Wave inundation on the Coral Coast of Fiji

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Abstract

The roaring winds of the Southern Ocean and the Tasman Sea can generate some large swells, big enough to cause inundation on the Coral Coast in the south west of Viti Levu in Fiji, some 3000 km to the north. These inundation events are sometimes associated with tsunami-like long waves that hit the shore and inundate the coast with brute force. These are locally known as loka waves. To understand the origin of the loka waves and how they become so destructive in a fringing reef environment, this research monitored the waves and water levels, for 2 years, at 4 locations across the reef at a pilot site in Maui Bay on the Coral Coast of Fiji. In order to test the size of waves necessary to cause coastal inundation, a validated numerical model, XBeach, was used to simulate the development, propagation and dissipation of these infragravity waves using different water level scenarios. The result of this analysis is intended as a predictive tool to evaluate the risk of coastal inundation from ocean surface waves that can be used to support an early warning system and coastal management tool for both the tourism industry and coastal communities on the Coral Coast.

Keywords: Infragravity waves, Fringing reef

1. Introduction

Storms and strong winds in the Southern Ocean can generate very large swells often exceeding 6m [2]. Some of these swells can propagate across great distances through the Tasman Sea and into the Pacific while losing little energy [1]. By the time they reach the Fiji island group some 3000 km to the north, the largest swells can cause coastal inundation and are associated with tsunami-like long waves that hit the shore and inundate the coast with brute force. These are locally known as loka waves.

In coastal oceanography, these long waves are known as infragravity (hereafter IG) waves (e.g. [5], [6], [8], [9], [10], [11]). IG waves are known to dominate the surfzone hydrodynamics during storm events and play a major role in facilitating overtopping of dunes and barrier islands [10]. In fringing reef environments, IG waves are formed when wave groups pump water onto the reef flat at a regular time interval; this cumulated water on the reef crest then propagates shoreward as an IG wave. Since 70% of the short wave energy can be dissipated [8] on the reef crest, IG waves are the dominant hydrodynamics process on the reef flat and therefore the dominant process that transports sediments [9]. IG wave behaviour during inundation on fringing reefs is not yet clear because there are not many observations during inundation events. Péquignet et al. [6] showed that, during Typhoon Man-Yi, in Guam, IG waves were not only the dominant process but also had a period close to the resonant frequency of the reef flat. This effect has been assumed to exacerbate coastal inundation [11] but this phenomenon may only occur during extreme events such as tropical storms. IG waves generation and dissipation is highly dependent on local conditions and reef shape (slope of the reef, bottom roughness…) thus these waves may vary greatly alongshore. These uncertainties prevent the development of simple empirical prediction tools making their contribution during inundation events difficult to predict.

The prevention of damage and asset loss due to coastal hazard is a priority for reducing the vulnerability of the coastal communities of the Pacific. This study aims to better understand the IG wave and coastal inundation on the Coral Coast of Fiji and to develop tools to facilitate the forecast of such events, and give the meteorological services the capacity to issue better informed early warning for wave coastal inundation. Field data of waves are presented below, along with a numerical model that simulates the generation and dissipation of the IG waves. In the discussion, an operational wave inundation forecast system is proposed as a tool to issue early warnings for the loka waves.

2. Methods

2.1 Field site

To understand the origin and fate of loka (i.e. IG) waves and how they become so destructive in the fringing reef environment of the Coral Coast of Fiji, this research consisted of monitoring the waves and water levels, for 2 years, along a cross-reef profile at a pilot site in Maui Bay, located on the Coral Coast of Fiji on the South coast of Viti Levu (Figure 1). In Maui Bay, the reef flat is approximately 600m wide bounded by a narrow opening in the reef (50m wide) to the east and a wide opening in the reef (150m wide) to the west. Either side of the reef passages are bounded by small algae ridges reaching Mean Sea Level (hereafter MSL). As a result, the reef flat in Maui Bay is an enclosed basin approximately 1.5m deep where the water level rarely reaches below MSL. The reef flat is up to 1.5m deep (relative to MSL) but dotted with numerous coral heads and micro-atolls reaching near MSL. The reef slope is very steep reaching 100m depth 200—300m offshore off the reef crest. At the shore, the beach is perched on a beach rock platform reaching 1m above MSL. The beach is composed of coarse sand, poorly sorted with a large fraction of coral rubble and debris. There are no dune systems and the beach ridge, while not clearly noticeable, reaches 3.5m above MSL.

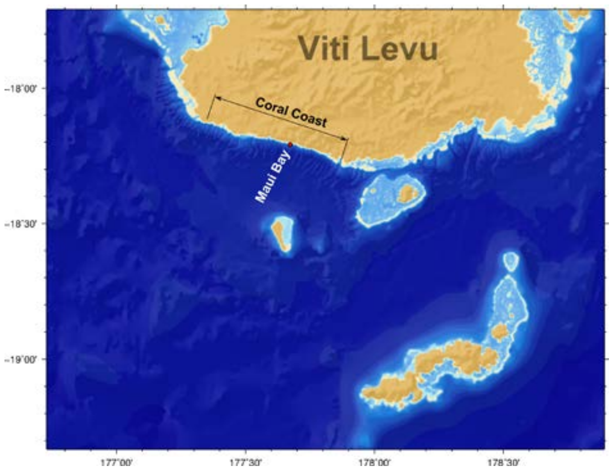

Figure 1. Map of the South of Viti Levu in Fiji. The red dot shows the location of the field site.

Tide on the South coast of Viti Levu is semi-diurnal with 1.2m amplitude. The wave climate is dominated by Southern Ocean swells and trade wind waves. The annual mean wave height is 2.15m with a peak period of 13s from the South(189º). The 99th percentile wave height is 3.93m and is often related (90% of the time) with large Southern Ocean swell [3].

Wave and water levels were recorded at 4 locations across the centre of the fringing reef (Figure 2) starting in March 2013 till November 2014:

- On the reef slope, at 20m depth with Acoustic Doppler Current Profiler (hereafter ADCP) equipped with a pressure sensor.
- On the reef crest with a pressure sensor.
- In the centre of the reef flat with a shallow water ADCP equipped with a pressure sensor.
- At the shore, 15m offshore from the beach rock with a pressure sensor.

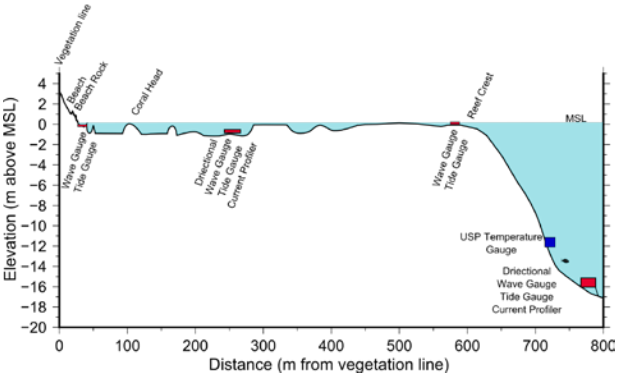

Figure 2. Conceptual cross-shore bathymetry of the reef flat in Maui Bay and instruments location.

The wave data were collected at each location every 3 hours, while the water level recordings were collected at a different rate for each location.

Root mean square wave height (Hereafter Hrms) was calculated as:

$$H_{RMS} = \sqrt{8.\int_{0.05}^{0.3} S df} \tag{1}$$

where S is the wave power spectra in $\mathrm{m^2 Hz^{-1}}$ and f is the wave frequency in Hz.
Similarly, infragravity wave height (Hereafter Hi) was calculated as:

$$H_i = \sqrt{8.\int_{0.005}^{0.05} S df} \tag{3}$$

The total instantaneous water level is recorded by every instrument during 2048s bursts every 3 hours. Outside of these bursts the total water level is considered to be the sum of the average water level, the IG wave amplitude (0.5*Hi) and the short wave amplitude (0.5*Hrms). Wave inundation is considered to happen when the total water level reaches over 3.5m (i.e. the elevation of the beach ridge).

2.2 Wave inundation model

To better understand the mechanism of inundation in Maui Bay and estimate the wave height threshold for inundation, a hydrodynamic model was used. The model used in this study is XBeach [10]. XBeach uses a wave action balance model to simulate the wind waves with single representative period and an explicit hydrodynamics model to simulate the propagation of long waves. The models are fully coupled and interact at every time step (here 0.1s). Hrms is an output of the wave model and Hi was calculated using equation 3, with the water level output from the model every 1s for 2048s allowing model warm up time.

2.2.1 Bathymetry

To run the model accurately a high resolution bathymetry was necessary. The bathymetry was created using a wide range of topography and bathymetry surveys (table 1).

Table 1 Data sources compiled to create the model bathymetry.

Dataset	Year	Location and method
Multi-beam bathymetry	2012	Offshore reef slope. Bathymetry on the Western half of the domain
Real time Kinematic GNSS survey	2013	Shoreline, beach rock, beach toe, beach top, reef crest
Single-beam bathymetry	2014	Reef flat area
Single-beam bathymetry	2014	Reef slope
Satellite derived	2013	Reef flat. Based on RTK and single beam of the reef flat

All the datasets were collated and interpolated to produce a 5m resolution bathymetry grid. The bathymetry was rotated (75º clockwise) so the offshore would face the model offshore boundary (Figure 3).

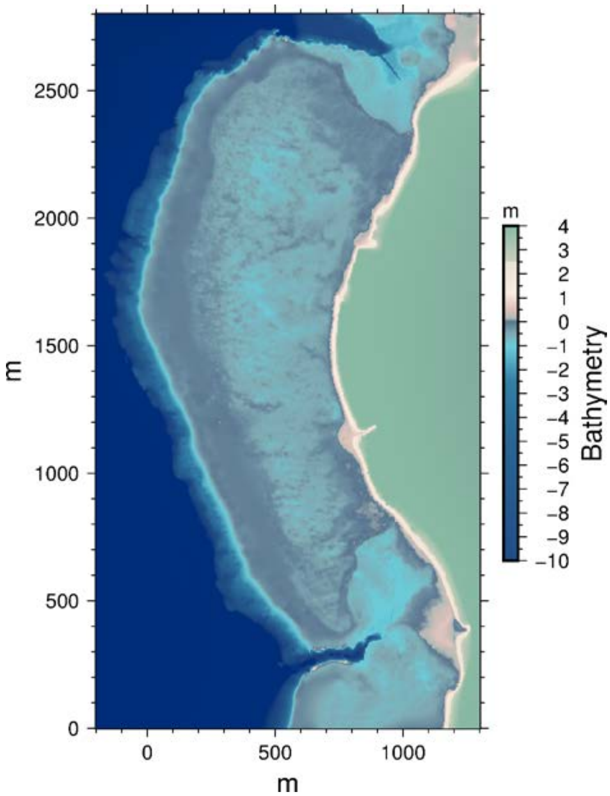

Figure 3. Bathymetry of Maui Bay rotated to fit the model requirement.

2.2.2 Model validation

XBeach is a well-tested model to simulate wave driven inundation [4]. In order to test the validity of the Maui Bay model during high swell conditions, the 3 largest measured wave events were simulated and compared with observed data. The model preformed reasonably well at all 3 sites (Table 2) with a RMS error below 0.05m at the shore. Therefore the model can be used for further investigation of coastal inundation with high confidence.

Table 2. Model root mean square errors for Hrms and Hi

Instrument location	Hrms RMS error	Hi RMS error (m)
Reef crest	0.11m (15%)	0.17 (18%)
Mid reef flat	0.07m (50%)	
shore	0.03m (24%)	0.05m (9%)

2.2.3 Inundation threshold

This study aims at better understanding the wave inundation process on fringing reef with the aim of reducing the vulnerability of local communities. One of the aspects of reducing vulnerabilities is to issue early warnings when inundation events are on their way. Using the tested numerical model this study asses the wave height threshold for coastal inundation in Maui Bay during 3 tidal levels:

- Mean High Water Neap (MHWN): 0.47m above MSL
- Mean High Water (MHW): 0.58m above MSL
- Mean High Water Spring (MHWS): 0.68m above MSL
- Mean Perigean Spring tide (MHWPS): 0.81m above MSL

The threshold was only tested for offshore swell waves with a significant wave height (Hs=Hrms*1.414) between 3—5m at a 0.5m increment, a 16s peak period and a southerly direction (190º). Inundation was considered to happen when the total water level at the shore exceeded 3.5m above MSL. The level corresponds to the elevation of the top of the beach.

3. Results

Field data collection recorded 21 month of wave and water level data between March 2013 and November 2014 but during this period no significant inundation event could be observed in Maui Bay.

3.1 Largest events

The three largest wave events recorded are presented here. The largest events were selected based on offshore wave height and inshore infragravity wave height. The 3 events selected include the 2 largest wave heights offshore and the 2 largest infragravity wave heights recorded at the shore (Figure 4). These events correspond to large swell events that peaked near high tide.

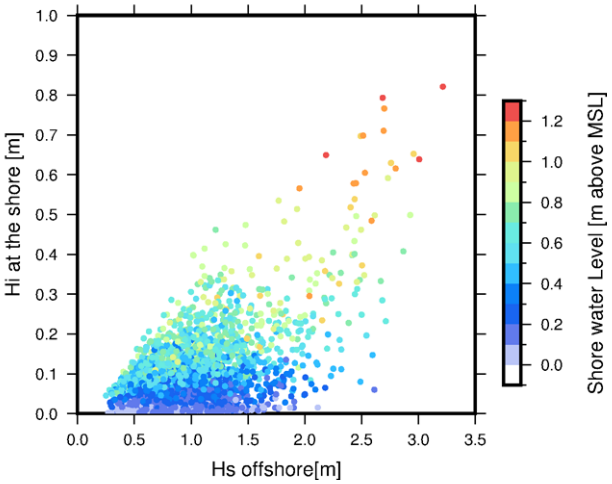

Figure 4 relationship between offshore RMS wave height and IG wave height at the shore.

3.1.1 30th May 2013

This wave event is the first event in a series that occurred between May and June 2013. Hrms offshore reached 2.1m with a peak period of 16s coming for the south (183º). On the reef crest (50m from the slope), Hrms had reduced to 0.78m and Hi increased to 0.53m. By the middle of the reef flat, Hs had reduced to 0.18m and 0.17m at the shore. Hi at the shore reached 0.50m. The event occurred during a neap high tide (0.5m above MSL) and the wave setup at high tide was 0.4m (Figure 5). The IG wave amplitude, during the event the IG RMS amplitude was 0.25m, and accounted to 25% of the water level anomaly (water level above the tide level) on the reef.

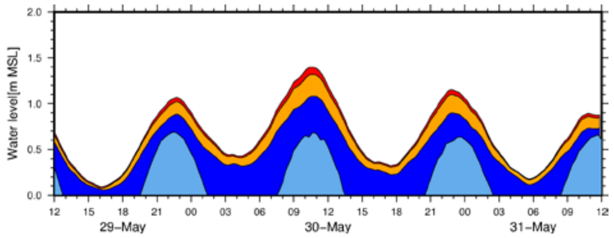

Figure 5. Contribution to the total water level at the shore for the 30th May 2013: tide (light blue), wave setup (blue), IG wave amplitude (orange) and short wave amplitude (red).

3.1.2 6th June 2013

The largest swell recorded was on the 6th June 2013 with Hrms of 2.3m, a peak period of 14s coming from the south (185º). The event also produced the largest infragravity wave height recorded near the shore (Hi=0.59m). The peak of the event occurred during a high neap tide (0.47m above MSL) with the total water level reached 1.0m above the expected high tide level (1.5 MSL) (Figure 6).

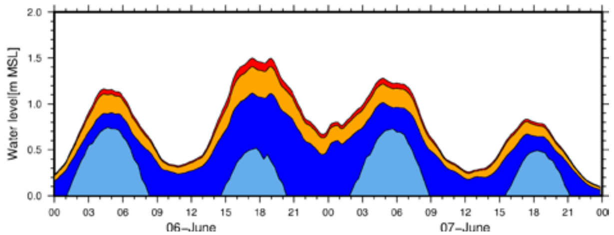

Figure 6. Contribution to the total water level at the shore for the 6th June 2013: tide (light blue), wave setup (blue), IG wave amplitude (orange) and short wave amplitude (red).

3.1.3 22nd June 2013

This event was very similar to the May event with similar waves offshore and nearshore and but at a higher tide. Hrms reached 1.97m offshore with a 14s peak period. On the reef crest, Hrms had reduced to 0.77m and Hi increased to 0.54m. By the middle of the reef flat, Hrms had reduced to 0.20m and remained at 0.20m to the shore. IG wave at the shore reached 0.58m.

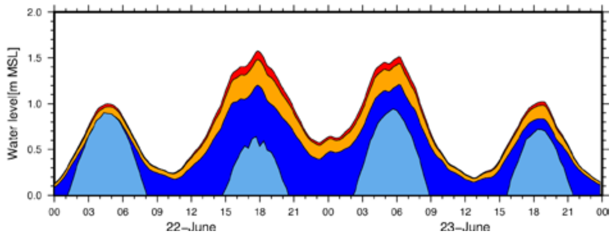

Figure 7. Contribution to the total water level at the shore for the 22nd June 2013: tide (light blue), wave setup (blue), IG wave amplitude (orange) and short wave amplitude (red).

All these 3 events showed a consistent pattern with the offshore wave height reduced by more than 90% at the shore and IG wave height between 0.5 and 0.6m. All these events occurred with an offshore water level close to the Neap Mean High Water mark (0.47m above MSL) but no event with a Hrms above 2.3m occurred at a higher water level. This limits the possibility for deriving empirical formula to forecast future inundation events. Instead, the numerical model can better estimate water levels during the inundation event.

3.2 Inundation threshold

The numerical model was run for 4 offshore water levels, a single spectral shape with a 16s peak wave periods with an increment of 0.5m for the waves until the inundation threshold of 3.5m was reached at the shore.

For the lowest tide scenario (i.e. MHWN), the maximum water level at the shore exceeded 3.5m for offshore wave height from 3.5m but this was located on a narrow part of the beach. The maximum water level consistently exceeded 3.5m only for offshore wave height of 4.5m.

For the MHW, the maximum water level was reached with offshore wave height of 4.5m.For the MHWS, the maximum water level was reached with offshore wave height of 4.0m. For the highest tidal water level simulated (MHWPS), the maximum water level was reached with offshore wave height of 3.5m (Table 3).

Interestingly, the scenarios with an offshore wave height of 3.5m resulted in a comparable maximum water level than the scenario with offshore wave height with 4.0m (Figure 8). This is because the wave boundary generation has a random component that can generate bigger wave group for a smaller offshore wave height.

Table 3 Offshore wave height threshold for inundation in Maui Bay.

Offshore water level (m above MSL)	Offshore peak wave period (s)	Offshore wave height (Hs) for inundation (m) (Hrms range)
MHWN	16	4.0—4.5 (2.8—3.2)
MHW	16	4.0—4.5 (2.8—3.2)
MHWS	16	3.5—4.0 (2.5—2.8)
MHWPS	16	3.0—3.5 (2.1—2.5)

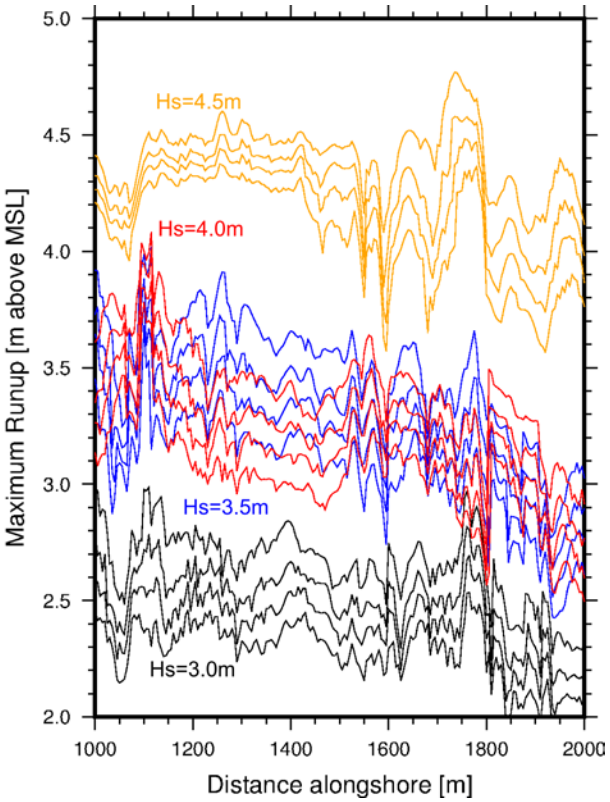

Figure 8. Maximum runup height for all the inundation scenarios. Each colour corresponds to an offshore significant wave height; for each colour the 4 curves are the results for each tidal level starting at the lower: MHWN, MHW, MHWS, MHWPS.

4. Discussion

Wave measurements and numerical simulation were used to better understand wave inundation on a tropical fringing reef in Maui Bay. Measurements showed that, at high tide, the wave setup was the most important contributor to total water level on the reef flat (above the expected tide level). Infragravity waves were contributing to approximately 30% of the total water level. Numerical simulations were used to predict the offshore wave height that would result in coastal inundation on the shore. The results presented here are a preliminary approach to better predict coastal inundation on a fringing coral reef. To date the Fiji meteorological services uses a single wave height threshold to guide the issuing of early warnings for wave inundation on the Coral Coast. Unsurprisingly, the results show that the offshore wave height needed to inundate the coast highly depends on the offshore water level. The wave period and the spectral shape of the offshore swell are also expected to play a major role because the two main contributors to the inundation are the wave setup and IG waves which are highly dependent on water level, wave period [7] and wave grouping [8]. Since wave setup and IG waves are also dependant on the shape (depth, width, roughness) of the reef, different thresholds should apply for different section of reefs on the Coral Coast. Further simulations are therefore necessary to test a large number of wave conditions and reef morphology. In particular the role of wave groupiness may become important during certain conditions when multiple distant swells occur together. In the meantime the wave threshold presented here, as well as considerations on the level of the predicted tide at the time of the event, can be used to improve the wave threshold used to issue coastal inundation warnings.

Coastal inundation warnings can also be further improved by using an operational forecasting system that simulates the probability of inundation. Forecasting coastal inundation is challenging because it involves predicting the wave height and the water level offshore, and the wave setup, infragravity wave height and short waves on the reef flat. The results presented here can be used as a quick assessment of the potential for inundation, but this does not take into account water level anomalies and variations in wave spectral shape. Using a wave inundation model such as XBeach for operational forecasting may be a solution. Such a forecasting system is being proposed for operational use at the Fiji Meteorological services (Figure 9). The system includes real time tide measurements to determine the mean sea level anomaly, wave measurements to validate offshore wave forecast, a high resolution wave forecast to include local bathymetry effect on the waves and produce detailed wave spectra and finally a wave inundation model similar to the model presented in this study but forced with locally measured water level and wave boundary condition derived from the high resolution wave hindcast. As wave setup and IG waves are the highest at high tide, the nearshore wave model and inundation are designed to run only at high tide. The model topography is also being improved to accurately simulate flooding depth and run up.

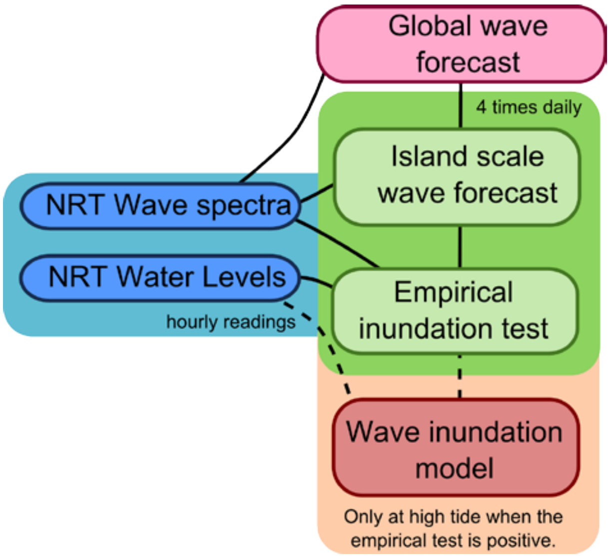

Figure 9. Proposed operational forecasting system for wave inundation on the Coral Coast of Fiji. NRT stand for Near real time measurements.

5. Conclusion

This study calculated the maximum water level for a range of wave height and tidal levels on the Coral Coast of Fiji. The results are proposed as an improvement to the early warning threshold presently used for coastal wave inundation. However the model developed for this study is ultimately going to be an important part of a proposed coastal impact forecasting system that has been designed to improve the forecasting capabilities of the Fiji Meteorological services.

6. Acknowledgements

Wave data presented in this study has been collected with the support and approval of the Fiji government and the Coral Coast communities of Tagaqe and Votua. Many staff of the Secretariat of the Pacific Community, the University of the South Pacific and the University of Auckland and the Mineral Resource Department of Fiji were actively involved in the field work, Zulfikar, Aseri, Salesh, Isei, Paul, Susan, Paul. The authors would like to thanks the Maui Bay Community and their representant Julian Hennings for making their boat available for surveys and instrument recovery and their support to the project.

This research was conducted through the WACOP project, financed by the European Union, Grant Number FED/2011/281-131.

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