Waikato Regional Council Technical Report 2021/25

Optimisation of the Waikato Regional Council tide gauge network

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Table of Contents

Figures

Tables

Executive summary

Waikato Regional Council (WRC) currently operates a tide gauge network to measure tidal and extreme sea levels in the Waikato region at Manu Bay, Raglan Wharf, Kawhia Wharf, Whitianga Wharf and Tararu (Thames). In addition to water levels, other data such as wind speed, wind direction, atmospheric pressure and water temperature (or a subset) are monitored at each location. The records are fragmented and of various lengths and quality. Furthermore, there is no clear strategy or documented approach to sea-level monitoring in the Waikato region and this lack of strategic planning and oversight is concerning. Considering the importance of the tide gauges with ongoing future changes in sea level, extreme coastal flooding and hydrodynamics under climate change it is now opportune to review the tide gauge network.

This review has been undertaken to ensure that WRC operates a tide network that is scientifically robust and serves resource management and climate adaptation by the Council into the future. Specifically, this review has:

1. Assessed the effectiveness of the tide gauge network to address WRC's current and future data requirements.
2. Identified data gaps and provided specific recommendations on how to address these.
3. Assessed the appropriateness of gauge management and provided recommendations for improvement.

The approach behind this review has been to assess the quality of the sea level records and the spatial distribution of the tide gauges in the context of the following:

1. The ways in which WRC uses the data, why the data is useful for WRC and how the data is used by others to achieve WRC objectives.
2. The policy and guidance that details why and how WRC should collect sea-level data.
3. The spatial and temporal variability of hydrodynamic and meteorological factors that control water levels in the Waikato region.

Although telemetry is an important operational aspect of the tide gauge network, this review does not cover issues of latency and redundancy of telemetered data.

The key summary points of this review are as follows:

- The Manu Bay (Raglan) tide gauge is sufficient for characterising water levels along the open west coast of the Waikato Region but monitoring long-term trends of sea-level rise will be difficult due to the significant wave exposure (which applies to any site along Waikato's west coast).
- A single long-term tide gauge would be sufficient for characterising water levels including sea-level rise along the open east coast of the Waikato Region.
- In general, tide gauges situated within estuaries and the Hauraki Gulf / Firth of Thames will have limited relevance for the wider region but will be locally relevant and important if situated in areas with specific hazard risk such as a high population or low-lying land, or adjacent to environmental monitoring sites.
  - Raglan Wharf, Whitianga Wharf and Tararu gauges are locally important for these reasons.
  - Compared to Manu Bay on the exposed open coast, Raglan Wharf is the best candidate site for maintaining a long-term record of sea-level rise on the west coast, although the record is fragmented so far and will be of most relevance to Whaingaroa (Raglan) Estuary.
  - Kawhia Wharf is less locally important but has a good record.
- A minimum record length of 30 years is required to resolve water level variations from all relevant signals including deriving sea-level rise trends.

- A recording frequency of 1 minute is most suitable, enabling measurement of long waves such as longer period (> 2 minutes) infragravity waves, meteotsunami and tsunami.
- Tide gauge records require minimal gaps to fully characterise seasonal water level changes in the record.
- Vertical land movement (VLM) needs to be monitored to interpret sea-level change relative to a known datum. Currently WRC only measure VLM at Tararu on an annual or bi-annual basis.
- Archived and telemetered water levels need to be adjusted for known rates of VLM.
- Monitoring of atmospheric pressure, wind speed and direction are required to interpret and understand the meteorological drivers of storm surge, WRC only record all these variables at Raglan Wharf and Tararu.

Based on the review the following recommendations are made:

- Maintain all existing tide gauges with the option of discontinuing Kawhia Wharf gauge when the Manu Bay and Raglan Wharf gauges become permanent and stable and modifications to the Raglan Wharf are complete.
- The Kawhia Wharf gauge site should be replaced with a radar gauge in the interim; avoiding the problems associated with the ageing bubbler in this location and being easier to maintain.
- Install and maintain an open-coast tide gauge in a suitable location on the Coromandel east coast.
- Plan temporary gauge deployments to help understand local water levels at specific areas of interest, particularly the estuaries and harbours where there are known or emerging coastal flooding or water quality issues.
- Vertical land movement should be routinely measured at all gauges following methods by Denys (2018).
- Ensure that all tide gauge installations record atmospheric pressure at sea level, wind speed and wind direction in addition to water levels. Water temperature is less important.
- Standardise sampling at 1 Hz with a 1-minute burst average (i.e., averaged every 60 samples) recorded every 1 minute, so that higher frequency energy can be recorded, this is especially important for the exposed gauge at Manu Bay. The standard deviation should also be recorded to measure significant wave height.

1 Introduction

Waikato Regional Council (WRC) currently operates a tide gauge network to measure tidal and extreme sea levels in the Waikato region at five sites, but this has been developed ad hoc over the years with varying, fragmented record lengths. The tide gauges are part of a WRC water level monitoring network that also records water levels in lakes and rivers.

An analysis of the sea-level data from WRC's gauges at Kawhia Wharf, Tararu (Thames) and Whitianga Wharf by NIWA (Stephens et al., 2015) provided useful information on tidal metrics, extreme water levels and the contributing factors to storm surge at each of these sites. NIWA found the data at these three gauges to be of good quality but noted a reliance on data collected in estuaries and recommended also collecting tidal data from the open coast.

Following Stephens et al. (2015), gauges at historic sites at Raglan Wharf and Manu Bay were reinstated and five more years of data collected. WRC gauges are currently located at Manu Bay, Raglan Wharf, Kawhia Wharf, Whitianga Wharf and Tararu (Thames) (Figure 1). In addition to water levels, other data such as wind speed, wind direction, atmospheric pressure and water temperature (or a subset) are monitored at each location. There is no clear strategy or documented approach to sea-level monitoring in the Waikato region e.g., the logic behind the locations of the tide gauges, asset management and maintenance of the gauges, the sampling strategy, importance of monitoring vertical land movement at areas where significant subsidence occurs, or whether standardisation of instrumentation or individual site requirements should dictate gauge installations. Considering the importance of the tide gauges with ongoing future changes in sea level, extreme coastal flooding and hydrodynamics under climate change it is now opportune to review the WRC tide gauge network.

This review aims to ensure that WRC operates a tide gauge network which is scientifically robust to inform the ongoing changing risks into the future. Specifically, this review will:

1. Assess the effectiveness of the tide gauge network to address WRC's current and future data requirements.
2. Identify any data gaps and provide specific recommendations on how to address these gaps.
3. Assess the appropriateness of gauge management and provide recommendations to improve gauge management.

The approach has been to review the quality and spatial distribution of the WRC tide gauges in the context of:

1. The ways in which WRC uses the data, why the data is useful for WRC and how the data is used by others to achieve WRC objectives.
2. The policy and guidance that details why and how WRC should collect sea-level data.
3. The spatial and temporal variability of hydrodynamic and meteorological factors that control water levels in the Waikato region.

Although telemetry is an important operational aspect of the tide gauge network, this report does not cover issues of latency and redundancy of telemetered data.

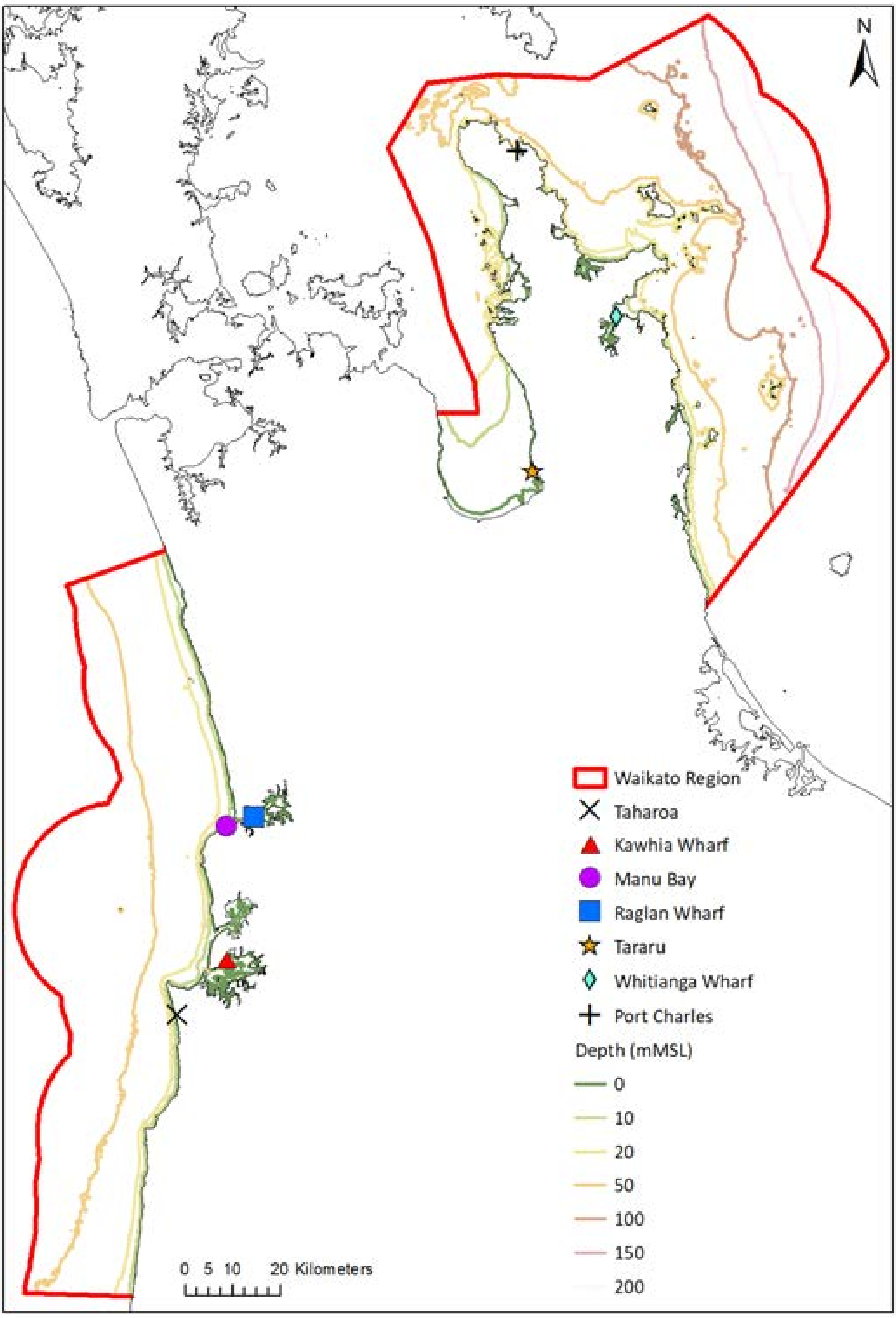

Figure 1. Locations of WRC tide gauges and Taharoa weather station, including regional bathymetry from a compilation of all available bathymetry in the Waikato region (Gardiner and Jones, 2020).

2 Data use

Understanding how data is currently utilised by WRC and is used by others are important considerations for reviewing the suitability of the existing tide gauge network and a brief review of data use is summarised here.

1. Water levels are used to help understand the zonation of intertidal habitats and to determine the intertidal elevation (e.g., Hunt, 2019) both as an explanatory variable when analysing sedimentation or ecological monitoring data, and for planning the position of monitoring sites.
2. Water levels are also a vital component of hydrodynamic modelling and tide gauge data can be used both as a boundary condition and/or for validation or calibration (e.g., Hunt and Jones, 2020).
3. Water levels are used by WRC to plan suitable tidal windows for the collection of remote sensed data such as aerial photos, LiDAR and drone data and to subsequently identify the water level at the time of remote sensed data capture (Hunt and Jones, 2020).
4. From a policy perspective, the landward boundary of the Coastal Marine Area (CMA) is defined as Mean High-Water Spring (MHWS). Accurate measurements of sea levels are needed for defining MHWS and will increasingly become more critical to track the landward migration of the MHWS boundary from ongoing sea-level rise.
5. The tide gauge data is particularly useful in quantifying risk from coastal hazards due to extreme water levels and are analysed periodically to update the understanding of risk exposure in the Waikato Region (e.g. Goring, 1995; Stephens et al., 2015, 2020). Understanding risk from extreme water levels is important for district councils who use the information for shoreline management studies, designing appropriate setback distances for development and designing suitable coastal defences. Telemetered water level data is also important during civil defence emergencies and to help with coastal flood warnings or for assisting with the evacuation process and over time will be critical for setting downstream boundary conditions for flood modelling and stopbank risk assessments.
6. Maintaining gauges over the long-term (>30 years) allows the trend in mean sea level to be established, over and above the climate variability that influences annual sea level at timescales of years to decades. The WRC gauges have also provided a baseline mean sea level (e.g. 1986-2005 average) on which sea-level rise projections from the Ministry for the Environment coastal guidance (Bell et al., 2017) can be added to inform adaptation priorities.
7. For adaptation to the impact of rising seas, any ongoing land subsidence will only exacerbate the rise in ocean sea level. For the southern Firth of Thames coast, sea-level trends from the Tararu gauge, alongside a co-funded NIWA and WRC project monitoring land and intertidal subsidence (Swales et al., 2016), has been instrumental in quantifying the higher rate of relative sea-level rise being experienced because of land subsidence and compression of underlying marine muds.
8. Stats NZ report coastal sea-level rise as an indicator of coastal environmental pressure. It would be regionally beneficial to report sea-level rise in the Waikato either as a nationally or regionally reported environmental indicator but compiling this indicator will require sound data collection.

3 Policy requirements and guidance

There is little policy or guidance that directly mandates or supports the operation of a tide gauge network and monitoring sea level by a council, other than the general requirement in s35 of the RMA to monitor "… the state of the whole or any part of the environment of its region or district—to the extent that is appropriate to enable the local authority to effectively carry out its functions under this Act". One of those newer (since 2017) functions of councils in Part II of the RMA is the "… the management of significant risks from natural hazards" as a matter of national importance [s6(h)].

Both the New Zealand Coastal Policy Statement (Department of Conservation, 2010) and Coastal Hazards and Climate Change guidance (Bell et al., 2017) contain information around the types and purposes of data, which includes sea level and these are summarised below.

3.1.1 New Zealand Coastal Policy Statement (NZCPS)

Of direct relevance to the measurement of water levels is Policy 24 Identification of coastal hazards, a, d, e and h, as follows (Department of Conservation, 2010):

> *Identify areas in the coastal environment that are potentially affected by coastal hazards (including tsunami), giving priority to the identification of areas at high risk of being affected. Hazard risks, over at least 100 years, are to be assessed having regard to:*
>
> *(a) physical drivers and processes that cause coastal change including sea level rise;*
> *(d) the potential for inundation of the coastal environment, taking into account potential sources, inundation pathways and overland extent;*
> *(e) cumulative effects of sea level rise, storm surge and wave height under storm conditions;*
> *(h) the effects of climate change on:*
> *(i) matters (a) to (g) above;*
> *(ii) (ii) storm frequency, intensity and surges; and*
> *(iii) (iii) coastal sediment dynamics;*
>
> *taking into account national guidance and the best available information on the likely effects of climate change on the region or district.*

3.1.2 Coastal Hazards and Climate Change guidance

National guidance for local government on coastal hazards and climate change (Bell et al., 2017) indicates that tide gauges form an important part of regional/unitary council monitoring. The guidance also notes that although long-term trends in sea level rise should be provided by national agencies, it relies on local and regional gauges to provide data including baseline mean sea level for adding projections and assessing the impact of vertical land movement, especially subsidence (Chapter 5, Bell et al., 2017). The guidance also notes that protocols are required to manage the tide gauge network and that a "gap analysis" would optimise the monitoring of water levels. The Bell et al. (2017) national guidance specifically notes in Chapter 11:

Monitoring of the natural environment should encompass:

- *collation of local and regional climate, coastal and ocean information (from national and regional sources, eg, wave information, surface temperature, winds, storms) and updated information on climate change projections for the region*
- *monthly and annual mean sea level, to track local (relative) sea-level rise (most councils operate a tide gauge(s)) will require protocols to ensure data accuracy is maintained and has minimal gaps*

- *land movement information and data from a continuous GPS recorder co-located near the main sea level gauge (if relevant to the region) and working partnership with Land Information New Zealand*
- *documentation of 'extreme' events – both weather-related and consequential events, such as flood levels, extent and depth of inundation, and episodes of erosion and deposition*

The establishment and maintenance of the monitoring framework should build on current information. A gap analysis can be undertaken to identify situations where monitoring efforts should be continued and/or where they need to be enhanced or better focused.

4 Water levels and hydrodynamics in the Waikato Region

To assess and select appropriate locations for the tide gauges it is necessary to understand the main factors contributing to estuarine and coastal water levels in the Waikato region. The water level recorded at a tide gauge is a combination of ocean processes that produce short or long waves over a range of frequencies and energies. An idealised summary of the relative energy contribution from each process shows that generally the largest amount of energy is provided by wind waves and semi-diurnal (twice daily) and diurnal (daily) tides (Figure 2). However, the contribution of each component to the resultant water level will vary with exposure and hence the location of the tide gauge and its sampling frequency.

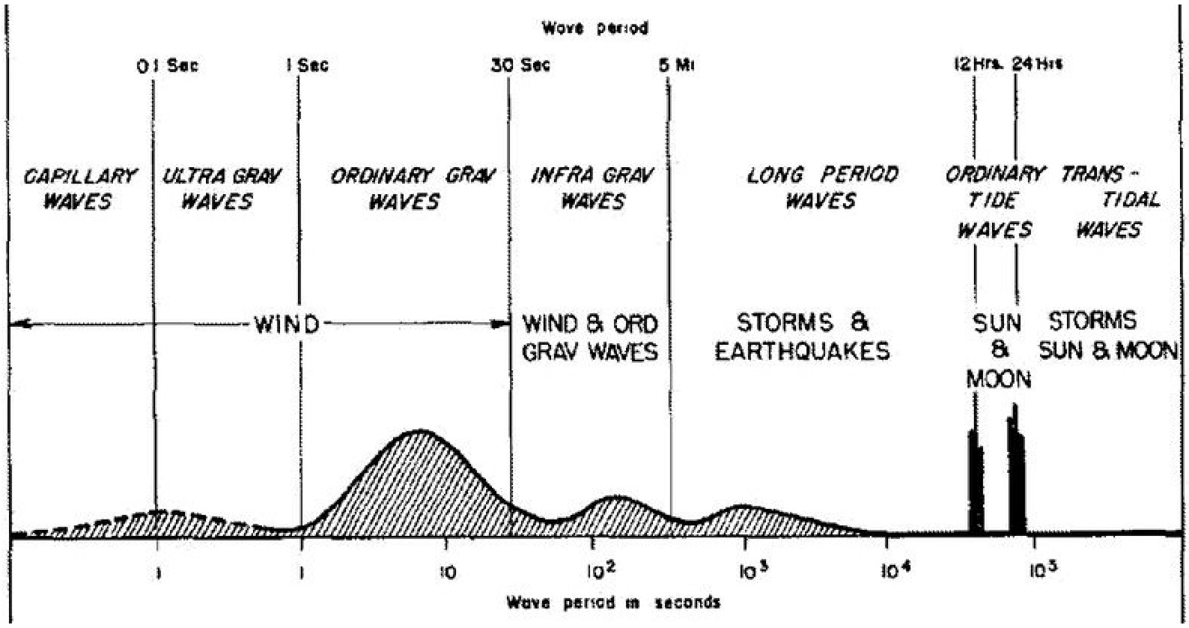

Figure 2. Classification of ocean processes according to wave period and the wave forming factors. The relative wave energy is shown by the curve (Munk, 1950).

The spatial variability of hydrodynamic conditions and water levels is important as it impinges on the ability to collect regionally representative data in the Waikato along with targeted areas where coastal-hazard or flood risk is high (to align with Policy 24, NZCPS). Practicalities tend to result in gauges sited in sheltered areas, either in estuaries or on breakwaters. To maximise the scientific, environmental management and hazard-risk management value from the tide gauges it is necessary to:

1. Position the gauges in locations that are collectively representative of the widest area possible whilst still recording the variability of tides, coastal storm extremes and rising sea level conditions around the region; and/or
2. Position the gauges in areas of specific local interest from an environmental monitoring or hazard perspective or priority.

In other words, whilst collecting coastal and estuarine water level data, a realistic balance needs to be struck between adequate spatial representation around the region without too much effort (and consequently budget) spent on recording local variations in the tidal regime which have little environmental, hazard-risk management or strategic interest.

This section of the report summarises the relative spatial and temporal distribution of physical processes that contribute to the make-up of coastal and estuarine water levels observed around the region, a detailed discussion of physical processes is provided in Appendix A. This description of physical processes was then used in Section 3 to assess the suitability of the current WRC tide gauge network.

5 Spatial distribution of water levels

Based on a regional analysis, of processes contributing to observed sea level (Appendix A) the Waikato Coastal Marine Area (CMA) can be split into four hydrodynamic zones as follows, noting coastal sea-level rise will be generally similar along the eastern and western areas respectively of the Waikato region (other than localised areas where ongoing land subsidence will locally exacerbate rising sea level).

1. West Coast (open coast, Port Waikato to Mokau)
   There is only small variability in phase and amplitude of the main tidal constituents along the open west coast of the Waikato Region. This small variability means that tidal levels and timing of the tide, nor height and occurrences of perigean-spring (king) tides, does not vary greatly along this section of coast. Tidal ranges are relatively large along the open west coast. The west coast is a windward shore, exposed to large swell and storm waves predominantly from the southwest. On average the west coast has the largest waves with the longest periods. Larger storm surge usually occurs in response to wind setup especially due to strong and sustained north to northwest winds. **Overall, a single <u>open coast</u> tide gauge situated on the west coast would be sufficient for characterising water levels along the entire open west coast.**

2. Pacific Coast Coromandel (open coast, south of Cape Colville)
   This region exhibits only a small amount of variability in the phase and amplitude of the main tidal constituents meaning that tidal levels and the timing do not vary greatly. The small amplitude of the solar S2 tidal constituent means that there is little difference between spring and neap tides; rather the N2 tidal constituent produces higher variability in tide heights at approximately monthly cycles. Generally, tidal constituent amplitudes are small meaning that this coast has the smallest tidal range in the Waikato region. There is no tidal distortion on the open coast south of Cape Colville. The east coast is mostly a leeward shore, protected from the prevailing regional wind and therefore on average will have smaller waves with shorter periods but, on occasion, experiences large waves from ex-tropical cyclones or occasionally, stalled anticyclonic systems offshore that can produce persistent north-easterlies. Sheltering from offshore islands and a varied coastal orientation means that the wave conditions will be locally variable. Storm surge on the east coast is primarily in response to low atmospheric pressure (with wind set-up secondary), which is associated with either storms or passing ex-tropical cyclones. **Overall, a single <u>open coast</u> gauge situated on the Pacific Coromandel coast would be sufficient for characterising water levels along the entire open coast between Cape Colville and the southern limit of the Waikato Region.**

3. Hauraki Gulf and the Firth of Thames
   The Hauraki Gulf exhibits large variability in both the amplitude and phase of the main tidal constituents in a north to south direction, meaning that both tidal elevations and the timing of the tide vary significantly throughout this region. Amplitudes increase to the south meaning that tidal ranges vary from small to large, tidal distortion also increases in a southerly direction to the southern Firth of Thames as the water depths decrease. The Hauraki Gulf is sheltered but occasional waves and storm surge occur in response to strong and sustained northerly winds (e.g., 5 January 2018 coastal-flooding event). As the tidal characteristics change throughout the Hauraki Gulf a single gauge will not be sufficient for characterising the tidal conditions in this area. **Gauges in this**

area will need to be situated in areas with specific hazard risk such as a high population, low-lying land or adjacent to environmental monitoring sites.

4. Estuaries
   Each estuary in the region will have a different tidal regime and the tidal regime will vary throughout an estuary. Wave generation in each estuary will be dependent on the estuary's orientation relative to prevailing wind direction and speed and therefore is difficult to generalise. Estuaries will be generally sheltered from offshore waves, but degree of sheltering will be dependent on estuary morphology. Estuaries can be suspectable to seiche but the magnitude and frequency of seiche will be specific to each estuary. Fluvially dominated estuaries exist throughout the Waikato Region with the majority on the west coast, gauges installed in fluvially dominated estuaries would likely be influenced by freshwater flow. **In general, tide gauges situated in estuaries will have limited relevance for the wider region but could be locally relevant and critical**. For example, if a relevant estuary-specific coastal flooding hazard, land subsidence or an area of high population needs to be monitored or if paired with other environmental monitoring.

In summary, a single open coast tide gauge on the west coast (Port Waikato – Mokau) and a single tide gauge on the east coast (south of Cape Colville) will be sufficient to measure water levels in these areas. Within the Hauraki Gulf and the other estuaries, a tidal gauge will generally only characterise the local conditions. Tide gauges should therefore only be situated in these areas where there is a specific local reason. However, some estuaries and sheltered embayment's which are not shallow and not susceptible to morphological change could provide a suitable environment for long-term monitoring of rising sea level as opposed to wave exposed open coast sites.

6 Temporal distribution of water levels

The hydrodynamic processes contributing to the water levels in the Waikato Region operate over a range of frequencies. The period of these signals range between 1 – 20 secs for wind waves to 20–30 years for the Interdecadal Pacific Oscillation (Figure 2 summarises the processes operating over frequencies up to the order of a month). Furthermore, there are inter-annual patterns in mean sea level which are primarily driven by seasonal sea temperatures. Longer records of sea level are more useful for the following reasons:

1. More extreme events are recorded thereby improving the ability to estimate likely return periods and characterise the hydrodynamic and meteorological factors that contribute to extreme events.
2. Resolving the 18.6 year lunar nodal cycle and longer climatic cycles and separating these influences from other factors contributing to water level.
3. Monitoring any long-term trends of sea-level rise and changes to storm surge frequency because of climate change.

In summary, the following temporal requirements will facilitate a robust dataset:

- **A minimum record length of 30 years to resolve water level variations from all relevant signals.**
- **A sampling and recording frequency of at least 1 minute, this sampling frequency will measure long waves with a period greater than 2 minutes such as the longer period infragravity and far infragravity waves and tsunami.**
- **Minimal gaps to fully characterise seasonal water level changes in the record**.

7 Review of existing tide gauge network

In this section WRC's existing tide gauge network is reviewed for suitability based on WRC data requirements, policy guidance (Section 1.1) and the spatial and temporal distribution of hydrodynamics, meteorology, and vertical land movement (Section 2 and Appendix A). The general approach has been as follows:

1. Assess the data from each gauge for completeness and quality.
2. Assess the location of each gauge individually and in the context of the regional distribution of the network to identify any gaps.
3. Recommend steps to improve the quality of the data.

The detailed methodology is presented in the following section.

8 Methodology

The water level records for each of the WRC gauges are shown in Figure 3. Short-term sea level records also exist for locations throughout the region including Port Charles (Goring and Bell, 2003), Whangamata (Senior, 2000) and Tairua (Bell, 1991). As these records are short in duration and do not form part of the WRC tide gauge network they have not been assessed here. Records with no water levels and double records have been removed prior to analysis. At Tararu (southern Firth of Thames) the water level record has been adjusted for vertical land movement (VLM) based on a linear subsidence rate of 3.1 mm/yr (Denys, 2019) and assuming that the gauge was levelled to Tararu Vertical Datum-1952 (TVD-52) when first installed. There is no evidence that the gauges vertical position has been adjusted since its initial installation and the adjustment for VLM is consistent with that used previously at Tararu (Stephens et al., 2015; Stephens, 2019).

To assess the temporal quality of the record and the historic reliability of the gauge any gaps greater than 20 days have been identified. Where possible the gaps in the record have been attributed to known faults to identify maintenance tasks that might improve the quality of the record in the future.

The frequency of the water level record used for the harmonic analysis was reduced to improve computational efficiency. At Manu Bay, Raglan Wharf, Kawhia Wharf and Whitianga a consistent sampling period of 10 minutes was chosen. For Tararu, water levels were sampled at 7.5 minutes prior to 7th February 1997 and re-sampled at a consistent frequency of 10 minutes after this date. Using the UTide Matlab function (Codiga, 2011) the reduced frequency water level record at each tide gauge was separated into basic harmonic constituents (Appendix B) and then reconstructed to create a water level which occurs due to tidal processes only (Figure 4).

To assess the tidal signal recorded at each tide gauge the water levels and main constituents have also been calculated on an annual basis where the record for a given year is longer than 6 months as follows:

a. Variations in average annual tidal range based on:
    i. Actual water levels recorded at the site.
    ii. Water levels predicted from annual constituents.
    iii. Water levels predicted from constituents from the entire record.
b. Variations in the height of mean annual water level from the actual water levels recorded.
c. Variations in the 3 main constituents M2, N2 and S2.

d. Variations in the standard deviation of annual water levels to show the lunar-nodal cycle based on:
    i. Actual water levels recorded at the site.
    ii. Water levels predicted from annual constituents.
    iii. Water levels predicted from constituents from the entire record.

The above information is useful for assessing the suitability of the gauge location based on the quality of the tidal signal recorded. Large changes to either water levels that cannot be explained by either the lunar-nodal cycle, climatic cycles, waves or storm surge could indicate distortion and modification of the tidal signal due to either temporary or progressive changes to the local morphology. These changes mean that the gauge location may be unsuitable for collecting long-term records of water level. Where appropriate the constituents at the tidal gauge are also compared to those offshore from a regional tidal model (MSL, 2017) to assess the amount of nearshore modification of the tidal signal and the generation of M4 overtides (Table 1).

Spectral analysis transforms the timeseries into the frequency domain. Viewing the spectrum is useful as it shows relative strength of the different periodicities in the data that are difficult to discern when viewing the timeseries. Here spectral analysis was undertaken on one year of each record using Fast Fourier Transformation function in Matlab. The frequencies have been labelled by their period in minutes and are categorised into different wave types (Figure 5) to be comparable with Figure 2. The year of data selected was the 12-month period with the most complete coverage (i.e. the least amount and duration of gaps in the timeseries) (coloured lines in Figure 5) and therefore the data analysed at each tide gauge is not concurrent. The frequency of sampling has changed throughout the record and at Manu Bay, Raglan Wharf and Kawhia Wharf the most complete year of data is not the data with the shortest sampling period (i.e., 1 minute). As the minimum detectable frequency is twice the minimum frequency (i.e., the Nyquist frequency) the analysis has also been undertaken on the higher frequency records at Manu Bay, Raglan Wharf and Kawhia Wharf (grey lines in Figure 5) despite the record having more gaps.

This review also considers the appropriateness of the monitoring equipment used to record water levels. The suitability of the sampling frequency is considered for each gauge as it limits the highest frequency component of the water level that can be detected. Any other parameters recorded at each gauge site are assessed for suitability in the context of data requirements.

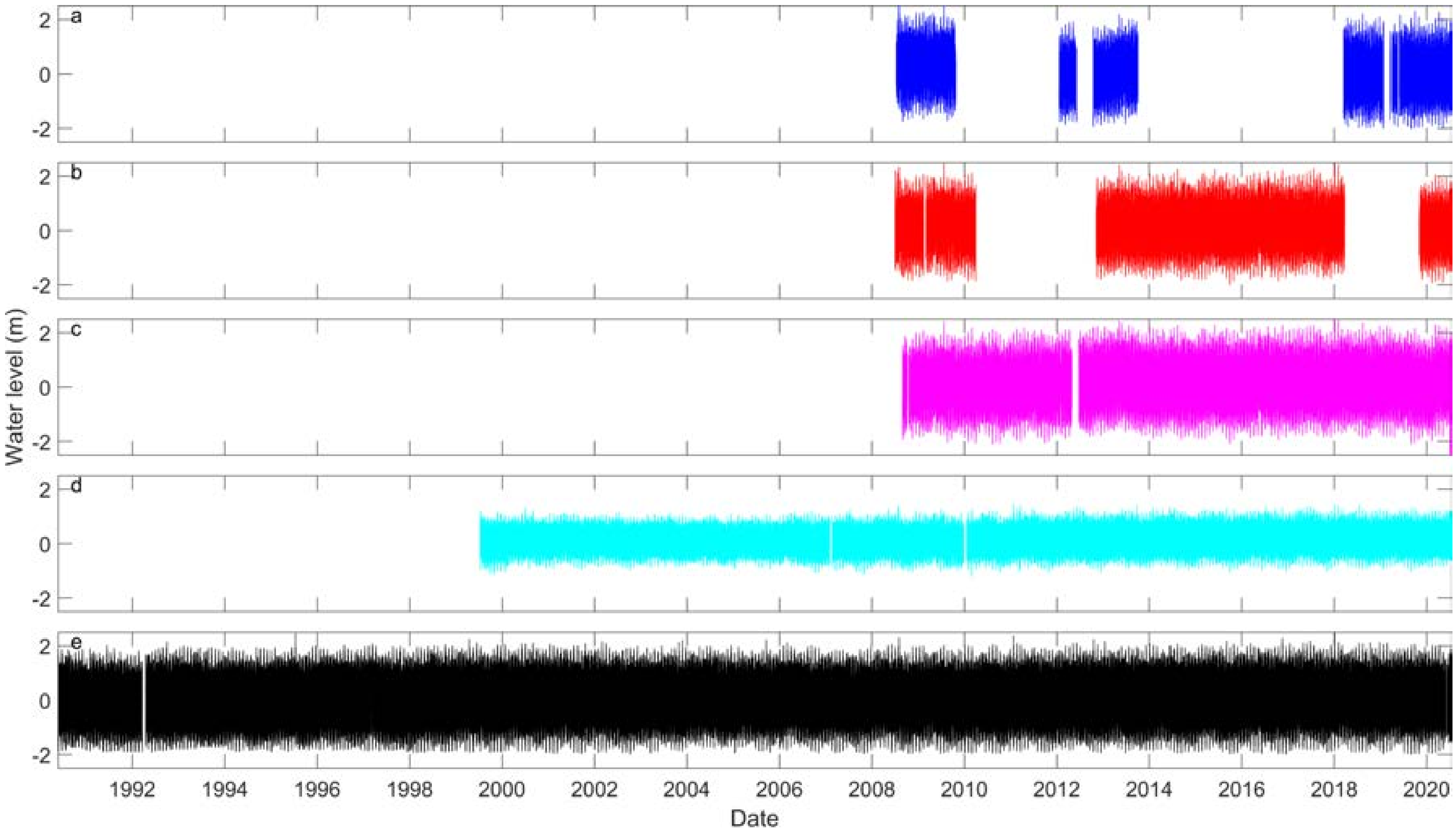

Figure 3. Timeseries of data from Manu Bay (a), Raglan Wharf (b), Kawhia Wharf (c), Whitianga Wharf (d) and Tararu (e). Tararu has been adjusted for VLM. Water levels have been plotted at 7.5 minutes (Tararu pre 7th February 1997) and resampled and plotted at 10 minutes (all other records). See Section 3.1 for details.

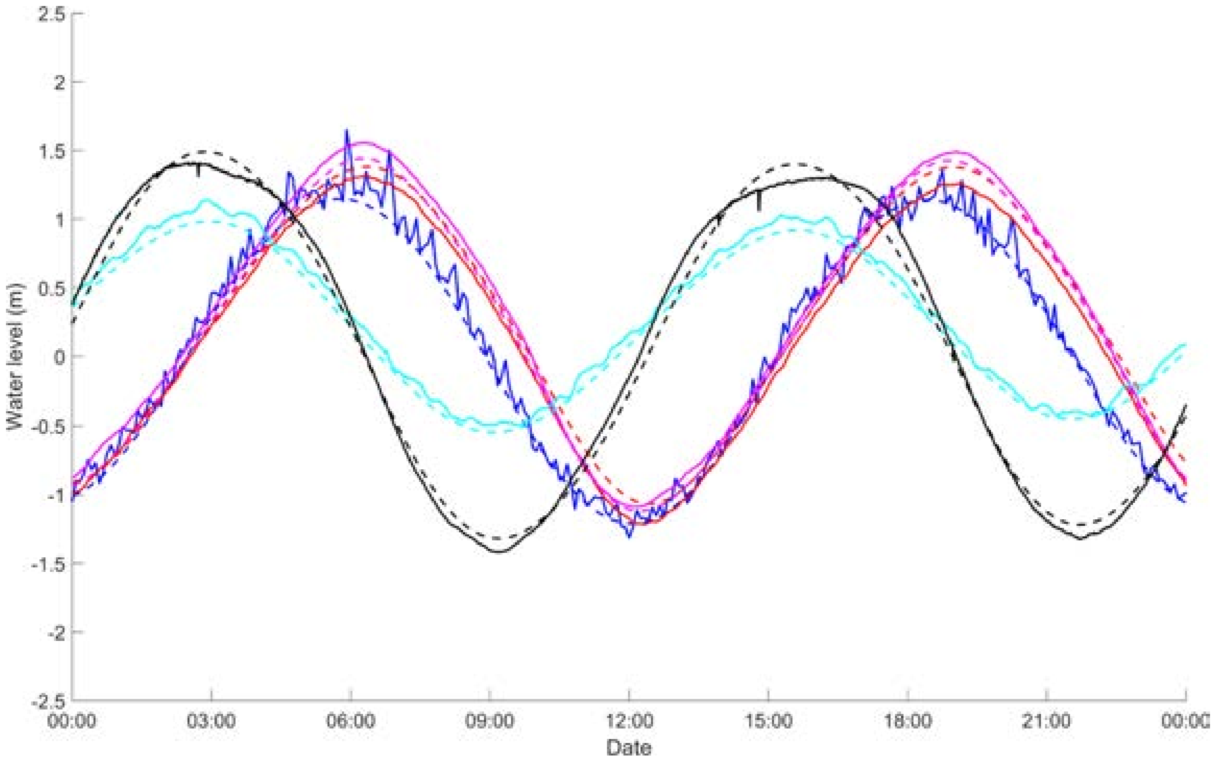

Figure 4. Representative tidal cycle from each gauge. The water level is measured relative to Moturiki Vertical Datum-1953 (MVD-53) at Manu Bay (blue), Raglan Wharf (red), Kawhia Wharf (purple) and Whitianga Wharf (cyan) and TVD-52 at Tararu (black). lines show gauge data (at original sampled frequency) and dashed lines show water level due to tidal processes only (resampled at 10 minutes), see Section 3.1 for details.

Table 1. Constituent summary from tide gauge records and a regional tidal model. Amplitude is the half-range of the constituent (metres) and phase is the timing of the crest of the tide relative to Coordinated Universal Time (degrees).

Location	Source	Constituent summary								
		M2 (12.42 hr cycle)		S2 (12 hr cycle)		N2 (12.65 hr cycle)		M4 (6.21 hr cycle)		M4/M2
		Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	
Manu Bay	Tide gauge	1.12	285	0.313	316	0.219	272	0.0178	49.4	0.02
Raglan Wharf	Tide gauge	1.12	301	0.3	337	0.213	290	0.0523	32.5	0.05
Raglan offshore	Regional model	1.16	286	0.317	317	0.22	271	0.02	53	0.02
Kawhia Wharf	Tide gauge	1.17	299	0.313	334	0.223	289	0.0576	360	0.05
Kawhia offshore	Regional model	1.18	286	0.321	317	0.223	272	0.019	55	0.02
Whitianga Wharf	Tide gauge	0.661	209	0.0855	274	0.137	183	0.0137	155	0.02
Mercury Bay	Regional model	0.76	202	0.1	264	0.157	174	0.004	288	0.005
Tararu	Tide gauge	1.29	213	0.198	271	0.261	187	0.0143	173	0.01
Southern Firth of Thames	Regional model	1.28	226	0.189	285	0.248	198	0.019	67	0.01

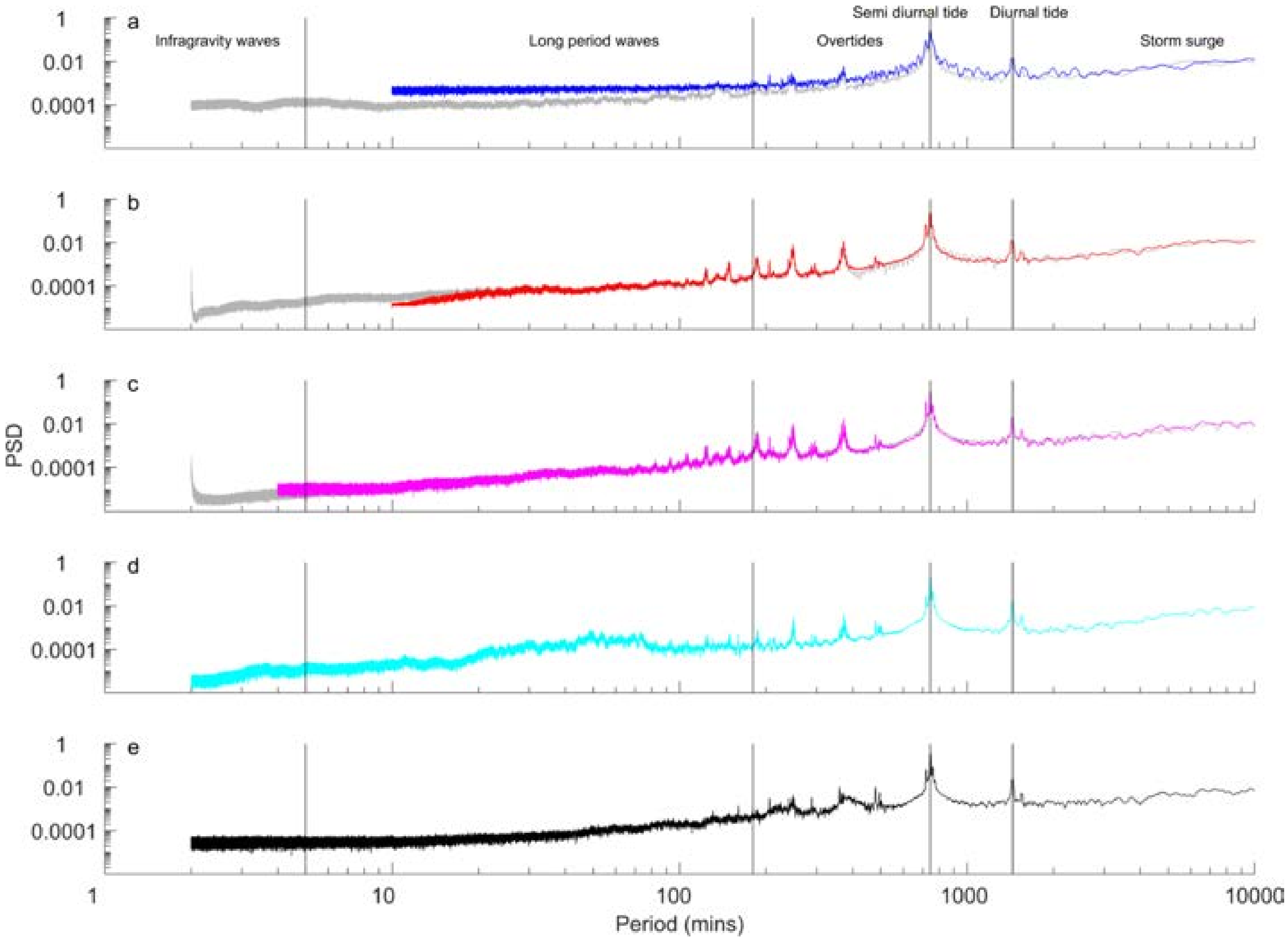

Figure 5. Spectral analysis of the most complete consecutive 12 months of recorded water levels (coloured lines) at Manu Bay (a), Raglan Wharf (b), Kawhia Wharf (c), Whitianga (d) and Tararu (e) tide gauges. At Manu Bay (a) and Raglan Wharf (b) the sampling period was 5 minutes, at Kawhia Wharf (c) the sampling period was 2 minutes, at Whitianga (d) and Taruru (e) the sampling period was 1 minute. At Manu Bay (a), Raglan Wharf (b) and Kawhia Wharf (c) the analysis has been repeated for a less complete 12-month period whilst water levels were being recorded with a 1-minute sampling period (grey lines).

9 Manu Bay (Raglan)

Table 2. Manu Bay summary

Location	Manu Bay boat ramp
Tide gauge type	Bubbler gauge
Parameters measured	Sea level, water temperature and barometric pressure
Sampling schedule	5-minute instantaneous sea level, 10-minute instantaneous water temperature, 5-minute instantaneous barometric pressure
Date of initial measurement	11th July 2008
Gaps in record longer than 20 days	26/10/2009 – 18/1/2012: Unknown reason 4/6/2012 – 7/7/2012: Unknown reason 7/7/2012 – 5/10/2012: Unknown reason 3/10/2013 – 29/3/2014: Unknown reason 29/3/2014 – 16/3/2018: Renovation of the breakwater 25/1/2019 – 17/3/2019: Unknown reason
Datum of gauge zero	Moturiki Vertical Datum 1953 (MVD-53)

Figure 6. Aerial photo image of Manu Bay tide gauge location showing the wider area (a) and the Manu Bay breakwater (b) with the bubbler (i) and the tide gauge instrumentation (ii). Extent of (b) is shown as a red box (a). Depth contours are in metres below MVD-53 from a compilation of all available bathymetry in the Waikato region (Gardiner and Jones, 2020).

The tide gauge at Manu Bay is a gas bubbler installed in the lee of the breakwater next to the Manu Bay boat ramp (Figure 6). The sampling interval was originally 1 minute and has been 5 minutes since 2013. The gauge was first installed in July 2008 but removed from the water during the renovation of the Manu Bay breakwater in 2018. The Manu Bay gauge was re-installed on 22nd March 2018 on the new Manu Bay breakwater with the bubbler tube concreted to the lee-side of the breakwater. Temperature and atmospheric pressure are also recorded at Manu Bay but wind speed and direction are not.

The Manu Bay gauge has been unreliable and has on occasions failed (Figure 3 and Table 2). Conversations with the NIWA staff who installed the gauge suggest that sediment contamination of the bubbler have contributed to the failure of this gauge. The bubbler comprises an aperture through which compressed air is expelled. Suspended sediment was observed to get lodged in the bubbler and block the aperture. Overall, the temporal coverage of the Manu Bay record is poor (Figure 3), with 6 gaps in the record of 20 days or more (Table 2) over the 12 years since initial deployment. When compared to a radar gauge, it is harder for WRC to maintain the bubbler gauge and to control for any vertical movement as the aperture is located underwater. However, due to the exposure of the site to inundation, waves and wind, a bubbler is the only viable tide gauge instrumentation option at this site. Maintenance is also further hindered by the energetic wave climate at this location.

The record at Manu Bay is also noisy (Figure 4) and spectral analysis of the record (Figure 5) indicates that there is more higher frequency (short period) energy (< ~90 minutes) at Manu Bay compared to the other tide gauges. The high frequency energy and noise in the record likely occurs due to wind waves, surge and infragravity waves propagating around the breakwater and up the boat ramp and larger waves breaking over the breakwater. This high-frequency energy from waves impacts on measurement of the "still water level". When comparing the spectra from the 1-minute dataset (Figure 5a, grey line) and the 5-minute dataset (Figure 3,3a, blue line) the shape of the signal is different with the 5-minute dataset having an overall higher spectral density. This disparity could be due to aliasing whereby the large amount of high frequency energy in the water level signal cannot be resolved in the 5-minute dataset and instead is attributed to the lower frequency part of the spectra. Resampling the 1-minute dataset at 5-minutes confirms that reducing the sampling frequency does result an overall greater spectral density but indicates that the sampling frequency may not be the only factor contributing to this difference (Figure 7). For the redeployment of the gauge in March 2018, NIWA installed an aperture or bell-housing (Figure 8) on the end of the bubbler to help dampen wave affects (see Pugh, 2004) and this may also reduce sediment contamination and gauge outages. This aperture may also contribute to the differing spectra between the 1-minute record (pre-aperture) and 5-minute record (post-aperture). The tide gauge records instantaneous water levels as opposed to burst averaged, this sampling is unusual for a tide gauge and will contribute to the noisy record.

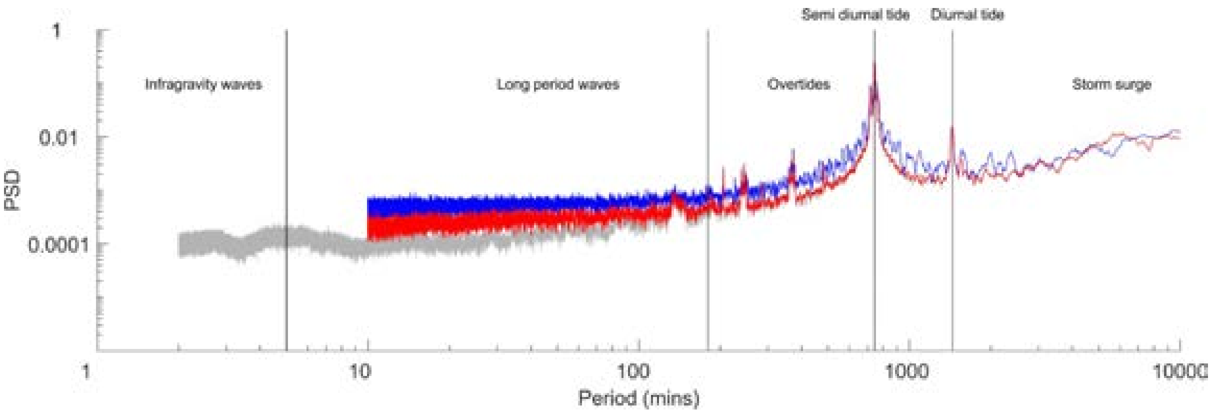

Figure 7. Spectra for Manu Bay tide gauge data for 1-minute resolution data recorded between October 2012 and October 2013 pre-aperture installation (grey line), the 1-minute dataset resampled at 5 minutes (red line) and the 5-minute resolution data recorded between July 2019 and July 2020 post-aperture installation (blue line).

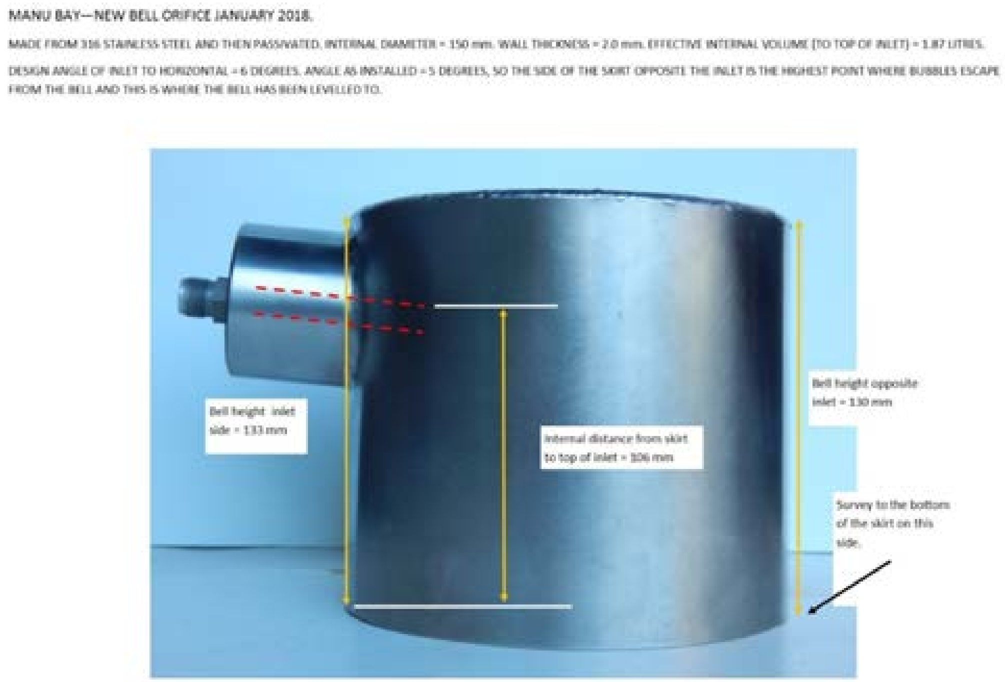

Figure 8. Aperture fitted to Manu Bay bubbler (Image: Pete Pattinson, NIWA)

The time series indicates that there is high frequency energy present during both calm (Figure 9a) and rough sea states (Figure 9b) at Manu Bay, which also affects other open-coast gauges around New Zealand (Rob Bell, pers. comm.). There is a possible modulation of high frequency energy which is especially apparent during rougher events whereby there is more high frequency energy at high tide compared to low tide (Figure 9b). This modulation likely occurs due to the greater effectiveness of the breakwater at low tide with fewer waves washing over the top of the breakwater and shallower water depths preventing the propagation of waves around the structure. Conversely at high tide waves wash over the top of the breakwater and can more easily propagate around the structure. Both the high frequency energy and the high / low tide modulation of the energy will adversely impact the long-term water level record at Manu Bay. Despite the site being exposed to rough sea conditions, this location is likely the only viable open coast site on the west coast of the Waikato Region.

Comparison of constituents recorded at the tide gauge with constituents from the regional model at a point offshore confirm that the phase and amplitude are very similar (Table 1). The M4/M2 ratio at the tide gauge (Table 1) indicate that the tide is slightly asymmetric although as noted in Section A.1 there is some tidal asymmetry throughout the west coast of the Waikato region so the asymmetry at the gauge is unlikely to be related to the local morphology and generation of overtides at the tide gauge site. Due to the gauges position on the open coast and the low variability in tidal conditions along the west coast (Section 2.1 and A.1) the tidal data recorded at Manu Bay is likely to be representative of the regional tidal conditions encountered along the <u>open</u> west coast of the Waikato region. Harmonic and spectral analysis (Figure 5a) indicate that the tide is dominated by the diurnal and semi-diurnal signal with almost no overtides. Annual analysis of water levels and tidal constituents is only possible for 2009, 2018 and 2019 but suggests there is no sizeable inter-annual variability in the three main constituents (Figure 10). Due to the limited length of the record, sea level rise or a complete nodal cycle cannot be discerned at this site (Figure 10). Tidal ranges recorded at the gauge and predicted from constituents appear to track similarly with the nodal cycle (Figure 10), but the record is too short to be certain. There is no reliable trend of mean annual water level because of the short, patchy record so far and the high frequency energy in the record, which hinders the measurement of average sea levels at this site. The record is also too short to calculate the probability and magnitude of extreme water levels.

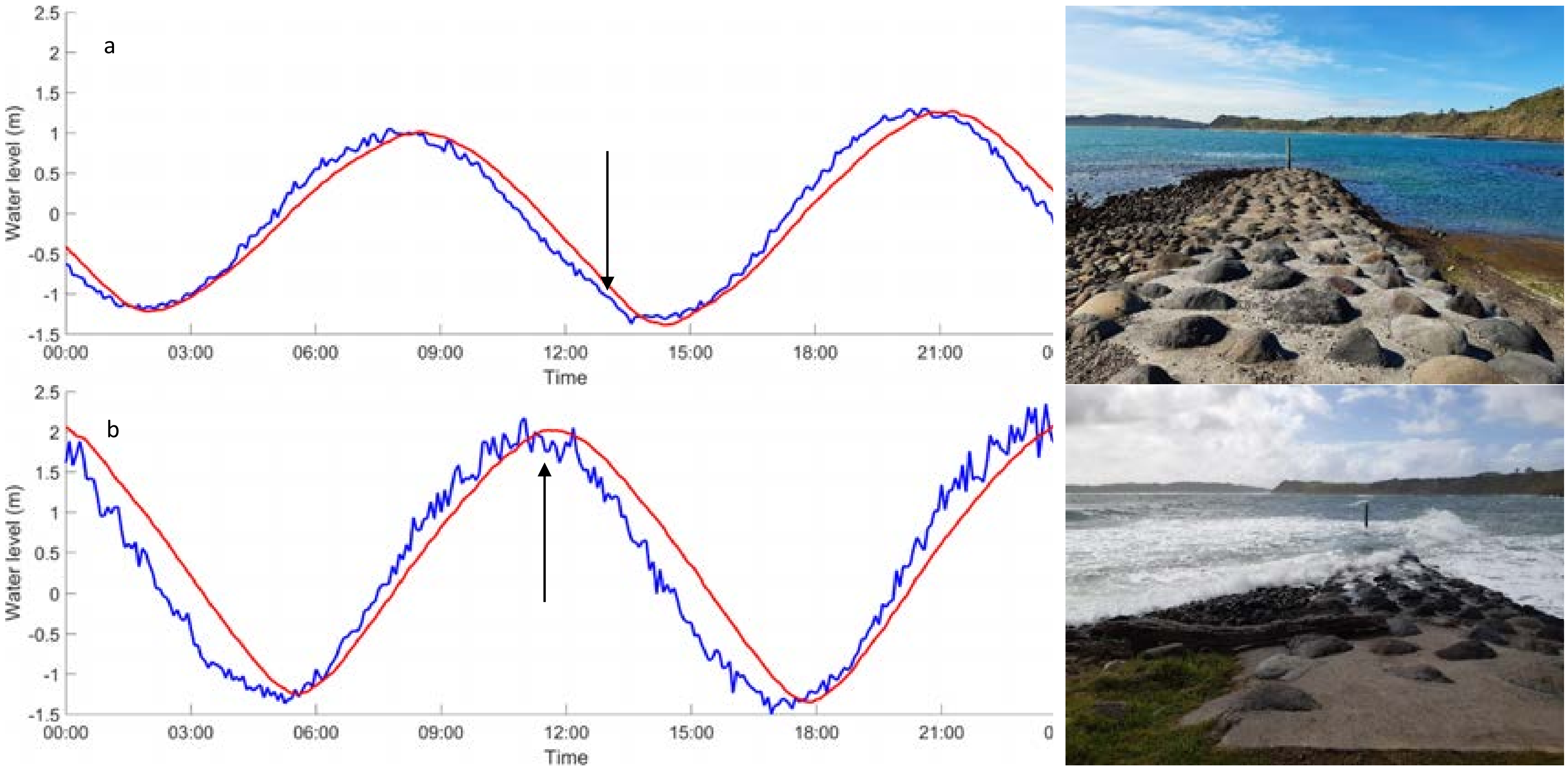

Figure 9. Water levels and images recorded at 13:18 (NZST) on the 17th August 2020 (a) and at 11:44 (NZST) on the 21st August 2020 (b) at Raglan Wharf (red line) and Manu Bay (blue line) tide gauges. The photos show Manu Bay at the time indicated by the black arrows (Images: Steve Hunt, WRC).

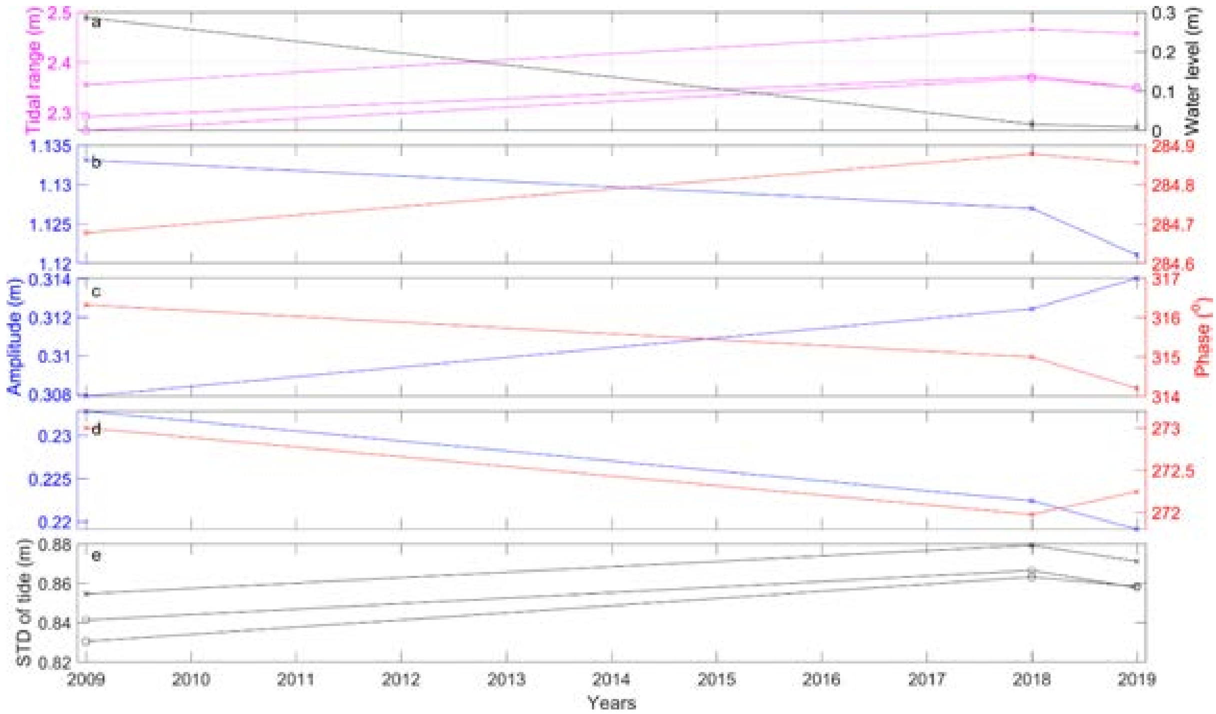

Figure 10. Summary for Manu Bay (a) of mean annual tidal ranges from the tide gauge record (magenta crosses), the reconstructed tidal record based on annual constituents (magenta squares) and the reconstructed tidal record based on constituents from the entire record (magenta circles) and a summary of mean annual water levels (relative to MVD-53) from the tide gauge record (black stars). The amplitude (blue line) and phase (red line) is shown for the main tidal constituents M2 (b), S2 (c) and N2 (d). The nodal cycle (e) is calculated from the annual standard deviation of the tide gauge record (black crosses), the reconstructed tidal record based on annual constituents (black squares) and the reconstructed tidal record based on constituents from the entire record (black circles).

10 Raglan Wharf

Table 3. Raglan Wharf summary

Location	Raglan Wharf
Tide gauge type	Radar gauge
Parameters measured	Sea level, barometric pressure, wind speed and direction.
Sampling schedule	5-minute instantaneous sea level, 5-minute instantaneous barometric pressure, 5-minute instantaneous wind speed and direction.
Date of initial measurement	1st July 2008
Gaps in record longer than 20 days	31/03/2010- 06/11/2012: Wharf fire 25/03/2018 - 01/11/2019: Gauge failure and uncertainty around wharf structure before eventual redeployment.
Datum of gauge zero	Moturiki Vertical Datum 1953 (MVD-53)

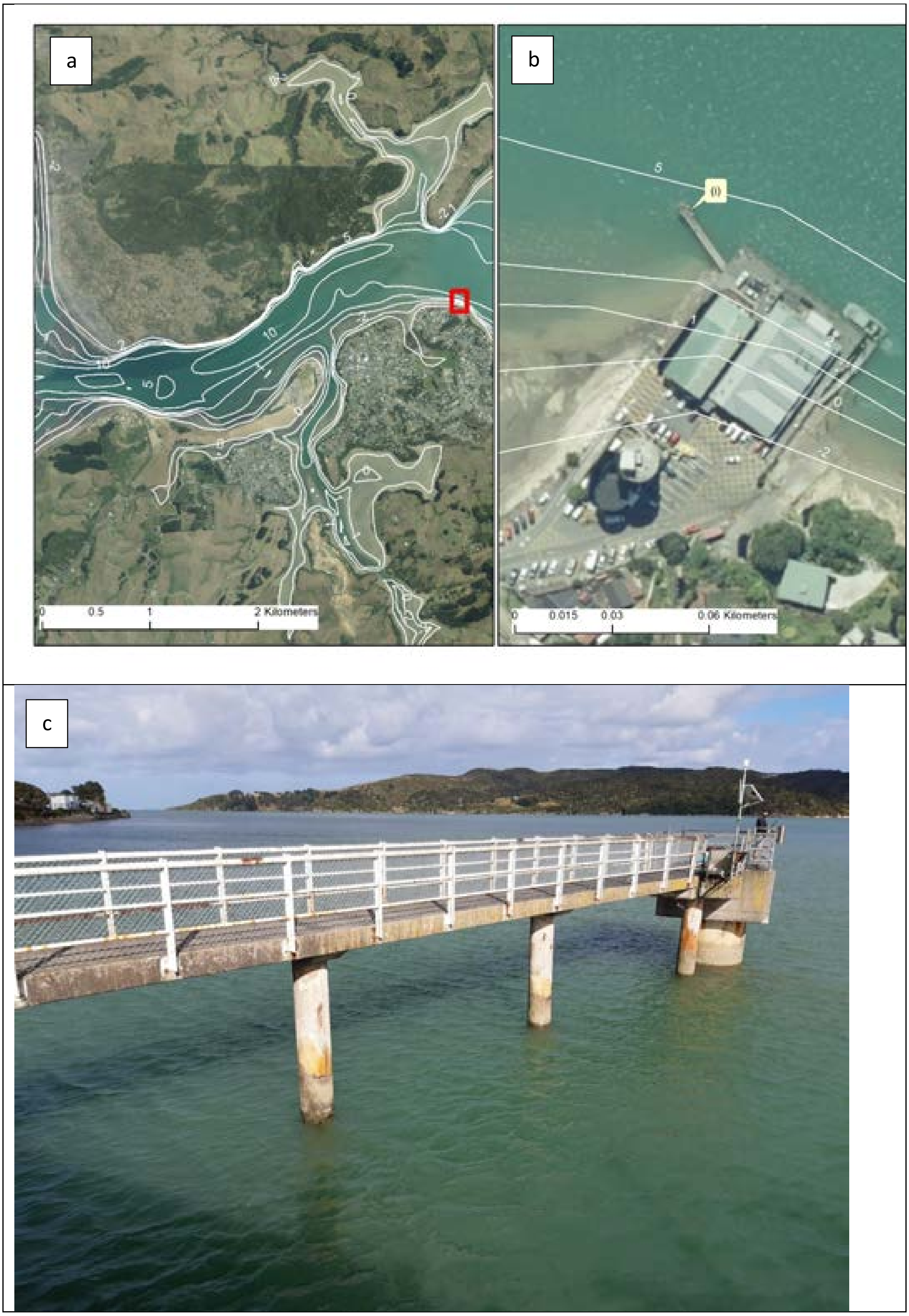

Figure 11. Raglan Wharf tide gauge location showing the wider area (a) and Raglan Wharf (b and c) with the tide gauge instrumentation (i). Extent of (b) is shown as a red box (a). Depth contours are in metres below MVD-53 from a compilation of all available bathymetry in the Waikato Region (Gardiner and Jones, 2020).

The Raglan Wharf tide gauge is a radar gauge installed on the dolphin at the seaward end of the wharf (Table 3 and Figure 11). The gauge was originally installed on the Raglan Wharf in July 2008 but was destroyed in a fire in April 2010. Following the refurbishment of the wharf, the gauge was re-installed in November 2012 and collected data until the housing corroded and collapsed in March 2018. The gauge was not initially reinstalled due to uncertainty over the future of the wharf structure, which is considered structurally unsound by Waikato District Council. Delays in the refurbishment of the wharf structure resulted in WRC choosing to re-install the gauge in November 2019. The gauge has been installed in such a way that it can be easily removed and relocated. The sampling interval was 1-minute prior to 2010, and 5-minute since 2010, with interruptions to the record meaning the timeseries is incomplete (Figure 3). The spectral analysis indicates that the tide gauge is not exposed to higher frequency energy from infragravity or longwaves (Figure 5b). The tide gauge is likely exposed to short-period wind waves generated within the estuary, but the sampling frequency is too coarse to resolve this high frequency energy. Water level data is recorded instantaneously as opposed to burst averaged and this is unusual for a tide gauge, despite this sampling schedule and the gauges exposure to wind waves the record does not seem particularly noisy and appears to be collecting robust data. Atmospheric pressure, wind direction and wind speed are also collected at this tide gauge site.

Harmonic analysis of the tidal record shows some modification of the tidal wave when compared to the phase and amplitude of the constituents from the Manu Bay tide gauge and the regional tidal model outside of the estuary (Table 1). The harmonic (Table 1) and spectral analysis (Figure 5b) show that there are more overtides compared to the gauge at Manu Bay and the open coast model results, confirmed by the higher M4 / M2 ratio, which indicates the tidal wave is less symmetrical compared to the open coast. The modification of the tidal wave is a commonly observed occurrence within the shallow waters of shoaling estuaries and the magnitude of asymmetry is generally dependent on the estuarine morphology. Annual analysis of the tidal record (Figure 12) shows no long-term inter-annual variability in tidal constituents and therefore, although the tidal signal at Raglan Wharf is modified compared to the open coast, the amount of modification has been temporarily consistent at this location over the duration of the record. The stability of the tidal signal is not guaranteed into the future and the tidal signal could be modified because of changes to estuarine morphological and rising sea levels. Annual analysis of the tidal record (Figure 12) also shows tidal ranges generally match changes to the nodal cycle; although the record is too short to identify either a full nodal cycle or long-term trends of sea level change. The record is also too short to calculate the probability and magnitude of extreme water levels.

Analysis of annual MSL of the more contiguous record at Kawhia Wharf to the south showed large variability compared to the gauges at Tararu and Whitianga with periods of prevailing northerly winds causing higher sea levels (Stephens et al., 2015) and it is likely that this variability in MSL occurs at Raglan Wharf as well. Although, it is possible that over many decades the wind-driven variability could average out (Stephens et al., 2015), this is not certain due to any future changes in the wind climate.

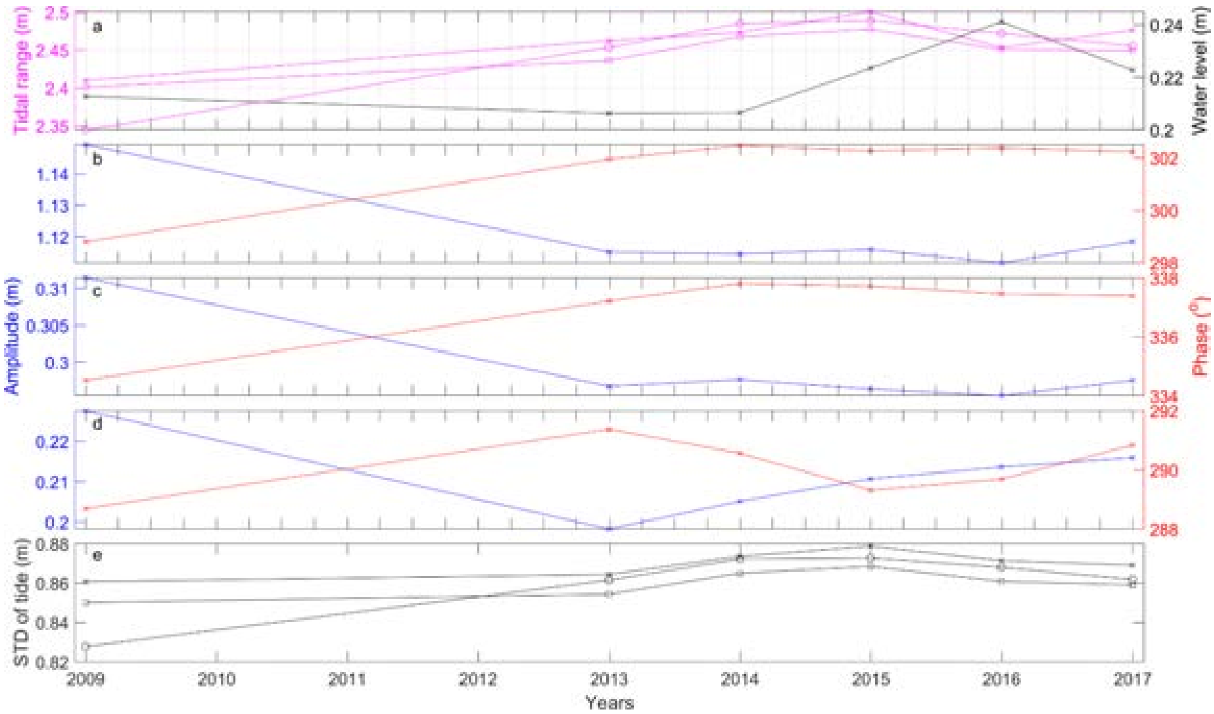

Figure 12. Summary for Raglan Wharf (a) of mean annual tidal ranges from the tide gauge record (magenta crosses), the reconstructed tidal record based on annual constituents (magenta squares) and the reconstructed tidal record based on constituents from the entire record (magenta circles) and a summary of mean annual water levels (relative to MVD-53) from the tide gauge record (black stars). The amplitude (blue line) and phase (red line) is shown for the main tidal constituents M2 (b), S2 (c) and N2 (d). The nodal cycle (e) is calculated from the annual standard deviation of the tide gauge record (black crosses), the reconstructed tidal record based on annual constituents (black squares) and the reconstructed tidal record based on constituents from the entire record (black circles).

11 Kawhia Wharf

Table 4. Kawhia Wharf summary

Location	Kawhia Wharf
Tide gauge type	Bubbler gauge
Parameters measured	Sea level and barometric pressure
Sampling schedule	2-minute instantaneous sea level, 5-minute instantaneous barometric pressure
Date of initial measurement	28th August 2008
Gaps in record longer than 20 days	29/04/2012 - 21/06/2012: Unknown reason
Datum of gauge zero	Moturiki Vertical Datum 1953 (MVD-53)

Figure 13. Aerial photo image of Kawhia Wharf tide gauge location showing the wider area (a) and Kawhia Wharf (b) with the bubbler location (i). Extent of (b) is shown as a red box (a). Depth contours are in metres below to MVD-53 from a compilation of all available bathymetry in the Waikato region (Gardiner and Jones, 2020).

The Kawhia tide gauge is a gas bubbler installed at Kawhia Wharf (Table 4 and Figure 13). The tide gauge was installed in August 2008 and is still recording data at the time of this review; although there are concerns around the condition of the bubbler which is becoming old and unreliable. The recording interval has been 2 minutes since 2012, and prior to this at a 1-minute interval. Water levels are sampled instantaneously as opposed to burst averaged which is unusual for a tide gauge, despite this sampling schedule the record does not seem particularly noisy. Atmospheric pressure is recorded but wind direction and wind speed are not, and the thermometer no longer works. The installation of a bubbler gauge at this location is problematic. It is difficult for WRC to maintain the bubbler gauge and to control for any vertical movement as the pressure outlet is located underwater. Furthermore, a bubbler gauge calculates water levels based on pressure which is dependent on density. Density varies with salinity and temperature; both of which can fluctuate in an estuary more than the open coast and theoretically influence the measured water levels (Pugh, 1996; Woodworth and Smith, 2003). A radar type gauge would be more suitable at this location as it is mounted out of the water and consequently would be easier to maintain and control for vertical land movement. A radar also measures depth independently of water density.

Harmonic analysis of the tidal record shows some modification of the tidal wave when compared to the phase and amplitude of the constituents from the regional model outside of the Harbour (Table 1) and when compared to the constituents recorded at the Manu Bay tide gauge (Table 1). The harmonic (Table 1) and spectral analysis (Figure 5c) also show that there are more overtides compared to the open coast and the gauge at Manu Bay, confirmed by the higher M4 / M2 ratio, indicating the tidal wave is less symmetrical compared to the open coast. The modification of the tidal wave is a commonly observed occurrence within the shallow waters of shoaling estuaries and the magnitude of asymmetry is generally dependent on the estuarine morphology. Annual analysis of the tidal record (Figure 14) shows no long-term inter-annual variability in tidal constituents and therefore although the tidal signal is modified compared to the open coast the tidal signal has been broadly consistent at this location over the duration of the record. Despite the historical stability of the tidal signal, there may be future changes in tidal characteristics from morphological changes in the estuary and rising sea level.

Mean annual tidal ranges and sea levels generally match changes to the nodal cycle, although the record is too short to identify either a full nodal cycle or long-term trends of sea level change (Figure 14). Previous analysis of annual MSL at Kawhia shows large variability compared to east coast sites (Tararu and Whitianga) with periods of prevailing northerly winds causing higher sea levels (Stephens et al., 2015). Kawhia is also highly susceptible to strong north-west winds which produce large storm-surges in the harbour (Stephens et al., 2015). Over many decades the wind-driven variability could average out (Stephens et al., 2015) but this is not certain due to any future changes in the wind climate. Although the record is still quite short it has previously been used to calculate the probability of extreme water levels by using wind data from Port Taharoa and Whatawhata (Stephens et al., 2015).

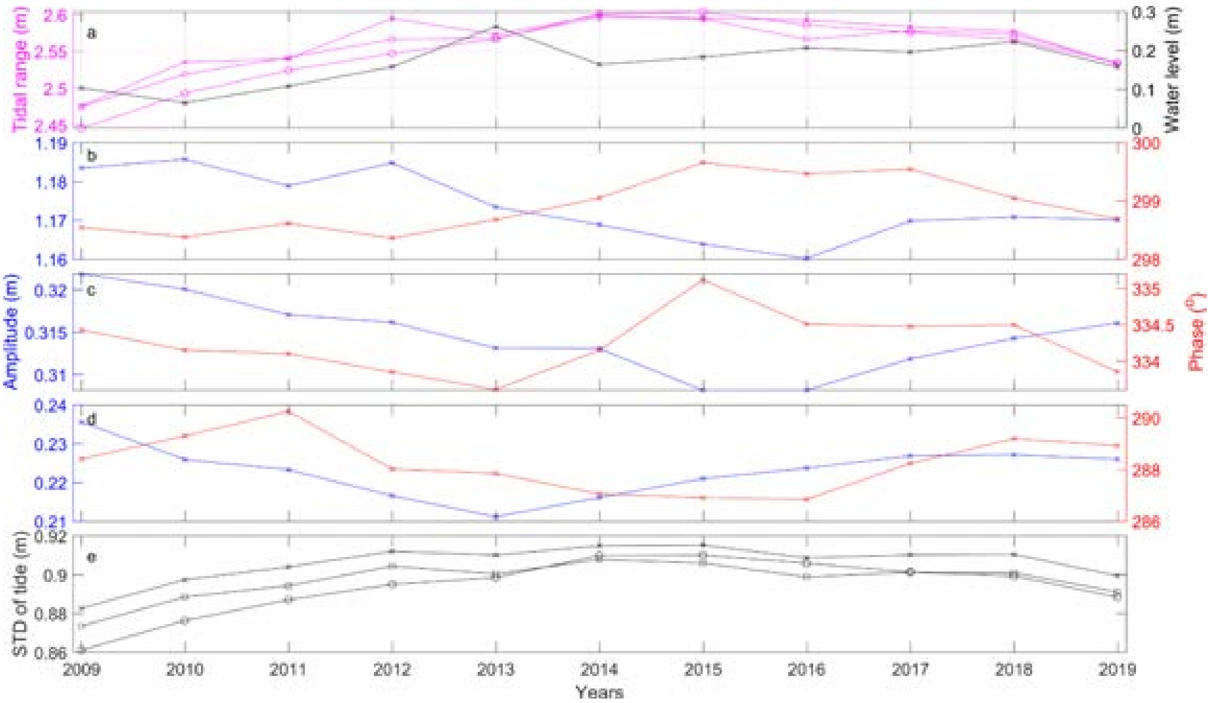

Figure 14. Summary for Kawhia Wharf (a) of mean annual tidal ranges from the tide gauge record (magenta crosses), the reconstructed tidal record based on annual constituents (magenta squares) and the reconstructed tidal record based on constituents from the entire record (magenta circles) and a summary of mean annual water levels (relative to MVD-53) from the tide gauge record (black stars). The amplitude (blue line) and phase (red line) is shown for the main tidal constituents M2 (b), S2 (c) and N2 (d). The nodal cycle (e) is calculated from the annual standard deviation of the tide gauge record (black crosses), the reconstructed tidal record based on annual constituents (black squares) and the reconstructed tidal record based on constituents from the entire record (black circles).

12 Whitianga

Table 5. Whitianga Wharf summary

Location	Whitianga Wharf
Tide gauge type	Radar gauge
Parameters measured	Sea level and barometric pressure
Sampling schedule	1-minute burst averaged sea level (sampling rate and sample duration unknown), 5-minute instantaneous barometric pressure
Date of initial measurement	13th July 1999
Gaps in record longer than 20 days	27/12/2009 – 18/1/2010: Unknown reason.
Datum of gauge zero	Moturiki Vertical Datum 1953 (MVD-53)

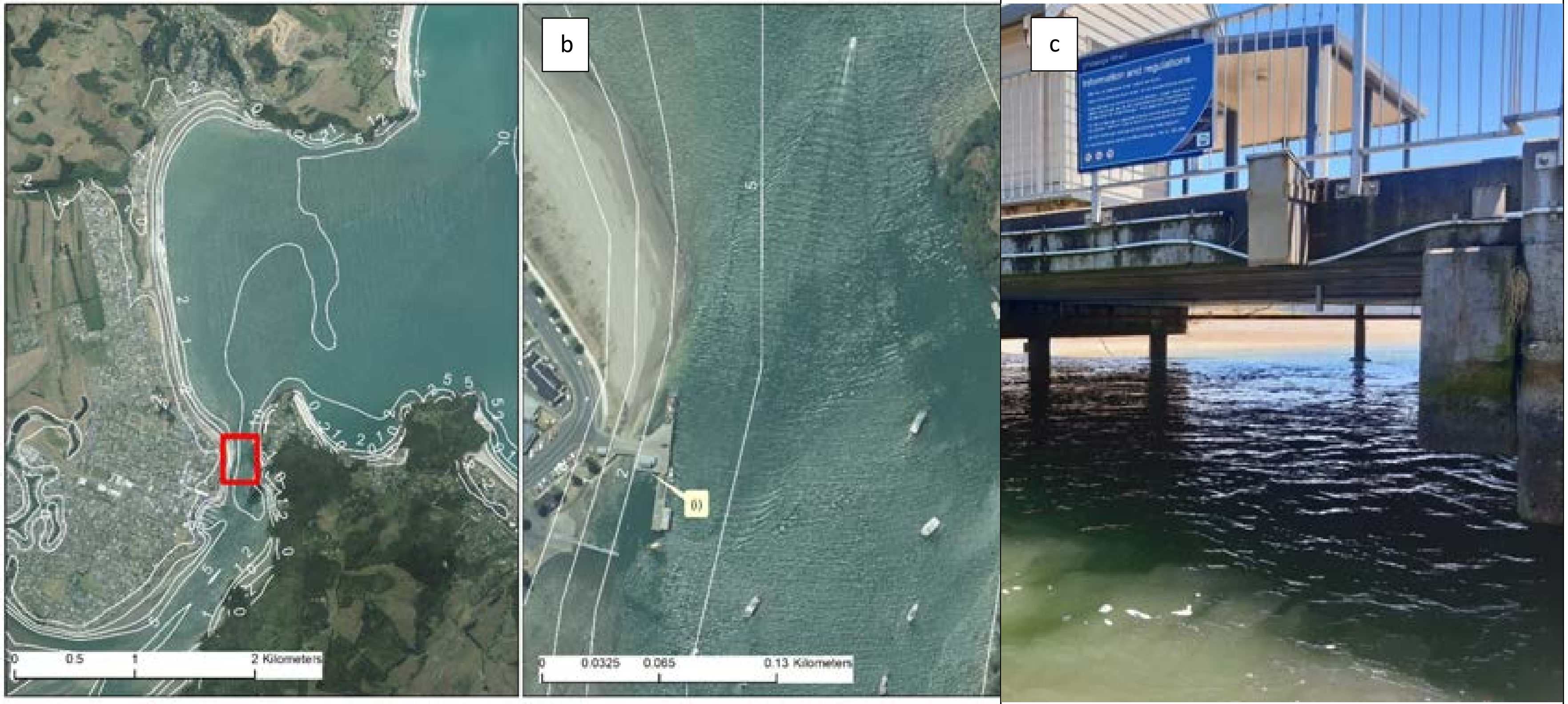

Figure 15. Whitianga Wharf tide gauge location showing the wider area (a) and Whitianga Wharf (b and c) with the tide gauge instrumentation (i). Extent of (b) is shown as a red box (a). Depth contours are in metres below to Auckland Vertical Datum 1946 (AVD-46) from a compilation of all available bathymetry in the Waikato region (Gardiner and Jones, 2020). AVD-46 is 0.0094 m below Whitianga Wharf gauge zero datum (MVD-53).

The Whitianga Tidal gauge is situated on the wharf inside the mouth of the Whitianga Estuary (Table 5 and Figure 15). The gauge is a radar type, and this site has an almost continuous record since its establishment in 1999. The recording interval was 5 minutes until 2009 and has been 1-minute since, the water levels presently being recorded are burst averaged, but the sampling rate and sample duration could not be determined by the Environmental Monitoring team at WRC. Atmospheric pressure is collected at the site but no wind direction or wind speed data. Although the record is relatively short it has previously been used to calculate the probability of extreme water levels by using wind data from other locations (Stephens et al., 2015).

Harmonic analysis and comparison of the Whitianga Wharf with the Moturiki Island tide gauge record (Goring, 1999), water level data collected in Mercury Bay between 22nd August and 20th November 2002 (Stephens et al., 2015) and with the regional tidal model indicates dissipation of the tidal wave at the tide gauge relative to the open coast (Tables 3.1 and 3.6). The M2 amplitude drops by between 0.05 and 0.12 m at the tide gauge compared to the open coast. The decrease in M2 amplitude is accompanied by a slight increase in the M4 amplitude, which increases the M4 / M2 ratio, indicating the tidal wave is less symmetrical compared to the open coast. The harmonic (Table 1) and spectral analysis (Figure 5d) also show that there are overtides within the tidal record but these are less significant than those measured at Kawhia or Raglan on the west coast.

Annual analysis of the tidal record shows significant long-term inter-annual variability in tidal constituents (Figure 16). Annual analysis of the main M2 (Figure 16b), S2 (Figure 16c) and N2 (Figure 16d) constituents at Whitianga show a reduction in amplitude between 2000 and 2006. This results in an overall reduction of measured mean tidal range (Figure 16a magenta crosses) by up to 0.1 m compared to the annual tidal range predicted from constituents (Figure 16a, magenta circles) and 0.2 m compared to the measured tidal range in 1999 prior to the amplitude reduction (Figure 16a magenta crosses). Although the record is long enough to record a complete nodal cycle and an apparent trend of rising sea level, the records are influenced by this reduction in amplitude of the main constituents (Figure 16). The record is also not yet long enough to resolve variations in MSLA due to climatic cycles and so cannot be used to reliably determine a sea-level rise trend.

A tide gauge was deployed between 1973 and 1974 by the Ministry of Works in a similar location to the WRC Whitianga Wharf gauge and analysis of that record (Smith, 1980) indicates that the M2 amplitude was around 0.73 m (Table 6) and therefore larger than the annual M2 amplitudes recorded between 1999 and 2020. In contrast to the changing constituents at the Whitianga Wharf tide gauge, the constituents outside of the estuary are more stable (Table 6). When comparing the M2 amplitude at Moturiki Island in 1999 with the M2 amplitude in Mercury Bay in 2002 a difference of only 0.01 - 0.02m is apparent (Table 6) despite the gauges being in different locations (the Moturiki gauge situated next to Tauranga in the Bay of Plenty 100 km to the south of Whitianga). The M2 amplitude at the Whitianga tide gauge is more variable with a difference of 0.06m over the same time period (Table 6).

Table 6. Summary of M2 amplitudes from other studies and locations

Time period	Open coast location	Open coast M2 amplitude (m)	Whitianga wharf M2 amplitude (m)	Reference
1973	N/A	N/A	0.731	Smith (1980)
1974	N/A	N/A	0.724	
14th July – 3rd November 1999	Moturiki Island tide gauge (Bay of Plenty)	0.737	0.683	Goring (1999)
22nd August - 20th November 2002	Motukorure Island (Mercury Bay)	0.747	0.625	Stephens et al. (2015)
	Pandora Rock (Mercury Bay)	0.755		

A possible mechanism for the reduction in the amplitude of the main constituents between the open coast and the gauge at Whitianga Wharf is “tidal-choking” whereby a shallow, narrow channel modifies the tidal signal through frictional affects resulting in a reduced tidal range and a phase lag inside the estuary relative to the open coast (Hill, 1994; Albrecht & Vennell, 2007). Changes in morphology at the mouth, possibly increased sedimentation over the delta system could then modify the amount of tidal choking at the Whitianga Gauge over time with a substantial amplitude reduction being particularly severe between 2000 and 2006 and the least severe in 1973 and 1974 when the amplitudes were almost consistent with the open coast.

Analysis of bathymetry from 1938, 1979 and 1995 indicates that the Whitianga inlet has infilled (Steeghs, 2007; Steeghs and Healy, 2007). Aerial photo analysis indicates further infilling with the ebb delta increasing in size between 1990 and 2002. Anecdotal evidence also indicates that this infilling became more severe and in 2005 / 2006 the inlet became so shallow that larger vessels could not leave the estuary at low tide (Steeghs, 2007). These patterns of infilling are broadly consistent with the increased tidal choking and reduced amplitude of the main tidal constituents at Whitianga Wharf up until 2006. Bathymetry data has been collected in 2007, 2014 and 2015 by the University of Waikato for WRC and analysis of this data could indicate if the inlet has subsequently eroded and opened and therefore account for the abrupt increase in the amplitude of the main tidal constituents since 2006 (Figure 16).

In summary, it is possible that tidal-choking leads to a variable amplitude reduction and phase lag at the Whitianga tide gauge compared to the open coast. The severity of the effect varies with morphological changes which regulate the amount of constriction at the estuary mouth; with the mouth being temporarily highly constricted between 2000 and 2006. It is also possible that the amplitude reduction between 2000 and 2006 could be in response to an anthropogenic modification to the estuary morphology such as dredging or construction of the waterways.

The spectral analysis also shows a distinct increase in high frequency energy between 16 and 100 minutes (Figure 5d) which has been previously attributed to seiche (Smith, 1980; Goring, 1999). The Seiche at the Whitianga tide gauge is typical with amplitudes of only a few centimetres which oscillate around the main tidal signal (Goring, 1999; Pugh, 2004) (Figure 4). The seiche does not present a coastal hazard but the presence of the seiche indicates that Whitianga could be particularly susceptible to inundation if the seiche is triggered by a larger forcing event such as a tsunami (Goring, 1999; Pugh 2004).

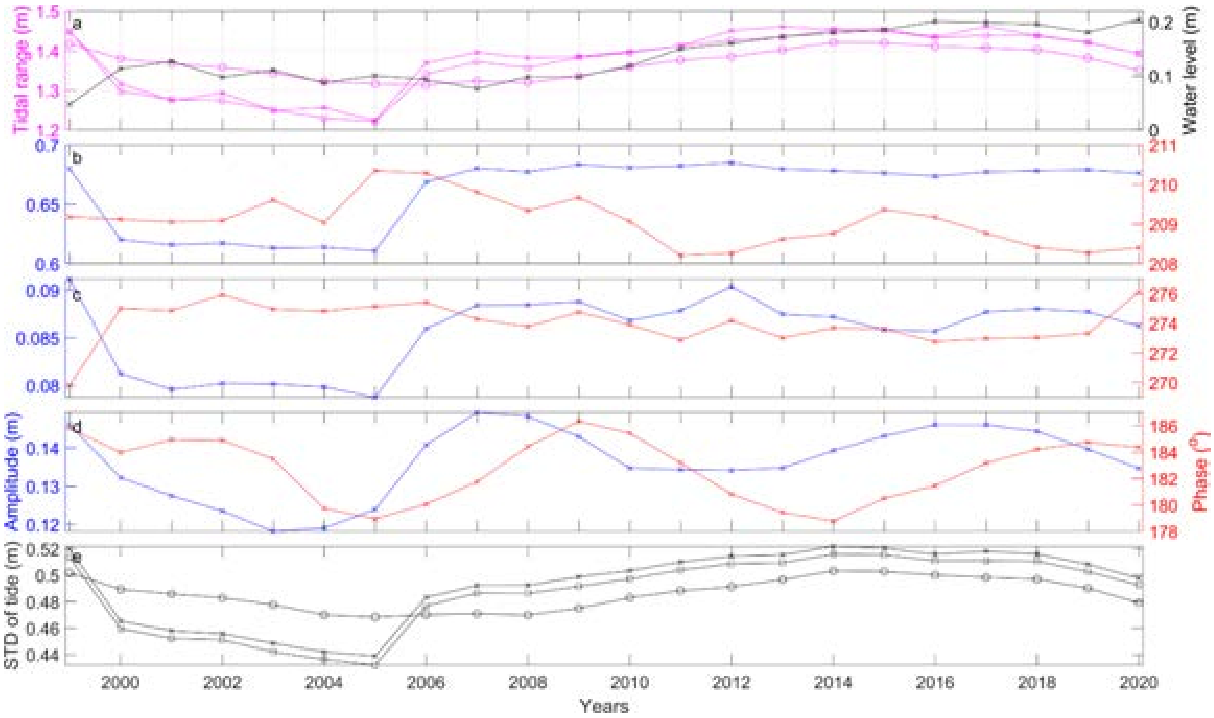

Figure 16. Summary for Whitianga Wharf (a) of mean annual tidal ranges from the tide gauge record (magenta crosses), the reconstructed tidal record based on annual constituents (magenta squares) and the reconstructed tidal record based on constituents from the entire record (magenta circles) and a summary of mean annual water levels (relative to MVD-53) from the tide gauge record (black stars). The amplitude (blue line) and phase (red line) is shown for the main tidal constituents M2 (b), S2 (c) and N2 (d). The nodal cycle (e) is calculated from the annual standard deviation of the tide gauge record (black crosses), the reconstructed tidal record based on annual constituents (black squares) and the reconstructed tidal record based on constituents from the entire record (black circles).

13 Tararu

Table 7. Tararu summary

Location	Thames Tararu platform
Tide gauge type	Ultrasonic sensor
Parameters measured	Sea level (and wave amplitude), barometric pressure, wind speed and wind direction.
Sampling schedule	1-minute burst averaged sea level (sampling rate and duration unknown), 5-minute averaged barometric pressure, 5-minute averaged wind speed and direction
Date of initial measurement	25th May 1990
Gaps in record longer than 20 days	27/12/2009 – 18/1/2010: Unknown reason
Datum of gauge zero	Tararu Vertical Datum 1952 (TVD-52)

Figure 17. Tararu tide gauge location showing the wider area (a) and platform (b and c) with the tide gauge instrumentation (i). Extent of (b) is shown as a red box (a). Depth contours are in metres below Auckland Vertical Datum 1946 (AVD-46) from a compilation of all available bathymetry in the Waikato region (Gardiner and Jones, 2020). AVD-46 is 0.1278 m below Tararu gauge zero datum (TVD-52) as surveyed on installation. Ongoing subsidence of gauge means that gauge zero is no longer at TVD-52.

The Tararu tide gauge is situated on a platform 0.6 km offshore to the north of Thames Township and the mouth of the Waihou River in the southwestern Firth of Thames (Figure 17). The gauge is an ultrasonic sensor without a stilling well, and this site has an almost consistent record since its establishment in 1990 (Table 7 and Figure 3.1). The recording interval was 7.5-minute until 1997, 5-minute until 2011 and has been at 1-minute since. The water levels presently being recorded are burst averaged and based on the sampling schedule used to record wave statistics (discussed further below) it is likely that the sampling rate is 1 Hz and the water levels are burst averaged over 1 minute but this could not be determined by the Environmental Monitoring team at WRC. Vertical land movement has been measured with GPS and shows that between 2007 and 2019 the gauge has subsided by a linear rate of 3.1 mm/yr (Denys, 2019). As the tide gauge and water level record have not been adjusted for vertical land movement the tide gauge datum (gauge zero) is no longer aligned with Tararu Vertical Datum-1952. The water level data logged by WRC and displayed on the WRC website is therefore incorrect and the measured water levels are deeper than the actual water levels.

During very low tides the water beneath the gauge becomes isolated from the rest of the Firth and no longer measures tidal levels with the gauge reading at low tide flattening out (Goring, 2003). The structure is unsound and will be replaced. Atmospheric pressure, wind speed and wind direction are also recorded at Tararu.

The Hauraki Gulf and the connected Firth of Thames is a large, enclosed embayment which progressively shallows towards the south. The embayment becomes more estuarine to the south with larger intertidal areas and increasing freshwater input predominantly from the Waihou and Piako Rivers. Comparison of constituents recorded at the tide gauge with constituents from the regional model in the southern Firth of Thames confirm that the phase and amplitude are very similar (Table 1). However, due to the enclosed morphology the tidal wave is inevitably modified as it travels through the Hauraki Gulf and into the Firth of Thames (Section 2.1 and A1) and therefore the applicability of these measurements to areas further north will be limited. The modelled phase results are slightly lagged compared to the tide gauge measurements and this could indicate that the friction parameter is not well calibrated in the model. Despite this possible calibration issue the model does indicate the relative potential variability in tidal characteristics and that the selection of a representative site in the Hauraki Gulf will be a compromise.

Harmonic (Table 1) and spectral analysis (Figure 5e) show that there are overtides although these are small compared to those encountered in the smaller estuaries of Kawhia and Raglan. The M4/M2 amplitude ratio (Table 1) indicates that the tidal signal is only slightly asymmetric. The relatively small overtide amplitudes and therefore tidal asymmetry relates to the morphology of the Firth of Thames, which although has estuarine characteristics is relatively large, open, and deep compared to the west coast estuaries. The spectral analysis (Figure 5e) also indicates that there is more higher-frequency (short period) energy (< ~20 minutes) at Tararu compared to the estuarine gauges at Whitianga Wharf, Kawhia Wharf and Raglan Wharf. This high frequency energy is likely due to waves that are generated locally and also propagate into the Firth of Thames (Section 2.1 and A.2).

Wave height is recorded at Tararu and is calculated as follows:

1. The water level is recorded at 1Hz over a 1-minute burst, the average, the minimum and the maximum water levels from the burst are retained.
2. The difference is then calculated between the average water level and both the minimum and maximum elevation.
3. The wave height is twice the smallest difference.

It should be noted that the metadata for Tararu in Wiski (WRC data logging software) incorrectly describes the wave parameter measured as “wave amplitude” but this statistic should be called “wave height”. The tide gauge instrumentation was changed on 22nd July 2011, prior to this date wave statistics were collected at 5-minute intervals using a burst frequency of 2Hz, the sample duration used is not known. Analysis of the wave data has noted that in general larger wave heights were recorded before tide gauge instrumentation and sampling schedule were changed (Stephens et al., 2015). Although the wave data would be useful the quality appears to be variable and validation with an independent instrument is required. Elsewhere it has been shown the standard deviation of the water level burst is correlated with significant wave height when sampling at 1Hz over a 3-minute burst, although the specific relationship needs to be validated with an independent wave gauge (Park et al., 2014; Sweet et al., 2015). Logging the standard deviation of each 1-minute burst and recording waves with an independent instrument would enable the approach to be tested at Tararu.

The spectral analysis also shows two increases in high frequency energy centred at around 6.6 and 4.1 hours (Figure 5e) which has been previously attributed to seiche (Goring, 2003). The seiche occurs over a similar frequency as the overtides. The overtides form spikes because they occur at regular frequencies whereas the seiche occurs over a wider range of frequencies and therefore forms lower wider peaks of energy (Figure 5e). The seiche does not present a coastal hazard and is also of a relatively long period compared to a typical tsunami and therefore it is unlikely that the seiche would amplify any incoming tsunami (Goring, 2003).

Annual analysis of the tidal record shows no long-term inter-annual variability in tidal constituents (Figure 18). Mean annual tidal ranges and sea levels generally match changes to the nodal cycle, the record is long enough to identify a full nodal cycle (Figure 18). The record is becoming long enough to resolve climatic cycles and shows an apparent trend of increasing MSL. The relatively rapid increase in mean annual sea level in 1998 - 2000 can likely be attributed to the IPO transitioning from a positive to a negative phase and has been observed elsewhere in New Zealand tide gauge records (Hannah and Bell, 2012). The gauge drying out during large spring tides will likely overestimate measurement of average annual MSL as low water will not be correctly measured; especially towards the peak of the nodal cycle. The record has previously been used to calculate the probability of extreme water levels (Stephens et al., 2015).

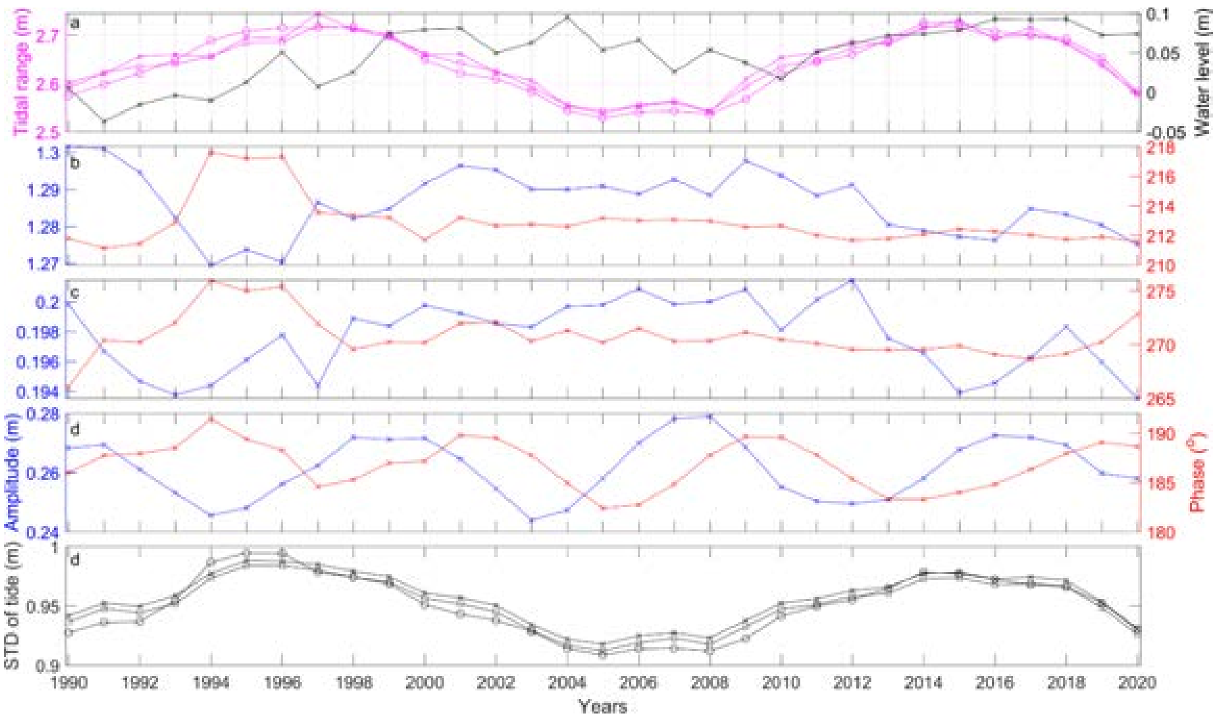

Figure 18. Summary for Tararu (a) of mean annual tidal ranges from the tide gauge record (magenta crosses), the reconstructed tidal record based on annual constituents (magenta squares) and the reconstructed tidal record based on constituents from the entire record (magenta circles) and a summary of mean annual water levels (relative to TVD-52) from the tide gauge record (black stars). The amplitude (blue line) and phase (red line) is shown for the main tidal constituents M2 (b), S2 (c) and N2 (d). The nodal cycle (e) is calculated from the annual standard deviation of the tide gauge record (black crosses), the reconstructed tidal record based on annual constituents (black squares) and the reconstructed tidal record based on constituents from the entire record (black circles).

14 Discussion

14.1.1 Gauge locations

Most of the existing WRC gauges are situated in estuaries due to the ease of access, availability of structures on which to mount them and the sheltered hydrodynamic environments. The disadvantage of this gauge placement is that they do not characterise the wider hydrodynamic environment as each estuary, and sometimes each location within an estuary, has distinct exposure to the various physical processes that form the resultant sea level record. However, hydrodynamic modelling of estuaries can complement a tide-gauge record at the single location by providing spatial information throughout an estuary, with calibration of the model much easier with a long-term gauge in place. Despite the limitation of estuarine gauges for wider regional monitoring purposes, the **Raglan Wharf**, **Whitianga Wharf** and **Tararu** gauges are in appropriate positions near both areas of environmental importance and where other monitoring occurs and areas of high coastal population or coastal hazard risk. The **Kawhia Wharf** record is the least useful gauge in terms of position, but it provides a suitable surrogate for the historically unreliable Raglan Wharf gauge and should be maintained until the Raglan Wharf gauge is established and any modifications to the Raglan Wharf structure are completed. Due to the exposure of the Manu Bay tide gauge to waves and the difficulty of accurately measuring the height of the sensor, the Raglan Wharf gauge may be better able to track trends of long-term sea level rise although any trend will be of most relevance to Whāingaroa (Raglan) estuary. However, the rate of sea level rise at the Raglan Wharf gauge will be of importance as Raglan has a large coastal population. The sizeable record at Kawhia, even if eventually the gauge is removed, has already provided a useful climatology of tides and storm-tide levels in Kawhia Harbour (Stephens et al., 2015; 2020).

There are other locations where tide gauges would be advantageous such as Tairua estuary which has environmental monitoring programmes for water quality, sedimentation, and benthic health. It is likely that other locations are relevant from a coastal hazards perspective, and these could be identified in cooperation with WRC Integrated Catchment Management (ICM) regional resilience team. As tide gauges are expensive to maintain it may be possible to install temporary gauges at sites such as Tairua. A temporary gauge in this location could be run alongside a regional open coast gauge for a shorter length of time (e.g., 1 – 2 years) to establish the relationship between the temporary gauge and a long-term open coast gauge. Water levels recorded at an open coast gauge could then be used to infer water levels at the temporary gauge site after the temporary gauge has been removed. This approach would not be suitable for areas where detailed water level data is required but it would help build-up an understanding of how water levels vary within the estuaries around the region. Pressure gauges on frames could also be utilised to temporarily deploy when extreme events such as cyclones are forecasted. Compared to an open coast permanent deployment, this again will help build-up an understanding of the impacts of extreme water levels on areas of coast without a permanent gauge installed.

The only open coast gauge is at Manu Bay and this gauge is important as it characterises the hydrodynamic environment of the wider open west coast area. The Manu Bay gauge is problematic, the absolute level of the gauge is difficult to survey, the record is noisy and the gauge is exposed to a rough hydrodynamic environment. However, despite these problems the gauge does have strategic value for recording an open coast tidal signal with which any estuary or temporary gauge deployment can be compared with. Furthermore, the Manu Bay gauge has use for model calibration and validation and for defining open coast water levels during storms. There are no alternative locations on Waikato's west coast to situate this gauge and analysis presented here suggests that no further open coast gauges are required for the west coast.

The most significant regional gap in the WRC tide gauge network is the open east coast of the Coromandel, as the Whitianga Wharf gauge is not representative of the wider Coromandel coast and is influenced by changes in the entrance morphology and delta system of Whitianga Estuary (similar issues are possible at other inside-harbour sites such as Tairua, Whangamata or Whangapoua). Spatial analysis of tidal characteristics along the eastern coast indicate that a single gauge will be sufficient to fill this gap in the tide gauge network and establishment of this gauge will support temporary gauging at specific sites of interest. Preliminary results from a temporary tide gauge deployment indicate that Port Charles is a suitable site for the open coast tide gauge as the tidal signal is very similar to that encountered on the open coast (Goring and Bell, 2003; MSL, 2017). Port Charles is an relatively open embayment (Figure 1) with a wharf structure on which a tide gauge could be mounted. Port Charles is situated towards the north of the Coromandel but does not appear to be influenced by the tidal asymmetry associated with Cape Colville (Section 2.1 and Figure A.1d). Port Charles area is also susceptible to tsunami inundation – such as the Tohoku-oki tsunami from Japan on 11 March 2011 which caused the inundation of some houses resulting in EQC claims (Borrero et al., 2013). Further investigation is required into the establishment of a Port Charles tide gauge site.

14.1.2 Record quality

Longer tidal records are more valuable for WRC with a minimum deployment of 30 years, particularly with ongoing sea-level rise. Therefore, each gauge needs to be viewed as a near permanent installation and its location needs to be optimised to make the investment worthwhile. Recording frequency varies between locations, but 1 minute is considered an optimal frequency to allow for higher frequency energy such as longer period infragravity and far infragravity (meteotsunami) waves and tsunami to be measured and should be standardised at all gauges. Increasing the recording frequency at Manu Bay is especially important to allow higher frequency energy in the record to be resolved more effectively and to allow a direct comparison of the record pre and post modification of the bubbler aperture. The sampling schedule varies between different gauges, all gauges should be programmed to sample at 1 Hz with a 1-minute burst average (i.e., averaged every 60 samples) recorded every 1 minute, this recommendation is consistent with the need to record higher frequency energy outlined above and the recommendations in National Environmental Monitoring Standards (NEMS, 2019). The standard deviation of each burst could be used to measure significant wave height, but this would need testing against an independent measurement of waves. Wave data presently collected at Tararu could be useful to provide an indication of wave conditions but is unvalidated. If data collection continues, then it should be independently validated with a wave sensor as a matter of priority.

Currently WRC undertakes a general site inspection every 8 weeks to check the logger, battery, and instrumentation and obtain reference readings of barometric pressure and water level. The reference readings are not detailed and are intended as a sense check to assess the general quality of the records rather than for calibration purposes. No corrections have been made to the instrumentation because of the reference readings. The **Tararu, Kawhia Wharf** and **Whitianga Wharf** gauges have minimal gaps and therefore the record is of good quality. Both **Raglan Wharf** and **Manu Bay** tide gauge records have large gaps and with the quality of the record compromised. Three of the most significant gaps in the records were due to the Raglan Wharf fire, uncertainty over the future of the Raglan Wharf structure and the renovation of the breakwater at Manu Bay; all beyond WRC's control. The installation of the new aperture (bell-housing) at Manu Bay is intended to reduce the outage rate of this gauge but it is not yet known how successful this modification has been (although it has substantially improved the performance of other open-coast bubbler gauges such as at Moturiki Island at Mt Maunganui).

A significant gap in the WRC maintenance schedule is the lack of measurement of vertical land movement and the benchmark stability that the gauge datum is referenced to. Measurements at Tararu identified a significant subsidence rate but nothing is known about rates of subsidence and uplift elsewhere. An annual survey of sensor height is undertaken by WRC to check the height relative to a known datum and this is intended as a basic check to identify any large movement of the gauge. It is unlikely that this technique will be able to establish trends of vertical land movement due to accuracy of the single annual survey and possible vertical movement of the local benchmarks. VLM should be measured at each gauge following the protocol written for WRC (Denys, 2018). Importantly, despite quantifying the VLM at Tararu no correction is made by WRC to the tide gauge instrumentation or the measured water levels. Therefore, gauge zero at Tararu is no longer aligned with Tararu Vertical Datum-1952 and the water levels measured and recorded at this site are incorrect. The incorrect water levels have implications for the telemetry data which is used to assess risk during a flood event, the water level data displayed on the WRC website and the logged data which is recorded and distributed.

Weather information is important as it allows an understanding of the meteorological conditions under which storm surge occurs and wind speed, wind direction and air pressure are currently not collected at **Manu Bay**, **Kawhia Wharf** and **Whitianga Wharf**. At a minimum, this data should be collected at each gauge, if this is not possible then an appropriate surrogate site should be identified.

Radar is the optimal gauge type as the gauge is mounted out of the water and is easy to access and less prone to damage, but can be briefly affected by movement of boats, swimmers or other objects that pass under the gauge. The use of a bubbler gauge at Manu Bay is appropriate but the bubbler at Kawhia Wharf is considered inappropriate for WRC in terms of access and maintenance and a radar type gauge would be more appropriate. The bubbler gauge at Kawhia should be replaced with a radar gauge before it fails to enable a continuous record.

15 Summary and recommendations

This review aims to ensure that WRC operates a tide network that is scientifically robust and serves resource management and climate adaptation by the Council into the future, the key summary points are as follows:

- The Manu Bay (Raglan) tide gauge is sufficient for characterising water levels along the open west coast of the Waikato Region, but monitoring long-term trends of sea-level rise will be difficult due to the significant wave exposure (which applies to any site along Waikato's west coast).
- A single long-term tide gauge would be sufficient for characterising water levels including sea-level rise along the open east coast of the Waikato Region.
- In general, tide gauges situated in estuaries and the Hauraki Gulf / Firth of Thames will have limited relevance for the wider region but will be locally relevant and important if situated in areas with specific hazard risk such as a high population or low-lying land, or adjacent to environmental monitoring sites.
    - Raglan Wharf, Whitianga Wharf and Tararu gauges are locally important for these reasons.
    - Compared to Manu Bay on the exposed open coast, Raglan is the best candidate site for maintaining a long-term record of sea-level rise on the west coast, despite the estuarine location and the fragmented record so far.
    - Kawhia Wharf is less locally important.
- A minimum record length of 30 years is required to resolve water level variations from all relevant signals including deriving sea-level rise trends.
- A recording frequency of 1 minute is most suitable, enabling measurement of long waves such as longer period (> 2 minutes) infragravity waves, meteotsunami and tsunami.
- Tide gauge records need minimal gaps to fully characterise seasonal water level changes in the record.
- Vertical land movement (VLM) needs to be monitored to interpret sea-level change relative to a known datum. Currently, WRC only measure VLM at Tararu on an annual or bi-annual basis.
- Archived and telemetered water levels need to be adjusted for known rates of VLM.
- Monitoring of atmospheric pressure, wind speed and direction are required to interpret and understand the meteorological drivers of storm surge, WRC only record all these variables at Raglan Wharf and Tararu.

The following recommendations are made:

- Maintain all existing tide gauges with the option of discontinuing Kawhia Wharf gauge when the Manu Bay and Raglan Wharf gauges become permanent and stable and modifications to the Raglan Wharf are complete.
- The Kawhia Wharf gauge site should be replaced with a radar gauge in the interim avoiding the problems associated with the ageing bubbler in this location and being easier to maintain.
- Install and maintain an open-coast tide gauge in a suitable location on the Coromandel east coast.
- Plan temporary gauge deployments to help understand local water levels at specific areas of interest, particularly the estuaries and harbours where there are known or emerging coastal flooding or water quality issues.
- Vertical land movement should be routinely measured at all gauges following methods by Denys (2018).

- Ensure that all tide gauge installations record atmospheric pressure at sea level, wind speed and wind direction in addition to water levels. Seawater temperature is less important.
- Standardise sampling at 1 Hz with a 1-minute burst average (i.e., averaged every 60 samples) recorded every 1 minute, so that higher frequency energy can be recorded, this is especially important for the exposed gauge at Manu Bay. The standard deviation should also be recorded to measure significant wave height.

References

Albrecht N, Vennell R 2007. Tides in two constricted New Zealand lagoons. New Zealand of Marine and freshwater Research, Vol. 41, pp. 103-118.

Arduin F, Rawat A, Aucan J 2014. A numerical model for free infragravity waves: Definition and validation at regional and global scales. Ocean Modelling, Volume 77: 20-32.

Aubrey DG, Speer PE 1985. A study of non-linear tidal propagation in shallow inlet / estuarine systems part I: Observations. Estuarine, Coastal and Shelf Science 21: 185-205.

Baart F, van Gelder P, de Ronde J, van Koningsveld M, Wouters B 2012. The effect of the 18.6-year lunar nodal cycle on regional sea-level rise estimates. Journal of Coastal Research, 28(2): 511–516.

Beavan RJ, Litchfield NJ 2012. Vertical land movement around the New Zealand coastline: implications for sea-level rise. GNS Science Report 2012/29. Lower Hutt, IGNS.

Bell R, Lawrence J, Allan S, Blackett P, Stephens S 2017. Coastal hazards and climate change, guidance for local government. Publication number: ME 1341. Wellington, Ministry for the Environment.

Bell RG 1991. Tairua estuary tides. DSIR Water Quality Centre Report No. 6001/1 prepared for Barnett Consultants, Hamilton.

Bell RG, Goring DC 1998. Seasonal variability of sea level and sea-surface temperature on the north-east Coast of New Zealand. Estuarine, Coastal and Shelf Science 46: 308-318.

Bell RG 2021. How will our coasts and estuaries change with sea-level rise? Implications for communities and infrastructure. Part I. In: Clark H ed. Climate Aotearoa: What’s happening & what we can do about it. Allen & Unwin. 61-92.

Bertin X, Olabarrieta M 2016. Relevance of infragravity waves in a wave-dominated inlet. Journal of Geophysical Research Oceans 121: 5418–5435.

Bertin X, de Bakker A, van Dongeren,A, Coco G, André G, Ardhuin F, Bonneton P, Bouchette F, Castelle B, Crawford WC, Davidson M, Deen M, Dodet G, Guérin T, Inch K, Leckler F, McCall R, Muller H, Olabarrieta M, Roelvink D, Ruessink G, Sous D, Stutzmann E, Tissier M 2018. Infragravity waves: From driving mechanisms to impacts. Earth-Science Reviews 177: 774-799.

Bolle A, Wang ZB, Amos C, De Ronde J. 2010. The influence of changes in tidal asymmetry on residual transport in the Western Scheldt. Continental Shelf Research 30: 871-882.

Borrero JC, Greer SD 2012. Comparison of the 2010 Chile and 2011 Japan tsunamis in the Far Field. Pure and Applied Geophysics 170: 1249-1274.

Borrero JC, Bell R, Csato C, de Lange W, Goring D, Greer SD, Pickett V, Power W 2013. Observations, effects and real time assessment of the March 11, 2011 Tohoku-oki tsunami in New Zealand. Pure and Applied Geophysics 170: 1229-1248.

Cagigal L, Rueda A, Castanedo S, Cid A, Perez J, Stephens SA, Coco G, Méndez FJ 2020. Historical and future storm surge around New Zealand: From the 19th century to the end of the 21st century. International Journal of Climatology 40(3): 1512–1525. https://doi.org/10.1002/joc.6283

Codiga DL 2011. Unified tidal analysis and prediction using the UTide Matlab functions. Technical Report 2011-01. Graduate School of Oceanography, University of Rhode Island, Narragansett, RI. ftp://www.po.gso.uri.edu/ pub/downloads/codiga/pubs/2011Codiga-UTide-Report.pdf [accessed 5 April 2017].

de Lange WP, Gibb JG 2000. Seasonal, interannual, and decadal variability of storm surges at Tauranga, New Zealand. New Zealand Journal of Marine and Freshwater Research 34: pp. 419-434

Denys P 2018. Monitoring vertical land motion at tide gauge stations: Recommended procedures. Waikato Regional Council Internal Series Report IS 2018-18. Hamilton, Waikato Regional Council.

Denys P 2019. Firth of Thames RSET Profile GNSS Data Analysis. Unpublished note summarising GPS survey results for Waikato Regional Council by Paul Denys, Otago University. WRC doc # 15002751.

Department of Conservation 2010. New Zealand Coastal Policy Statement 2010. Wellington, Dept. of Conservation.

Dyer KR 1997. Estuaries: A physical introduction. 2nd ed. Chichester, John Wiley.

Friedrichs CT, Aubrey DG 1988. Non-linear tidal distortion in shallow well-mixed estuaries: A synthesis. Estuarine, Coastal and Shelf Science 27: 521-545.

Gardiner S, Jones H 2020. Habitat mapping for the Waikato region coastal marine area: Bathymetry and substrate type. Waikato Regional Council Technical Report 2017/34. Hamilton, Waikato Regional Council.

Goring DG 1995. Short-term variations in sea level (2-15 days) in the New Zealand region. New Zealand Journal of Marine and Freshwater Research 29: 69-82.

Goring D 1999. Whitianga sea-level recorder: Preliminary analysis. NIWA Client Report: CHC99/87 prepared for Environment Waikato (Waikato Regional Council), Hamilton, New Zealand.

Goring DG, Bell RG 1999. El Niño and decadal effects on sea-level variability in northern New Zealand: A wavelet analysis. New Zealand Journal of Marine and Freshwater Research, 33(4): 587-598.

Goring D 2003. Analysis of Tararu sea-level record: 1992-2003. NIWA Client report: CHC2003-062 prepared for Environment Waikato (Waikato Regional Council), Hamilton, New Zealand.

Goring DG, Bell RG 2003. Preliminary analysis of Port Charles sea levels. NIWA letter report., 1 May 2003. WRC doc # 22118604.

Goring DG 2008. Extracting long waves from tide-gauge records. Journal of Waterway, Port, Coastal, and Ocean Engineering 134(5): 306-312.

Goring DG 2009. Meteotsunami resulting from the propagation of synoptic-scale weather systems. Physics and Chemistry of the Earth 34: 1009–1015.

Gorman RM, Bryan KR, Laing AK 2003a. Wave hindcast for the New Zealand region: Deep-water wave climate. New Zealand Journal of Marine and Freshwater Research 37: 589-612.

Gorman RM, Bryan KR, Laing AK 2003b. Wave hindcast for the New Zealand region: Nearshore validation and coastal wave climate. New Zealand Journal of Marine and Freshwater Research 37: 567-588.

Guedes RMC, Bryan KR, Coco G 2013. Observations of wave energy fluxes and swash motions on a low-sloping, dissipative beach. Journal of Geophysical Research: Oceans 118: 3651-3669.

Haigh ID, Eliot M, Pattiaratchi C 2011. Global influences of the 18.61 year nodal cycle and 8.85 year cycle of lunar perigee on high tidal levels. Journal of Geophysical Research, 116, C06025, doi:10.1029/2010JC006645.

Hannah J 1990. Analysis of mean sea level data from New Zealand for the period 1899-1988. Journal of Geophysical Research 95(B8): 12,399-12,405.

Hannah J 2004. An updated analysis of long-term sea level change in New Zealand. Geophysical Research Letters, Vol. 31, L03307, doi:10.1029/2003GL019166.

Hannah J, Bell RG 2012. Regional sea level trends in New Zealand. Journal of Geophysical Research 117, C01004. doi: 10.1029/2011JC007591.

Heath RA 1976. Estimates of the components of sea surface elevation contributing to the long-term variation of mean sea level around New Zealand. Journal of the Royal Society of New Zealand 6(2): 95-105.

Heath RA 1977. Phase distribution of tidal constituents around New Zealand. New Zealand Journal of Marine and Freshwater Research 11(2): 383-392.

Heath RA 1981. Tidal asymmetry on the New Zealand coast and its implications for the net transport of sediment. New Zealand Journal of Geology and Geophysics 24: 361-372.

Heath RA 1985. A review of the physical oceanography of the seas around New Zealand – 1982. New Zealand Journal of Marine and Freshwater Research 19: 79-124.

Hill AE 1994. Fortnightly tides in a lagoon with variable choking. Estuarine, Coastal and Shelf Science 38: 423-434.

Hunt S, Bryan KR and Mullarney JC 2015. The influence of wind and waves on the existence of stable intertidal morphology in meso-tidal estuaries. Geomorphology 228: 158-174.

Hunt S, Bryan KR, Mullarney JC, Pritchard M 2016. Observations of asymmetry in contrasting wave and tidally-dominated environments within a mesotidal basin: Implications for estuarine morphological evolution. Earth Surface Processes and Landforms 41(15): 2207-2222.

Hunt S, Bryan KR, Mullarney JC 2017. The effect of wind waves on spring-neap variations in sediment transport in two meso-tidal estuarine basins with contrasting fetch. Geomorphology 280: 76-88.

Hunt S 2019. Regional Estuary Monitoring Programme (REMP) intertidal sedimentation measurements, results and review of methodologies. Waikato Regional Council Technical Report 2019/04. Hamilton, Waikato Regional Council.

Hunt S, Jones HE 2020. The fate of river-borne contaminants in the marine environment: Characterising Regions of Freshwater Influence (ROFIs) and estuary plumes using idealised models and satellite images. Marine Pollution Bulletin 156, 111169.

Jay DA 1991. Green's Law revisited: Tidal long-wave propagation in channels with strong topography. Journal of Geophysical Research 96(C11): 20,585-20,598.

Jay DA, Leffler K, Degens S 2011. Long-term evolution of Colombia River tides. Journal of Waterway, Port, Coastal, and Ocean Engineering 137(4): 182 – 191.

Khojasteh D, Hottinger S, Felder S, De Cesare G, Heimhuber V, Hanslow DJ, Glamore W 2020. Estuarine tidal response to sea level rise: The significance of entrance restriction. Estuarine, Coastal and Shelf Science 244, 106941.

Komar PD 1998. Beach processes and sedimentation. 2nd ed. Englewood Cliffs, N.J. Prentice Hall.

Laing AK 2000. New Zealand wave climate from satellite observations. New Zealand Journal of Marine and Freshwater Research 34: 727-744.

Levy R, Naish T, Bell R, Golledge N, Clarke L, Garner G, Hamling I, Heine Z, Hreinsdottir S. Lawrence J, Lowry D, Priestley R, Vargo L 2020. Te tai pari o Aotearoa – Future sea level rise around New Zealand's dynamic coastline. In: Hendtlass C, Morgan S, Neale D eds. Coastal systems and sea level rise: What to look for in future. 11-20. Special Publication 4, NZ Coastal Society, Nov 2020. https://www.coastalsociety.org.nz/media/view/publications/sea-level-rise/ [accessed 4 August 2021]

Loughet-Higgens MS, Stewart RW 1962. Radiation stress and mass transport in gravity waves, with application to 'surf beats'. Journal of Fluid Mechanics 13: 481-504.

MacDonald AB 2020. Identification of long period wave events and generating mechanisms at Mount Maunganui, New Zealand. MSc Thesis, School of Environment, Auckland University.

MSL 2017. Tide gauge analysis – Assessment of the tidal wave distortion within the Waikato coastal marine area. Prepared by MetOcean solutions Ltd. for WRC. WRC Internal Series report 2018/17. Hamilton, Waikato Regional Council.

Munk W 1950. Origin and generation of waves. Coastal Engineering Proceedings, 1(1), 1. https://doi.org/10.9753/icce.v1.1

NEMS 2019. National Environmental Monitoring Standard, Water Level. Water Level Field Measurement Standard, Version 3.0.0. Date of Issue: July 2019. https://www.nems.org.nz/ [accessed 23 August 2021].

Orford JD, Pethick J 2006. Challenging assumptions of future coastal habitat development around the UK. Earth Surface Processes and Landforms 31: 1625 – 1642.

Park J, Heitsenrether R, Sweet W 2014. Water level and wave height estimates at NOAA tide stations from acoustic and microwave sensors. Journal of Atmospheric and Oceanic Technology 31(10): 2294-2308.

Peng D, Hill EM, Meltzner AJ, Switzer AD 2019. Tide gauge records show that the 18.61-year nodal tidal cycle can change high water levels by up to 30 cm. Journal of Geophysical Research: Oceans 124: 736–749.

Pickrill RA, Mitchell JS 1979. Ocean wave characteristics around New Zealand. New Zealand Journal of Marine and Freshwater Research 13 (4): 501-520.

Pontee N 2013. Defining coastal squeeze: A discussion. Ocean and Coastal management 84: 204 – 207.

Pugh D 1996. Tides, surges and mean sea-level. Chichester, John Wiley.

Pugh D 2004. Changing sea levels: Effects of tides, weather and climate. Cambridge, UK, Cambridge University Press.

Senior AK 2000. Whangamata tides. NIWA Consultancy Report EVW00216/1 prepared for Environment Waikato (Waikato Regional Council).

Smith DN 1980. Sea level oscillations, hydrology and sedimentology of Mercury Bay. MSc thesis, University of Waikato.

Speer PE, Aubrey DG 1985. A Study of non-linear tidal propagation in shallow inlet/estuarine systems Part II: Theory. Estuarine, Coastal and Shelf Science 21: 207-224.

StatsNZ 2019. Coastal sea-level rise. https://www.stats.govt.nz/indicators/coastal-sea-level-rise [accessed 31 August 2021].

Steeghs L 2007. Morphodynamics of the Whitianga Tidal Inlet, Buffalo Bay, New Zealand. MSc thesis, University of Waikato.

Steeghs L, Healy T 2007. Tidal inlet configuration and bathymetric changes resulting from active sedimentation, Buffalo Bay, New Zealand. Journal of Coastal Research, SI 50 (Proceedings of the 9th International Coastal Symposium), Gold Coast, Australia. 716 – 720.

Stephens S, Robinson B, Bell R 2015. Analysis of Whitianga, Tararu and Kawhia sea-level records to 2014. NIWA Client Report No. HAM2015-046. Prepared for Waikato Regional Council, Hamilton, New Zealand.

Stephens SA, Bell RG, Lawrence J 2018. Developing signals to trigger adaptation to sea-level rise. Environmental Research Letters 13(10): 104004, https://iopscience.iop.org/article/10.1088/1748-9326/aadf96

Stephens S 2019. Storm-tide analysis of Tararu sea-level record. August 2018 (minor updates November 2019). NIWA Client Report No. 2018289HN. Prepared for Waikato Regional Council, Hamilton, New Zealand.

Stephens SA, Bell RG, Haigh ID 2020. Spatial and temporal analysis of extreme storm-tide and skew-surge events around the coastline of New Zealand. Natural Hazards and Earth System Sciences 20: 783-796.

Swales A, Denys P, Pickett V, Lovelock CE 2016. Evaluating deep subsidence in a rapidly-accreting mangrove forest using GPS monitoring of surface-elevation benchmarks and sedimentary records. Marine Geology 380: 205–21.

Swales A, Bell RG, Lohrer A 2020. Estuaries and lowland brackish habitats. In: Hendtlass, C, Morgan S, Neale D eds. Coastal systems and sea level rise: What to look for in future. Special Publication 4, NZ Coastal Society, Nov 2020: 55-64. https://www.coastalsociety.org.nz/media/view/publications/sea-level-rise/ [accessed 4 August 2021]

Sweet WV, Park J, Gill S, Marra J 2015. New ways to measure waves and their effects at NOAA tide gauges: a Hawaiian-network perspective. Geophysical Research Letters 42:9355-9361.

Symonds G, Huntley DA, Bowen AJ 1982. Two-dimensional surf beat: Long wave generation by a time-varying breakpoint. Journal of Geophysical Research 87(C1): 492-498.

Thiebaut S, McComb P, Vennell R 2013. Prediction of coastal far infragravity waves from sea-swell spectra. Journal of Waterway, Port, Coastal, Ocean Engineering (ASCE) 139: 34-44.

Walters RA, Goring DG, Bell RG 2001. Ocean tides around New Zealand. New Zealand Journal of Marine and Freshwater Research 35: 567-579.

Woodroffe CD 2002. Coasts: Form, process and evolution. Cambridge, UK, Cambridge University Press.

Woodworth PL, Smith DE 2003. A one year comparison of radar and bubbler tide gauges at Liverpool. International Hydrographic Review 4(3).

Appendix A

A.1 Tidal processes

The propagation and behaviour of the tidal wave can be described through tidal constituents. The spatial distribution of tidal constituents has been modelled using a regional scale calibrated and validated tidal model (MSL, 2017) to describe the main characteristics of the tidal wave in the WRC CMA (Figure A1). The main tidal constituents that form the semi-diurnal (twice-daily) tide are M2 (Figure A.1a and A.1e) and N2 (Figure A.1c and A.1g) which are driven by the Moon and the S2 tide (Figure A.1b and A.1f) which is driven by the Sun. These tidal constituents, and the resultant semi-diurnal tide, propagate in a counter-clockwise direction as a trapped Kelvin wave with a full 360˚ range of phase around New Zealand (Heath, 1977, Heath, 1985 Walters et al., 2001). This cyclic propagation around New Zealand means that in the Waikato Region the tidal wave travels in a northerly direction up the east coast of the Coromandel Peninsula and in a southerly direction into the Hauraki Gulf / Firth of Thames and along the west coast (Figure A.1). Both M2 (Figure A.1a) and N2 (Figure A.1c) exhibit an increase in amplitude towards the coast which is characteristic of the tidal wave propagating as a trapped Kelvin wave (Walters et al., 2001). The S2 constituent shows a similar increase in amplitude on the west coast but not on the east Coromandel coast where only small amplitudes of 0.1 m are encountered (Figure A.1b). On a regional scale the largest M2, N2 and S2 constituents are encountered on the west coast and the Inner Hauraki Gulf / Firth of Thames.

Spring tides have a larger tidal range and occur when the Moon, Sun and Earth are aligned (a new or full Moon) and neap tides have a reduced tidal range and occur when the Sun and Moon are at right angles relative to the Earth. The influence of the Sun and Moon on water levels are predominantly represented by the S2 and M2 constituents. The slightly different frequencies and the interactions between the S2 and the M2 constituents create the spring-neap cycle (Pugh, 2004) as the tidal forcing goes in and out of phase over the 14.75 days, which is the beat cycle of these constituents. There is very little variability between spring and neap tidal ranges along the east coast of the Coromandel which is contrast to the rest of the region. This lack of a spring neap cycle can be explained by the very small S2 amplitude (Walters et al., 2001) which is around 0.1 m along the east Coromandel coast (Figure A.1b).

Apogean tides have a reduced tidal range and occur when the Moon, in its “monthly” elliptical orbit, is at its maximum distance from the Earth and Perigean tides have an increased tidal range and occur when the Moon is closest to the Earth during the same orbit. The M2 and N2 constituents interact to create the Apogean / Perigean tidal cycle which has a beat period of 27.55 days, called the Anomalistic month (Pugh, 2004). Because the N2 amplitude (Figure A.1c) is larger relative to the S2 amplitude (Figure A.1b) on the east coast of the Coromandel the Apogean / Perigean tidal cycle causes larger variations in tidal range than the more well-known spring-neap cycle (Stephens et al., 2015). Elsewhere in the region the spring-neap cycle causes the main variations in tidal range. Exceptionally large tidal ranges occur when the spring tide occurs at the same time as the Perigean tide (Pugh, 2004)- these events are called Perigean-spring or King tides and peak around every 7 months (see NIWA’s red-alert tide days calendars for Firth of Thames, Taranaki and Bay of Plenty).

The tidal signal can become asymmetric with different durations during the flood and ebb tide (Heath, 1981). The asymmetry in the tidal signal from seabed friction can be detected through the non-liner growth of overtides relative to the fundamental tidal constituents (Heath, 1981; Aubrey and Speer, 1985; Speer and Aubrey, 1985). As the fundamental M2 tidal constituent distorts an M4 overtide is generated (Pugh, 2004) and the ratio of M4/M2 can be used to identify areas of tidal distortion (Heath, 1981; Friedrichs and Aubrey, 1988).

The resolution of the regional tidal model (Figure A.1) is inappropriate for identifying tidal distortion in the immediate nearshore area or within estuaries, but the ratio can be used to identify any regional patterns of tidal distortion over the continental shelf (Figure A.1d). The magnitude of M4/M2 is low throughout the region and does not exceed 0.02 (Figure A.1d), this is consistent with other research (Heath, 1981) and indicates that the there is no significant tidal asymmetry outside of the estuaries and nearshore regions. The tide is slightly asymmetric around Cape Colville, in the southern shallow part of the Hauraki Gulf / Firth of Thames and along the west coast of the region (Figure A.1d). The tidal asymmetry around Cape Colville likely occurs due to the flow curvature around the headland and the associated pressure gradient perpendicular to the shoreline, with more seabed friction on the inside curvature as it rounds the cape. This pressure gradient creates an enhanced M4 constituent and over the long-term a depression of mean sea level compared to offshore (Pugh, 2004). For this reason, although the asymmetry around Cape Colville is likely to be minor, in general tide gauges should not be situated on headlands as the gauge records will not be representative of the wider tidal conditions (Pugh, 2004). The increased M4/M2 ratio in the Hauraki Gulf and the Firth of Thames occurs due to the frictional effects of the shallower water and intertidal areas (Friedrichs and Aubrey, 1988). The M4 constituent becomes more significant in a southerly direction (Figure A.1d) as the water gets shallower and the intertidal areas increase in extent (Figure A.1h). The reason for the slightly larger M4/M2 ratio (1.5%) in the Tasman Sea is not clear. Although water depths are shallower than those on the Coromandel (Figure A.1h) they are not as shallow as the inner Firth of Thames where a comparable M4/M2 ratio is modelled (Figure A.1d). There is an appreciable M4/M2 tidal distortion at Cape Reinga to the north (Heath, 1981) and the distortion off the west coast of the Waikato Region could be part of the same tidal process.

A.1.1 Tides in estuaries

As the tide crosses the New Zealand continental shelf and enters the shallow water, embayments, and estuaries along the Waikato coastline the tidal signal is modified and distorted. Modification of the tidal signal can occur due to the following processes (Khojasteh et al., 2020):

1. Reflection or resonance of the tidal signal (Dyer, 1997).
2. Damping of the tidal signal due to frictional affects associated with shallow water depths (Jay, 1991, Dyer, 1997; Woodroffe, 2002) or a constricted channel connecting a lagoon to the open sea (Hill, 1994; Albrecht and Vennell, 2007).
3. Amplification of the tidal signal due to funnelling (Jay, 1991; Dyer, 1997; Woodroffe, 2002).
4. Distortion of the tidal signal from its sinusoidal shape (tidal asymmetry) associated with non-linearity of tidal propagation in shallow water (Speer and Aubrey, 1985; Friedrichs and Aubrey, 1988).

The largest spatial modifications to the tide will occur within estuaries, where there is a marked contrast in morphology compared to the open coast, as they shallow and ultimately transition into creeks, rivers and streams as the tide diminishes. It is also possible that the tidal signal will change over time, including from sea-level rise (Jay et al., 2011; Bolle et al., 2010; Swales et al., 2020) as estuary morphology is dynamic and subject to modification by humans and climate-change derived changes in sedimentation. Furthermore, as morphology and resultant tidal signal are linked in a non-linear fashion, where the morphology modifies the tide and the tide then modifies the morphology, the two factors can be difficult to separate, and will be increasingly confounded by rising sea level.

As the tidal signal is unique to each estuary, and spatially varies, it is difficult to generalise on a regional scale without site specific information. The uniqueness of the tides at each location within an estuary means that the sea-level record is only applicable to that site and may not apply even to other areas of the same estuary. However, the use of hydrodynamic modelling enables the tides of the entire estuary system to be quantified – but calibration of such models is greatly enhanced and expedited if even a single tide-gauge record is available, even if it was a temporary deployment over several months.

A.1.2 Nodal cycle

The nodal Tide is a gradual change in tidal amplitude with a period of 18.6 years and occurs due to the varying declination[1] of the Moon's orbit relative to the Earth's orbit around the Sun (Pugh, 2004; Haigh et al., 2011; Peng et al., 2019). The amplitude of change that the nodal cycle causes varies with latitude (Pugh, 2004) and due to site specific characteristics of the tides and local bathymetry (Peng et al., 2019). Analysis of tide gauges indicates that the average amplitude of the nodal cycle is only several mm around New Zealand (Hannah, 1990). In particular, for the long-term gauge at Moturiki (Mt Maunganui) the nodal tide amplitude is ~14 mm (Rob Bell, pers. com., formerly NIWA), which is probably applicable to the eastern Coromandel. The nodal cycle mainly influences tidal range and therefore levels of high and low water over the 18.6 year period, but it can also influence mean sea level in shorter term tidal-gauge records (Baart et al., 2012).

[1] Over the 18.6-year cycle, the alignment of the Moon's orbit and the Earth's equator covers a range from +28.9° and +18.3°

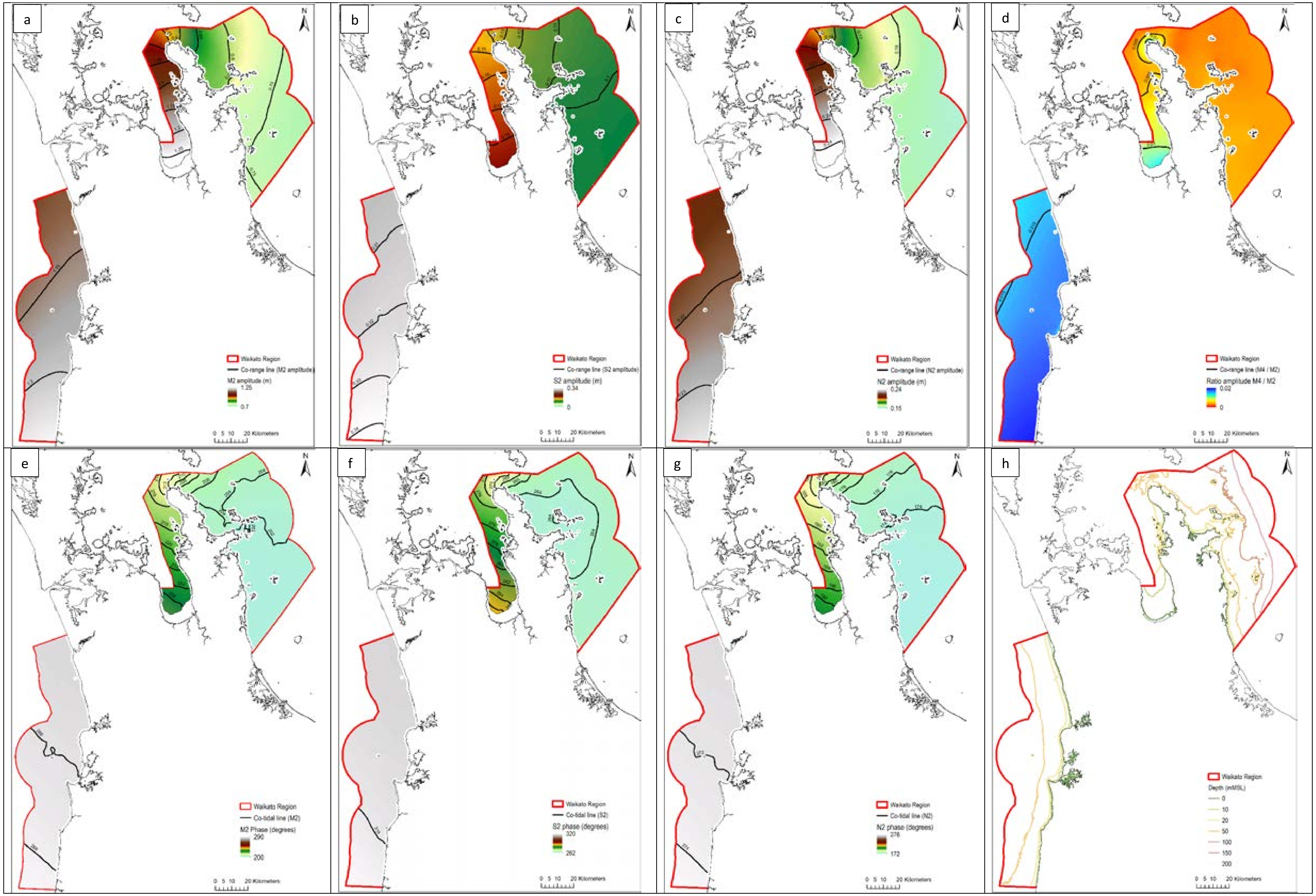

Figure A. 1. Co-range and co-tidal charts showing M2 amplitude (a) and phase (e), S2 amplitude (b) and phase (f), N2 amplitude (c) and phase (g) and M4/M2 amplitude ratio (d) from a regional tidal model (MSL, 2017). Amplitude is the half-range of the constituent (metres) and phase is the timing of the crest of the tide relative to Coordinated Universal Time (degrees). Regional bathymetry (h) from a compilation of all available bathymetry in the Waikato region (Gardiner and Jones, 2020).

A.2 Wind waves

Wind waves and swell typically have a period < 20 secs (Komar, 1998) (Figure 2) and can modify water levels through wave setup and runup. Depending on the requirements, the sampling schedule and the capability of the water-level gauge, these waves can be filtered from the record, either with a stilling well or through post-processing of the data. Alternatively, wave amplitude can be theoretically measured at the tide gauge using an optimised sampling frequency (Sweet et al., 2015) that would be high enough to resolve waves but is still at a frequency that minimises excessive storage and telemetry costs. The size of a wind wave depends on the wind strength and the length of ocean over which the wind blows (i.e. the fetch). Shorter period storm waves are generated locally by winds and the resultant wave climate is dependent on local wind strength and fetch. Longer period waves (generally called swell), typically 8–20 seconds, are generated by distant storms and propagate across the ocean even though they are no longer being sustained by the wind. The resultant wave climate is dependent on not only the wind strength and fetch but also the distance from and the exposure to the resultant swells.

It is the varied exposure of the Waikato region to both local winds and longer-period swells that creates a diverse wave climate (Pickrill and Mitchell, 1979; Laing, 2000; Gorman et al., 2003a; 2003b). In New Zealand, the wave climate is dominated by waves that are generated by the prevailing westerly and south-westerly winds (Figure A.2a, A.2b and A.2d) with the strongest winds occurring to the south of New Zealand (Figure A.2e). Relative to these dominant wind-sea and swell patterns the west coast of the Waikato Region is a wave exposed, high-energy, windward shore (Pickrill and Mitchell, 1979). As such, it experiences the highest average significant wave heights (Figure A.2a) and longest average peak periods (Figure A.2d) in the Waikato Region (Gorman et al., 2003b) with waves predominantly from the south west direction (Pickrill and Mitchell, 1979; Gorman et al., 2003b) (Figure A.2a). Shorter period waves (Figure A.2f) are generated by the local prevailing westerly and south-westerly winds (Figure A.2b and A.2a) and tend to be orientated in a more westerly direction. Longer period swell waves (Figure A.2c) are generated from storms to the south of New Zealand and propagate in a south-westerly direction to the west coast (Pickrill and Mitchell, 1979).

In contrast, the east coast of the Coromandel Peninsula is <u>on average</u>, a much less exposed, low-energy leeward shore (Pickrill and Mitchell, 1979) which experiences the lowest average significant wave heights (Figure A.2a) and shortest average peak period (Figure A.2d) in the Waikato Region (Gorman et al., 2003b). These wind waves are generated by local winds blowing over short fetches. Occasional wind and/or swell waves originate from intense low-pressure systems, often ex-tropical cyclones, that track south-southeast across the north of New Zealand. Although these wind and swell events are episodic, usually short in duration and restricted to the summer/autumn months (i.e. the Pacific cyclone season), they can still be significant in terms of wave height, coastal hazard and erosion.

The Hauraki Gulf / Firth of Thames is also sheltered from the regionally prevailing south-westerly winds and the wind record at the Tararu tide gauge shows that topographically-steered northerly and north-northwesterly winds are more frequent (Figure A.3b). The northerly and north-northwesterly wind directions have potential fetches of 100 and 20 km respectively and therefore there is clear potential for wave generation within the Hauraki Gulf and Firth of Thames (Hunt, 2019). The wind record from Tararu tide gauge (Figure A.3b) and wave hindcast data from a central point at a water depth of 4 m below lowest astronomical tide (LAT) indicate that the Firth of Thames is exposed to both long- and short-period waves. Long period waves occasionally propagate into the Firth whereas the more common shorter period waves are generated along the large fetch coincident with the prevailing northerly wind direction. No wave data has been collected in the Firth of Thames so the hindcast data cannot be verified. Low pressure troughs over New Zealand can create strong and sustained northerly winds (Stephens et al., 2015) and it is likely that these events cause sizeable short-period waves in the Firth of Thames (e.g. 5 January 2018 event).

Waves within estuaries are usually generated locally by wind blowing over the water within the estuary across short fetches. Therefore, the size of the waves and the frequency of their formation will depend on wind speeds, wind directions and the available fetch within an estuary. On occasions it is possible that waves could propagate into an estuary from the open ocean and this will depend on swell direction and the orientation depth and morphology of the estuary mouth. Little is known about the wave climate in the estuaries of the Waikato Region but studies in Whaingaroa (Raglan) Harbour (Hunt et al., 2015; 2016; 2017) indicate that the internal wave climate is likely to be complex and specific to a given estuary.

A.2.1 Climate change

Changes in wave height and the frequency of extreme waves are possible with climate change but predictions are not straightforward and likely to be locally specific (Bell et al., 2017).

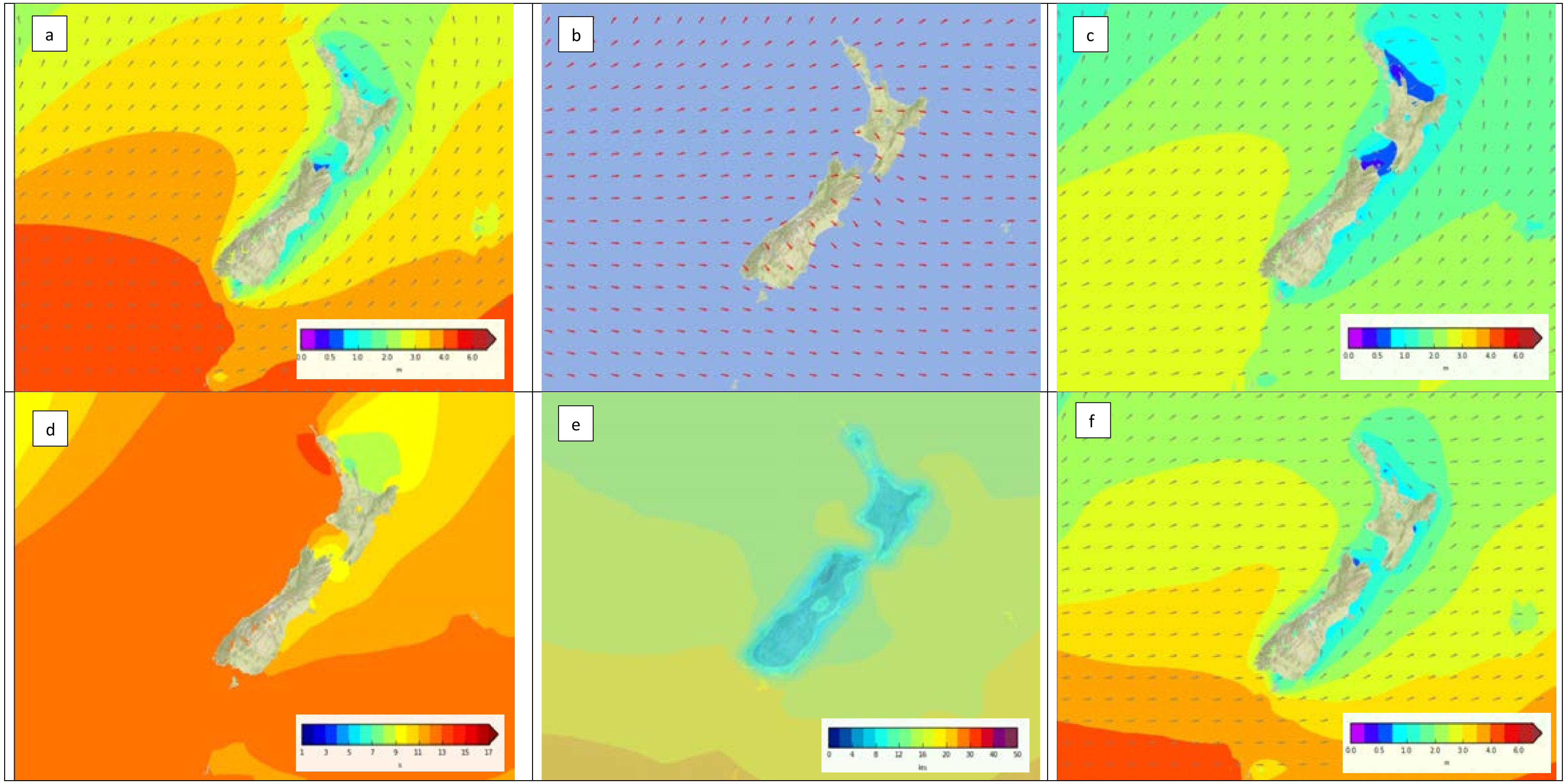

Figure A. 2. Modelled hindcast data showing Mean significant wave height and direction (a), Mean wind direction (b), Mean swell wave height and direction (c), Mean peak period (d), Mean wind speed (e), Mean sea wave height and direction (f). Data from MetOcean View (https://metoceanview.com).

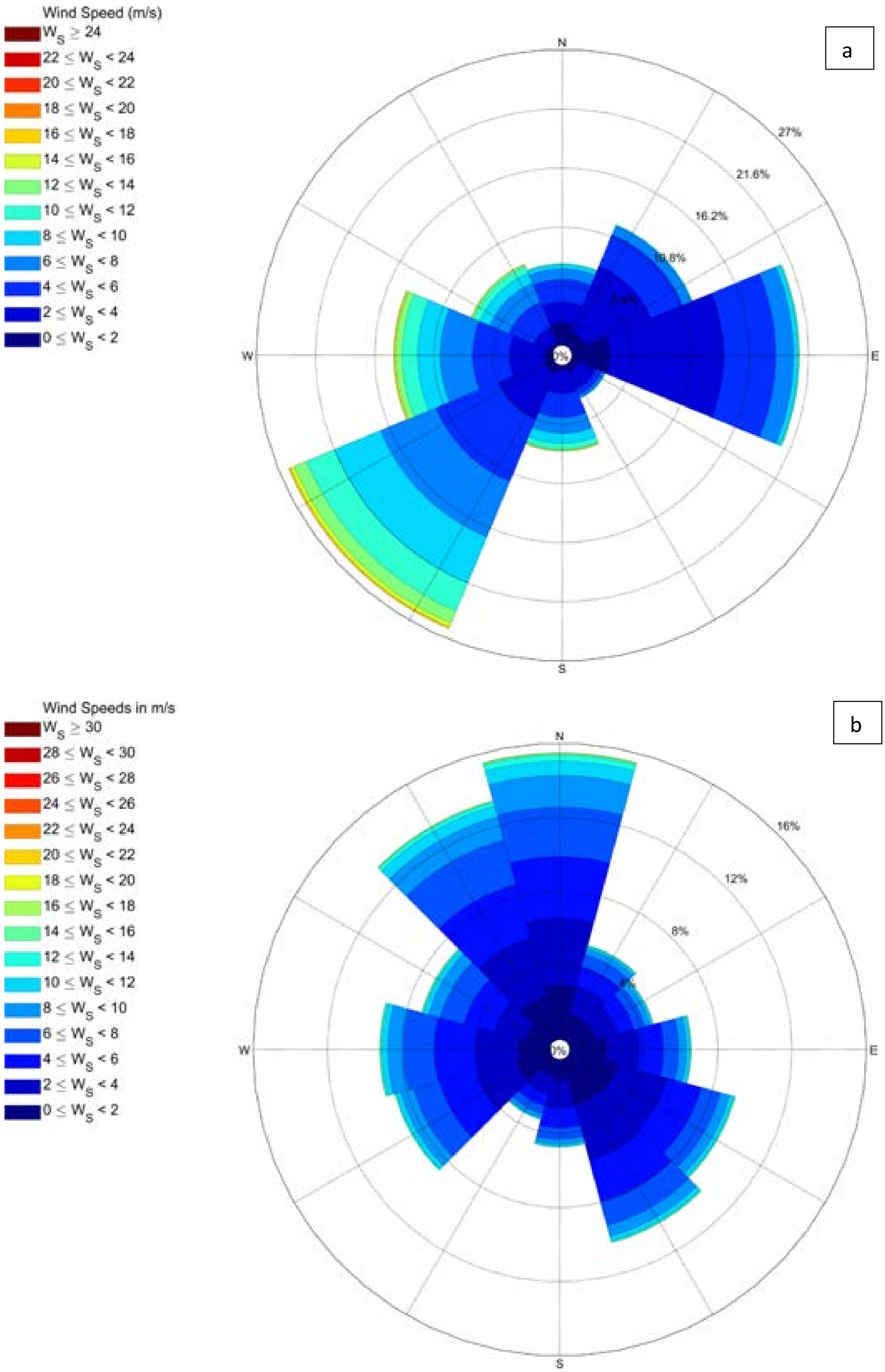

Figure A. 3. Wind roses from Taharoa (a) on the west coast of the region and Tararu (b) near Thames township.

A.3 Infragravity and far infragravity waves

Infragravity waves are long period waves typically ranging between 20–300 seconds with relatively small amplitudes (Komar, 1998) (Figure 2). Longer period far infragravity waves, which include meteotsunami (caused by moving low-pressure systems offshore) or long waves bound to groups of offshore swell through large-scale radiation stresses, typically have periods of 5–20 minutes but can extend up to 1 hour, particularly on the eastern coasts of New Zealand (Goring, 2009; Thiebaut et al., 2013, MacDonald, 2020). Far infragravity waves can be further amplified by local seiching or continental shelf resonance.

The way waves break and dissipate in shallow water is defined in part by their steepness, which is the ratio between wave height and wavelength (Komar, 1998). As infragravity and far infragravity waves are far less steep than conventional waves they consequently behave differently as they propagate into shallow water. Regular waves have a relatively large wave height and short wavelength so become steep and break easily in shallow water causing saturation and dissipation of wave energy at the shore. Infragravity and far infragravity waves have a relatively small amplitude and a very long wavelength so do not become steep enough to break readily in shallow water. Instead, they slow down and increase in height in shallow water, exhibiting a tsunami-like surging up a beach and if the wave is big enough can run up a considerable distance beyond the shoreline due to the large volume of water within a single wavelength over several minutes.

In summary, conventional waves tend to reduce in size towards the shoreline, whereas infragravity waves increase in size towards the shoreline. Infragravity waves can temporarily increase the sea level leading to inundation, modify sediment transport pathways on beaches, cause dune erosion, modify tidal currents in inlets and initiate seiche in harbours and estuaries (Bertin et al., 2018). Infragravity and far infragravity waves can be measured at tide gauges (Goring, 2008) using a sampling frequency that is high enough to resolve the waves. Infragravity and far infragravity waves are generally formed either from the grouping of wind/swell waves through the two processes outlined in the next two subsections (Bertin et al., 2018; Thiebaut et al. 2013) or generated offshore by moving and/or sharply dropping low-pressure systems known as meteotsunami (Goring, 2008; MacDonald 2020), as they appear at the shore as a tsunami-like surge.

A.3.1 Bound waves

Bound waves are formed offshore in deep water due to the different momentum experienced under waves of different amplitudes within a wave group (Longuet-Higgans and Stewart, 1962). The amplitude variation within a wave group occurs due to interactions between different wave trains which combine to form the wave group. When the wave trains are in phase the amplitude of the wave group increases and when the wave trains are out of phase the amplitude of the wave group decreases. The part of the wave group with larger amplitudes transports more momentum than the smaller amplitudes. This difference in momentum pushes down the mean water level more under the larger amplitude part of the group relative to the smaller amplitude part of the group forming a long period infragravity or far infragravity wave which is phase-locked to the wind-wave or swell group (Bertin et al., 2018; Thiebaut et al, 2013).

A.3.2 Moving breakpoint

Infragravity waves can also form due to the varying position of the breakpoint as the wave group enters shallow water (Symonds et al., 1982). The part of the wave group with larger amplitudes breaks further offshore whereas the part of the wave group with smaller amplitudes breaks nearer to the shore causing the position of the breakpoint, and the gradient of radiation stress, to vary in time (Bertin et al., 2018). This time-variation in the gradient of radiation stress is balanced by a time-variation in wave setup creating energy at infragravity frequencies (Bertin et al., 2018). By definition, moving breakpoint waves occur in the surf zone and therefore, although of significance for coastal hazards, they generally cannot be directly measured by tide gauges which are usually situated in deeper water. However, infragravity waves in estuaries can be caused partly by the moving breakpoint due to waves breaking over the ebb tidal delta and the infragravity waves propagating into the estuary during the flood stage of the tide (Bertin and Olabarrieta, 2016).

A.3.3 Regional distribution of infragravity waves

It is likely that infragravity waves will be larger and more frequent on the west coast of the region as infragravity waves are generated by and associated with shorter period wind waves (Thiebaut et al. 2013) and the west coast has the most energetic wave climate (Section A.2). Global modelling of free infragravity waves indicates that the west coast of the Waikato Region has a particularly energetic infragravity wave field (Arduin et al., 2014) and infragravity waves have been measured at Ngarunui Beach, Raglan (Guedes et al., 2013). Little is known about infragravity waves throughout the rest of the region, apart from measurements and analysis straddling the Region's east coast in outer Hauraki Gulf-Marsden Point (Goring, 2008) and the Bay of Plenty (MacDonald, 2020), which indicate far infragravity wave heights can be 0.6 m or higher.

A.4 Storm surge

Storm surge refers to a temporary (typically less than ~15 days) increase in sea level above the predicted tide and arises due to a combination of wind and a drop in atmospheric pressure as described in the subsections below. Storm surge is usually expressed as the probability of a water level being exceeded or equalled, which can be used to estimate the risk of flooding or inundation which is important for coastal management (Pugh, 2004; Stephens et al., 2015). The annual exceedance probability (AEP) describes the probability of a given water level occurring each year and is expressed as a percentage. The average recurrence interval (ARI) describes the average amount of time between water levels of a similar magnitude.

As records of water levels are relatively short (years to decades) from most tide gauges in New Zealand, the observations need to be extrapolated to estimate rarer events using extreme-value models. This extrapolation is commonly done by either using generalised extreme value (GEV) distributions fitted to measured annual maxima (Pugh, 2004) or by using the generalised Pareto distribution (GPD) fitted to observed values that exceed a defined threshold (Stephens et al., 2015). The ability to accurately estimate storm surge and especially rarer, more extreme events, is dependent on the length and quality of the tide gauge record. For example, when using the GEV distribution extrapolation the maximum return period should not exceed four times the length of the actual record (Pugh, 2004). Therefore, a commitment to maintaining long records is vital to both estimate extreme events and improve understanding around the causes and drivers of storm surge which vary around the Waikato region.

A.4.1 Wind

Wind setup from onshore wind results in water to pile up against the downwind coast e.g. winds blowing down into the Firth of Thames from the northerly quadrant. The magnitude of wind setup increases with longer distances over which the wind blows, larger wind speeds and shallower water depths (Pugh, 2004). Coriolis force also deflects open coastal waters, with shore-parallel winds that blow with the coast on the left also causing water level setup e.g. along the western Waikato coast, this arises from strong north to northwesterly winds, while on the open eastern Coromandel coast, nearshore waters are setup during strong south-easterly winds and well as onshore north-easterlies. Although waves also occur due to wind they are commonly considered in sea level studies as a distinct process and have been described separately (Section A.2).

In New Zealand, the magnitude of storm-surge appears to vary with relative exposure to the prevailing westerly wind conditions (Goring, 1995). Both the west coast and the Firth of Thames are susceptible to storm surge during strong and sustained winds from the northwest (Stephens et al., 2015). Along the west coast of the Waikato Region the north-westerly wind contains both shore-parallel and shore-perpendicular components and the wind drag and lateral Coriolis force causes water levels to increase along the coast and in estuaries – as do direct onshore westerly winds. In the Firth of Thames, the wind drag causes increased water levels downwind at the southern end of the Firth. Strong and sustained winds from the north-west generally occur in response to low-pressure troughs passing over New Zealand. Along the east coast of the Coromandel, onshore or cross-shore winds are generally not as sustained or as strong and are therefore less important in elevating water levels (Stephens et al., 2015). However, extreme wind setup can occur on the eastern seaboard when an offshore anticyclone stalls or a slow-moving deep ex-tropical cyclone can result in sustained north-easterly winds e.g., storm surge of 6-8 March 1954 and 9-10 April 1968 (cyclone *Gisele* – "Wahine storm") recorded by a gauge in Tauranga Harbour (de Lange and Gibb, 2000).

A.4.2 Atmospheric pressure

The inverted barometer effect is a regional sea level response to changes in atmospheric pressure , where high air pressure depresses the sea surface and low air pressure temporarily allows the sea surface to rise. Theoretically, a decrease in air pressure every 1 millibar below the average barometric pressure of the region (around 1015 mb for the Waikato Region) will result in a 1 cm increase in sea level (Pugh, 2004). For example, a low barometric pressure on 990 mb would contribute an inverted-barometer setup in sea level of around 25 cm. In the Waikato Region the influence of atmospheric pressure on storm surge is more dominant along the east coast of the Coromandel because of reduction in air pressure is usually associated with intense low-pressure systems that move along the north-east coast of the North Island (Goring and Bell, 2003; Goring, 1995; Stephens et al., 2015). These low-pressure systems are often ex-tropical cyclones (Stephens et al., 2015). Ex-tropical cyclones can also move along the west coast of New Zealand.

A.4.3 Climate change effects on storm surge

Changes in the frequency and magnitude of storm surge are possible with climate change but projections have shown changes in storm surge heights are not likely to be substantial – especially when compared with the dominant influence of sea-level rise (Bell et al., 2017). Recent climate-ocean modelling of storm surges around New Zealand has confirmed that in northern regions of New Zealand, storm surge heights for a 50-year return period event are likely to remain the same or a slight decrease of a few centimetres for RCP4.5 and RCP8.5 projections (Cagigal et al., 2020; Figure 8).

A.5 Mean sea level anomaly

The mean sea level anomaly (MSLA) describes the variation of the non-tidal sea level over timescales ranging from monthly to decadal relative to mean sea level (Stephens et al., 2020). MSLA can occur in response to winds, storminess and coastal water densities (salinity and temperature) which in turn are related to seasonality and climatic modes such as the El Niño–Southern Oscillation (ENSO) (Heath, 1976; Bell and Goring, 1998; Stephens et al., 2020). Monthly averaged MSLA in New Zealand follows a seasonal pattern and peaks between March and June, usually in April for the north-eastern seaboard, and is dominated by thermo-steric sea-level adjustments and secondary forcing variables of barometric pressure and alongshore wind stress (Bell and Goring, 1998; Stephens et al., 2020). The seasonal-only variations in MSLA are of interest as although they are small in magnitude with amplitudes of around 0.04–0.08 m recorded in New Zealand tide gauges (Bell et al., 2017, Appendix J), they appear to exert an important control on the timing of both extreme storm-tide and skew-surge events around New Zealand (Stephens et al., 2020).

Over longer timescales ENSO operates on a 2–4 year cycle (Bell and Goring, 1998; Goring and Bell, 1999; Hannah and Bell, 2012; Bell et al., 2017). Generally, across New Zealand, ENSO contributes up to around ±0.12 m to MSLA (Bell et al., 2017, Appendix J). El Niño episodes generally depress mean sea level and La Niña episodes elevate mean sea level (Goring and Bell, 1999; Hannah and Bell, 2012). Analysis of sea surface temperature records at Leigh (Hauraki Gulf) indicate that El Niño and La Niña events reduce and increase upper water-column temperatures respectively, which are hypothesised to drive the changes in MSLA along the eastern seaboard (Goring and Bell, 1999). The Interdecadal Pacific Oscillation (IPO) is a long-term 20–30 year oscillation of sea-surface temperature patterns in the wider Pacific Ocean that can influence the frequency and intensity of ENSO (Goring and Bell, 1999; Hannah and Bell, 2012). IPO has influenced annual sea level in New Zealand by ± 0.05 m and occurs as an abrupt increase in sea level as the IPO index shifts from positive to negative followed by stability or gradual decrease (Bell et al., 2017, Appendix J; Hannah and Bell, 2012).

A.6 Sea-level rise

As global temperatures rise the ocean sea level increases due to two mechanisms (Bell et al., 2017): i) water volume increase occurs as ocean waters warm and ii) water mass increases as land ice melts and releases water into the oceans.

From 1900 up to 2018, the average rise in mean sea level in New Zealand waters has been 1.77 ±0.05 mm per year (mm/yr) (StatsNZ, 2019), which is slightly higher than the global-average rate (Bell, 2021). Splitting the four longest New Zealand tide-gauge records into approximately 60-year halves reveals the rate of rise has accelerated two-fold in recent decades, with an average rise of only 1.21 ±0.11 mm/yr from 1900–1960 increasing to 2.44 ±0.10 mm/yr from 1961–2018 (StatsNZ, 2019). More recently, since 1993, called the ‘satellite era’, analysis has shown, albeit over a shorter period over 27 years, the rise in global mean sea level has increased further to a rate of 3.5 mm/yr (Bell, 2021).

Sea-level rise will further accelerate in the future due to increased warming from greenhouse gases emissions and the delayed response to increasing loss of polar ice sheets (Bell et al., 2017; Bell, 2021). Therefore, it is important to monitor rates of sea-level rise and patterns of storm surge as it will impact the zonation of intertidal habitats (Orford and Pethick, 2006; Pontee, 2013), increase the frequency of flooding and inundation, change patterns of erosion and accretion (Bell et al., 2017) and as an early signal and trigger for dynamic adaptive pathways planning for adaptation of low-lying coastal areas (Bell et al., 2017; Bell, 2021).

Sea-level rise is measured by analysing trends in mean annual sea level (Hannah, 2004; StatsNZ, 2019) which is the average sea level calculated during a calendar year. There is likely to be small variations in sea-level rise around the region due to differences in oceanographic processes (Hannah and Bell, 2012, Bell et al., 2017, Bell, 2021) which means there will be uncertainty on the spatial variability around the Waikato region and therefore needs monitoring.

When calculating sea level rise the length of the record is critical because sea level changes due to factors such as climatic cycles (Section A.5) can obscure the relatively small signal from sea-level rise. To calculate annual mean sea level an entire year of data is required to minimise influence of the seasonal MSLA. Then around 5 years of annual mean sea levels would be required minimise the influence of the ENSO cycle, 18.6 years of annual mean sea levels would be required to minimise influences of the nodal cycle (Section A.1.2) and at least 30 years of annual mean sea levels are required to minimise the influence of the IPO. In summary, 30 years of sea level data with a nearly complete record would be required at a minimum to begin to track rates of ongoing sea-level rise due to climate change. Building on existing sea-level gauge data records already provides a head start. Ideally in the past, with slower rates of rise in sea level, 50 years was seen as the prerequisite for establishing linear trends (Hannah and Bell, 2012; Bell et al., 2017).

A.7 Vertical land movement and relative (local) sea-level rise

Sea levels are measured relative to the vertical position of the tide gauge. If the land and/or structure to which the tide gauge is attached is either subsiding or rising, then this vertical structure and land movement must be quantified to enable the sea level to be expressed relative to a datum. Of particular concern are areas that exhibit ongoing subsidence (e.g., settling of sedimentary basins, inter-seismic slow-slip), which exacerbates the rise in ocean sea level, and brings forward in time when a given mean sea level threshold is reached (Levy et al., 2020). Therefore, tide-gauge installations measuring relative sea-level rise in areas of higher subsidence will be an essential component of coastal management to predict when a local adaptation threshold (e.g., number of coastal flood events or a pre-set rise in mean sea level) might occur and therefore when the next adaptation pathway should be implemented, given sufficient lead time (Stephens et al., 2018).

Analysis of vertical land movement at near coastal sites in New Zealand using more than 10 years of continuous GPS data, complemented by wide spatial coverage of InSAR (satellite radar measurements), indicate that the Waikato region is experiencing some subsidence on the west coast and near stability or slight uplift on the Coromandel, with localised areas of subsidence such as the northern Hauraki Plains and the reclaimed foreshore areas of the Thames / Tararu coastline (Beavan and Litchfield, 2012; Levy et al., 2020).

Regionally, GPS measurements have been undertaken annually by WRC, NIWA and the University of Otago at a series of intertidal sedimentation monitoring sites in the southern Firth of Thames and the Tararu tide gauge (Section 3.6). The latest survey data indicates that the sedimentation monitoring sites are subsiding at a rate of between 8.7 – 9.4 mm/yr and the tide gauge is subsiding at a rate of 3.1 mm/yr (Denys, 2019). The difference between the relatively coarse national datasets (although the new InSAR analysis is increasing the spatial resolution) and the site-specific measurements demonstrates the requirement to regularly measure vertical land movement at each tide gauge and the associated benchmarks. A protocol to measure this subsidence has been prepared for WRC (Denys, 2018) but has not yet been implemented.

A.8 Tsunami

Tsunami is not an important factor for situating tide gauges, but tide gauges do record water levels during tsunami and provide useful local information, such as resonance from tsunami (Borrero and Greer, 2012; Borrero et al., 2013). To effectively measure the tsunami a sampling and recording interval of 1 minute is optimal (Goring, 2008) and the gauge facility should be structurally robust especially if situated on the exposed open coast.

A.9 Seiche

Seiche occurs due to local resonant oscillations of sea level in the nearshore area and can be initiated by internal and surface gravity waves, winds, atmospheric pressure disturbances and seismic activity (Pugh, 2004). Seiche occur within semi-enclosed bodies of water such as estuaries and typically form high frequency oscillations around the dominant tidal signal, with periods less than 30 mins and amplitudes of a few centimetres but can be much larger if initiated by tsunami (Pugh, 2004). There has been no systematic study of seiche in the Waikato Region and it is difficult to generalise without site specific measurements or modelling but Whitianga is known to be susceptible to high frequency and low amplitude seiche (Goring, 1999).

A.10 River flows

Where river flows are high they can modify water levels with the most likely impact occurring in the lower reaches of tidal rivers, these are: Waikato River Estuary, Awakino River Estuary, Marokopa River Estuary, Mokau River Estuary, Waihou River Estuary and Piako River Estuary.