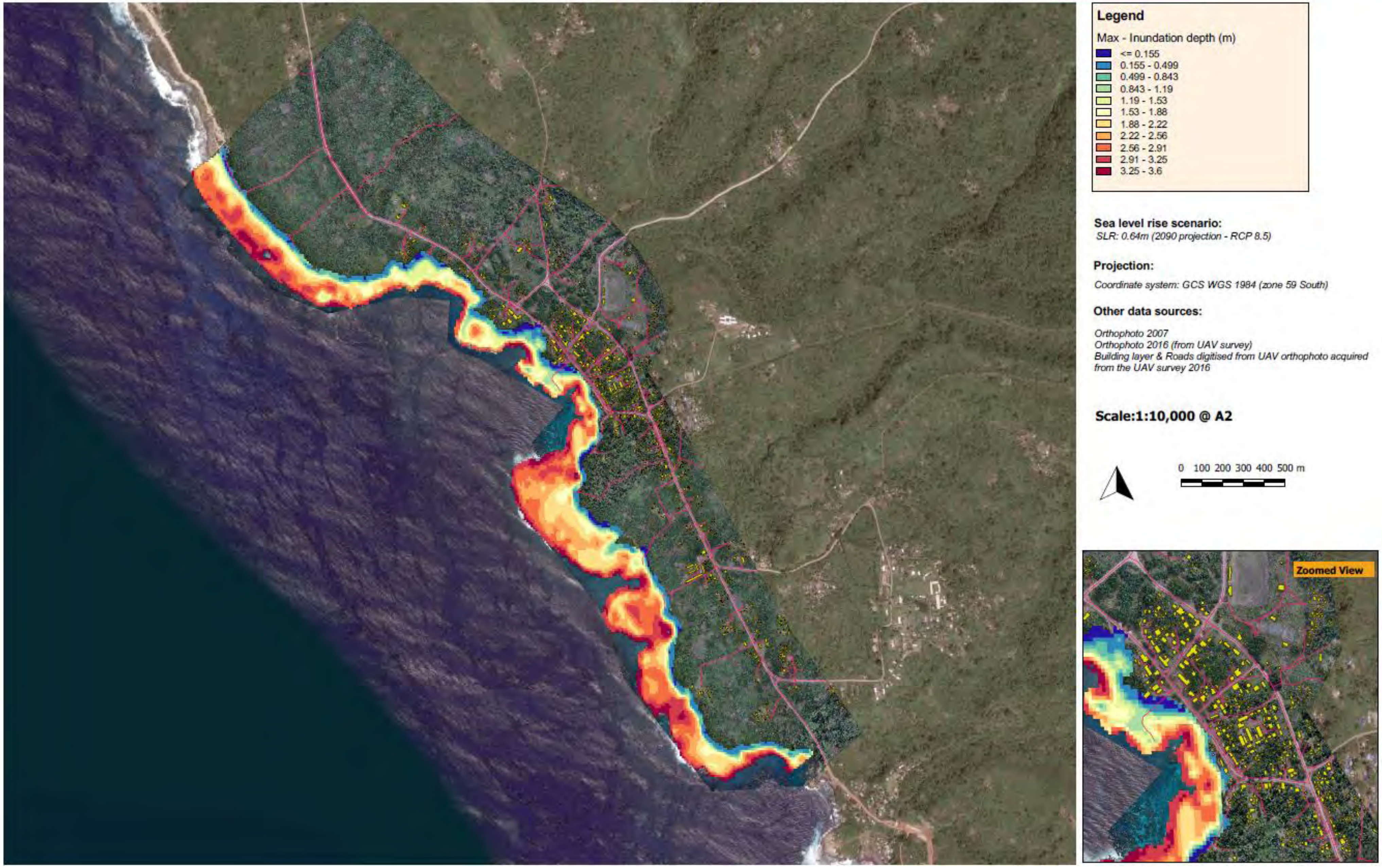
NEW ZEALAND
FOREIGN AFFAIRS & TRADE

Swell Inundation Map
200 year Return Period with SLR
Lenakel, Tanna Island - Vanuatu

Pacific Community
Communauté du Pacifique



IX. ANNEX C: Participants at the July 2018 KFW Hazard and Risk Workshop, and agenda

Vanuatu Government

1. Mr Ettienne Ravo
   Acting SG, Tafea Province
   Email: eravo@vanuatu.gov.vu

2. Mr David Martin
   Tafea Provincial Planning Officer
   Isangel, Tanna Island
   Email: dmartin@vanuatu.gov.vu;

3. Ms. Jenny Tuasu
   Physical Planning

4. Mr. Lui Mael
   Physical Planning

5. Mr. Freeman Gulu,
   Administrator Lenakel Town Municipal
   PO Box 198, Lenakel
   Tanna Island
   Email: glnumanian@gmail.com

6. Mr. Sampson Jerry
   Senior Town Planner
   Port Vila Municipal Council
   Email: jsampson@vanuatu.gov.vu

7. Ms Sharon Boe
   Mapping Section
   Department of Lands
   Email: srboe@vanuatu.gov.vu

8. Mr Jeffery Kaitip
   Department of Local Authorities
   PMB 9021, Port Vila
   Email: jkaitip@vanuatu.gov.vu

9. Mr Tom Maimai
   Environment
   No 2. Area
   Port Vila
   Email: tmaimai@vanuatu.gov.vu

10. Ms Camillia Garae
    Geology Mines
    Port Vila
    Email: gcamillia@vanuatu.gov.vu

11. Johnny Tarry Nimau
    Coordinator| PARTneR Project (Pacific Risk Tool for Resilience)
    National Disaster Management Office (NDMO) Port Vila
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    Email: Johnie@vanuatu.gov.vu

12. Mr Neil Malosu
    Depart of Water Resources
    George Pombidon
    Port Vila
    Email: nemalsu@vanuatu.gov.vu

13. Mr Michel Leodoro
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14. Mr Taio Johnny
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    Isangel,
    Tanna Island
    Email: tjohnny@vanuatu.gov.vu

15. Ms Juli Ungaro
    NIWA
    Email: Juli.Ungaro@niwa.co.nz

Facilitators

16. Dr Philip Haines
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    Environment, Eastern Australia
    Mobile: +61 (0) 417 208 240
    BMT WBM Pty Ltd,
    Level 8, 200 Creek Street,
    Brisbane, Queensland, 4000
    Australia
    Email: Philip.Haines@bmtglobal.com

17. Ms Maggie Muurmans
    Coastal Community Engagement Program Coordinator

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Gold Coast Campus QLD 4222
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T+ 0434 412 101
Email m.muurmans@griffith.edu.au

Pacific Community (SPC)

18. Mr Jens Kruger
    Manager – Ocean & Coastal Geoscience
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19. Herve Damlamian
    Oceanographer
    Email: herved2@spc.int

20. Mr Judith Giblin
    Senior Technical Officer - Oceanography
    Email: judithg@spc.int

21. Ms Virginia (Ginny) Rokoua
    Programme Administrator
    Email: virginiar@spc.int

22. Mr Olivier Dalang
    Geospatial Systems Developer
    PREP
    Email: olivierd@spc.int

Day 1	Monday, 6 August 2018		
Time	**Activity description**	**Lead**	**Activity type**
8.30am	Registration		
9.00am	Welcome	VMGD	Dialogue
	Introduction of participants	SPC	Dialogue
	Workshop outline and objectives	SPC	Presentation
10.00am	Morning tea		
10.20am	Introduction to coastal risk assessments	SPC	Presentation
	Coastal development policies in Vanuatu	GoV	Presentation / Dialogue
	Coastal hazard mapping in Lenakel, methodology and products	SPC	Presentation
1.00pm	Lunch		
2.00pm	Coastal zone management challenge	Griffith Uni	Group work
3.00pm	Afternoon Tea		
3.30pm	Continued: Coastal zone management challenge	Griffith Uni	Group work
	Wrap up day one	SPC	Discussion and feedback
4.30pm	Closing		

Day 2	Tuesday, 7 August 2018		
Time	**Activity Description**	**Lead**	**Activity type**
9.00am	Case study: Assessing vulnerability and adaptation options, Lifuka Island, Tonga	SPC	Presentation
10.00am	Morning tea		
10.20am	Case study: Climate change adaptation plan, Choiseul Bay Township, Solomon Islands	BMT	Presentation
11.20am	Land zoning in Lenakel, and introduction to group work	GoV	Presentation / Dialogue
11:30am	Post TC Pam PDNA	GoV	Presentation / Dialogue
11:40am	Asset / value inventory mapping	BMT / SPC	Group work and feedback
1.00pm	Lunch		
2.00pm	Consequence scale and likelihoods	BMT / SPC	Group work and feedback
3.00pm	Afternoon tea		
3.30pm	Risk assessment	BMT / SPC	Group work and feedback
	Risk evaluation and land use zoning	BMT / SPC	Discussion and feedback
	PARTNER Work on Lenakel	NIWA	Presentation
4.30pm	Closing		

Pacific Community
spc@spc.int | www.spc.int
Headquarters: Noumea, New Caledonia