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WRL TR 2018/21 | August 2019

By M J Blacka, C D Drummond, P F Rahman and B M Miller

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Summary of Key Information

This report presents the methodology and results of a hydrodynamic investigation for the Muri Lagoon and Avana Harbour system, and forms part of the Environmental Investigations within the Mei Te Vai Ki Te Vai project. The hydrodynamics of the Muri Lagoon system have been investigated several times previously, and the basic hydrodynamic functions are already known, so what is different about this investigation?:

1. We have completed a new survey of the lagoon topography and bathymetry, and this is the first survey covering the whole lagoon since the early 1990s. Our survey has covered areas of the system that were previously measured as well as new areas that have not been measured before, and so we are now able to understand and quantify how the lagoon has physically changed over the past three decades.
2. We have completed several months of near continuous and simultaneous lagoon data collection for water levels, currents, water temperature and waves, as well as short term gauging of flows within various sections of the lagoon. These measurements are more detailed, more accurate and cover the complete lagoon/channel/harbour system compared with previous investigations in the 1980s and 1990s that only covered a few specific areas and for short periods of time.
3. The new data sets have allowed us to build on the basic knowledge of lagoon hydrodynamics, to now understand the more complex lagoon functions. We have quantified the key processes throughout the complete lagoon system, and we now have a much improved understanding of how the lagoon functions under different wave, tide and climatic conditions. We also now have a much better understanding of the features that control the hydrodynamics of the lagoon system; and how, why and under what conditions these features impact flushing.

The results of the investigation have confirmed some previous theories, identified new characteristics, and importantly, allowed us to better understand how the system functions and the role of hydrodynamics in the water quality of the lagoon.

Lagoon Bathymetry

Over the past 30 years there has not been major infilling or overall adjustments to the bathymetry of the Muri Lagoon and Avana Passage system, however, there are localised areas that have changed. Our recent survey indicates that low-flow areas of the lagoon system have infilled slightly, which is in-turn concentrating flows within channel areas and resulting in slight deepening of these dominant flow areas.

With an updated and much more detailed bathymetry survey of the lagoon we can now conclude:

- The northern Avana Harbour/Passage area is generally deeper now than it was in surveys from the 1990s, in particular in the predominant flow channels. However, since the 2006 harbour survey there has been notable build-up of the sand shoals on either side of the main channel, and deepening of the channel in some areas.
- Over the past 25 years there has probably been slight shallowing of the algae-rubble ridges across the channel from Aroko to the northern end of Oneroa, particularly in the area immediately south of the former fish trap. These shallower areas across the channel were certainly identified in historical literature so they are not a new feature. However, within the accuracy limitations of the surveys from the 1990s, it is considered likely that the ridges have increased in elevation slightly.
- There has been minimal change or slight deepening of most of the main Muri Lagoon basin. This trend of basin deepening was also detected in the last bathymetric change analysis in 1993 which looked at change in the decades leading up to the 1990s.
- There has likely been slight deepening of the areas where flows concentrate around the ends of the various motu.
- The nearshore area of the main lagoon basin extending from the northern side of Taakoka, across to the main Muri Beach area has likely shallowed/infilled slightly.
- The recent survey is the only time the area outside of the motu has been measured, so there is no previous survey data to compare with in this area. However, aerial photos show that the deposits of coral rubble inside the fringing reef and between the reef and the motu continue to grow, adjust and evolve.

Of these localised bathymetric changes, our analysis has shown that the adjustments in bathymetry most influencing the hydrodynamics of the system are the shallow area of channel between Aroko and Oneroa/Motutapu, and the deposits of coral rubble seaward of the motu. Nevertheless their influence on lagoon hydrodynamics and the extent to which the changes may have resulted in changes to hydrodynamics, are very limited.

Lagoon Water Levels

From this investigation we have learnt a range of new information about the lagoon water level processes, and their role as the key driver of lagoon flows and flushing. Water levels in the lagoon are very different to the surrounding ocean, and even vary from location-to-location within the lagoon. With these characteristics quantified, we now have a much improved understanding of how the lagoon functions in response to varying waves and tides.

Lagoon Water Level Setup:

- Breaking waves along the fringing reef between Titikaveka and Motutapu result in wave setup, which in-turn causes the water level in Muri Lagoon to be continuously perched above the open ocean sea level.
- The lagoon water level setup is very closely linked with the size of the waves breaking on the reef. During typical wave conditions the lagoon water level is constantly about 0.3 m above the ocean level at all stages of the tide, and during larger waves the lagoon water level sits 0.5 m or more above the surrounding ocean. Measurements of the correlation between wave height and lagoon water level are shown in Figure 1 where the wave height (orange line) is plotted with the non-tidal variations (setup) of lagoon water level (thick dark blue and light blue lines).
- There is very little wave setup in the Avana Harbour and Passage area, so there is typically a drop in water level of 0.2 to 0.25 m that occurs across the shallow area of channel between Aroko and the northern end of Oneroa and southern end of Motutapu.

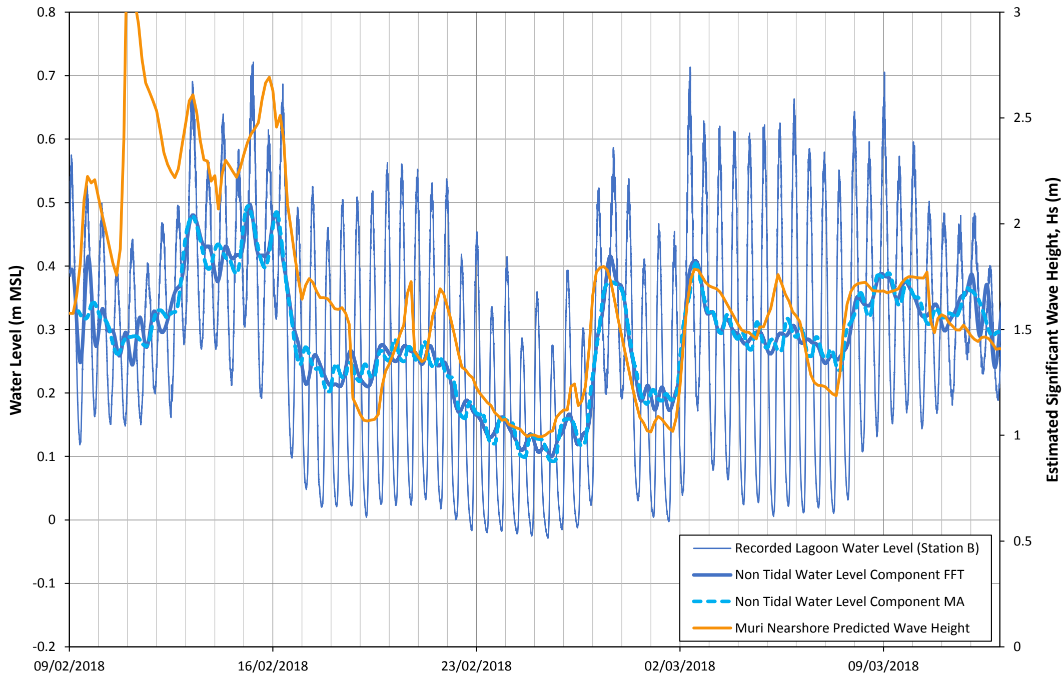


Figure 1: Measured link between Lagoon water level and wave height on the fringing reef

Lagoon Tides:

- Tides in the ocean along the Muri coast (outside of the reef) are basically the same phase and range as on the north coast of Rarotonga where they are gauged at Avatiu Port.
- High tide in the lagoon occurs at the same time as it does in the surrounding ocean, however, low tide is delayed by around 15 to 20 minutes in the main Muri Lagoon Basin and 25 minutes in the area between Oneroa and Motutapu.
- The tide range in the main lagoon basin is only 80% of the tide range of the surrounding ocean, and in the area between Oneroa and Motutapu the tide range is only 65% of the ocean tide range.
- Tides in Avana Harbour and in the channel at the Avana Stream delta are basically the same phase and range as in the ocean.

Currents and Flows

Our measurements clearly show that flow through the lagoon is primarily driven by a gradient in lagoon water level caused by longshore variations in wave setup. In the simplest sense, we can summarise the process of lagoon currents as:

- Wave setup is generally the highest in the south due to the higher wave energy, and there is no wave setup at the north due to the deep water of Avana Passage. This gradient is the driver for the south to north flow of water through the lagoon that occurs most of the time.
- Larger waves breaking on the reef increases lagoon water level setup, which in turn steepens the hydraulic gradient and increases flows through the lagoon.
- At high water levels (high tides and/or pumped up lagoon), currents through the lagoon are much faster due to the steeper hydraulic gradient.
- At low water levels (low tides and small to average wave conditions), the shallow ridge in the main channel adjacent the northern end of Oneroa restricts drainage of the lagoon. This restriction flattens the water surface gradient for areas to the south (including the main lagoon basin), and flows through the lagoon all-but stop once the lagoon drains to a low tide level of around 0.05 m MSL.

In reality a range of other factors add complexity to the generation and behaviour of lagoon currents, most notably the effect of wave direction impacting Rarotonga. Variations in wave direction change the longshore gradient in wave setup along the Muri reef, and our new data sets show that the way water moves through the lagoon can be very sensitive to these changes. Lagoon flows tend to function somewhere between the two extreme modes:

- *Mode 1: Typical behaviour, south-westerly to south-easterly offshore wave direction*: These conditions result in higher lagoon water level setup along the southern coastline, with wave energy and wave setup decreasing south to north along the Muri outer reef. Under these wave conditions the currents in the lagoon move from south to north, driven by the gradient in lagoon water level setup. The lagoon currents likely originate in the Tikioki Beach area and move northward through Muri, before exiting through Avana Passage.

- *Mode 2: A-typical behaviour, westerly through northerly to easterly wave direction*: On less frequent occasions when dominant wave conditions approach Rarotonga from west, north or northeasterly directions, the behaviour of the lagoon notably differs from the norm. During the incoming tide, currents tend to move south to north through the lagoon basin, though at a much lower velocity than typical. During the falling stage of the tide, currents tend to rotate, initially moving onshore and progressively draining the lagoon southward as the tide falls. During these conditions it is likely that the net movement of water through the main lagoon basin is significantly reduced.

Figure 2: Different "Modes" of Lagoon flow patterns

Simultaneous measurements of currents and water levels at various locations throughout the system have allowed us to better understand and quantify flows through the lagoon and channels, and how they change under different environmental conditions. Generally, flows through the lagoon:

- Are much greater at high tide and during periods with higher wave energy;
- Almost completely stop at low tide.

At high tide and when the lagoon water level setup is higher than average, the flows through the system are largely controlled by the general arrangement of the various motu and channels. These processes are likely to be very similar now to what they were several decades ago.

However, during periods of lower lagoon water level our analysis has shown that the algae-rubble ridge across the channel between Aroko and the northern end of Oneroa forms somewhat of a control on lagoon hydrodynamics. South of this ridge, the lagoon water levels are superelevated by wave setup, the tide range is reduced and the tide phase is lagged. North of this ridge, there is minimal wave setup and the tides are the same range and phase as the surrounding ocean. The influence of this shallow section of channel is particularly important during periods of lower water level (low tide or low wave conditions), when the level of the ridge impacts drainage and flows through the lagoon. Our measurements have shown that the lagoon almost never drains below the level of the algae-rubble ridge and that the drainage slows significantly as the water level approaches the ridge level. The water surface throughout the lagoon to the south of the ridge becomes flat, and there is no hydraulic gradient to drive flows through the lagoon. This process creates a temporary halt in lagoon flows until the tide begins to rise again.

These results provide new insights into the influences on lagoon flows:

- Changes in bathymetry around the Avana Stream Delta, in Avana Harbour and Avana Passage (such as slight sedimentation, build-up of sand shoals or dredging) have little to no impact on the flushing or currents through Muri Lagoon.
- The vast majority of water moving through the system occurs at higher tide levels, and the speed of currents and general lagoon flow patterns do not appear to have changed to any measurable degree over the past three (3) decades.
- Given the importance of the algae-rubble ridge across the channel at Aroko as a controlling feature on drainage of the lagoon during low tide levels, slight changes in the level of the ridge over the past 30 years would in-turn have resulted in slight changes to the lagoon hydrodynamics at low lagoon water levels.

Changes in Lagoon Hydrodynamics?

Flows Entering the Lagoon:

Comparison of data from previous hydrodynamic analysis suggests that over the past 30 years there has been no measurable change to the wave setup process that is the key driver of lagoon currents and flows. The relationship between water level setup and wave height that has been measured in our recent investigation is almost identical to that measured some 30 years ago (Figure 3).

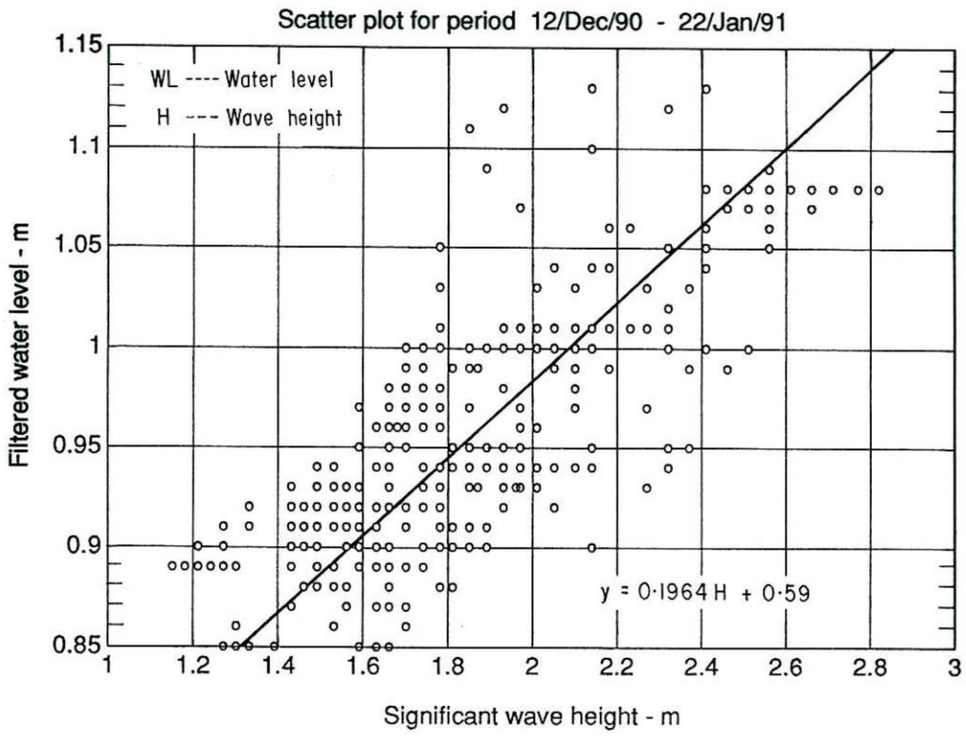
Our mapping and survey has shown that the highest areas along the fringing reef are generally the coral rubble deposits that sit slightly landward of the algal ridge which forms the “reef crest”. This indicates that flows into the lagoon would be more influenced by the level and arrangement of the coral rubble deposits, than flushing through the grooves and spurs along the outside reef edge. Nevertheless our observations along the outer reef show that the spurs and grooves through the reef crest and in the surf zone are not filled with debris. It is the seaward slope of the reef face and the level of the algal ridge that control the wave setup level generated by breaking waves, and the elevation of the coral rubble deposits in-turn influence the flows into the lagoon that are generated by the wave setup. At lower stages of the tide it is plausible that the rubble deposits influence the location and rate that water can enter the lagoon, however, during these low water level periods the restricted drainage of the lagoon is expected to control the rate of water movement through the lagoon more so than the coral rubble deposits along the outer reef.

Flows Moving through the Lagoon and channels:

Flow patterns within the main Muri Lagoon basin and currents in the channel adjacent Nukupure Park, were measured in an investigation in 1992. When we compare the results from that study with the currents that we have measured in 2018, we have found no major changes in the hydrodynamics at these locations. While this does not confirm that changes have not occurred in some areas of the system or during specific conditions, it does demonstrate that, within the constraints of available previous data sets, there is no overall quantifiable changes to the lagoon hydrodynamics.

Flows Leaving the Lagoon:

In 1979 an experiment was undertaken to measure the flows leaving the Muri system through Avana Harbour during a complete tide cycle. This experiment was repeated in our investigation, albeit with a significantly more sophisticated approach. Comparison of the two data sets has shown that there has definitely not been any dramatic change in the peak flow rate moving through the system over the past 35 years. When considered in combination of with our other data sets for currents, the differences in the measured flow rates and discharge volumes are likely to be within the natural range of fluctuations that occur with varying wave and tide conditions.



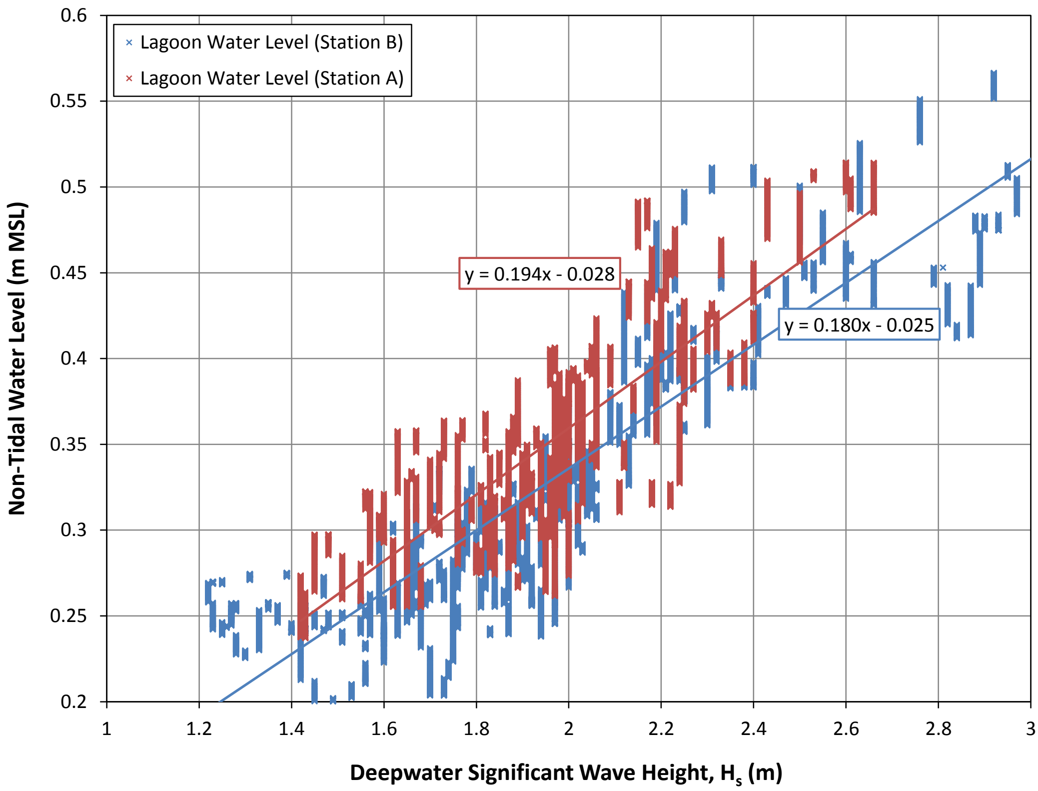


Figure 3: Comparison of present and historical relationship for wave setup at Muri

(Top: 1992 data; Bottom: 2018 data; Note: Difference in water level datum on Y axis of plot)

Flushing

Our survey of the lagoon bathymetry has allowed us to gain a much better understanding of the volume of water in the various sections of the lagoon/channel/harbour system, and how much of this water is within the intertidal zone. When combined with the more detailed data on lagoon water levels, currents and flows, we have also now gained a better understanding of the rates of lagoon flushing. We estimate:

- Approximately 50% of the overall system volume lies within the intertidal zone. This means that at least half of the water volume is exchanged every spring tide cycle by the rise and fall of the tide, regardless of the wave driven flushing.
- The volume of water measured to pass through Avana Passage in a typical tide cycle and with typical wave conditions is approximately equivalent to the total mid-tide volume of water in the overall system.
- 1 to 1.2 million m^3 of water flows northward through the main lagoon basin in a single tide cycle during typical conditions. This is almost equivalent to the total volume of the lagoon basin at high tide. It can therefore be assumed that water in most parts of the lagoon basin is exchanged every one to two tide cycles.
- Depending on the environmental conditions, the main lagoon basin volume is exchanged every 8-30 hours. While this is a large range, it does confirm that the lagoon is typically flushed in timescales of hours and not days, though during very low-flow conditions it may take one to two days to flush.

Nevertheless while water generally flushes through most parts of the lagoon quickly, we have identified localised areas with slower water movement. These areas are simply a consequence of the naturally occurring physical arrangement of the lagoon/motu/reef system and the current patterns that prevail. There are also some environmental conditions such as lower wave energy, specific wave directions and periods with lower ocean levels that also result in reduced rates of lagoon flushing. The most notable area with lower rates of water movement is the immediate Muri Beach foreshore area between the Pacific Resort and Taakoka. These areas with naturally lower rates of water movement will be more sensitive to changes in contaminants in the lagoon.

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Acronyms and Abbreviations

ADCP	Acoustic Doppler Current Profiler
ADV	Acoustic Doppler Velocimeter
BOM	Australian Bureau of Meteorology
GNSS	Global Navigation Satellite System
ICI	Infrastructure Cook Islands
MFEM	Ministry of Finance and Economic Management, Cook Islands Government
Motu	Reef top Island/islet
MSL	Mean Sea Level (Datum)
MTVKTV	Mei Te Vai Ki Te Vai
PMU	Project Management Unit
PSLM	Pacific Sea Level Monitoring Programme
RTK	Real Time Kinematic
SEAFRAME	Sea Level Fine Resolution Acoustic Measuring Equipment
SOPAC	Pacific Islands Applied Geoscience Commission
SPC	Secretariat of the Pacific Community
SWAN	Simulating Waves Nearshore (Numerical Wave Model)
TGZ	Tide Gauge Zero
UAV	Unmanned Aerial Vehicle
UNSW	The University of New South Wales
WRL	Water Research Laboratory

1 Introduction

1.1 Overview

In January 2017, the Cook Islands Government launched the Mei Te Vai Ki Te Vai project (MTVKTV). Mei Te Vai Ki Te Vai, or "*From the Water to the Water*" in Cook Islands Māori, is about restoring the water quality of the coastal lagoons of the islands of Rarotonga and Aitutaki. The project name describes the cycle of water both in terms of the hydrological cycle and the cycle of human water use. 'Mei Te Vai Ki Te Vai' also refers to the meeting of different bodies of water, such as groundwater or a stream flowing from the catchment and meeting with the lagoon at the coastline.

The Project Steering Group, led by the Ministry of Finance and Economic Management (MFEM), includes a number of key government agencies that together provide unified governance and policy direction. The Project Management Unit (PMU) led by consultants GHD and including a number of local staff, is responsible for managing the MTVKTV project, which also includes support from a number of specialist consultants.

On Rarotonga the MTVKTV project has focussed on Muri Lagoon, its catchment and surrounding communities (Figure 1.1, Figure 1.2 and Figure 1.3). Muri Lagoon has had a history of water quality and flushing concerns, culminating with outbreaks of macro algae growth in recent years. Anecdotally the growth of algae has been linked to anthropogenic sources of nutrients, including the impacts of wastewater disposal from residences and tourism accommodations in the fringing community, as well as agricultural practices in the catchment.

Broadly, the objectives of the MTVKTV project for Rarotonga included:

- Developing a scientific understanding of issues and their sources to guide decision making;
- Identifying, developing and implementing short-term management responses;
- Providing a road map for investment in long-term wastewater management;
- Developing a concept design for a long-term wastewater management solution;
- Engaging with the local community across a number of areas.

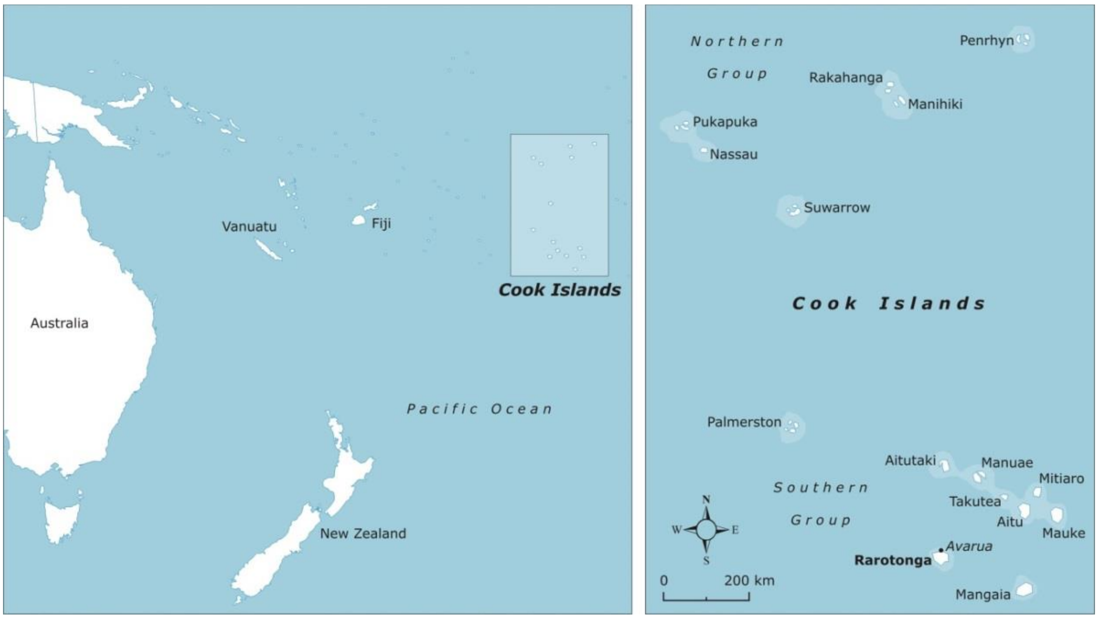


Figure 1.1: Location of Rarotonga

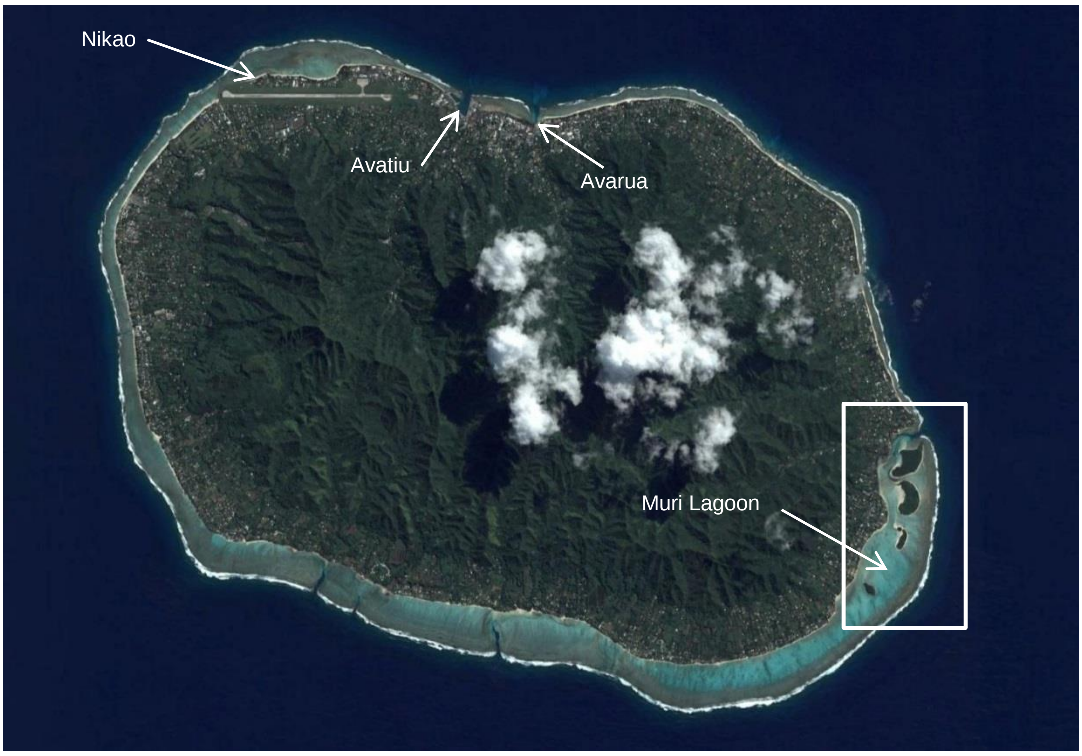


Figure 1.2: Island of Rarotonga and location of Muri Lagoon

Figure 1.3: Muri Lagoon and Avana Passage

1.2 Hydrodynamic Investigation

As part of the Environmental Investigations for Muri, the Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Sydney was engaged to undertake an assessment of lagoon hydrodynamics for the Muri Lagoon and Avana Harbour system (Figure 1.3). Other components of the Environmental Investigations included catchment terrain mapping, groundwater investigations, streamflow gauging, water quality investigations in both runoff and the lagoon, as well as ecological monitoring in the lagoon.

Components of WRL's hydrodynamic investigation included:

- Undertaking a survey and mapping of lagoon bathymetry and fringing topography, extending from Paringaru Stream in the south to Avana Passage in the north;
- Analysis of the lagoon bathymetry and comparison with previous surveys;
- Capture of a range of hydrodynamic data sets throughout the lagoon including water levels, currents and waves, over a time period of several months;
- Development of a detailed and quantified understanding of the lagoon hydrodynamics and processes;
- Comparison of current hydrodynamic processes with information from previous hydrodynamic investigations;
- Development of a numerical model to simulate the hydrodynamic processes, and use of this model to investigate a range of potential scenarios/changes.

The methodology and results of the hydrodynamic investigation are presented in this report. Other outputs from the investigation include extensive geospatial survey data sets (bathymetry and topography), aerial imagery and video, and various hydrodynamic data sets.

The structure of this report is:

- Section 2 - Geospatial lagoon survey;
- Section 3 – Overview and methodology of hydrodynamic data collection;
- Sections 4 and 5 – Analysis of lagoon hydrodynamics;
- Section 6 – Numerical hydrodynamic modelling.

1.3 Physical Description of Muri Lagoon

The Muri Lagoon and Avana Harbour system is comprised of several key features (Figure 1.3):

- A natural passage through the reef at the northern end, with depths in the range of 10 m;
- A small harbour with a jetty and several moorings just inside the northern passage;
- Three sand islands ('motu') perched on the reef pan and set midway between the fringing reef and the mainland beach, Koromiri, Oneroa and Motutapu;
- A fourth motu, Taakoka, that is toward the southern end of the lagoon and is of volcanic origin (geologically different to the other motu);
- A main shallow lagoon basin in the Muri area and extending further south, with depths of around 1.3 to 1.7 m;
- A network of channels extending from the main lagoon to the Avana passage, including between each of the motu and the mainland, with typical depths around 0.5 m;
- Several streams that discharge into the lagoon and channels, with the larger being the Paringaru Stream at the southern end and the Avana Stream near the northern end.

The bathymetry, geology, sediments and hydrodynamics of the Muri Lagoon system have been investigated numerous times over the past 50 years, with results reported in Dahl (1976), Kirk (1980), Carter (1985), Holden (1992), Collins (1993; 1995) and Smith (2006), as well as more recent work by SPC and AECOM.

On the basis of the previous investigations, it is known that the hydrodynamics of the Muri Lagoon and Avana Harbour system are strongly influenced by wave breaking along the fringing reef, and that currents generally move northward through the system before draining through Avana Passage. The hydrodynamics are modulated by the effect of tides on submergence of the fringing reef and lagoon depth.

Oblique aerial images in Figure 1.4 provide further visual context of the lagoon arrangement and predominant features.

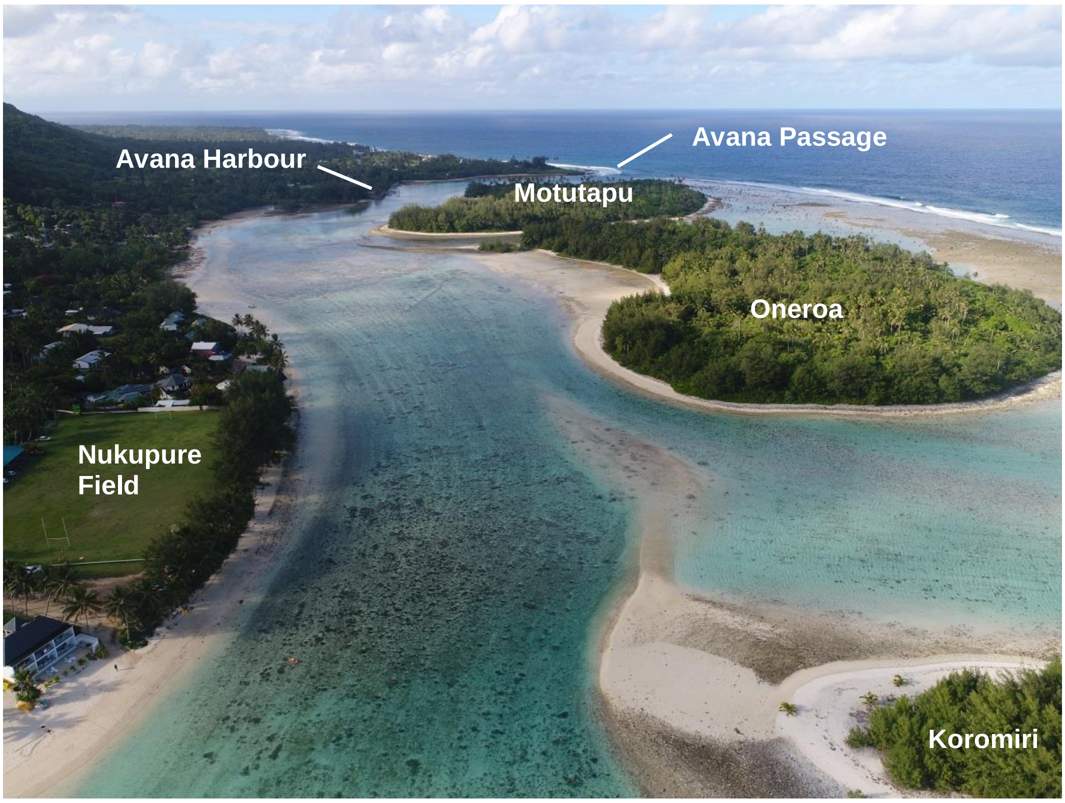


Figure 1.4: Oblique aerial images of the Muri Lagoon and Avana Passage system
(T) Looking north from Muri toward Avana Passage (B) Looking south over Muri Lagoon

1.4 Work Programme

Data collection for the project was undertaken between February and May 2018, with three field trips during this period as outlined in Table 1.1.

Table 1.1: Field work programme

Trip	Dates	Activities
Trip 1	2/02/2018-15/02/2018	Topographic survey Most of bathymetric survey Deployment of hydrodynamic monitoring stations
Trip 2	6/02/2018-13/04/2018	Completion of bathymetric survey Retrieval, download and redeployment of monitoring stations Current profiling
Trip 3	18/05/2018-31/05/2018	Retrieval of monitoring stations

2 Geospatial Lagoon Survey

2.1 Survey Background

Bathymetric surveys of Muri Lagoon and Avana harbour have been undertaken numerous times in the past, with different surveys covering various areas. Analysis of previous surveys is presented in Section 2.4. The present survey was required to be undertaken for a number of reasons, including:

- To develop a contemporary understanding of the lagoon bed morphology;
- To allow comparison with historical survey data and analysis of potential changes in the lagoon bathymetry;
- To contribute to the development of the understanding of lagoon hydrodynamic processes;
- To underpin the development of a bathymetric elevation model on which to base the numerical hydrodynamic model of the lagoon.

Muri lagoon has a wide range of terrain that provides a challenge for completion of a holistic survey, varying from water depths in excess of 10 m through the Avana Passage, down to areas that are intertidal and are emergent at low tide. For this reason no previous survey has included complete coverage of the lagoon system, as was required for this project.

2.2 Survey Methodology

2.2.1 Geodetic Datum and Survey Control

For consistency with existing geospatial data sets used within the Cook Islands, the survey was undertaken with horizontal coordinates specified in the WGS84 coordinate system and UTM zone 4 (south) projection. Two vertical elevation datums are used on Rarotonga, being TGZ (Tide Gauge Zero) and more commonly MSL (Mean Sea Level). It is understood that TGZ originates as the tide gauge zero for the original University of Hawaii gauge at Avarua, and that the MSL datum is adopted as 0.6139 m above TGZ (BOM, 2010). Presumably 0.6139 m TGZ was estimated to be the actual mean sea level on the Avarua tide gauge at some point in time. To maintain long term consistency of the vertical MSL datum (since actual mean sea level is varying with time), survey bench mark BM27 has since been adopted as 4.7407 m above the MSL datum (National Tide Facility, 2002).

In the Muri area Infrastructure Cook Islands (ICI) have previously collected static GNSS observations for reasonable occupation times on three benchmarks as shown in Table 2.1.

Table 2.1: Summary of bench marks in Muri area (Provided by ICI)

Benchmark Name	Location	Horizontal Position[1]	Elevation (m Ellipsoid Ht)	Elevation (m MSL)
Bolt 1	Dead ball line at southern end of Nukupure Field	424369.467 m E 7649466.599 m N	15.779	2.150
Bolt 2	CICC yard, Ngatangiia	424428.448 m E 7650605.155 m N	15.398	1.780
BM7 No. 3	Roadside adjacent Jim Rennie's residence. In hedge on seaside of Main Road	423555.302 m E 7648145.667 m N	16.781	3.125

1. Horizontal coordinates specified in WGS84, UTM Zone 4S

On average, the vertical correction between ellipsoid height and MSL datum was determined to be -13.634 m on the basis of the surveyed bench marks in Table 2.1, and this was the value adopted for all elevation corrections in this project.

In general Bolt 1 was used as the reference survey control mark for the majority of the survey work undertaken in this project (Figure 2.1). For a small amount of bathymetry data collection at the northern end of the lagoon, a temporary benchmark was established in the front of Avana Waterfront Apartments and used as the reference survey control. A static GNSS survey was undertaken for this temporary marker, with several hours of occupation time. The position was subsequently determined by Auspos analysis.

Figure 2.1: Location of Bolt 1 survey control bench mark, Nukupure Field

2.2.2 Survey Equipment

A suite of surveying equipment was utilised to allow data capture over the wide range of conditions at Muri. The equipment is summarised in Table 2.2.

Table 2.2: Summary of geospatial survey equipment used

Equipment/Method	Areas Targeted	General Survey Elevation Range
eBee RTK fixed-wing UAV	Intertidal and subaerial sections of reef, beach and adjacent community	Above 0 m MSL
Pole-mounted Trimble R8 RTK-GNSS	Lagoon areas where water depth was suitable for wading	Between 0 m MSL and -1.5 m MSL
Ceescope single beam echosounder	Lagoon and harbour areas that were deeper than ~0.5 m	Below -0.3 m MSL
M9 Riversurveyor ADCP	Lagoon and harbour areas that were deeper than ~0.5 m	Below -0.3 m MSL

To provide as high resolution survey data as possible across intertidal and subaerial zones, a fixed-wing eBee RTK UAV was flown. This survey method uses photogrammetric techniques combined with on-board RTK-GNSS positioning, to provide a very high resolution point cloud of survey data and an orthorectified photo mosaic. GNSS corrections were provided to the UAV in real time from a Trimble R8 GNSS base station receiver positioned on the Bolt 1 benchmark described in Section 2.2.1. A Trimble HPB450 radio transmitter was used to broadcast position correction data over the complete Muri Lagoon area throughout the UAV flights (the base station setup is captured in Figure 2.1). The UAV flies on a pre-programmed flight schedule, collecting aerial imagery as required to produce the desired survey data resolution.

Figure 2.2 shows the eBee RTK UAV being launched at Nukupure Field, while Figure 2.3 shows an example of the UAV software mid-way through a pre-planned flight schedule.

Figure 2.2: Launching of the eBee RTK survey UAV at Nukupure Field

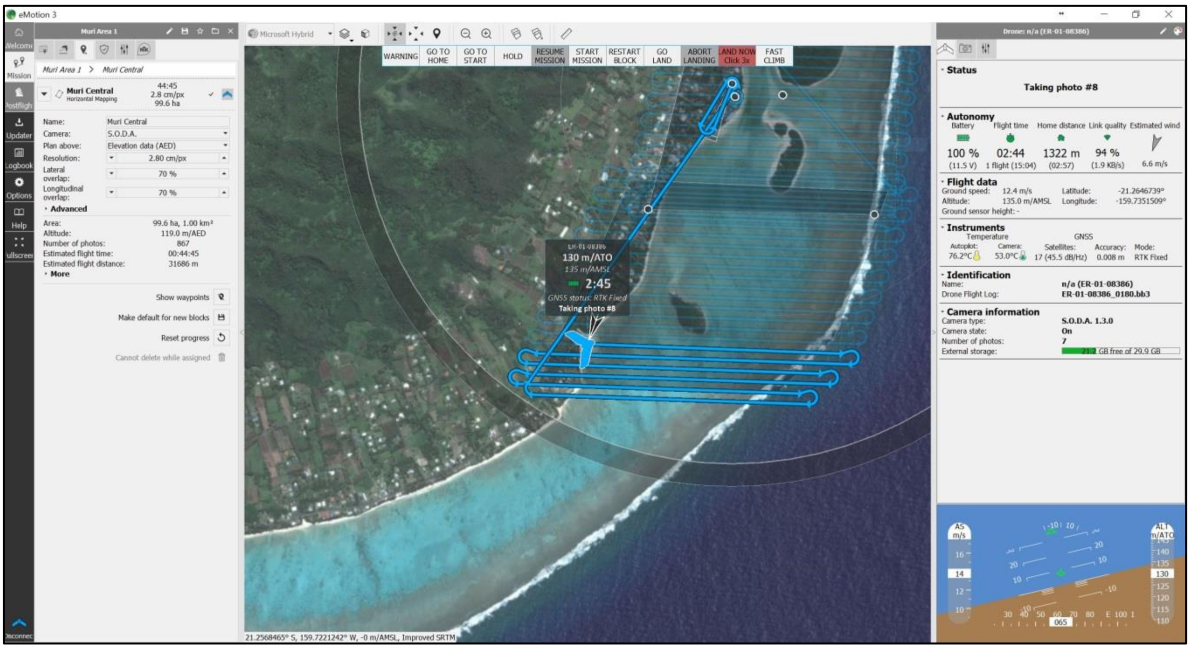


Figure 2.3: Automated UAV flight execution plan for southern survey zone

For open water areas where water depths exceeded approximately 0.5 m, two pieces of equipment were used to collect bathymetric survey data. The first was a Cee Hydrosystems ceeScope single beam echosounder, while the second was an M9 Riversurveyor ADCP. Both instruments were mounted on a kayak, along with on-board 12 V power supply, inverter and notebook PC for data logging. Throughout the bathymetric survey, positioning and elevation data was provided by a Trimble R8 GPS receiver operating in RTK-GNSS mode, with corrections from the base station as previously described.

Figure 2.4: Bathymetric survey kayak with CeeScope single beam echosounder

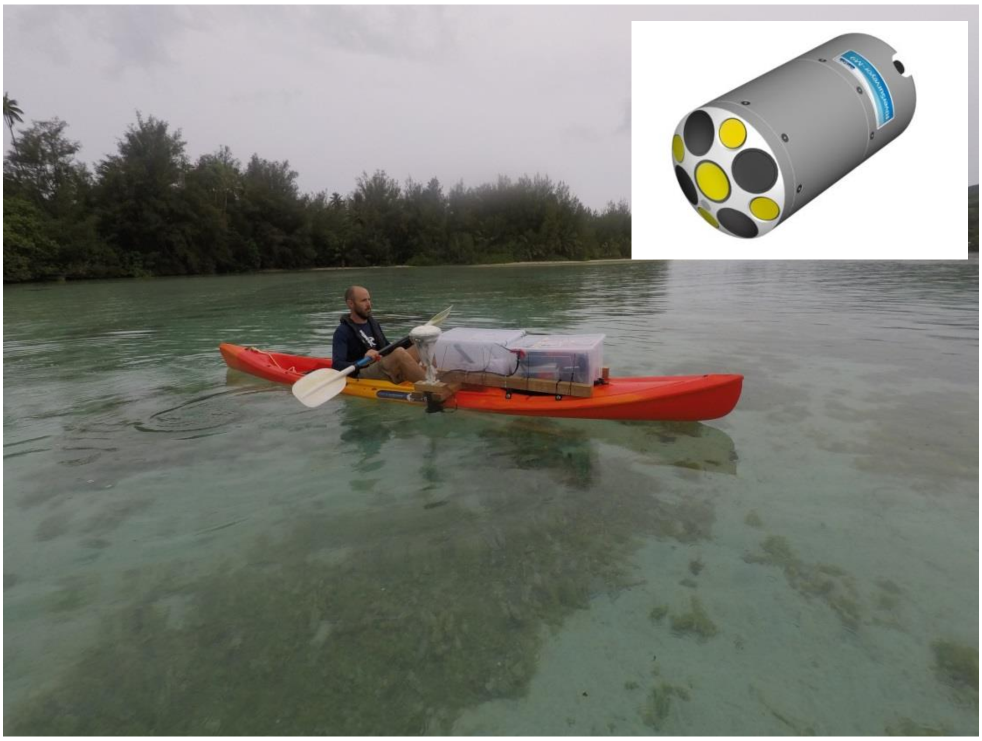


Figure 2.5: Bathymetric survey kayak with M9 Riversurveyor ADCP

In areas where access with a kayak was difficult due to reef formations or too shallow for echosounding, bathymetric survey data was collected by wading with a pole mounted Trimble R8 GPS receiver, operated in RTK-GNSS mode (Figure 2.6).

Figure 2.6: Wading RTK-GNSS bathymetric survey

2.3 Survey Approach

UAV survey flights were undertaken at low tide on the mornings of 5/02/2018 and 6/02/2018. The UAV recorded 2649 aerial images, flown at a height of approximately 100 m. The area covered by the UAV and the resulting orthophoto mosaic is shown in Figure 2.7. Analysis of the UAV survey was undertaken using the software suite Pix4D, including production of the orthophoto and point cloud of survey data. While georeferencing and control of the survey was provided from the survey base station in RTK mode, a network of approximately 20 ground control points were strategically positioned throughout the domain (including on motu and outer reef), with some used as additional control points and others used as check points. The resulting analysis was shown to have an RMS error of approximately 15 mm horizontal and 25 mm vertical, and when combined with the accuracy of the ground control point survey on which the analysis was based, is expected to have had an overall accuracy of better than 0.1 m in both horizontal and vertical geolocation. Data from the UAV was restricted to areas above the water surface at the time of the survey, and as such was cropped to elevations above ~0 m MSL in most areas.

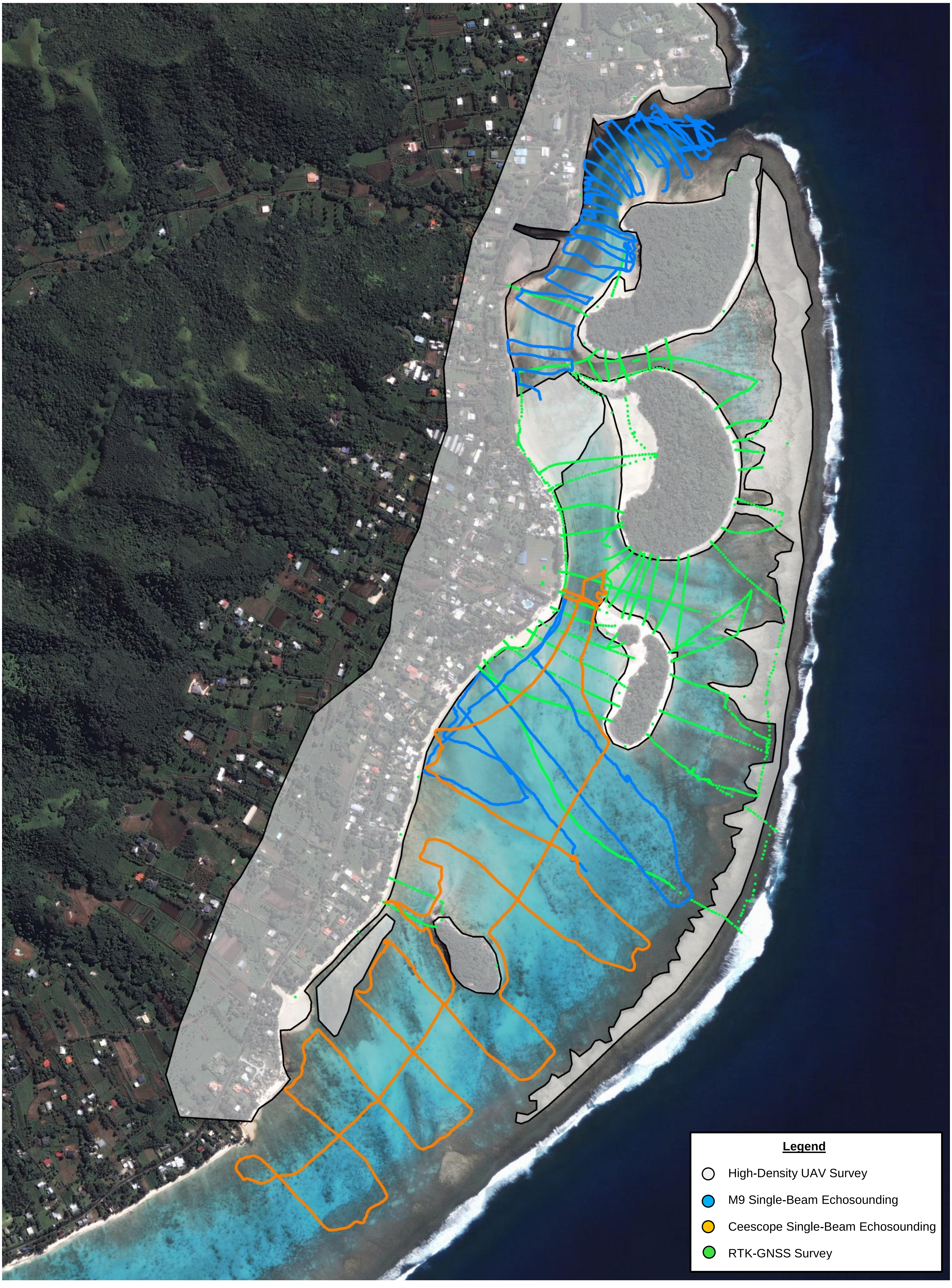
During the first field deployment, the M9 Riversurveyor ADCP was used to collect bathymetric survey data from a kayak. The main lagoon channel west of Motutapu, Avana Harbour and Avana Passage areas were covered, as well as a small section of the main Muri Lagoon Basin. On the second field deployment the ceeScope single beam echosounder was used to continue the bathymetric survey, with areas in the main lagoon basin around Taakoka and further south covered. Both echosounding techniques are expected to have an accuracy of the order of at least 0.1 m horizontal and 0.1 m vertical.

During both the first and second field deployments bathymetric data was collected for shallow areas of the lagoon by wading with a pole mounted RTK-GNSS system. Data was predominantly collected in profiles across the lagoon/channels, and the measured points are expected to have an accuracy of a minimum 0.1 m horizontal (likely better than 0.05 m for most data points) and 0.1 m vertical.

2.4 Survey Results

The output of each component of the survey has been merged to produce an overall elevation data set comprising both topographic and bathymetric data. In areas above ~0.1 m MSL, the data set comprises a closely spaced point cloud from the UAV survey, while areas below -0.1 m MSL are comprised by survey profiles collected by wading or echosounding which are spaced at varying resolution around the lagoon. Map 01 shows the final survey coverage. A high resolution georeferenced orthophoto mosaic was also developed and is shown in Figure 2.7.

Figure 2.7: High resolution orthophoto mosaic from UAV survey



Survey Date:
February and April 2018

Coordinate System:
WGS 84, Z4s, UTM

Elevation Datum:
MSL

Mei Te Vai Ki Te Vai

Map 01: Bathymetric and Topographic Survey of Muri Lagoon, Avana Harbour and Surrounding Areas

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2.5 Comparison of Results with Historical Survey Data

A number of bathymetric surveys of the Muri Lagoon and Avana Harbour/Passage areas have been undertaken since the early work of Shepard (1948), though the vast majority of the data sets were unable to be located at the time of preparing this report. These survey data sets are summarised in Table 2.3. The coverage of the electronically available data sets and a comparison between surveys is presented in Maps 02 to 08. The comparison has been made for three different "zones", these being the Avana Harbour/Passage area, the northern channel area adjacent to Motutapu, and the main lagoon basin area. These zones were selected, as they roughly match the zones used in the previous bathymetric change analysis presented in Collins (1993; 1995).

Table 2.3: Previous surveys of Muri Lagoon and Avana Harbour

Survey Reference	Survey Coverage Summary	Availability of Data
Shepard (1948)	10 survey lines between village of Ngatangiia and Motu Tapu.	Not available
Kirk (1980)	Echosounding profiles, bottom samples and estimates of depth to bedrock	Not available as electronic data set
Gauss (1981)	Survey of the harbour area as part of a larger programme of seabed studies in the nearshore areas of Rarotonga 21 closely spaced profiles were made in the Avana harbour between the mainland and Motu Tapu and the northern tip of Oneroa.	Not available as electronic data set
Brill (1984)	18 survey lines between the mainland, Oneroa, and Koromiri.	Not available as electronic data set
Carter and Steer (1984)		Not available as electronic data set
Collins (1993)	Survey of Avana Harbour Area undertaken August 1990	Available electronically. Presented in Collins (1993)
Collins (1993)	Survey of Muri Lagoon Area undertaken May 1992	Available electronically, Presented in Collins (1993)
Collins (1993, 1995)		Available electronically
Smith (2006)	Avana Harbour area	Available electronically
UNSW (2018)	Complete Avana Harbour and Muri Lagoon system	Available electronically

While this is the best comparison of potential bathymetric changes throughout the lagoon system that is possible with the available data sets, it is important to note that there are a number of limitations that need to be considered when interpreting the results. These limitations include:

- The accuracy of survey methods has improved greatly with time. Whereas the 2018 survey undertaken for this project has a horizontal positioning accuracy of better than 0.1 m, the positioning accuracy of the survey in 2006 was likely limited to being of the order of 1 m, and the surveys of the 1990s less accurate than that. These inaccuracies can result in both overall shifts and misalignment of the survey data sets (due to datum/survey control accuracy), as well as random errors in horizontal and vertical positioning due to instrumentation accuracy limitations.

- The historical survey points are localised and not of high density. There is therefore opportunity for very localised features (such as individual rocks/boulders) to result in scatter in the results of bathymetric change.

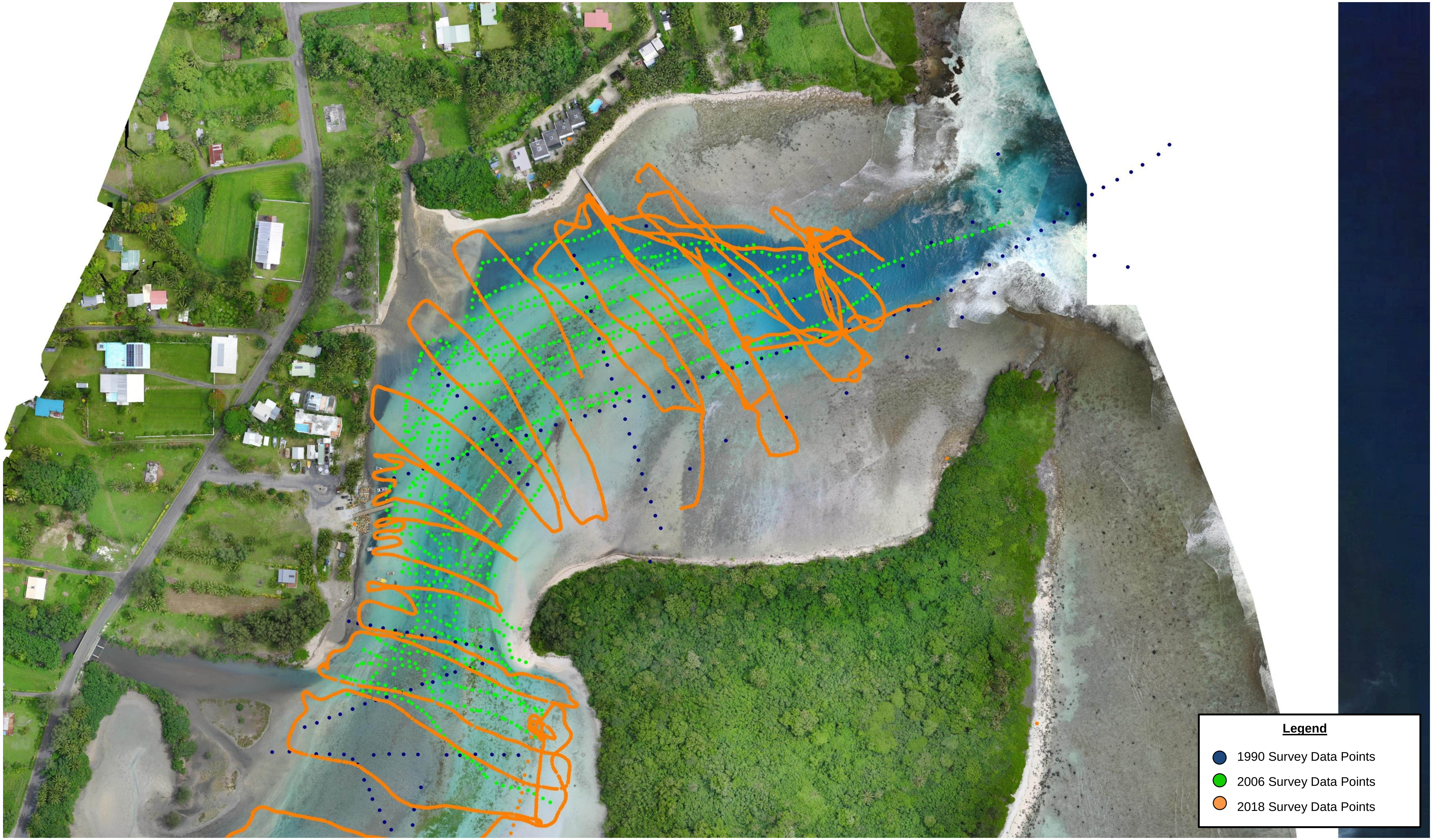
- There is expected to be short term fluctuations (storm based for example), seasonal fluctuations, and long term fluctuations in bathymetry and topography around the lagoon. Given the large timeframes between surveys, it is difficult to separate the changes into shorter or longer term fluctuations.

Annotations have been included on the maps showing important features of the bathymetric change analysis. While there is a reasonable amount of scatter in the results, the following trends have been identified:

- The northern Avana Harbour/Passage area is generally deeper now than it was in 1990, in particular in the predominant channels (Map 03). However, Since 2006 there has been notable accretion of the sand shoals on either side of the main channel, and deepening of the channel areas themselves (Map 04).
- There has probably been slight growth of the algae-rubble ridges across the channel between the Aroko foreshore and the northern end of Oneroa, and also between Aroko and the southern end of Motutapu (Map 06). These shallow ridges across the channel were certainly identified in historical literature so they are not a new feature. However, it is difficult to tell how much shallower they may have become in recent decades (if at all), as historical survey lines do not pick up the high point of the ridge. There has also been work in this area to remove the historical fish trap.

- There has been minimal change or slight deepening of most of the main Muri Lagoon basin (Map 08). This trend of basin deepening was also detected in the last bathymetric change analysis (Collins, 1993) which looked at change in the decades leading up to the 1990s.
- There has likely been slight deepening of main flow channels where they round the ends of the various motu (Map 08).
- The nearshore area of the main lagoon basin extending from the northern side of Taakoka, across to the main Muri Beach area has likely shallowed/infilled slightly (Map 08).

Overall, these trends indicate that low-flow areas of the lagoon system have potentially infilled slowly, which is in-turn concentrating flows within channel areas and resulting in slight deepening of the channels.



Survey Date: 1990, March 2006, February 2018	Mei Te Vai Ki Te Vai
Coordinate System: WGS 84, Z4s, UTM	Map 02: Bathymetric Survey Coverage of Avana Harbour Area, 1990, 2006 and 2018
Elevation Datum: MSL	

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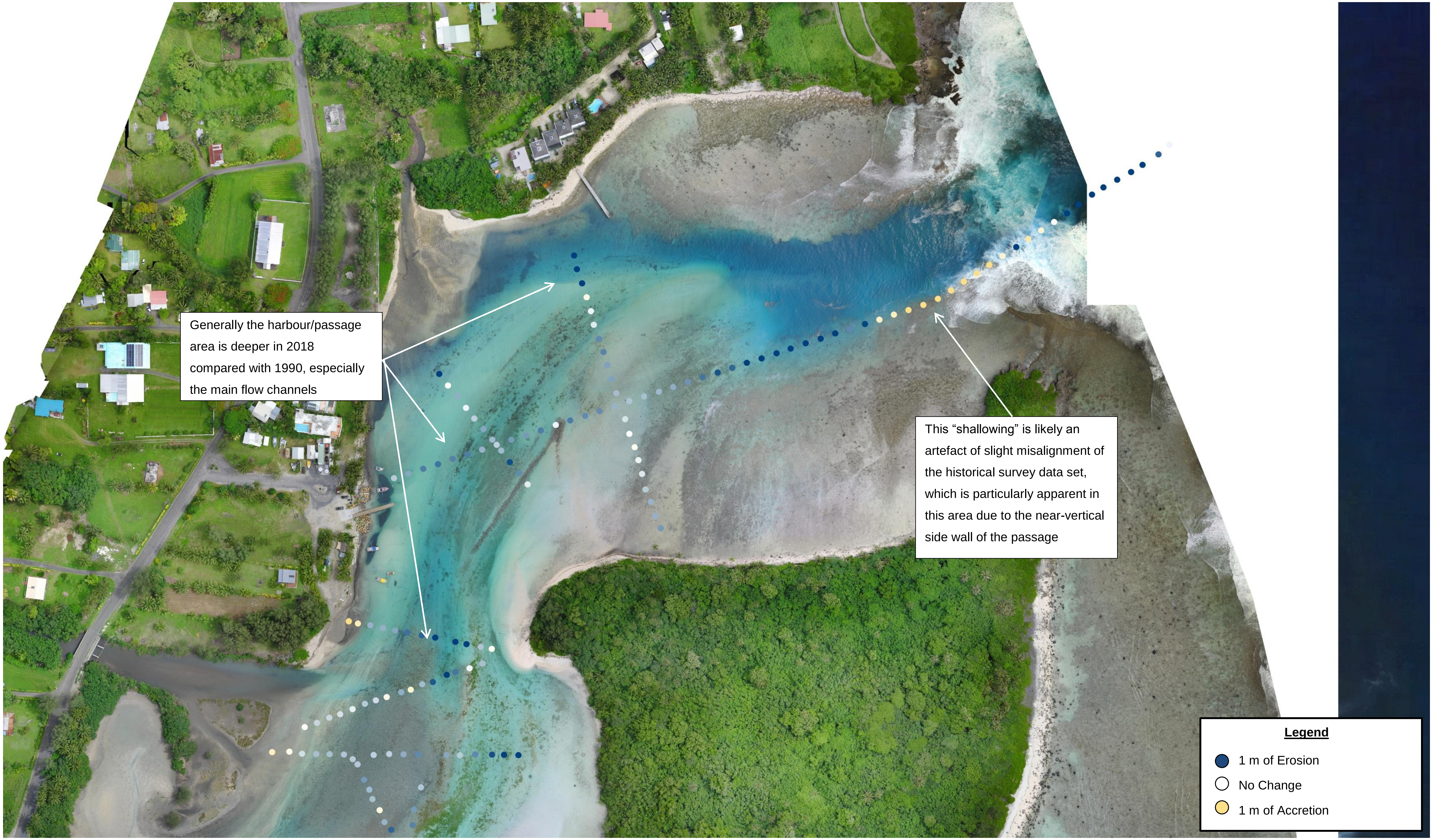

Survey Date: 1990, February 2018	Mei Te Vai Ki Te Vai
Coordinate System: WGS 84, Z4s, UTM	Map 03: Comparison of Bathymetry in Avana Harbour Area between 1990 and 2018
Elevation Datum: MSL	

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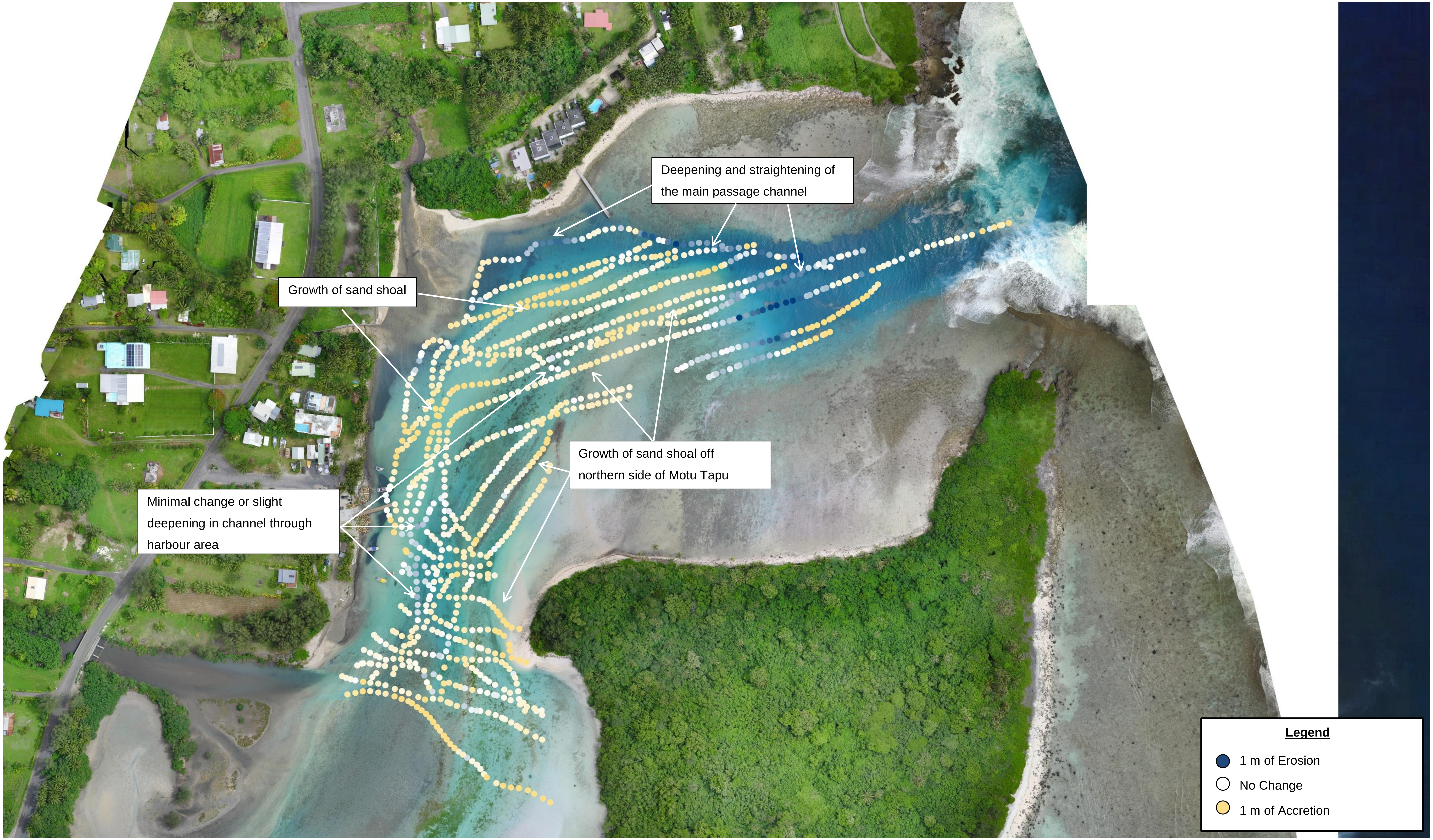

Survey Date: March 2006, February 2018	Mei Te Vai Ki Te Vai
Coordinate System: WGS 84, Z4s, UTM	Map 04: Comparison of Bathymetry in Avana Harbour Area between 2006 and 2018
Elevation Datum: MSL	

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Survey Date: 1990 and 2018	Mei Te Vai Ki Te Vai
Coordinate System: WGS 84, Z4s, UTM	Map 05: Bathymetric Survey Coverage of Northern Channel Area, 1990 and 2018
Elevation Datum: MSL	

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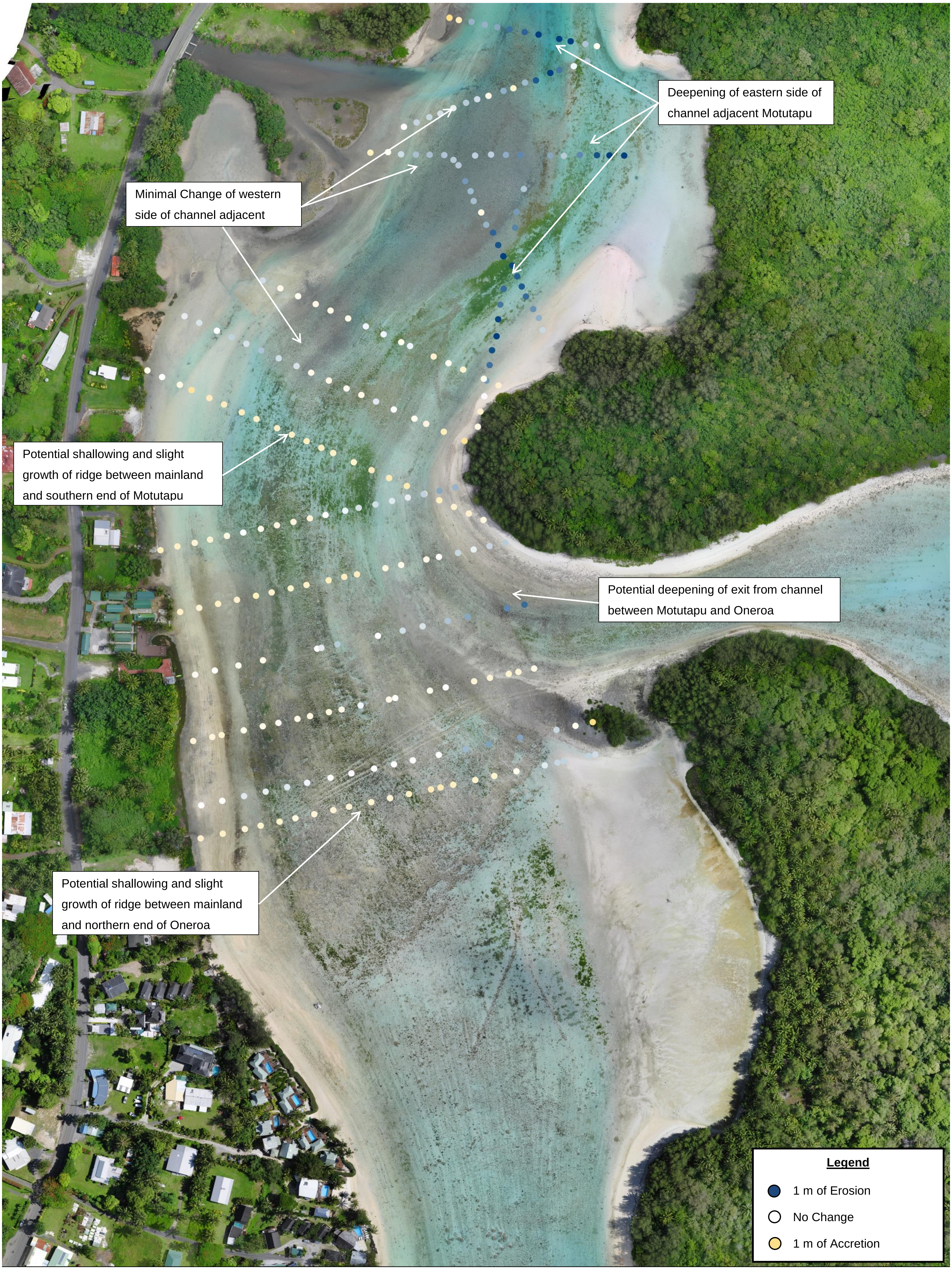

Survey Date: 1990 and 2018	Mei Te Vai Ki Te Vai
Coordinate System: WGS 84, Z4s, UTM	Map 06: Comparison of Bathymetry in Northern Channel Area between 1990 and 2018
Elevation Datum: MSL	

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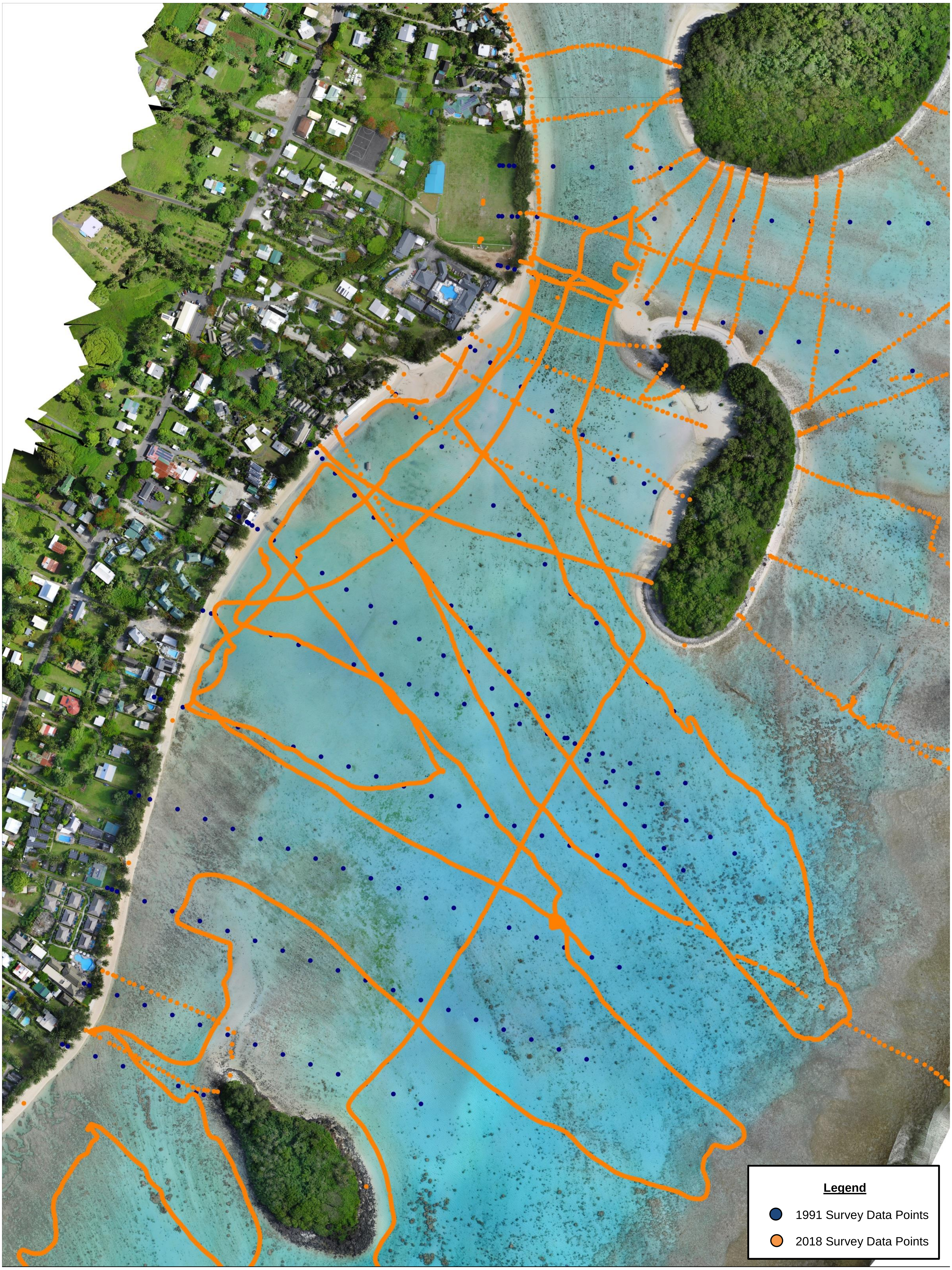

Survey Date:
1991 and 2018

Coordinate System:
WGS 84, Z4s, UTM

Elevation Datum:
MSL

Mei Te Vai Ki Te Vai

Map 07: Bathymetric Survey Coverage of Main Lagoon Area, 1991 and 2018

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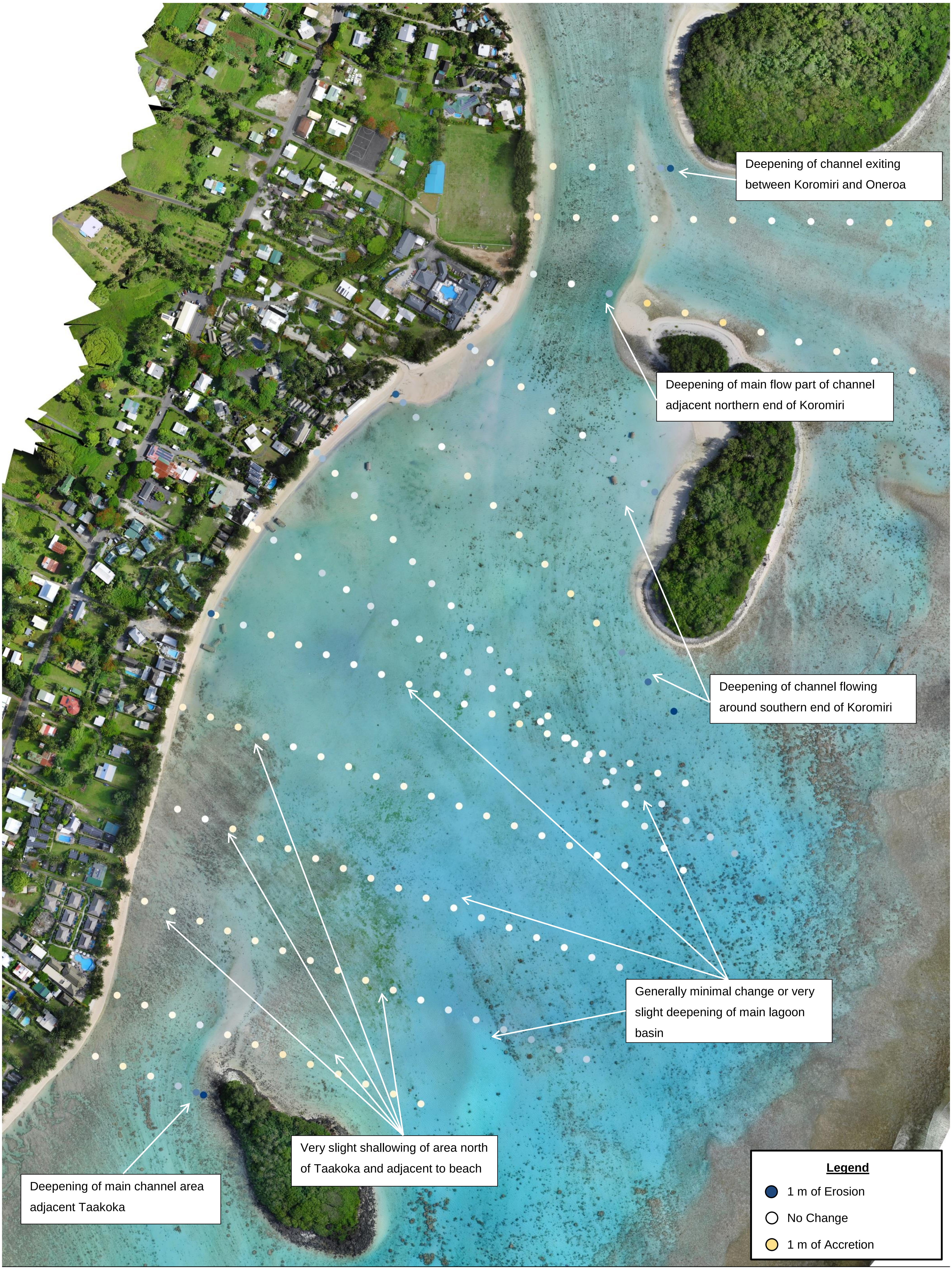

Survey Date: 1991 and 2018	Mei Te Vai Ki Te Vai
Coordinate System: WGS 84, Z4s, UTM	Map 08: Comparison of Bathymetry in Main Lagoon Area between 1991 and 2018
Elevation Datum: MSL	

3 Hydrodynamic Data Collection Programme

3.1 Overview of Data Collection Programme

Historically the hydrodynamics of the Muri Lagoon system have been investigated numerous times, including both field data collection programmes and conceptual numerical modelling. Considerable planning was put into the current hydrodynamic investigation so as to build on the previous studies, and also allow relative comparisons between the present lagoon processes and those that may have been occurring historically.

Given the complexity of hydrodynamic processes at Muri, it was important to base the hydrodynamic analysis primarily on a high quality field data collection campaign, with subsequent use of the numerical model only as a tool to explore the relative impact of various scenarios. The data collection program focussed on recording data sets that would:

- Allow comparison with historical data sets;
- Close knowledge gaps; and
- Allow a more holistic understanding of hydrodynamic processes to be developed.

The hydrodynamic data collection program set out to record data sets including water levels, currents and waves at key locations around the lagoon. A network of continuous logging monitoring stations was established during the first deployment, with the locations of the stations chosen on the basis of our existing understanding of the lagoon processes from previous investigations. The monitoring locations are shown in Map 09 and the station equipment detailed in Section 3.2. Where possible concurrent data sets were collected for the various monitoring locations and data types, however, due to the different data storage and power specifications of the instrumentation, this was not possible across the complete monitoring period. Figure 3.1 shows the timing of each of the data sets that were collected at each location throughout the monitoring.

To provide an improved understanding of spatial variation in currents and to understand flows passing through various sections of the lagoon, profiling of currents and flow gauging was also undertaken on one occasion. The current metering transects that were profiled were co-located with the continuous monitoring stations wherever possible, or at locations that had been profiled in previous investigations (see Map 10).

In addition to the data recorded by WRLs network of monitoring stations, water level data from the SeaFRAME tide gauge at Avatiu Port was obtained from the Bureau of Meteorology, as well as forecast wave conditions from the NOAA Wavewatch III global wave model, for the duration of the monitoring program.

After approximately three weeks of deployment the current meter at station C (near Muri Beach Club) was tampered with, which subsequently destroyed the sensor electronics. Data recorded up until that point was able to be retrieved from the instrument memory card. This issue was discovered by the project team during station maintenance in April 2018. It was decided by the team that deployment of further instruments at that location was a high risk due to the large number of people swimming and wading in the area, and so no further data collection was undertaken at Station C.

For the first deployment period, the water level gauge at Station E failed so no water level data was recorded at that location. An alternative gauge was used for the second deployment period.

Monitoring Station Locations

Station A	424028.592 mE, 7648618.157 mN
Station B	424458.604 mE, 7648764.836 mN
Station C	424447.794 mE, 7649407.804 mN
Station D	424636.765 mE, 7649509.733 mN
Station E	424567.575 mE, 7650017.884 mN
Station F	424480.472 mE, 7650306.523 mN
Station G	424743.278 mE, 7648581.366 mN

Survey Date: April 2018	Mei Te Vai Ki Te Vai
Coordinate System: WGS 84, Z4s, UTM	Map 09: Continuous Hydrodynamic Monitoring Station Network
Elevation Datum: MSL	

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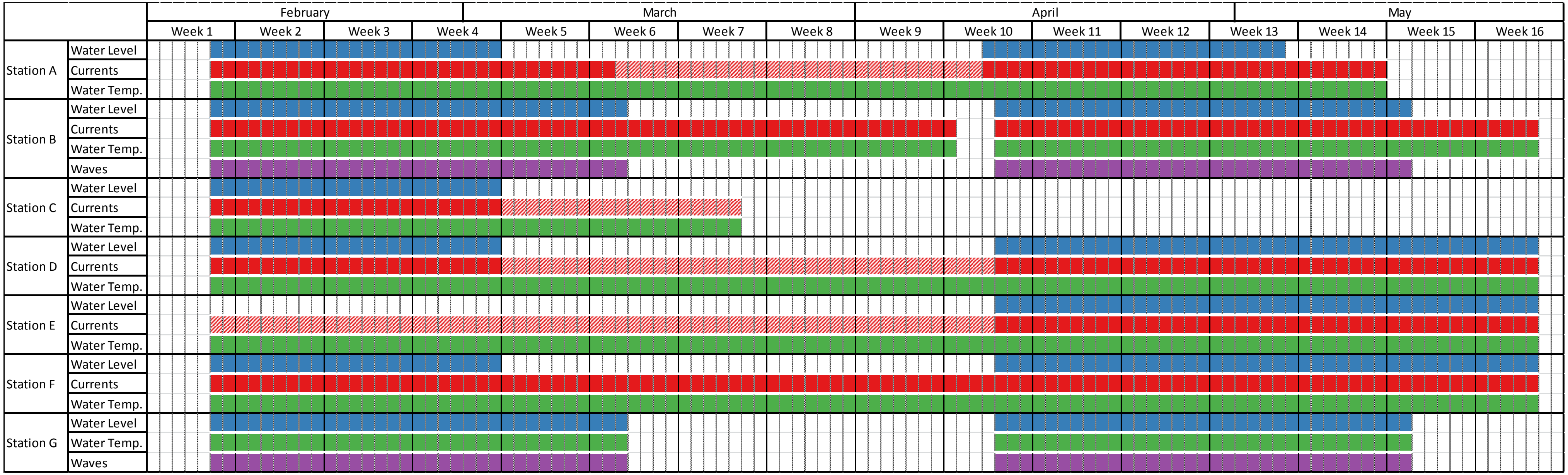
Figure 3.1: Data collection schedule



Note: Hatched colours indicate that current data was recorded, however, the data contains erroneous values at low stages of the tidal cycle (discussed further in 3.2.3)

3.2 Methodology and Equipment

3.2.1 Monitoring Station Overview

Each fixed position monitoring station had a 40 kg custom fabricated concrete mooring block, integrated with instrumentation mounts. Station G (located within the wave break zone on the outer reef fringe) also had two additional 60 kg cast steel weights for additional mooring stability. All instruments (water level, wave and current) recorded data on internal memory and were also powered by internal batteries. Water level loggers were fitted inside a small section of perforated PVC tube to provide protection from any debris impacts and to reduce the effects of biofouling. The PVC tube was cast into the concrete mooring block. Current meters were attached to a stainless steel bracket that was also cast into the concrete mooring block. This system allowed easy removal of the instruments from the mooring block for download and maintenance prior to redeployment. Photos of the monitoring stations are shown in Figure 3.2 to Figure 3.7.

On 11/04/2018 all monitoring instruments were removed from the lagoon to download data sets and undertake maintenance. This included preliminary checks of the data quality and instrument functions, removal of biofouling, and changing of batteries as needed. The position and elevation of all monitoring stations was also surveyed using RTK-GPS, to allow the elevation of each station and their water level records to be reduced back to the same MSL datum.

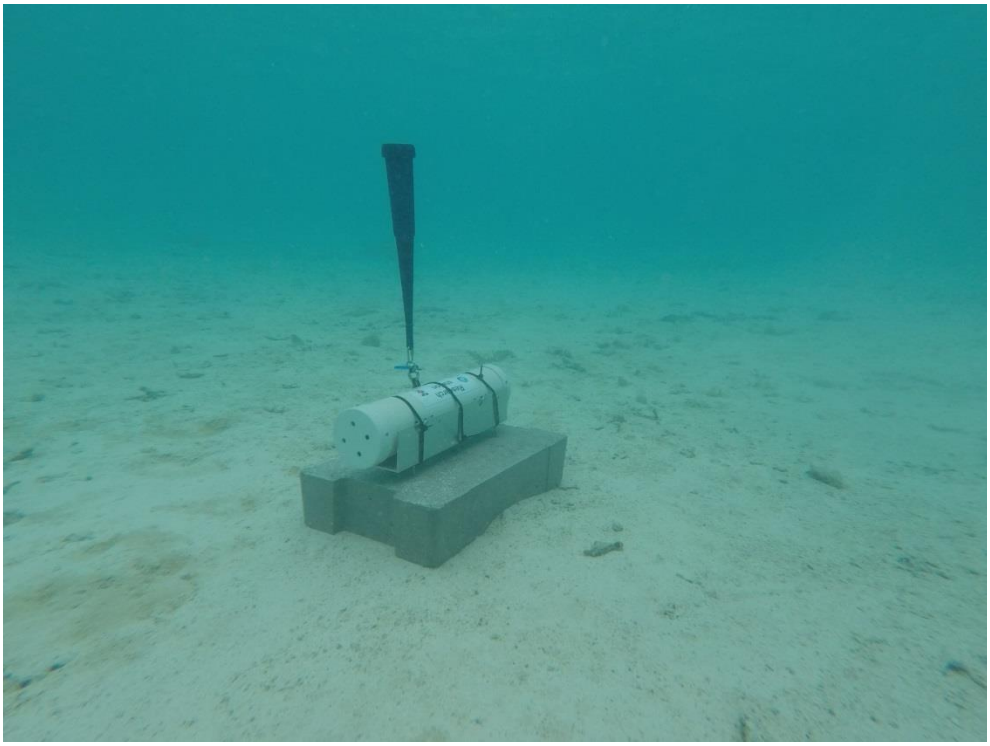


Figure 3.2: Monitoring Station B

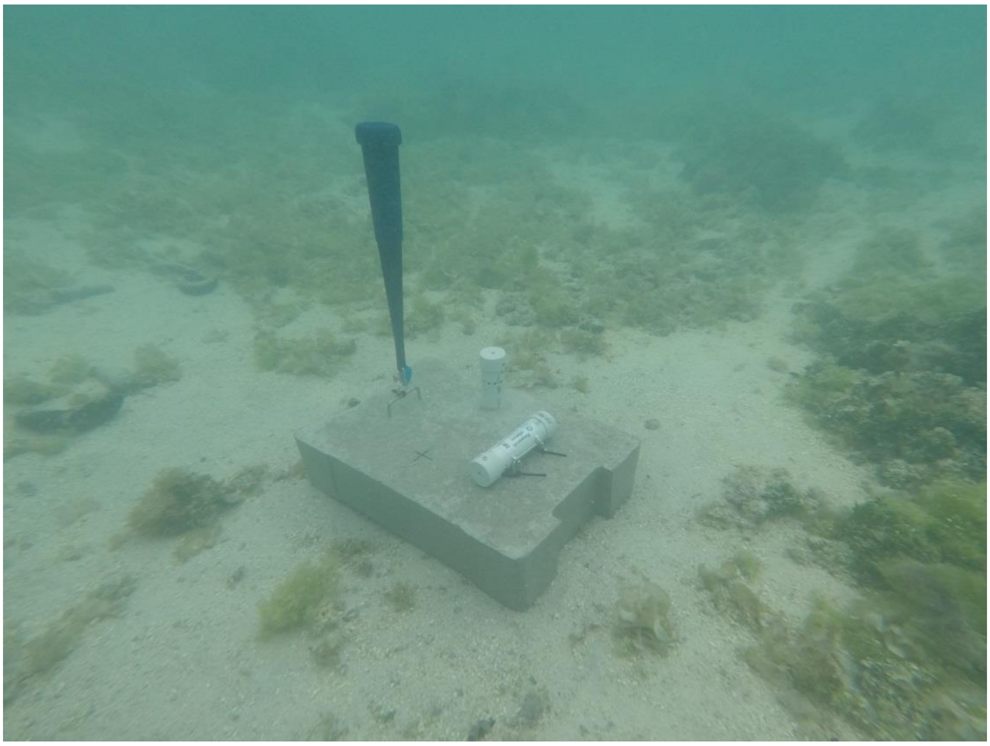


Figure 3.3: Monitoring Station C

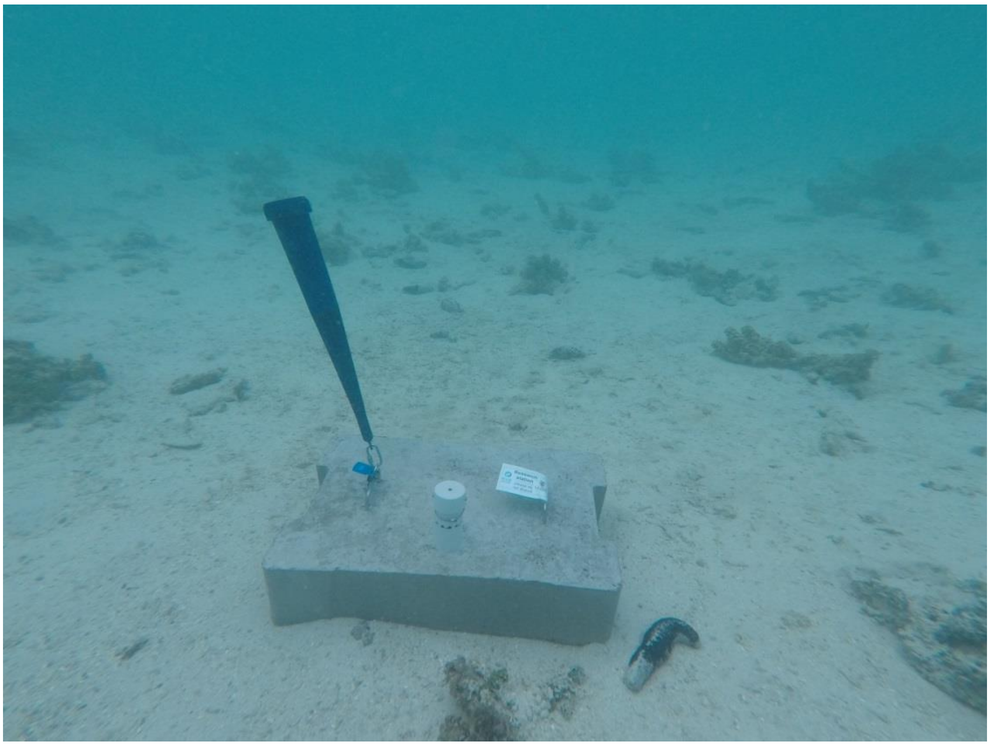


Figure 3.4: Monitoring Station D

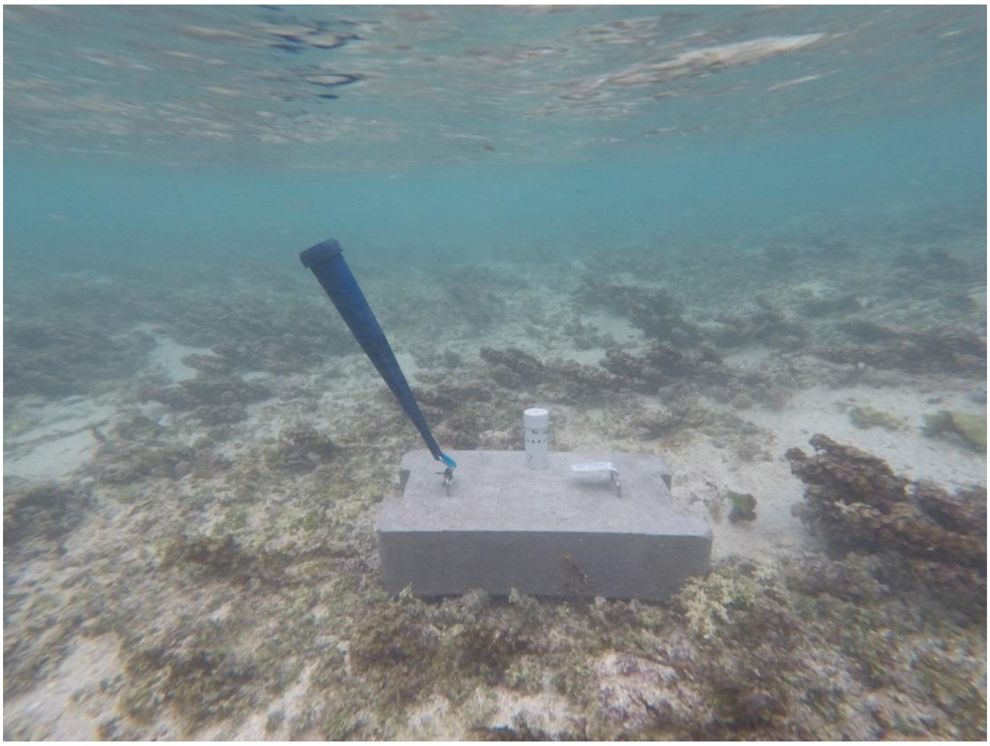


Figure 3.5: Monitoring Station E

Figure 3.6: Monitoring Station F

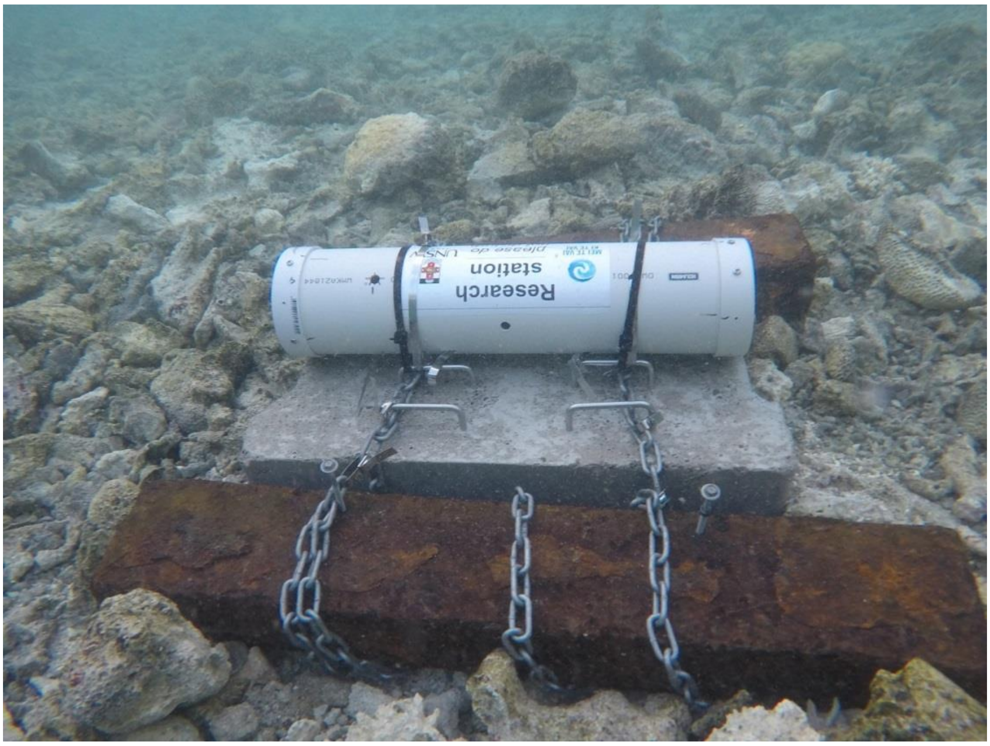


Figure 3.7: Monitoring Station G

3.2.2 Continuous Water Level Measurements

Continuous water level measurements were collected using various pressure based water level meters including:

- Heron Dipperlog Nano (used at stations where wave data was not measured);
- RBR Duo (used at stations where both wave and water level data was required).

The Heron Dipperlog Nanos recorded water level at a frequency of 1 minute during the first deployment, and at a lower 5 minute frequency during the second deployment (to prolong the data collection period). Data from the first deployment was filtered with a 6 minute moving average filter to smooth out short term fluctuations in water level associated with waves. The RBR Duos were used to record water level data at a much higher frequency (6 samples per second) so that the record could be used for analysis of both waves and water levels. The recorded data was subsampled to a frequency of 1 minute for analysis of water levels.

As the water level loggers all measure absolute pressure, the raw measurements include pressure changes due to both changing water levels and changing atmospheric pressure. Atmospheric pressure was measured continuously throughout the monitoring campaign by two baro-loggers located within the Muri township, with the data also compared against a NIWA operated atmospheric pressure gauge located at the Cook Islands Meteorological Service site in Nikao. All barometric pressure gauges provided very consistent results. The data from the baro-loggers was used to correct for the barometric pressure fluctuation component of the water level measurements.

3.2.3 Continuous Current Measurements

Current measurements were made using Marotte HS tilt-drag type current meters. These instruments function on the principle of drag, whereby each instrument has a unique calibrated relationship between the current velocity moving past the instrument body and the amount of drag that is generated on the body. The instruments are hinged from the very bottom and are buoyant so sit vertically in the water column when there is no flow velocity. As flow velocity increases, drag force on the instrument also increases and the instrument begins to tilt. The tilt angle is recorded, along with tilt direction, which are then converted to an accurate record of current speed and direction using the instrument's unique calibration.

The Marotte HS current meters internally record current speed and direction at a frequency of 1 sample per second. This data was subsequently averaged across 1 minute intervals to smooth out high frequency fluctuations in velocity and also the effects of instrument dynamics resonance on the measurements.

Ideally the Marotte current meters would be positioned so the instrument body is around mid-level within the water column, so that they are collecting measurements of depth-averaged current velocities. This was not possible at all times/stations due to the tidal fluctuations and lagoon water level pumping. In most cases the instruments were considered to provide a reasonable representation of typical current velocities, with the instrument slightly more submerged at higher water levels, and just becoming emergent at very low stages of the tide. Once the instrument begins to touch the water surface the records are not reliable. For most stations this occurred infrequently or not at all, with the exception of monitoring station E where it occurred for the bottom part of each tide cycle. This was unavoidable due to the shallow water depths in this area of the lagoon. The minimum water level that each current meter was able to reliably measure current speed was determined, and the data records for currents were filtered to remove erroneous measurements at low water levels. This filtering process was only possible when concurrent water level data was available at the same location as the current meter.

3.2.4 Current Profiling and Flow Gauging Measurements

On 9/04/2018, lagoon currents were measured across six (6) nominated cross-channel transects multiple times throughout almost a full tidal cycle. These measurements, termed "current profiles", differ from the continuous current metering data collection in that the depth-averaged currents were measured at regularly spaced intervals across the entire channel cross section, as opposed to only at one location on the transect. The locations where current profiling was completed are shown in Map 10, where it can be seen that the locations are generally adjacent to the continuous monitoring stations. The exception to this was the profile locations that were measured in Avana Harbour, which were aligned with a historical flow gauging location presented in Kirk (1980), to allow comparison between present and past gauged flowrates.

The current profiles provide an indication of the distribution of currents across the channel, and also provide a more reliable estimate of the volumetric flowrate as opposed to just the current speed and direction. By comparing the measured currents across the full channel with the currents measured on the nearby continuous monitoring stations, we are also able to better understand the site-specific correlation between full channel currents and the currents measured at a single location by the local continuous monitoring stations. This allows improved estimates of lagoon flowrates from the continuous current metering data.

Depth-averaged currents at Profiles 1 to 4 (see Map 10) were measured about every 10-20 m across the channel by wading with an Acoustic Doppler Velocimeter (ADV). The specific instrument used was a Sontek Flowtracker2 (Figure 3.8). Depth-profiled currents at Profiles 5 and 6 were measured using the M9 Riversurveyor ADCP (Figure 2.5), mounted on a kayak that was paddled back and forward across the channel transects.

3.2.5 Wave Measurements

Wave data was recorded using RBR Duo pressure based wave gauges, which collect high frequency (6 Hz) samples of the water surface elevation. This data is able to be post-processed to provide an indication of swell and infragravity wave motions.

3.2.6 Continuous Water Temperature Measurements

The Heron and RBR Duo water level loggers, as well as the Marotte HS current meters all measured water temperature. This allowed multiple measurements of water temperature at each monitoring station throughout the data collection period.

Figure 3.8: Current metering between Oneroa and Motutapu with Flowtracker2 ADV

Survey Date: April 2018	Mei Te Vai Ki Te Vai
Coordinate System: WGS 84, Z4s, UTM	Map 10: Current Profile Locations
Elevation Datum: MSL	

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4 Analysis of Hydrodynamic Processes

4.1 Analysis of Water Level Fluctuations

4.1.1 Tidal Fluctuations

A formal program of ocean water level recording is undertaken by the Australian Bureau of Meteorology as part of the Pacific Sea Level Monitoring (PSLM) programme, with a SeaFRAME tide gauge located at Avatiu Port. This station provides a continuous and lengthy historical record of sea levels for Rarotonga. The complete set of water level data recorded by the network of local monitoring stations installed in Muri Lagoon (as described in Section 3.2) during this project is shown in Appendix A, along with data from the Avatiu tide gauge for the monitoring period. This data is also available electronically. Figure 4.1 shows a one week extract of recorded water level fluctuations in Muri Lagoon and Avana Harbour under typical conditions.

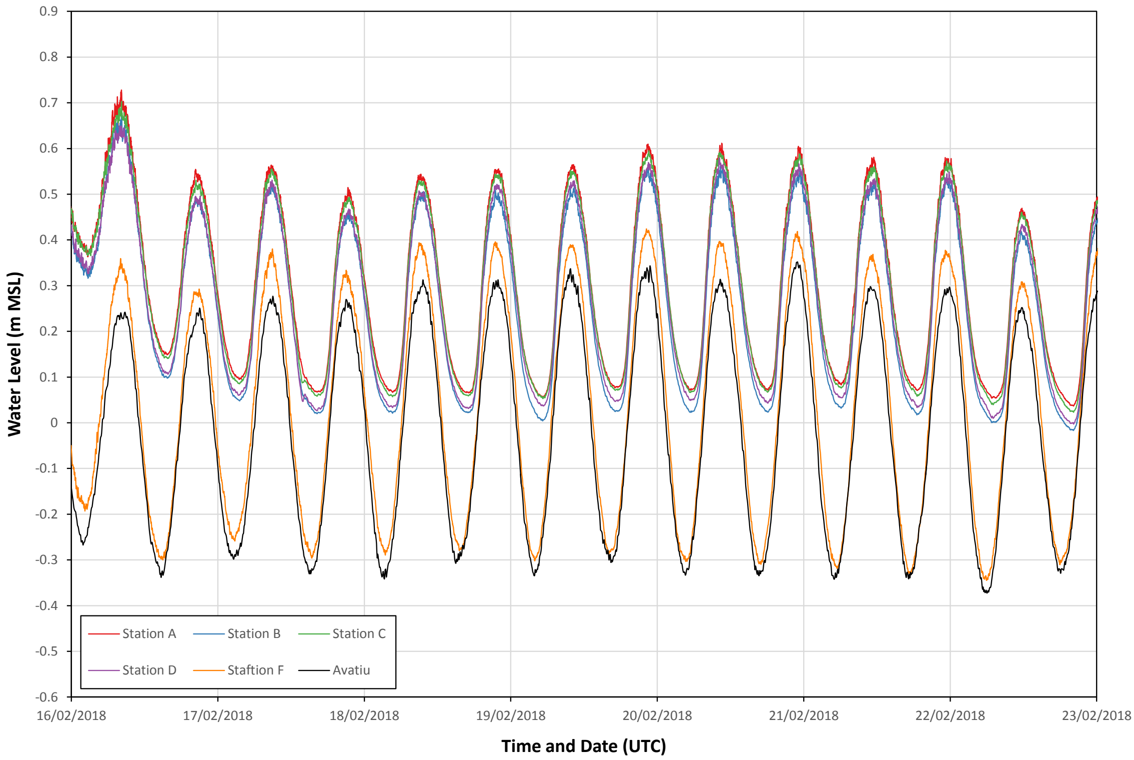


Figure 4.1: Example water level fluctuations in Muri Lagoon and Avana Harbour

Visual inspection of the water level records collected at the monitoring stations around Muri Lagoon showed that water levels at Station F (near the Avana stream delta, just south of Avana Harbour) appeared to have a very similar range and phase to the ocean tides recorded on the north coast at Avatiu. A cross-correlation analysis of the water level records between Station F data sets and

Avatiu data sets was undertaken using Matlab, and showed that there was zero time lag between Avana and Avatiu tides for the first period of instrument deployment (February to April 2018) and only a 1 minute lag for the second deployment period (April to May 2018). The cross-correlation process was verified by artificially lagging the Station F water level data by various time periods, and checking that the analysis correctly identified the artificial lag period, which it did. This analysis confirms that:

- There is no measurable phase difference in ocean tides on the southeast coast of Rarotonga compared with the north coast.

The cross-correlation analysis was repeated for the water level data recorded at each of the monitoring stations within the lagoon, with the tide lag information summarised in Table 4.1.

Table 4.1: Phase lag of tides within Muri Lagoon and Avana Harbour, compared with Avatiu

Monitoring Station	Tide Lag Deployment Period 1 (mins)	Tide Lag Deployment Period 2 (mins)
Station A (Between Taakoka and Beach)	16	13
Station B (Muri Lagoon)	18	15
Station C (Nukupure Park)	17	NA
Station D (Koromiri/Oneroa Channel)	19	20
Station E (Oneroa/Motutapu Channel)	NA	25
Station F (Main Channel, Avana Stream Delta	0	1

Based on water level records collected between 8th December 1990 and 23rd January 1991 in Muri Lagoon near Nukupure Park, Holden (1992) reported an average tide lag in Muri Lagoon of 50 minutes. This differs quite significantly from the results of this current investigation which showed:

- Tides in the main lagoon basin and the in the channel near Nukupure Park lag the ocean tides by approximately 15 to 20 minutes;
- Tides in the narrow channel between Oneroa and Motutapu have a slightly longer lag of 25 minutes;
- Tides in Avana Harbour and in the channel at the Avana Stream delta have no lag.

Further analysis and discussion on tide lags is presented in Section 4.1.3.

4.1.2 Lagoon Water Level Setup

In considering the water level records collected at the various monitoring stations (Appendix A and Figure 4.1), it is immediately apparent that water levels in Muri Lagoon are constantly superelevated above ocean water levels at all stages of the tide. This process of lagoon water level "pumping" is discussed in Callaghan et al. (2006) on the basis of lagoon water level measurements taken on the atolls of Manihiki and Rakahanga in the Northern Group of the Cook Islands. The perching of water levels is driven by breaking waves on the fringing reef, with the magnitude of water level pumping in direct proportion to the size of the waves.

While Holden (1992) identified the wave driven lagoon water level pumping process at Muri for large wave events, it is understood that the analysis of lagoon water level records was largely undertaken on a de-trended water level record (mean water level removed). As such, the analysis did not report the effect of lagoon pumping that occurs at all times, even during typical or lower wave conditions. It is thought that:

- The continuous superelevation/perching of the lagoon water levels at Muri has not previously been fully understood until the current investigation, nevertheless is a key driver dictating the hydrodynamic processes of the lagoon.

Figure 4.2 shows a time series of water level data recorded from the main Muri Lagoon basin (Monitoring Station B), along with the non-tidal component of the lagoon water level, which is the water level averaged across a tide cycle as determined by both Fast Fourier Transform (FFT) analysis and Moving Average (MA) methods. Overlaid on this plot is the predicted nearshore significant wave height breaking on the fringing reef at Muri, which has been estimated from a local wave transformation of the NOAA Wavewatch III wave model predictions for Rarotonga. It can be seen that:

- There is a very strong correlation between lagoon water level setup/pumping, and the size of waves breaking on the fringing reef.

Figure 4.3 shows a scatter plot of wave height versus lagoon water level setup. It can be clearly seen that for all monitoring locations with the exception of Station F (near Avana Stream delta), that there is an obvious relationship between wave height and lagoon water level setup. It is also worthwhile noting that:

- The water level in the main Muri Lagoon basin is perched above the open ocean sea level by almost 0.3 m during typical wave conditions (nearshore significant wave height of 1.4 m). This increases to a setup of almost 0.5 m with a 2 m nearshore significant wave height.

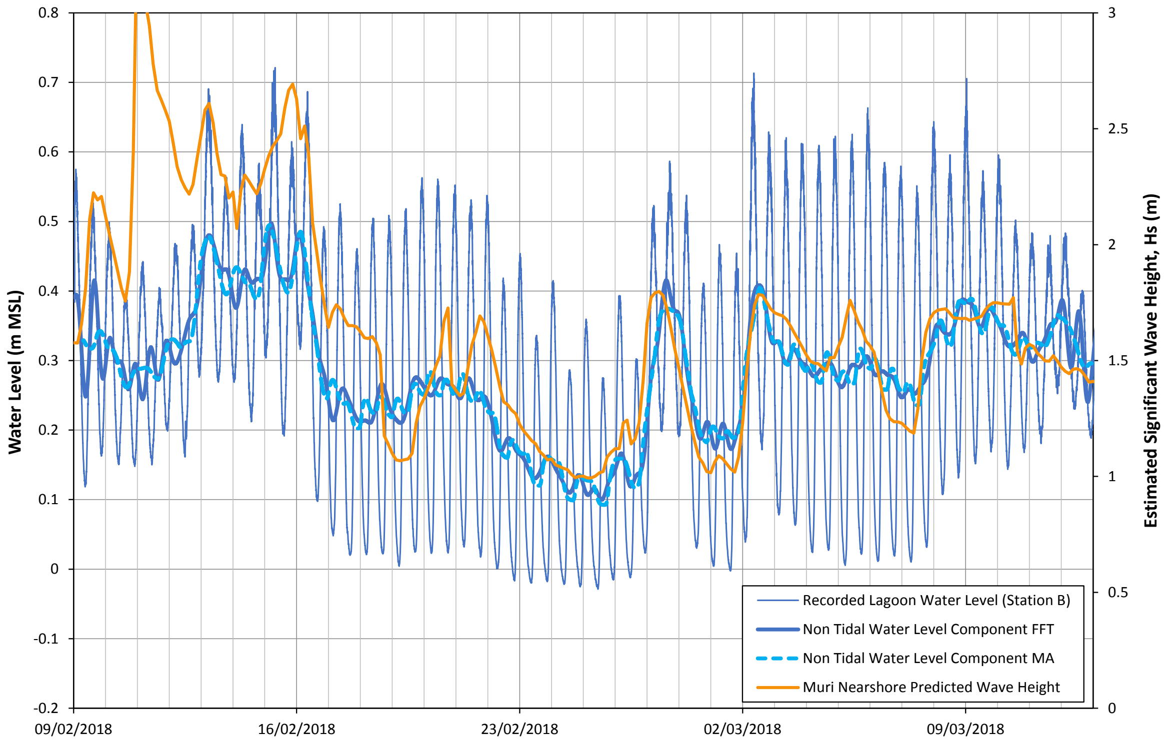
- The magnitude of lagoon water level setup/pumping decreases south to north through the lagoon.

Water level setup near Nukupure Park (Monitoring Stations C and D) is slightly lower than the main lagoon basin (Monitoring Stations A and B), and setup further north in the channel between Oneroa and Motutapu is lower again. There was only very minimal water level setup in the channel near Avana Stream delta (Monitoring Station F), and it can be seen from the water level records in Appendix A, Figure 4.1, and Figure 4.3, that:

- There is typically a rapid drop in lagoon water levels of 0.2 to 0.25 m that occurs across the shallow ridge in the main lagoon channel between Aroko and the northern end of Oneroa, in particular at low tide.

In summary:

- Water levels in Muri Lagoon are continuously perched at a higher level than ocean water levels due to the effect of wave pumping on the fringing reef;
- Under average wave conditions, water levels in the lagoon are approximately 0.3 m higher than the ocean, for all stages of the tide. This pumping increases in proportion to increasing wave conditions.



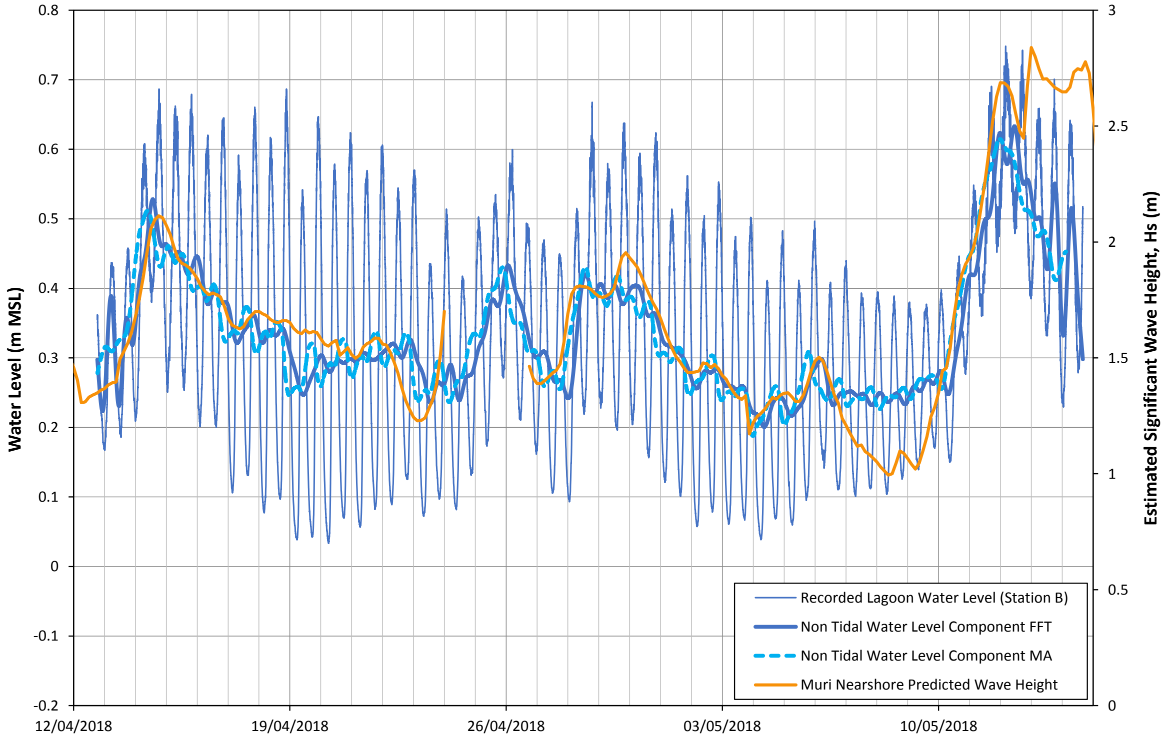


Figure 4.2: Muri Lagoon recorded water level pumping

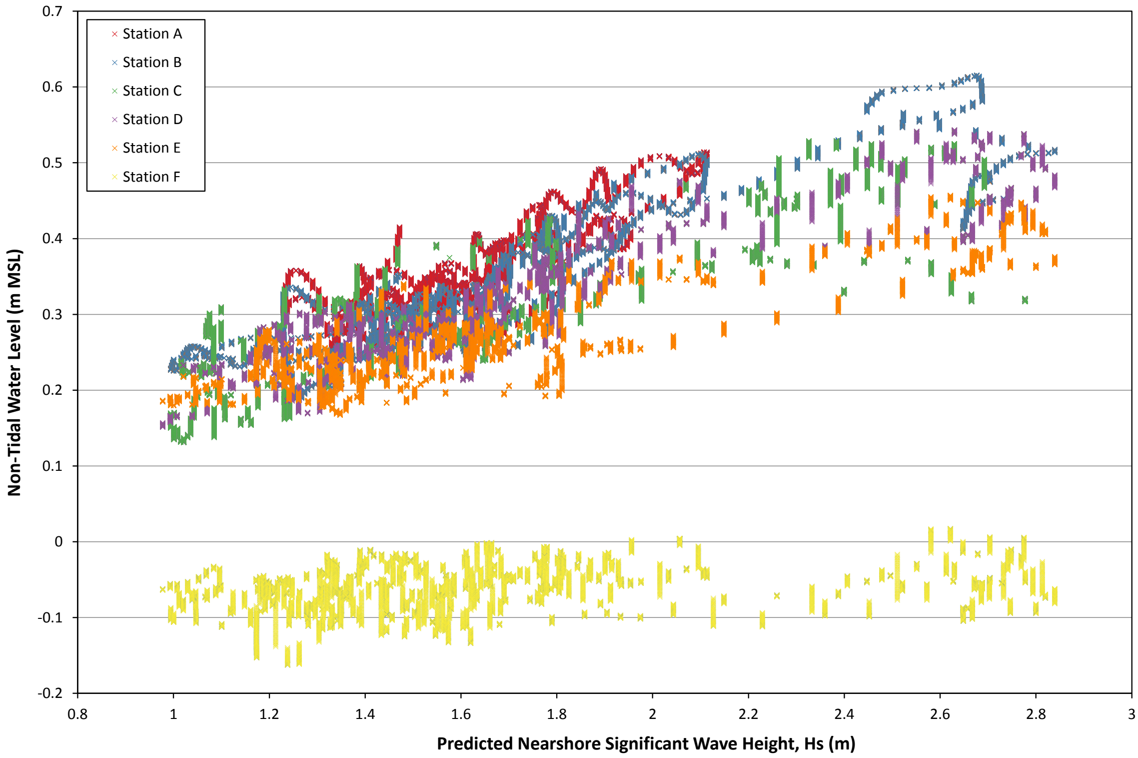


Figure 4.3: Relationship between lagoon water level setup and wave height

4.1.3 Discussion of Water Level Processes

It is apparent that the wave driven pumping of lagoon water levels in Muri Lagoon likely plays a significant role in the hydrodynamics of the system. While it was previously known that the lagoon water levels increased during large wave conditions (Holden, 1992), the fact that the lagoon water levels are superelevated above the ocean even during typical wave conditions was not previously well understood. The importance of this water level pumping on lagoon currents is discussed further in Section 4.2.

While the water level processes associated with tidal fluctuations and wave driven pumping are relatively apparent when considering the recorded water level data sets, there are also many more discreet nuances of the lagoon water levels that can be ascertained on closer inspection of the water level records at each of the sites around the lagoon. Some of these processes are discussed below.

Figure 4.4 presents one week of water level data during a spring tide period and a second week of water level data during a neap tide period. Both records have relatively average wave conditions. Figure 4.5 presents a closer view of the water level records that focuses on a small number of tidal cycles. From these figures it can be seen that:

- Within the main Muri Lagoon basin (Monitoring Station B) the tide range is approximately 80% of the full ocean tide range, while further north in the channel between Oneroa and Motutapu (Monitoring Station E) the tide range is further reduced to only 65% of the ocean tide range.

- At low tide, the water level in the main lagoon basin is almost the same as within the channel further north, yet at high tide the water level in the main lagoon basin is markedly higher than in the channel further north.

- The lag of tides in the lagoon is almost non-existent at the high tide peak, but is significantly more pronounced at low tide.

Water levels measured at Station E (within the channel between Oneroa and Motutapu):

- Have the lowest tidal range of all areas within the lagoon (Figure 4.4);
- Are effected slightly less by wave driven pumping (Figure 4.3);
- Are the last to experience a change from outgoing to incoming tides (Figure 4.5).

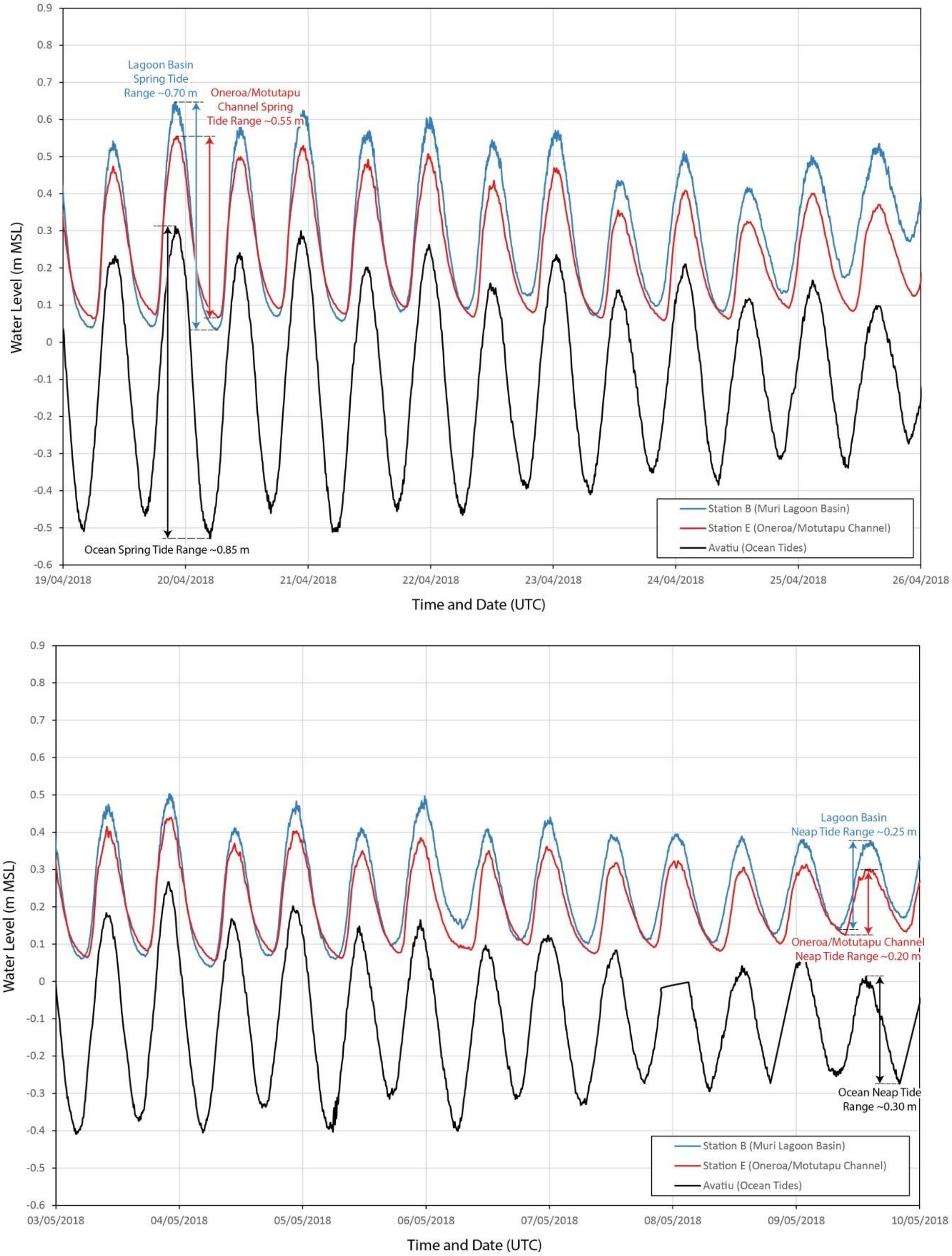


Figure 4.4: Variation in tidal range with spring tides (T) and neap tides (B)

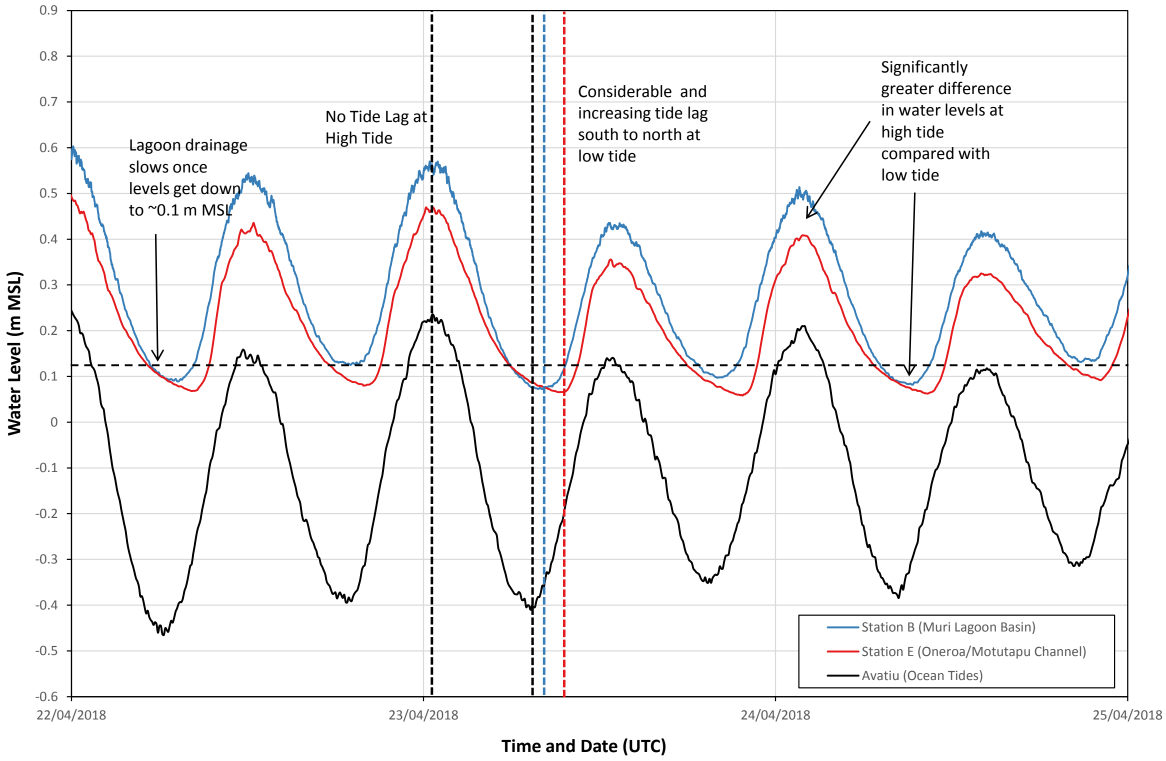


Figure 4.5: Nuances of tidal water levels throughout lagoon and channels

4.2 Analysis of Currents and Flushing

4.2.1 Overview

The complete set of current meter data recorded by the network of local monitoring stations installed in Muri Lagoon (as described in Section 3.2) is shown in Appendix B, overlaid with water level data at each monitoring station. This data is also available electronically. As an example, Figure 4.6 shows a one week extract of recorded current meter data from Monitoring Station D located in the channel between Koromiri and Oneroa. To assist in interpreting the results from the current metering, an animation of the current meter time series has also been produced which shows the current speed and direction at each monitoring station throughout the monitoring programme.

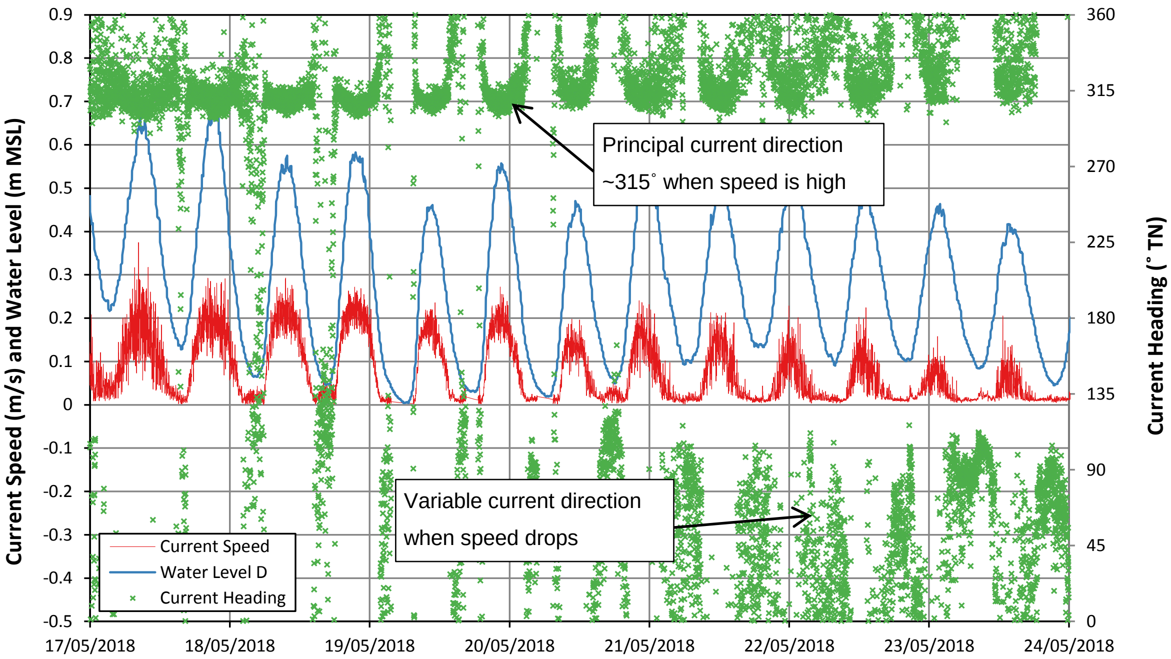


Figure 4.6: Example of one week of current meter data from Monitoring Station D

As expected, analysis of currents from individual monitoring stations shows that both the current speed and directional signature vary from station-to-station around the lagoon. All locations show a strong variation in current speed with water level fluctuation, and most have a principal current direction. When interpreting the current directional data plotted for each station in Appendix B, it is worthwhile noting that:

- During higher current speeds the current direction tends to be focussed in a relatively narrow directional band (315˚ TN at Station D in Figure 4.6 for example), and this is a good indication of the dominant flow direction.
- During very low current speeds the recorded data tends to show a broader scatter in direction or an alternative directional focus, however, this needs to be interpreted with the low current speed in mind – it is simply the current meter wandering in directional record due to the low current speed/drag, in the same way that a wind anemometer records changing wind directions under light variable winds. In actual fact, due to the low current speeds, there is minimal flow at these times.

To summarise the recorded current data, current “rose” plots have been produced for each monitoring station. These plots show all of the 1 minute averaged observations of current data at a particular station, overlaid in a compass arrangement to indicate current heading, with the distance from the centre of the compass indicating current speed. The lagoon water level at the time the observation was taken is indicated by the colour of the dot. The current rose plots provide a very simple way to understand characteristics of currents at particular locations, such as dominant flow directions, range of current speeds, etc. However, they provide no indication of how currents vary with time, and therefore do not allow “event-based” analysis of the data. This instead requires consideration of the time series data plots in Appendix B.

4.2.2 Currents at Monitoring Station A

The full time series plots of current data from Monitoring Station A (between Taakoka and beach) are provided in Appendix B1, and have been summarised into a current rose plot in Figure 4.7. It can be seen from these plots that at Monitoring Station A, currents were generally:

- Very low in speed compared with other monitored locations around the lagoon, peaking at around 0.35 m/s but typically less than 0.1 m/s;
- Having a very broad directional spread compared with other locations, indicating that there is often no consistent flow of water moving in any particular direction through this area;
- Skewed to have more dominant “principal” flow directions of about 20˚ (toward the north) and 200˚ (toward the south), but with faster currents generally moving in the northward principal direction;
- Correlated to water level, with faster currents occurring at higher water levels.

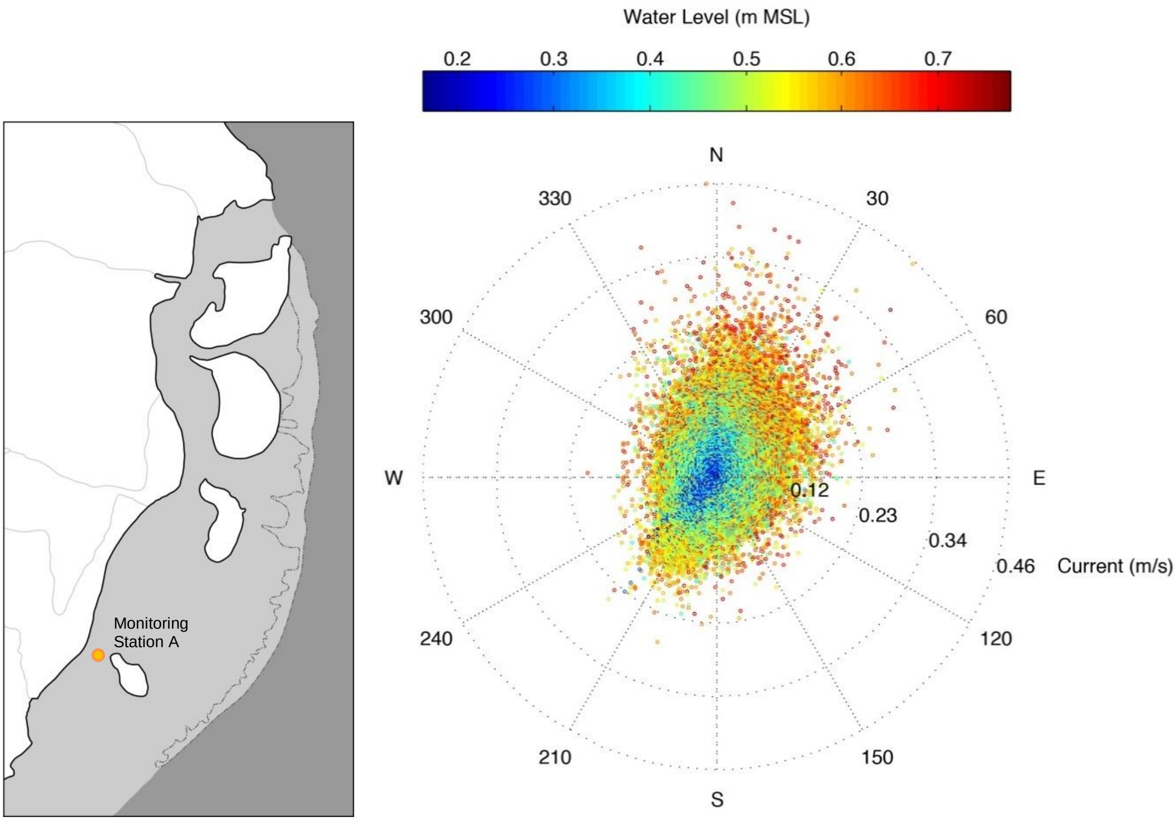


Figure 4.7: Scatterplot of current speed, heading and water level for Monitoring Station A

Consideration of the time series plots of current data shows that at Monitoring Station A:

- Typical conditions have very slow net northward movement of water;
- There were extended periods where currents remained lower than 0.1 m/s, and there was no clear flow direction (17th February to 27th February for example).
- During these periods it is expected that there is only very slow net movement of water along the lagoon foreshore area between the Paringaru Stream and the Pacific Resort;
- These periods occur when there is average or lower than average wave height breaking on the outer reef, or when the wave direction is not out of the southerly quadrants.

Observations taken on the field trips indicated that current flow speeds were slightly higher in the deeper part of the channel directly adjacent to the western edge of Taakoka, compared with the central part of the channel where the monitoring station was located.

4.2.3 Currents at Monitoring Station B

The full time series plots of current data from Monitoring Station B (in central area of main lagoon basin) are provided in Appendix B2, and have been summarised into a current rose plot in Figure 4.8. It can be seen from these plots that at Monitoring Station B, currents were generally:

- Having a relatively broad spread of directions, though skewed with a dominant flow direction in the northerly quadrants, in particular toward about 20˚ TN;
- Closely correlated to water level, with faster current velocities observed at higher water levels;
- Limited to current speeds of approximately 0.3 m/s, though generally lower than 0.2 m/s.

From consideration of the time series of current data recorded at Monitoring Station B, it can be seen that flows in the main lagoon basin tend to operate in one of two modes for several days at a time:

- Currents generally flowing northward (for example 11th to 15th February, 11th to 14th March, 13th to 16th April), which occurs when Rarotonga is exposed to waves from a southeasterly to southwesterly direction;
- Currents being more closely linked to tidal fluctuation but generally moving into the lagoon and southward, which occurs when Rarotonga is exposed to more northerly waves from west through north to east. During these conditions faster west-southwesterly currents flow at higher stages of the tide, swinging around to southeasterly currents and decreasing in speed through the falling stage of the tide. This appears as “slanting” clusters of observations in the current heading data shown in Appendix B2 (for example 5th to 7th March).

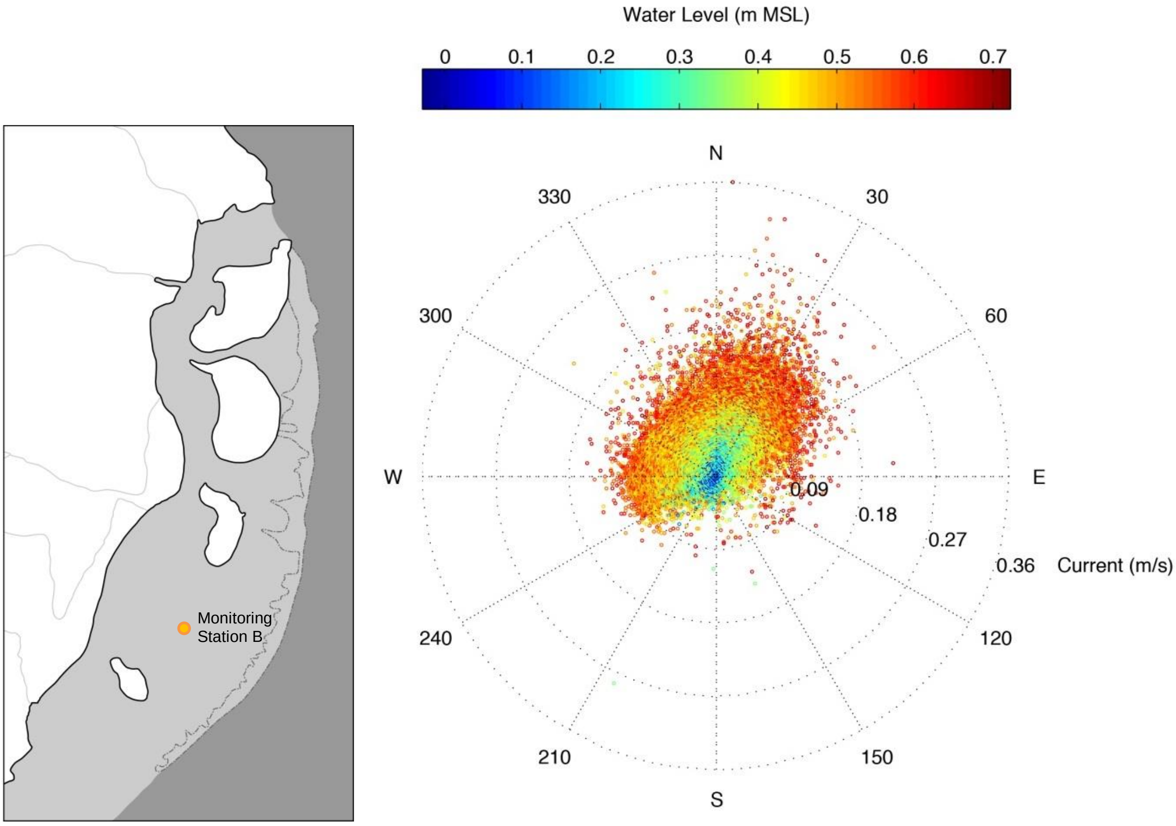


Figure 4.8: Scatterplot of current speed, heading and water level for Monitoring Station B

4.2.4 Currents at Monitoring Station C

The full time series plots of current data from Monitoring Station C (in the main channel adjacent to Nukupure Park) are provided in Appendix B3, and have been summarised into a current rose plot in Figure 4.9. It can be seen from these plots that at Monitoring Station C, currents were generally:

- Unidirectional with the principal flow direction continuously northward at all stages of the tide for many consecutive days;
- Closely correlated to water level, with much faster currents flowing at higher lagoon water levels;
- Significantly faster than current speeds in the main lagoon basin, as expected due to the narrowing of the channel through this area. Current speeds up to 0.6 m/s were regularly observed.

Flows at Monitoring Station C rarely moved in a direction other than northward, and on rare occasions when this did occur it was at very low speeds (less than 0.1 m/s), and as such was mostly associated with wandering of the current meter. Analysis of the timeseries data in Appendix B3 shows that there were no periods when flows moved southward with any notable speed.

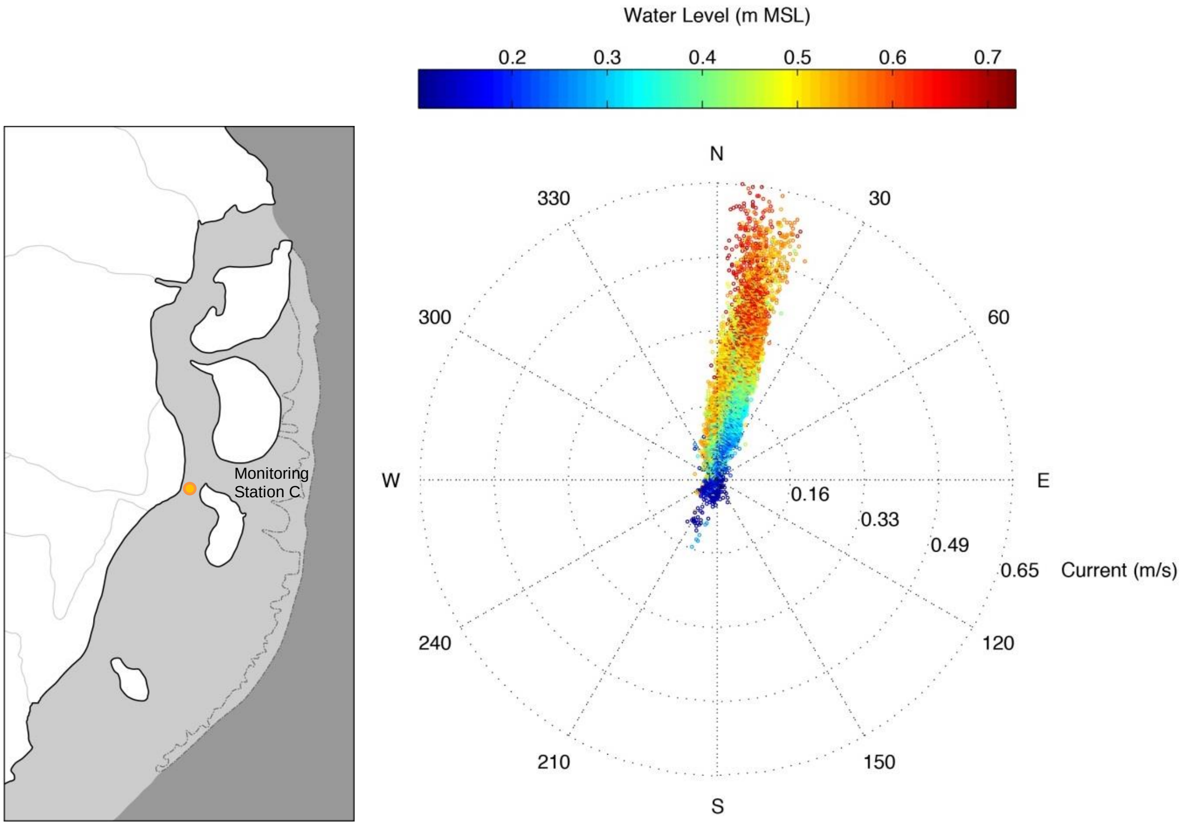


Figure 4.9: Scatterplot of current speed, heading and water level for Monitoring Station C

4.2.5 Currents at Monitoring Station D

The full time series plots of current data from Monitoring Station D (in the small channel between Koromiri and Oneroa) are provided in Appendix B4, and have been summarised into a current rose plot in Figure 4.10. It can be seen from these plots that at Monitoring Station D, currents were generally:

- Focussed in an "incoming" westerly direction toward the main channel, with several short periods of flow reversal to an "outgoing" easterly direction toward the outer reef;
- Ranging in speed up to about 0.5 m/s, with higher current speeds occurring when the currents were flowing into the main channel;
- Correlated with water level, with higher currents occurring during periods of higher water level.

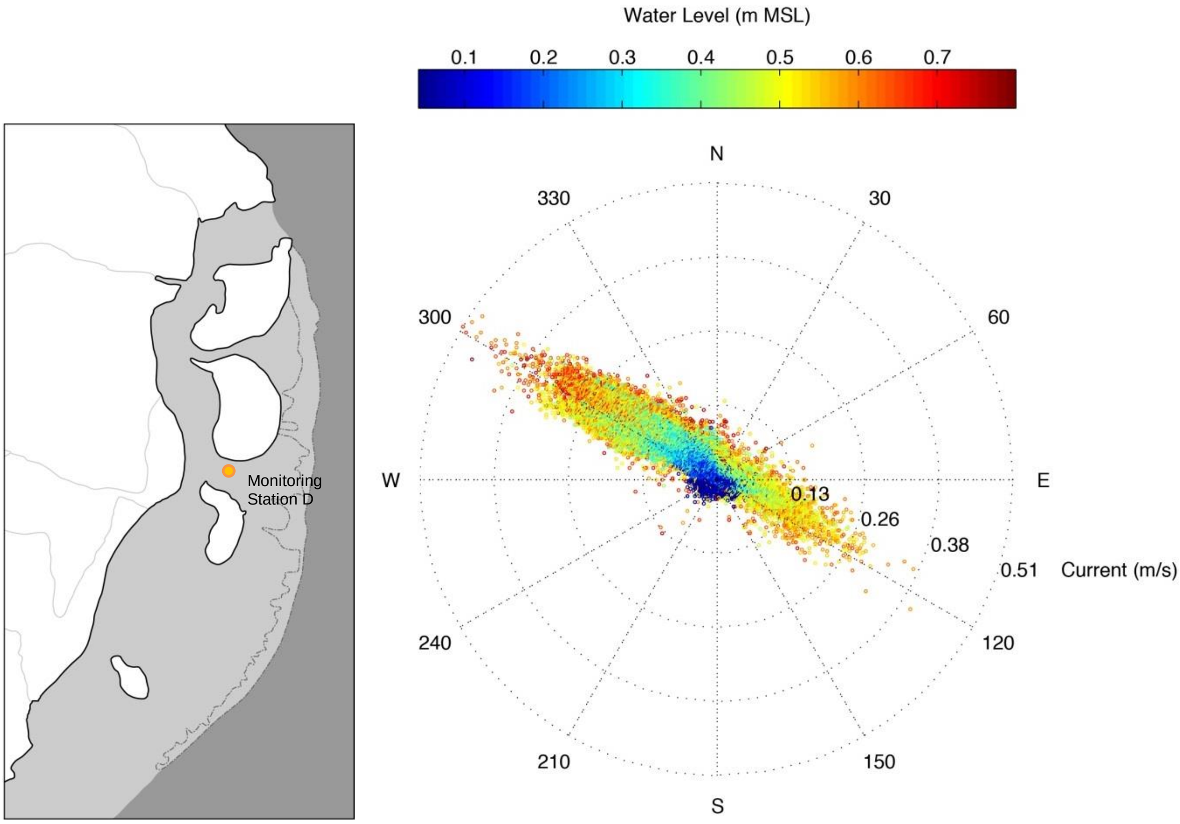


Figure 4.10: Scatterplot of current speed, heading and water level for Monitoring Station D

Consideration of the time series of current data (Appendix B4) shows, that for the vast majority of time, currents at Monitoring Station D move west and flow into the main channel. On occasion for short periods of several days, currents reverse and flow from the channel back toward the outer reef. These occurrences appear to be linked with the onset of large wave conditions on the outer reef and the rapid pumping up of lagoon water levels, however, such wave events did not always result in flow reversals at this location. It is likely a particular combination of wave, water level and tidal fluctuation that results in the flow reversals through this channel, though no clear correlation could be determined to date.

4.2.6 Currents at Monitoring Station E

The full time series plots of current data from Monitoring Station E (in the small channel between Oneroa and Motutapu) are provided in Appendix B5, and have been summarised into a current rose plot in Figure 4.11. It can be seen from these plots that at Monitoring Station E, currents were generally:

- Unidirectional with flows moving from the outside of the motu toward the west and joining the main channel;

- Very consistent with continuous current velocity of at least 0.3 m/s at all stages of the tide, all day, every day, and peaking with velocities up to about 0.6 m/s;
- Closely correlated with lagoon water level, with higher water levels resulting in faster current speeds.

Whereas currents at all other monitoring stations tended to cease flowing at low lagoon water levels, currents at Monitoring Station E were incredibly continuous and absolutely unidirectional no matter the stage of the tide.

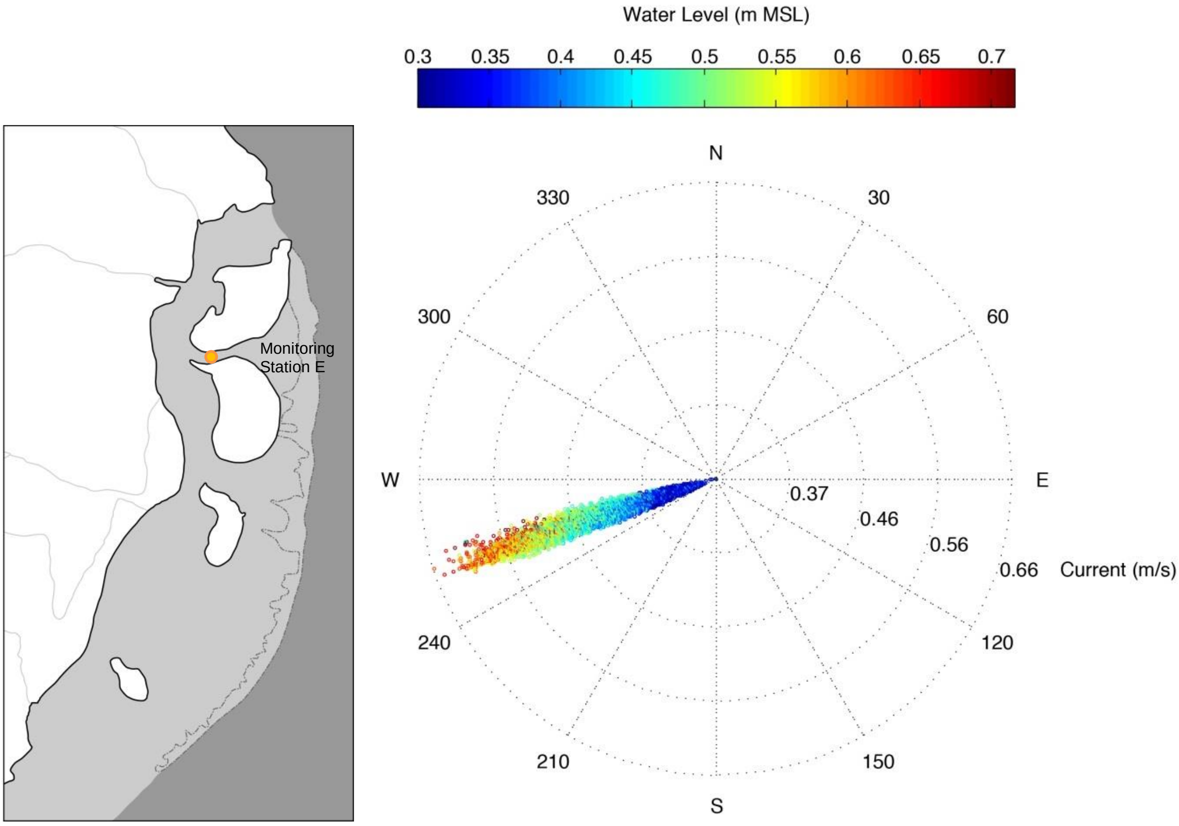


Figure 4.11: Scatterplot of current speed, heading and water level for Monitoring Station E

4.2.7 Currents at Monitoring Station F

Based on the analysis of current movements from the other monitoring stations, and the conceptual understanding of lagoon processes presented in Section 1.3, Monitoring Station F is located nearest the "outlet" for lagoon flows (Avana Passage). That is to say, that generally other incoming water enters and flows through the lagoon, before passing Monitoring Station F and returning to the ocean through the passage.

The full time series plots of current data from Monitoring Station F are provided in Appendix B6, and have been summarised into current rose plots in Figure 4.12 and Figure 4.13. The difference between the rose plots is that the observed currents are correlated with the local water level at Station F in Figure 4.12, whereas the currents are correlated with water level in the main lagoon basin (Station B) in Figure 4.13.

It can be seen from these plots that at Monitoring Station F, currents were generally:

- Quite unidirectional, with flows moving northward towards Avana Passage for the vast majority of the time;
- At low tide there is typically a period of slack water whereby there is very little flow either outwards (northward) or inwards (southward);
- Faster than observed elsewhere in the lagoon, with peak current velocities regularly exceeding 0.5 m/s during spring tides, and on occasion reaching almost 1 m/s during a period of pumped up lagoon water level;
- More closely correlated with water level in the main lagoon basin to the south, compared to the local water level in Avana Harbour at the northern end of the lagoon i.e. faster currents flowing at Station F occur when the water levels are high in the main lagoon, and are not really linked to water levels at Avana Harbour.

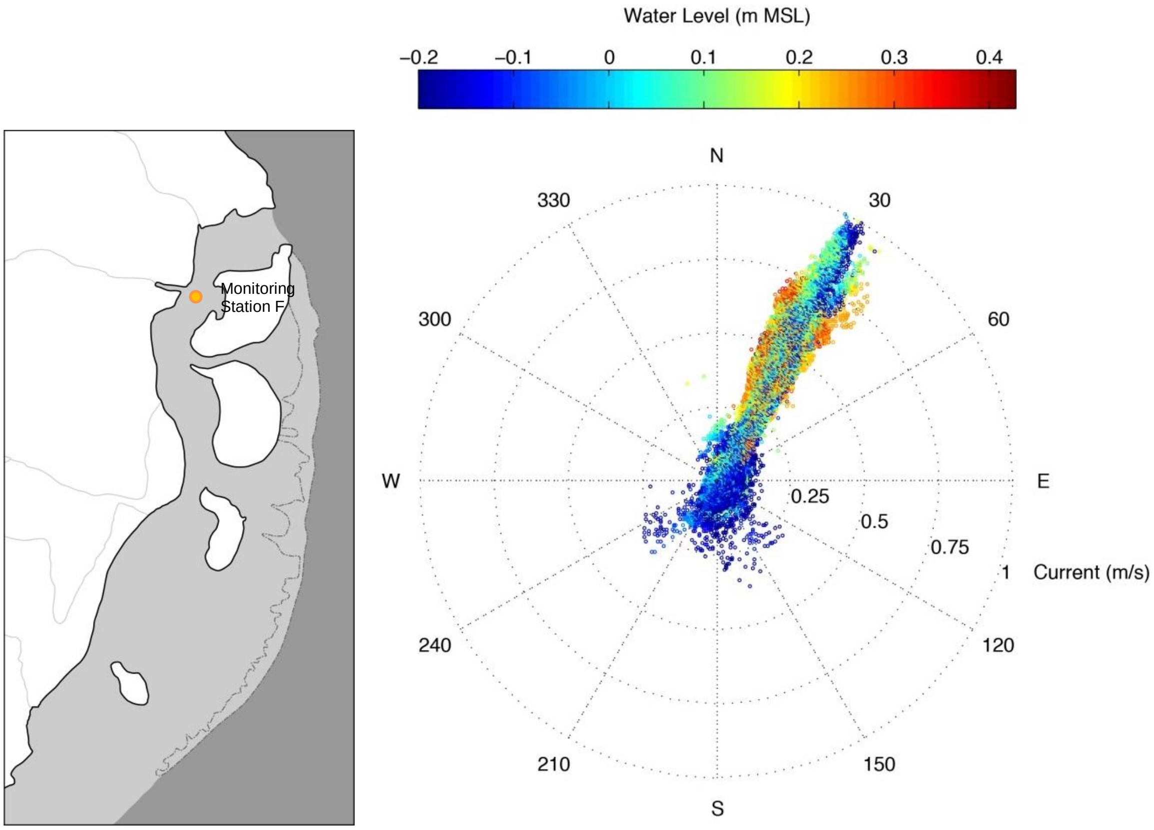


Figure 4.12: Scatterplot of current speed, heading and water level for Monitoring Station F (Water level is local water level at Station F)

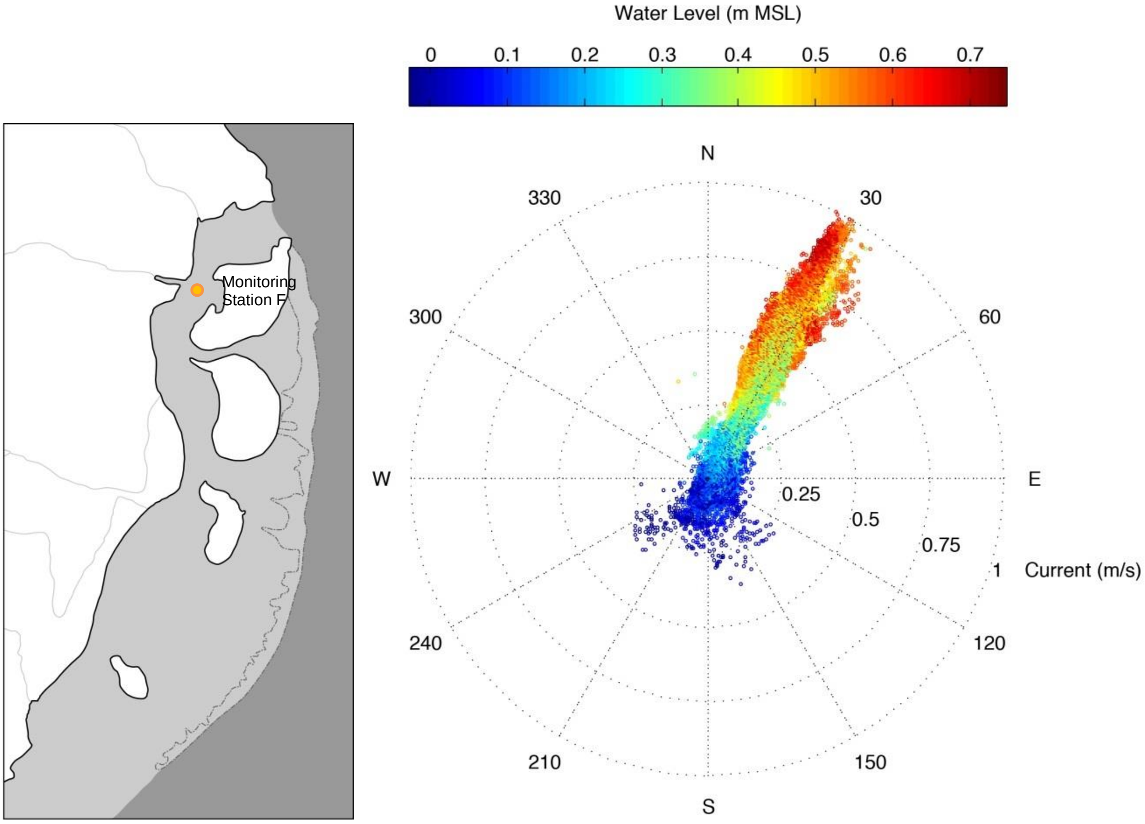


Figure 4.13: Scatterplot of current speed, heading and water level for Monitoring Station F (Water level is Muri Lagoon water level at Station B)

4.2.8 Flow Gauging Results

On the 9/04/2018 currents were measured across six cross-channel transects (see Map 10 for locations) multiple times throughout a near-complete tidal cycle (as discussed in Section 3.2.4). Profiles 1 to 4 were measured three to four times during the day, while currents at Profiles 5 and 6 in the Avana Harbour/Passage area were measured much more regularly. The results of the current profiling are summarised in Figure 4.14 and Figure 4.15, with the detailed results provided in Appendix D. During the current profiling data collection period, the ocean tidal range measured at Avatiu varied from approximately -0.15 m MSL at low tide to 0.15 m MSL at high tide (~0.3 m tide range), while the estimated local significant wave height along the Muri fringing reef was approximately 2 m (larger than the average wave height of ~1.4 m). There was also a considerable rainfall event at the time, with notable catchment runoff and stream flows entering the lagoon.

The gauged flowrates at the Avana Harbour and Avana Passage profiles (Profiles 5 and 6) throughout the monitoring period are summarised in Figure 4.14. During the low tide period, flows moved toward the ocean with a flowrate of approximately 18 m^3/s. Flows continued to increase throughout the monitoring period, peaking at approximately 53 m^3/s during the high tide peak. While the ocean tides were relatively low in range (neap) during the flow gauging, the wave height on the fringing reef was above average. This combination of tide range and wave height is estimated to have resulted in water levels in the Muri Lagoon basin ranging from approximately 0.25 m MSL at low tide up to 0.5 m MSL at high tide. While the tide range is more like a typical neap tide range for the lagoon, the additional pumping of lagoon water levels by the above average wave conditions at the time, meant that the lagoon high tide water level was actually more like a typical spring high tide level. This is supported by the current speeds measured at the continuous Monitoring Station F during the corresponding high tide peak, which reached approximately 0.5 m/s, a relatively typical value for spring high tides during average wave conditions (see Appendix B).

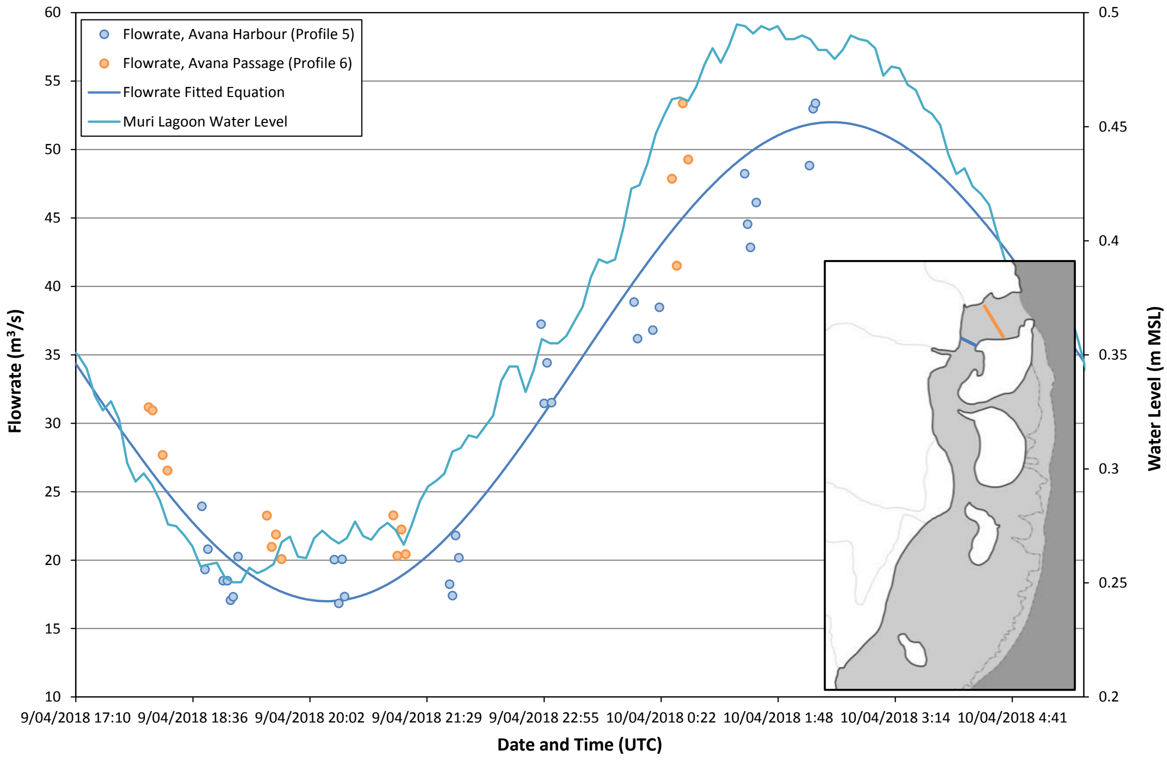


Figure 4.14: Gauged flowrates exiting Avana Harbour and Passage

Using a sine function as an approximation of the flowrate recorded to be moving through Avana Harbour and Avana Passage (dark blue line in Figure 4.14):

- It is estimated that the total discharge volume during the complete tide cycle was of the order of 1.54 million m^3. This is considered to be typical of conditions when flows through the lagoon are driven by southerly waves, such that the effective lagoon area begins well south of Taakoka.

Based on the lower frequency current profiling undertaken at Profiles 1 to 4 during the gauging period, the distribution of flows measured to be moving through the various sections of the lagoon system are summarised in Figure 4.15. Due to the irregular and unsynchronised timing at which profiling was undertaken, these values are considered best estimates only, grouped into “low tide”, “mid tide” and “high tide” observation periods. There is a misclose in flows measured to be moving through the lagoon of up to 15%, which is associated with accuracy limitations in this kind of data collection, as well as the potentially significant and highly variable catchment runoff entering the system as ungauged inflows from creeks. Nevertheless this data provides a very good understanding of the relative distribution and magnitude of flows among the various lagoon channels, and is the first time such data has been measured for Muri Lagoon.

Figure 4.15: Approximate distribution of lagoon flows based on current profiling data recorded 9/04/2018

Note: The flows between Taakoka and Koromiri (indicated by the dashed line and italics) have been inferred as the difference in measured flows between the channel at Nukupure Field and the channel between Taakoka and the beach.

4.3 Summary and Discussion of Hydrodynamic Processes

The only previous recording and analysis of water level fluctuations in Muri Lagoon and Avana Harbour system were presented in Kirk (1980) and Holden (1992). Kirk (1980) presented concurrent water level/stage measurements with measurements of flow rate and currents for a period of one tidal cycle, all recorded near Avana Harbour. It has been shown in the present investigation that water levels in Avana Harbour (Monitoring Station F) are almost the same as open ocean tides, whereas water levels in all areas of the lagoon to the south of Aroko are in fact perched well above ocean tides. So while the short hydrodynamic data collection in Kirk (1980) did provide an indication of discharge from the lagoon through the passage, it provides little useful information regarding lagoon water levels or the hydrodynamic drivers of lagoon flows at Muri.

Holden (1992) also presented the results from a range of current metering and water level gauging at various locations around the lagoon. Water levels were recorded in the main channel adjacent Nukupure Park (labelled station 4 in the report, and equivalent to Monitoring Station C in this investigation). However the analysis of lagoon water levels was primarily undertaken for a de-trended data set (mean removed). This unfortunately precluded the analysis from identifying one of the key hydrodynamic drivers and the function of the lagoon.

It has been shown in this investigation that water levels in Muri Lagoon are perched well above ocean tides for the vast majority of time due to the process of wave breaking on the outer reef. Even during periods of lower than average wave energy, the lagoon water levels rarely drop below the mean sea level of the ocean. Figure 4.17 provides a summary of typical lagoon water level planes as a south/north long section through Muri Lagoon to Avana Passage, along with the bed profile of the lagoon along this section. This figure identifies the average water level, as well as high tide and low tide levels during spring and neap stages of the cycle, for average wave conditions.

It can be seen in Figure 4.17 that:

- The perched lagoon water levels create a notable hydraulic gradient from south to north through the lagoon. This gradient is the fundamental driver for the south to north flow of water through the lagoon that occurs for the majority of the time.
- Increased wave energy breaking on the reef acts to increase lagoon water level setup, which in turn steepens the hydraulic gradient and increases current flow through the lagoon.
- At high water levels (high tides and/or pumped up lagoon), there is a relatively continuous water level gradient south to north through the lagoon.

- At low water levels (low tides and small to average wave conditions), the shallow ridge in the main lagoon channel adjacent the northern end of Oneroa (Figure 4.16, Chainage 950 to 1,150 m in Figure 4.17), significantly restricts/retards drainage of the lagoon. This ridge has a crest elevation of around 0 to 0.05 m MSL and higher parts become emergent at low lagoon water levels.
- This restriction flattens the water surface gradient for areas to the south (including the main lagoon basin), and flows through the lagoon all but stop once the lagoon reaches a low tide level of around 0.05 m MSL. This is shown by the asymmetry in the lagoon water level records that occurs at low tide (Figure 4.5).

While the influence of large wave events on lagoon water levels was identified in Holden (1992), as well as the correlation between wave height and lagoon current speed, the continuous and always-present effect of waves on the perching of lagoon water levels was not well identified. While it is the effect of waves that dominate flushing of the lagoon, this is a somewhat indirect process. The waves themselves do not "push" faster currents through the lagoon, but instead act as a one-way pump that adds water into the lagoon. The radiation stress gradients that occur due to breaking waves at the reef edge generate significant setup of the lagoon water levels, and combined with the long drainage flow path to Avana Passage, result in "perching" of the lagoon. This higher lagoon water level and hydraulic gradient through the lagoon is actually the driver of currents through the system, as illustrated in Figure 4.18.

During periods of lower lagoon water level our analysis has shown that the ridge across the channel between Aroko and the northern end of Oneroa (Figure 4.16) forms somewhat of a control on lagoon hydrodynamics. This is the same area that was investigated in CCCI (2016), when they explored the impact of the former large fish trap on currents through the channel in this area, and the benthic mapping undertaken by MMR/SPC (2011) shows the area to be algae and rubble. With the more holistic data set that has been collected in the present investigation, it has been determined that south of this ridge the lagoon water levels are superelevated by wave setup, the tide range is reduced and the tide phase is lagged. Whereas north of this ridge, there is minimal wave setup and the tides are the same range and phase as the surrounding ocean.

CCCI (2016) found that despite the restrictions on currents from the former large fish trap across the channel, there was still reasonable currents moving through the channel and that flushing was adequate. Nevertheless the fish trap has since been removed. During their experiments the current speeds were measured at high tide, and the current speed averaged across the channel was consistent with current speeds at high tide recorded by the monitoring stations in the present investigation. However, the influence of this shallow section of channel is particularly important during periods of lower water level (low tide or low wave conditions), when the level of the ridge impacts drainage and flows through the lagoon.

Measured data shows that the lagoon almost never drains below the level of the algae-rubble ridge and that the drainage slows significantly as the water level approaches the ridge level. The water surface throughout the lagoon to the south of the ridge becomes flat, and there is no hydraulic gradient to drive flows through the lagoon. This process creates a temporary halt in lagoon flows until the tide begins to rise again.

Figure 4.16: Exposed algae/rubble ridge spanning across the channel at Aroko during very low water level

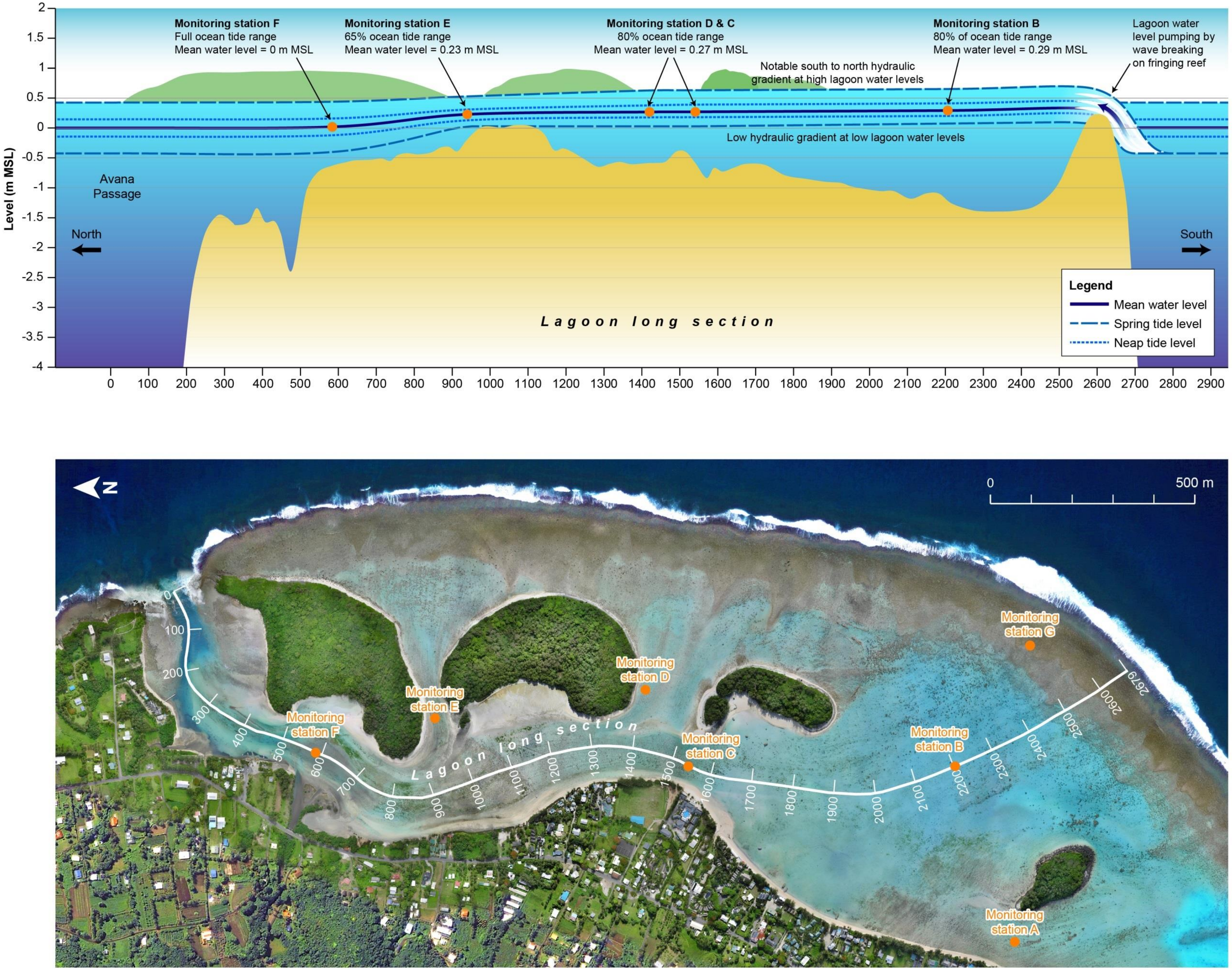


Figure 4.17: Long section of lagoon water level characteristics

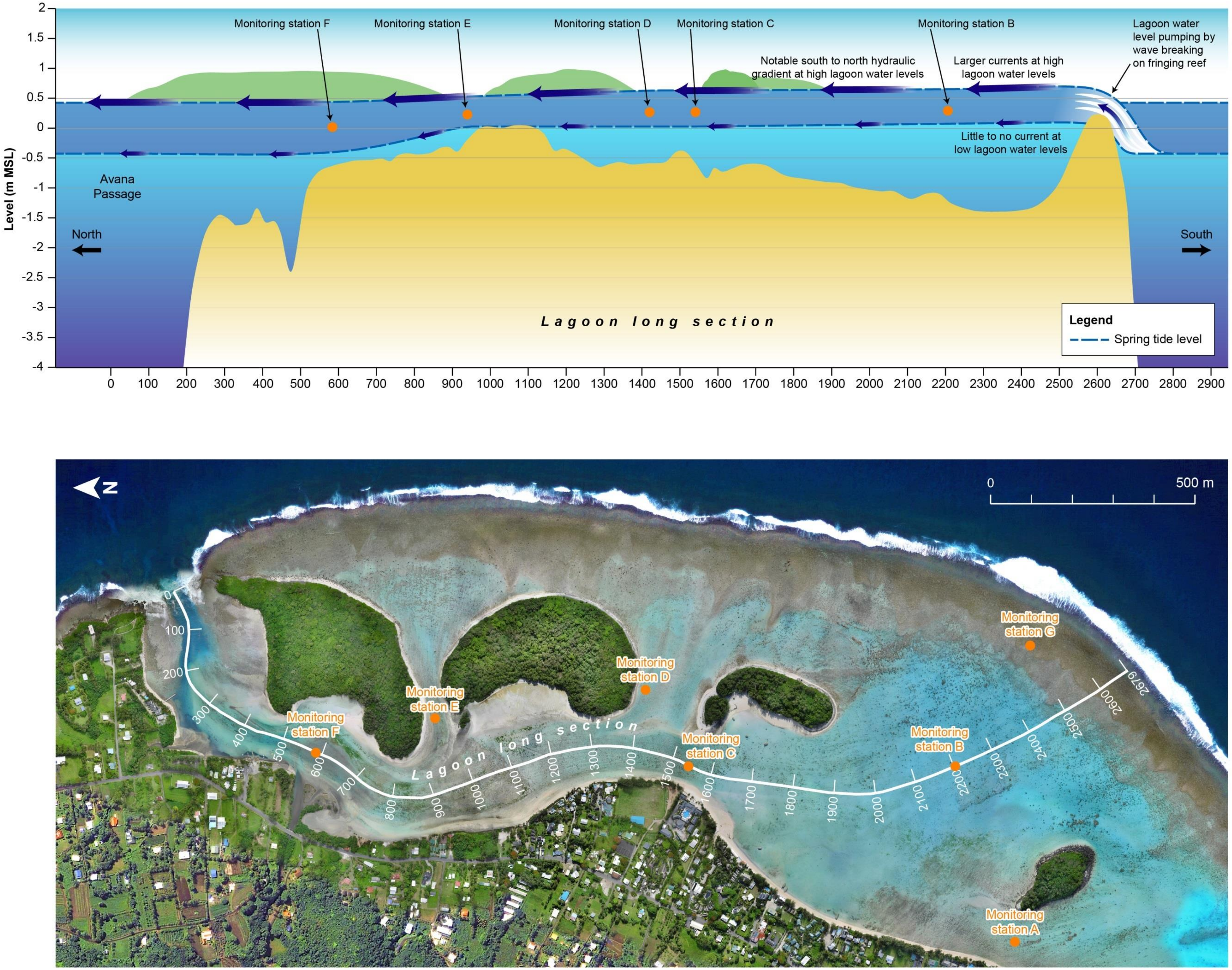


Figure 4.18: Long section of lagoon current characteristics

In Section 4.2 it was identified from the current meter data that the current speeds through the lagoon are closely linked to lagoon water level at all of the continuous monitoring sites. Figure 4.19 provides a summary of scatter-plots of current speed observations versus water level for all monitoring stations. This summary highlights two key hydrodynamic characteristics:

- Higher lagoon water levels undoubtedly result in faster current speeds;
- Once lagoon water levels drop to around 0.1 m MSL, there is very little movement of water through the lagoon, despite the ocean water level (and water level in Avana Passage) still being some 0.2 to 0.3 m lower than the lagoon water level at these times.

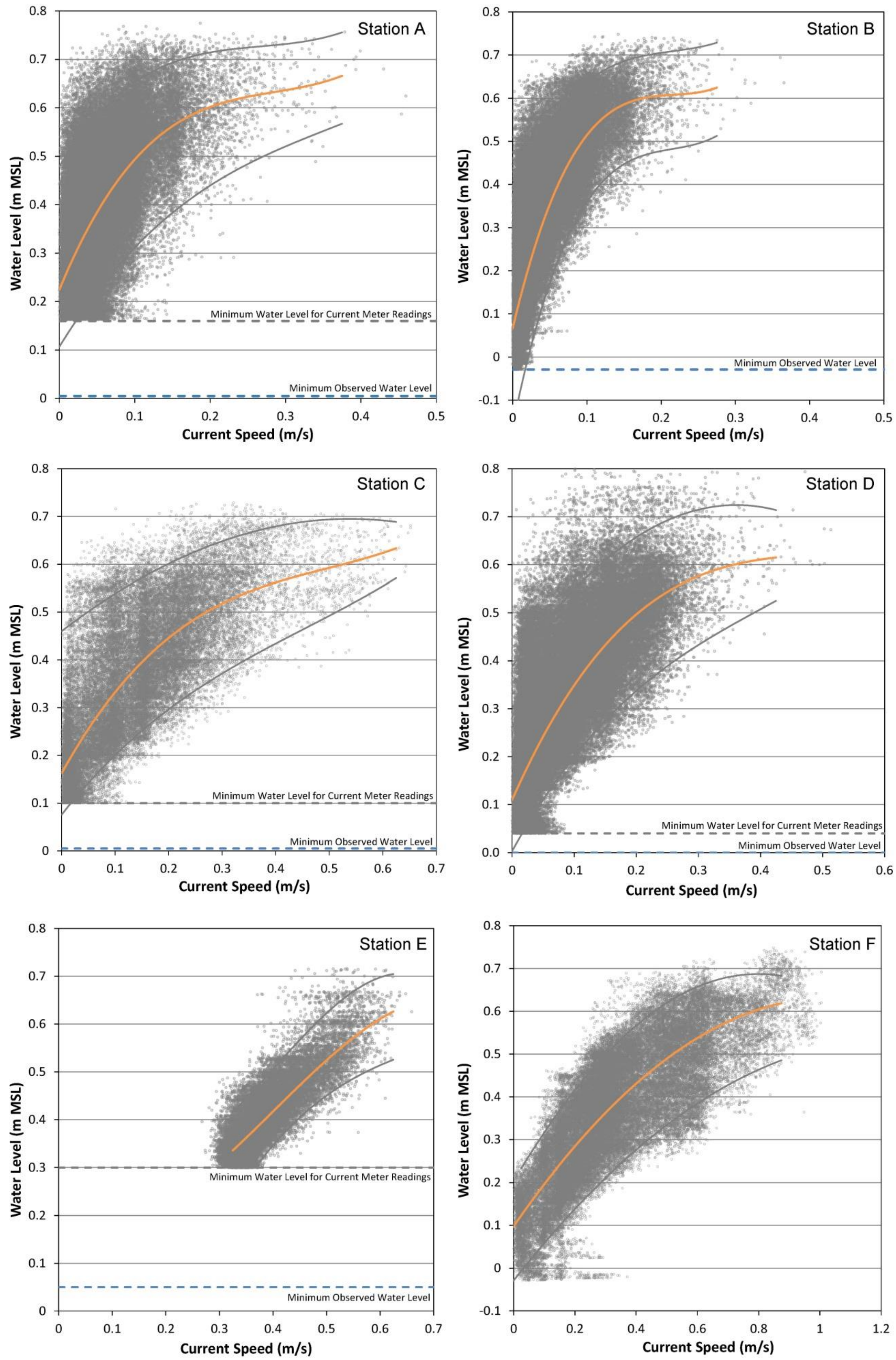


Figure 4.19: Relationship between current speed and lagoon water level

Detailed analysis of the synchronised current meter, water level and wave data allow a number of very discreet hydrodynamic nuances to be ascertained for the lagoon. From this analysis it can be concluded that the hydrodynamic behaviour of the lagoon largely operates between two different modes:

- *Mode 1: Typical behaviour, south-westerly to south-easterly offshore wave direction*: Rarotonga is typically impacted by wave conditions which approach the island from the southwest to southeast quadrant (WACOP, 2016; WRL, 2018). These conditions result in higher lagoon water level setup along the southern coastline, with wave energy and setup decreasing south to north along the Muri coastline. The typical lagoon function under these wave conditions has currents moving from south to north, driven by the gradient in lagoon water level setup. The lagoon currents likely originate in the Tikioki Beach area and move northward through Muri, before discharging through Avana Passage. As has been shown from the observed data, currents are notably higher at more elevated lagoon water levels such as high tide or periods of additional lagoon setup.

- *Mode 2: A-typical behaviour, westerly through northerly to easterly wave direction*: On less frequent occasions when offshore wave conditions approach Rarotonga from west, north or northeasterly directions, the behaviour of the lagoon notably differs from the norm. During these conditions the currents in the main lagoon basin show more discreet behavioural trends, transient in nature and at times becoming divergent in direction. During the incoming tide currents tend to move south to north through the lagoon basin, though at a lower velocity than typical. On the falling stage of the tide, currents tend to rotate, initially moving onshore and progressively turning southward past Taakoka as the tide falls. During these conditions it is hypothesised that the net movement of water through the main lagoon basin is significantly reduced. Water moving through the lagoon basin also becomes divergent, with some flow continuing north toward Avana through the main channel at high tide, while other portions of flow move south past Taakoka toward Titikaveka. An example of these lagoon hydrodynamic characteristics can be seen in the data from 5th to 7th March 2018.

The magnitude, and in some cases direction, of currents differs throughout the tide cycle for both modes. Figure 4.20 and Figure 4.21 illustrate the two simplified lagoon hydrodynamic modes for low and high water levels.

Figure 4.20: Indicative current patterns for lagoon hydrodynamic mode 2 (southwest to southeast wave directions)

Figure 4.21: Indicative current patterns for lagoon hydrodynamic mode 2 (west through north to northeast wave directions)

With the significantly more accurate bathymetric survey of the lagoon undertaken for this project (Section 2), and an improved understanding of the lagoon areas that form part of the hydrodynamic system, it is now possible to also develop an improved estimate of the effective lagoon volume and flushing. An analysis of the depth-volume relationship for various areas of the lagoon system is presented in Figure 4.22 and Table 4.2. The lagoon system was considered in three separate areas based on the hydrodynamic characteristics (see inset map within Figure 4.22):

1. The section of main lagoon channel, Avana Harbour and Avana Passage areas, north of the shallow ridge across the main channel to Oneroa. This area is hydrodynamically different to the remainder of the lagoon system, as it experiences full ocean tides and very minimal wave driven setup (dark blue area in figure);
2. The section of fringing reef, main channel and inter-motu channels north of Koromiri. This area is shallow, experiences modest wave setup and wave driven currents, and almost always drains to the north through Avana Passage (yellow area in figure).
3. The main Muri Lagoon basin. This area is typically deeper, has lower flushing rates but higher wave setup, and the hydrodynamics are more sensitive to other drivers such as wave direction. The area typically drains from south to north through Avana Passage and during these conditions the lagoon likely extends as far south as Tikioki Beach. However, during certain wave conditions the area drains both south and north from Muri at varying stages of the tide (green area in figure).

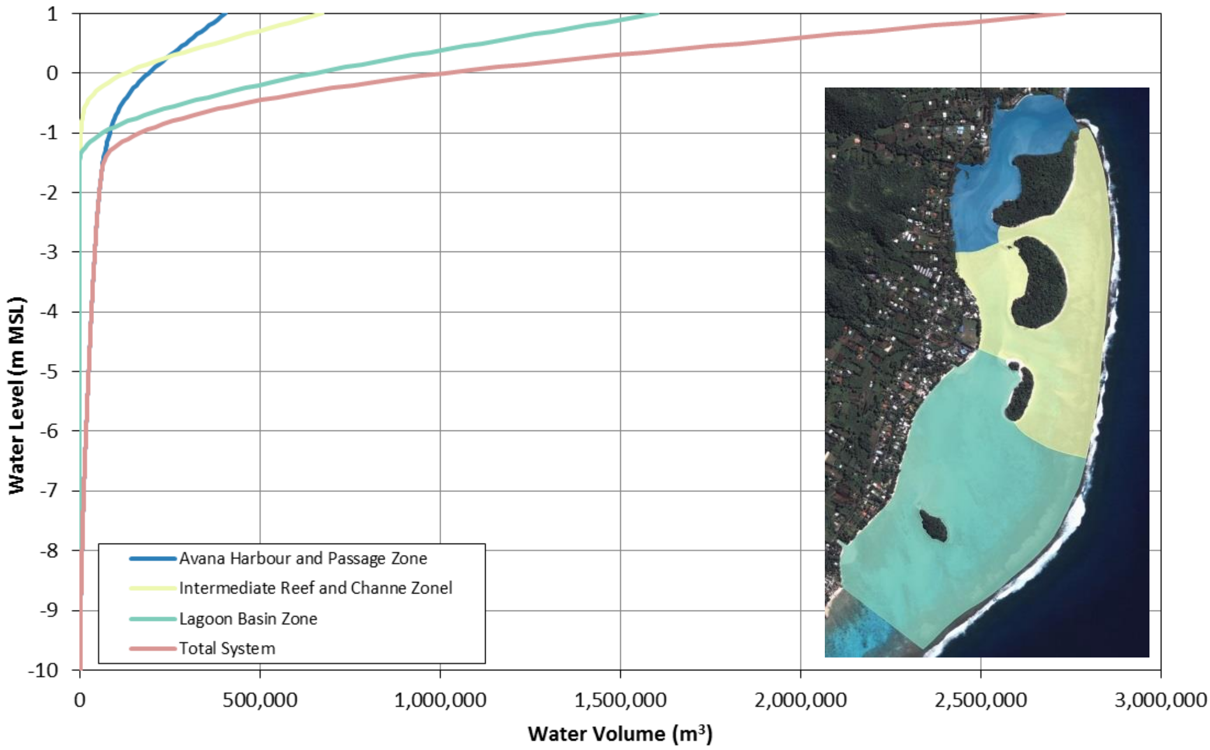


Figure 4.22: Analysis of lagoon volumes

Table 4.2: Volumetric analysis of Muri Lagoon and Avana Harbour system

Lagoon Zone	Spring Low Tide Level (m MSL)	Spring High Tide Level (m MSL)	Volume Below Low Tide (m^3)	Volume Below High Tide (m^3)	Intertidal Volume (m^3)
Avana Harbour/Passage	-0.43	+0.43	126,180	277,680	151,500
Int. Reef & Channel	-0.20	+0.53	67,690	389,840	322,150
Lagoon Basin	0.07	0.68	759,720	1,334,420	574,700
Total	-	-	953,590	2,001,940	1,048,350

From the volumetric analysis it is clear that the vast majority of the lagoon system volume occurs at relatively shallow water depths, in areas where the seabed is above -1.5 m MSL. While the Avana Passage zone is relatively deep, it contributes only a fraction of the system's total volume. in contrast, the main lagoon basin area south of Nukupure Field and Koromiri contains the majority (two thirds) of the system's volume. In total the lagoon system (combination of all three areas in Figure 4.22) is estimated to have a volume of up to 2 million m^3 at high tide, during typical wave conditions, and an intertidal volume of approximately 1 million m^3. The volumetric analysis of the lagoon combined with the hydrodynamic data set, provides a range of insights into the flushing characteristics of the various lagoon zones:

- The volume of water measured to pass through Avana Passage in a typical tide cycle is approximately equivalent to the total mid-tide volume of water in the overall system;
- Approximately 50% of the overall system volume is within the intertidal zone. This means that at least half of the water volume is exchanged every tide cycle by the rise and fall of the tide, regardless of the wave driven flushing;
- More than 10 times the volume of water in the Avana Harbour/Passage moves through the passage in a typical tide cycle, so this area is considered to be very well flushed;
- The vast majority of water in the intermediate reef/channel zone north of Koromiri is within the intertidal range, and this area is therefore also very well flushed;
- It can be estimated that 1 to 1.2 million m^3 of water flows northward through the main lagoon basin in a single tide cycle during typical conditions. This is almost equivalent to the total volume of the basin at high tide. It can therefore be assumed that water in most parts of the lagoon basin are exchanged every one to two tide cycles.
- At a conservatively low average flow rate of 10 m^3/s the total main lagoon basin volume would be exchanged in 30 hours. This is a lower flow rate than the minimum measured to be passing through the channel at Nukupure Field at any stage of the tide cycle.

Alternatively, at the peak measured high tide flow rate of 36 m^3/s the lagoon would be flushed in around 8 hours.

It can therefore be concluded that the vast majority of the Muri Lagoon and Avana Harbour system is very well flushed. During typical conditions it can be expected that water from the majority of the main lagoon basin is exchanged at least once per day, though there may be periods when the lagoon flushing rate temporarily reduces due to lower wave conditions, and during these periods it may take several days to exchange the water volume. A notable area of lagoon that regularly experiences lower water movement and reduced flushing is the zone immediately north of Taakoka and adjacent the nearshore stretch of Muri Beach up to the Pacific Resort. Water does still move through this area (i.e. it is not a stagnation zone), though at reduced rates compared with the main flow paths through the lagoon basin and the channel. This is not considered to be a new characteristic that has developed due to a change in hydrodynamics, but is more likely associated with the general arrangement of this section of the lagoon.

5 Comparison of Current and Past Analysis of Hydrodynamics

Holden (1992) presents the results of the main previous hydrodynamic investigation of the Muri Lagoon and Avana Harbour system. This investigation included a range of hydrodynamic measurements such as:

- Water level gauging at a monitoring station located adjacent Nukupure Park (equivalent to Monitoring Station C in the present investigation;
- Simultaneous current metering at a location in Avana Passage and at a location in the channel adjacent Nukupure Park, for several weeks;
- Non-simultaneous current metering at a location between Koromiri and Oneroa for a short period of 30 hours;
- Non simultaneous current metering at a location in the main channel adjacent the southern end of Motutapu for a period of 16 hours;
- Drifter drogue deployments in the main lagoon basin.

Kirk (1980) also presents results from a short period of flow gauging at Avana Passage.

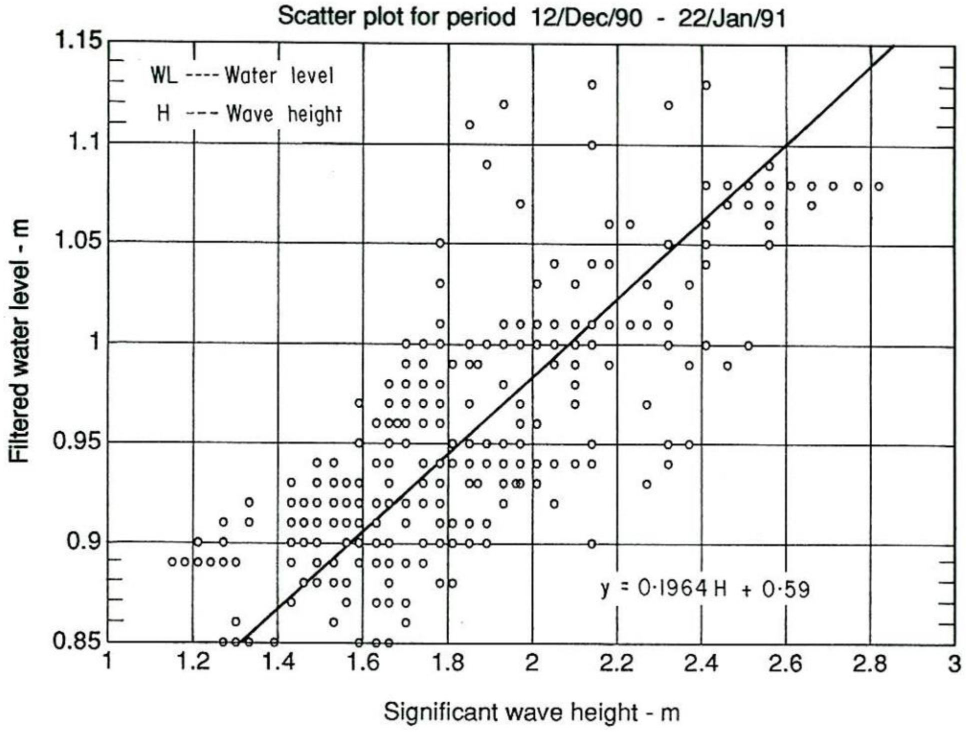
In this section of the report we compare a range of hydrodynamic indicators to ascertain if there have been any obvious changes to the hydrodynamics of the system between the previous investigations in the 1980s and 1990s, and this investigation some 20 – 30 years later.

5.1 Analysis of Historical Water Level Measurements

While it has been identified in this investigation that there is very little lag between tides in Muri Lagoon and ocean tides at Avarua/Avatiu (about 15 minutes at low tide and negligible at high tide), Holden (1992) reported a lag of around 50 minutes. Other than synchronisation issues with instrumentation, it is unclear why this conclusion was found in the previous investigation. It is considered very unlikely that the physical processes controlling tide fluctuations in the lagoon would have changed.

In this investigation the tide range in the main lagoon basin was estimated to be 80% of the Avatiu tide range, while the tide range between Oneroa and Motutapu was 65% of the Avatiu tide range. Though not explicitly reported in Holden (1992), the lagoon tide range recorded in the channel adjacent Nukupure Park during the 1992 monitoring period was estimated to be at least 70% of the tide range recorded at Avarua during the same period. It is therefore considered likely that there has been very little change in tidal range in the main lagoon basin over the past 30 years.

Consistent with the present investigation, Holden (1992) identified a clear correlation between wave height and lagoon water level setup. In the previous investigation, lagoon water level setup was correlated against wave height from a deep water wave buoy moored off the south-eastern coast of Rarotonga. For the purpose of comparison with the historical data, we have replotted the non-tidal lagoon water level component (setup) measured during the present investigation, against predicted deep water significant wave height off the south-eastern coast of Rarotonga. The two plots are shown in Figure 5.1 for comparison, and both include a linear trend line for the relationship between water level setup and wave height. Both the present and historical data sets show very good agreement for this relationship. This provides a high degree of confidence that the wave driven water level setup at Muri Lagoon, which is the main driver of lagoon currents and flushing, has changed very little in the past three decades.



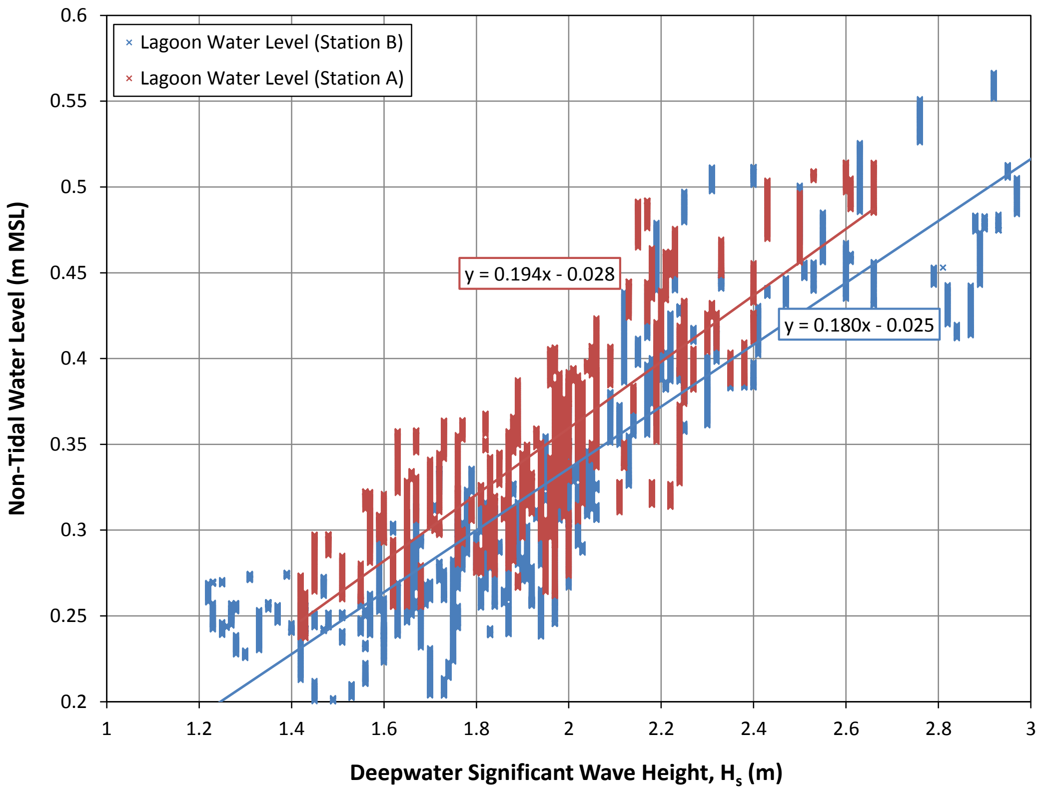


Figure 5.1: Comparison of present and historical relationship for wave setup at Muri (Note: there is a vertical datum difference between data plots)

5.2 Analysis of Historical Current and Flow Measurements

Holden (1992) analysed currents measured in the channel adjacent Nukupure Park. The summary rose plot of this current data has been reproduced in the left of Figure 5.2, while the currents measured at a similar location in the present investigation are shown in the right of Figure 5.2. The number of directional bins is slightly different between the plots, nevertheless it is apparent that the currents have a very similar dominant direction, directional distribution and range of velocities. The only notable difference is that in the historical data set, very low speed currents moving south-southwest back into the lagoon basin appeared to occur for a greater percentage of the time compared with the present investigation. In actual fact these current reversals typically only occur at very low water levels, and in most instances this portion of the data has been filtered from the present investigation as it was below the minimum water level limit for the current meter. As such this difference is more likely an artefact of measurement technique and not a change in physical processes.

This indicates that, within measurable limits and the natural range of currents at this site, the key characteristics of currents leaving the main Muri Lagoon basin through the channel adjacent Nukupure Park are unlikely to have changed to any notable amount in the past three (3) decades.

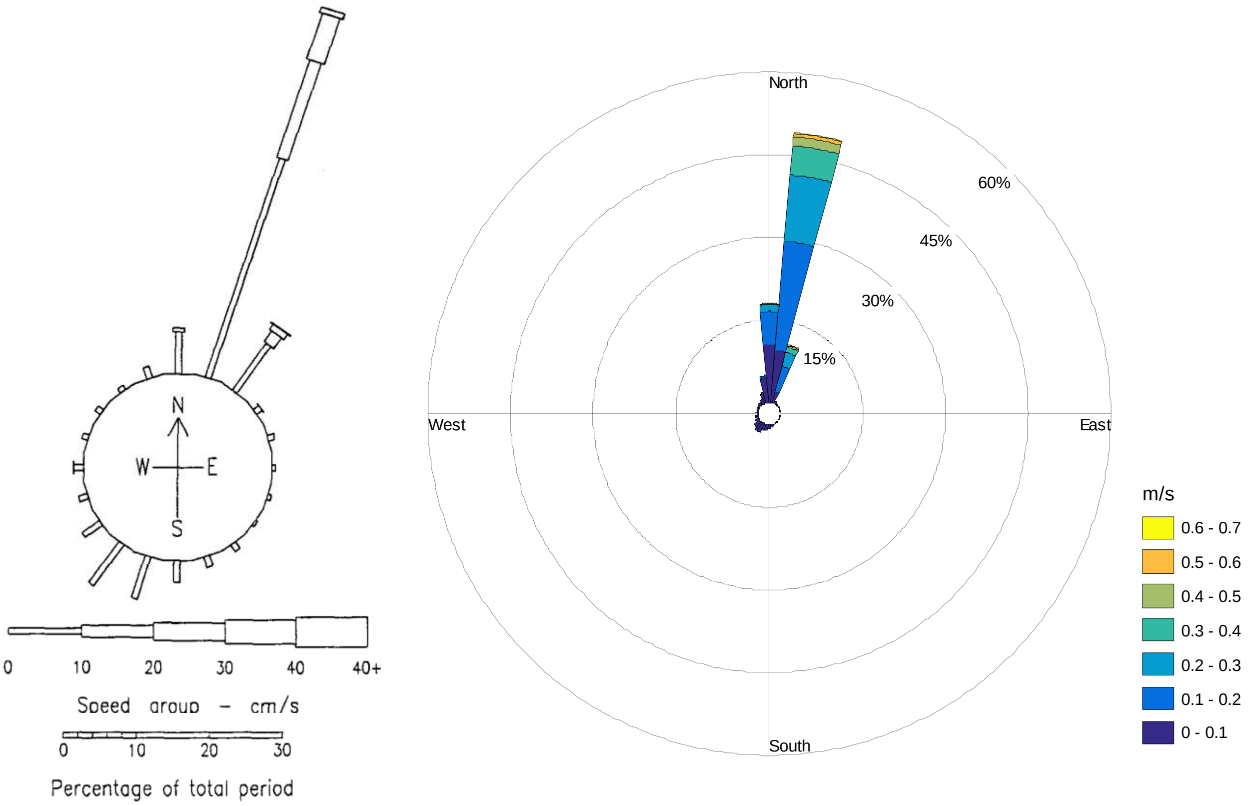


Figure 5.2: Comparison of historical and present currents at Monitoring Station C

Holden (1992) also presented measurements taken using drifter drogues in the main lagoon basin on two separate occasions. The results of the drifter experiments are reproduced in Figure 5.4 and Figure 5.5. During the first deployment, the drifters moved through the lagoon basin toward Muri Beach at a speed of the order of 0.03 to 0.1 m/s. In contrast to this, during the second deployment the drifters moved north toward Koromiri, before moving on the eastern side of the motu. Interestingly these two alternative current patterns in the main lagoon basin have also been observed in the present investigation, and are indeed consistent with the modes of lagoon hydrodynamics presented in Figure 4.20 and Figure 4.21. Likewise the currents measured during the historical drogue deployments are very plausible when considered against the rose plot of currents from Monitoring Station B in the present investigation, which was located in a similar position to the drogue releases (Figure 5.3).

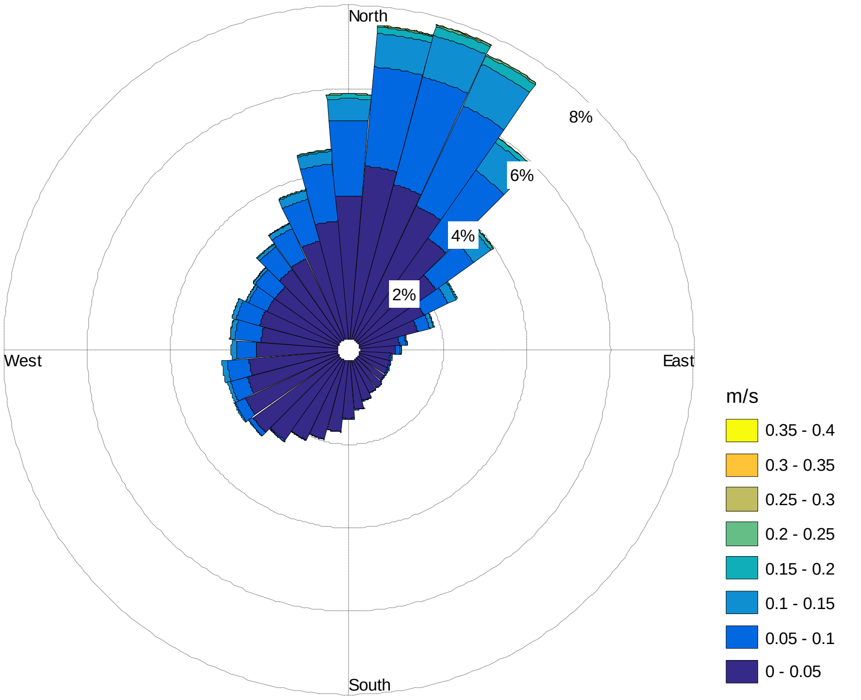


Figure 5.3: Rose plot of currents measured at Monitoring Station B in present investigation

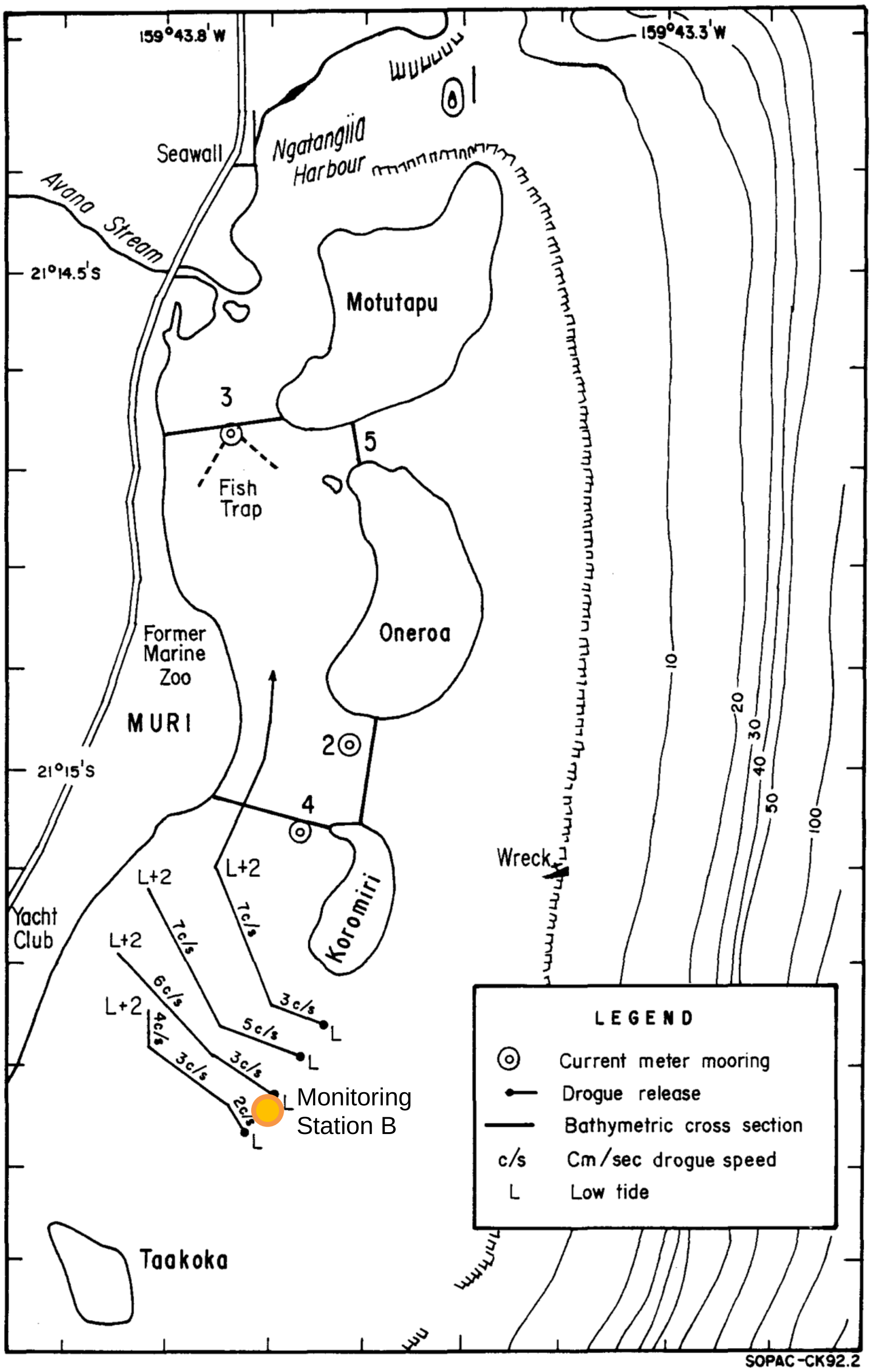


Figure 5.4: Historical drogue current measurements from Holden(1992)
Measurements taken on 10/12/1990, with deep water H_s = 2.4 m
(Location of Monitoring Station B in present investigation is overlayed)

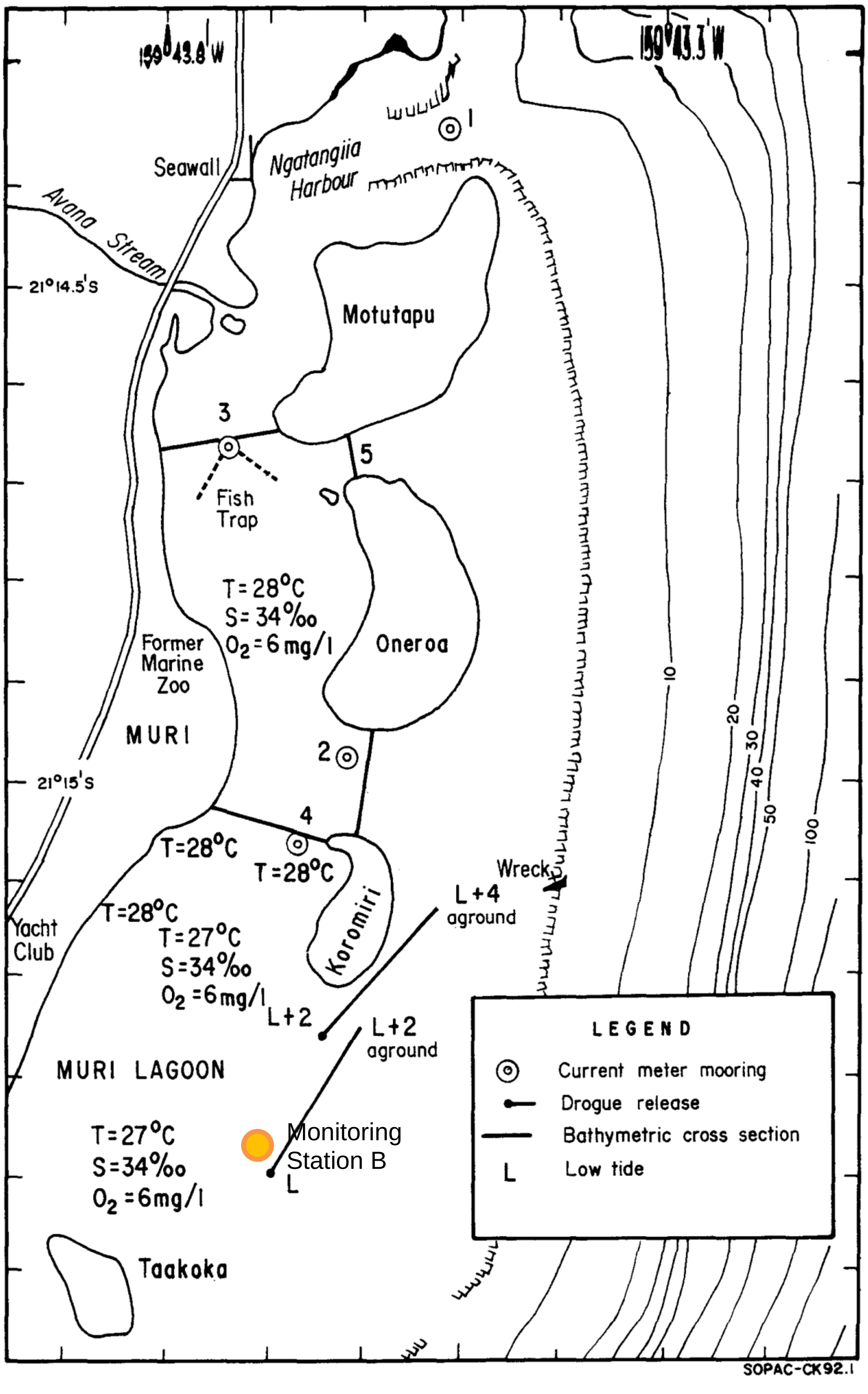


Figure 5.5: Historical drogue current measurements from Holden(1992)
Measurements taken on 24/01/1991, with deep water H_s = 2.5 m
(Location of Monitoring Station B in present investigation is overlayed)

Kirk (1980) presented the results of current metering at Avana Harbour for one complete tide cycle, undertaken on 8/12/1979. This data is able to be compared with the current metering and flow gauging completed in the present investigation on 9/04/2018 (Figure 5.6). Whereas the present flow metering was undertaken by continuously profiling velocities at many points in the water column across the complete channel cross section using a modern ADCP instrument, the historical gauging was undertaken by timing the movement of dye dropped in the water. The modern technique is expected to be significantly more accurate at capturing the spatial and temporal variation of flows across the channel cross section compared with the historical method, and this should be considered when comparing the data sets.

Despite the differences in measurement technique, there are a number of valuable observations that can be taken from this comparison:

- The peak flow measured at high tide was estimated to be quite similar but slightly higher in the historical gauging compared with the present investigation. Nevertheless the difference is expected to be within the range of peak flows that would occur on any given day with varying waves and tides.
- The minimum flow measured at low tide was incoming at around 5 m^3/s in the historical gauging (i.e. flow coming back into the harbour from the ocean), compared with around 15 m^3/s outgoing in the present investigation. Velocity measurements taken at Monitoring Station F (Appendix B) indicate that depending on the wave climate, typically slack water or slightly incoming flows to Avana Harbour do still regularly occur at low tide, though on occasion the flow continues out to sea throughout the complete tide cycle. It is therefore likely that this difference between historical and present investigations is simply a result of the difference in wave climates at the time of data collection.
- Despite having a slightly lower peak discharge, the total flow out to sea through the passage during the complete tide cycle was estimated at 1,540,000 m^3 during the present investigation, compared with 960,000 m^3 in the historical data collection.

Given the natural variation in flow regimes that occur as a result of varying wave and tide conditions, this comparison suggests that there has not been a dramatic or measurable change to the overall flows exiting the system through Avana Passage. From the available data it is reasonable to conclude that peak flow rates moving out of the system through Avana Harbour and Passage are unlikely to have changed considerably in the past 40 years, and any changes would be within the natural range of variation.

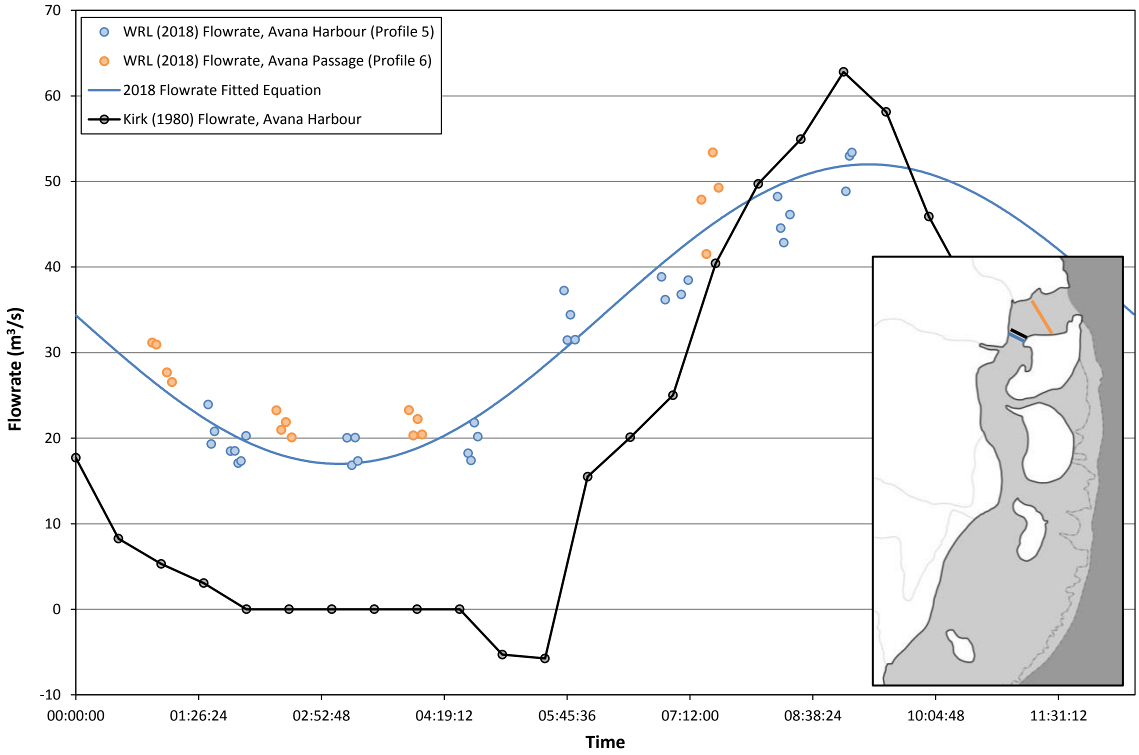


Figure 5.6: Comparison of flow gauging results at Avana in 2018 and 1979

6 Numerical Modelling

6.1 Model Overview

On the basis of our detailed understanding of drivers for lagoon hydrodynamics from analysis of the field data, it was considered that the most suitable modelling approach within project constraints would be a hybrid of various custom developed and site-specific empirical formulations, combined with several numerical modelling tools. This approach helped to overcome the limitations that would exist if a single numerical modelling package was selected to simulate all processes, as no single modelling package is able to simulate all of the complex hydrodynamic processes well. An overview of the modelling approach is provided in Figure 6.1.

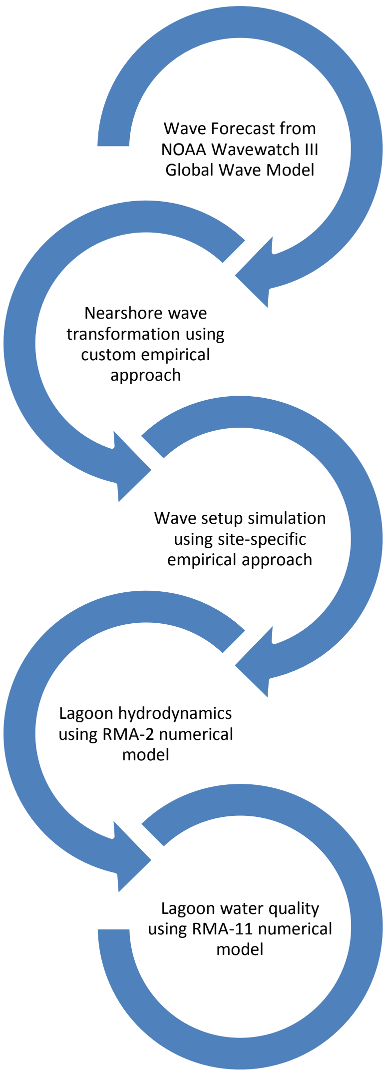


Figure 6.1: Components of modelling approach

6.1.1 Waves and Wave Setup

The initial step of the model development was to acquire forecast estimates of the wave conditions in deep water in the vicinity of Rarotonga. This forecast was sourced from the Wavewatch III global grid numerical wave model operated by NOAA (Tolman, 2009). This model provides a 6 hourly forecast of wave conditions on a coarse grid, and the forecast at the nearest four grid points to Rarotonga were used (Figure 6.2). At each 6 hourly time step, the forecast at the point nearest where the most energetic waves were coming from was adopted as the best estimate of deep water wave conditions impacting the island.

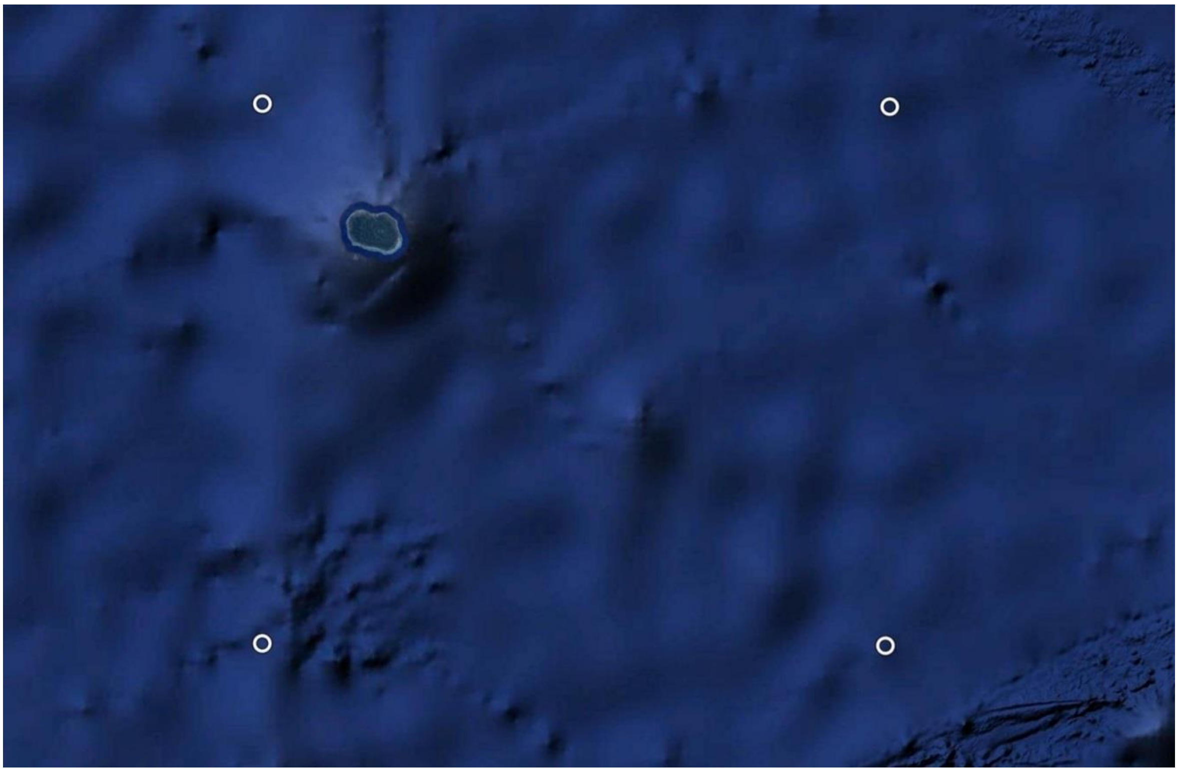


Figure 6.2: Output locations from NOAA Wavewatch III global wave grid

The forecast deep water wave conditions were then transformed to a nearshore wave prediction along the reef at Muri using a custom-developed empirical transformation. This transformation considered the sheltering effect of the island and the nearshore shoaling/refraction of waves as they approach the reef. The transformation was developed on the basis of the wave transformation modelling undertaken by the Geoscience Division of the SPC as part of the WACOP project (Bosserelle et al., 2015).

Within the WACOP project, a 34 year deep water wave hindcast for the period 1979 to 2013 was used (Durrant et al., 2013; Trenham et al., 2014) in combination with a nearshore fine resolution numerical wave model of the bathymetry around Rarotonga, to produce a hindcast of nearshore wave conditions for the same period at many locations around the island (Bosserelle et al., 2015). All nearshore wave data from SPC's 34 year hindcast was considered, and an empirical equation developed by WRL that best predicted the wave transformation from deep to shallow water for the nearshore locations at Titikaveka (southern end of study area) and Avana Passage (northern end of study area), as shown in Figure 6.3.

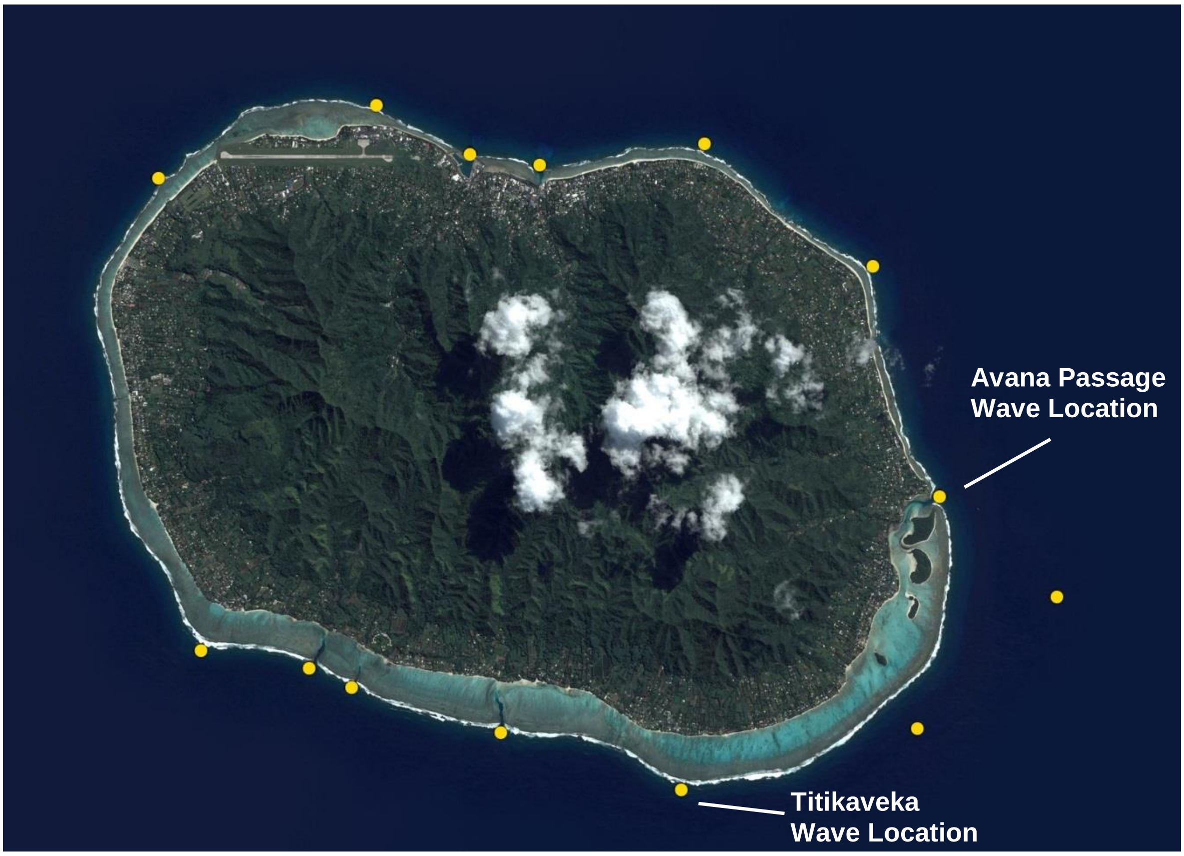


Figure 6.3: Output locations for nearshore wave transformation modelling Bosserelle et. al., (2015)

A correlation between the forecast nearshore wave conditions and the water level setup measured in Muri Lagoon during the field data monitoring period was made, and this analysis used to develop a site-specific relationship between nearshore significant wave height and lagoon water level setup. This relationship is shown in Figure 6.4 below. A 2^{nd} order polynomial relationship was selected for consistency with other published literature regarding water level set up on fringing reefs (example: Callaghan et al., 2006).

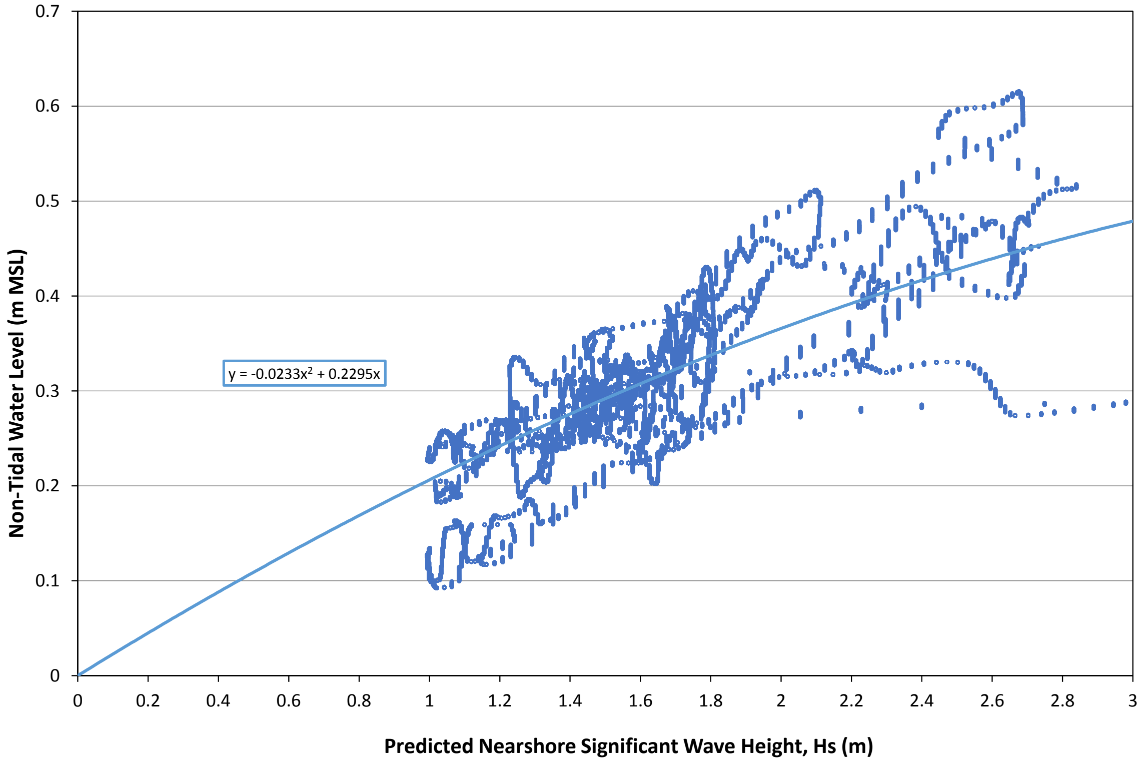


Figure 6.4: Relationship between nearshore wave height and lagoon wave setup

6.1.2 Lagoon Hydrodynamics

An RMA-2 numerical model (King, 2018; version 8.6a) of the reef and lagoon area was developed to simulate the hydrodynamics through the lagoon system, including fluctuations of water levels, currents and flows. RMA-2 is a two-dimensional depth-averaged finite element hydrodynamic model. The model covered the lagoon and reef area between Tikioki Beach at the southern extent and Avana Passage at the northern extent. The arrangement of the RMA-2 model is shown in Figure 6.5, and the progressive development of the model discussed in Section 6.2.

Figure 6.5: RMA-2 numerical model mesh

The RMA-2 model had a variable mesh resolution with higher element density in areas where more complex changes to hydrodynamics occur (such as in the channels around the motu), and lower element density in less complex areas (such as the main lagoon basin). The structure and density of the mesh can be seen in Figure 6.5. Hydrodynamic processes in the model were forced by two parameters:

- The effect of ocean tides; and
- The effect of wave breaking on the fringing reef.

At the northern end of the lagoon in the area of Avana Passage, an ocean tide water level boundary was applied (blue model boundary line in Figure 6.5). This was the same tide as observed or forecast for Avatiu, as it has been shown in the analysis of the field data sets that the ocean tides outside of the lagoon in the Avana area have the same phase and amplitude as Avatiu (Section 4.1.1). Along the fringing reef of the lagoon a separate water level boundary condition was applied that consisted of two components:

- The ocean tide fluctuation (same as the northern boundary);
- The effect of wave-driven water level setup, where the setup component was calculated using the relationship shown in Figure 6.4.

The two-part water level boundary on the fringing reef allowed for both temporal variation in wave setup due to changing wave conditions, as well as special variation in setup due to a gradient in wave energy along the Muri reef.

Within the model domain the bathymetric and topographic detail as measured in the project surveys (Section 2) was applied across the mesh. Each element was also assigned a roughness parameter on the basis of the bottom type and its effect on flows. The various roughness zones of the model are shown in Figure 6.6.

6.1.3 Lagoon Water Quality

The RMA-2 hydrodynamic model was extended to an RMA-11 model (King, 2018; version 9.0h) to simulate the movement of pollutants throughout the numerical model domain. RMA-11 is a finite element water quality model for simulation of three dimensional estuaries, bays, lakes, rivers and coastal regions. Constituents that can be represented include temperature, BOD/DO, the nitrogen cycle (including organic nitrogen, ammonia, nitrite and nitrates), the phosphorous cycle (including organic phosphorous and phosphates), algae growth and decay, cohesive suspended sediment, non-cohesive suspended sediment (such as sand), conservative constituents, and Coliforms.

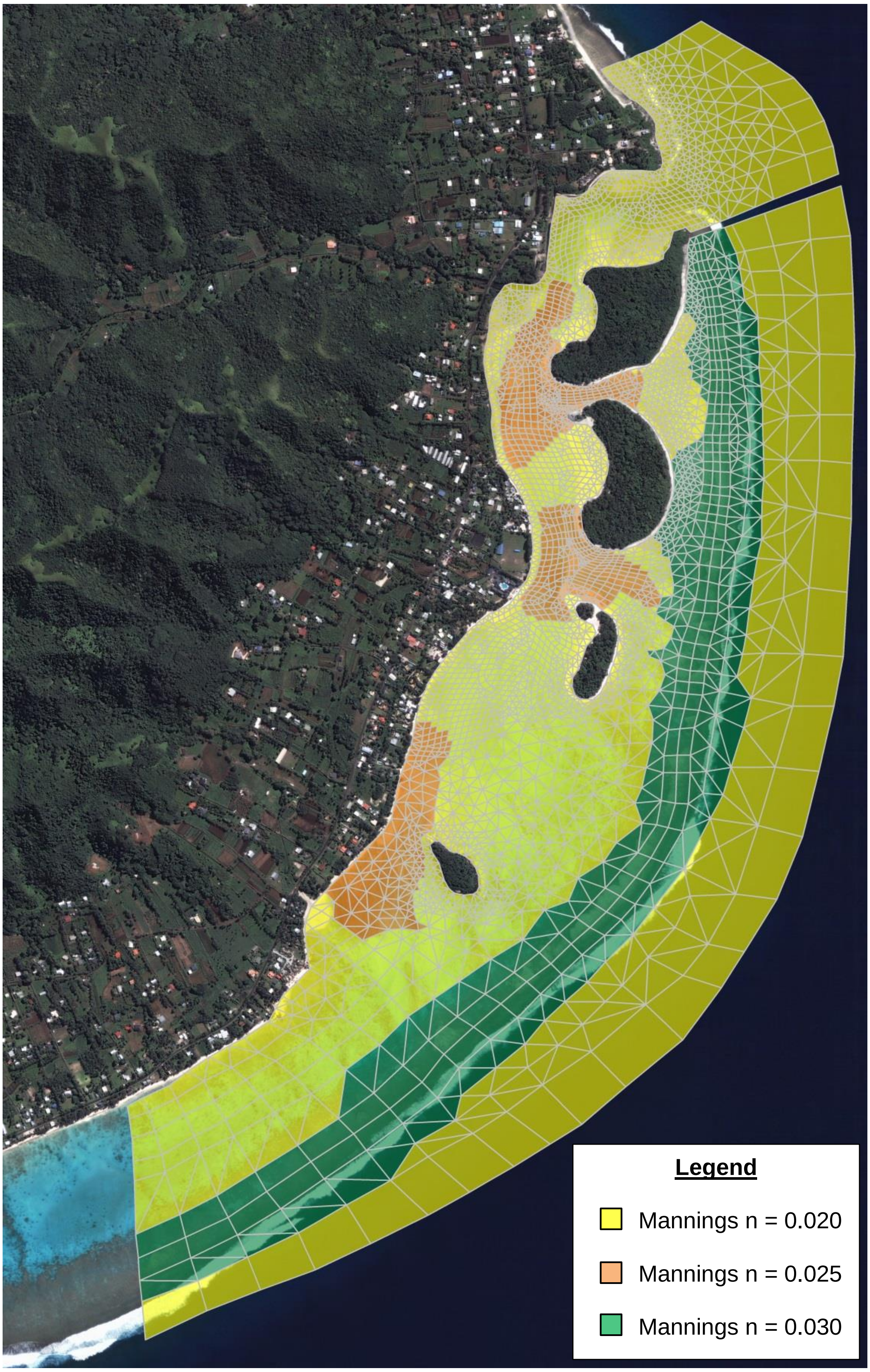


Figure 6.6: RMA-2 numerical model bed roughness zones

6.2 Model Development

The hybrid empirical/numerical model was developed so as to progressively increase its prediction skill and complexity through a series of steps, and in each case the time period spanning 9/02/2018 to 13/03/2018 was used as a calibration data set to evaluate the results of model changes. Model predictions for this period were compared against the measured data sets for both water levels and currents at the various measurement locations throughout the lagoon (Map 09). The series of model improvements and changes are summarised in Table 6.1.

Table 6.1: Progressive Steps for Development of Numerical Hydrodynamic Model

Change Ref. No.	Description of Model Changes
1	Pilot model with course resolution mesh, domain that only extended as far south as Paringaru Stream, uniform bed roughness and operated with a spatially uniform tidal water level boundary only (no wave setup);
2	As per (1) but with variable bed roughness and marshing calculations introduced for shallow flow zones;
3	As per (2) but with the inclusion of a simplified spatially uniform time varying wave setup component as well as tides along the fringing reef boundary
4	Full model developed with extended southern domain to Tikioki Beach, improved mesh resolution and bathymetry replication in key areas, boundary conditions as per (3)
5	As per (4) but with adjustments to bed roughness and marshing parameters
6	As per (5) but with a more robust method for calculating spatially uniform time varying wave setup introduced to fringing reef boundary
7	As per (6), but with a surface wind field applied to investigate effect of winds on hydrodynamics
8	As per (6) but with introduction of a fixed south-to-north gradient on time varying wave setup applied along fringing reef boundary
9	As per (8) but with introduction of a spatially and temporally variable wave setup applied along fringing reef boundary
10	Sensitivity testing of various magnitudes of wave setup applied along fringing reef boundary

In undertaking the model development steps outlined in Table 6.1, it became clear that:

- Achieving accurate predictions of water level fluctuations throughout the lagoon and harbour system was relatively straight forward for most conditions, and that the empirical fringing reef water level boundary calculation provided reasonable results;
- Achieving currents of the correct magnitude throughout all zones of the lagoon was more complicated, with the distribution of lagoon currents being very sensitive to the longshore gradient in wave setup that was applied along the reef boundary – a clear indication that the lagoon currents at Muri depend on both the size and direction of waves.

The hybrid empirical/numerical model components were adjusted to allow the model to reproduce as best as possible the measured water levels and currents throughout the lagoon for the calibration period. This process of adjustment included tweaks to localised areas of model roughness, changes to wetting/drying areas of the model mesh, and predominantly changes to the model boundary conditions for wave setup along the fringing reef. The model performs well for most periods of time and most areas within the lagoon, though for short periods of time and specific events/conditions its prediction accuracy is less robust. This is primarily due to limitations such as:

- The accuracy of deep water wave forecasts from the NOAA global wave model;
- The un-calibrated empirical wave transformation used to convert deep water wave conditions to nearshore wave conditions;
- The combination of the above two factors resulting in occurrences when the longshore gradient in wave setup along the fringing reef is poorly predicted, which in turn results in poor predictions of currents in the lagoon;
- Model boundary effects from the wave setup boundary condition.

Figure 6.7 provides plots of measured versus modelled water levels, and Figure 6.8 provides plots of measured versus modelled current speed for the calibration period. These plots are at the same locations as the key lagoon monitoring stations along the main flow path through the lagoon.

While further improvements and calibration of the model are definitely possible, this would first require improvements to measurements of nearshore waves at multiple locations along the Muri coastline, and development of a fully calibrated nearshore wave transformation model to better predict the longshore gradient in wave setup. Nevertheless, at this point in time the model is considered to provide the ability to simulate the key hydrodynamic processes in the lagoon, and is fit-for-purpose in the assessment of relative changes to hydrodynamics in response to various scenarios that explore changes in the lagoon.

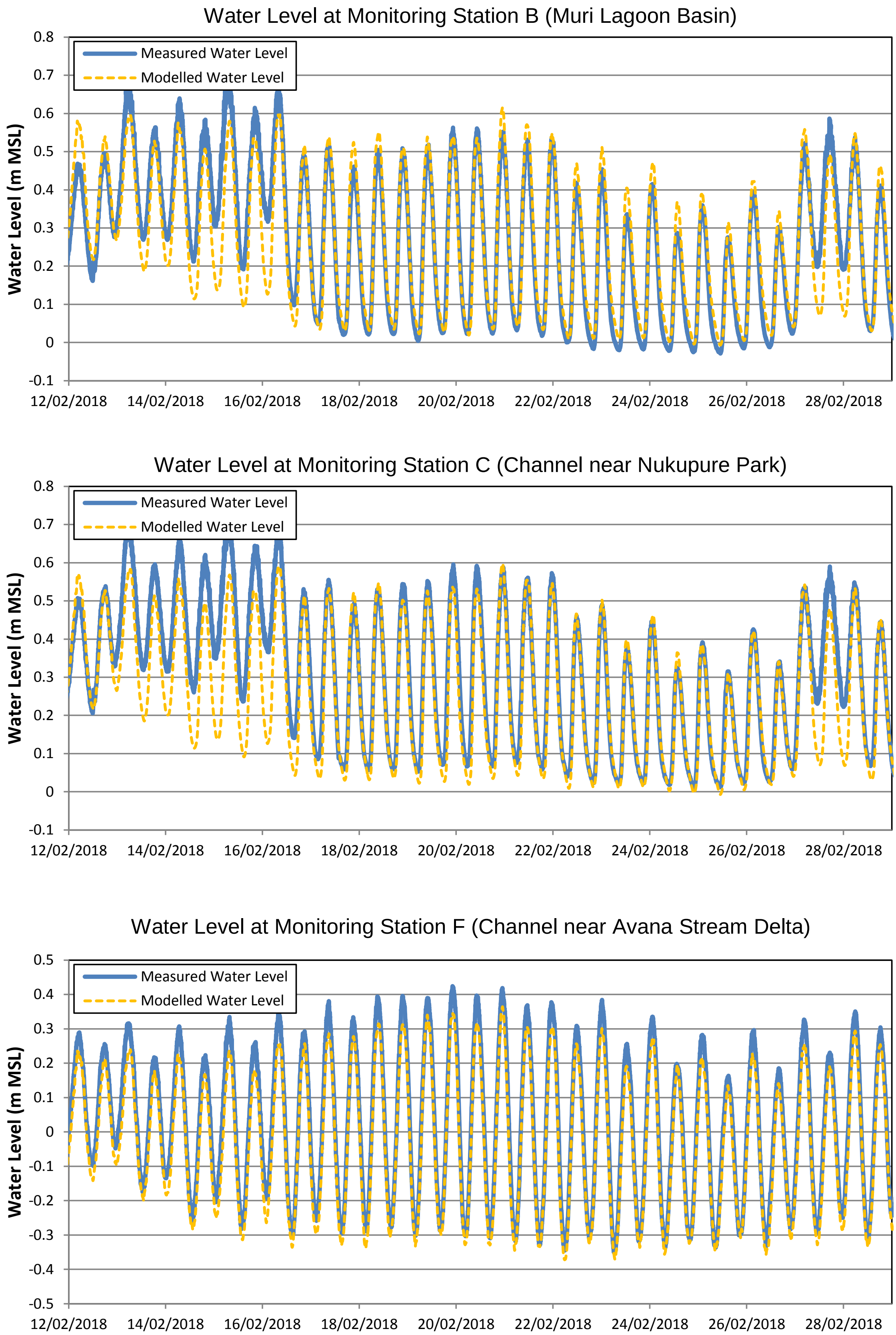
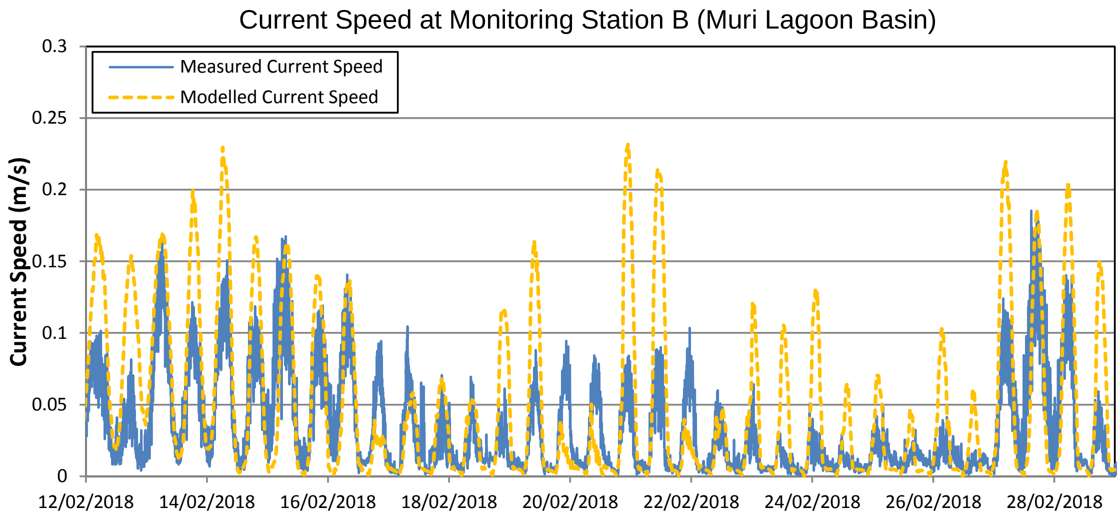
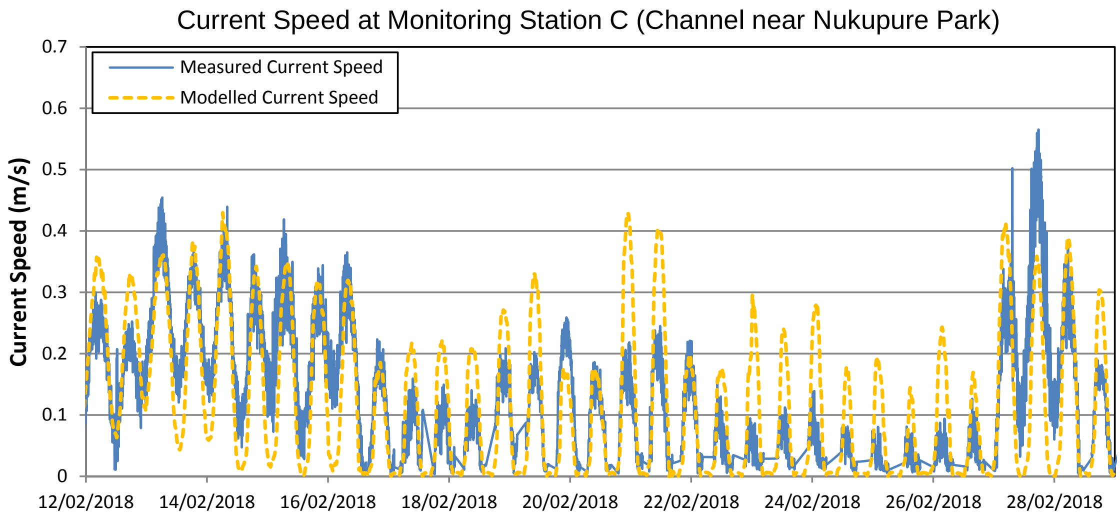


Figure 6.7: Comparison of modelled water levels versus measured water levels





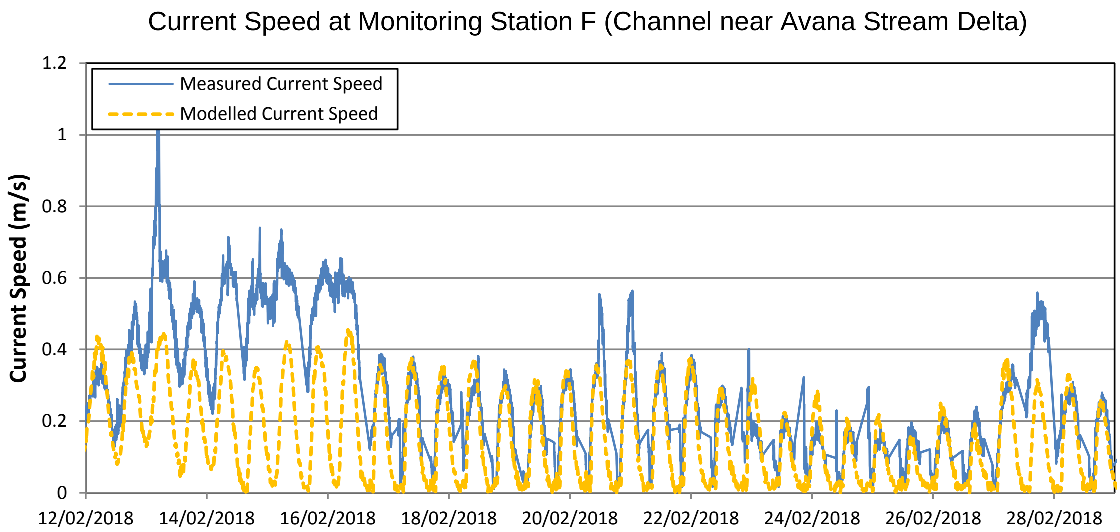


Figure 6.8: Comparison of modelled current speeds versus measured current speeds

6.3 Summary of Modelled Scenario Simulations

A number of scenarios were initially explored with the model, to simulate the lagoon hydrodynamics for various states including:

- Neap tide conditions;
- Spring tide conditions;
- Small wave conditions;
- Large wave conditions.

The model was then used to simulate the effect of lowering the shallow coral rubble ridge at Aroko (Figure 4.16), simulating the effect of the channel bed being dredged to a constant depth of -0.5 m MSL along a length of approximately 500 m (a lowering of the channel bed level by 0.2 to 0.6 m). The area of bed that was adjusted in the model is shown in Figure 6.9 and Figure 6.10.

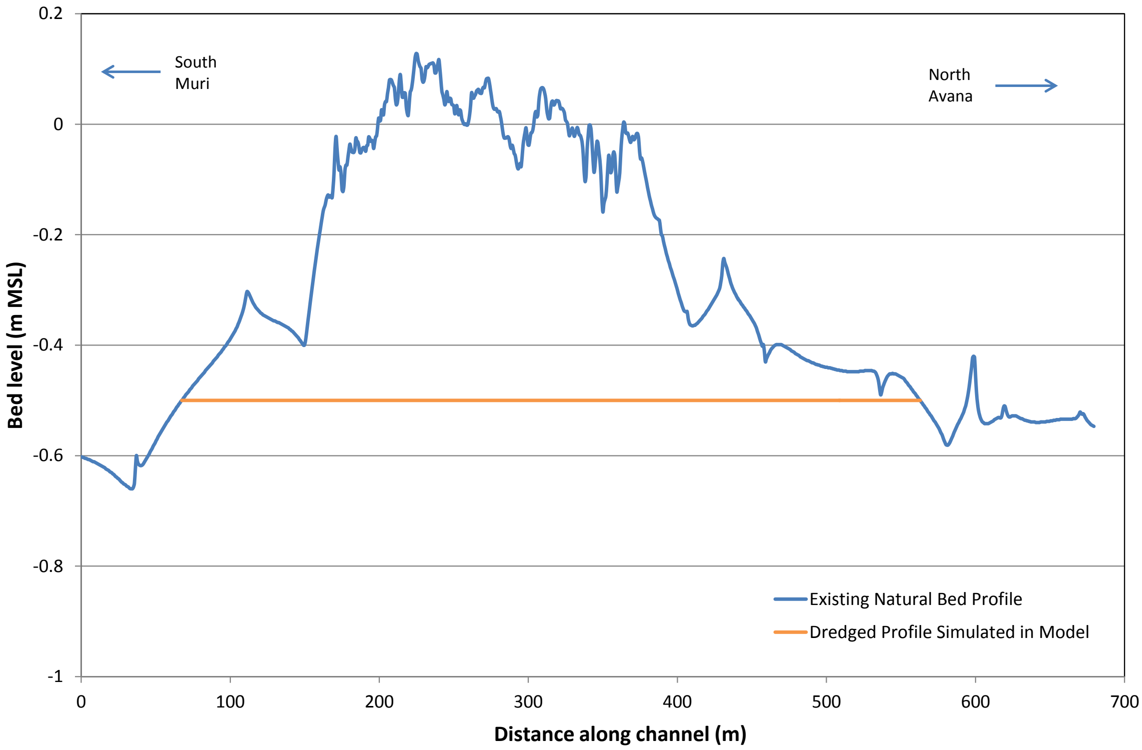


Figure 6.9: Existing 'natural' and modified 'dredged' bed profile simulated in model

Figure 6.10: Area of bed lowered in model simulation

The model was also used to investigate lagoon flushing and the mixing/transport of a conservative tracer constituent, introduced as a point source at several locations within the model domain. This included simulations of:

- An initial constituent release in the centre of the main lagoon basin;

- An initial constituent release close to the shoreline at Muri Beach;
- An initial constituent release from Paringaru stream; and
- The above three cases repeated with the channel bed at Aroko in the lowered/dredged form.

Figure 6.12 shows the locations of the constituent release points. For all of these cases, the conservative constituent was released into the model at a rate of 100 g/s for a period of 1 hour, after which the no further constituent was added. This allowed for observation of the movement of the pollutant within the lagoon, as well as the duration for the pollutant to flush through the system.

Figure 6.11 provides a summary of the hydrodynamics (water levels and wave conditions) for the release period, and period immediately following. The ocean tide range at the time of release was midway between spring and neap (~0.6 m ocean tide range), and the wave conditions were slightly less energetic than average. These conditions are considered to be quite typical for Muri and a good representation of the typical lagoon flushing. Periods of both higher and lower lagoon flushing regularly occur, and this should be considered when interpreting the results.

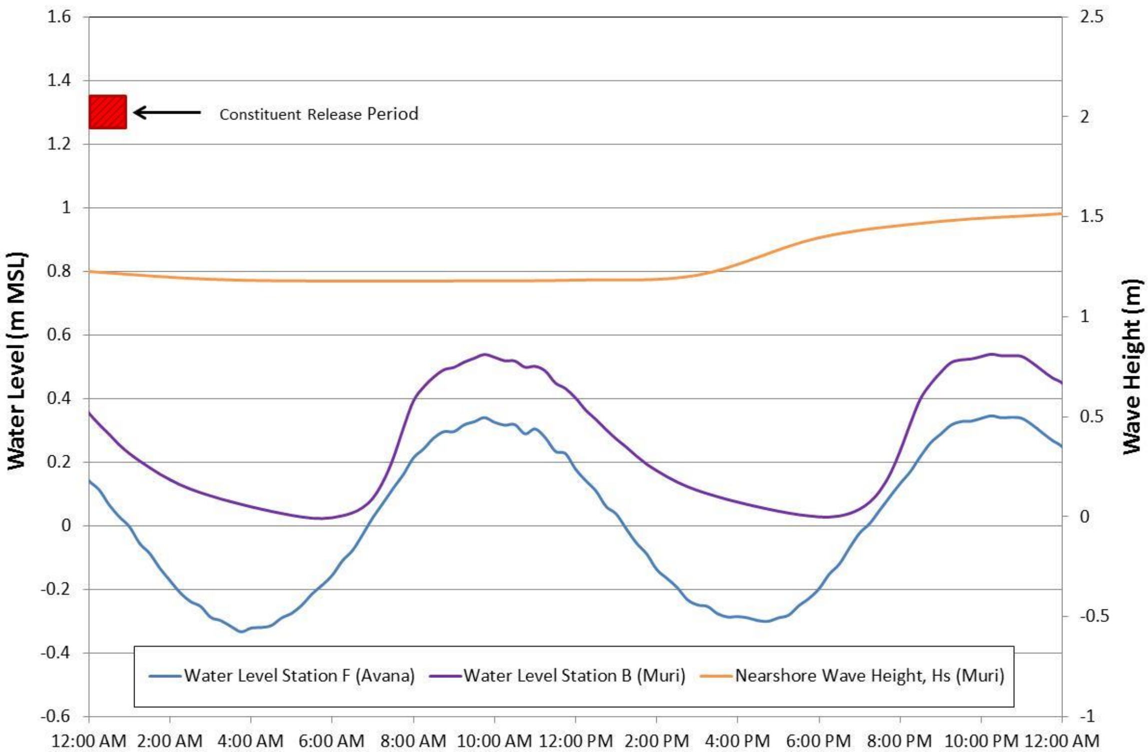


Figure 6.11: Hydrodynamics during and immediately after constituent release

Figure 6.12: Constituent release locations

6.4 Summary of Learnings from Modelling Runs

The initial model runs simulated the hydrodynamics of the lagoon under various conditions, allowing for further understanding of the hydrodynamic flow fields through the lagoon under different conditions. Largely these runs provided confirmation of the understanding of lagoon hydrodynamics that had already been developed on the basis of the field data and observations collected from the lagoon.

6.4.1 Impact of Lowering the Rubble Ridge across the Channel at Aroko

The hydrodynamic model was used to simulate a period of approximately one month, with both the existing natural channel at Aroko, and subsequently with the channel dredged to a depth of -0.5 m MSL. A one-week sample of the results of the two model runs are summarised in Figure 6.13 (water level analysis) and Figure 6.14 (current speed analysis) for the main lagoon basin at Station B and Muri Beach area at Station A.

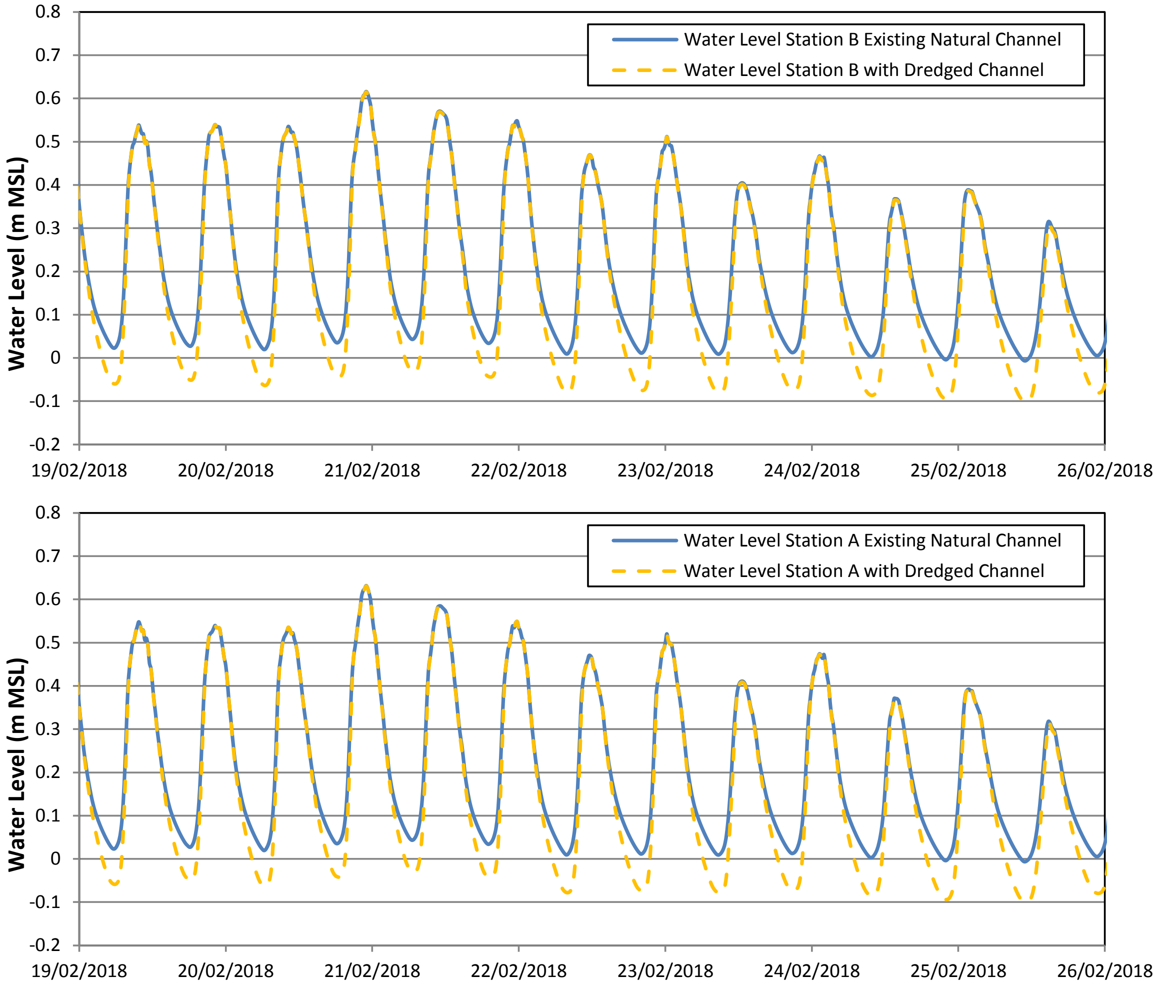


Figure 6.13: Impact of dredged channel at Aroko on Muri Lagoon water levels

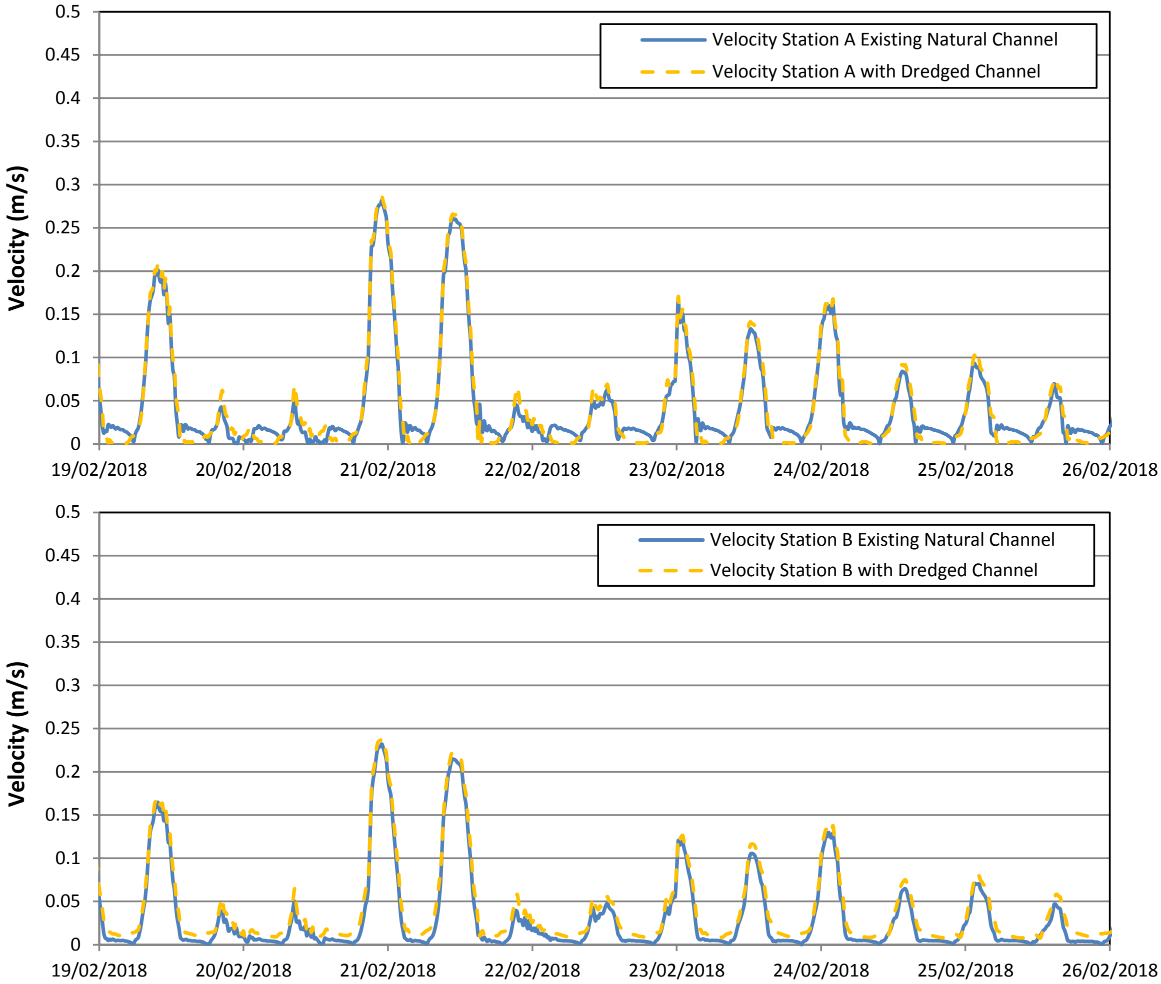


Figure 6.14: Impact of dredged channel at Aroko on Muri Lagoon current velocities

The results of this analysis provide some valuable insights. Firstly, Figure 6.13 shows that lowering the ridge across the channel at Aroko will have little impact on high tide water levels in Muri Lagoon, however, will result in low tide water levels that are notably lower in the lagoon. This is postulated to occur as the lagoon is able to drain to a lower level at low tide without the “weir” effect that the ridge across the channel at Aroko creates, as described in Section 4.3. Secondly, the changes to current velocities in the main Muri Lagoon basin (Station B) and in the channel between Taakoka and Muri Beach (Station A), as a result of lowering the channel ridge at Aroko, are negligible.

These results indicate that a modification such as dredging the northern stretches of the main channel, would have only very minor impact on flushing of the lagoon in the Muri Beach area. However, the modifications would likely change the water level regime in the lagoon, in-turn having potential impacts on lagoon water temperatures and marine ecology.

6.4.2 Flushing of Constituents Through the Lagoon System

Figure 6.15 to Figure 6.18 provide a summary of the results for the model simulations of a conservative tracer constituent released at key locations within the lagoon. The tracer was released just prior to low tide (Figure 6.11), and allowed to disperse and advect through the model domain. These figures demonstrate that for the simulated hydrodynamic conditions:

- There is very little flushing during the initial part of the simulation corresponding to low tide, however, as the tide comes in and wave driven currents increase, the tracer flushes through the system relatively quickly;
- A tracer released almost anywhere in the lagoon would flush through the system within 24 hours of being released;
- A tracer entering via the nearshore area of Muri Beach or via the Paringaru Stream would remain in higher concentrations near to the western lagoon shoreline all the way through the system until eventually flushing out to sea via Avana Passage (in the Muri Beach area in particular);
- There are several areas with lower flushing rates where the tracer tended to remain for longer periods of time, including:
    - Muri Beach, just south of the Vai Te Renga Stream outlet;
    - In the Aroko Saltmarsh and Avana Stream delta area;
    - In the Turangi Stream delta area.

These results support the flushing rates estimated on the basis of the field investigation and discussed in Section 4.3, indicating that in general the lagoon is relatively well flushed. Nevertheless there are a-typical periods when certain combinations of climatic and ocean conditions result in reduced flushing rates.

At end of 1 hour constituent release

3 hours after end of constituent release

9 hours after end of constituent release

12 hours after end of constituent release

18 hours after end of constituent release

21 hours after end of constituent release

Figure 6.15: Results of constituent release at location 1, outer lagoon

At end of 1 hour constituent release

3 hours after end of constituent release

6 hours after end of constituent release

9 hours after end of constituent release

12 hours after end of constituent release

15 hours after end of constituent release

Figure 6.16: Results of constituent release at location 2, Muri Beach

At end of 1 hour constituent release

3 hours after end of constituent release

6 hours after end of constituent release

9 hours after end of constituent release

12 hours after end of constituent release

15 hours after end of constituent release

Figure 6.17: Results of constituent release at location 3, Paringaru Stream outlet (Part A)

18 hours after end of constituent release | 21 hours after end of constituent release | 24 hours after end of constituent release

Figure 6.18: Results of constituent release at location 3, Paringaru Stream outlet (Part B)

7 Conclusions and Discussion

This report has outlined the methodology and results of an extensive hydrodynamic investigation of the Muri Lagoon and Avana Harbour system, and forms part of the Environmental Investigations undertaken within the Mei Te Vai Ki Te Vai project. This hydrodynamic investigation has comprised a range of components including:

- An extensive topographical and bathymetric survey of the lagoon system and fringing coastline;
- Several months of near continuous data collection for water levels, currents, water temperature and waves, as well as short term gauging of flows within various sections of the lagoon;
- Development of a numerical model to further explore hydrodynamic processes and various lagoon scenarios.

The combined results of a more holistic bathymetric survey and simultaneous hydrodynamic data sets throughout the lagoon have allowed a more complete understanding of the lagoon processes to be developed. With regards to the hydrodynamic processes of the lagoon system, the results of the investigation have confirmed some previous theories, identified new features, and importantly, allowed us to better understand the role of the system hydrodynamics in the lagoon water quality.

7.1 Hydrodynamics

The key process that drives flushing of Muri Lagoon is the effect of wave breaking along the fringing reef. The breaking waves generate wave setup which results in the lagoon water level being continuously perched or super-elevated compared with the surrounding ocean. This perched water level in-turn drives flows and flushing of the whole lagoon system. The speed and direction of lagoon flows have been measured to be very sensitive to variations in both the size and direction of waves impacting Rarotonga. The fluctuation of tides also modulate the speed of currents moving through the system, with much faster currents occurring at higher stages of the tide, and very low currents occurring at low stages of the tide. These tidal and wave processes have not changed in previous decades, and so it is concluded that the key drivers of lagoon flushing and currents are also unlikely to have changed to any significant degree.

An important process that has been identified in this investigation is the difference in hydrodynamic characteristics that occur for the lagoon and channels south of Motutapu, compared with the area around the Avana Stream delta and the harbour/passage to the north. Figure 7.1 shows the two separate zones of the lagoon system that are dominated by different hydrodynamic processes, along with the transition zone that occurs in the Aroko/Oneroa/Motutapu area. In the southern “lagoon zone” (light blue in Figure 7.1), water levels have a restricted tidal range and are dominated heavily by wave setup. Wave driven flows out of this zone toward the north are controlled by a shallow ridge across the lagoon channels in the area indicated as the “transition zone” (orange in Figure 7.1). This ridge restricts the minimum level that lagoon water levels drain down to at low tide, and also retards the rate of drainage. Within the Avana Harbour/Passage and channel areas north of the “transition zone” (dark blue in Figure 7.1), full ocean tidal range is experienced and there is very little measurable wave setup. As a result, water levels in the harbour area are very similar to the ocean and are lower than the lagoon area. These hydrodynamic characteristics allow the conclusion that:

- Changes within the harbour and passage area (such as moderate sedimentation or dredging) would have negligible impact on the hydrodynamics or flushing of Muri Lagoon, as the lagoon hydrodynamics are controlled further “upstream” to the south by the shallow ridge across the lagoon channel.

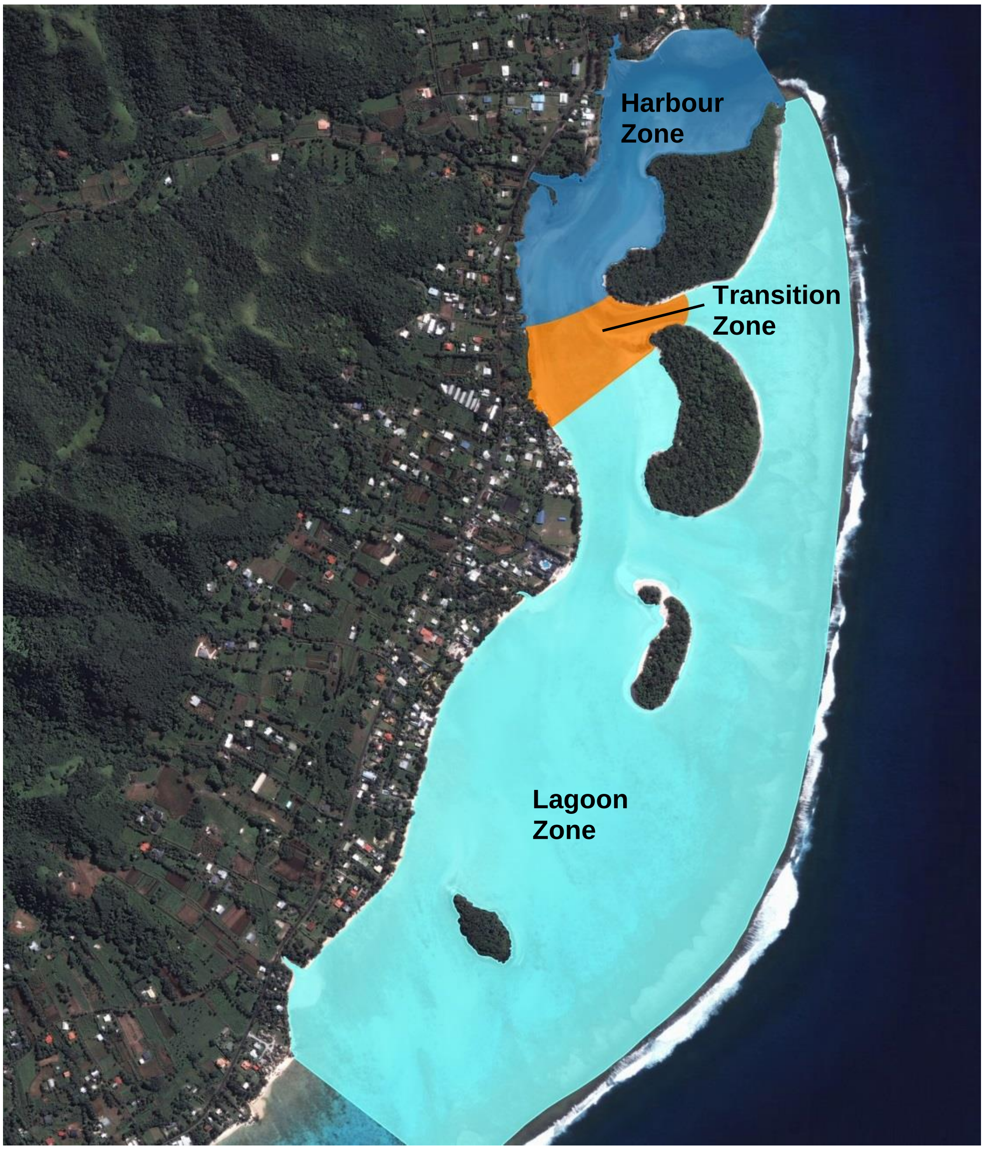


Figure 7.1: Lagoon hydrodynamic zones

7.2 Flushing

Generally, the recorded data sets indicate that Muri Lagoon has a relatively high turn-over of water, and when compared with available historical data sets, provide no reason to believe that flushing rates have changed to any significant degree in the past three (3) decades. This infers that changes to the system hydrodynamics are unlikely to be the primary cause of changes to lagoon water quality or outbreaks of macro algae.

Nevertheless while water flushes through most parts of the lagoon quickly (at least once per day), there are localised areas with lower water movement. These areas are simply a consequence of the naturally occurring physical arrangement of the lagoon/motu/reef system and the current patterns that result. There are also some environmental conditions such as lower wave energy, specific wave directions or periods of lower sea level that also result in lower rates of lagoon flushing. The most notable area with lower rates of water movement is the Muri Beach area between the Pacific Resort and Taakoka. While water does still move through these areas, albeit at a slower rate, they will likely be more sensitive to changes in contaminants within the lagoon.

7.3 Bathymetry

When compared with historical survey data from the early 1990s, the results of the present bathymetric survey suggest that it is unlikely that there has been significant overall changes to the bathymetry of the lagoon and channel system (such as massive infilling) during this period. As expected there have been localised areas of change, and these are all located in areas that are considered to be dynamic and evolve with the natural sediment transport drivers, such as:

- Sand shoals around the harbour/passage area, which change shape in response to wave action through the passage, and erode in response to high currents during large storm surge events (cyclones) or accrete during periods of lower current velocity;
- Sand spits off the trailing tip of the various motu, which fluctuate in alignment in response to current patterns and waves;
- Deposition zones that occur where current speeds are naturally low, accreting during normal times and eroding during periods of larger storm surge;
- Deposits of coral rubble between the motu and the fringing reef, which build and mobilise during periods of large storm surge and waves.

All of these zones of localised bathymetric change are expected to fluctuate in response to natural drivers, but can also be exacerbated by high sediment loads in catchment runoff, as was experienced in April 2018 during the current investigation.

7.4 Interventions

To alter the hydrodynamics of the lagoon system to any significant degree would require very drastic physical works, and would not be “restoring” the natural hydrodynamic function of the lagoon as much as modifying the system to compensate for other anthropogenic impacts (such as elevated contaminants in runoff and groundwater). This kind of response is not considered to be the best way of addressing the long term issues for Muri Lagoon.

Smaller scale targeted works could be undertaken which may see small gains in water movement through the system. However, the results of the investigation and scenario testing with the numerical model suggest that these would primarily improve flows in areas of the system that are already well flushed, and make little difference to areas that naturally have lower rates of water movement. Examples of such works primarily include:

- Lowering of the shallow algal-rubble ridge across the main channel near the northern end of Oneroa (in the orange area of Figure 7.1), so that the bed level matches areas of the main channel further south and north.
- Planned re-distribution of portions of the rubble that is deposited between the motu and the fringing reef.

Both of these concepts are achievable and would have slightly different impacts on water movement, as well as other environmental impacts.

Dredging of the shallow ridge in the main lagoon channel at Aroko would require removal of up to approximately 0.5 m of material over an area of 1.5 to 2.0 hectares (a volume of around 10,000 m^3). Model predictions show that this intervention would have the following potential impacts:

- Allow the main lagoon area to drain by about an additional 0.1 m at low tide, equating to an additional 100,000 m^3 (10%) of intertidal lagoon volume;
- Very little change in lagoon water levels at high tide;
- Slight increase in current speeds through the lagoon channel under most conditions (predicted to be about a 20% increase in current speeds through the main channel near Nukupure Park);
- No notable increase in current speeds inshore of Taakoka or along the southern nearshore Muri Beach area;
- Very slight increase in current speeds through the main lagoon basin.

While the predictions show that this intervention would slightly improve flows of water through the system, it is likely that these improvements would primarily occur where lagoon flows are already relatively high, and that areas with naturally lower flow rates would be altered very little (such as the along the Muri beachfront area). Furthermore, lowering of low tide water levels could have a range of other significant environmental impacts that should be given further consideration, as well as the direct impacts on benthic ecology in the area of works. For example, more obvious indirect impacts include:

- The intertidal sand flat zone will extend further into the lagoon at low tide and new areas of lagoon bed will be exposed;
- Longer periods of time with slightly shallower water in the lagoon, which will alter water temperatures;
- Ecological processes that have evolved to be in equilibrium with the current water level regime would no longer be in equilibrium, such as corals that would be exposed for longer periods of time at low tide and more frequently, as well as sensitive wetland areas such as the Aroko saltmarsh.

Our mapping and survey has shown that the highest areas along the fringing reef are the coral rubble deposits that sit slightly landward of the algal ridge forming the “reef crest”. The slope of the reef face and the level of the algal ridge control the wave setup level in the lagoon that is generated by breaking waves. However, as the coral rubble deposits form the highest bund along most parts of the outer reef, it is likely that they also influence the flows into the lagoon. This has been noted both during field observations along the outer reef as well as wave tank testing undertaken by WRL during the investigation. At lower stages of the tide it is likely that the rubble deposits can influence the location and rate that water can enter the lagoon, however, during these low water level periods the restricted drainage of water out of the lagoon is expected to control lagoon flushing more so than the coral rubble deposits impacting flows entering the lagoon across the outer reef.

While the build-up and evolution of the coral rubble deposits is a naturally occurring process, planned rearrangement or redistribution of the material in targeted areas would likely improve lagoon flushing during periods of lower lagoon water level. These improvements in flushing would, however, be mostly associated with the outer lagoon areas between the motu and fringing reef, and the already well flushed channels that flow in between the motu. To minimise negative environmental impacts of such works, it is suggested that:

- No rubble material be removed from the lagoon system, as breakdown of the coral rubble eventually forms part of the natural sediment supply to the motu and beaches;
- Rearrangement of the rubble would need to be planned in such a way as to minimise any changes to wave energy and exposure of the motu beaches.

Undoubtedly the Muri Lagoon system is hydrodynamically complex and a sensitive environmental area. The indirect environmental impacts of any intervention, through both changes to physical lagoon processes and through execution of the works, requires careful consideration before progressing, and an EIA should be undertaken to document the potential cultural and environmental impacts, as well as consideration of the costs and benefits of the works (including environmental, social and financial aspects).

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